East Wanneroo District Structure Plan

District Water Management Strategy – Addendum 1

Prepared for Department of Planning, Lands and Heritage

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land and water solutions

Disclaimer and Limitation

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1 INTRODUCTION

This addendum to the *East Wanneroo District Structure Plan – District Water Management Strategy* (EWDWMS) (Urbaqua, 2021) has been prepared to support the rezoning of revised *East Wanneroo District Structure Plan* stage 1 areas from Urban Deferred to Urban zoning under the Metropolitan Region Scheme.

On 25 June 2025, the Western Australian Planning Commission resolved to transfer the East Wanneroo District Structure Plan - Precincts 7, 8 and Part of Precinct 15 from the Urban Deferred zone to the Urban zone pursuant to Clause 23 of the Metropolitan Region Scheme (MRS). The land rezoned forms part the stage 1 boundary, that is the subject of this addendum. Lifting of urban deferment over areas outside of the amended stage 1 boundary presented in this addendum will not be progressed until a district groundwater management scheme – phase 2 has been designed and approved, including under the *Environmental Protection Act 1986* (EP Act) for implementation and its governance and delivery mechanisms are agreed. Any lodged local structure plans and subdivisions will not be progressed prior to lifting of urban deferment.

This addendum presents information from groundwater modelling undertaken since the EWDWMS was prepared, including a confirmed district scale controlled groundwater level (Figure 1) that has been applied to develop a revised boundary for the stage 1 areas (Figure 3)and provides supplementary guidance for the development of precinct scale water management strategies.

1.1 Background and scope of the addendum

The *East Wanneroo District Structure Plan – District Water Management Strategy* (EWDWMS) (Urbaqua, 2021) was endorsed by the Department of Water and Environmental Regulation (DWER) in April 2021 noting that a district groundwater management model and implementation strategy would be developed by the WAPC prior to local structure planning.

Section 2 of this addendum provides a summary of the outcomes of district groundwater modelling and outlines a preliminary district groundwater management scheme concept that has been developed and identifies the proposed strategy for its refinement and implementation which will be led by the Water Corporation.

DWER advises that:

"If local structure planning proceeds before the development of the district groundwater management scheme, DWER may consider that Stage 1 in Figure 1.16 in the district structure plan (October 2020) could progress if appropriate land is being set aside for flood management and the future connection to a district scale groundwater management scheme. DWER will not be in a position to consider local water management strategies for Stages 2 and 3 before the district scale solution is resolved."

Detailed district groundwater modelling has resulted in a refinement of the controlled groundwater level based on the principles established in the EWDWMS that is provided in Section 2 (Figure 1) of this addendum. This modelling has led to necessary revisions to the previously described Stage 1 area to remove some areas that cannot yet be developed. It has also enabled the inclusion of other areas that were previously excluded that is also provided in Section 2 (Figure 3) of this addendum.

Supplementary design guidance for local groundwater and stormwater drainage systems to address the requirements of the EWDWMS are provided in Section 3 of this addendum and an update to the EWDWMS implementation framework is provided in Section 4.

2 MANAGEMENT OF GROUNDWATER AT DISTRICT SCALE

This section summarises district-scale groundwater modelling, including supplementary and updated district-scale groundwater management information and outlines the current groundwater management scheme concept. This section should be read in conjunction with Section 5.2 of the EWDWMS.

2.1 Controlled groundwater level

As a key output from the district scale modelling, a district-scale controlled groundwater level has been defined based on the principles established in the EWDWMS summarised below:

- The DWMS proposes a controlled groundwater level based on the 1986 to 1995 average annual maximum groundwater level (AAMGL).
- The 1986 to 1995 AAMGL (preliminary Controlled Ground Level (CGL)) was determined as follows:
    - Water level data from 1986 to 1995 was filtered from WIR dataset described in Section 3.5.1 of Appendix 1.
    - Bore data was filtered such that only “shallow bores” (in which the top of the screen was less than 15 m below the average water level for the bore between 1986 and 1995) in the Superficial Aquifer were used for the analysis.
    - Where there were groups of nested or adjacent bores, water level data from the highest screened bore that had a mostly complete set of water level data was selected for the CGL.
- Following the screening process, 90 shallow screened bores were selected for the estimation of the CGL:
    - 85 of the shallow screened bores had 8 or more years of maximum water levels measured between June and November so the AAMGL was calculated as the average of the measured maximum water levels.
    - The remaining 5 bores had 6 or less years of maximum water level data. For these bores the AAMGL was calculated by adjusting the measured maximum water level to an AAMGL, using an average adjustment estimated from the 80 bores that had a complete data record (10 years of data).
- The lakes within the EWDSP area are throughflow wetlands, so are also expressions of the groundwater table. An AAMGL was estimated for the lakes that had measured surface water levels over the period from 1986 to 1995, including Lake Mariginiup, Lake Jandabup, Lake Gnangara, Lake Adams and Lake Badgerup.
- The CGL plane (Figure 1) was generated by contouring (using a kriging analysis) the lake AAMGL and bore AAMGL values across the EWDSP area.

The CGL plane and contours, developed through district scale modelling, are available on request from the Department of Planning, Lands and Heritage (DPLH) for use in the development of precinct scale water management system designs.

Local scale investigations and modelling will be required to support development of precinct scale local water management strategies including determination of any necessary revisions to the CGL.

If the local scale CGL departs from the CGL determined through the district-scale modelling, the system may not function as intended. Therefore, where it is proposed to amend the district scale CGL in local areas, it will be necessary to consider the district scale implications of these changes through refined local scale modelling, extending beyond the boundaries of individual precincts where necessary.

Areas where local scale groundwater modelling will be required to support local structure planning includes precincts 15 and 16, precincts 11 and 12, and precincts 10 and 24.

2.2 District scale groundwater modelling

The groundwater modelling report provided in Appendix 1 details the development and calibration of detailed district scale groundwater flow modelling. The report also presents the outcomes of future scenario simulations carried out to inform concept engineering design for the district groundwater management scheme.

Groundwater modelling presented in Appendix 1 indicates that there are parts of the EWDSP area that are largely unimpacted by shallow depths to groundwater under a future wet climate scenario.

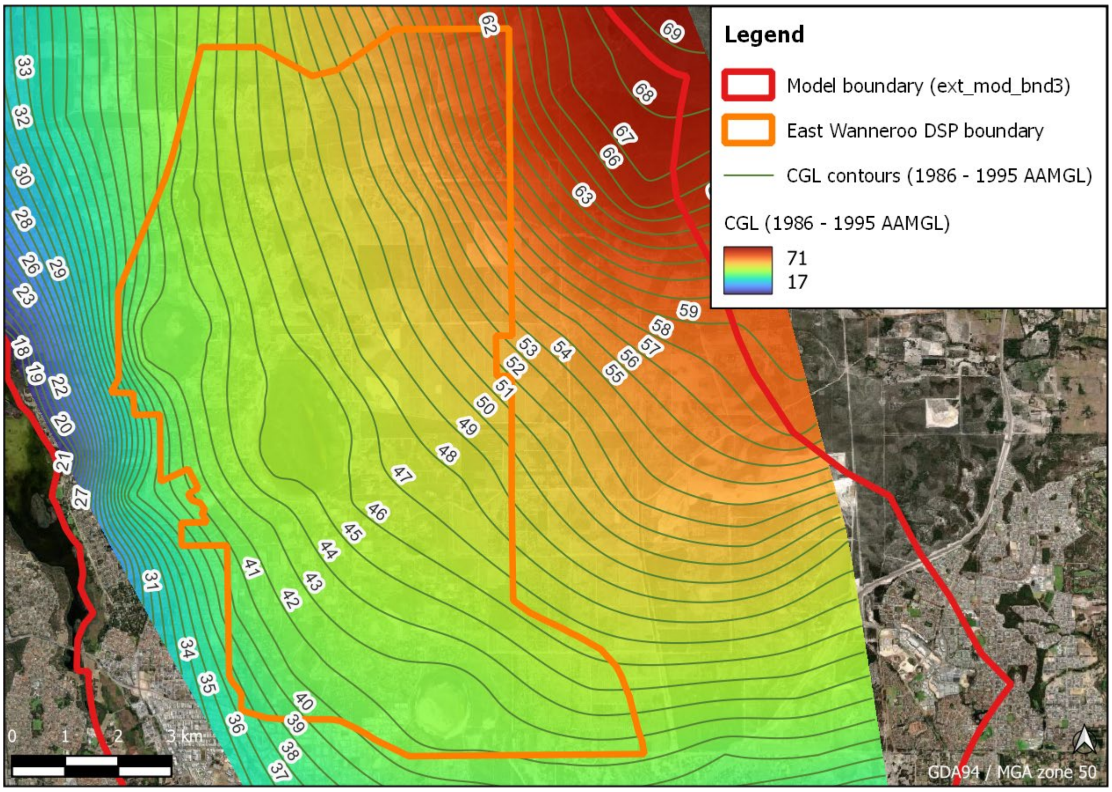

Figure 1: Revised controlled groundwater level (Pentium Water, 2025)

Figure 2 presents the spatial extent of areas that will have less than 2 m clearance to the maximum groundwater level simulated by the groundwater model in the wet climate scenario. Figure 3 presents a revised spatial extent for the stage 1 development areas that were previously identified in the EWDSP area.

Areas outside of the revised stage 1 areas shown in Figure 3 are excluded from development until the district groundwater management scheme – phase 2 has been designed and approved for implementation and its governance and delivery mechanisms are agreed, as outlined in Section 4.2 of this addendum.

2.2.1 Lake water level analysis

Groundwater modelling and associated analysis of lake water levels presented in Appendix 1 indicate that lake water levels will fluctuate with future climate or rainfall patterns and some scenarios result in exceedances of current environmental trigger values (for Lake Mariginiup and Lake Jandabup) without development. However, critical freeboard and spill levels are not breached in these simulations, indicating there is minimal flood risk to surrounding properties.

In simulations with partial development (stage 1 areas), where no subsoils are installed (or areas that require subsoil drainage are not progressed) similar seasonal and inter-annual fluctuations are observed but the whole record is shifted to higher water levels in general such that current environmental trigger values are significantly and frequently exceeded. Critical freeboard and spill levels are not breached, indicating minimal flood risk to surrounding properties remains.

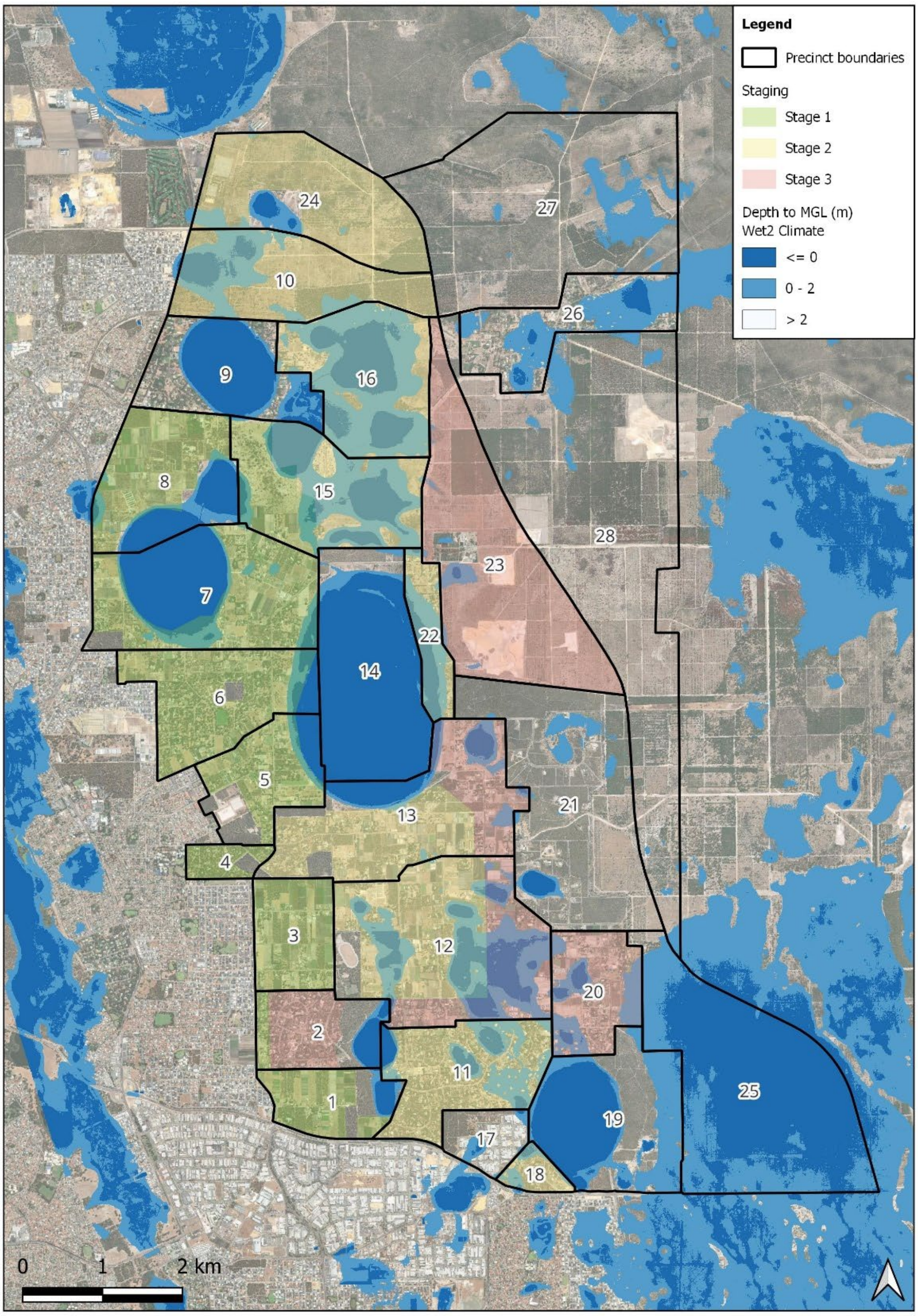

Figure 2: Depth to highest predicted groundwater level (Pentium Water, 2025)

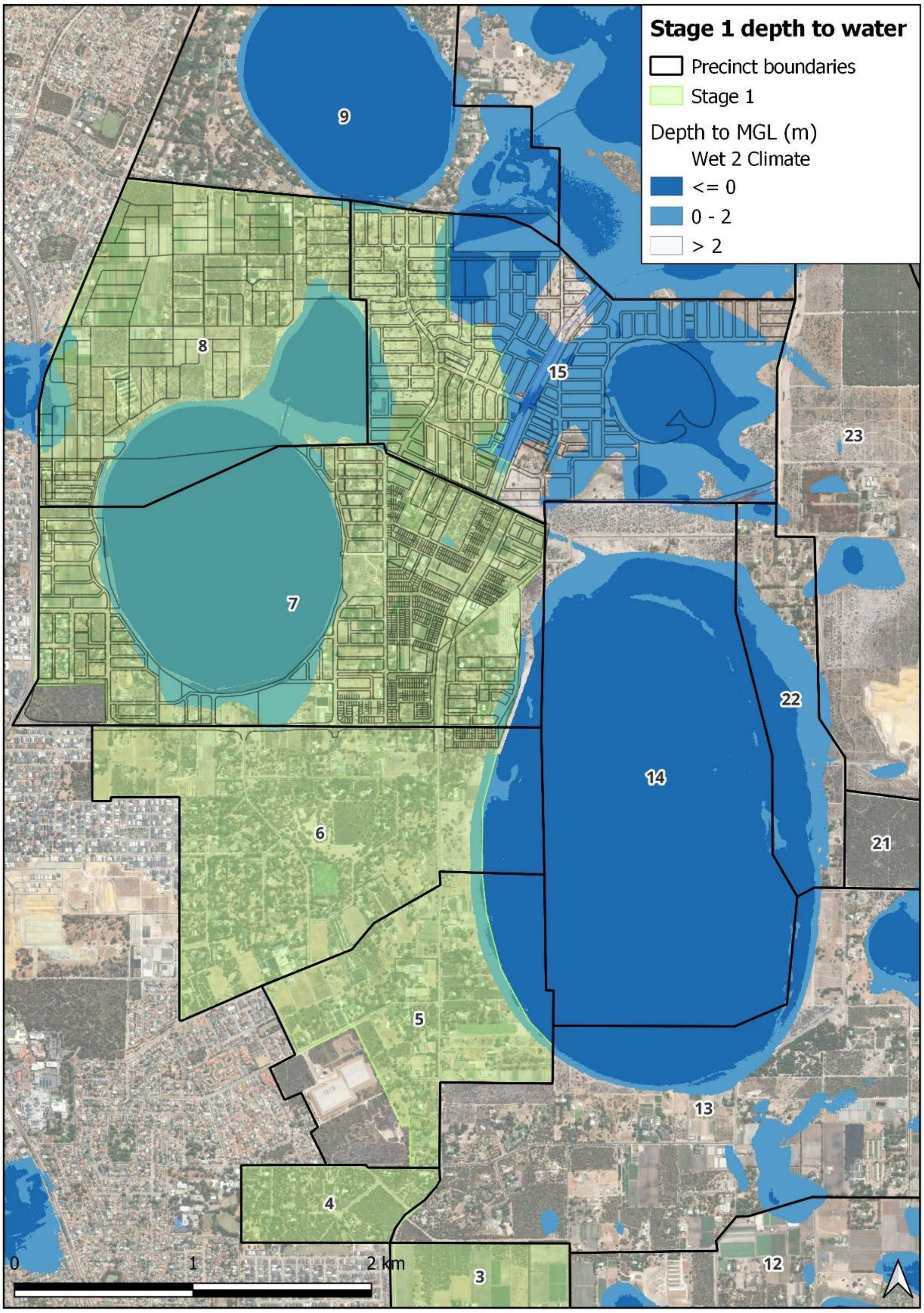

Figure 3: Revised stage 1 areas (Pentium Water, 2025)

This means that development of the revised stage 1 areas will increase the risk of environmental damage due to rising water levels around the margins of Lake Mariginiup. However, the predicted extent of these potential water level rises does not result in a flood risk to existing private residential buildings or infrastructure, even when considered in tandem with a 1% AEP flood event.

The design of proposed new residential buildings and infrastructure in revised stage 1 areas must therefore include consideration of these predicted water level rises to ensure that new subdivisions, and their drainage infrastructure will function effectively.

To mitigate the identified water level rises in Lake Mariginiup resulting from development of the revised stage 1 areas, an interim groundwater management scheme concept has been developed (groundwater management scheme phase 1) and modelled. This scheme is described in Section 2.3 below and will be implemented in response to post development water level changes in Lake Mariginiup.

Simulations that introduce water level management at Lake Mariginiup by transfer pumping water to Lake Jandabup (groundwater management scheme phase 1) during seasonal periods of elevated groundwater levels, indicate that the 'no-development' condition at Lake Mariginiup can be achieved, with full development of the EWDSP area.

In simulations with full development of the EWDSP area, the same fluctuations in Lake Mariginiup are observed again and the whole record is elevated further. In this case, current environmental trigger values are significantly and continuously exceeded, and both the critical freeboard and spill levels are breached on several occasions.

In all the scenarios described above, similar changes are predicted at Lake Jandabup, although the larger size of the lake generally reduces the amount of vertical change observed. However, transfer pumping from Lake Mariginiup increases water levels in Lake Jandabup such that the absolute maximum peak environmental trigger value is exceeded more frequently than in other simulations. Additionally, the critical freeboard level is breached once in one, full development, simulation indicating potential for flood risks to surrounding properties.

This means that in full development simulations, there are actual predicted flooding risks to existing residential buildings and infrastructure. Therefore, full development (beyond the revised stage 1 areas) cannot be supported without mitigation of predicted water level rise in Lake Mariginiup and Lake Jandabup.

As discussed above, groundwater modelling and associated analysis of lake water levels indicate that control of lake water levels within Lake Mariginiup may be required following development of stage 1 areas to maintain healthy lake ecosystems within Lake Mariginiup itself. Following full development of the EWDSP area, control of lake water levels within other lakes is likely to be required to maintain healthy lake ecosystems and manage flood risks to properties.

2.3 Groundwater management scheme phase 1 concept

Groundwater modelling and associated analysis of lake water levels presented in Appendix 1 and summarised in Section 2.2 of this addendum indicate that control of water level within Lake Mariginiup will be required following development of stage 1 areas, to maintain a healthy lake ecosystem.

Therefore, as a contingency planning measure, a conceptual 'phase 1' of the groundwater management scheme has been identified, comprising a transfer pumping station and pipeline via government owned land from Lake Mariginiup to Lake Jandabup as shown in Figure 4.

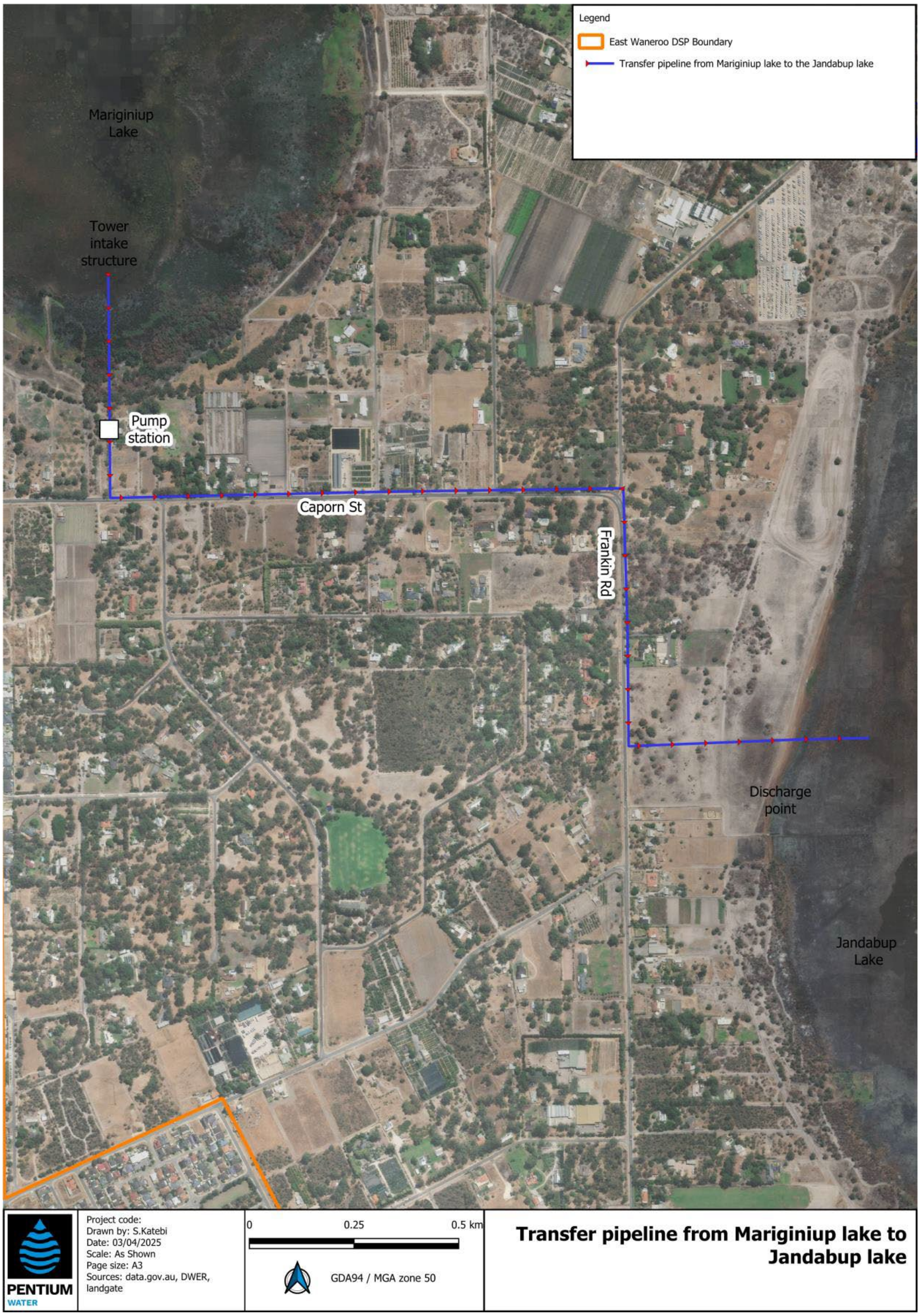

Figure 4: Transfer pipeline route from Lake Mariginiup to Lake Jandabup (Pentium Water, 2025)

2.4 Groundwater management scheme phase 1 implementation

Successful implementation of phase 1 of the groundwater management scheme is reliant on development of engineering designs supported by a detailed project plan with funding in place for construction.

Key elements of the project plan will include:

- Triggers for phase 1 operation (aligned with the district monitoring program),
- Likely timeline and costs for delivery (including approval under the *EP Act*), and
- Governance arrangements (including detailed costs and funding mechanisms).

The Water Corporation is developing engineering designs and a detailed project plan for implementation of phase 1 of the groundwater management scheme as part of stage 1 development. A preliminary outline of the key project plan elements is provided below.

2.4.1 Triggers for phase 1 implementation

The design and delivery of the groundwater management scheme has commenced by the Water Corporation for the revised stage 1 areas. This represents a change from the expected implementation pathway as outlined in the EWDSP, which proposes it be included as a component of the District Development Contribution Plan (DDCP) for East Wanneroo, prepared by the WAPC and implemented through an amendment to the City of Wanneroo District Planning Scheme No. 2.

Preparation of the draft groundwater management scheme has however, indicated a size and complexity more suited to implementation by the Water Corporation, under the provisions of the *Water Services Act 2012,* rather than as a component of the DDCP under the *Planning and Development Act 2005.*

The groundwater management scheme will become part of the Water Corporation's Urban Drainage District. This will require the Minister for Water to designate the scheme as a drainage area under the *Water Services (Water Corporations Charges) Regulation 2014* and allow Water Corporation to recover infrastructure and operating costs in the district.

Under the Water Corporation's Infrastructure Network Funding Model, drainage scheme components are funded through the collection of Standard Infrastructure Contributions (SIC) from developers. In accordance with the Minister's Guidelines for Infrastructure Contributions, there is scope to collect Special Developer Infrastructure Contributions (SDIC) where- "*the cost of delivering services to provide for a particular development may differ significantly from the standard charge*".

An SDIC would be established on the basis that all scheme beneficiaries contribute to the cost. The cost will be based on the concept design and estimates included in this addendum, and subsequent reviews by the Water Corporation.

The trigger for commencement of operation of phase 1 of the groundwater management scheme has been determined based on modelling and previous assessments of ecological water requirements for Lake Mariginiup and Lake Jandabup (Kavavos et al., 2020) and Gnangara Mound Ministerial Statement criteria (DoW, 2004). Phase 1 shall commence operation when water levels exceed 42.6.m AHD.

This trigger will be reviewed following completion of baseline wetland condition assessments undertaken by the Water Corporation (see section 4.3).

2.4.2 Likely timeline and costs for delivery

Environmental approvals will be required for construction and management of phase 1 of the groundwater management scheme including potential need for a s38 referral to the EPA. The EPA's assessment will be contingent on completion of baseline wetland condition assessments for both Lake Mariginiup as the source, and Lake Jandabup as the receptor.

Therefore, the timeline and costs for delivery will need to include consideration of the necessary timeframes to complete wetland assessments and satisfy environmental approval requirements. It is likely that the overall timeframe for design development, completion of investigations and approvals processes, and construction may exceed three to four years.

The cost to construct a pump station at Lake Mariginiup and a transfer pipeline from Lake Mariginiup to lake Jandabup including an outlet structure in Lake Jandabup has been estimated by the Water Corporation to be $15-30 M.

2.4.3 Governance arrangements

The design and delivery of the groundwater management scheme phase 1 is being undertaken by the Water Corporation consistent with the arrangements described in Section 2.4.1.

2.5 Groundwater management scheme phase 2 preliminary concept

Groundwater modelling and associated analysis of lake water levels presented in Appendix 1 and summarised in Section 2.2 of this addendum indicate that control of lake water levels will be required at full development to maintain healthy lake ecosystems and manage flood risk to properties. A preliminary conceptual groundwater management scheme has been developed and is presented in Figure 5 comprising construction and operation of an integrated system of groundwater and lake water level management infrastructure. A more detailed conceptual engineering report is provided in Appendix 2.

The preliminary conceptual design presented in this DWMS Addendum and the attached engineering report is subject to review, revision and refinement followed by development of detailed engineering designs by the Water Corporation and therefore should not be relied upon for future designs.

2.6 Groundwater management scheme phase 2 implementation

The design and delivery of the groundwater management scheme phase 2 is to be undertaken by the Water Corporation consistent with the arrangements for phase 1 that were described in Section 2.4 above.

The implementation pathway for the phase 2 groundwater management scheme is anticipated to be as follows.

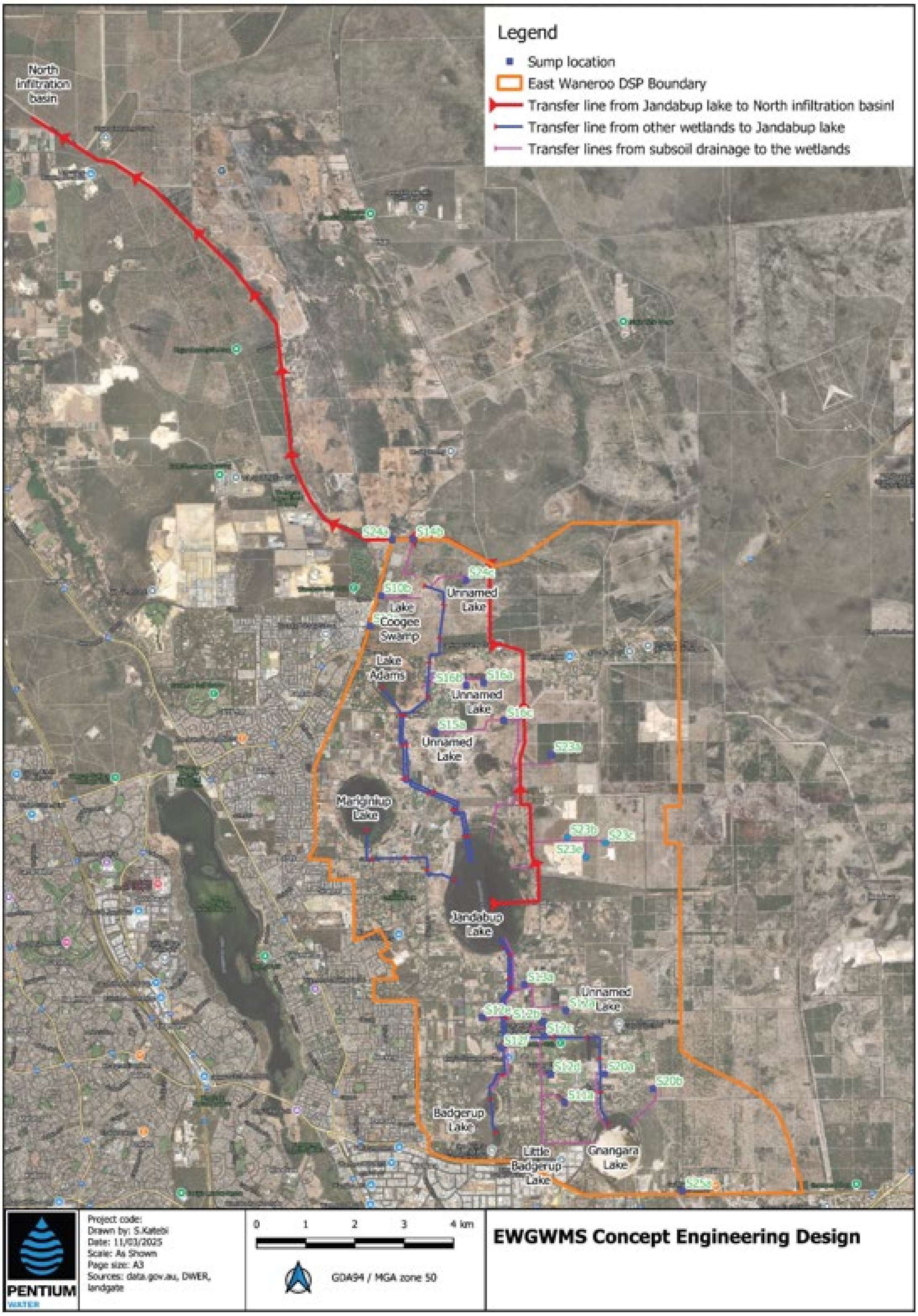

Figure 5: District groundwater management scheme preliminary concept (Pentium Water, 2025)

Water Corporation is to:

- Undertake technical, planning, and environmental studies and engineering investigations towards preparation of a detailed EWGMS Infrastructure Plan.
- Confirm the scheme components including total capital and operating costs required to deliver the scheme including a delivery plan.
- Confirm the financial model to determine recoup of capital and ongoing operating costs of running the scheme, including a review of the SDIC calculations, annual services charges and the need for Operating Subsidy if required.
- Identify and go through the relevant process to seek funding from the Government to deliver the work required for the scheme.
- Build, operate and maintain the scheme.
- Acquire approval from the Minister for Water to designate the new area as part of Water Corporation's Urban Drainage District, to apply annual service charges to all properties that benefit from or contribute to the need for the scheme. Under the provisions of *Water Services (Water Corporations Charges) Regulation 2014,* this can only occur after the delivery of scheme infrastructure.

Monitor and review the SDIC scheme to ensure the recoup of costs are in accordance with the financial model.

3 SUPPLEMENTARY DESIGN GUIDANCE

This section provides supplementary and updated information for the design of precinct scale surface water and groundwater management systems in East Wanneroo and should be read in conjunction with Section 5.3 of the EWDWMS.

3.1 Staging and consideration of risks to surrounding land

The lifting of urban deferment was approved by the WAPC with consideration of modelling presented in the DWMS and GWMS Report (Appendix 1), which included definitions of surface water and ground water catchments that were used to develop the GWMS concept (Appendix 2). Deviation from these catchments, interconnection of flows and other assumptions contained within those reports will present risks to the objectives of the GWMS.

Therefore, local water management strategies supporting precinct structure plans are required to address the entire precinct and consider all upstream and downstream connected catchments. Local water management strategies for portions of precincts will not be accepted.

For precincts that are partially within the revised stage 1 areas shown in Figure 3, the structure plan and local water management strategy should address land uses and water management strategies for the entire precinct. This includes conceptual designs for stormwater and groundwater management systems, supported by appropriate scaled modelling.

Portions of precincts that are outside of the revised stage 1 areas shown in Figure 3 will remain 'Urban Deferred' under the Metropolitan Region Scheme until phase 2 of the groundwater management scheme has been scoped, designed and the requirements for its implementation fully understood.

Following lifting of urban deferment, planning and development in these areas may proceed subject to completion and approval of appropriate amendments to the relevant precinct structure plan and a supporting local water management strategy.

3.1.1 Eastern boundary of revised stage 1 areas in precinct 15

In the preliminary groundwater management scheme concept, parts of the stage 1 areas in precinct 15 are part of a catchment that will ultimately be subject to pumped discharges to be delivered in phase 2 of the GWMS. However, it is anticipated that, with careful planning and design, these areas can be developed in the short term. To demonstrate that these, and other areas on the eastern boundary of stage 1 areas, can be developed it is necessary to demonstrate that surface water and groundwater drainage system designs can be reasonably delivered and managed under the following three distinct but inter-related development scenarios:

1. Development of stage 1 areas with interim drainage infrastructure pending progression of future stages.
2. Development of the whole precinct with permanent drainage infrastructure, i.e. showing how temporary infrastructure will be modified as future stages proceed.
3. Development of stage 1 areas in isolation, i.e. assuming that stage 2 areas never proceed, and all drainage infrastructure is permanent.

3.1.2 Western boundary of precinct 8

Whilst the entirety of precinct 8 is within the revised stage 1 area, rising groundwater levels have been observed in developed areas directly to the west of precinct 8. Water management strategies and designs for subdivisions within precinct 8 must include consideration of this issue and avoid any additional flooding or inundation impacts to existing properties.

3.2 Design of precinct scale groundwater management systems

Precinct scale groundwater management systems are to be designed with catchment outlets at the controlled groundwater level described in section 2.1 and shown in Figure 1.

All areas shown within the subsoil drainage extent mapped in Figure 6 are to be provided with a subsoil drainage network designed in accordance with the requirements below. The design must ensure catchments are consistent with the GWMS concept and be developed in consultation with the DWER and the City of Wanneroo.

The design of subsoil drainage systems presented at precinct scale in local water management strategies will need to be supported by local scale groundwater investigations and modelling or assessment that includes consideration of:

- any revisions to the proposed district scale CGL that may be necessary, including departure of the subsoil drainage extent shown in Figure 6.
- upstream boundary conditions from areas where no subsoil drainage is proposed.
- potential impacts to surrounding unfilled and undrained land, as well as existing dwellings and infrastructure.
- risks (e.g. climate, land use change) to development (buildings, infrastructure and amenity) and the environment from future groundwater level rise.

Areas where local scale groundwater modelling will be required to support local structure planning include precincts 15 and 16, precincts 11 and 12, and precincts 10 and 24.

In other areas, 1-dimensional groundwater modelling to consider mounding between drainage lines may be sufficient at the local water management strategy stage, provided the inputs and outputs of modelling are consistent with district scale modelling.

If the local scale CGL departs from the CGL determined through the district scale modelling, the system may not function as intended. Therefore, where it is proposed to amend the district scale CGL in local areas, it will be necessary to consider the district scale implications of these changes through refined local scale modelling, extending beyond the boundaries of individual precincts where necessary.

Local scale modelling may also be required in Stage 2 and 3 areas determined through further refinement of the Phase 2 GWMS concept.

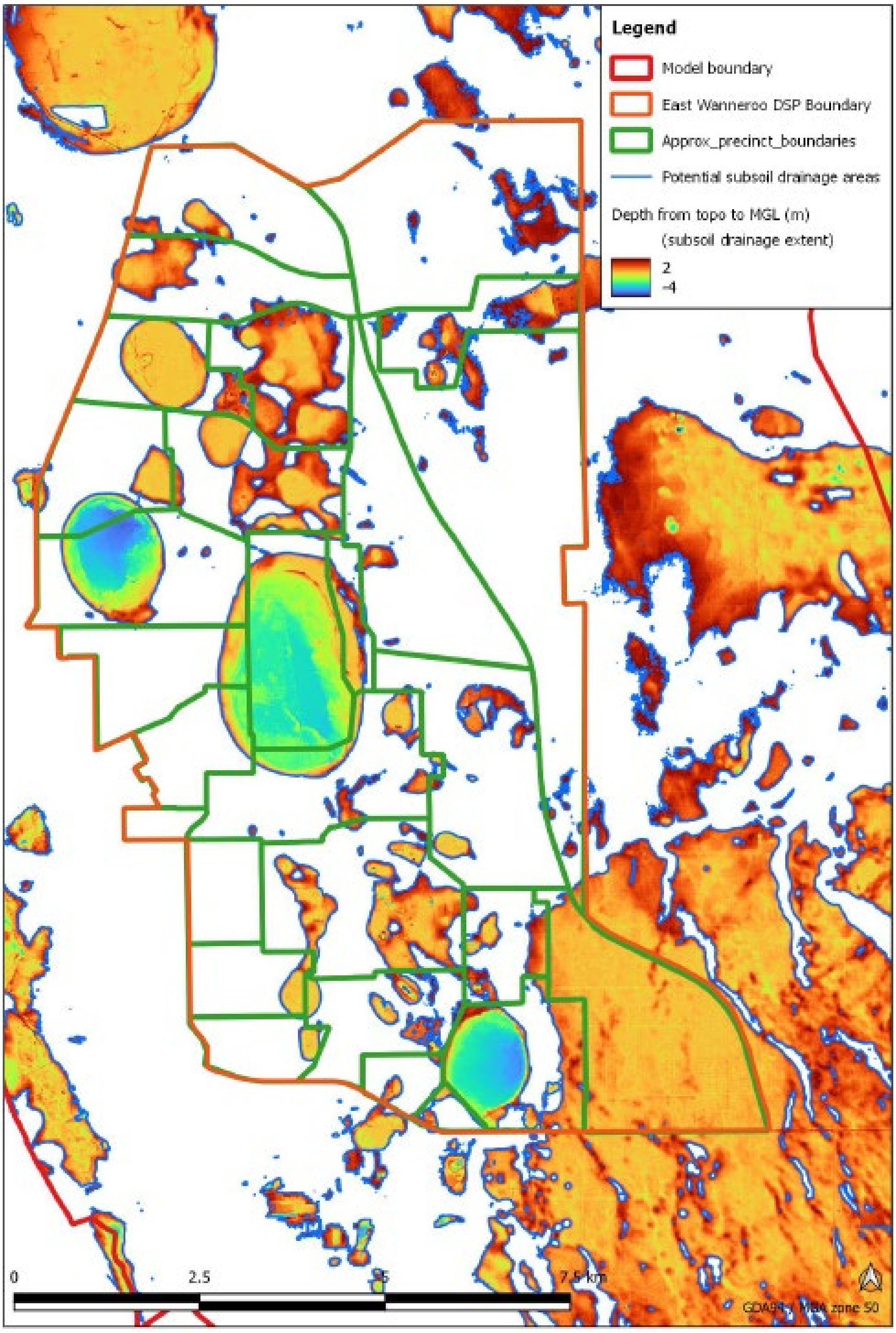

Figure 6: Subsoil drainage extent (Pentium Water, 2025)

3.3 Flood risk and stormwater management system performance assessment

There are significant flooding and inundation risks associated with development of the EWDSP area. When considering these risks, it is critical to appropriately weigh the consequences of flooding and inundation and provide mitigation strategies, even when the likelihood is low.

For example, the usually applied design rainfall event for streets in residential development is the 20% AEP event. However, it is normal practice to require that the 1% AEP event is also considered in design to ensure that flooding can be appropriately and safely managed in multi-functional public open spaces without entering private property, damaging critical infrastructure, or preventing emergency access and egress.

Where catchments are typically internally draining and require the use of pumps to manage groundwater and stormwater levels, it is necessary to address the consequences of major storm events occurring concurrently with an unplanned shutdown of pumped systems.

The design of appropriately sized stormwater and groundwater management systems presented at precinct scale in local water management strategies must be plausible, with catchments that are well thought out, feasible and practically implementable with the GWMS including considerations such as:

- sensitivity to infiltration rates and other uncertainties in groundwater estimation,
- amenity for existing and future residents,
- land tenure,
- creation of reserves,
- access arrangements, and
- ongoing management etc.

Designs will need to be supported by detailed local catchment scale modelling that includes consideration of the risks associated with groundwater levels before and after implementation of the district groundwater management scheme. This should include but not be limited to:

- Model scenarios representing the impact of major rainfall events concurrent with seasonal inundation and groundwater level rise due to:
  - short-term power disruptions to pump systems, and
  - longer-term environmental discharge issues.
- Cumulative assessment of flood and drainage performance impacts from all direct and indirect discharges to wetlands, including from catchment areas beyond the precinct boundary.

Local catchment scale modelling will need to demonstrate compliance with peak flow criteria specified in the DWMS and any future discharge criteria determined through refinement of the GWMS concept by the Water Corporation. Where the refinement of the GWMS concept changes discharge criteria, it shall supersede the criteria within the DWMS.

Where precincts are partially within the stage 1 areas but also contain land in future stages that is unable to be developed at present, the local water management strategy is required to address the whole precinct. In these precincts, surface water and groundwater drainage system designs should be based on the following three distinct but inter-related development scenarios:

1. Development of stage 1 areas with interim drainage infrastructure pending progression of future stages.

2. Development of the whole precinct with permanent drainage infrastructure, i.e. showing how temporary infrastructure will be modified as future stages proceed.
3. Development of stage 1 areas in isolation, i.e. assuming that stage 2 areas never proceed, and all drainage infrastructure is permanent.

Modelled scenarios must address the combined risks of major rainfall event flooding and groundwater inundation. This should be achieved through inclusion of a range of groundwater conditions from district scale modelling and by addressing climate change considerations in accordance with the recommendations of *Australian Rainfall and Runoff* (as updated).

The selection of model parameters for modelling must be supported by site-specific investigations. District scale modelling has demonstrated that the efficacy of stormwater and groundwater management systems are highly sensitive to the modelled hydraulic conductivity. Therefore, geotechnical investigations including well distributed infiltration testing will be necessary for presentation in all local water management strategies.

3.4 Multi agency water management report assessment

Due to the significant complexity of water management requirements in the EWDWMS area and the various roles and responsibilities of involved agencies, a multi-agency approach to the assessment of water management reports supporting local structure plans and subdivisions is necessary.

Key principles that will be considered by agencies through their assessment of local water management strategies and urban water management plans include:

- Developers must deliver proof of concept through local water management strategies that address key technical tests in full and do not leave them for subsequent stages of the planning and development process.
- Protection of significant wetlands with appropriately defined buffers and careful design of drainage infrastructure is non-negotiable.
- Assessment will be risk-based and staged, with technical/design risks the highest priority and development staging requires establishment of firm triggers.

Key risks and considerations identified in the workshop that need to be addressed in local water management strategies included:

- What is the risk of inundation to existing and proposed properties and how is it mitigated?
- How will the proposed drainage system function (proof-of-concept)?
- Can the development responsibly operate without an approved district groundwater management scheme?
- What are the risks to wetlands and other environmental assets and how are they mitigated?
- What are the implications of pumps being overwhelmed and/or failing and how will the proposed drainage system design perform under a wet climate scenario?
- What are the lifecycle costs and maintenance requirements for the proposed drainage system?
- Are there any proposed deviations from design criteria and/or concepts presented in the EWDWMS and this addendum, and how are they justified?
- What are the implications for adjacent developments associated with the proposed drainage system design and how are they being communicated and managed?

4 IMPLEMENTATION FRAMEWORK

This section provides supplementary and updated information related to the delivery of water management for developments in East Wanneroo and should be read in conjunction with Section 6 of the EWDWMS.

As specified in the EWDWMS, a single local water management strategy is required to be prepared to accompany a local structure plan for each precinct.

4.1 Stage 1 areas

Areas outside of the revised stage 1 areas shown in Figure 3 are excluded from development until the requirements for lifting of urban deferment have been satisfied such that the district groundwater management scheme – phase 2 has been designed and approved for implementation and its governance and delivery mechanisms are agreed, as outlined in Section 4.2 of this addendum.

For precincts that are partially within the stage 1 areas but also contain land in future stages that is unable to be developed at present, the local water management strategy is required to address the whole precinct. Endorsement of the local water management strategy will be limited to stage 1 areas until the requirements for lifting of urban deferment have been satisfied at which time, it may be necessary to amend the local water management strategy to gain final endorsement in full.

4.1.1 Addressing wetland protection requirements

All precincts that contain or abut a wetland are required to prepare a Wetland Evaluation and a Wetland Buffer Assessment to be provided as a part of technical documentation to support local structure planning.

The guidance document *A methodology for the evaluation for the evaluation of wetlands on the Swan Coastal Plain, Western Australia* (DBCA 2017) should be utilised by proponents reviewing wetland boundaries and management categories.

Portions of precincts that are outside of the revised stage 1 areas shown in Figure 3 will remain 'Urban Deferred' under the Metropolitan Region Scheme until phase 2 of the groundwater management scheme has been fully designed and approved for implementation and its governance and delivery mechanisms are agreed. Following lifting of urban deferment, it may be necessary to undertake additional and/or updated wetland evaluations for these precincts.

4.2 Reporting for future stages

For precincts that are wholly outside the stage 1 areas, local water management strategies will not be considered for endorsement by DWER until the requirements for lifting of urban deferment have been satisfied such that the groundwater management scheme – phase 2 has been designed and approved for implementation and its governance and delivery mechanisms are agreed including completion of the following elements:

- Design, cost and funding have been confirmed.
- Triggers for (phased) construction have been established.
- Environmental and planning approvals have been obtained.

4.3 Wetland modelling and monitoring

The WAPC has prepared a DDCP for East Wanneroo, in accordance with the requirements of the DSP. As outlined in section 2.6, responsibility for the groundwater management scheme component of the DDCP will be transferred to the Water Corporation, to be implemented under the provisions of the *Water Services Act 2012*.

Water Corporation will undertake the district-level monitoring program and baseline wetland assessments to meet environmental approval requirements for phase 1 of the GWMS, involving the transfer of water between Lake Mariginiup and Lake Jandabup.

The DDCP will include the preparation and implementation of Wetland and Foreshore Management Plans. The funding arrangements for these components of works are currently under consideration. The components of the monitoring program and wetland assessments will be as follows, consistent with the objectives of the EWDWMS:

Pre-development

- Provide baseline water quality and level information for district scale design purposes.
- Establish more accurate assessments of the existing health of surface and groundwater systems (including wetlands and native vegetation) in East Wanneroo.

During and post development

- Demonstrate compliance with specified wetland water level criteria and to meet environmental approval requirements.

The demonstration of compliance with specified wetland water level criteria will be undertaken by the Water Corporation. Other environmental monitoring and assessments that will be undertaken during and post development include:

- Provide ongoing assessments of surface and groundwater system (including wetlands and native vegetation) health.
- Provide early warning for arising issues enabling adaptive management of surface and groundwater management systems.
- Review the performance of water quality and quantity management systems and propose design adjustments where necessary.

4.4 Appendix 3 provides the scope of works that has been proposed for these works. Roles and responsibilities

An updated summary of roles and responsibilities for implementation is provided in Table 1.

Table 1: Summary of roles and responsibilities

Implementation Item	Responsibility	Planning Stage
Develop district groundwater management model and implementation strategy	WAPC/City of Wanneroo	Complete, see Section 2 and Appendix 1
Design and commence delivery of district groundwater management scheme	Water Corporation	Prior to local structure planning for future stages, see Section 2 and Appendix 2.
Prepare and implement developer contributions plan	WAPC/City of Wanneroo	Underway, see Section 4 and Appendix 3.

Implementation Item	Responsibility	Planning Stage
Referral to the EPA of specific mechanisms and provisions to adequately secure, protect and manage the environmental values within the East Wanneroo area	Landowner/ developer	Local structure plan (local water management strategy)
Implement district monitoring program (as proposed in the developer contributions plan)	City of Wanneroo/Water Corporation	Prior to local structure planning for future stages, see Section 4 and Appendix 2.
Potable water supply planning and connection to main distribution network	Water Corporation	Local structure plan (local water management strategy)
Wastewater planning and connection to main distribution network	Water Corporation	Local structure plan (local water management strategy)
Development of local stormwater drainage and groundwater management concepts including site investigations, modelling and assessment (see Section 2 for supplementary design guidance)	Landowner/ developer	Local structure plan (local water management strategy)
Development of conceptual Landscaping plan incorporating wetland protection and WSUD	Landowner/ developer	Local structure plan (local water management strategy)
Development of refined water balance and confirmation of fit-for-purpose water sources	Landowner/ developer	Local structure plan (local water management strategy)
Identification of water source for irrigation of public open space	Landowner/ developer	Local structure plan (local water management strategy)
Acid sulfate soils investigations/ potential acid sulfate soils management plan	Landowner/ developer	Local structure plan (local water management strategy)
Geotechnical investigations	Landowner/ developer	Local structure plan (local water management strategy)
Flora and fauna investigations (see Section 4 for supplementary guidance)	Landowner/ developer	Local structure plan (local water management strategy)
Implementation of pre-development monitoring program	Landowner/ developer	Local structure plan (local water management strategy)
Confirmation of post-development monitoring program	Landowner/ developer	Local structure plan (local water management strategy)
Design of water distribution networks	Landowner/ developer	Subdivision (urban water management plan)
Design of wastewater reticulation networks	Landowner/ developer	Subdivision (urban water management plan)
Design of drainage networks	Landowner/ developer	Subdivision (urban water management plan)
Aboriginal consultation	Landowner/ developer	Subdivision (urban water management plan)
Stormwater and contamination management plan	Landowner/ developer	Development Application

Client: Department of Planning, Lands and Heritage

Report	Version	Prepared by	Reviewed by	Submitted to Client	
				Copies	Date
Preliminary draft	V1	HB	GC/SMS	Electronic	24/03/2025
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Appendix 1 Groundwater modelling report

EAST WANNEROO GROUNDWATER FLOW MODEL

Development, calibration and future scenario simulations

CDPEWMOD_01_R001_RevC

14th March 2025

Document Status

Version	Purpose of document	Authored by	Reviewed by	Review Date
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Approval for Issue

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Executive Summary

Background

The Department of Planning, Lands and Heritage (DPLH) is overseeing the implementation of the East Wanneroo District Structure Plan (EWDSP). As part of this process a District Water Management Strategy (DWMS) (Urbaqua, 2021), was prepared, this identified groundwater to present a potential risk to the environment, including:

- Water logging and loss of amenity.
- Damage to infrastructure.
- Loss of capacity of stormwater management systems.
- Increased prevalence of mosquitoes and other nuisance insects.
- Sterilisation of land for development due to unfeasible costs of earthworks and imported sand, without appropriate groundwater management.

The DWMS states that a detailed local groundwater model of the EWDSP area will be prepared to consider predicted hydrological changes in more detail and quantify the likely groundwater level changes. A groundwater model of the East Wanneroo DSP area has been constructed by Pentium Water, in consultation with the Department of Water and Environmental Regulation (DWER) and DPLH.

EWDSP Setting

The hydrogeological setting of the EWDSP area is summarised in Table ES1.

Table ES1 – Setting of EWDSP area

Item	Commentary
Climate	• Temperate climate, with dry hot summers and cold wet winters. Annual average rainfall between 2010 and 2021 has been 702mm.
Land use	• Urban, commercial, industrial along some western and southern parts. • Market gardens, pastoral, and rural residential in the centre of the study area. • Native vegetation (predominantly banksia woodland) scattered throughout but predominantly in the eastern parts. • Pine plantations and cleared pine plantations.
Geology	• Quaternary Superficial formations, including Tamala Sand, Bassendean Sand.
Hydrogeology	• Shallow superficial aquifer overlying the Leederville Aquifer. Connectivity between the two is limited, except for the northern part of the study area where the Kardinya Shale is absent, allowing leakage from the Superficial Aquifer into the underlying Leederville.
Surface water and drainage	• North-south chain of wetlands, including 3 major lakes, formed in the interdunal depressions between Bassendean and Spearwood Dune Systems. • The lakes are throughflow lakes with groundwater flowing from east to west towards the coast. • Water levels in the lakes are largely controlled by groundwater inflow with lake levels fluctuating seasonally. • There are no surface drainage features removing surface runoff from the study area.
Groundwater flow system	• Inflow from the northeast, near the top of the Gnangara groundwater mound. • Outflow to the west / southwest, with an overall gradient towards the coast. • Recharge varies depending on land use, vegetation type and depth to groundwater. • Bore abstraction by Water Corporation and various private licensed and unlicensed water users. • Leakage from the Superficial aquifer into the underlying Leederville aquifer, in the north of the study area.

Model Construction

The numerical model was constructed based on a model domain extending from about 6.5 km north of the EWDSP to 6 km south and considered surface water bodies. The presence of the Gnangara mound and regional flow patterns defined the boundary conditions.

The numerical model grid comprised a typical cell size of 160 m x 160 m, refined to 40 m x 40 m in the EWDSP area. The model was parameterised based on 5 layers representing the Superficial Aquifer, together with 88 pilot points (K_h, K_v, S_y), with the Parameter Estimation software suite (PEST) used for inverse calibration of the model based on data for the period between 2010 and 2021.

Lakes were represented using the MODFLOW LAK3 package, which modelled the interaction between groundwater and the lake geometry.

Recharge, a key input to the model was defined using a recharge function as described by Davies (2022), which is a compromise between a fully coupled unsaturated – saturated zoned model and assumed linear recharge rates. The recharge function was used to define input time series for recharge and evapotranspiration across a range of land uses and climate scenarios.

The model incorporated time series data supplied by DWER and Water Corporation (e.g., water level data, abstraction volumes, leakage rates), and was successfully calibrated for use for assessment of indicative impacts from the proposed development.

Model Objectives and Approach

The model was developed to inform the concept engineering design for the water management scheme in the EWDSP area. The key objectives comprise:

- Estimating the spatial extent of subsoil drainage in the EWDSP
- Estimating subsoil drainage flow rates
- Estimating subsoil drainage volumes requiring management through the groundwater control system.

To test these objectives the model considered a range of climate and development scenarios:

- Climate Scenarios based on the AWO National projections for future climate, specifically:
  - Wet_1: rcp85_CZ10_MRNBC-CNRMdaily (average rainfall of 684.1 mm/yr)
  - Wet_2: rcp45_CZ10_QME-MIROC5daily (average rainfall of 684.9 mm/yr, highest monthly rainfall (447mm), peak rainfall of 1318 mm/yr)
  - Dry_1: rcp85_CZ10_CCAM-ISIMIP-ACCESS1daily (average rainfall of 430.8 mm/yr)
  - Int_1: rcp85_CZ10_QME-MIROC5daily (average rainfall of 593.5 mm/yr)
- Development
  - No development
  - Staged development to 2040 with no subsoil drainage (to assess the need for groundwater management during the early stages of the development)
  - Staged development (assuming one staging sequence)
  - Full buildout

Additional scenarios were run to assess the capacity of the wetlands to store additional urban drainage water and requirements for lake level management including:

- Full buildout
  - Discharge of subsoil drainage into the lakes with no further management
  - Discharge of subsoil drainage into the lakes and transfer pumping into Lake Jandabup and out of the DSP area to manage water level
- Staged to 2040
  - Discharge of subsoil drainage for the ‘Staged to 2040’ area into the lakes with no further management
  - Discharge of subsoil drainage for the ‘Staged to 2040’ area into the lakes with pumping from Lake Mariginiup to Lake Jandabup only

Model Intent

The numerical model has been constructed to facilitate predictive modelling of the proposed development under various development pathways and climate scenarios.

The groundwater model has been developed as a design tool and will be available for future studies to further inform decision making processes associated with the development of the East Wanneroo DSP area including the conceptualisation and preliminary design of a district groundwater management scheme. It is however a regional scale model to be used to inform concept level design of a district water management scheme, and would require refinement of the of the model grid and further inputs to inform detailed local scale engineering design.

Key observations

Lake Mariginiup

- Without development, Lake Mariginiup water levels are likely to occasionally exceed the absolute maximum peak levels during higher rainfall periods (i.e., wet scenarios).
- With development, Lake Mariginiup water levels will likely exceed the absolute maximum peak water level and may also overtop in the event that urban drainage is directed into the lakes (as proposed under the DWMS) under all bar extremely dry climate scenarios that were simulated. Ongoing monitoring and water level management (adaptive management practices) will be required once development commences.
- A scheme to remove excess water from Lake Mariginiup will likely be required to enable full development in the vicinity of the lake should wetter climates be experienced. Modelling indicates pumping can be used to control lake levels to acceptable maximum water levels.
- With or without development, in a dry future climate Lake Mariginiup may become dry even with the planned reductions in abstraction rates.

Lake Jandabup

- With development, Lake Jandabup water levels will likely exceed the absolute maximum peak water level and may also overtop in the event that urban drainage is directed into the lakes (as proposed under the DWMS) under all bar extremely dry climate scenarios. Ongoing monitoring and water level management (adaptive management practices) will be required once development commences.
- For “Staged to 2040” development Lake Jandabup appears to have some available (buffer) storage for the management of subsoil drainage water and transfer of excess water from Mariginiup.
- Adaptive management practices will also be required at Lake Jandabup following development around the lake.
- An offsite water disposal scheme is likely to be required to enable full development to manage excess water during later stages of development. Modelling indicates pumping can be used to control lake levels to acceptable maximum, with flow rates of up to 1500 L/sec required to discharge water offsite.

Lake Gnangara

- Further work is required at this lake to determine key environmental and engineering lake threshold levels. Pentium Water has estimated key water levels in the lake for this assessment. With development, Lake Gnangara water levels will likely exceed the absolute maximum peak water level (as estimated by Pentium) and may also overtop in the event that urban drainage is directed into the lakes (as proposed under the DWMS) under all bar extremely dry climate scenarios.
- Ongoing monitoring and water level management (adaptive management practices) will be required once development commences.
- Modelling indicates pumping can be used to control lake levels to acceptable maximum.

Maximum groundwater level observations

- Development across the East Wanneroo area results in higher simulated maximum groundwater levels than with no development on the western side of the DSP area. These higher levels occur where there is adequate clearance to groundwater and subsoil drainage is not required to manage rising groundwater levels. The increased recharge due to urbanisation, therefore, causes groundwater to mound in those areas.

Maximum groundwater levels were simulated to be up to 2.5 m higher than no development levels during high rainfall periods.

- Development across the East Wanneroo area results in lower simulated maximum groundwater levels than would occur with no development through parts of the East Wanneroo DSP area because groundwater levels will be managed and controlled through subsoil drainage.

Annual subsoil drainage volumes

- There is significant variability in the simulated volume of subsoil drainage water that will be generated following full buildout of the DSP area, with annual subsoil drainage volumes ranging from 2 GL/yr to more than 30 GL/yr in a wetter climate, and from 0 GL/yr to about 3 GL/yr in a dry climate scenario.
- Due to the uncertainty in the future climate, there is significant variability and uncertainty in potential future subsoil drainage volumes across the DSP area. With this uncertainty, a subsoil drainage harvesting scheme currently does not appear to be commercially viable given this unpredictability.

Staged development to 2040 without subsoil drainage

- Simulated staged development on the western side of the DSP area, in areas that do not require groundwater management infrastructure to be installed, increased maximum water levels by up to 1 m in Lake Mariginiup during high rainfall periods, and increased groundwater levels on the western side of the DSP area by up to 1 m. From the modelling, there is a small or negligible impact of this early staged development on water levels in the other major lakes.

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List of acronyms

Acronym	Description
AAMGL	Annual average maximum groundwater level
ASM	available soil moisture content
AWO	Australian Water Outlook
CGL	Controlled groundwater level
DCP	Developer contribution plan
DEM	Digital elevation model
DNI	Daily net inflow
DPLH	Department of Planning, Lands and Heritage
DWER	Department of Water and Environmental Regulation
DWMS	District Water Management Strategy
EWDSP	East Wanneroo District Structure Plan
EWGM	East Wanneroo Groundwater Model
ET	Evapotranspiration
IL	Interception loss
m AHD	metres above height datum
m bgl	metres below ground level
MGL	maximum groundwater level
ML/yr	megalitres per year
PET	Potential evapotranspiration
PRAMS	Perth region aquifer modelling system
RO	Run off
SMC	Soil moisture content
WC	Water Corporation

1. Background

The East Wanneroo District Structure Plan (EWDSP) area lies within the Swan Coastal Plain about 18 km to the north of Perth CBD. The EWDSP (Figure 1) was endorsed by the Western Australian Planning Commission in late 2020 and provides a long-term vision for urban development extending across 8,047 hectares (ha) of land divided into 28 precincts (WAPC, 2020). In accordance with Better Urban Water Management (WAPC 2008), a District Water Management Strategy (DWMS) was prepared by Urbaqua (2021) to outline the surface water and groundwater management strategies to be implemented for development within the EWDSP area.

The East Wanneroo DWMS identifies groundwater level rise as a key risk to development of East Wanneroo. Rising groundwater results in risks to the environment from increased lake and groundwater levels causing excessive depths and durations of inundation and/or waterlogging of wetlands and vegetation, as well as risk to development. Key risks to the development include:

- Water logging and loss of amenity or function in parks and other open spaces.
- Damage to infrastructure such as roads, retaining walls and other paved areas.
- Loss of capacity in stormwater management systems.
- Increased prevalence of mosquitoes and other nuisance insects.

A significant impact to development would be the sterilisation of land due to unfeasible costs of earthworks and imported engineering fill sand in areas of rising groundwater.

Sections 5.2 and 5.3 of the DWMS outline the requirements for the management of groundwater at a district and precinct scale, respectively. The DWMS indicates that it is necessary to undertake further work to design and test the district groundwater management system to ensure impacts of groundwater level changes will not impact on wetlands and/or the proposed development.

The DWMS states that a detailed local groundwater model of the EWDSP area will be prepared to consider predicted hydrological changes in more detail and quantify the likely groundwater level change at a more localised level. The DWMS also states that the groundwater model could be used as a design tool to provide more detailed estimates of the volume of groundwater that may need to be managed in the future.

This report details the development and calibration of the EWDSP area groundwater flow model. This report also presents the outcomes of future scenario simulations carried out to inform the concept engineering design for the EWDSP area water management system. The concept design and associated cost estimate form part of the Developer Contribution Plan (DCP) documentation.

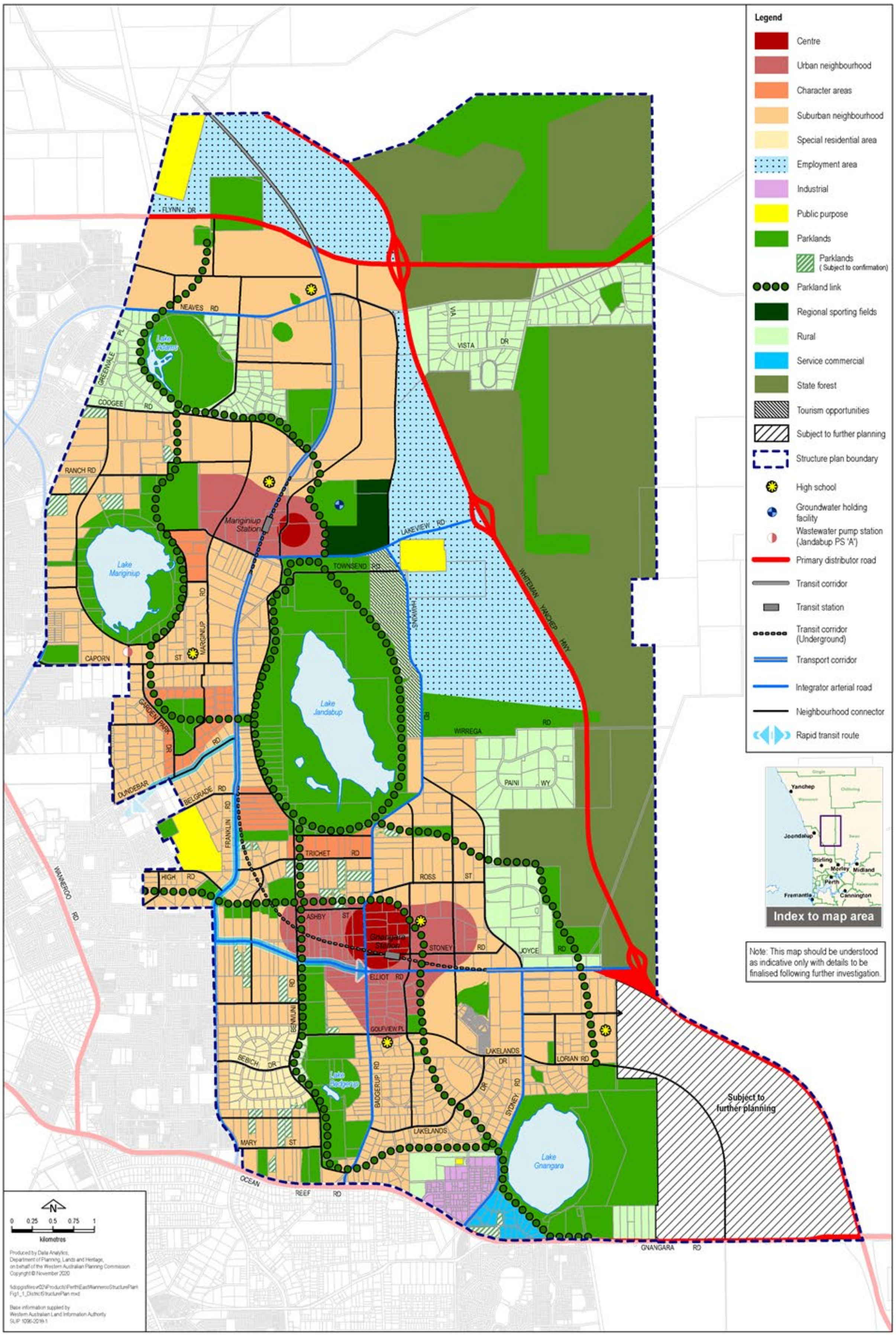


Figure 1: East Wanneroo District Structure Plan (WAPC, 2020)

2. Numerical groundwater model objectives and report structure

2.1. Model objectives

The East Wanneroo groundwater flow model (EWGM) was developed to inform the concept engineering design for the water management scheme in the East Wanneroo DSP area.

The key objectives of the East Wanneroo groundwater model (to be documented in a separate report) are as follows:

- Estimate the spatial extent of subsoil drainage across the East Wanneroo DSP area by assessing post-development groundwater rise without subsoil drainage.
- Estimate subsoil drainage flow rates to inform the water management infrastructure design.
- Estimate the subsoil drainage volumes that will require management through the groundwater control system, under a range of climate scenarios, for a range of development scenarios including:
    - staged development (assuming one staging sequence).
    - Staged development to 2040 with no subsoil drainage.
    - full build out.
- Assess groundwater and lake levels for no development, staged development and at full buildout.

The approximate extent of the study area (and the numerical model boundary) is shown in Figure 2. The study area extends approximately 6.5 km north, 5.7 km south, 7 km east and 1.5 km west of the EWDSP.

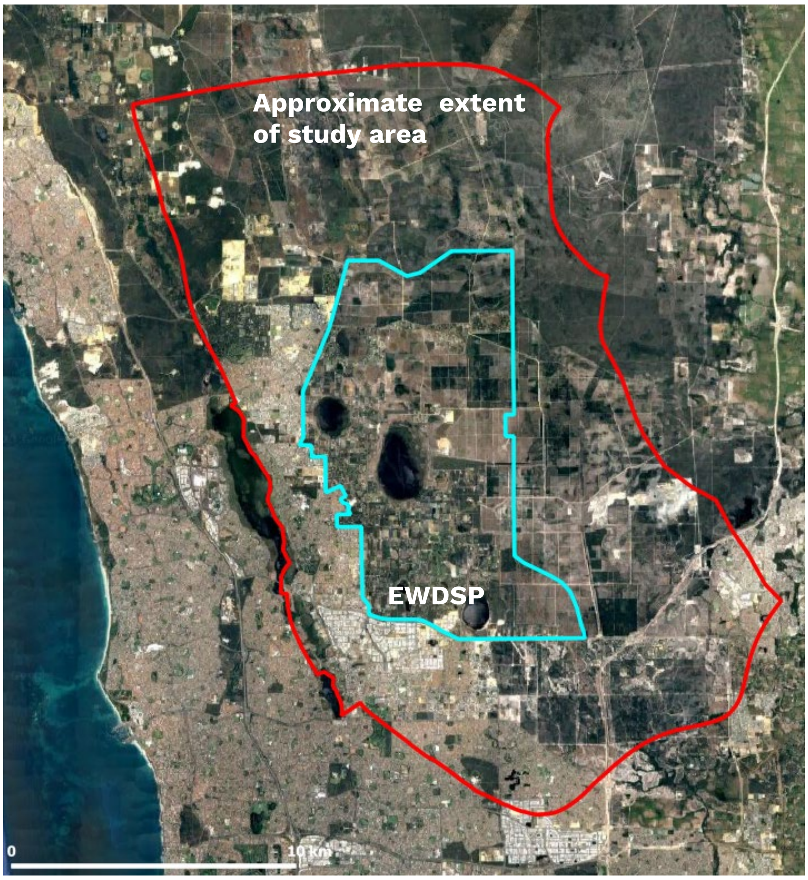


Figure 2 Study area.

2.2. Report structure

The report comprises the following chapters, describing the site conceptualisation, model construction and calibration.

1) **Background** – project context.
2) **Numerical model objectives and report structure** (this section).
3) **Data collation and analysis** – overview of data sources, data review and application to the numerical model.
4) **Conceptual hydrogeological model** – summary of the conceptual model of the study area.
5) **Model construction** – detailing the construction of the numerical model.
6) **Model calibration** – detailing the ability of the model to replicate historical data.
7) **Future scenario modelling** – model outcomes for four key future scenarios ranging from wet to dry future climate conditions.
8) **Modelling sensitivity** – discussion of model sensitivity.
9) **Lake level management concept simulations** - model outcomes for lake water balance scenarios including discharge of drainage water into lakes and pumped water level management for the wet to dry future climate conditions.
10) **Model limitations** – summary of model limitations.
11) **Key implications and take-aways** – summary of findings, risks.

3. Data collation and analysis

3.1. Data source summary

Data from multiple sources has been collated and analysed to inform the East Wanneroo area conceptual hydrogeological model and to provide inputs and parameters for the East Wanneroo groundwater model (EWGM). A summary of the data sources is provided in Table 1.

Table 1: Summary of data sources

Data type	Source
Schematization data (Section 3.2)	
Geomorphology and regional geology	Davidson, WA, 1995, Hydrogeology and groundwater resources of the Perth Region, Western Australia, Geological Survey, Bulletin 142. Davidson, W.A., & Yu, X, 2008, Perth regional aquifer modelling system (PRAMS) model development: Hydrogeology and groundwater modelling, Western Australia Department of Water, Hydrogeological record series HG 20. Gozzard, J. R., 2007, Geology and landforms of the Perth Region: Western Australia Geological Survey, 126p. Geospatial mapping data supplied by DWER (from Hisayo Thornton, Enterprise Data and Architecture group)
Study area lithology	Department of Water and Environmental Regulation (DWER) 2022, Water Information Reporting, Government of Western Australia. Available from: https://wir.water.wa.gov.au/Pages/Water-Information-Reporting.aspx
Surface topography	1m DEM from LiDAR survey supplied by DWER
Lake bathymetry	Bathymetry images provided by DWER 1m DEM from LiDAR survey supplied by DWER
Base of Superficial Aquifer	5m base of Superficial Aquifer contours supplied by DWER (from Hisayo Thornton, Enterprise Data and Architecture group) PRAMS layer elevation data (from Joel Hall, Aquatic Science Branch)
Land use	Annual or biennial raster data sets of land use between 1990 and 2019 from the PRAMS model, provided by DWER (from Joel Hall, Aquatic Science Branch) Aerial imagery review for the past 20 years from the MNG Access Portal Groom, PK 2004, Rooting depth and plant water relations explain species distribution patterns within a sandplain landscape, Functional Plant Biology, vol 31, pp 423 – 428. Silberstein R, Walker S, Hick W, Higginson S, Dawes W and Dumbrell I 2012, Water use of pine plantations on Gnangara groundwater mound. CSIRO, Australia, September 2012.
Input time-series data (Section 3.3)	
Climate data	Queensland Government 2022, SILO – Australian climate data from 1889 to yesterday, Queensland Government. Available from: https://www.longpaddock.qld.gov.au/silo/ [2 September 2022].

Data type	Source
Abstraction data	Licensed abstraction data (monthly) provided by Water Corporation for Water Corporation abstraction bores (from Dave Rushton, Operational Asset Management) Monthly metered abstraction data / monthly adjusted entitlement data from groundwater license holders provided as gridded data points from PRAMS model, provided by DWER (from Joel Hall, Aquatic Science Branch) Annual unlicensed bore abstraction data for groundwater subareas provided by DWER (from Joel Hall, Aquatic Science Branch)
Lake supplementation	Annual supplementation data provided by DWER (from Joel Hall, Aquatic Science Branch) Bore abstraction data provided by Water Corporation in abstraction dataset
Leakage from base of Superficial Aquifer	Daily and monthly time series data and annual average data provided by DWER using PRAMS 3.6 (from Joel Hall, Aquatic Science Branch)
Recharge and evapotranspiration	Xu, C, Canci, M, Martin, M, Donnelly M and Stokes, R 2008, Perth regional aquifer modelling system (PRAMS) model development: Application of the vertical flux model, Department of Water, Western Australia, Hydrogeological record series HG 27. Davies, CG 2022, *Subsurface drainage for sustainable urban development*, Doctoral thesis, University of Western Australia. CyMod Systems, 2009. Perth Regional Aquifer Modelling System (PRAMS) model development: Calibration of the Coupled Perth Regional Aquifer Model PRAMS 3.0. Report prepared by CyMod Systems Pty Ltd. Hydrogeological record series HG28, Department of Water, Western Australia. CyMod Systems 2014, Construction and calibration of the Perth Regional Aquifer Model PRAMS 3.5.2, prepared for Department of Water by CyMod Systems Pty Ltd, November 2014.
Parameter data (Section 3.3.7.5)	
	CyMod Systems, 2009. Perth Regional Aquifer Modelling System (PRAMS) model development: Calibration of the Coupled Perth Regional Aquifer Model PRAMS 3.0. Report prepared by CyMod Systems Pty Ltd. Hydrogeological record series HG28, Department of Water, Western Australia. CyMod Systems 2014, Construction and calibration of the Perth Regional Aquifer Model PRAMS 3.5.2, prepared for Department of Water by CyMod Systems Pty Ltd, November 2014. McArthur, J (2022), Investigation of superficial aquifer connectivity and lake-groundwater interaction in the Wanneroo-Joondalup Area, Department of Water and Environmental Regulation, Government of Western Australia. Semeniuk, V and Semeniuk, VK 2004, Sedimentary fill of basin wetlands, Swan Coastal Plain, southwestern Australia. Part 1: sediment particles, typical sediments and classification of depositional systems, Journal of the Royal Society of Western Australia, vol 87, pp 139 – 186. Domenico, PA and Schwartz, FW 1990, Physical and Chemical Hydrogeology. John Wiley and Sons, New York, 824 p.
Model calibration data (Section 3.5)	
	Department of Water and Environmental Regulation (DWER) 2022, Water Information Reporting, Government of Western Australia.

Data type	Source
	Available from: https://wir.water.wa.gov.au/Pages/Water-Information-Reporting.aspx
Scenario and decision support data (Section 3.6)	
	Bureau of Meteorology 2022, Australia Water Outlook, Australian Government. Available from: https://awo.bom.gov.au/products/projection
	WAPC 2020, East Wanneroo District Structure Plan, Produced by Data Analytics, Department of Planning, Lands and Heritage on behalf of the Western Australian Planning Commission, November 2020.
	Land use staging data (DPLH)
	Lake Jandabup future supplementation provided by DWER (email from Joel Hall, 21st September 2022)
	Water Corporation abstraction, provided by DWER (email from Joel Hall, 1st December 2022)

3.2. Schematization Data

3.2.1. Geomorphology

The central and eastern side of the study area extends across the Bassendean Dune System, a gently undulating eolian sand plain comprised of Bassendean Sand (Q_{pb}). The western side of the DSP area overlies the Spearwood Dune System, a complex of calcareous coastal dunes that consist of an aeolinite core (the Tamala Limestone, Q_{pk}) with tracts of a slightly calcareous surficial residual sand (Tamala Sand, Q_{pcs}) remaining from dissolution and leaching of the limestone (Figure 3) (Davidson and Yu 2008).

A chain of wetlands, including 3 major lakes have formed in the interdunal depressions between the Bassendean Dune system and Spearwood Dune system. Other wetlands, consisting of swamps and lakes have formed in depressions within both the Bassendean and Spearwood Dune Systems.

3.2.2. Regional Geology

3.2.2.1. Superficial formations

Surface geology mapping shows the uppermost superficial formations within the East Wanneroo area (Figure 3). The superficial formations are the Quaternary age sediments that extend across the Swan Coastal Plain. The stratigraphic relationship of the superficial formations is shown in sections presented by Davidson and Yu (2008) (Figure 4).

The deposits encountered within the study area are predominantly:

- Bassendean Sand through the central and eastern side of the domain
- Tamala limestone, an eolian calcarenite, as either limestone or residual leached yellow sand through the western side of the model domain
- Surficial lacustrine and swamp deposits in low lying wetland and lake areas.
- Gnangara Sand and the Ascot Formation towards the base of the Superficial Formations.
- Interbedded sands and clays of the Guildford Formation may be encountered on the south-eastern corner of the model domain where it interfingers with the Bassendean Sand.

Summary descriptions of the Superficial Formations within the study area are given below based on information provided in Davidson (1995), Davidson and Yu (2008) and Gozzard (2007):

- <u>Bassendean Sand</u> is a leached pale grey to white, fine to coarse grained but predominantly medium-grained, moderately sorted, subrounded to rounded quartz sand. Bassendean Sand is typically leached of calcareous material compared to other coastal deposits, but often features a limonite cemented layer, colloquially termed 'coffee rock'.

- Tamala Limestone is an eolian calcarenite (rather than a true limestone), comprised of carbonate-cemented dune sand and includes abundant rhizoliths (calcretised tree root casts), calcreted wave-cut platforms and caves (Gozzard, 2007). The quartz sand is generally fine- to coarse-grained, but predominantly medium-grained, moderately sorted, and subangular to rounded. Some areas feature abundant solution channels and cavities, whereas other areas are extremely hard and dense where there has been intense calcretisation and silcretisation.
- Swamp and lacustrine deposits are found in low lying areas that are often inundated permanently or seasonally with fluctuations in the groundwater level. These areas accumulate clays, and organic matter forming low-permeability peaty deposits. These sediments are typically anaerobic and can lead to the formation of sulfide rich minerals and are a source of acid sulfate generating soils.
- Gnangara Sand is predominantly of fluvial origin, and consists of pale grey, fine to very coarse grained, very poorly sorted, subrounded to rounded quartz sand with abundant feldspar.
- The Ascot Formation represents a sequence of depositional events in the shallow marine zone of prograding shoreline. It consists of hard to friable, grey to fawn calcarenite with thinly interbedded sand and commonly contains shell fragments, glauconite and phosphatic nodules near the base of the formation.
- The Guildford Formation (formerly called the Guildford Clay) is predominantly of fluvial origin and consists of pale grey, blue, but mostly brown, silty, and slightly sandy clay, which interfingers to the west with the Bassendean Sand and Gnangara Sand.

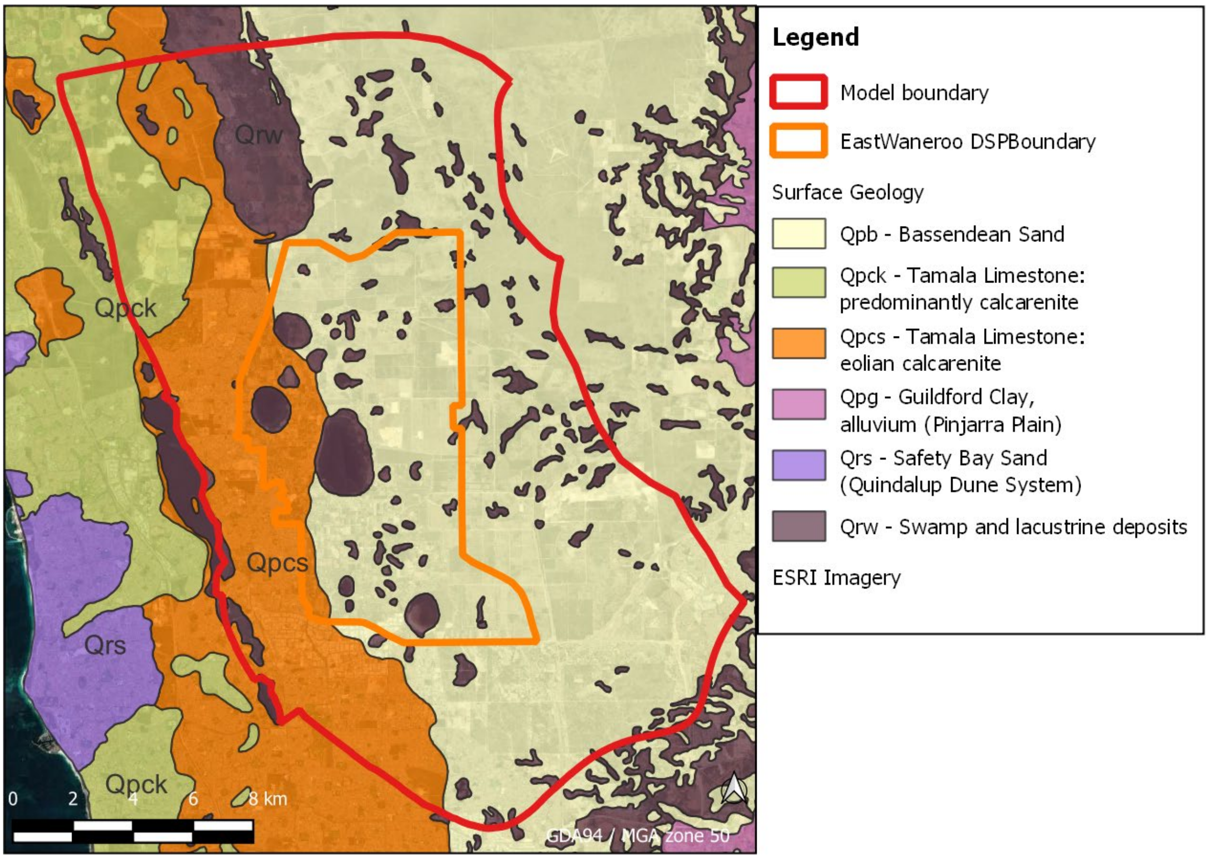


Figure 3: Surface geology (map data provided by DWER Geospatial Services)

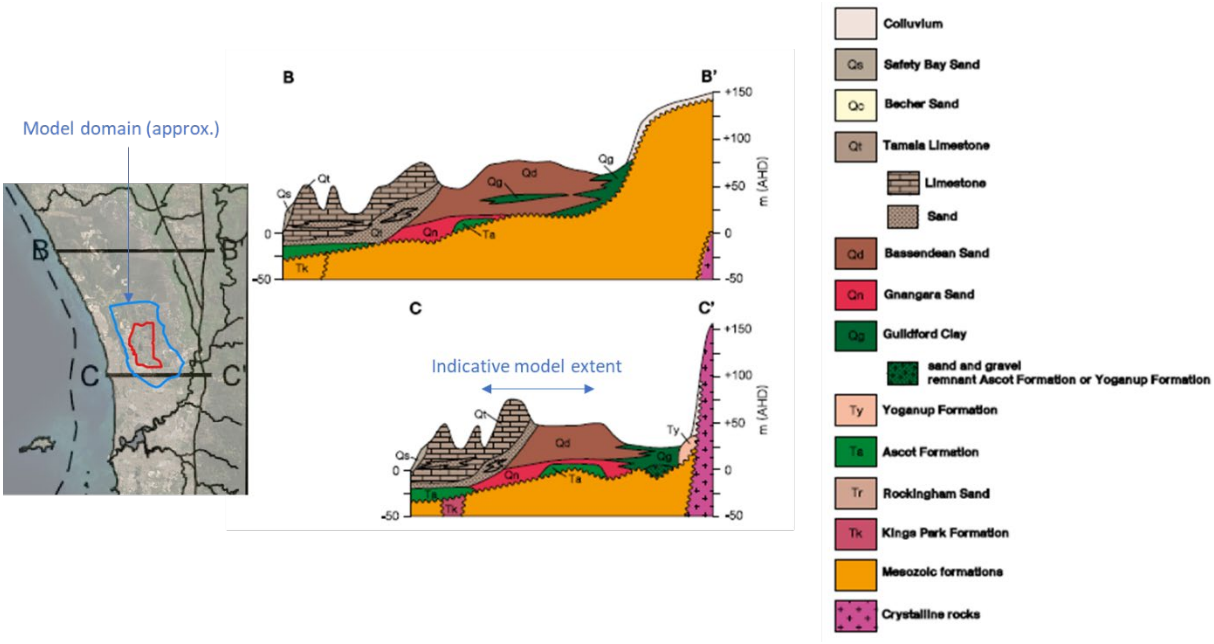


Figure 4: Geological sections through the Superficial Aquifer showing stratigraphic relationships (modified after Davidson and Yu, 2008)

3.2.2.2. Basal formations

The geology of the formations between the Superficial and Leederville aquifer indicates whether the formations will act as a confining layer or will allow for downward or upward leakage to/from the underlying Leederville Aquifer.

The basal formations immediately underlying the study area are shown in Figure 5 and described below (Davidson and Yu 2008):

- The Pinjar Member (Kwlp) (Leederville Formation) is the upper member of the Leederville Formation and comprises mixed marine and non-marine interbedded grey sandstone, dark grey to black siltstone and shale, with some lignite and micaceous material.
- The Wanneroo Member (Kwlw) (Leederville Formation) consists of interbedded sandstones, siltstones and shales of marine and non-marine origin.
- The Kardinya Shale Member (Kcok) (Osborne Formation) is a dark green to black, commonly puggy and glauconitic, moderately to tightly consolidated, interbedded siltstone and shale. It is an overlying confining layer across parts of the Leederville Aquifer inhibiting leakage into the aquifer and is pinched out beneath the Pinjar Member and Wanneroo Member.
- The Mirrabooka Member (Kcom) (Osborne Formation) is a dark greenish brown sandstone composed of poorly to moderately sorted fine sand to gravel-sized quartz fragments and glauconite, with thin shale and siltstone interbeds.
- Molecap Greensand (Kcm) consists of fine- to medium-grained, yellowish-brown to greenish-grey, glauconitic, silty, and locally clayey sandstone.
- Poison Hill Greensand (Kcp) comprises yellowish green to dark green, fine- to very coarse-grained, very poorly sorted, commonly rounded and spherical, richly glauconitic, silty and locally clayey sand.

A study of the hydrogeology of the Leederville Aquifer (Leyland 2011) showed some differences in the extent of some of the basal formations compared to those presented in Figure 5. Within the study area, the main difference appears to be with the Pinjar member to the north-east, which was found to extend further to the south and west than indicated in the Davidson and Yu (2008) report. PRAMS data provided by DWER for the development of the groundwater model report has generally been adjusted to take into account the differences identified by Leyland (2011).

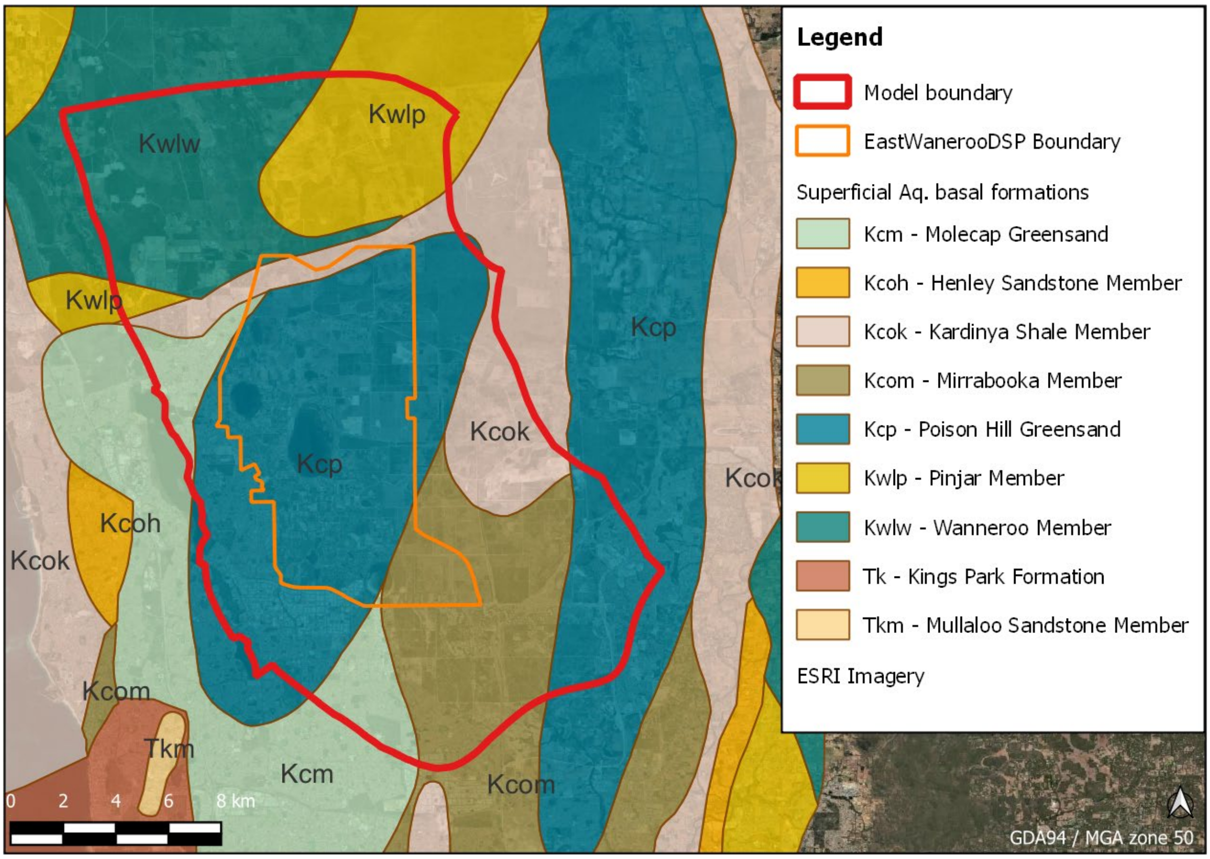


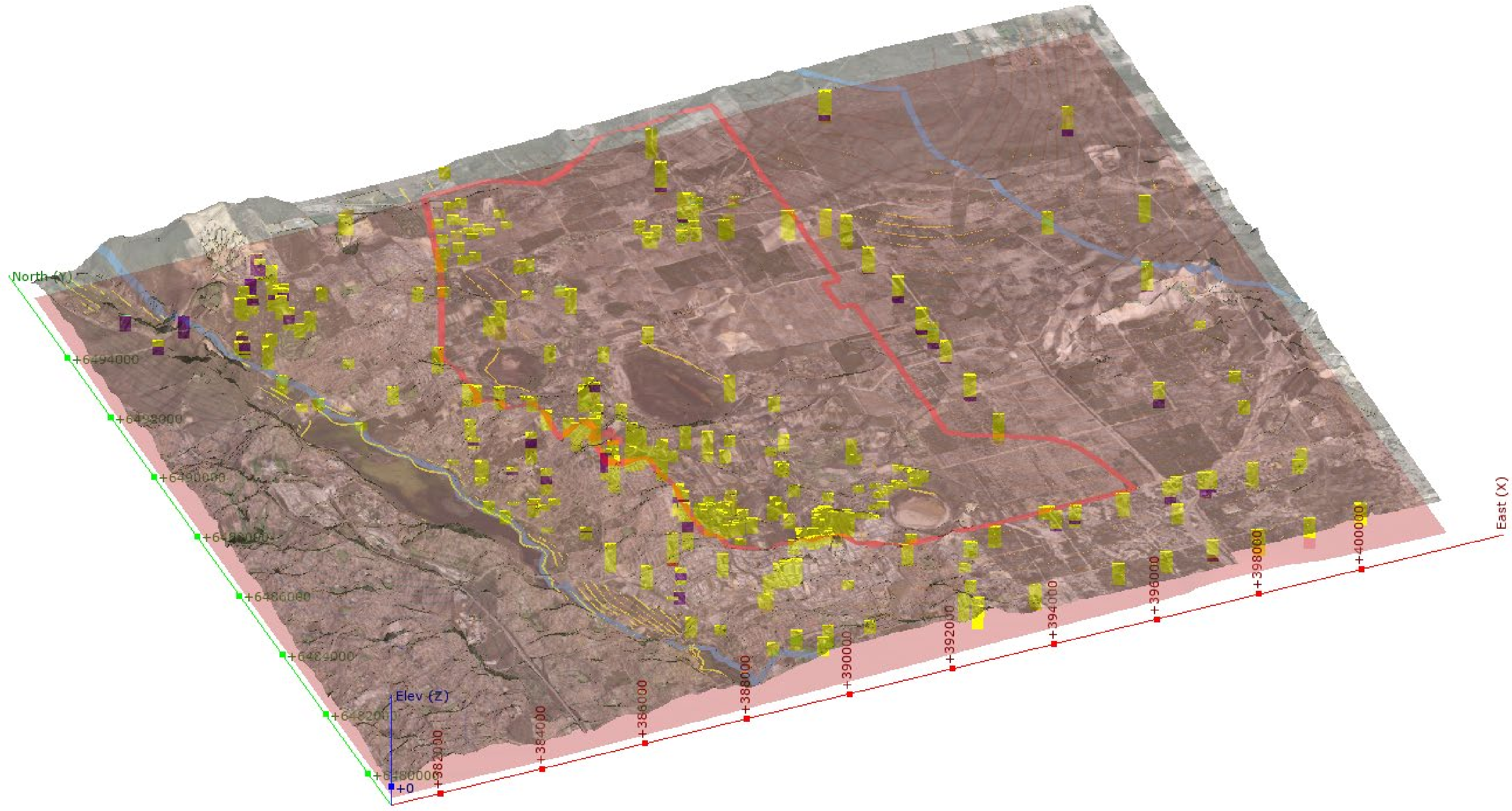
Figure 5: Basal units underlying Superficial Formation (after Davidson and Yu 2008)

3.2.3. Study area lithology

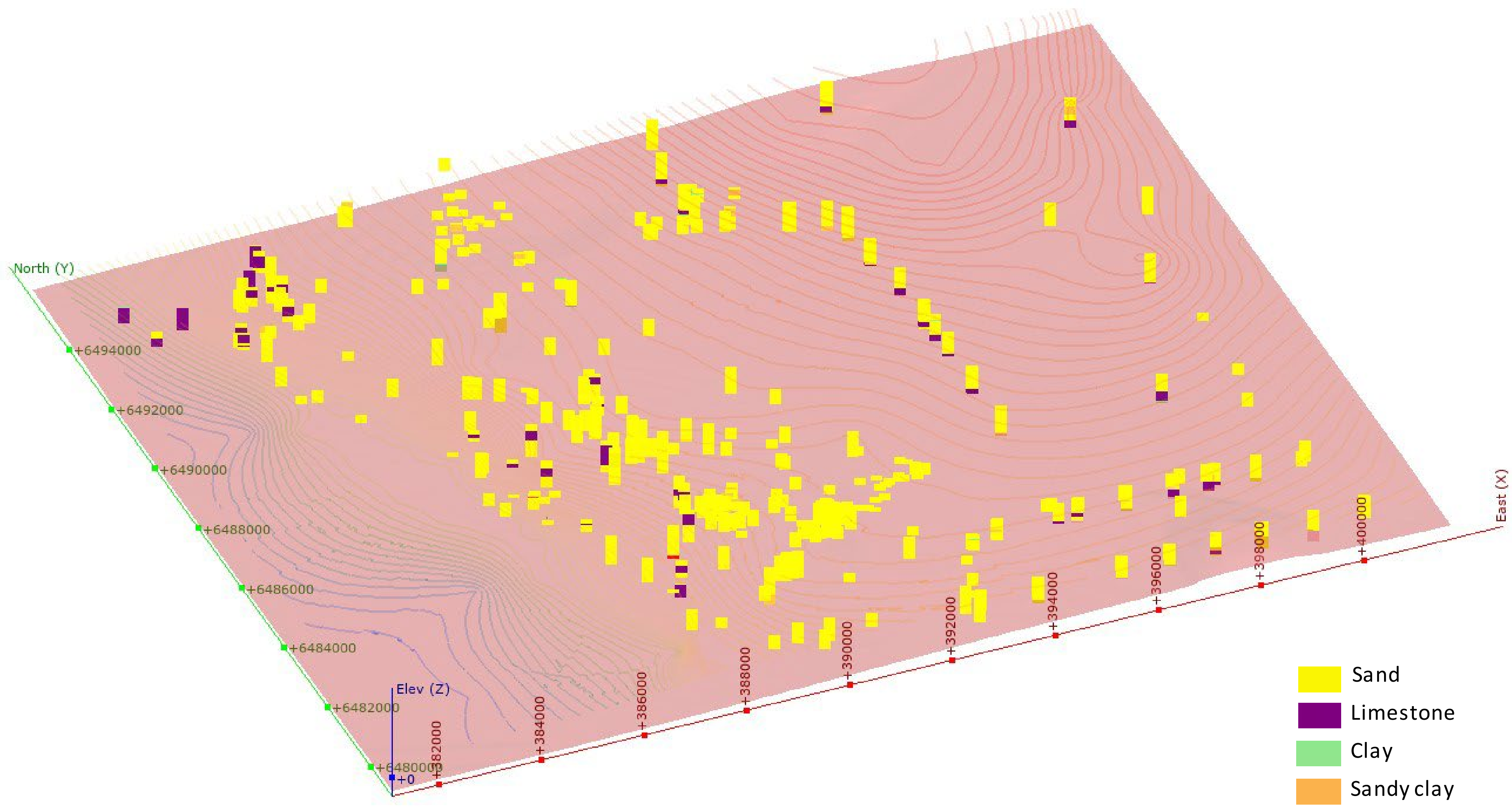
Lithological logs from the Water Information Reporting (WIR) database (DWER 2022) were extracted and filtered for the lithology of the Superficial Aquifer.

The filtered lithological data was entered into Leapfrog Works 3D modelling software for visual inspection. The bore lithology across the EWDSP area is shown in Figure 6. The lithology across the study area consists of:

- Sand (either Bassendean Sand or Tamala Sand)
- Limestone (potentially the Ascot Formation) at the base of a small number of eastern bores
- Tamala Limestone in some bores on the western side of the model, primarily in the north-western part of the model domain and east of Lake Joondalup.
- Occasional sandy clay layers.



(a) Including surface imagery



(b) Without surface imagery and above base of Superficial Aquifer

Figure 6: Bore lithology across EWDSP area

3.2.4. Surface topography

Surface topography data (LiDAR) was provided by DWER as a 1 m DEM (Digital Elevation Model) across the study area, as shown in Figure 7. This figure shows a line of dunes along the western side of the EWDSP area (Spearwood Dune System) and a gently undulating dune system through the central and eastern parts of the model domain (Bassendean Dune System), with higher topographic elevations near the north-eastern corner.

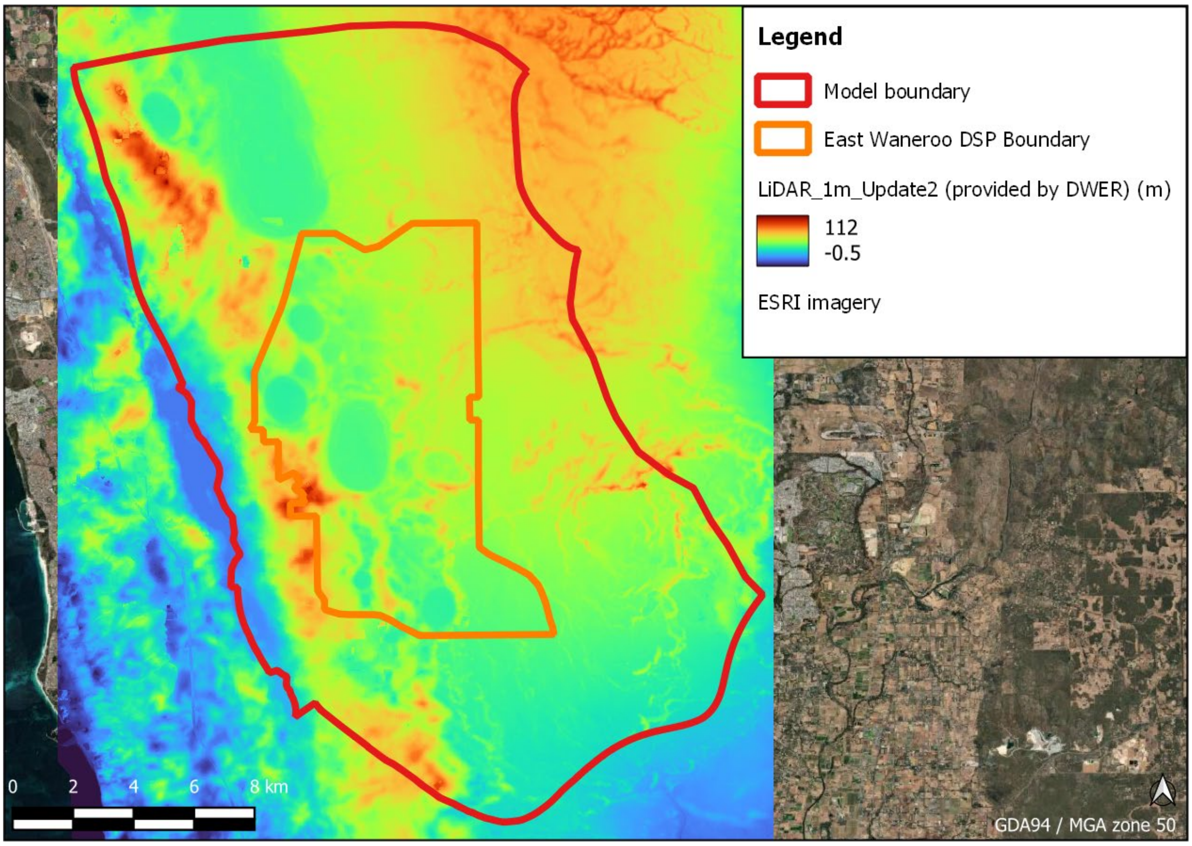


Figure 7: Surface topography from 1m DEM

3.2.5. Lake bathymetry

Scanned images of lakebed bathymetry were provided by DWER for the three major lakes:

- Lake Jandabup, Lake Gnangara and Lake Mariginiup (Figure 8).

Digital elevation models (DEMs) for the base of each lake were obtained as follows:

- Lake Mariginiup – although this lake likely contained some water, the 1m LiDAR DEM (Figure 7) showed a lower surface across the lake than the bathymetry provided, so the LiDAR DEM was used to determine the lake base (i.e. top of the sediment bed).
- Lake Jandabup – the water surface was evident by a flat surface on the 1m LiDAR DEM through the central section of this lake. A merged lake base surface was generated based on LiDAR data above the water surface and the georeferenced lake bathymetry (interpolated to a DEM) below the water surface.
- Lake Gnangara – no water evident in the LiDAR data so the LiDAR DEM was used for the base surface of the lake.

Geospatial software was used to generate depth to surface area and volume relationships at regular (5 cm) intervals.

Figure 8: Bathymetry data for Lake Mariginiup, Lake Jandabup, and Lake Gnangara

3.2.6. Base of superficial aquifer

Base of superficial aquifer contours (at 5 m intervals) were provided by DWER as part a standard geospatial dataset. A digital elevation model (DEM) (50 m grid) was interpolated from the contours as shown in Figure 9. This DEM is consistent with the elevation grid used for the PRAMS model (top of layer 4) (Figure 10).

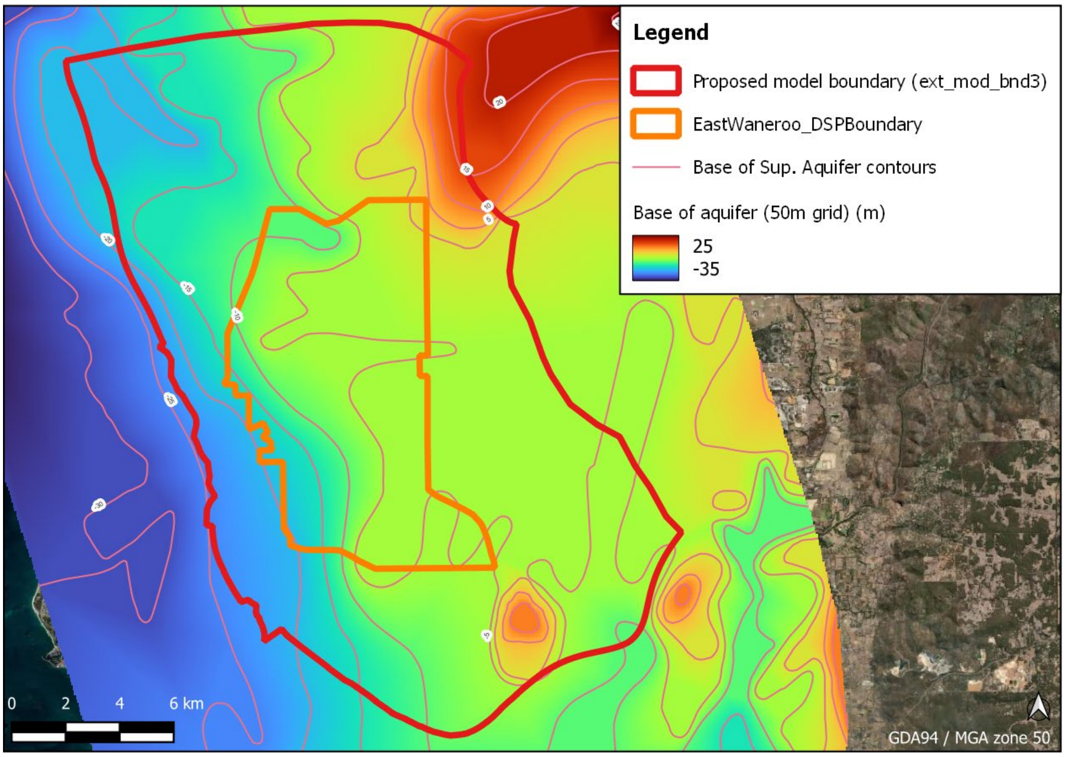


Figure 9: Base of Superficial Aquifer contours (5 m) and interpolated DEM (50 m grid)

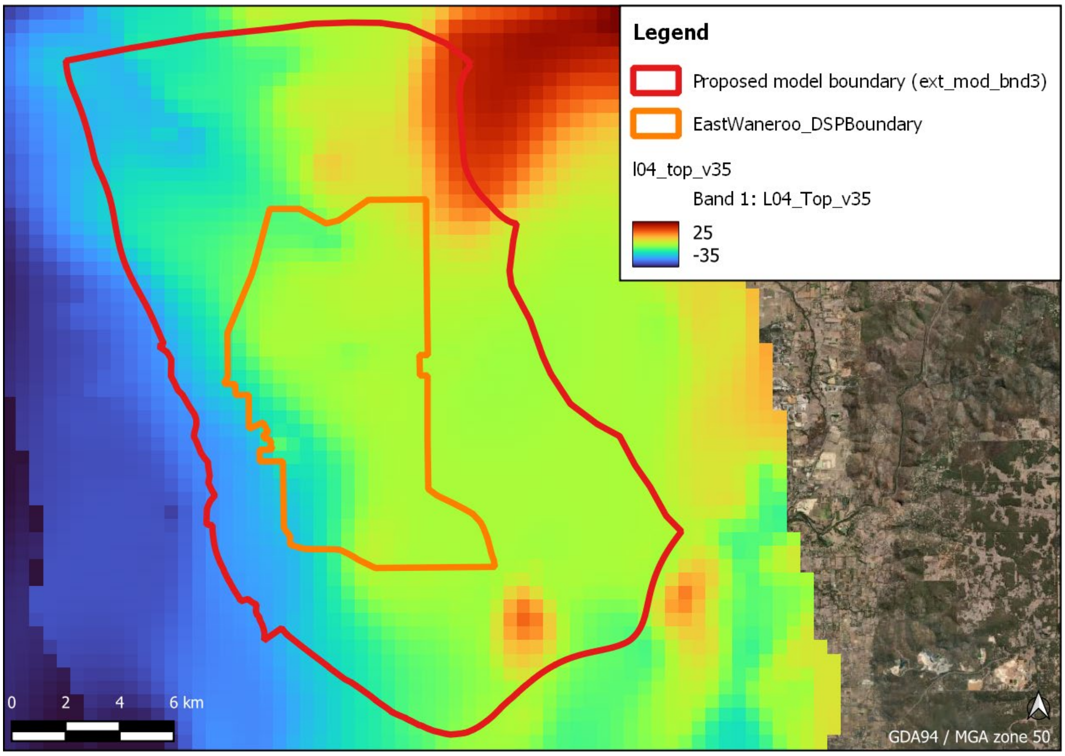


Figure 10: Base of Superficial Aquifer from the PRAMS model (i.e., top of Layer 4)

3.2.7. Land use

Annual/biennial land use rasters have been provided by DWER for the period from 1990 to 2030. These datasets are used for the PRAMS groundwater flow model. The DWER land use coverages specify up to 14 land use codes, based on the dominant vegetation type occurring within the cell or the dominant economic activity (CyMod 2014). A comparison of the coverages shows changes in land use over time. The land use coverages from 2010 and 2019 are shown in Figure 11 and Figure 12, respectively.

A review of aerial imagery using the MNG Access mapping portal was undertaken to visually assess land use change over time. Based on the review of aerial imagery in conjunction with the land use rasters, simplified land use polygons were determined across the study area falling under nine generalised land categories (Figure 13). Sixteen of the polygon areas were observed to have a changing land use over the model calibration period (2010 to 2021), shown by the cross-hatched areas in Figure 13.

Areas where the water table is above or below the assumed maximum rooting depth of 9 m for Banksias (Groom 2004) and 18 m for pines (Silberstein et al. 2012) are also shown Figure 13.

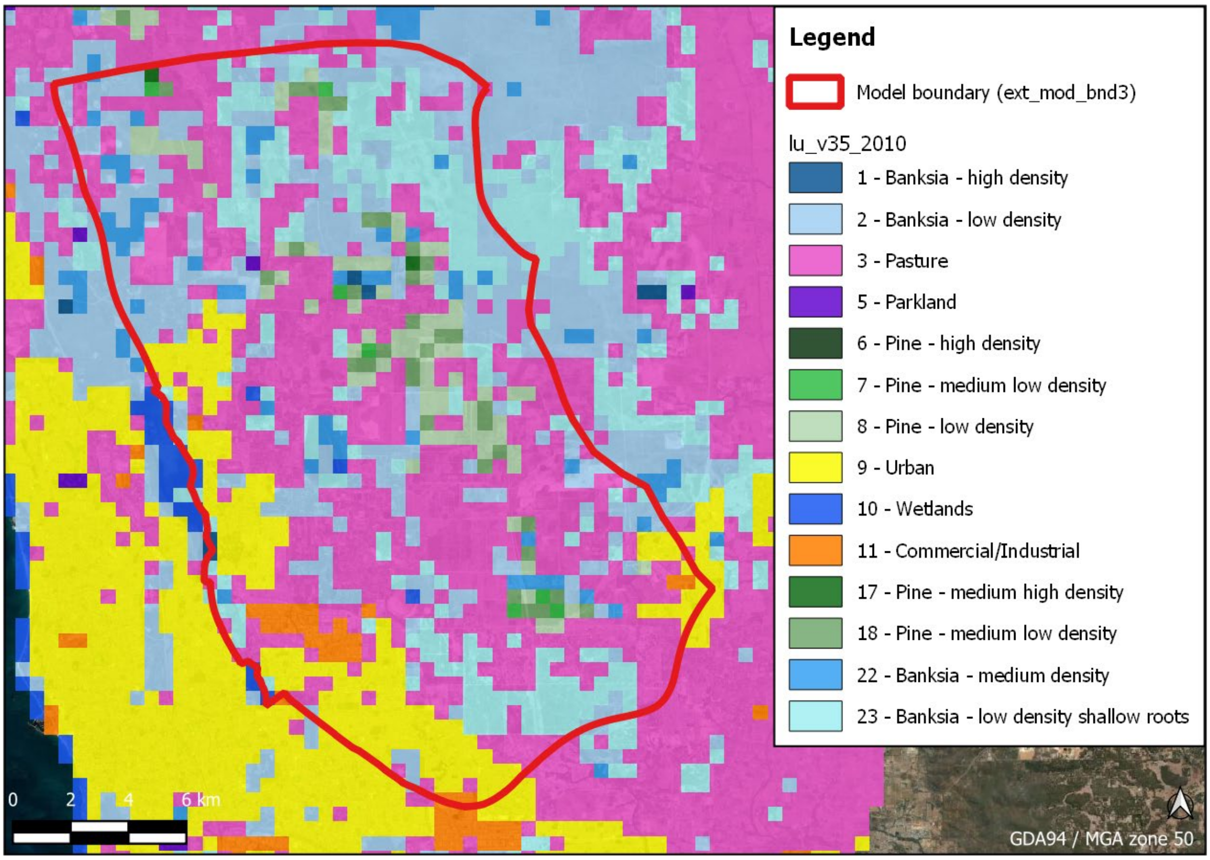


Figure 11: 2010 land use layer from PRAMS model

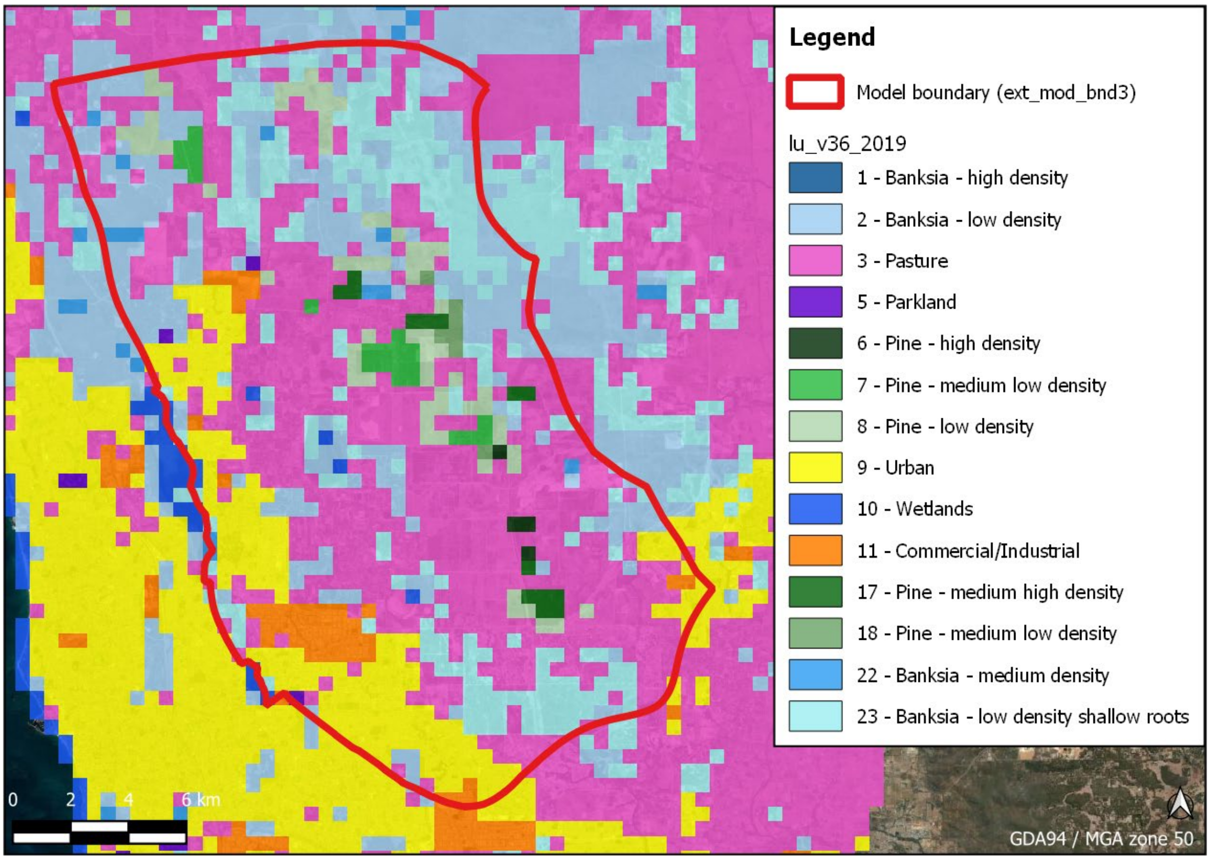


Figure 12: 2019 land use layer from PRAMS model

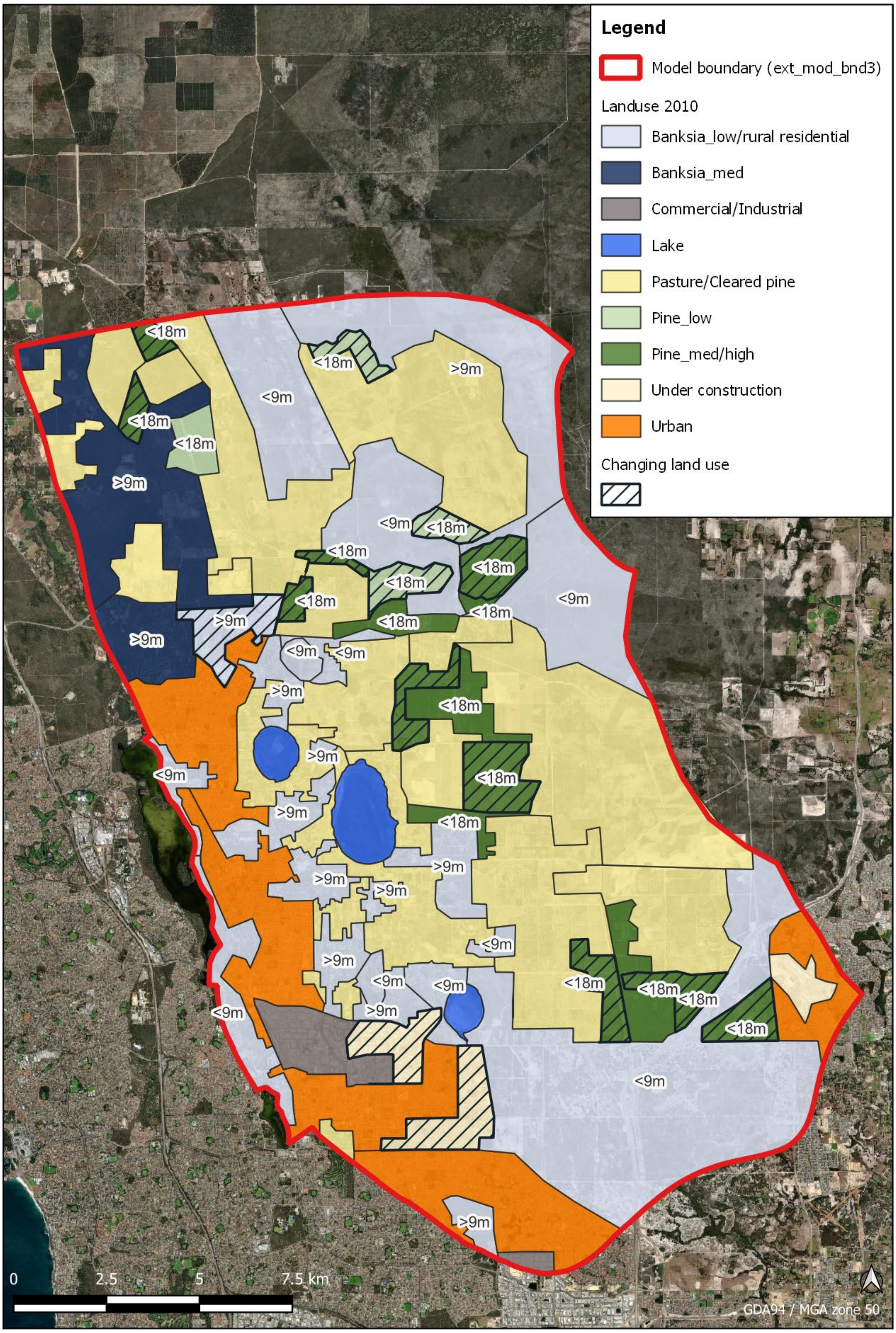


Figure 13: Identified land uses across the model domain (2010)

3.3. Input time-series data

3.3.1. Climate data

Climate data was obtained from SILO (Queensland Government, 2022) for grid points across the study area. Daily time-series data from 1970 to 2021 were obtained for:

- Rainfall (daily_rain)
- Potential evapotranspiration (et_short_crop), based on the Penman-Monteith method for estimating reference evapotranspiration (FAO56) (Zajaczkowski and Jeffrey, 2020)
- Morton lake evaporation (evap_morton_lake), based on the method outlined by Morton (1983) to estimate evaporation over shallow lakes (Zajaczkowski and Jeffrey, 2020)

The climate data did not vary between grid points across the study area. A single set of climate data was selected for the study, obtained from a grid point immediately southeast of Lake Jandabup, with latitude and longitude co-ordinates of - 31.75 and 115.85, respectively.

Monthly rainfall for the site is shown in Figure 14 and monthly evaporation data is shown in Figure 15.

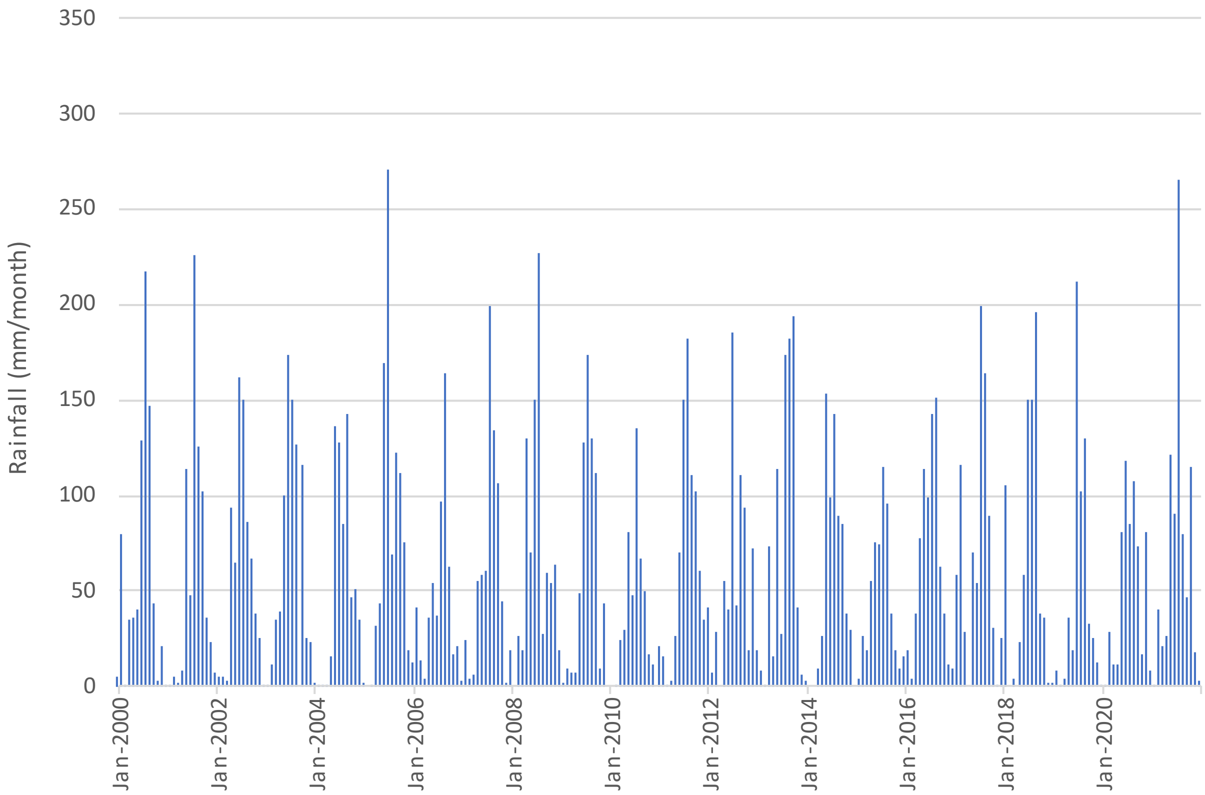


Figure 14: Monthly rainfall for the study site (Queensland government, 2022)

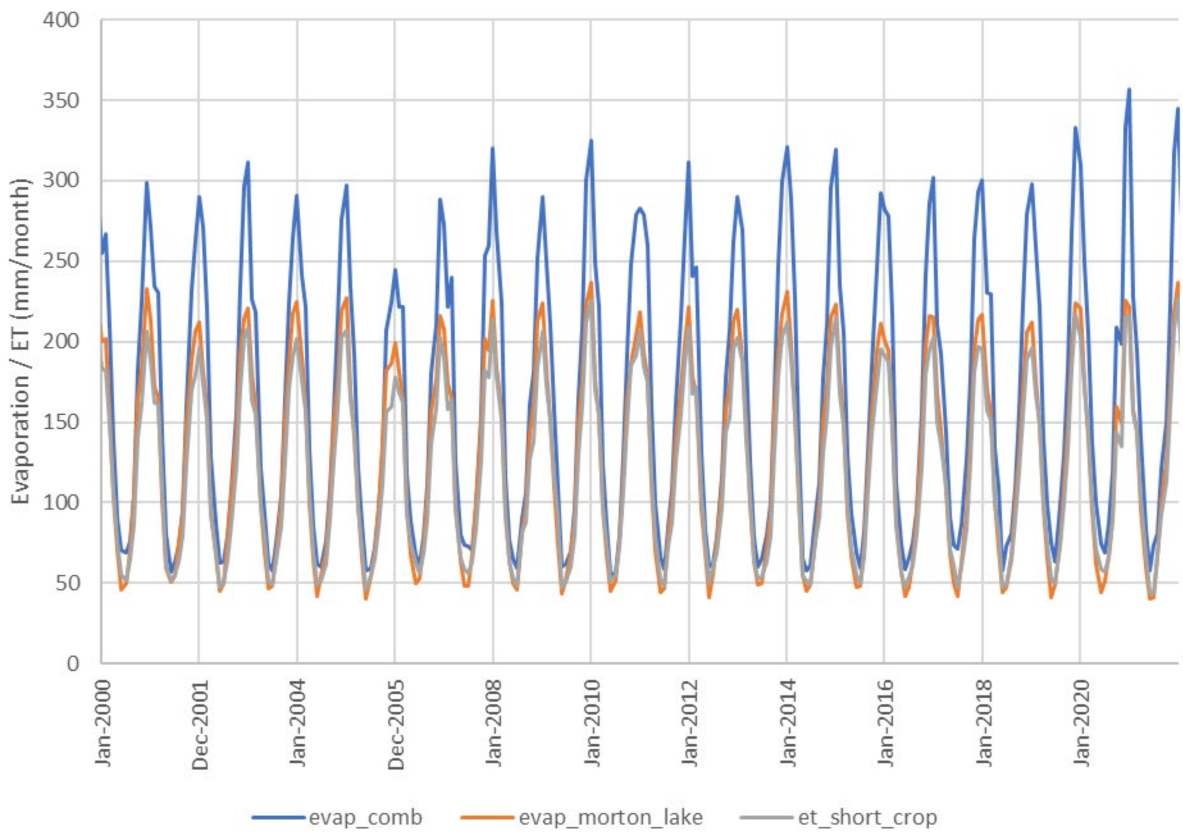


Figure 15: Evaporation and evapotranspiration for the study site (Queensland government, 2022).

3.3.2. Abstraction

Groundwater is abstracted from the study area as:

- Licensed abstraction by Water Corporation (WC) for public water supply.
- Licensed abstraction by groundwater license holders, primarily for irrigation.
- Unlicensed bore abstraction, primarily as garden bores in residential areas.

3.3.2.1. Water Corporation abstraction

Monthly abstraction data for all WC abstraction bores within the model domain area and within the Superficial Aquifer was provided by WC (personal communication from Dave Rushton, Operation Asset Management team, on 13 October 2022) for the period from January 2000 to July 2022. The WC abstraction bore locations are shown on Figure 16.

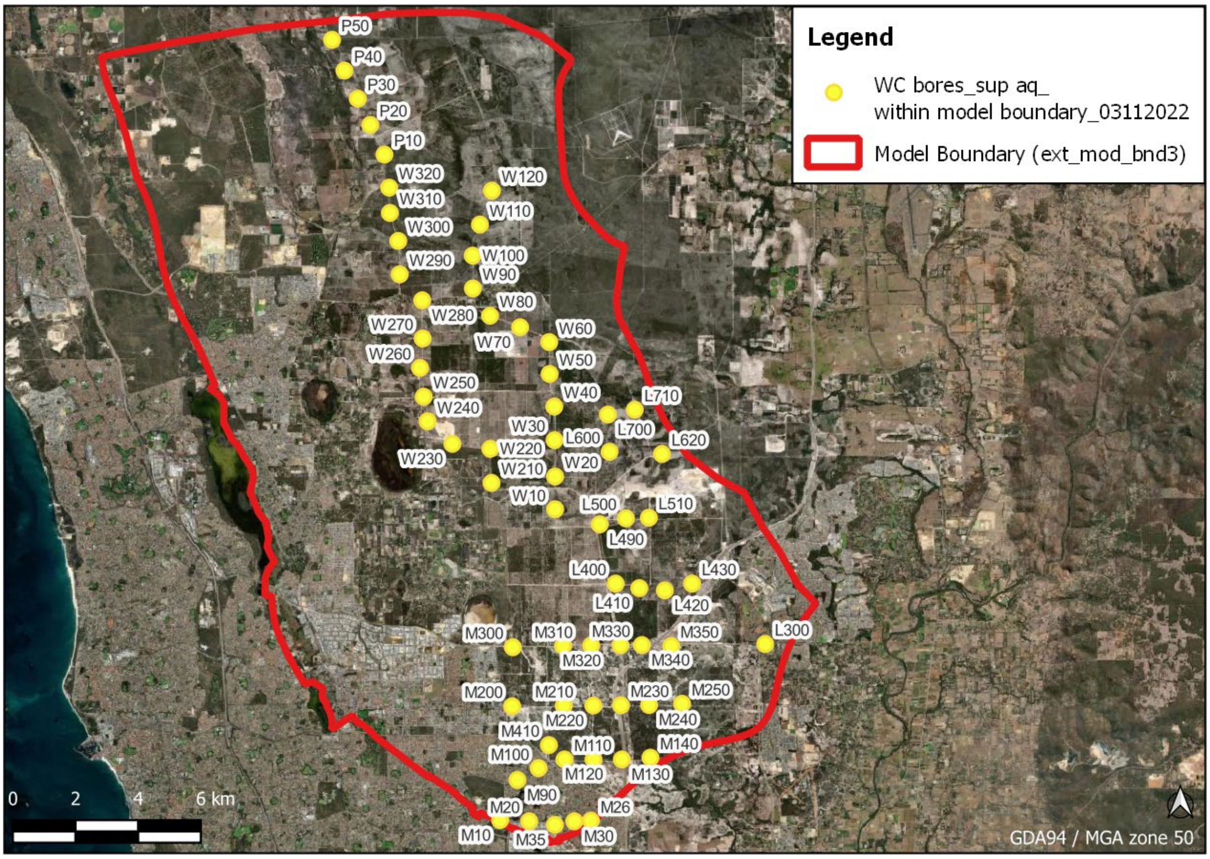


Figure 16: Water Corporation abstraction bores within the Superficial Aquifer and within the model domain

3.3.2.2. Licensed abstraction data

Licensed abstraction data was provided by DWER as a combined set of measured and estimated abstraction rates from drawpoints at the centroid of 500 m by 500 m grid cells (i.e. a layer used in the PRAMS model). The licensed abstraction drawpoints are shown in Figure 17.

The licensed abstraction data is an average daily rate, from each centroid drawpoint, for each month between July 2000 and December 2018. Abstraction data for 2019, 2020 and 2021 was assumed to be the average of the preceding 3 years of data.

Following development of the groundwater model, the licensed abstraction data from DWER was assumed to be uniformly distributed over each PRAMS grid cell and was converted to equivalent rates across the East Wanneroo groundwater model grid.

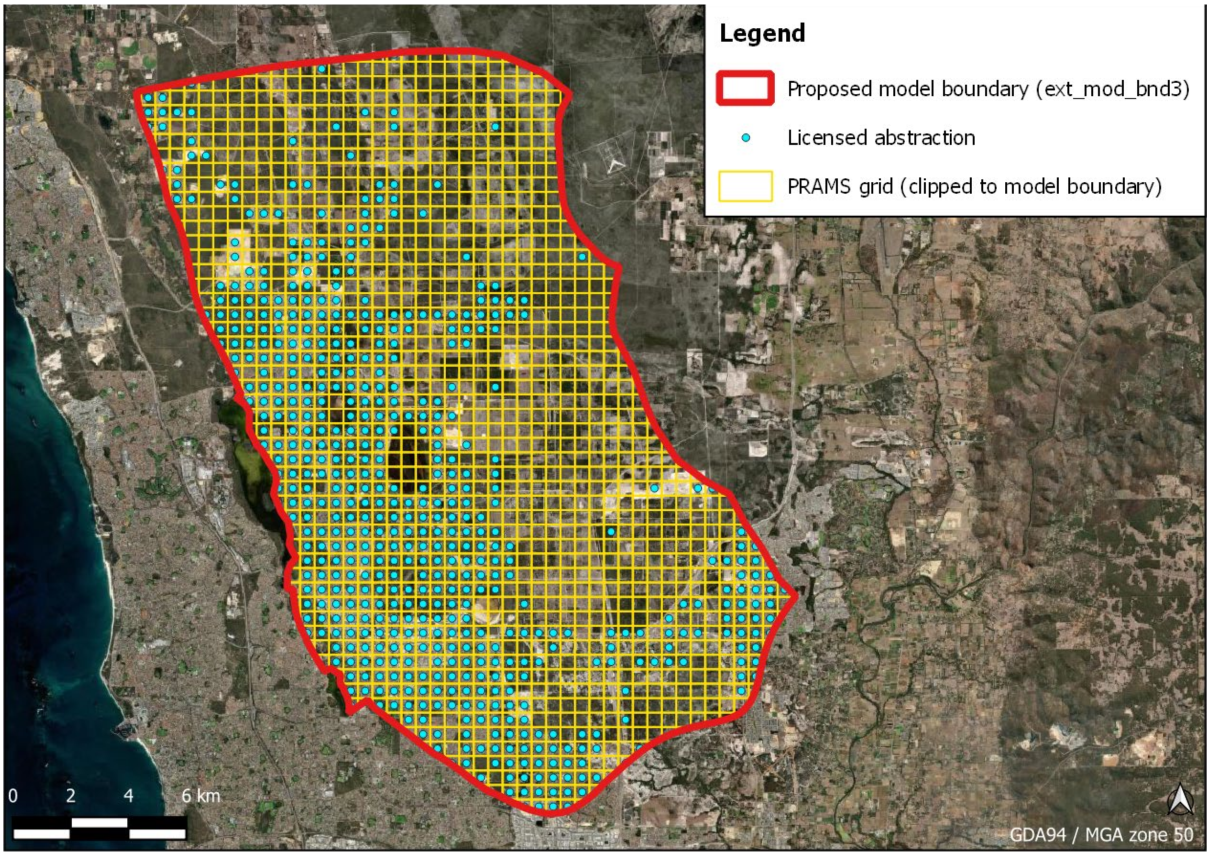


Figure 17: Licensed abstraction points (based on PRAMS licensed abstraction data)

3.3.2.3. Unlicensed abstraction data

Annual unlicensed abstraction data was provided by DWER for each groundwater subarea, for the period from 2000 to 2019. The 2019 data was assumed to apply to 2020 and 2021.

Areas likely to have unlicensed bore use were identified from aerial imagery (as shown in Figure 18). It was assumed that unlicensed groundwater bores were installed in both urban and rural residential lots, but no unlicensed abstraction was allowed for in lots that had a groundwater licence.

For subareas fully contained within the model domain, annual unlicensed abstraction data was applied in full, however annual abstraction was reduced for those subareas that crossed the model boundary. The reduction percentage was estimated based on the area of unlicensed abstraction within and outside of the model boundary.

Abstraction rates were not provided for the small area within the North Swan groundwater subarea. The flux across unlicensed areas in the adjacent subarea (State Forest) was applied to the North Swan area at the edge of the model domain. Adjusted annual unlicensed abstraction areas for the subareas within the model domain are presented in Table 2.

The (adjusted) annual abstraction rates were converted to monthly rates, assuming a constant abstraction distribution across 9 months of the year with no abstraction during the winter months (June, July and August). The adjusted unlicensed abstraction rates were assumed to be evenly distributed across both urban and rural residential areas.

Table 2: Adjusted annual unlicensed abstraction rates for groundwater subareas within the model domain (ML/yr)

Superficial Subarea	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Adams	62.0	62.0	62.0	62.0	62.0	62.0	62.0	62.0	62.0	62.0	62.0	62.0
Carramar	369.0	408.0	389.0	447.0	476.0	505.0	505.0	505.0	505.0	505.0	505.0	505.0
Jandabup	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0
Joondalup	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
Lake Gnangara	743.0	686.0	686.0	800.0	829.0	858.0	886.0	915.0	915.0	915.0	915.0	915.0
Mariginiup	316.0	316.0	316.0	316.0	316.0	316.0	316.0	316.0	316.0	316.0	316.0	316.0
Neerabup	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Nowergup	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pinjar	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6
Ballajura	1310.9	1310.9	1310.9	1310.9	1310.9	1310.9	1310.9	1310.9	1310.9	1310.9	1310.9	1310.9
Henley Brook	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6
Improvement Plan 8	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Landsdale	39.0	39.0	47.0	62.0	62.0	62.0	66.0	70.0	70.0	70.0	70.0	70.0
Plantation	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
State Forest	294.3	294.3	278.7	278.7	278.7	278.7	278.7	278.7	278.7	278.7	278.7	278.7
Whiteman Park	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Whitfords	833.7	847.6	843.0	856.9	856.9	856.9	858.1	859.2	859.2	859.2	859.2	859.2
Reserve	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wanneroo Wellfield	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
North Swan	10.5	10.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0

Note: The small area of North Swan on the eastern side of the model was assumed to have the same unlicensed abstraction flux across the unlicensed abstraction area as State Forest, the adjacent subarea.

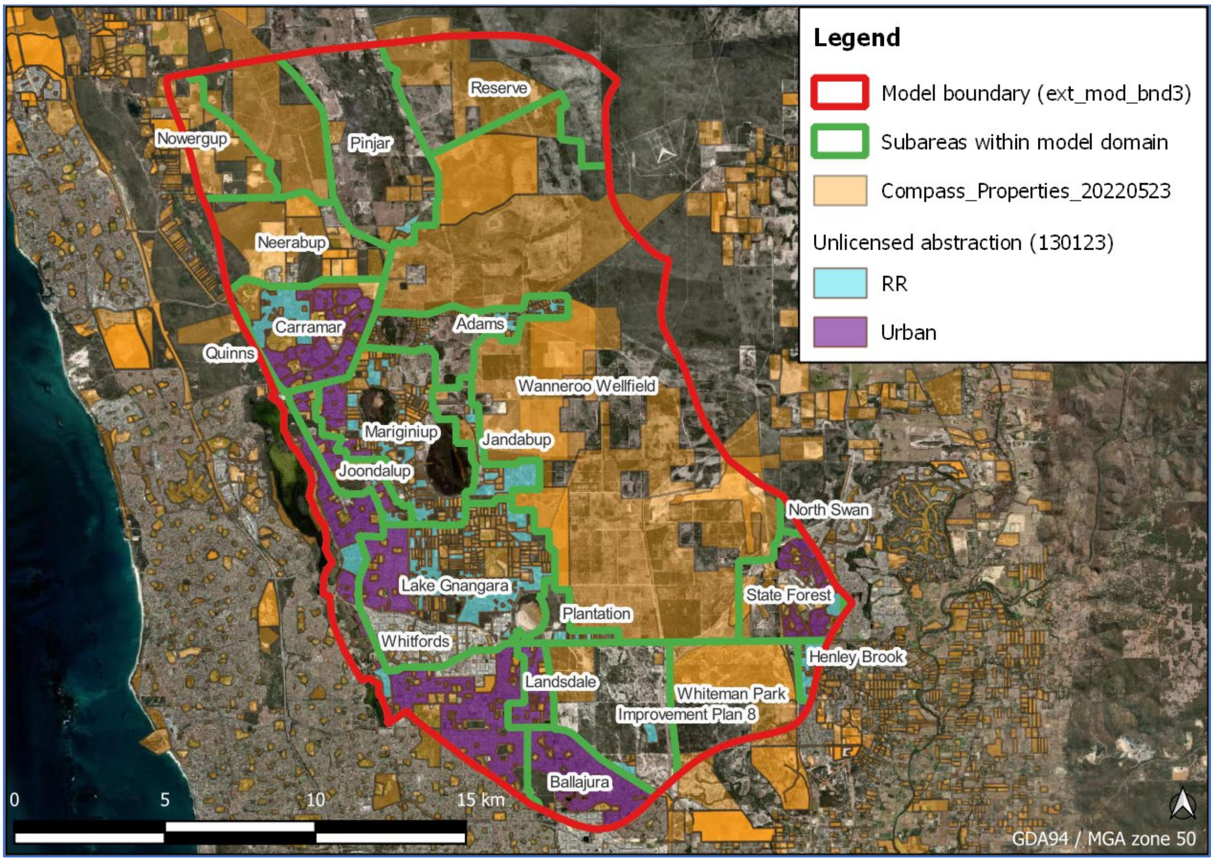


Figure 18: Areas identified for unlicensed abstraction

3.3.3. Irrigation return flow

Irrigation return flow is the excess irrigation water that is not removed from the surface via evapotranspiration or direct drainage and is returned to the aquifer.

With the water efficiency measures being implemented across Perth over the last two decades, it was assumed that irrigation return flow is negligible across the study area for both licensed and unlicensed abstraction for the proposed model calibration period from 2010 to 2021. This has been discussed by Cymod (2014) for unlicensed bore abstraction, with the conclusion drawn that gross and net unlicensed abstraction are similar from 2009 onwards.

3.3.4. Lake supplementation

Jandabup Lake water levels were maintained over the proposed model calibration period (2010 to 2021) by water additions from WC abstraction bores W210 and W220. The annual supplementation volumes were provided by DWER (Table 3). The distribution of the annual supplementation volumes into monthly volumes was based on the monthly abstraction distribution from bore W210 and W220.

Table 3: Lake Jandabup supplementation volume (ML)

Water year	Supplementation volume (ML)
2000-01	1111
2001-02	963
2002-03	1110
2003-04	973
2004-05	924
2005-06	899
2006-07	1403
2007-08	1249
2008-09	1061
2009-10	899
2010-11	1493
2011-12	1161
2012-13	867
2013-14	1331
2014-15	1170
2015-16	1312
2016-17	1226
2017-18	886
2018-19	1304
2019-20	1422
2020-21	1301

3.3.5. Stormwater inflow

Data on stormwater inflow into the major lakes has not been assessed as runoff across the study site is considered to be low.

3.3.6. Leakage from/into the Superficial Aquifer

Leakage rates between the Superficial Aquifer and underlying formations have been provided by DWER. The rates have been estimated from the PRAMS model for the leakage zones shown in Figure 20. The leakage rates are based on the vertical flux into PRAMS layers 4 and 5, tracking the vertical flux to/from the Kardinya Shale, which is the lithological unit controlling flow between the Superficial Aquifer and Leederville Aquifer.

Leakage time series have been provided by DWER as daily and monthly time series from July 2000 to June 2019, as shown in Figure 19 for the monthly time series. Annual average leakage rate estimates are provided in Table 4.

All flow between the Superficial Aquifer and Leederville Aquifer is an outflow from the Superficial Aquifer, as indicated by the negative flow rates in Figure 5 and Table 4. Leakage flow rates are high in Zones 4, 5 and 6, where the Kardinya Shale pinches out.

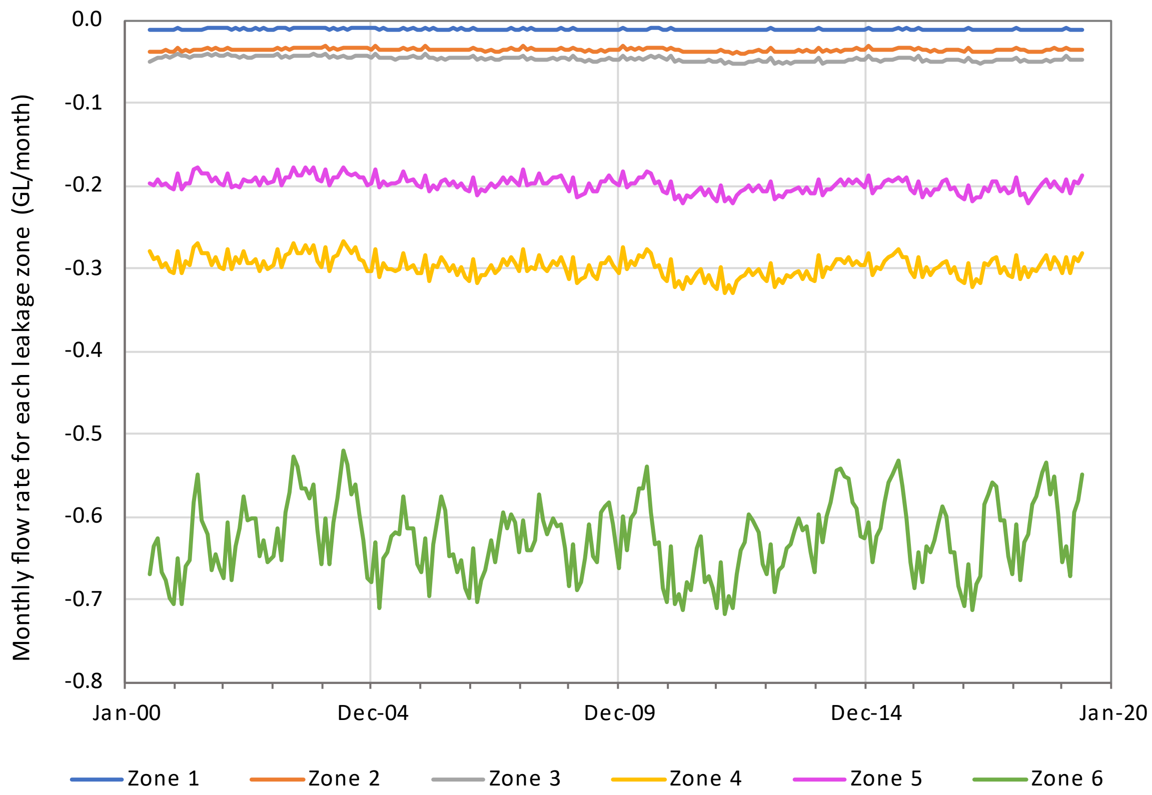


Figure 19: Monthly vertical flow rates for each leakage zone (negative rates indicate leakage from Superficial Aquifer)

Table 4: Average annual vertical flow from/into the Superficial Aquifer (negative values indicates downward flow into the Leederville Aquifer)

Leakage zone	Average annual vertical flow rate into leakage zones (GL/yr)
1	0.1
2	0.4
3	0.5
4	3.4
5	2.3
6	7.1
TOTAL	**13.8**

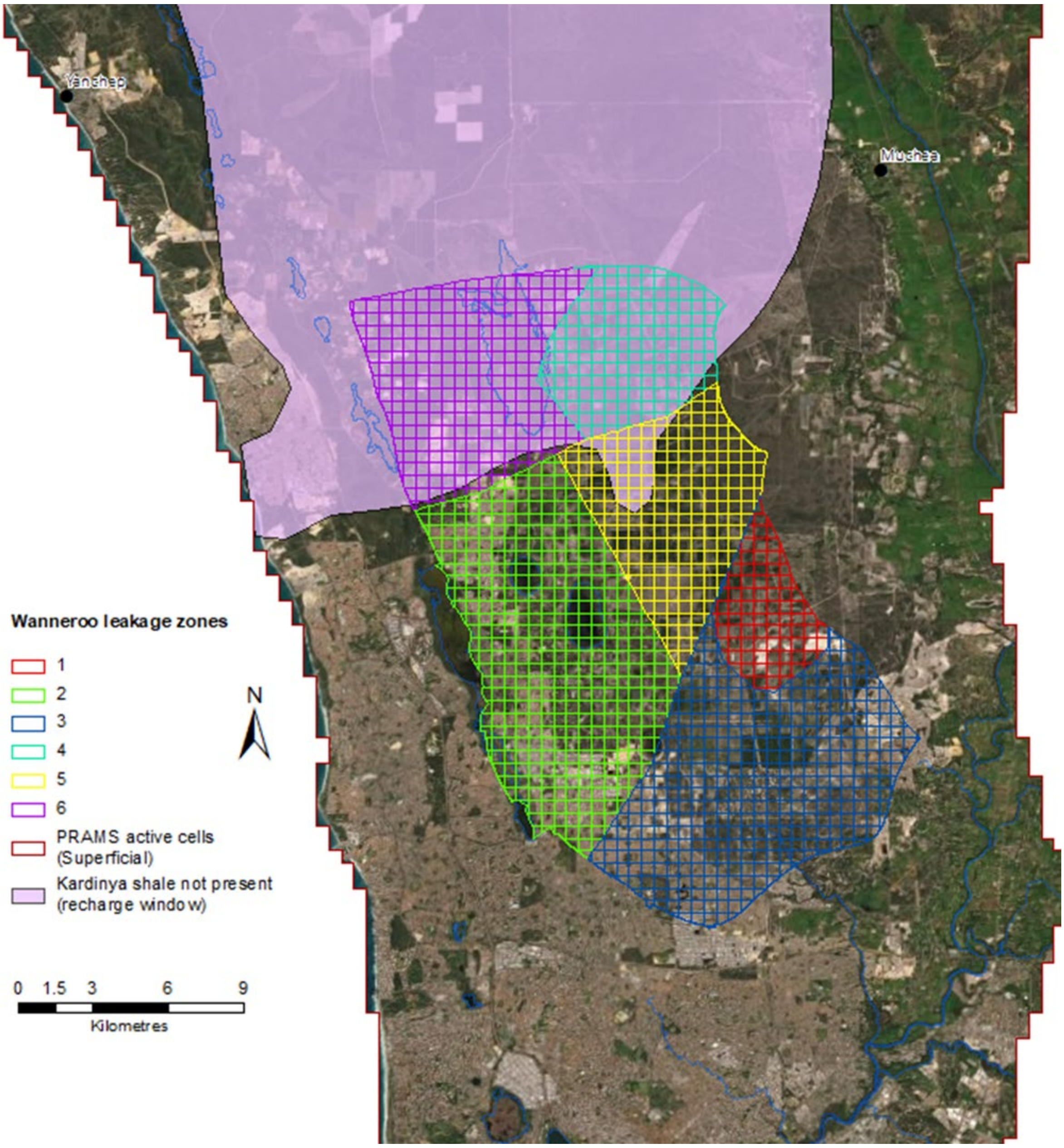


Figure 20: Zones used to estimate leakage rate from Superficial Aquifer (image provided by DWER)

3.3.7. Recharge and evapotranspiration

3.3.7.1. Recharge zones

Recharge is dependent on climate, land use (including vegetation type), soil properties and depth to groundwater. To incorporate this dependency into the EWGM, recharge zones were identified based on land use characteristics and depth to groundwater.

Recharge zones were not identified based on soil properties because the study area is predominantly underlain by Bassendean Sand and Tamala Sand (Spearwood Sand). As the estimated soil water holding capacity of these soils is similar across the upper 1 m of soil (Table 5), the available soil moisture content was assumed to be the same for both soil types to simplify zoning.

Recharge zones for the groundwater model, based on land use, changes to land use and depth to groundwater are presented in Table 6 and Figure 21.

Table 5: Soil water holding capacity for study area soils (after Xu et al. 2008)

Depth (m)	Estimated soil water holding capacity (%)
Spearwood Soil Profile	
0 – 0.15	6.0
0.15 – 0.5	3.5
0.5 – 50	4.0
Bassendean Soil Profile	
0 – 0.15	3.5
0.15 – 0.5	3.0
0.5 – 50	3.0

Table 6: Recharge zones for the EWGM including zones with changing land use (colour coded to match Figure 21 and Excel worksheet *Recharge zone TS*)

Recharge zone code	Land use	Depth to groundwater	Land use change and year
RZ1	Pasture / cleared pine / under construction (i.e., areas where there are several or large cleared areas not yet developed	-	
RZ1A	Under construction		To RZ7 (2016)
RZ1B	Under construction		To RZ8 (2017)
RZ2	Banksia - low density/ rural residential blocks	<9 m	
RZ3	Banksia - low density/ rural residential blocks	>9 m	
RZ3A	Banksia - low density/ rural residential blocks	>9 m	To RZ1 (2012) to RZ7 (2015)
RZ4	Banksia medium density	>9 m	
RZ5	Pine - low density	<18 m	
RZ5A	Pine - low density	<18 m	To RZ1 (2013)
RZ5B	Pine - low density	<18 m	To RZ1 (2015)
RZ6	Pine – med/high density	<18 m	
RZ6A	Pine – med/high density	<18 m	To RZ1 (2011)
RZ6B	Pine – med/high density	<18 m	To RZ1 (2012)
RZ6C	Pine – med/high density	<18 m	To RZ1 (2013)
RZ6D	Pine – med/high density	<18 m	To RZ1 (2015)
RZ7	Urban	-	
RZ8	Commercial/Industrial	-	
RZ9	Lakes[1]		

[1] Recharge and evaporation from the lakes will be specified separately in the MODFLOW Lake package and are not included in the recharge function spreadsheet. RZ1 input time-series will be specified in the Lake package for lake cells that are dry

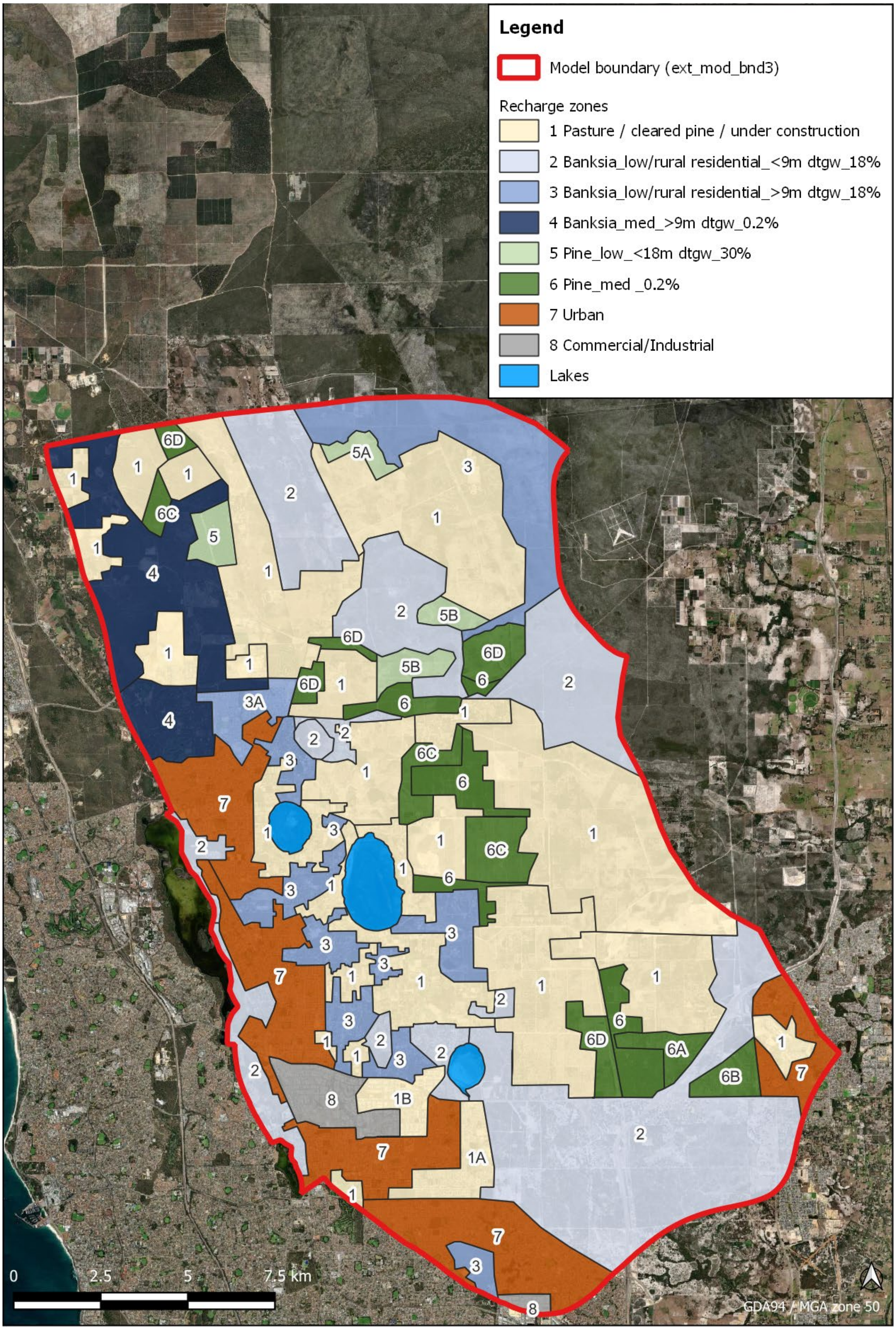


Figure 21: Recharge zones across the model domain, based on land use and depth to groundwater

3.3.7.2. Recharge rate estimation using the recharge function

A recharge function has been described by Davies (2022), which is a compromise between the complexity of a fully coupled unsaturated/saturated zone model and the simplicity of assumed linear recharge rates. The recharge function can be used to develop input time series for recharge and evapotranspiration (ET) in a groundwater model.

Use of the recharge function ensures there is no double accounting of evapotranspiration in the groundwater model and generates reasonable rates and trends for recharge when compared to the vertical flux model implemented in PRAMS (Davies 2022).

A recharge function has been developed for the study area in Excel, based on the conceptual recharge function described by Davies (2022):

- The recharge function is based on hydrological parameters (rainfall, irrigation, runoff, interception loss, soil ET, groundwater ET).
- Input in the form of daily time series of rainfall and potential ET (PET) is required for the recharge function (obtained from the SILO climate database for the EWGM) along with varying parameters for different land uses.
- The recharge function tracks the inflows and outflows illustrated in Figure 22.

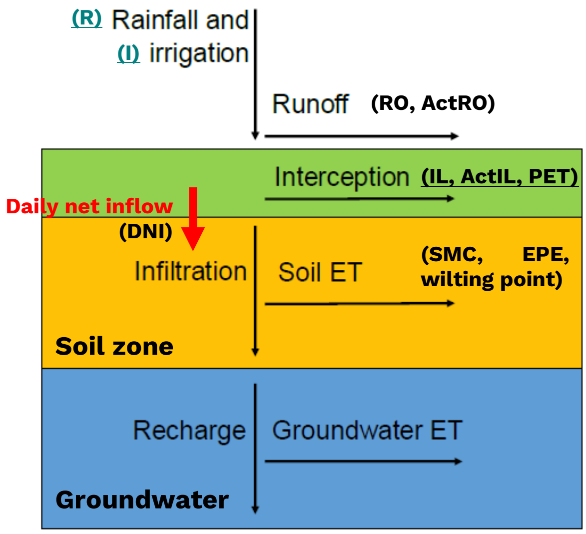


Figure 22: Recharge function concept (after Davies 2022)

The recharge function accounts for daily water inflows and outflows to the upper soil surface to generate gross or net recharge time series and excess potential evapotranspiration time series as outlined below:

- Inflows
  - Rainfall (R) and irrigation (I) are inflows to the system (note: at this stage irrigation is not being applied for the EWGM through the recharge function)
- Outflow (1)
  - The first outflow is runoff (RO). The recharge function removes surface runoff at a specified fraction of rainfall after a user defined rainfall depth is applied. Actual runoff (ActRO) is limited by the depth of rainfall available for runoff. (Note: runoff is assumed to be zero for the EWGM as runoff from the Bassendean and Spearwood Sands in the study area is considered negligible).
- Outflow (2)
  - The second outflow is interception loss (IL). Actual interception loss (ActIL) is constrained by the depth of water available for interception loss after rainfall runoff and the daily potential evapotranspiration rate (PET). The term “interception loss” is a proxy for other hydrological processes such as litter and pavement evaporation, initial loss and depression storage.
- Daily Net inflow into the soil zone
  - The daily net inflow (DNI) into the soil zone (shaded yellow in Figure 22) is given below:
    - DNI = R + I – ActRO – ActIL – remaining PET (after ActIL is removed)

(noting that DNI is 0 if the value calculated for DNI is negative)

- As *PET = ActIL + the PET remaining after ActIL is removed)*, the daily net inflow can also be written as follows:
  - DNI = R + I – ActRO – PET
- Soil zone
  - The water holding capacity of the soil zone is treated as a reservoir that has the capacity of the available soil moisture content (ASM) (within an assumed 1 m depth of soil), noting that the ASM equals the difference between the field capacity and wilting point. The soil "reservoir" is therefore assumed to have the wilting point as the lower bound and the field capacity as the upper bound.
  - Soil moisture content (SMC), which has units of length (i.e., the depth of water within the assumed 1 m depth of soil), is tracked within the recharge function as it is the measure of how full the soil reservoir is every day.
  - The SMC at the start of each daily timestep has an initial value equal to the SMC at the end of the previous timestep. Water is then added/removed from the soil reservoir daily by the daily net inflow to the soil zone.
- Soil Zone water balance
  a. If the initial SMC + DNI dries the soil beyond the wilting point, the SMC is limited to the wilting point and Excess PET (EPE) is the potential evapotranspiration that would dry the soil beyond the wilting point (i.e. excess below wilting point). [no recharge]
  b. If the initial SMC + DNI is greater than the field capacity, the SMC is limited to the field capacity and the Gross Recharge (GR) is the excess soil moisture above field capacity that will drain from the soil zone and be available to recharge groundwater.
  - The soil moisture content at the end of each timestep is therefore:

$$SMC_t = SMC_{t-1} + R + I - ActRO - ActIL - EPE - GR$$

- Groundwater
  - Recharge from the soil zone occurs once the excess soil moisture above field capacity is achieved (b in Soil Zone water balance)

3.3.7.3. Recharge function application to each land use

The recharge function has been used to estimate input time series of recharge for each land use in Figure 13.

Recharge function parameters were adjusted for each recharge zone to generate either gross recharge and excess potential evapotranspiration time series, or a net recharge time series for use in the EWGM, as follows:

- For cleared soils and pastures the calculated daily Gross Recharge and Excess PET are used to generate monthly time series for inclusion as recharge and evapotranspiration in the MODFLOW groundwater flow model (EVT module with an extinction depth of 1 m).
- For wooded areas that have the water table above the maximum rooting depth but not within 1.5 m of the ground surface, net recharge (NR) is calculated as follows:

  NR = GR – a x EPE
- where *a* is a constant that is obtained empirically by matching the net annual average recharge percentage to referenced average recharge percentages (e.g., from PRAMS as shown in Table 7). *a x EPE* represents plant transpiration, accounting for tree roots removing water from the soil profile and groundwater.

  This approach can result in negative recharge during the summer months when tree roots can remove water from the water table in the absence of any rainfall recharge.
- In wooded areas that have the water table within 1.5 m of the ground surface, additional evaporative losses can occur through evapotranspiration from the capillary fringe or bare soil evaporation. This surficial evaporative loss in wooded areas can be represented by the Excess PET time series calculated for cleared soils (implemented in the EVT package) minus *a x EPET, which ensures that the total potential evapotranspiration is conserved.*
- For wooded areas that have the water table below the maximum rooting depth, net recharge (NR) time series are generated by increasing the field capacity of the soil to empirically match the net annual average recharge percentage to reference recharge percentages (e.g., PRAMS).

This approach simulates tree roots extracting water from the deeper soil profile reducing net recharge, but not extracting groundwater so there is no negative recharge during the summer months.

- For urban and industrial areas, the recharge function is used to generate time series for four different surface types: paved lot areas, paved road areas, roof areas and pervious areas. Interception loss and available soil moisture parameters for each of these surface types are provided in Table 9. The recharge times series for these urban and commercial/industrial land uses are generated based on summed proportional recharges for each surface type based on an average proportional area of each surface type within an urban or commercial/industrial land use setting.
- Urban areas that appear to have large or several areas under construction are assigned the pasture/cleared pines gross recharge rate, but no Excess ET is included as the vegetation has largely been removed.
- The recharge function worksheets for each of the identified land uses are given in Table 8 (vegetated land uses) and Table 9 (urban and commercial / industrial land uses), along with the assumed parameters.
- The initial recharge time series to be used for model calibration are provided in Table 8. There is, however, a significant spread of recharge rates obtained from the different PRAMS calibrations for areas of low and medium density Banksia (as shown in Table 7). The recharge function calculations will not form part of the calibration parameter set.

Table 7: Recharge percentages from PRAMS model calibration (provided by DWER)

Code	Landuse	Recharge 1 (PRAMS 3.5) % rainfall	Recharge 2 (Xu et al 2009) % rainfall
1	Banksia – high density	0.3	10.0
2	Banksia – low density	17.8	38.0
3	Pasture	42.7	45.0
6	Pine – high density	0.2	0.0
7	Pine – medium density	0.2	0.0
8	Pine –low density	30.2	28.0
9	Urban	66.5	50.0
11	Commercial / Industrial	68.0	63.0
17	Pine – medium high density	0.0	0.0
18	Pine – medium low density	0.9	8.0
22	Banksia – medium density	0.2	18.0

Table 8: Summary of recharge function worksheets for vegetated areas showing the starting recharge time series that will be used for model calibration (*Recharge function_01112022.xlsx*)

Generic land use	Function worksheet	Specific land use	Assumed parameters	Target woodland recharge rate	Recharge rate as % of average annual rainfall between 2000 and 2021 (715 mm/yr)	Gross or net recharge
Pasture/cleared pine / under construction	*Pasture/cleared*	Pasture/cleared pine	Interception Loss = 2 mm Field capacity = 50 mm Wilting point = 20 mm	NA	39.6	Gross recharge (Excess ET applied within EVT module)
Woodland with the water table within the root zone (Banksia and pine)	*Pine low_shal 30%_720mm*	Low density pine Water table within root zone	Interception Loss = 2 mm Field capacity = 50 mm Wilting point = 20 mm a = 0.07	~30% annual average recharge for 720 mm annual average rainfall	29.7	Net recharge
	Banksia low_shal 18%_720mm	Low density Banksia Water table within root zone	Interception Loss = 2 mm Field capacity = 50 mm Wilting point = 20 mm a = 0.15	~18% annual average recharge for 720 mm annual average rainfall	18.3	Net recharge
	Pine med_shal_ .2%_720mm	Medium density Pine Water table within root zone	Interception Loss = 2 mm Field capacity = 50 mm Wilting point = 20 mm a = 0.28	~0.2% annual average recharge for 720 mm annual average rainfall	-0.3	Net recharge
Woodland with the water table below the root zone (Banksia and pine)	*Banksia low_deep 18%_720mm*	Low density Banksia Water table below root zone	Interception Loss = 2 mm Field capacity = 195 mm Wilting point = 20 mm ASM - available soil moisture content = 175 mm	~18% annual average recharge for 720 mm annual average rainfall	17.5	Net recharge
	Banksia med_deep .2%_720mm	Medium density Banksia Water table below root zone	Interception Loss = 2 mm Field capacity = 420 mm Wilting point = 20 mm ASM = 400 mm	~0.2% annual average recharge for 720 mm annual average rainfall	0.2	Net recharge

Table 9: Summary of recharge function worksheets for urban and commercial/industrial areas (*Recharge function_01112022.xlsx*)

Land use	Function worksheet	Assumed parameters		Percentage of total area	Time series	Recharge rate as % of average annual rainfall (715 mm/yr)
		Interception Loss (mm)	SMC (mm)	%		
Urban	*Impervious road pavement*	2	ASM = 0 mm	23	Net Urban recharge	63.9
	Impervious lot pavement	2	ASM = 5 mm	20		
	Impervious - roof	1.5	ASM = 0	30		
	Pervious	2	Field capacity = 50 mm Wilting point = 20 mm ASM = 20 mm	27		
Commercial / Industrial	*Impervious road pavement*	2	ASM = 0 mm	27	Net Commercial/Industrial recharge	67.3
	Impervious lot pavement	2	ASM = 5 mm	27		
	Impervious - roof	1.5	ASM = 0	32		
	Pervious	2	Field capacity = 50 mm Wilting point = 20 mm ASM = 20 mm	14		

3.3.7.4. Recharge time series for the model

Average daily recharge rate time series (based on monthly rates) have been generated for each of the recharge zones.

- In zones that had a changing land use over the proposed model calibration period, recharge rates were "cut and pasted" together based on the timing of the land use change.
- Recharge time series for each recharge zone are summarised in the worksheet *Recharge zone TS*, within the *Recharge Function_01112022* workbook.

3.3.7.5. Evapotranspiration time series for the model

- The applied recharge rates are net rates accounting for evapotranspiration losses, except for the pasture/cleared land use (recharge zone RZ1). Evapotranspiration rates are therefore only applied to recharge zone 1 (including zones 1A and 1B) on Figure 21, and to those zones that change to zone 1 (RZ1) over the simulation period.
- The applied evapotranspiration rate across the pasture/cleared zones is equal to the Excess PET (EPET) described in Section 3.3.7.2, that would dry the soil beyond the wilting point.

3.3.8. Lake precipitation and evaporation

- Lake precipitation rates are 100% of the daily rainfall across the lake surface. Daily rainfall data from SILO was used to obtain average daily precipitation rates (based on monthly rainfall) for the lakes within the DSP area.
- Daily Morton Lake evaporation data from SILO was used to obtain average daily evaporation rates (based on monthly evaporation) for the lakes within the DSP area.

3.4. Parameter data

3.4.1. Aquifer parameters

Department of Water have previously reviewed available data in the Perth area to determine aquifer parameters and parameter ranges.

A recent study has been carried out by DWER investigating geological heterogeneity in the Superficial Aquifer in the Joondalup and Wanneroo area. Study results indicate that lower hydraulic conductivity values are required in the Tamala Sand, relative to the Bassendean Sand, to match lake stage and groundwater level observations in the study area (McArthur, 2022).

Superficial aquifer parameters for formations in the study area are summarised in Table 10, based on PRAMS model calibration information and the recent DWER study (Cymod 2009, Cymod 2014, McArthur, 2022).

Table 10: Aquifer parameters

Formation	Average specific yield	Hydraulic conductivity (horizontal) (m/day)
Bassendean Sand	0.2	10 – 50
Tamala Sands	0.1 – 0.2	1 - 20
Tamala Limestone	0.2 – 0.3	100 - 1000
Gnangara Sand	0.2	20
Guildford Formation	0.05	0.1 - 1
Ascot Formation	-	8 - 20

A vertical to horizontal hydraulic conductivity ratio of 1:10 can be used to define the vertical hydraulic conductivity (Cymod 2009).

3.4.2. Lake parameters

- Sediment bed thickness is assumed to be 1 m, based on the sediment bed thickness identified at other wetlands on the Perth Coastal Plain (Semeniuk and Semeniuk, 2004)
- The common sediments in the wetland basins that are found between the Spearwood and Bassendean dune systems are peat, diatomite, calcilutite (carbonate mud), diatomaceous peat, organic enriched diatomite or calcilutite and carbonate skeletal gravel and sand, as well as quartz sand and kaolinite-dominated mud.
- A hydraulic conductivity ranging from 10 m/day to 0.01 m/day, (representing a fine sand to silt soil range, Domenico and Schwarz 1990) has been assumed for the sediment bed hydraulic conductivity. This range will be revisited during model calibration.

Table 11: Lake parameters

Lake parameter	Assumed value
Sediment bed thickness	1 m
Sediment bed hydraulic conductivity	0.01 to 10 m/day

3.5. Model calibration data

3.5.1. Groundwater levels

Bore water level data extending across much of the Perth area were supplied by DWER for the period from 1975 to 2019. Bore water levels were also extracted from the Water Information Reporting database (DWER 2022) for bores across the study area to obtain recent observation data. Excluding bores likely to be used for model boundary conditions, 91 bores within the model domain (Figure 23), were identified having at least 2 data points per year (typically minimum, end of summer, and maximum, end of winter readings) post 2010 (the proposed to start of model calibration)

Groundwater contours across the study area were generated from maximum end of winter water levels (extracted from the DWER data in the months of August, September or October) for the years 2010, 2015 and 2019 (Figure 24). The contours included lake maximums for these years as the lakes are expressions of the groundwater table. The contours indicate groundwater is flowing in a westerly direction across the northern half of the model domain, moving to a south-westerly and then southerly direction towards the southern end of the model domain. The 2015 contours were selected for determination of the model boundary.

Water levels across three transects over the model domain (shown in Figure 25) are shown by the hydrographs in (Figure 26).

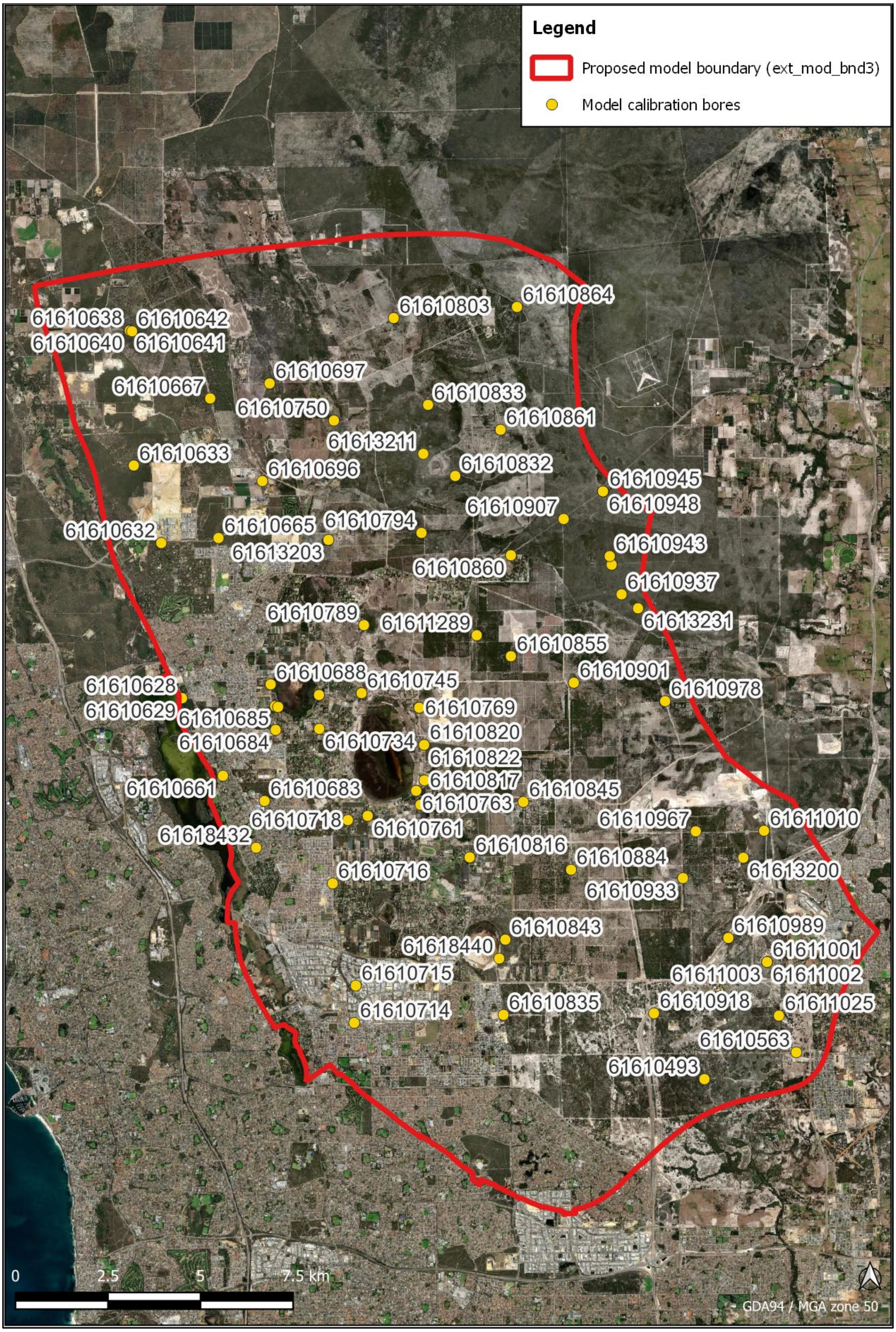


Figure 23: Observation bores for model calibration

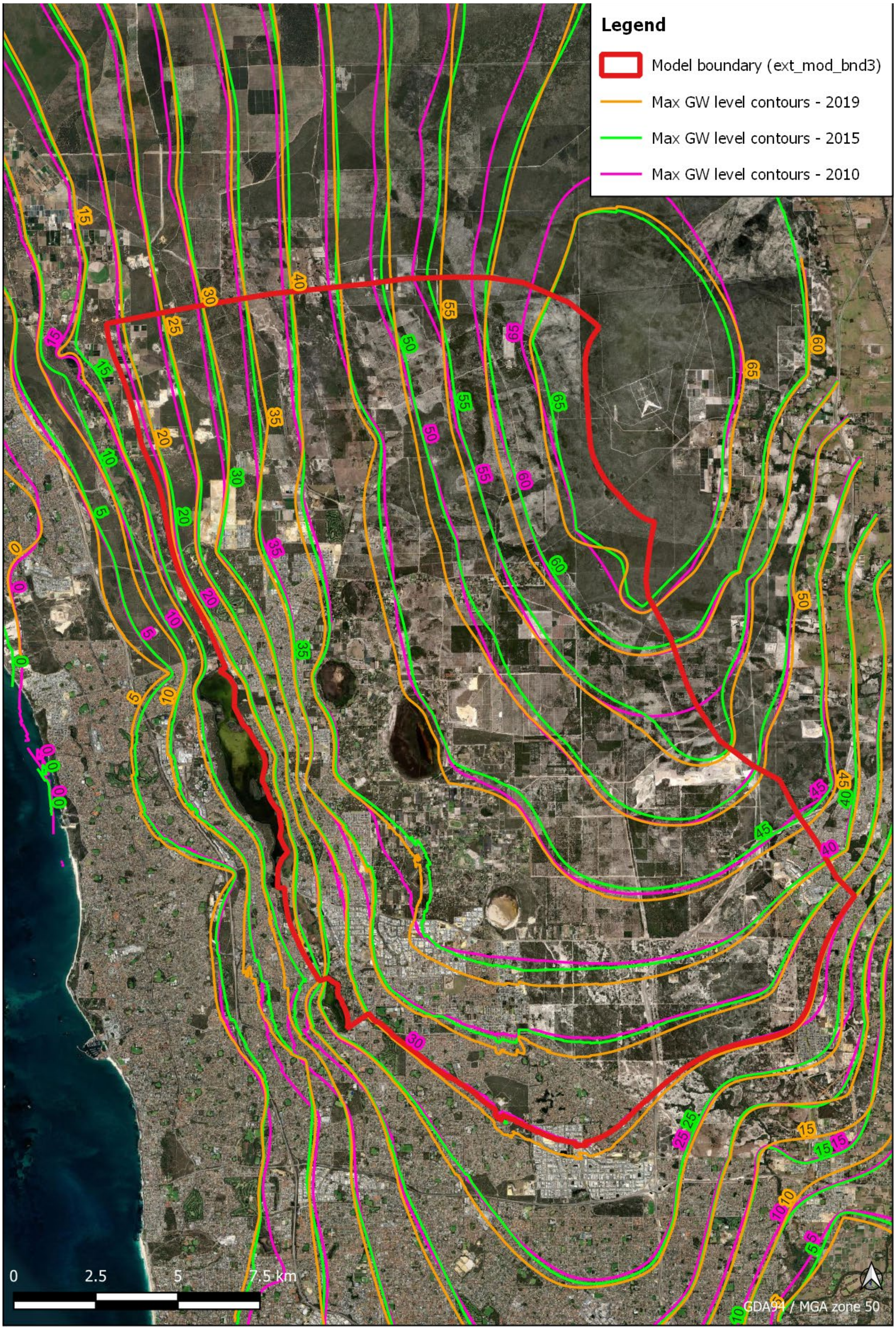


Figure 24: Maximum groundwater contours 2010,2015 and 2019 (from DWER data)

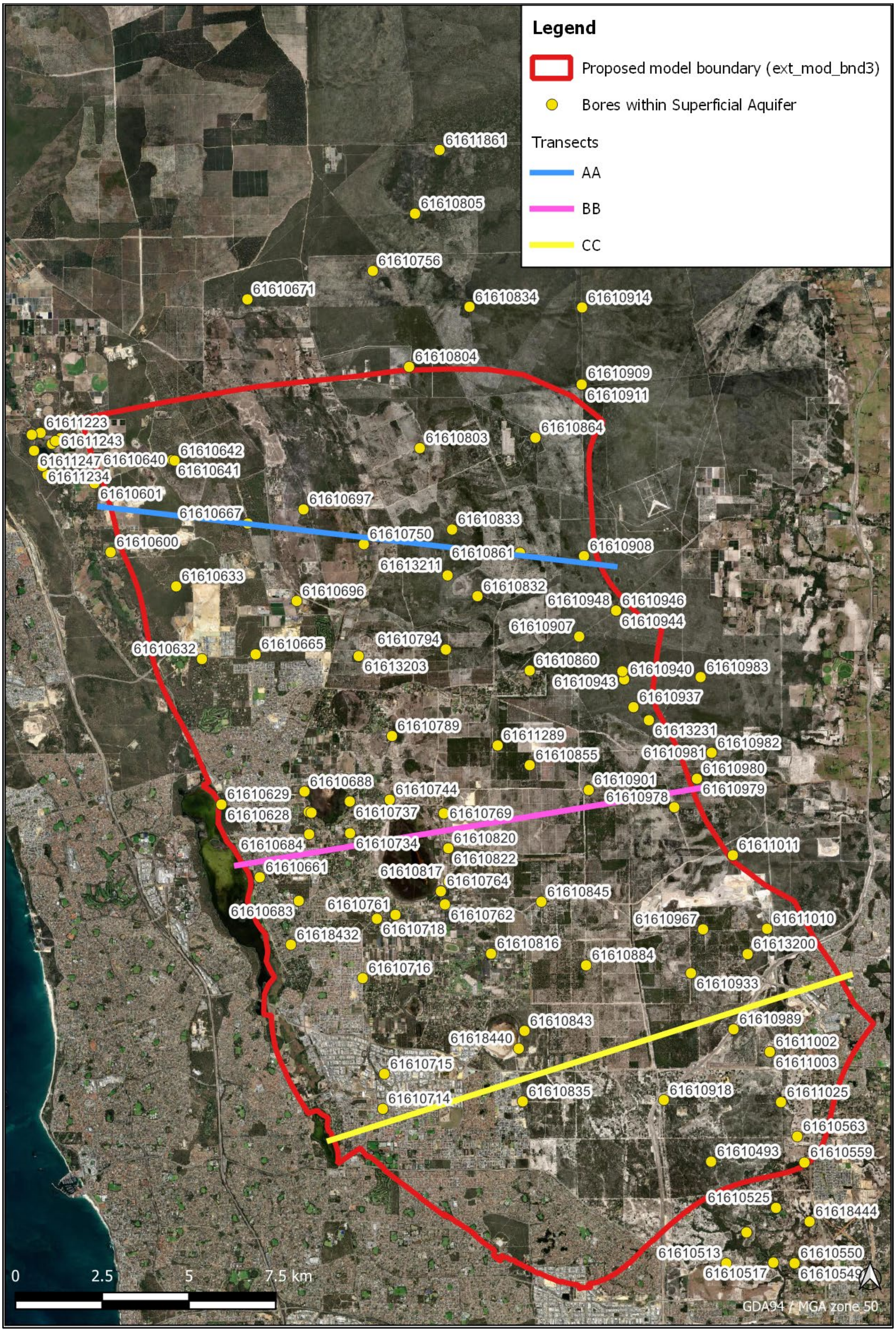


Figure 25: Transects across model domain for hydrographs shown in Figure 25)

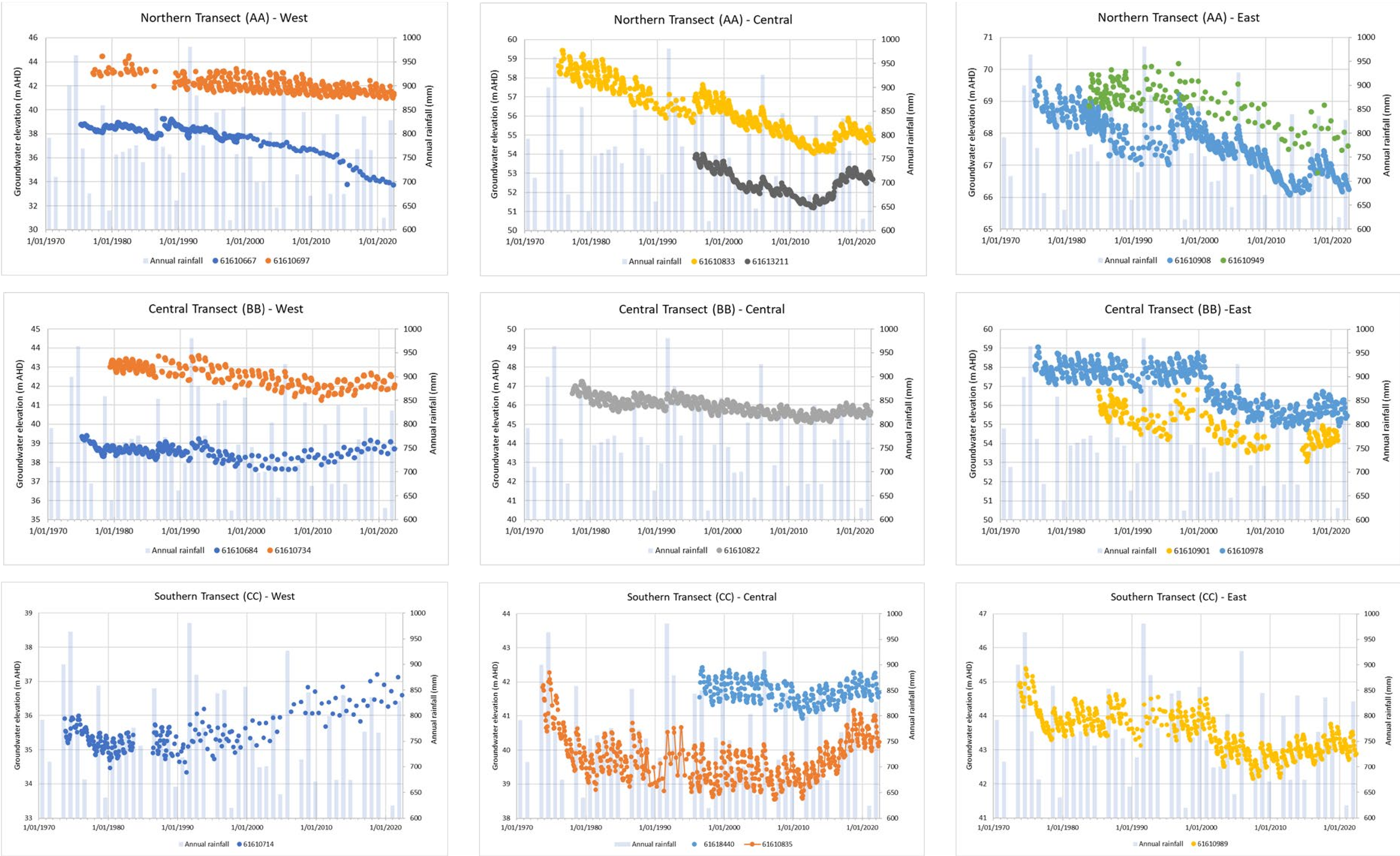


Figure 26: Bore hydrographs for three transects across the study area / model domain.

3.5.2. Lake water levels

Lake water levels were downloaded from the Water Information Reporting website for the following:

- Lake Jandabup (within the model domain)
- Lake Mariginiup (within the model domain)
- Lake Gnangara (within the model domain)
- Lake Joondalup (on the western boundary)
- Lake Goollelal (on the western boundary).

Measured lake water levels, along with maximum allowable, minimum allowable and preferred minimum peak (spring water levels) where available are presented in Figure 27 for the major lakes, and in Figure 28 for the lakes on the western boundary of the study area.

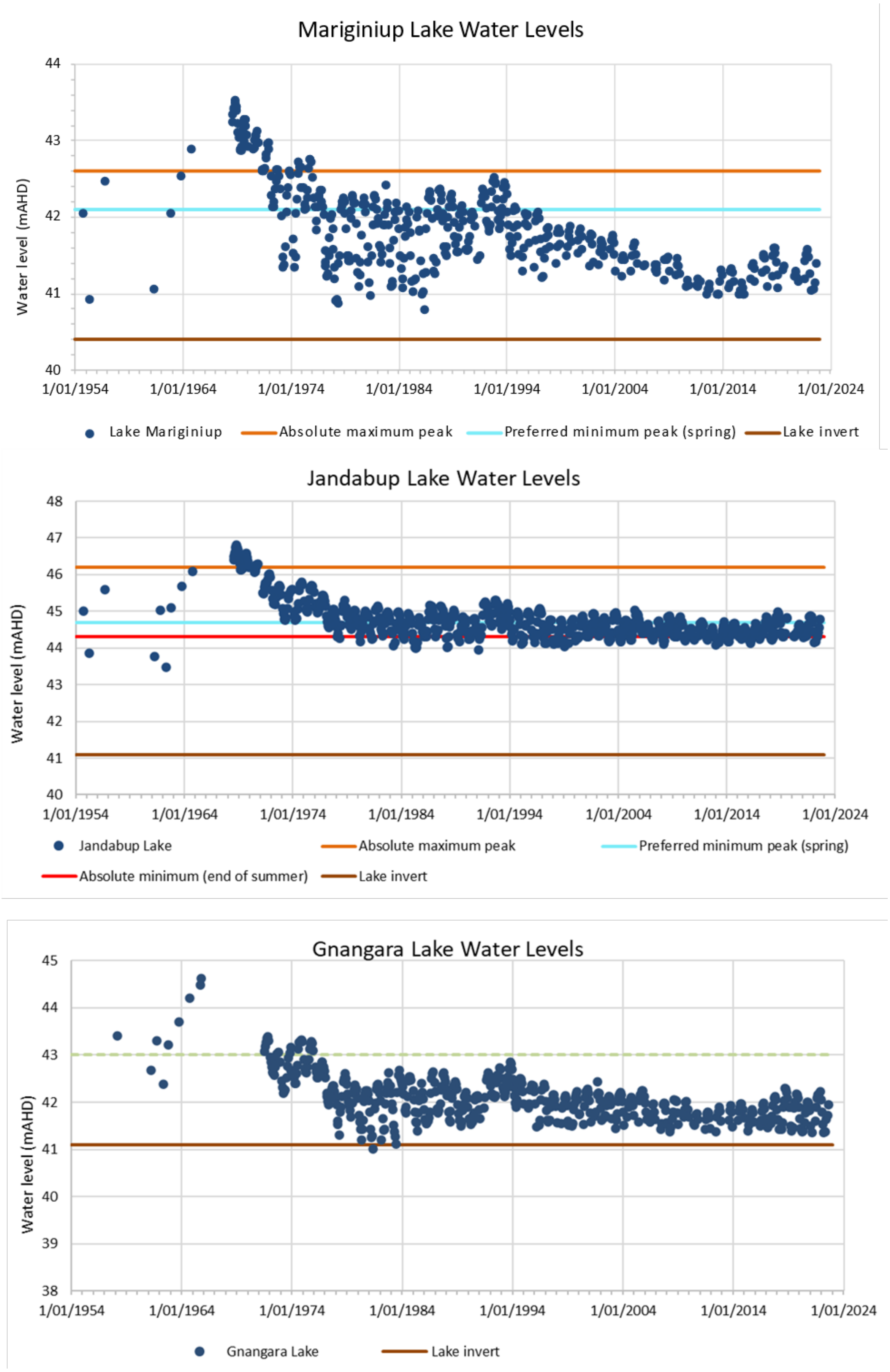
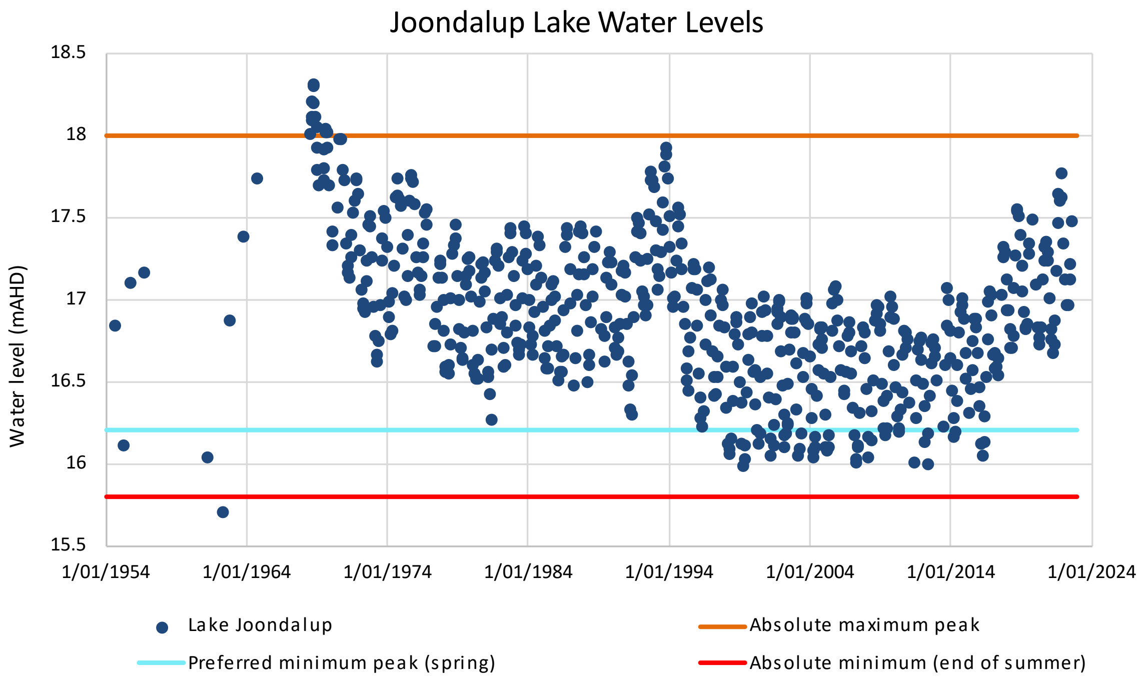


Figure 27: Water levels for the major lakes



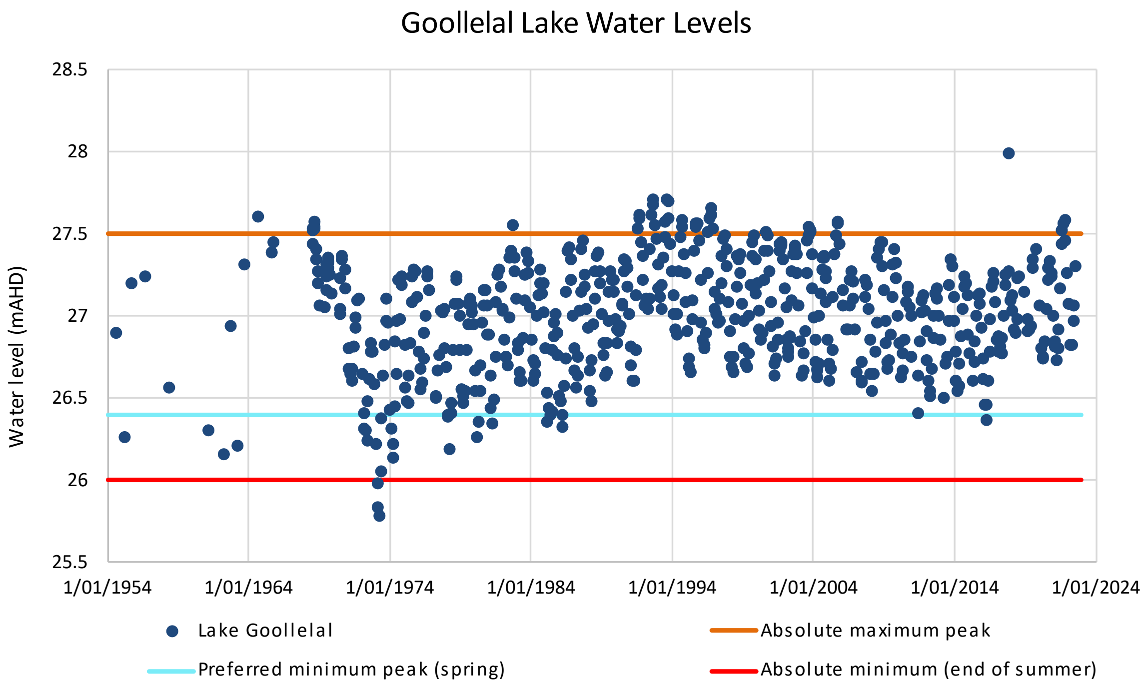


Figure 28: Water levels for the lakes on the western model boundary

3.6. Future Scenario data

3.6.1. Projected climate scenario data

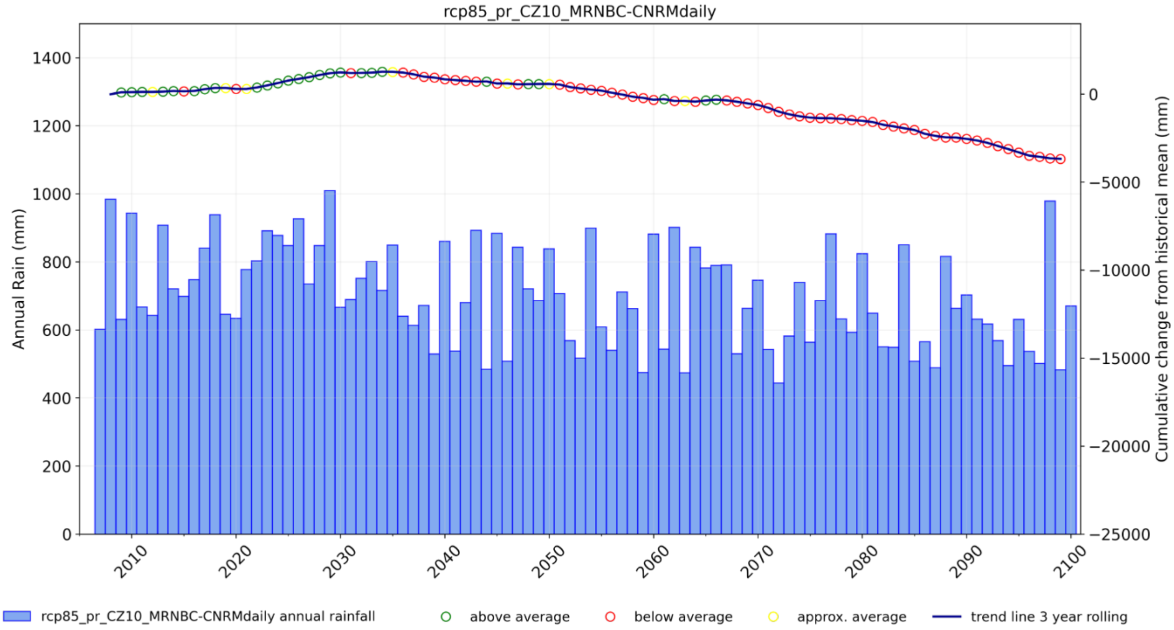
Projected climate scenario data (daily precipitation and evapotranspiration data between 2006 and 2099) was provided by DWER for a location near the centre of the model domain. The projected climate data is based on outputs from the Australian Water Outlook (AWO) National Hydrological Projections data set.

The AWO projections are generated according to two greenhouse gas concentration pathways (RCP4.5 and RCP8.5), four CMIP5 Global Climate Models (GCMs), one dynamically downscaled Regional Climate Model (RCM) and three bias correction approaches, resulting in thirty-two projections of daily precipitation, soil moisture, potential evapotranspiration (PET) and runoff.

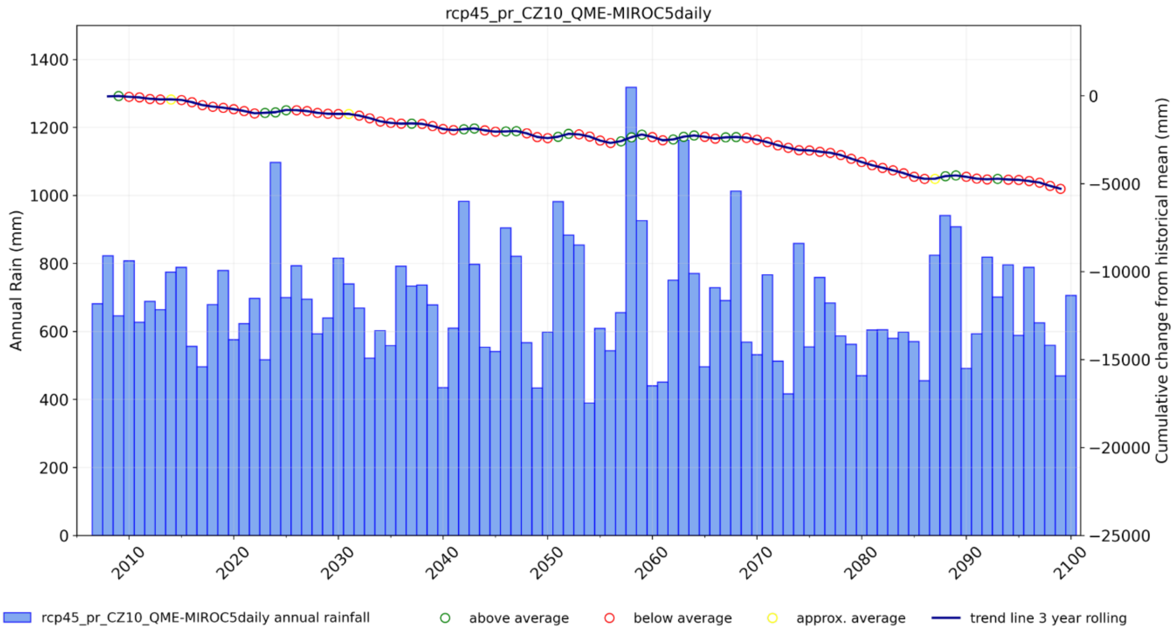
The narrative associated with the AWO National Projections datasets is that all future scenarios are plausible. For this groundwater modelling project, the upper and lower bounds are of most interest as this will likely provide maximum and minimum projected groundwater levels and subsoil drainage volumes.

Four future climate scenarios have been selected to achieve the modelling objectives. The selected climate scenarios and the reasoning behind the selection are outlined below:

- Wet_1: rcp85_CZ10_MRNBC-CNRMdaily (Scenario ID number 26).
  A wet scenario having
  - A high average annual rainfall of 684.1 mm/yr over the future scenario simulation period (from January 2023 to December 2099), which is only 10 mm lower than the highest average annual rainfall scenario.
  - 3 consecutive wet years with annual rainfall above 800 mm and 6 consecutive years with an annual rainfall above 700 mm.
  - 3 consecutive years with an annual rainfall less than 600 mm.
- Wet_2: rcp45_CZ10_QME-MIROC5daily (Scenario ID number 16).
  A wet scenario with:
  - The highest monthly rainfall (447 mm in July 2057).
  - The highest annual rainfall year (1318 mm in 2057).
  - The highest 2 year moving average and the 3rd highest 3 yr moving average (as 2058 is also a high rainfall year with 926mm).
  - Average annual rainfall of 684.9 mm/yr which is less than 10 mm below the highest average annual rainfall scenario.
- Dry_1: rcp85_CZ10_CCAM-ISIMIP-ACCESS1daily (Scenario ID number 17).
  A dry scenario that has:
  - Low average annual rainfall of 430.8 mm/yr over the future scenario simulation period
  - A strongly drying climate trend indicated by the annual rainfall time series exhibiting a high cumulative deviation from the mean.
- Int_1: rcp85_CZ10_QME-MIROC5daily (Scenario ID number 32)
  An intermediate scenario that has:
  - An average annual rainfall of 593.5mm/yr (between the Dry_1 and Wet_1 scenarios)
  - Periods of high consecutive rainfall, with the fourth highest 2yr and fourth highest 3yr moving average annual rainfall.
  - The lowest maximum monthly rainfall of the selected scenarios.
- Time series of annual precipitation and PET for the future climate scenarios are presented in Figure 29 and Figure 30.
- The PET data provided in the AWO National Projections database is based on the Penman method of estimation whereas the SILO data is based on the Penman-Monteith (FAO56) method of estimation. The AWO PET data was adjusted to ensure the future scenario PET data was consistent with the type of PET data applied to model calibration.

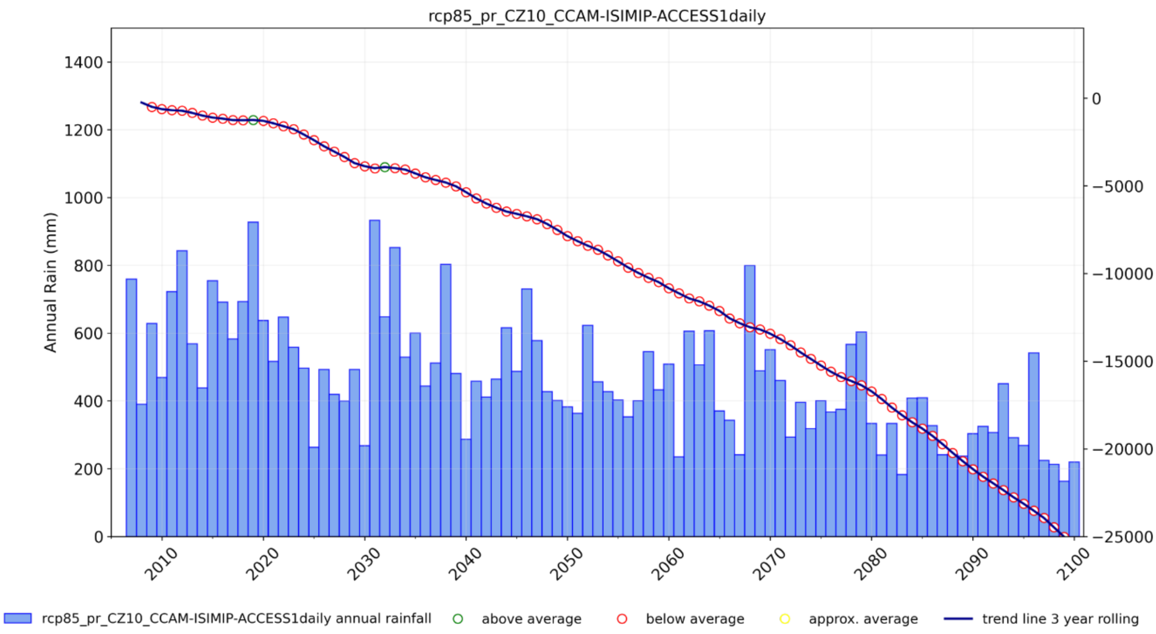


(a) Wet_1

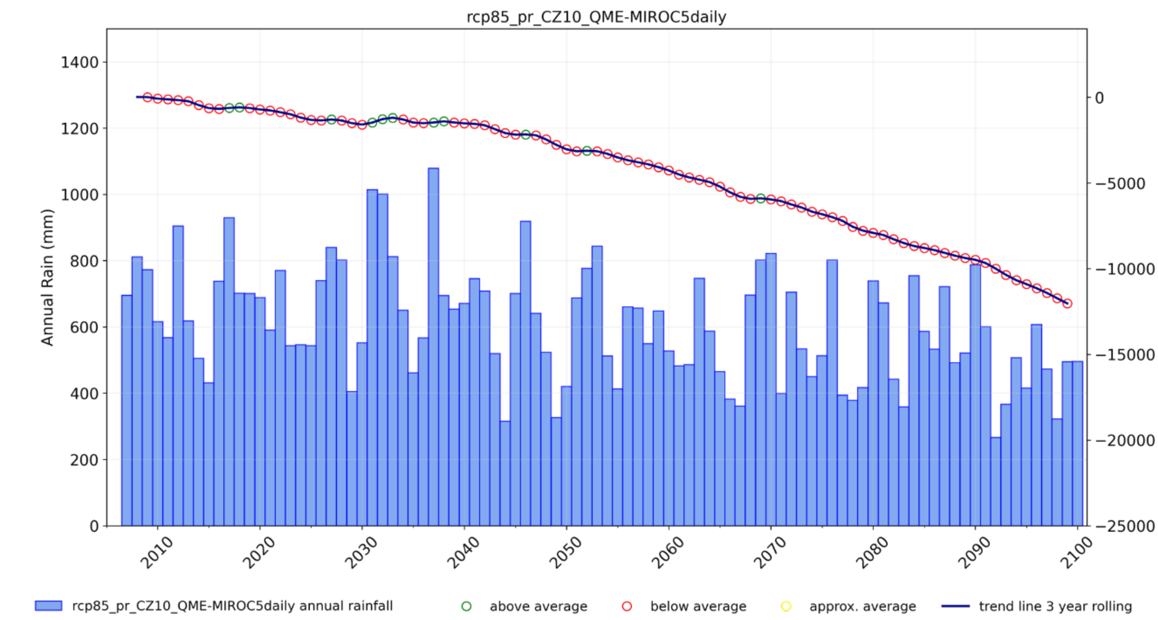


(b) Wet_2

Figure 29: Annual rainfall data and cumulative change from the historical mean rainfall for the selected (a) Wet_1 and (b) Wet_2 climate scenarios



(a) Dry_1



(b) Int_1

Figure 30: Annual rainfall data and cumulative change from the historical mean rainfall for the selected (a) Dry_1 and (b) Int_1 climate scenarios.

Additional data to provide context as to how the future scenarios compare to historical rainfall are presented in Table 12. Figure 31 compares the future rainfall to the modelled rainfall over the calibration period (2010 to 2022).

Table 12: Summary rainfall statistics for historical and future modelled climates

Rainfall (mm)	Historical (2060 to 2022)	Short -term historical as modelled (2010 – 2022)	Wet_1	Wet_2	Int_1	Dry_1
Mean Annual	741	622	684	685	594	431
Peak Annual	1284	747	1010	1318	1078	933
Peak Monthly	741	236	348	447	274	307
Peak Daily	138	71	124	152	135	78

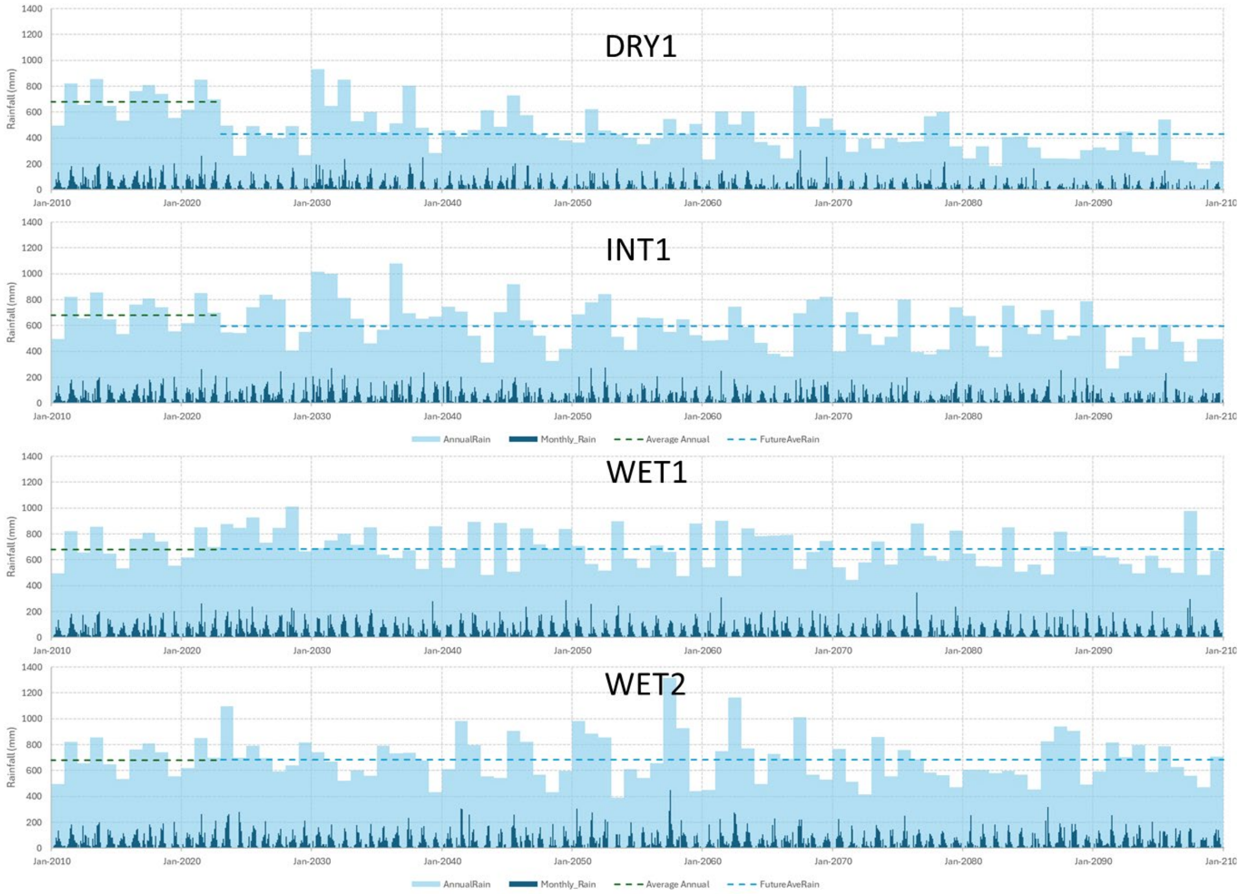


Figure 31: Modelled monthly rainfall for each future climate scenario

The selection of 4 of the 32 future climate scenarios that were chosen for the predictive modelling are highlighted in Figure 32 to show how the modelled rainfalls compare to the full range of future climate scenarios. Whilst each of the climate scenarios represent an equally plausible future climate (noting that as with any model none of them are likely to represent an exact future reality), the chosen range of climates encompass the full bandwidth of predictions and thus modelled outputs are also likely to cover the range of future climate possibilities.

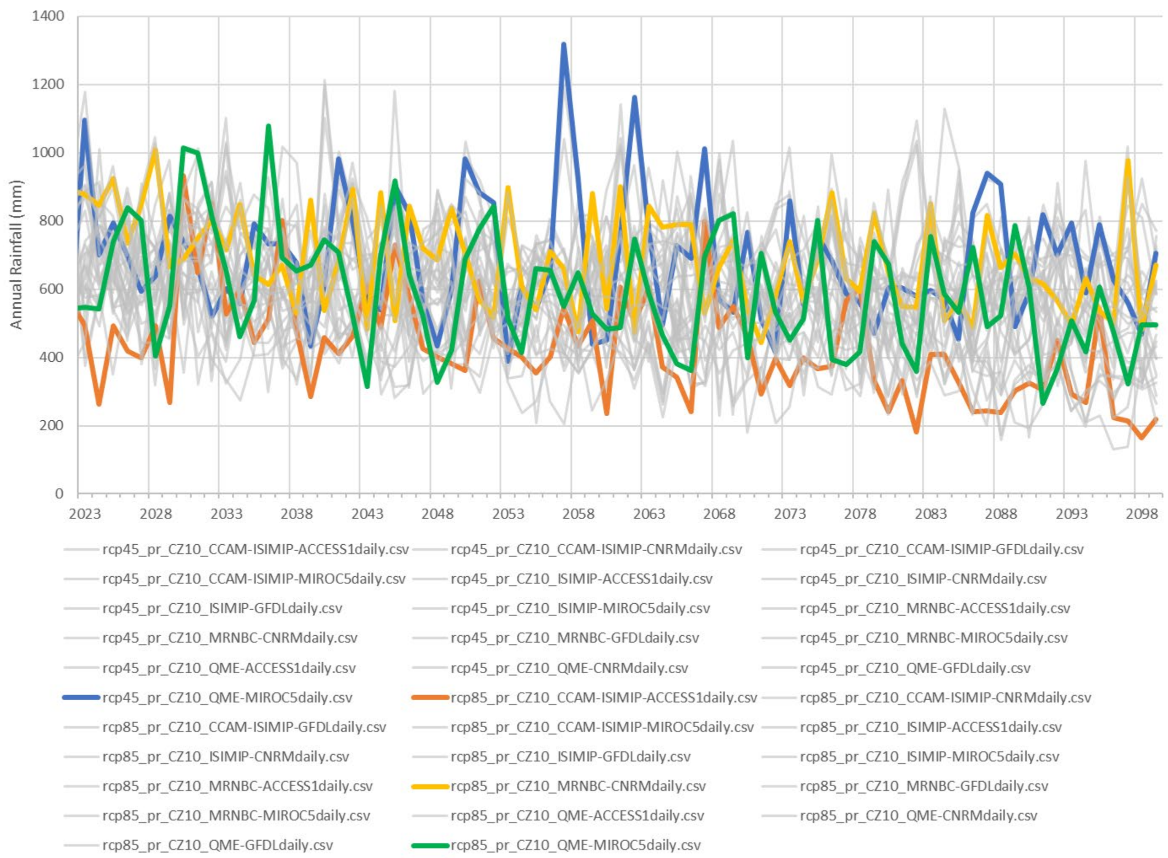


Figure 32: Annual rainfall for each future climate scenario (Yellow = Wet_1 Blue = Wet_2, Green = Int_1, Orange = Dry_1)

3.6.2. Land use and staging for future scenarios.

Future land uses to be incorporated into the future scenario modelling are shown in the EWDSP (Figure 1). Preliminary development staging for the EWDSP area has been prepared by Pentium Water (and reviewed by DPLH), as shown in Figure 33. The development stages provide temporal controls on recharge and abstraction rates within the DSP area throughout the future modelling scenarios.

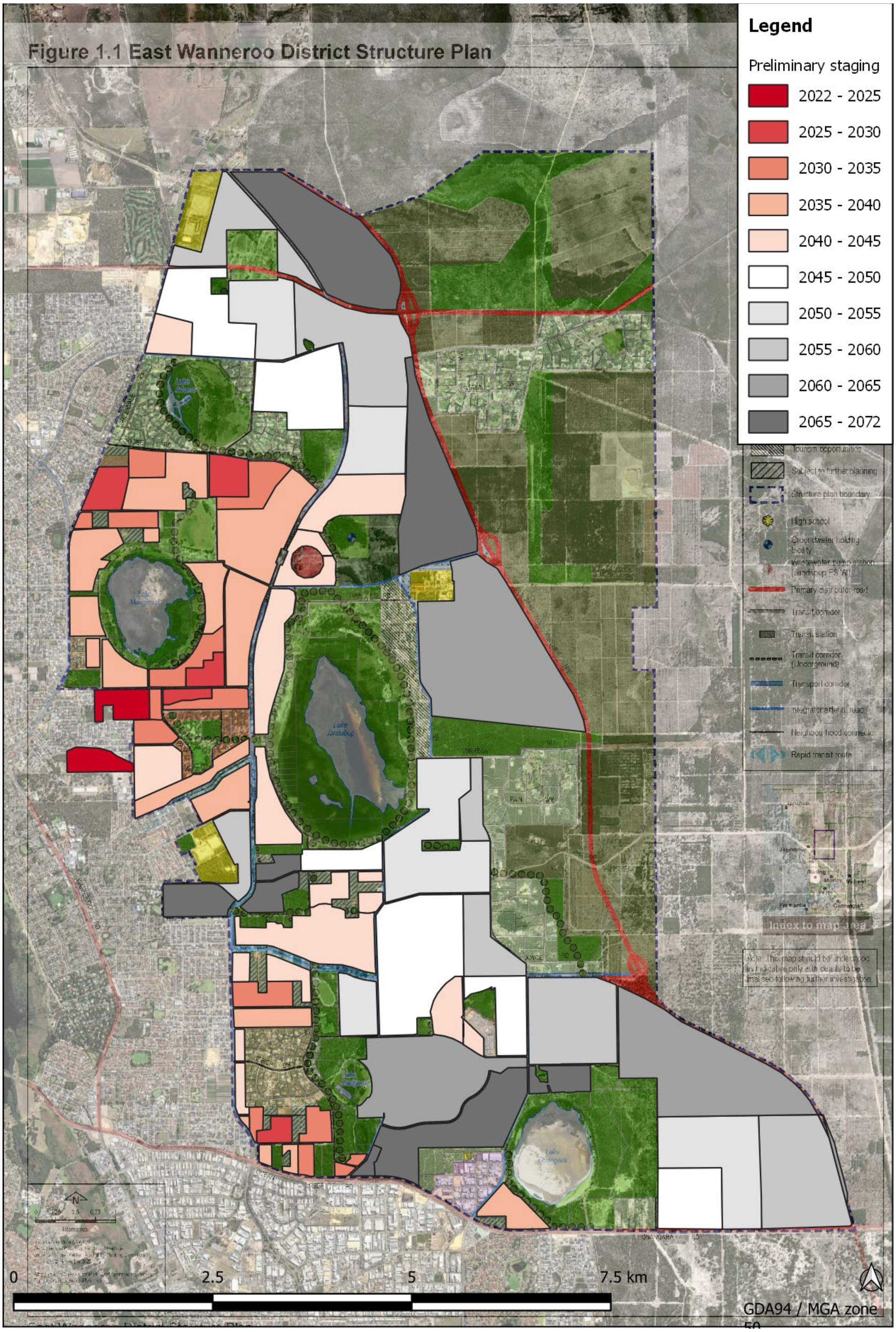


Figure 33: Preliminary staging across the East Wanneroo DSP area (overlying the East Wanneroo DSP)

3.6.3. Future scenario recharge and PET

Future recharge rates and excess PET rates were calculated using the recharge function outlined in Section 3.3.7. Existing recharge zones (Figure 21) were intersected with the preliminary staging areas to determine areas of changing land use within the DSP area. Outside of the EWDSP area, land use was assumed to remain unchanged. Other future land uses from the EWDSP were identified, such as specified high school locations and district playing field.

Based on the above intersections and review of existing and future land uses, 59 unique recharge and PET time series zones were generated for each future climate scenario.

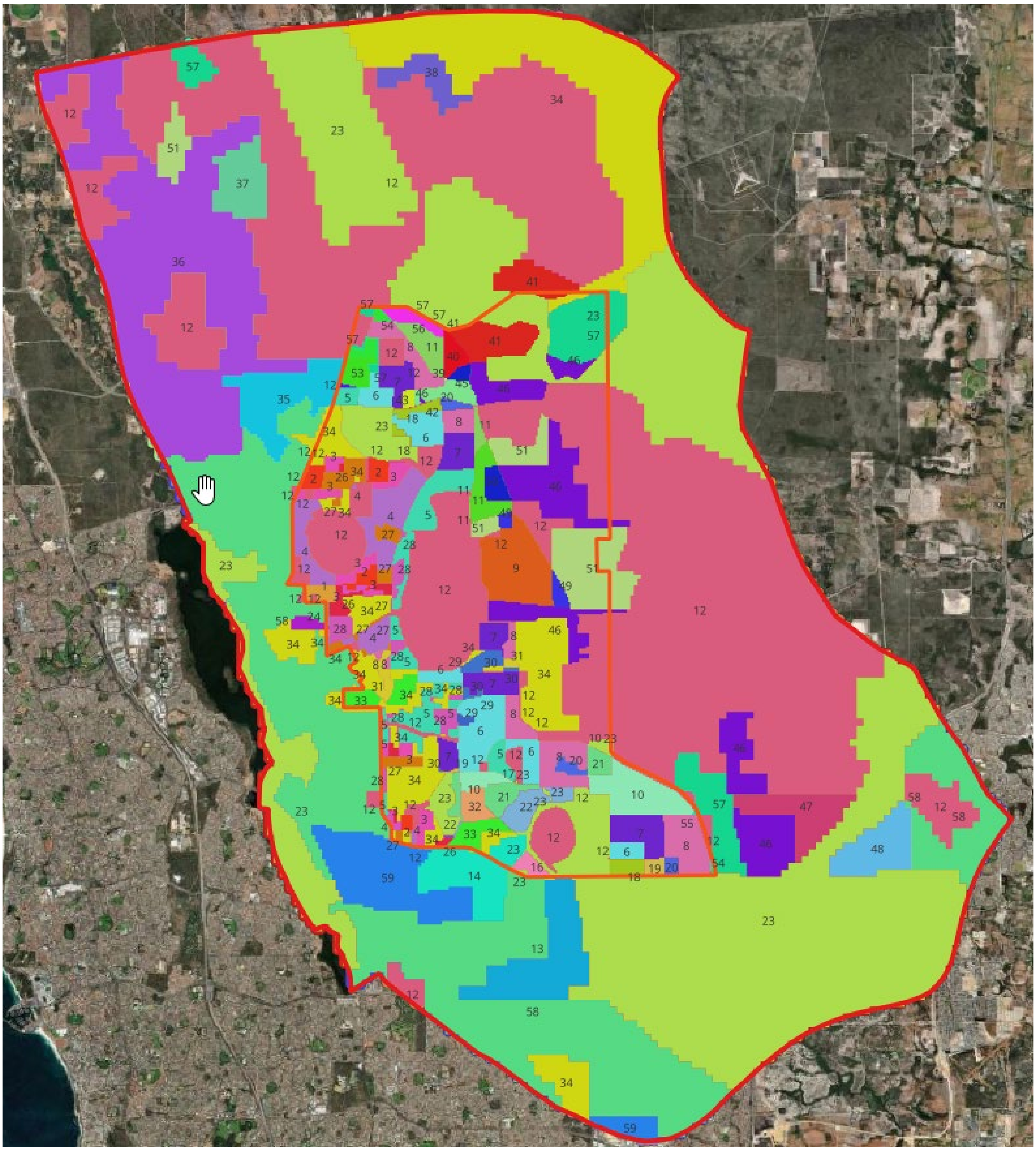


Figure 34: Future recharge and PET time series zones arising from intersection of existing land use zones with future staging.

3.6.4. Proposed controlled groundwater level (CGL)

Subsoil drainage will be included in the EWGM within the EWDSP area at the proposed controlled groundwater level (CGL). The extent of subsoil drainage will be based on future scenario simulations.

- The DWMS proposes a controlled groundwater level based on the 1986 to 1995 average annual maximum groundwater level (AAMGL).
- The 1986 to 1995 AAMGL (preliminary CGL) was determined as follows:
    - Water level data from 1986 to 1995 was filtered from WIR dataset described in Section 3.5.1.
    - Bore data was filtered such that only "shallow bores" (in which the top of the screen was less than 15 m below the average water level for the bore between 1986 and 1995) in the Superficial Aquifer were used for the analysis.
    - Where there were groups of nested or adjacent bores, water level data from the highest screened bore that had a mostly complete set of water level data was selected for the CGL.
- Following the screening process, 90 shallow screened bores were selected for the estimation of the CGL:
    - 85 of the shallow screened bores had 8 or more years of maximum water levels measured between June and November so the AAMGL was calculated as the average of the measured maximum water levels.
    - The remaining 5 bores had 6 or less years of maximum water level data. For these bores the AAMGL was calculated by adjusting the measured maximum water level to an AAMGL, using an average adjustment estimated from the 80 bores that had a complete data record (10 years of data).
- The lakes within the EWDSP area are throughflow wetlands, so are also expressions of the groundwater table. An AAMGL was estimated for the lakes that had measured surface water levels over the period from 1986 to 1995, including Lake Mariginiup, Lake Jandabup, Lake Gnangara, Lake Adams and Lake Badgerup.
- The CGL plane (Figure 35) was generated by contouring (using a kriging analysis) the lake AAMGL and bore AAMGL values across the EWDSP area.

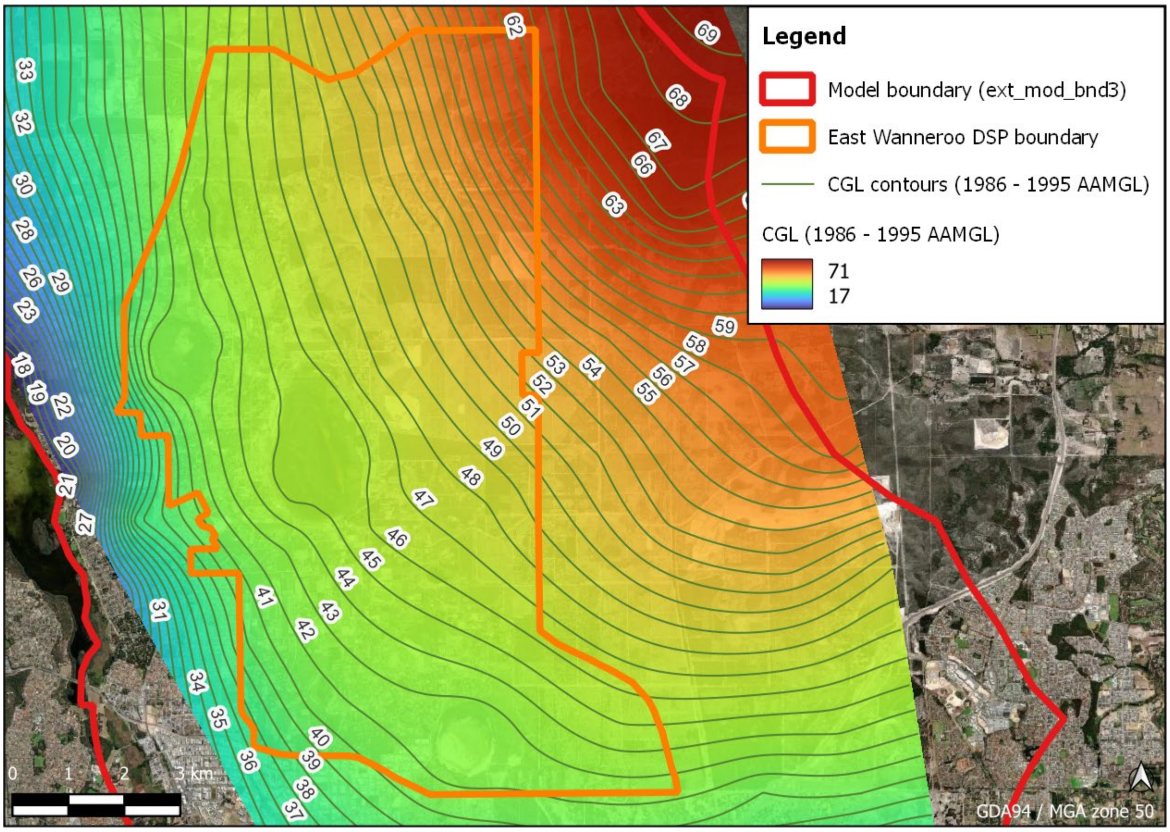


Figure 35: Proposed controlled groundwater level (1986 to 1995 AAMGL)

3.6.5. Lake Jandabup supplementation for future scenarios

If Lake Jandabup supplementation is required for the future scenario models, an average supplementation rate from the last decade will be used. The requirement for supplementation will be assessed during the future scenario modelling.

3.6.6. Potential future abstraction for future scenarios

As for the model calibration period, future abstraction will occur in the form of Water Corporation abstraction, licensed abstraction, and unlicensed abstraction. These rates and are based on the changes in abstraction that will occur to protect the Gnangara groundwater system, as outlined in the *Gnangara groundwater allocation* plan (Government of Western Australia, 2022).

Annual Water Corporation abstraction after 2028 has been provided by DWER (Table 13). These rates were distributed monthly, based on average monthly Water Corporation abstraction data over the model calibration period.

Future licensed abstraction was estimated, based on current licensed abstraction rates, existing and future land use, and development staging, as follows:

- Outside of the EWDSP area licensed abstraction was assumed to remain unchanged until 2028, at which time it reduced by 10%.
- Within the EWDSP area, licensed abstraction remains unchanged in areas with no change in land use, and with no license reduction as the East Wanneroo DSP area is exempt from licence reductions (DWER 2022).
- Within the EWDSP area, in areas of urban development, licensed abstraction remains unchanged (no license reduction), until the area is developed as indicated by the preliminary staging map (Figure 33). When the area is developed, the existing licensed abstraction rates are replaced by averaged irrigation rates across for public open space, primary schools and some high schools that do not have specified locations within the DSP.
- For areas within the EWDSP area that have a land use change other than urban (such as high schools and the district playing fields), licensed abstraction remains unchanged (no license reduction), until the area is developed at which time licensed abstraction rates are based on irrigation rates calculated for each specific land use.
- Future unlicensed abstraction was assumed to become zero following development within the EWDSP area but elsewhere remained at 70% of the average unlicensed abstraction over the last 3 years of calibration. This reduction of 30% was included to account for the recent reduction in the number of irrigation days for bore owners.
- Total annual abstraction at full build-out across the EWDSP area, including Water Corporation abstraction, licensed and unlicensed private abstraction, is estimated to be 6.1 GL.

Table 13: Future Water Corporation rates within the East Wanneroo groundwater model domain (provided by DWER)

Bore ID	Annual abstraction (2028 onwards)
M10	300
M100	150
M110	100
M130	100
M20	200
M200	100
M35	300
M90	300
W10	440
W110	50

Bore ID	Annual abstraction (2028 onwards)
W120	50
W20	300
W260	300
W270	300
W280	200
W30	100
W310	100
W40	250
W50	200
W70	100
M10	300
M100	150
M110	100
M130	100
M20	200
M200	100
M35	300

For the 'no development' scenario:

- Future unlicensed abstraction was assumed at 70% of the average unlicensed abstraction over the last 3 years of calibration. This reduction of 30% was included to account for the recent reduction in the number of irrigation days for bore owners.
- Annual Water Corporation abstraction rates were continued as the average of the last 3 years of model calibration until 2028, at which time the Water Corporation rates changed to those provided by DWER (Table 13). These rates were distributed monthly, based on average monthly Water Corporation abstraction data over the model calibration period.
- Similarly, private licensed abstraction rates continued as the average of the last 3 years of model calibration until 2028, at which time the rates were reduced by 10%.

A summary of the changes made to abstraction for the future model simulations is provided in Table 14.

Table 14: Summary of abstraction applied to future model predictions

User	Historical (calibration)	Future - No-Dev	Future – Dev (within DSP area)
Water Corp	As measured	Provided by DWER	Provided by DWER
Licenced	Measured and estimated – provided by DWER	Reduced by 10% (Gnangara Allocation Plan)	No change where existing landuse remains (exempt), irrigation rates over PoS and schools
Unlicenced	Estimated - provided by DWER	Reduced by 30% (reduced watering from 3 days to 2 days)	Reduced to zero

3.6.7. Potential leakage for future scenarios

Leakage from the Superficial Aquifer to the Leederville Aquifer was assumed to continue at the average rate from the last 3 years of model calibration, which is an annual rate of approximately 14.5 GL/year.

4. Conceptual hydrogeological model

The data outlined in Section 3 provides the basis for:

- the conceptual hydrogeological model for the model domain.
- order of magnitude flow quantification for an annual average water balance.

The conceptual hydrogeological model for the East Wanneroo groundwater flow model is outlined in Section 4.1 and illustrated in Figure 36, which includes the estimated flow volumes presented in the annual average water balance (Section 4.2).

4.1. Overview of the conceptual hydrogeological model

Climate

- The study area experiences a temperature climate, characterised by distinctly dry hot summers and cold wet winters. Average annual rainfall over the thirty-year period between 1971 and 2000 was 758 mm, but had reduced to 702 mm between 2010 and 2021 (the model calibration period). The annual average potential evapotranspiration over the model calibration period is 1460 mm.

Topography

- The study area extends across the Bassendean and Spearwood Dune systems. The topography is elevated in the north-eastern corner of the study area within the Bassendean Dune system, then falls to the south, and falls towards the west and south-west before rising over a ridge in the Spearwood Dune system then down the lower elevations of Lake Joondalup and Lake Goollelal.

Land use

- Land use across the study area includes:
  - Urban and commercial / industrial areas mostly along some western and southern parts
  - Market gardens, pastural areas and rural residential areas through the central region
  - Native vegetation areas, predominantly banksia woodlands, scattered throughout the study area, but particularly through eastern parts.
  - Various densities of pine plantation from cleared pines and low-density pines through to medium to high density pines, mostly through the eastern half of the study area.

Geology

- The Quaternary Superficial Formations across the study area are predominantly comprised of:
  - SAND from the two dune systems (Tamala Sand to the west; Bassendean Sand through central and eastern parts),
  - LIMESTONE locally interbedded through parts of the western side of the study area (Tamala Limestone), and locally in some areas near the base of the Superficial Aquifer on the eastern side of the domain (potentially Ascot Formation).
- Northern parts of the study area are underlain by the Pinjar Member and Wanneroo Member of the Leederville Formation. In this area Kardinya Shale, the lithological unit controlling leakage from the Superficial Aquifer is pinched out allowing leakage into the Leederville Aquifer. The remainder of the study area is either underlain by Kardinya Shale, or members that overlie Kardinya Shale, including the Mirrabooka Member of the Osborne Formation, Molecap Greensand and Poison Hill Greensand.

Base of Superficial Formations

- The base of the Superficial Formations is at an elevation of about 18 m AHD near the north-eastern corner of the study area, reducing to -25 m AHD on the western side.

Surface water and drainage

- A chain of wetlands, including 3 major lakes, have formed in the interdunal depressions between the Bassendean and Spearwood dune systems. Other wetlands, consisting of swamps and lakes have formed in depressions within both the Bassendean and Spearwood Dune Systems.
- Lakes within the study area are throughflow lakes, so the water table on the up-gradient side of the lakes is generally slightly higher than the lake water level, indicating discharge

of the groundwater into the lakes. On the down-gradient side of the lake the water table elevation is lower than the lake level indicating outflow from the lakes into the groundwater system.

- The water level in the lakes is largely maintained by groundwater inflow and the lake water levels fluctuate seasonally, in phase with the water table fluctuations, however the amplitude of the fluctuations in the lake can be greater than the seasonal water table fluctuations during periods of either heavy rainfall or extended high evapotranspiration. Water levels are supplemented in Lake Jandabup.
- There are no surface drainage features removing surface runoff from the study area.

*Inflow and outflow processes (*Figure 36*)*

- Groundwater inflow occurs in the north-eastern corner of the study area which is near the top of the Gnangara groundwater mound.
- Recharge occurs at varying rates across the study area depending on land use, vegetation type and depth to groundwater.
- In wooded areas the net recharge rates vary from about 0% of rainfall in more densely wooded areas up to 30% of rainfall in low density wooded areas (e.g., low density pine).
- In cleared / pasture areas gross recharge is higher at about 40% of rainfall, however if groundwater is shallow in these areas evapotranspiration losses can result in lower net recharge rates.
- In urban and commercial/industrial areas, net recharge rates are higher at about 64% and 67%, respectively, as there is more runoff from impervious surfaces directed into the subsurface through drainage systems and soakwells and less surface losses through evapotranspiration.
- Net recharge across the lakes is effectively a discharge from the groundwater system as evaporative losses from the lake surfaces are greater than rainfall inflow.
- Irrigation is a potential source of recharge to the Superficial Aquifer, however with increases in water efficiency measures over the last two decades, irrigation return water across the study area is considered negligible.
- Bore abstraction is a groundwater discharge process. In the East Wanneroo area, groundwater is abstracted by Water Corporation (licensed) and private water users (both licensed and unlicensed).
- Leakage from the Superficial Aquifer into the Leederville Aquifer occurs across the study area. The highest leakage rates are in those parts of the model domain that are in direct contact with members of the Leederville Formation.

Aquifer Framework

- The Superficial Aquifer is an unconfined aquifer formed by the groundwater contained in the Quaternary Superficial Formations. The base of the Superficial Aquifer is the base of the Superficial Formations.
- The depth of the Superficial Aquifer varies from up to 67 m on the eastern boundary down to about ~36 m on the western boundary and locally down to ~28 m near the southern boundary where the base of the Superficial Formations is locally mounded.
- The proposed model boundary has been developed based on maximum groundwater contours for 2015 (which were similar to the 2010 and 2019 maximum groundwater contours).
- The boundary conditions for the model domain are:
  - No flow (where the boundary is perpendicular to the groundwater contours):
  - across the northern boundary
  - across the central and southern parts of the eastern boundary
  - Transient specified head boundaries along:
    - the northern section of the eastern boundary (along the 68 m AHD groundwater contour) in the area of inflow from the Gnangara groundwater mound.
    - along the western boundary, which is predominantly aligned with the 18 m AHD groundwater contour, but also circles the edge of Lake Joondalup.
    - at the southern end of the western boundary there is a short stretch of no flow between the 18 m AHD groundwater contour and the higher water level elevation of Lake Goollelal, and between Lake Goollelal and the southern boundary contour.
    - along the southern boundary on the 30 m AHD contour.

- The model domain extends to the base of the Superficial Aquifer.

Groundwater Flow Direction

- Groundwater is flowing in a westerly direction across the northern half of the site, moving to a south-westerly and then southerly direction towards the southern end of the model domain.
- Based on bore hydrographs from transects across the model domain (Figure 26), water levels in developed areas on the western and south-western side of the model domain appear to be remaining constant or have risen over the last decade likely due to urban development, whereas water levels across the northern and eastern parts of the model domain have fallen over the last decade.

4.2. Water balance

An annual water balance has been calculated across the model domain over the calibration period (2010 to 2021). The water balance flows are based on the conceptual hydrogeological model outlined in Section 4.1 and the data collated and analysed in Section 3. The estimated flows for the water balance are presented in Table 15.

The water balance flows were estimated as follows:

- Groundwater inflows and outflows were estimated using Darcy's Law and PRAMS hydraulic conductivity values across segments of the model boundary. The inflows and outflows were compared to flows derived from a flow net analysis by Davidson (1995). Flow channels 1 (part of), 2 ,3 and 4 from Davidson's Gnangara Mound (South) analysis cover a similar area as the model domain.
  - Davidson indicated an annual flow rate of ~820 ML/yr and ~11,680 ML/yr (for channels 1 to 4) across the 70 m AHD and 60 m AHD contours, respectively. These rates are consistent with the water balance inflow rate of 1,340 ML/yr for the 67 m AHD contour.
  - Davidson indicated an annual flow rate of 35,900 ML/yr and 47,400 ML/yr across the 30 m and 20 m contours, respectively. These flow rates are higher than the water balance outflow of 32,730 ML/yr estimated for the western and southern outflow boundary that extends across the 18m AHD contour (western side) and 30 m AHD contour (southern side).
- The recharge rates presented in Excel workbook *Recharge function_01112022.xlsx*, were applied across the recharge zones shown in Figure 21 and the pasture recharge rate was applied across the dry areas within the lake polygons to generate average annual recharge rates.
- 100% of rainfall and Morton Lake evaporation rates were applied across the water surface of the three major lakes.
- The Jandabup Lake supplementation flow rate was estimated based on the W210 and W220 abstraction volumes.
- Water Corporation abstraction rates were based on monthly data provided by Water Corporation.
- Leakage and private (licensed and unlicensed) abstraction rates were based on rates provided by DWER.

The balance of the inflows and outflows across the model domain reflects the change in groundwater storage. This storage change is estimated to be a loss of about 5 GL/yr, which correlates to a fall in the water table across the model domain of about 75 mm/year over the calibration period from 2010 to 2021 (assuming a specific yield of 0.2).

The water balance provides order of magnitude flows that can be compared to calibration output from the EWGM.

Table 15: Annual average water balance across the model domain, within the Superficial Aquifer, for the proposed model calibration period (2010 to 2021)

Parameter	Annual Inflow/Outflow (ML/yr)	Annual Inflow/Outflow normalised to the model domain area (mm/yr)	Annual inflow/outflow as a % of total rainfall across the model domain (%)
INFLOWS			
Groundwater inflow across NE boundary (from Gnangara Mound)	1,340	4	0.5%
Lake recharge	1,170	3	0.5%
Gross recharge across pasture/cleared areas	36,860	105	14.9%
Net recharge across developed areas	21,020	60	8.5%
Net recharge across wooded areas	18,680	53	7.6%
Lake supplementation	1,090	3	0.4%
TOTAL INFLOWS	**80,160**	**228**	**32.4%**
OUTFLOWS			
Lake evaporation	2,530	7	1.0%
Evapotranspiration in pasture/cleared areas	assume negligible as WLs are low		0.0%
Water Corporation abstraction	10,470	30	4.2%
Licensed private abstraction	20,800	59	8.4%
Unlicensed abstraction	5,100	14	2.1%
Leakage into underlying aquifers	13,840	39	5.6%
Groundwater outflow across W and S boundary	32,730	93	13.2%
TOTAL OUTFLOWS	**85,470**	**243**	**34.6%**
Change in storage	-5,310	-15	-2.1%
Change in water table elevation (mm) (assuming Sy = 0.2)	-	-75	-

Notes:

1) The model domain is approximately 35,200 ha.
2) Annual average rainfall was 702 mm between 2010 and 2021.
3) Total inflows and outflows from the Superficial Aquifer are less than 100% of rainfall as some of the recharge estimates are based on net recharge, rather than gross recharge estimates with associated evapotranspiration.

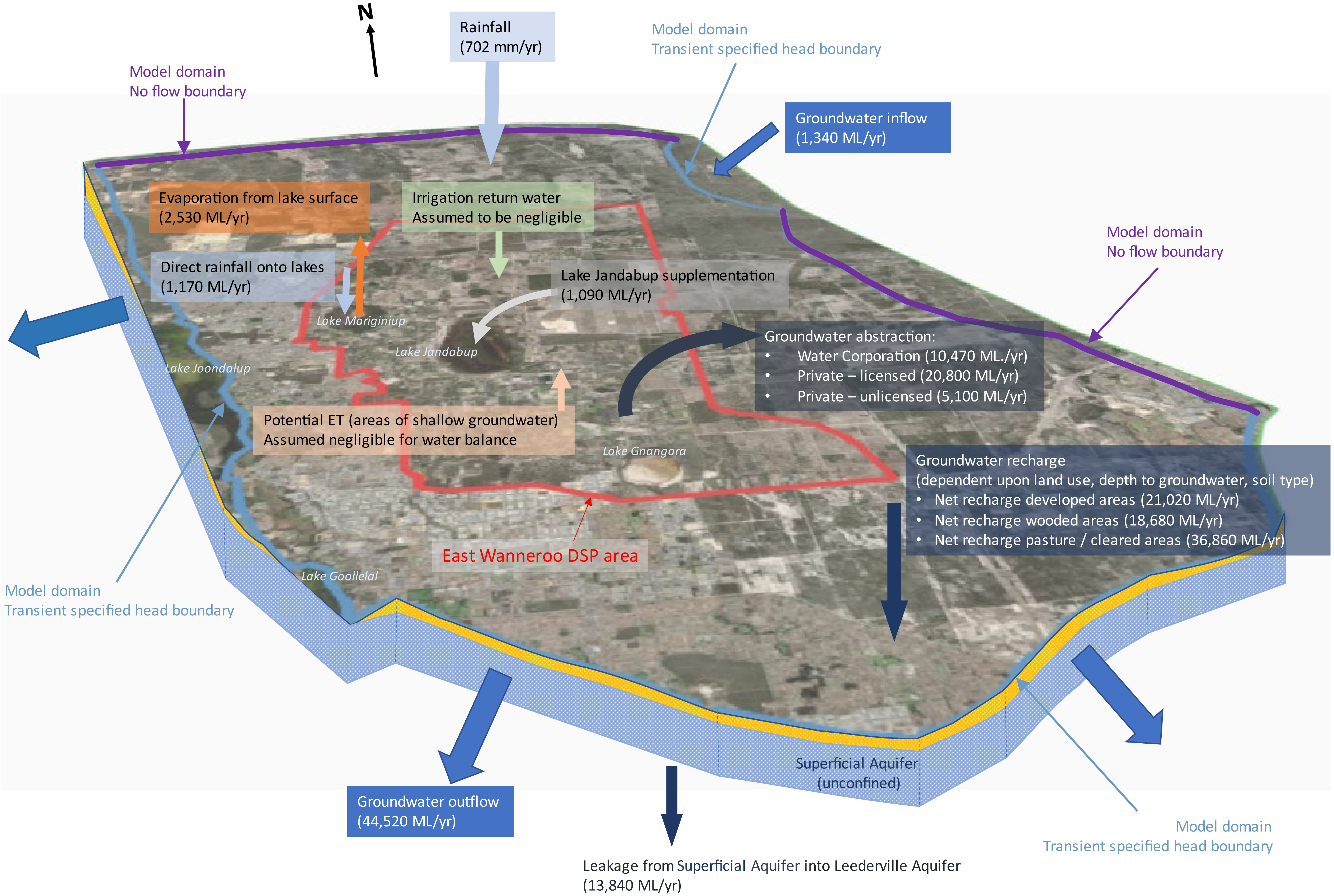


Figure 36: Conceptual hydrogeological model for the East Wanneroo groundwater model domain (not to scale, bracketed volumes are annual average flow rates for the period from 2010 to 2021

5. Model construction

5.1. Model code

MODFLOW USG (Panday et al, 2017) is the software package selected to model the groundwater flow field across the East Wanneroo area.

- MODFLOW USG solves the groundwater flow equation using unstructured grids.
- MODFLOW-USG also contains an optional Newton-Raphson formulation, based on the formulation in MODFLOW-NWT, for improving solution convergence and avoiding problems with the drying and rewetting of cells.
- Drying/rewetting of model cells is likely to occur in the East Wanneroo groundwater model due to the requirement for thin cells near the water table to implement the lake package (LAK3 MODFLOW package) which was used to simulate the major wetlands.

Groundwater Vistas (version 8) is the graphical user interface (GUI) selected to run the groundwater flow modelling software. This software provides a graphical interface for building, running and analysing numerical flow and transport models based around the USGS modelling packages including MODFLOW, MODFLOW USG, MODPATH, MT3D and related packages. MODFLOW USG and Groundwater Vistas are both well-recognised groundwater flow modelling software packages used by the international groundwater flow modelling community.

5.2. Simulation period

For calibration purposes, the model simulates groundwater flow over an eleven-year period from September 2010 to August 2021. Model stress periods are monthly with four time-steps per stress period and a timestep multiplier of 1.2, resulting in 132 model stress periods for model calibration.

The spin-up requirements for the model require some consideration:

- Due to changing land uses and changing water use practices in the East Wanneroo area, there is no identifiable period that can be considered steady state. As the groundwater table is not in quasi-equilibrium with the hydrological system at the start of model calibration, an initial steady state simulation is not suitable.
- Using a measured hydraulic head distribution as the initial condition at the start of model calibration is also not ideal as the early time steps may not solely reflect the model stress, but could include an adjustment of model head values to offset the lack of correspondence between model hydrologic inputs and the initial head values (Anderson et al, 2015)
- A 4-year simulation that repeated the first 12 months of model input data (i.e., from September 2010 to August 2011) four times was carried out to assess water level trends if this data period was used for spin-up. The parameter values presented in Table 16 were used for this 4-year simulation. The resulting water level hydrographs at 8 dummy well locations are shown in Figure 37 for the 4 year simulation.
- The simulation was then repeated with the following parameter changes:
    - Kh zone 4 increased to 5 m/day.
    - Kh zone 5 increased to 20 m/day.
    - Kh zone 6 increased to 15 m/day.

  The hydrographs for the second simulation are shown in Figure 38.
- A comparison of the two sets of hydrographs shows the dependency of the simulated water levels on the aquifer properties and the potential for the initial water table at the start of the calibration period to vary significantly from the measured initial water surface if an extended artificial spin-up period is used.
- Based on this assessment, the measured/interpolated 2010 maximum groundwater surface was applied as an initial head condition for a short spin-up period of 12 months (30 days per month), based on hydrological parameters for the 12 months from September 2010 to August 2011. This spin-up approach was designed to generate a head distribution throughout the model, without the initial heads deviating significantly from the measured head distribution.

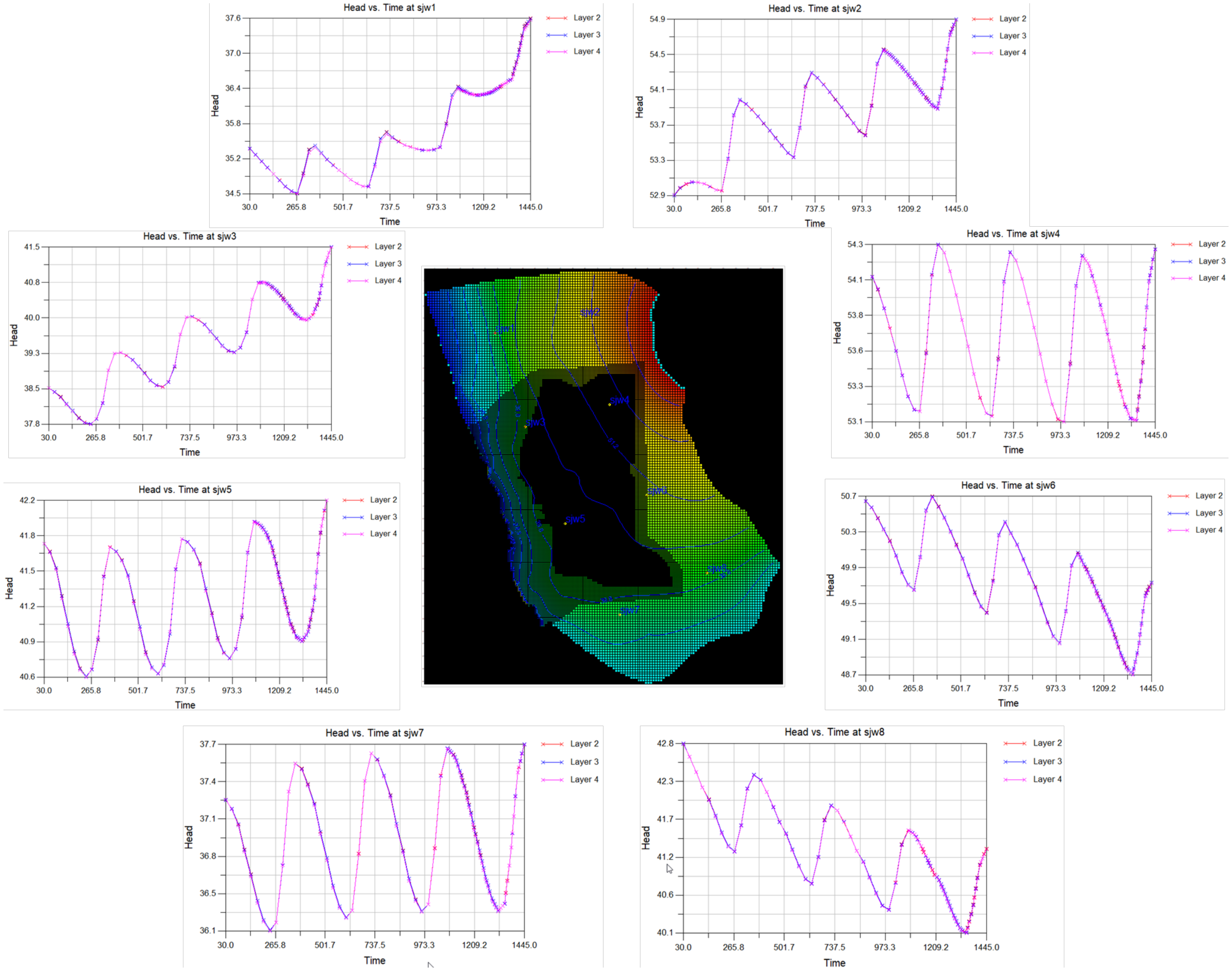


Figure 37: Hydrographs from 8 dummy bores based on a 4-year simulation period that repeats the first 12 months of model input data

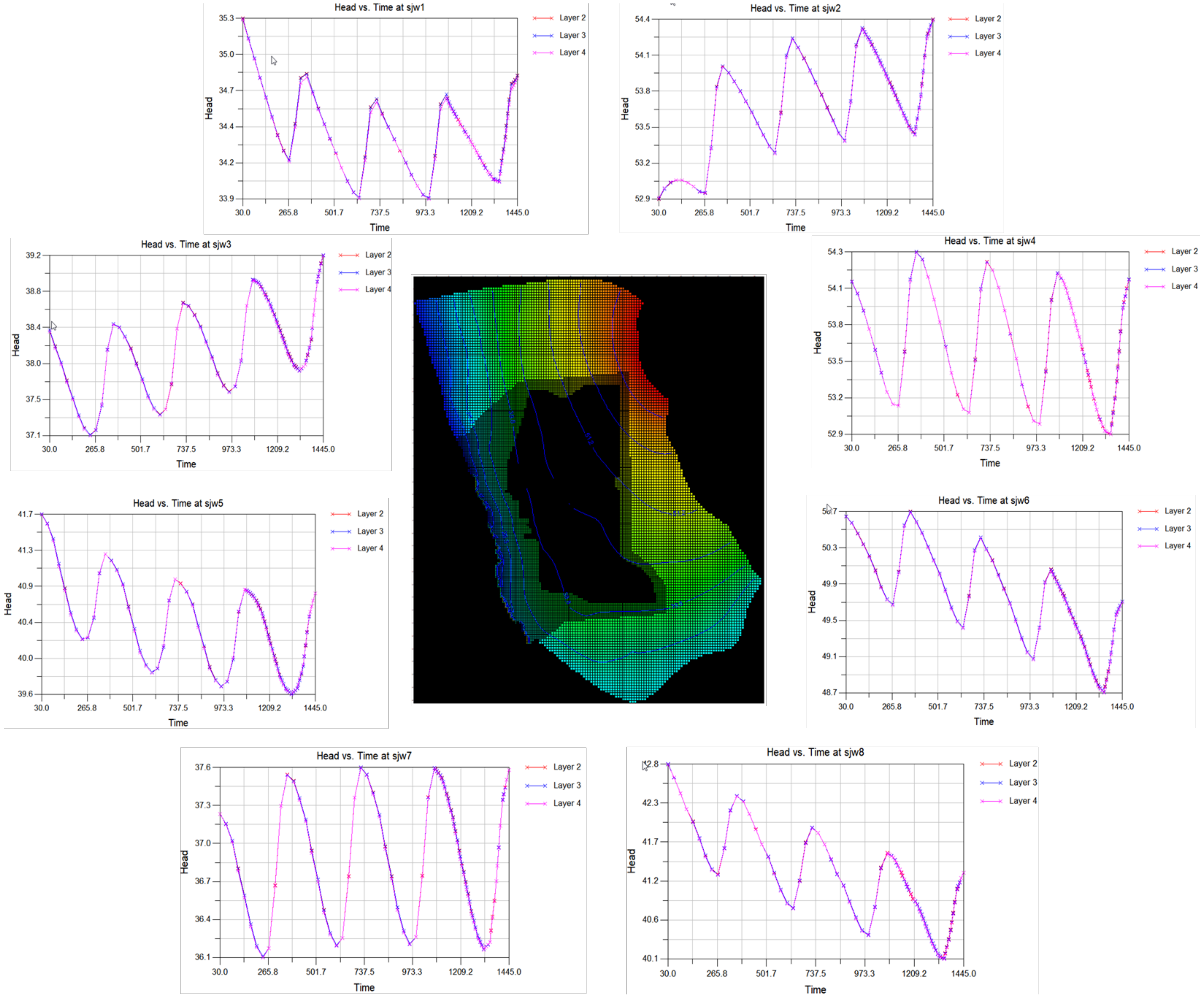


Figure 38: Hydrographs from 8 dummy bores based on a 4-year simulation period that repeats the first 12 months of model input data with some aquifer parameters adjusted

5.3. Model domain and grid

The model domain extends from Lake Pinjar, about 6.5 km north of the EWDSP boundary, Malaga which is about 6 km south of the EWDSP boundary. The model domain extends to Lake Joondalup on the western side of the model domain, and out to the suburb of Ellenbrook on the eastern side.

The model domain was defined taking into consideration nearby surface water bodies, the presence of the Gnangara groundwater mound and the maximum groundwater contours from 2010, 2015 and 2019 to establish no flow portions of the boundary and specified head portions of the boundary.

The final model domain boundary was based on the 2015 maximum water level contours, as shown in Figure 39.

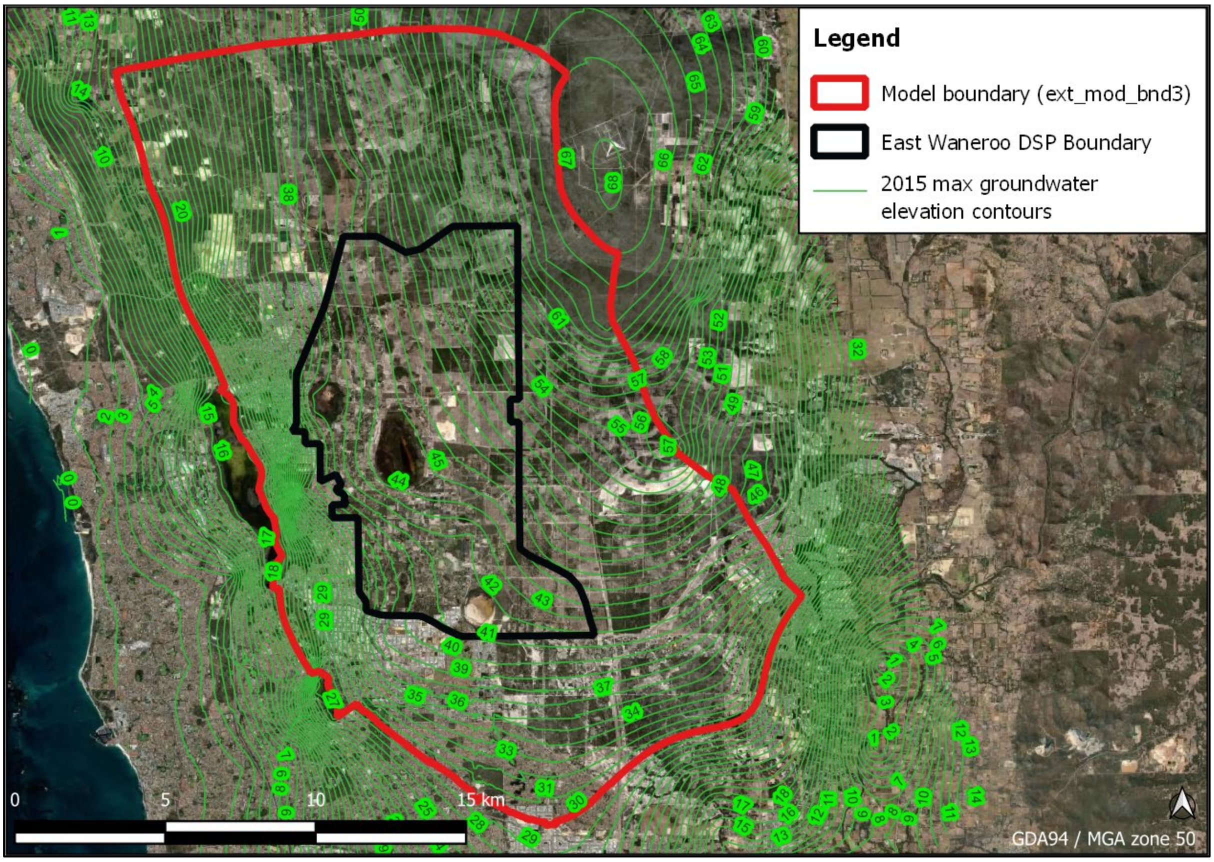


Figure 39: Model domain

5.3.1. Grid design

- The base model grid consists of 166 rows and 143 columns of uniform spacing with a cell dimension of 160 m x 160 m.
- Quadtree refinement has been applied to focus the model resolution in the area of interest (i.e. within the East Wanneroo DSP area), where the cell dimensions are reduced to 40 m x 40m.
- A transition zone, with a cell dimension of 80 m x 80 m, surrounds the focus zone and extends westward to the model boundary encompassing the area where groundwater discharges into Lake Joondalup.
- The model grid is shown in Figure 40.

5.3.2. Model layers

- The model was designed with 5 layers:
  - Top of layer 1 is based on the 1m LiDAR of the site topography (Section 3.2.4, Figure 7) modified at the lakes to represent the surface of the lake, and adjusted where necessary at the edges of the lakes to be a minimum of 0.5m above the bottom of layer 1.
  - Bottom of layer 1 is approximately at the elevation of a seasonal maximum groundwater surface (derived from the maximum water levels from 2010, 2015 and 2019), with the lake bathymetry inserted within the lake polygon areas resulting in a variably thickness for Layer 1.
  - Layers 2 and 3 are approximate 2 and 5m thick respectively.
  - The base of layer 4 is 3m above the bottom of layer 5.
  - The base of layer 5 is based on the base of aquifer surface as shown in Figure 9 (Section 3.2.6)
- Three transects showing the model layer elevations are shown in Figure 41.

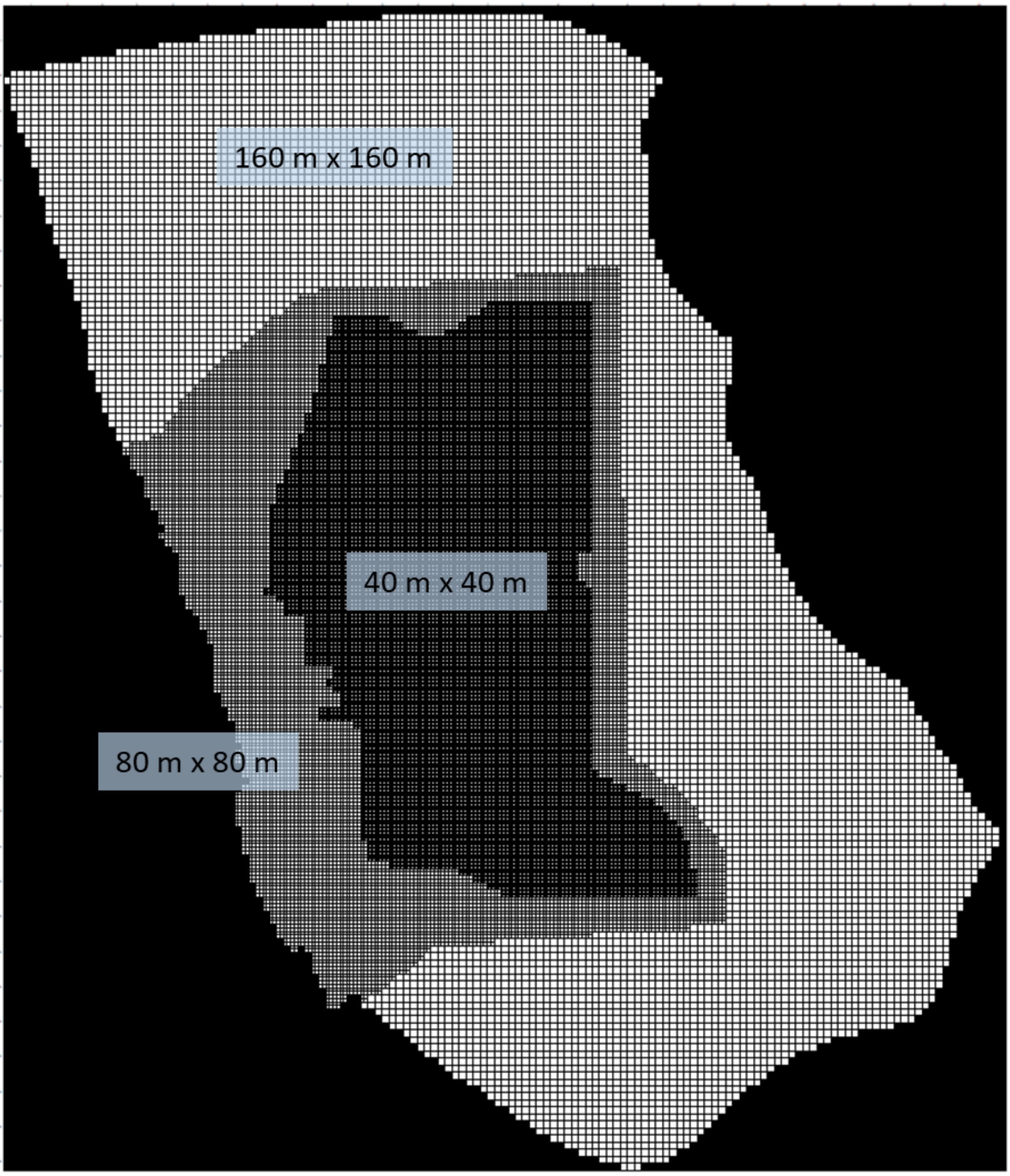


Figure 40: Model grid with quadtree refinement and model cell dimensions

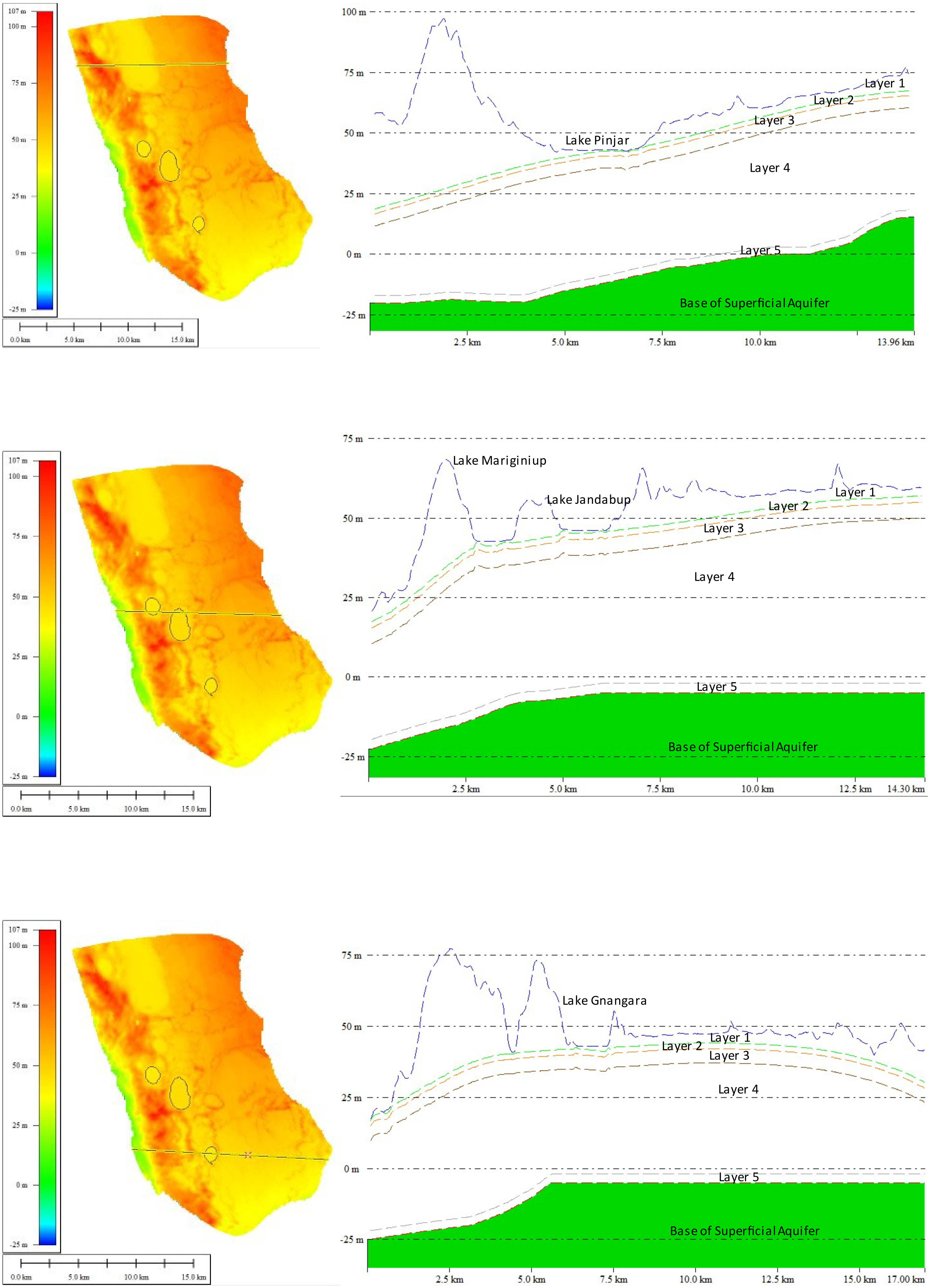


Figure 41: Transects through the model domain showing layer elevations.

5.4. Model geology and aquifer parameter zones

- The model has been divided into aquifer parameter zones based primarily on surface geology mapping, with consideration given to:
  - the recent study carried out by McArthur (2022), which presented alternate interpretations of both the Tamala Limestone and Tamala Sand contact and the Tamala Sand and Bassendean Sand contact.
  - the distribution of aquifer properties within PRAMS.
- Seven lithological zones have been included in the model construction (Figure 42). The zones are assumed to extent across all model layers to the full depth of the aquifer. The zones have been defined to allow for initial, upper and lower bound parameter values to be specified.
- The zones can be summarised as follow:
  - Zone 1 is Bassendean Sand which is mapped across eastern parts of the model.
  - Surface geology mapping shows Zone 2 as Tamala Sand but this area was reinterpreted as Bassendean Sand by McArthur (2022) (Figure 43). The properties assigned to this zone encompass both lithologies.
  - Surface geology mapping shows Zone 3 as Bassendean Sand but this area was reinterpreted as Tamala Sand by McArthur (2022). The properties assigned to this zone encompass both lithologies.
  - Zone 4 is a lower conductivity transition zone which appears to occur in the contact zone between the Tamala Sand and Tamala Limestone. The potential extent of this zone was identified visually as the area of steep hydraulic gradient from groundwater contours across the model domain in conjunction with the interpreted contact presented by McArthur (2022). The properties assigned to this zone encompass the properties of Tamala Sand and a lower conductivity transition zone as the extent of this zone is not known.
  - Zone 5 is mapped as Tamala Limestone. This zone encompasses properties of both Tamala Sand and Tamala Limestone.
  - Zone 6 and 7 are mapped as Tamala Sand with aquifer properties corresponding to Tamala Sand only.

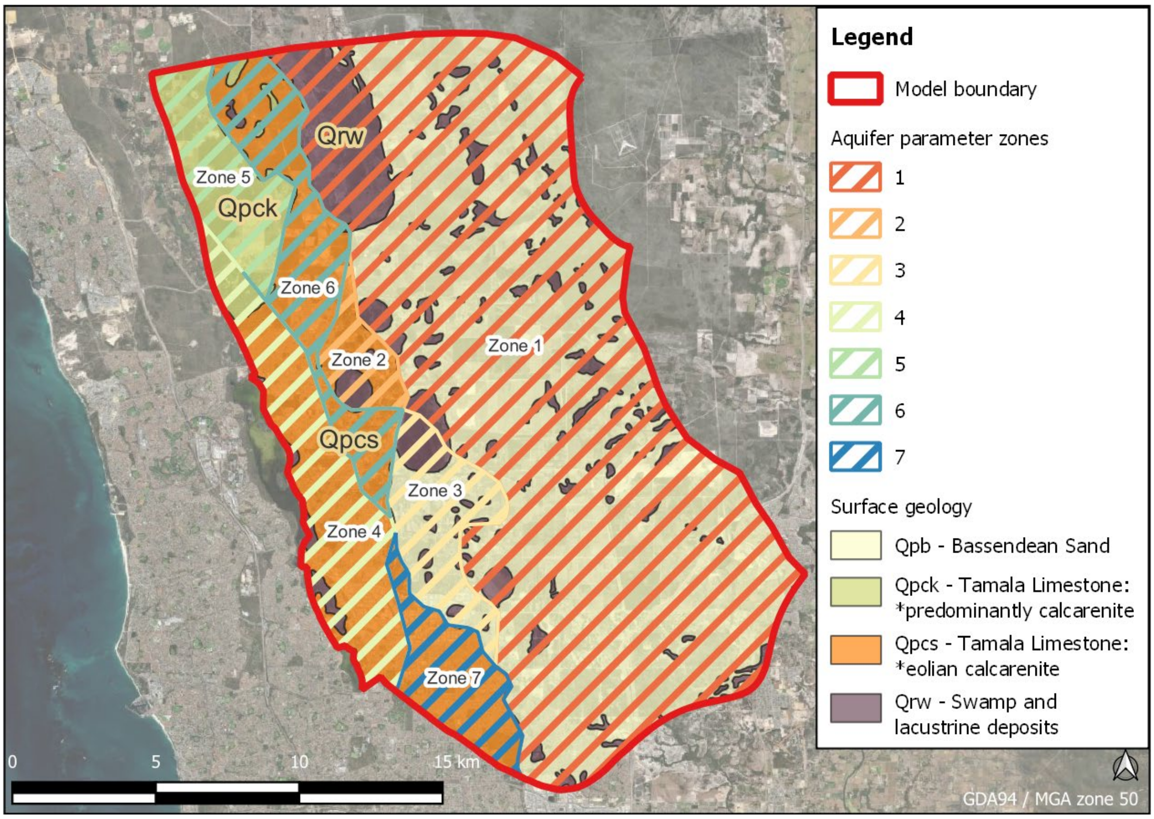


Figure 42: Aquifer parameter zones compared to surface geology mapping

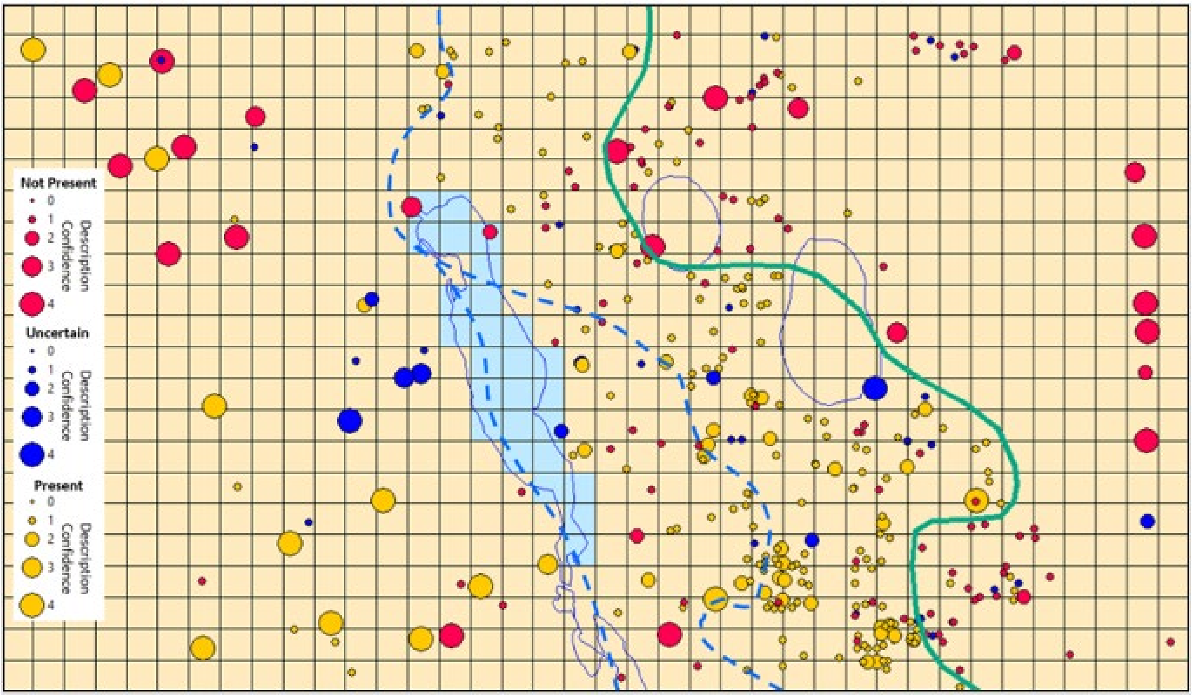


Figure 43: Tamala Sand-Bassendean Sand contact interpretation (green line) inferred from borehole lithological data, with Tamala Limestone contact interpretations shown (blue dashed lines) (after McArthur 2022)

5.5. Model parameters

The model aquifer parameters, including assumed initial values and upper and lower bounds, for the seven zones outlined in Section 5.5. are summarised in Table 16. These values are consistent with the aquifer properties outlined in Table 10 (Section 3.3.7.5).

Table 16 Aquifer properties for the assumed model lithology zones

Description	Zone	K_h init	K_h min	K_h max	K_v init	K_v min	K_v max	Ss	Sy range	Sy_init
Bassendean Sand	1	20	10	40	2	1	4	0.0005	0.15 – 0.25	0.2
Tamala Sand / Bassendean Sand	2	10	1	40	1	0.1	4	0.0005	0.1 - 0.25	0.15
Tamala Sand / Bassendean Sand	3	20	1	40	2	0.1	4	0.0005	0.1 - 0.25	0.2
Tamala Sand / Transition zone	4	2	0.5	10	0.2	0.05	1	0.0005	0.1 - 0.2	0.15
Limestone / Tamala Sand	5	15	1	50	1.5	0.1	5	0.0005	0.1 - 0.3	0.15
Tamala Sand	6	10	1	20	1	0.1	2	0.0005	0.1 - 0.2	0.15
Tamala Sand	7	10	1	20	1	0.1	2	0.0005	0.1 - 0.2	0.15

5.6. Boundary conditions

- Around the model boundary, six reaches were identified as either constant head boundaries (CHD) (i.e., time variant specified-head boundaries) or general head boundaries (GHB), with the remaining segments of the model boundary considered no flow boundaries.
- These boundary conditions mapped to the model grid are shown in Figure 44, where dark blue cells have a time-variant specified head condition (CHD) and light blue cells have general head boundary condition (GHB). Details of the type of boundary condition for each reach are summarised in Table 17.

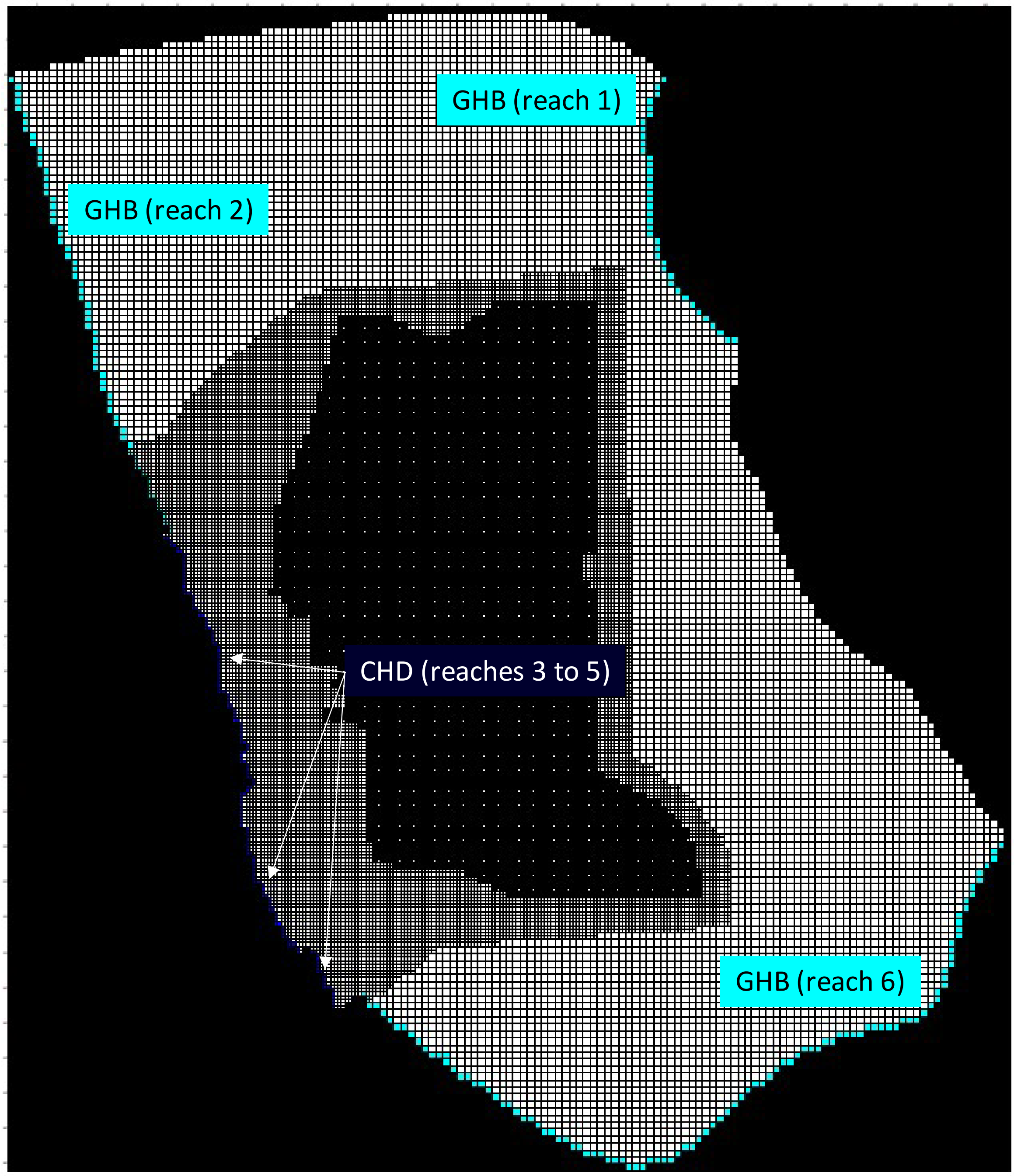


Figure 44: Boundary conditions (CHD and GHB)

Table 17: Details of the constant head and general head boundary condition reaches

Description	Reach	Type of boundary condition	Initial conductance (m2/day)	Approximate head elevation (mAHD)	Bore/lake used for water level data and any adjustment
Northern end of eastern boundary (near the top of the Gnangara Mound)	1	GHB	10,000	68	Bore: 61610908 Adj: +0.6 m
Northern end of western boundary	2	GHB	10,000	18	Bore: 61610600 Adj: +1.5 m
Lake Joondalup	3	CHD	-	17	Lake Joondalup measured water levels
Western edge between Lake Joondalup and Lake Goollelal	4	CHD	-	18	Bore: 61610600 Adj: +1.5 m
Lake Goollelal	5	CHD	-	27	Lake Goollelal measured water levels
Southern Boundary	6	GHB	10,000	30	Bore: 61610559 Adj: 0 m

- The head boundary condition time series are based on water level data for nearby bores or lakes, with the water levels adjusted slightly based on the location of the bores against the 2015 maximum groundwater contours at the model boundary. The time series data source for each boundary and any adjustments made to the data are included in Table 17 and the bores, lakes and boundary condition reaches are shown in Figure 45.

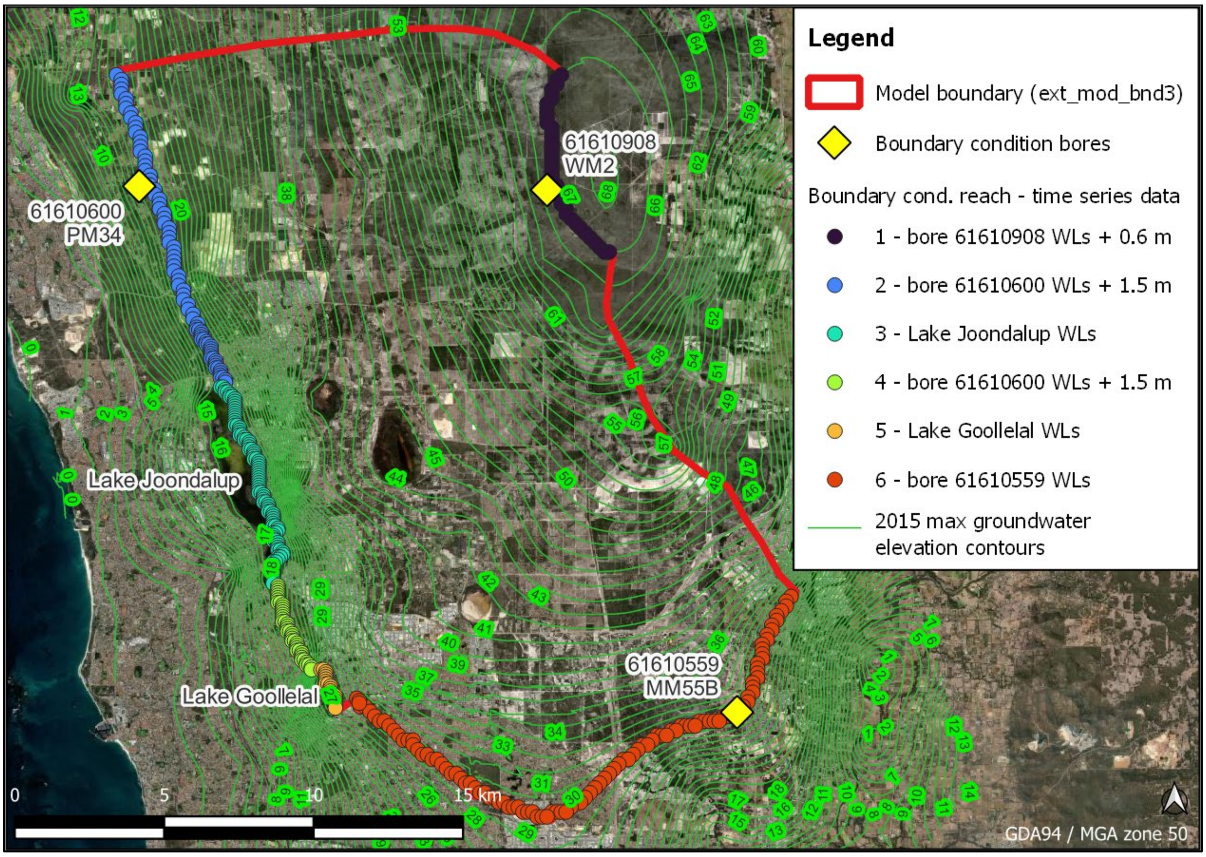


Figure 45: Boundary condition reaches and associated source for time series water level data

5.6.1. Recharge

- The recharge zones shown in Figure 21 have been applied to the groundwater model as shown in Figure 46.
- The transient recharge rates applied to the recharge zones are described in Section 3.3.7.

5.6.2. Evapotranspiration

- Evapotranspiration is applied to the model grid across the same zones as recharge (shown in Figure 46).
- As the applied recharge rates are net rates except for the pasture/cleared land use, evapotranspiration rates are only applied to recharge zone RZ1 (including RZ1A and RZ1B) (shown as zones 1, 1A and 1B on Figure 21) or those zones that have a changing land use and become RZ1 zones over the simulation period.

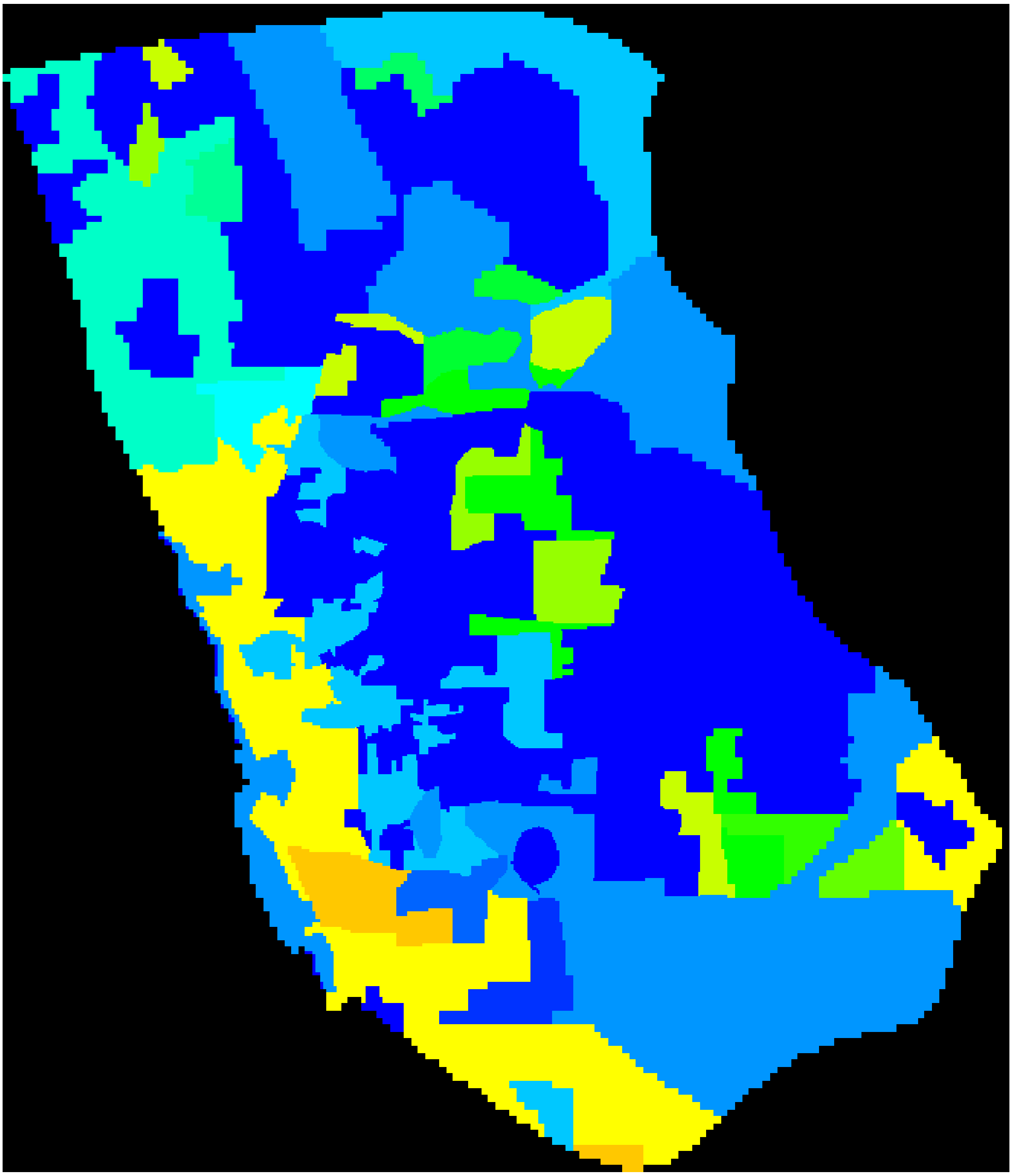


Figure 46: Recharge zones applied to the model grid

5.6.3. Abstraction

- All abstraction (including Water Corporation, licensed and unlicensed abstraction) was applied to the groundwater model using the MODFLOW Well package. To apply this package all abstraction rates must be combined into a single dataset.
- The abstraction datasets were combined as follows:
    - Water Corporation abstraction bores were intersected with the model grid. The bore abstraction rates were converted to average daily rates and assigned to the intersected model cells.
    - Licensed abstraction time series were generated for each model grid cell using the methodology outlined in Section 3.3.2.2
    - Unlicensed abstraction time series were generated for each model grid cell using the methodology outlined in Section 3.3.2.3.
    - The different abstraction rates were added together for each model cell to generate a total abstraction dataset which was applied in layer 4 of the model using the MODFLOW Well package.

5.6.4. Leakage

- Leakage from the base of the Superficial Aquifer into the underlying formations has been included in the model using the MODFLOW Well function across every cell of layer 5 (i.e., across the 3m thick base layer of the model)
- The leakage flow rate applied to the Well function for each model cell is based on the rates provided from the PRAMS model for the six leakage zones outlined in Section 3.3.6. The leakage volume applied to each cell depended on the cell size, resulting in 15 different model leakage zones as shown in Figure 47.

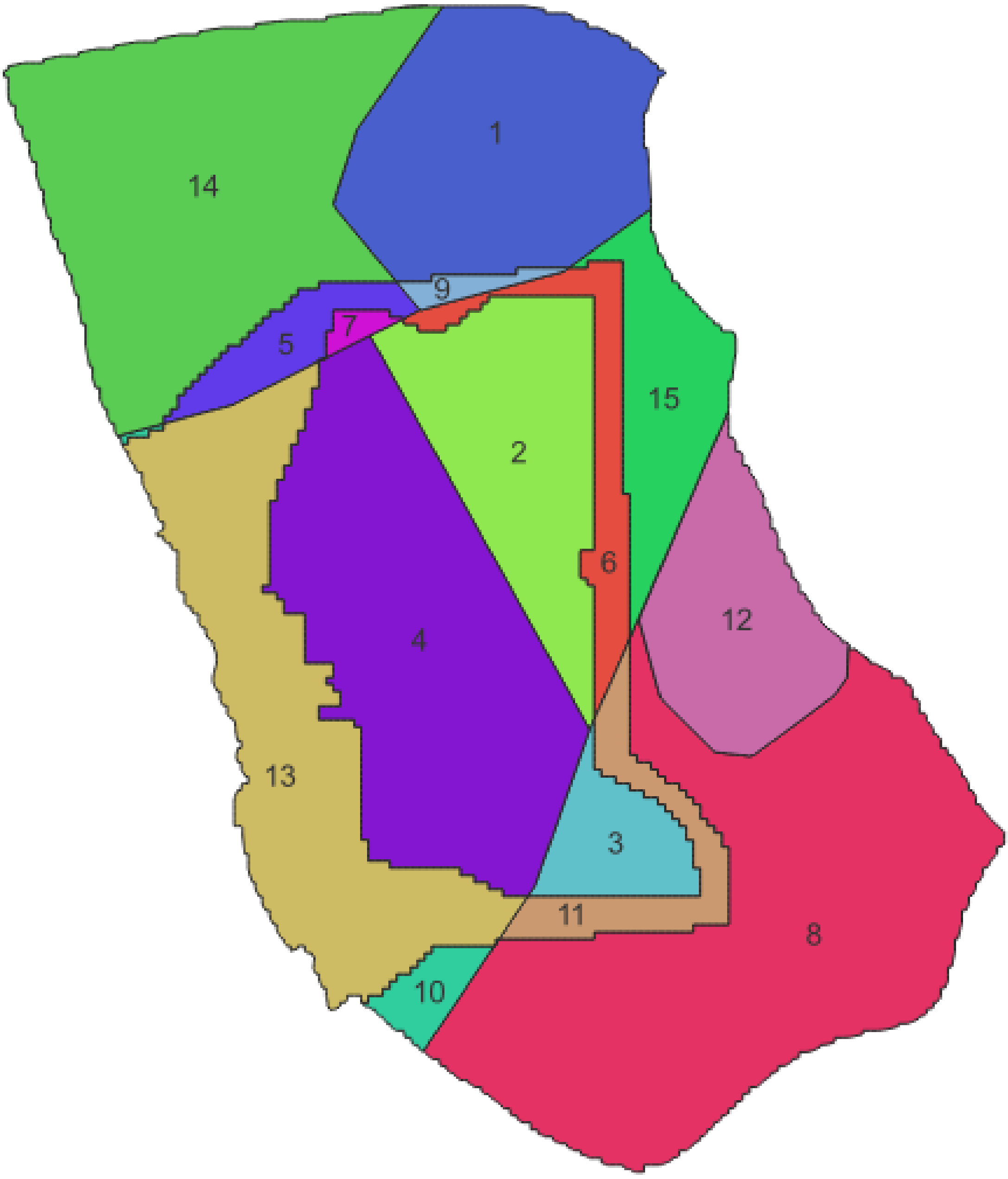


Figure 47: Model leakage zones

5.6.5. Lakes

- The MODFLOW LAK3 package was used to simulate Lake Mariginiup, Lake Jandabup and Lake Gnangara as surface water bodies in layer 1 of the groundwater model.
- The lakes were assigned to be within layer 1 because the lake bathymetry was included in the base of the layer 1 surface.
- The lake properties, initial conditions and upper and lower bound stage elevations are presented in Table 18.
- Average daily rainfall time series (based on monthly rainfalls calculated from SILO daily data) were entered as the precipitation rate in the lake package.
- Average daily evaporation rates (based on monthly Morton Lake evaporation rates calculated from the SILO daily data) were entered as the evaporation rate in the lake package.
- No runoff into the lakes was allowed for in the model.

- No withdrawals occurred from any of the lakes, except Lake Jandabup which had a negative withdrawal included to simulate lake supplementation. The supplementation rate was an average daily rate based on the time series data outlined in Section 3.3.4.

Table 18: Lake parameters

Lake name	Lake number	Initial stage (m AHD)	Minimum stage (m AHD)	Maximum stage (m AHD)	Sediment bed hydraulic conductivity (m/d)	Sediment bed thickness (m)
Lake Mariginiup	1	41.175	40.3	42.6	0.1	1
Lake Jandabup	2	44.54	43.8	46.2	0.1	1
Lake Gnangara	3	41.757	41.05	43	0.1	1

5.7. Initial values

5.7.1. Aquifer parameters

- Initial aquifer parameters are presented in Table 16.

5.7.2. Lake parameters

- Initial lake water levels are presented in Table 18.

5.7.3. Water levels

- Initial pre-spinup water levels for the model are based on the 2010 maximum groundwater level surface (which is an interpolated surface derived from shallow screened bore data across the model domain. Shallow screened bores were assumed to be those that had the top of screen <15 m below the average annual water level).
- The grid centroids were intersected with the initial water table surface and imported into the groundwater model to provide the pre-spinup initial head values for all model layers.
- The actual initial head distribution post-spinup will vary depending on the input parameters, but the difference from the pre-spinup initial head distribution is being minimised by only spinning up the model for a 12-month period.

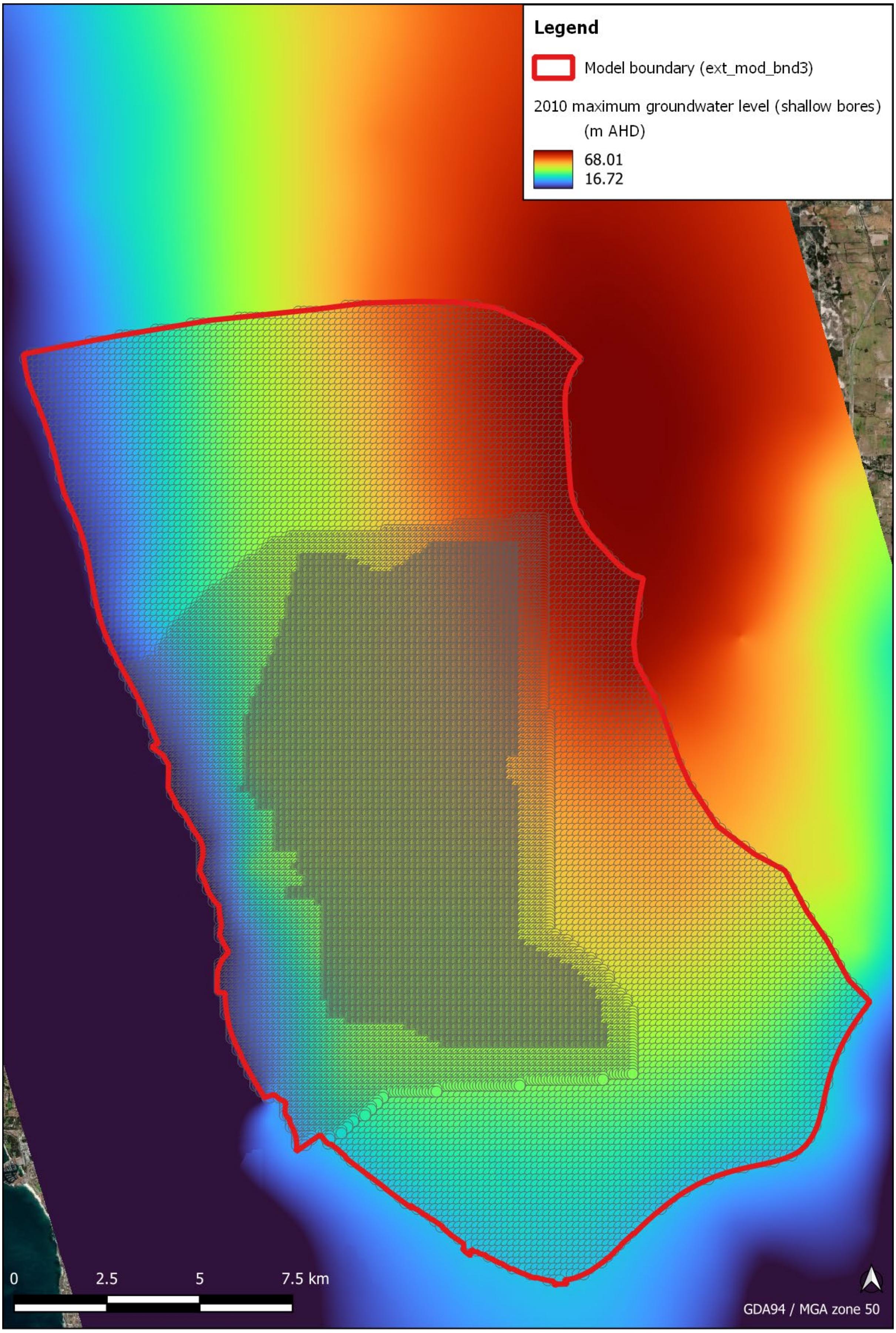


Figure 48: 2010 maximum groundwater surface used for initial head conditions

6. Model calibration

6.1. Calibration methodology

The PEST software suite was used for inverse calibration of the EWGM. Inverse calibration resulted in parameter estimates across a pilot point grid for:

- horizontal hydraulic conductivity (K_h)
- vertical hydraulic conductivity (K_v)
- specific yield (S_y).

BEOPEST with singular value decomposition (SVD) was used for the inverse calibration simulations to reduce the computer runtimes.

By using pilot points, aquifer parameters were estimated at each pilot point location. Horizontally distributed hydraulic conductivity and specific yield property fields (matrices) were determined through interpolation of the pilot point values across the model domain. Parameters were assumed to be constant over the full depth of the Superficial Aquifer (i.e., over the 5 model layers).

The pilot points were located across the model domain at a 2000 m x 2000 m grid spacing, resulting in 88 pilot points for each of K_h, K_v and S_y, as shown in Figure 49. Initial pilot point values were based on two zones representing the Bassendean Sand formation and the Spearwood Sand formation. The initial parameter zones are shown in Figure 49, and the initial pilot point values for each zone are presented in Table 19.

Table 19: Parameters estimated during automatic model calibration using PEST

Soil zone	Parameter	Initial parameter value	Minimum parameter value	Maximum parameter value
Bassendean Sand	K_h	20	0.1	50
	K_v	2	0.01	5
	S_y	0.25	0.1	0.3
Spearwood Sand	K_h	10	0.1	50
	K_v	1	0.01	5
	S_y	0.2	0.1	0.3

Two zones were used to estimate initial pilot point values, however a single zone across the model domain was assumed for the inverse calibration simulation. This approach was taken to reduce imposed constraints on the property fields and prevent jumps in parameter values across zone boundaries. The upper and lower bound values applied to the pilot points across the model domain are given in Table 19.

Several parameters were estimated independently through data collation and analysis and were not included as parameters for estimation through inverse calibration. These estimated parameters include:

- Lakebed hydraulic conductivity which was estimated based on available data and inspected during inverse calibration runs to ensure lake water levels were adequately simulated.
- Recharge and PET which were estimated using the recharge function outlined in Section 3.3.7
- Abstraction and leakage from the Superficial Aquifer to the Leederville Aquifer which were estimated from data collation and analysis, as outlined in Section 3.3.2 and Section 3.3.6, respectively.

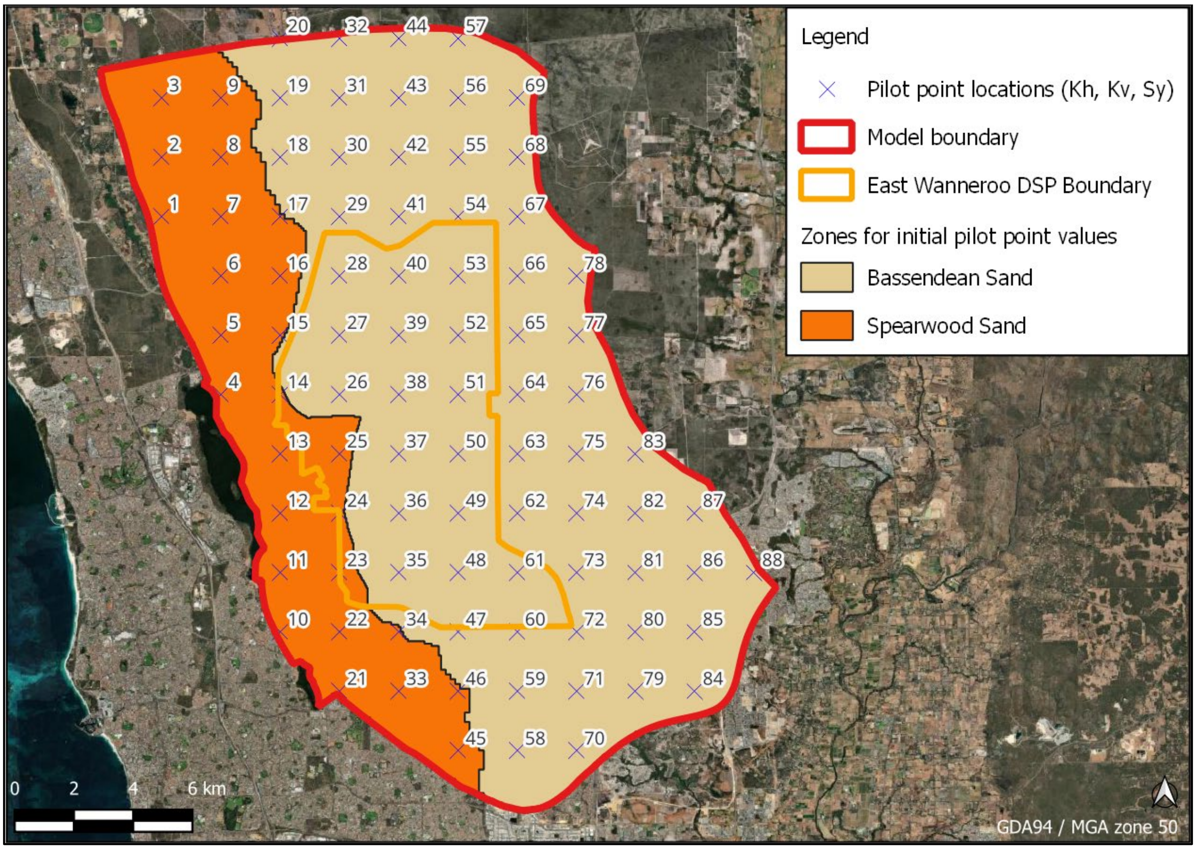


Figure 49: Pilot point locations and aquifer parameter zones for the initial pilot point parameters

6.2. Observation data

To estimate the extent of subsoil drainage, drainage inflows and lake water levels, it was necessary to calibrate the groundwater flow model to absolute water levels rather than to water level changes. Observed water levels across the model domain therefore formed the target dataset for model calibration.

Observation data in the form of bore and lake water levels were extracted from data supplied by DWER and from the Water Information Reporting database for the model calibration period (between September 2010 and August 2021). A map of the target locations, including the observation count for each location, and the model layer that the target was applied to, is shown in Figure 50. The targets were not weighted during model calibration.

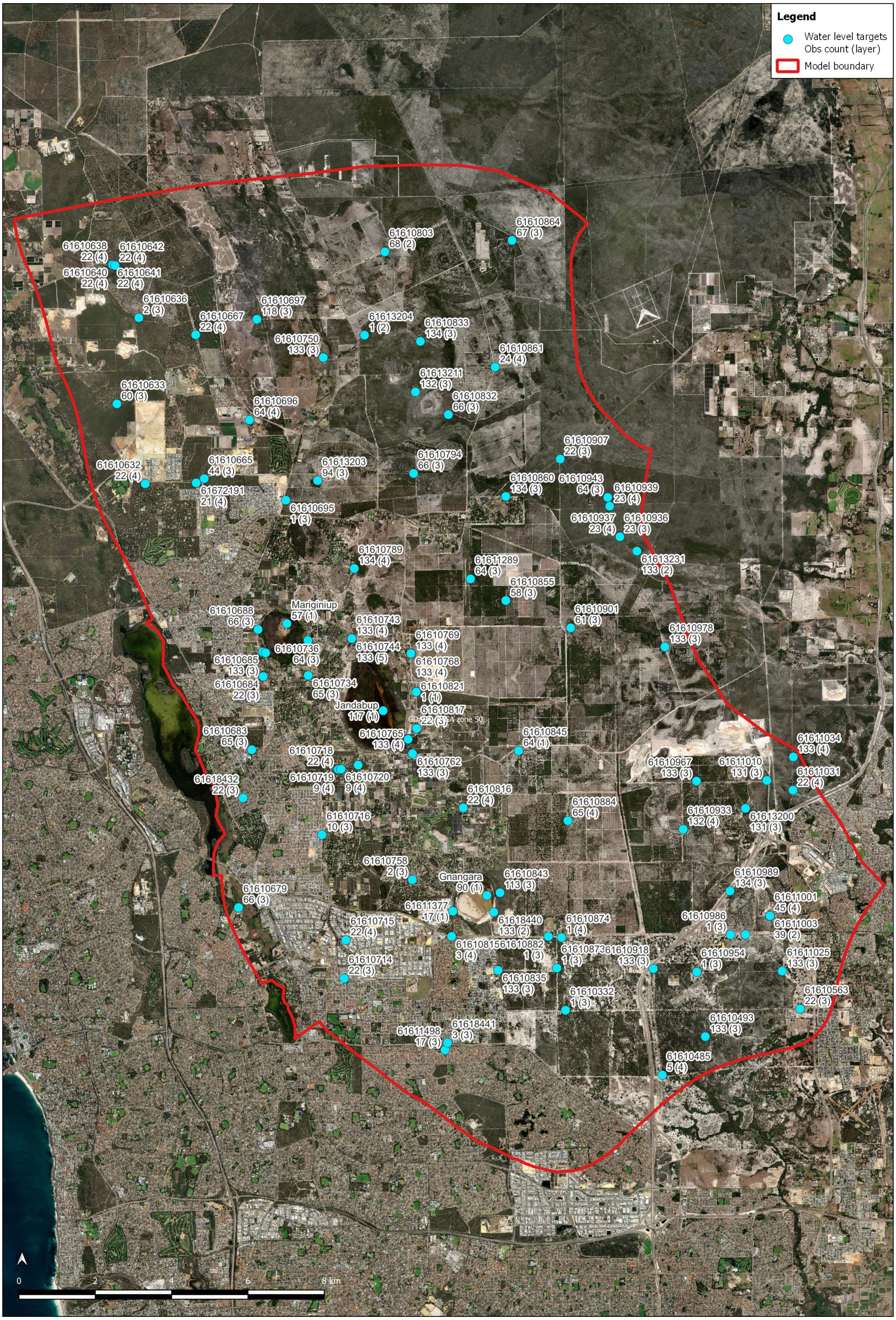


Figure 50: Water level target locations, number of observations at each target (2nd line of label) and the target model layer (in brackets)

6.3. Calibrated parameter values

The parameter values estimated for each pilot point through inverse calibration are presented in Appendix A. The parameter fields obtained through interpolation of the pilot point parameter values are shown in Figure 51, Figure 52 and Figure 53 for horizontal hydraulic conductivity, vertical hydraulic conductivity and specific yield, respectively.

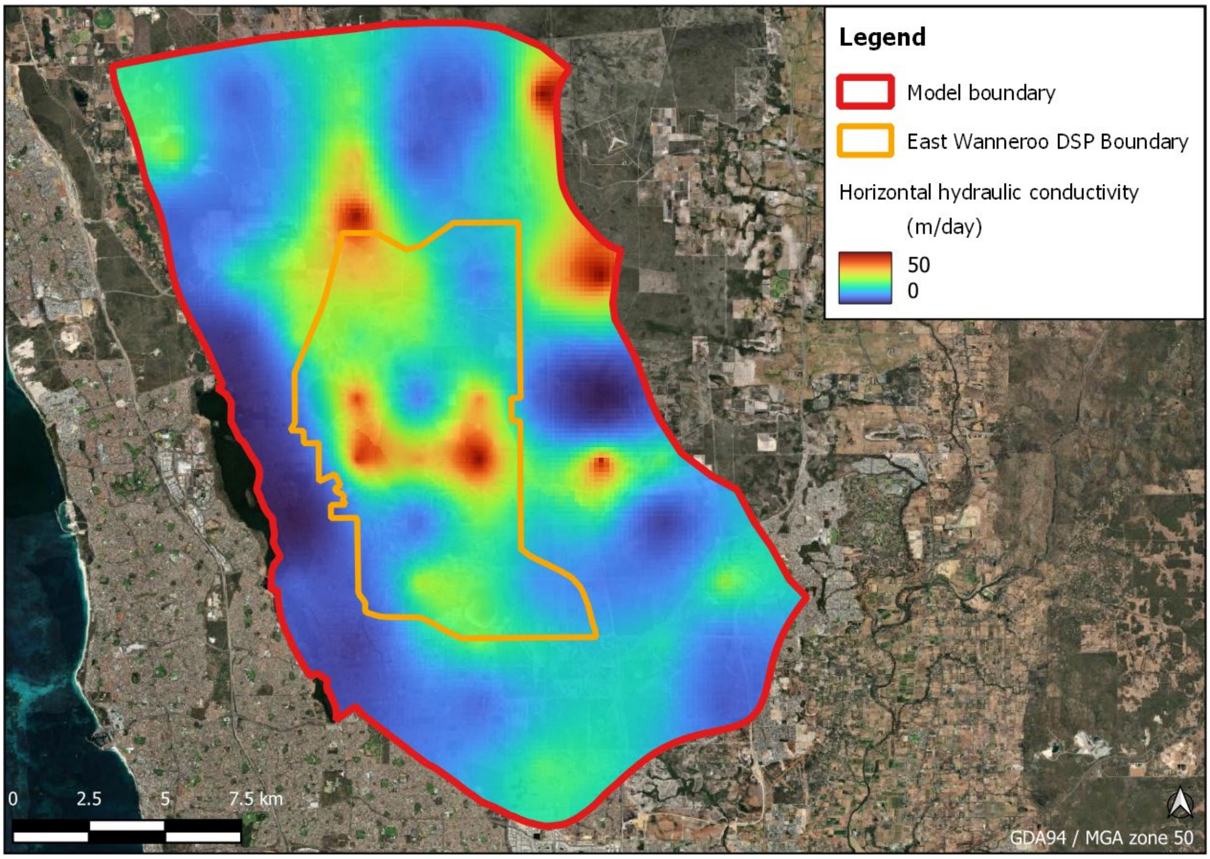


Figure 51: Calibrated horizontal hydraulic conductivity distribution

Most of the pilot points (77 out of 88) had calibrated horizontal hydraulic conductivity values between 1 m/day and 35 m/day which is expected for the Spearwood Sands and Bassendean Sands that extend across the model domain. Only four pilot points hit the upper bound of 50 m/day, indicating an adequate parameterisation of horizontal hydraulic conductivity.

Model calibration shows there is an area of low horizontal hydraulic conductivity immediately east of Lake Joondalup (Figure 51) on the western boundary, consistent with the zone recognised to have a steep hydraulic gradient (sometimes referred to as the "groundwater waterfall"). Through the central parts of the model domain the horizontal hydraulic conductivity is higher and generally consistent with the range of parameter values expected for Bassendean Sand (10 to 50 m/day). Towards the north-eastern corner of the model domain the hydraulic conductivity appears to be high, which is expected near the top of the Gnangara Mound where infiltration rates are high, however this area is near the model boundary so may be impacted by boundary effects. On the eastern side of the model, there appear to be some areas of lower hydraulic conductivity which may be due to some interfingering of the Guildford Formation with the Bassendean Sand Formation.

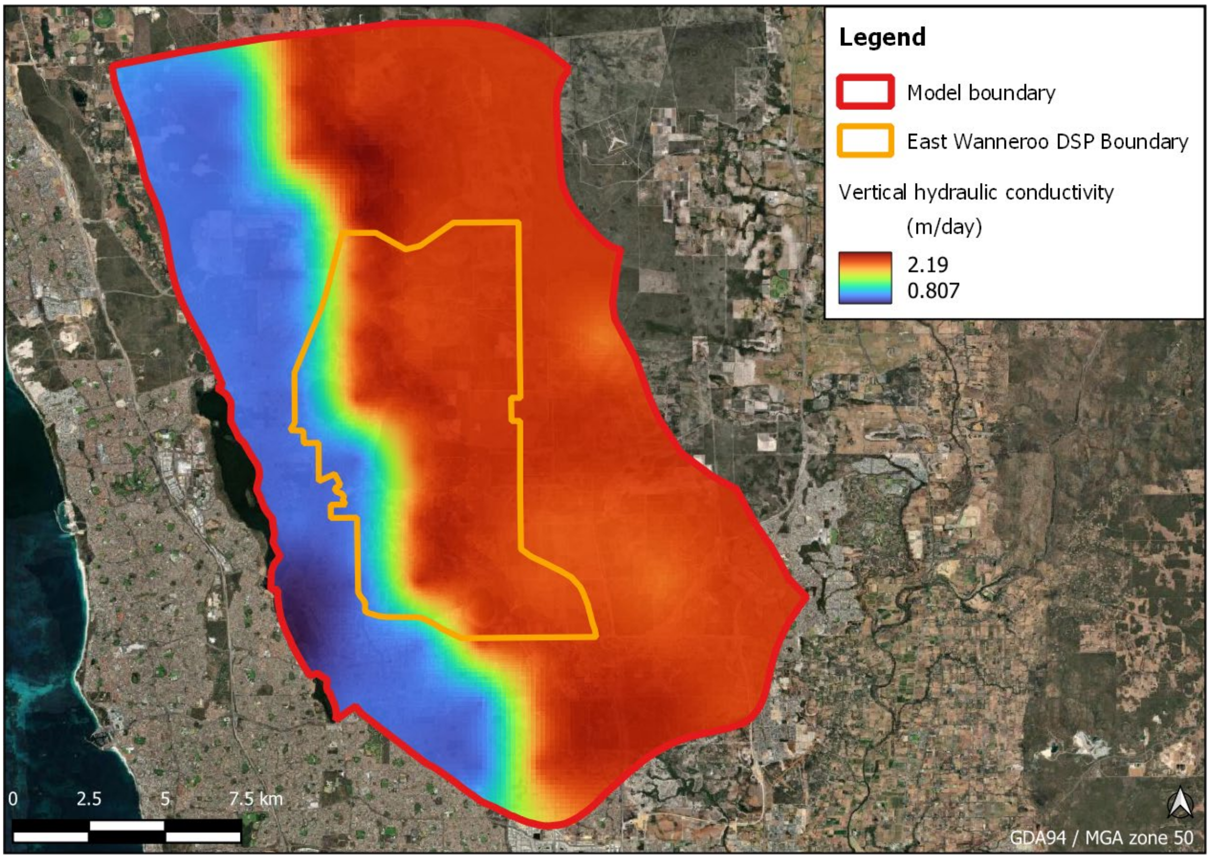


Figure 52: Calibrated vertical hydraulic conductivity distribution

All of the vertical hydraulic conductivity pilot point values ranged between 0.8 m/day and 2.2 m/day, with an average horizontal to vertical conductivity ratio for all of the pilot points of 10.1, which is consistent with the accepted ratio of 10 (referred to in Section 3.4.1). There appears to be a higher vertical conductivity to the east of the model domain associated with the Bassendean Sand Formation and a lower vertical conductivity to the west, however the clear separation between the two formations is predominantly a modelling artefact arising from the initial conditions applied to the model calibration.

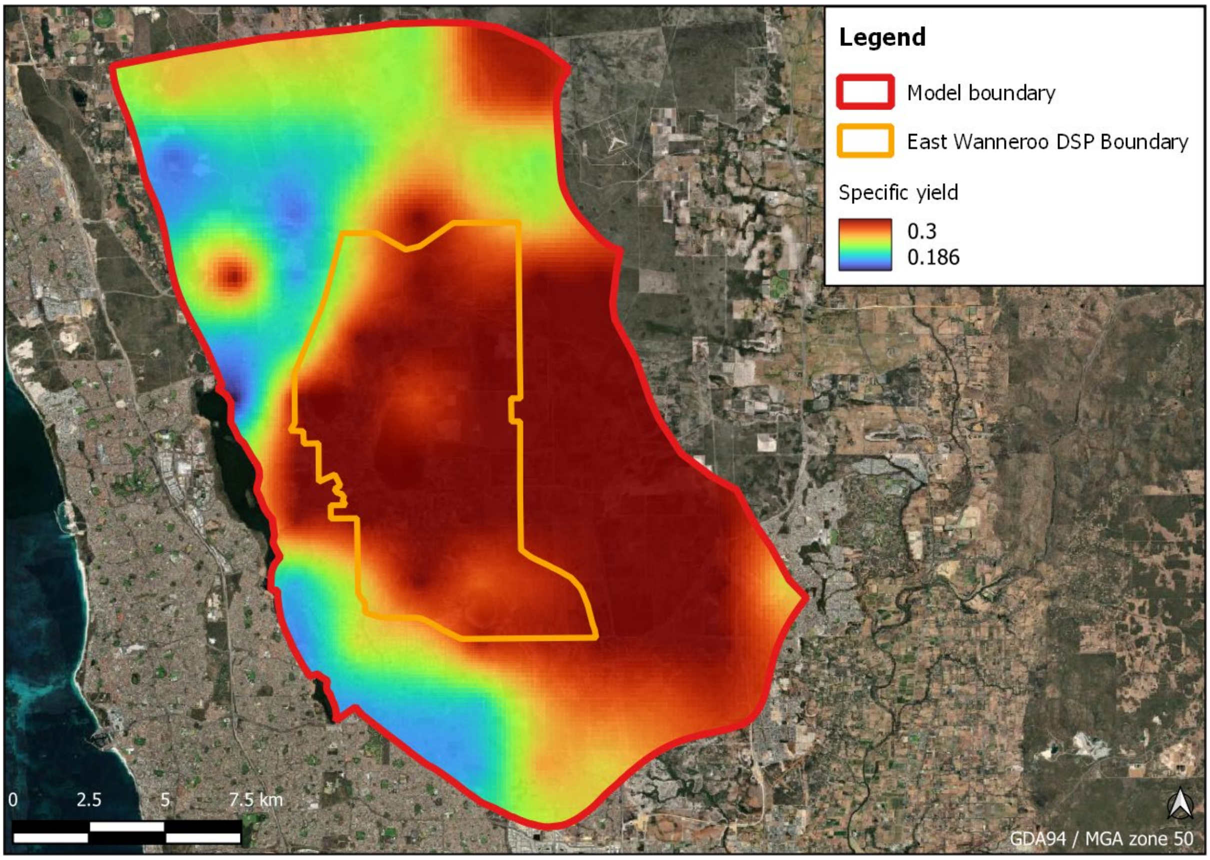


Figure 53: Calibrated specific yield distribution

Almost 40% (34 out of 88) of the specific yield pilot points hit the upper bound of 0.3. This is not ideal, but there is limited information on the specific yield of the Bassendean Sands and Spearwood Sands so it is not clear if 0.3 is the upper bound. Further investigations of specific yield are likely required in this area, but the values obtained from model calibration are considered appropriate.

The specific yield distribution (Figure 53) appears to be relatively high across much of the Bassendean Sand Formation, with areas of lower specific yield through parts of the Spearwood Sand Formation and on the western side of the model domain.

6.4. Calibration hydrographs

Calibration hydrographs, including measured and simulated time series for all target observation bores are provided in Appendix C. Calibration hydrographs for select bores within the EWDSP area are shown in Figure 54 and Figure 55. Calibration hydrographs for select bores within the model domain but outside of the EWDSP area are shown Figure 56. Where there are nested bores or deeper bores nearby, the shallowest bores with water level data are shown in these figures.

The calibration hydrographs generally show good agreement between measured and simulated groundwater levels across the EWDSP area, however the simulated water level is slightly lower than measured across much of the EWDSP area.

There are some issues with the calibration on the western side of the model domain, particularly in the area recognised as having a steep hydraulic gradient. On the western side of Mariginiup Lake out to Joondalup Lake, the simulated water levels rise at a faster rate than for the measured water levels, which may indicate higher than actual recharge rates are being simulated over the existing urban area west of Mariginiup Lake.

The calibration hydrographs show that both the seasonal and annual trends are generally well matched across much of the model domain both temporally and in the magnitude of the water level fluctuations.

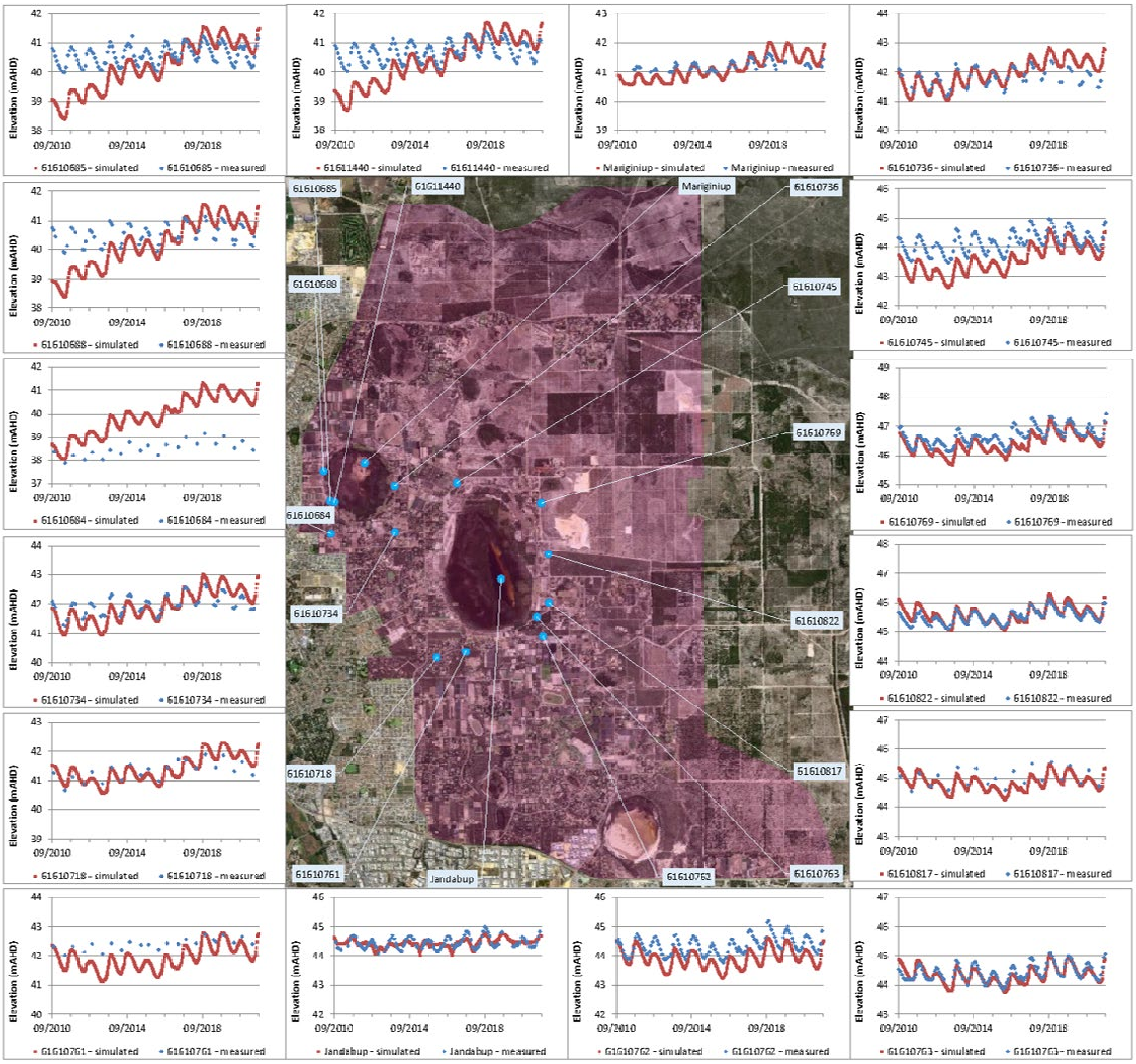


Figure 54: Calibration hydrographs for select target observation bores around Lake Mariginiup and Lake Jandabup

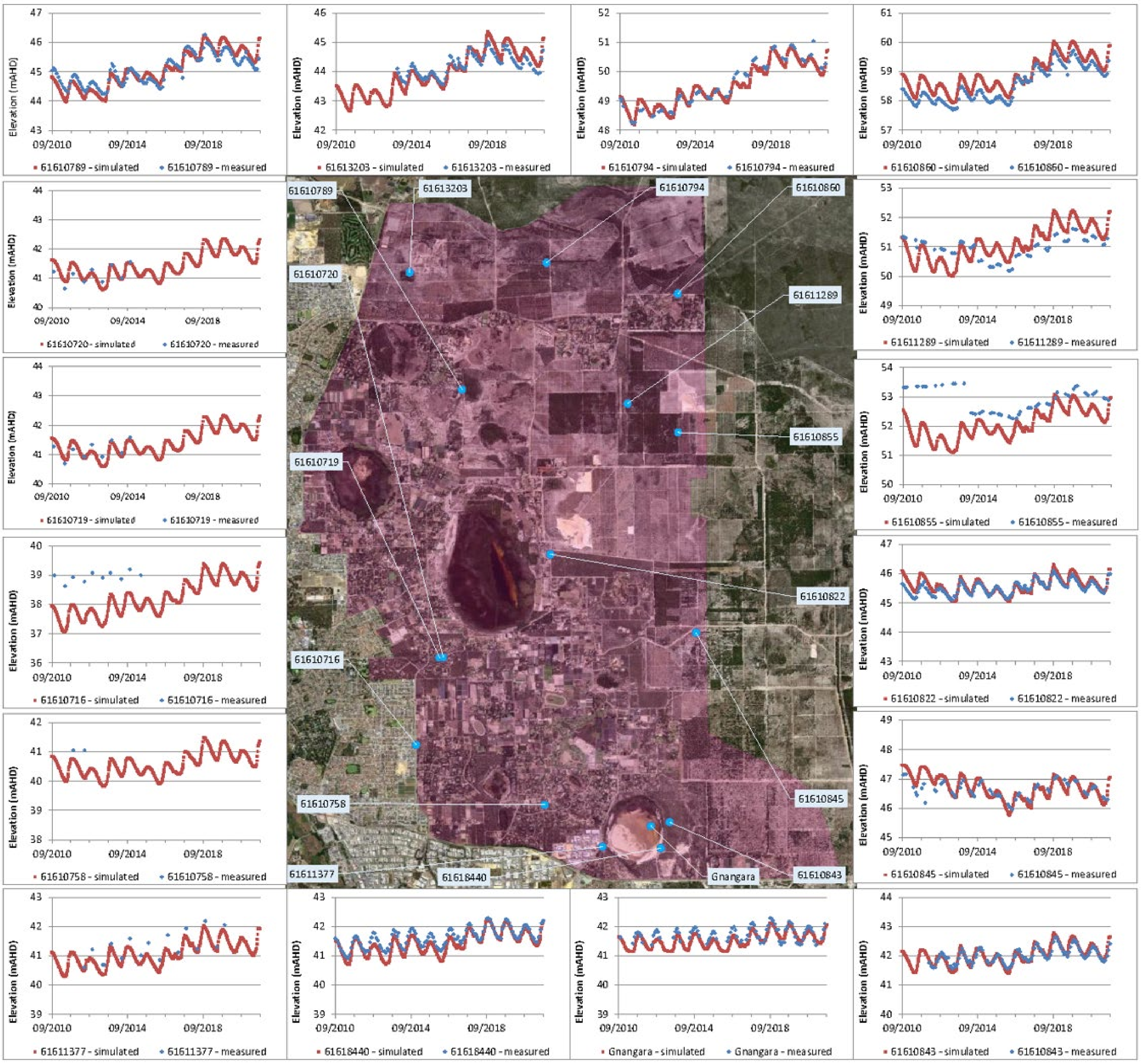


Figure 55: Calibration hydrographs for select target observation bores within the East Wanneroo DSP area and around Lake Gnangara

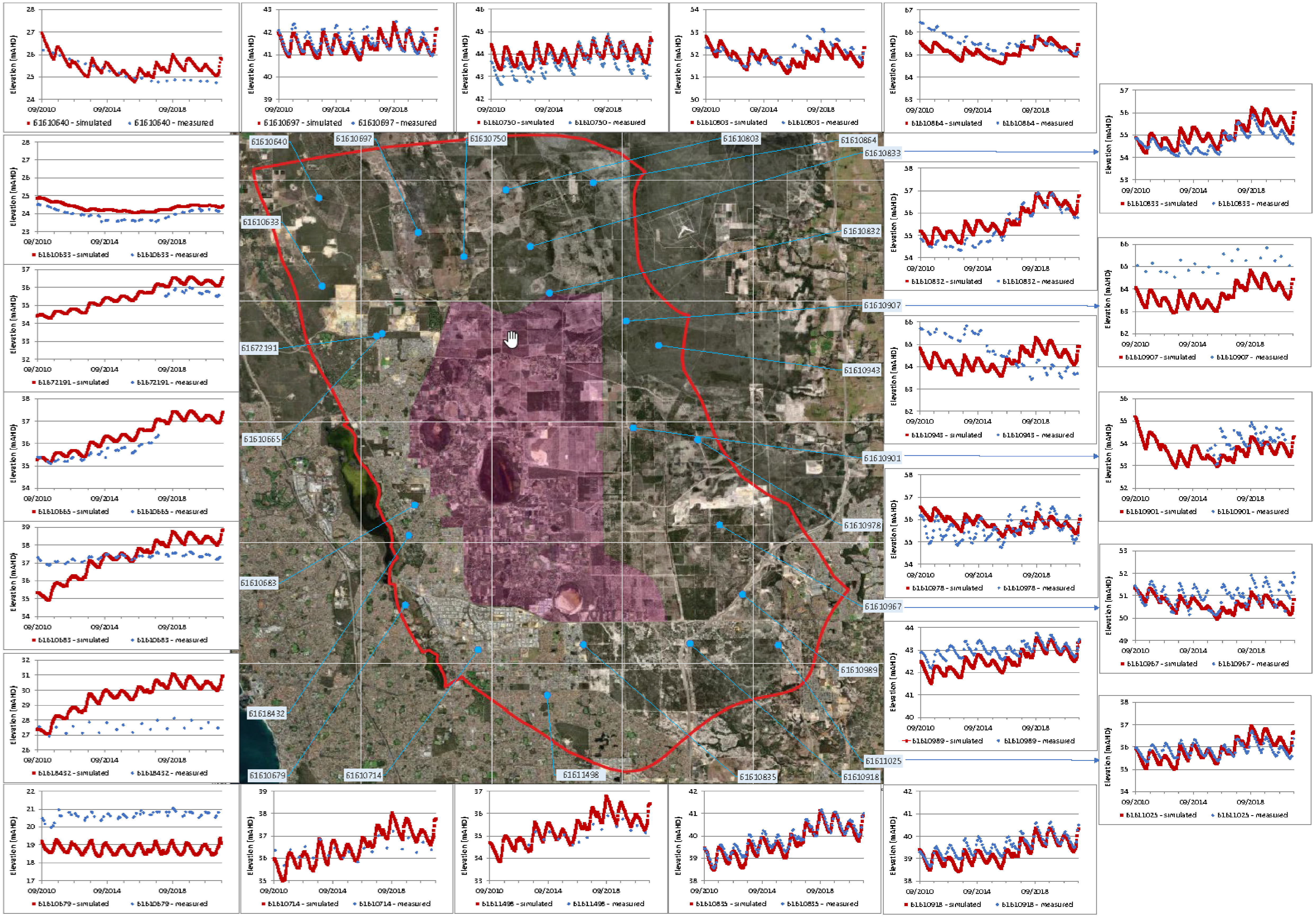


Figure 56: Calibration hydrographs for select target observation bores within the model domain but outside of the East Wanneroo DSP area

6.5. Calibration statistics and residuals

A summary of the model calibration statistics is presented in Table 20 for the model domain and for the EWDSP area as a subarea of the model domain.

The calibration statistics indicate the following:

- The scaled mean absolute residual is 0.91% across the model domain and 1.44% across the EWDSP area, which is within the error margin of 5% agreed upon in the proposed methodology for the groundwater modelling exercise (RPS, 2022).
- The low residual mean of 0.055 across the EWDSP area and 0.096 across the model domain suggests that there is minimal bias in the model results.
- The positive absolute residual means of 0.32 and 0.42 across the EWDSP area and model domain, respectively, indicate that simulated heads are on average slightly lower than measured groundwater levels, which needs to be a consideration when undertaking and interpreting the future scenario simulations. This is consistent with the information presented in the calibration hydrographs for the target bores (Figure 54 and Figure 55), which show simulate water levels are slightly lower than measured across much of the model domain.
- The scaled root mean square error of 1.35% across the model domain and 1.98% across the EWDSP area are very low and attempts to reduce this error any further is likely to result in overfitting.
- Detailed time series statistics for each target, including average, median, minimum, maximum and the range of groundwater head values for both the measured and simulated time series, are presented in Appendix B.

Table 20: Model calibration statistics

Statistic	Value
Model domain statistics	
Number of observations	6733
Range in observations	46.451
Max +ve Residual	2.340
Max -ve Residual	-3.132
Residual Mean	0.096
Absolute Residual Mean	0.423
Scaled Mean Absolute Residual	0.91%
Root Mean Square Error (RMSE)	0.625
Scaled RMS Error	1.35%
Statistics across East Wanneroo DSP area	
Number of observations	3383
Range in observations	21.854
Max +ve Residual	2.340
Max -ve Residual	-2.107
Residual Mean	0.055
Absolute Residual Mean	0.315
Scaled Mean Absolute Residual	1.44%
Root Mean Square Error (RMSE)	0.433
Scaled RMS Error	1.98%

6.6. Calibration water balance

The average annual model water balance over the calibration period is presented in Table 21. The water balance shows that more water goes into storage across the model domain than is removed from storage, with a change in storage of 6.2 GL/yr which corresponds to an annual rise in groundwater level of about 90 mm/yr (for an assumed specific yield of 0.2) over the calibration period. This is consistent with much of the measured data across the model domain showing increasing groundwater levels.

Table 21: Average annual model water balance during model calibration

Parameter	Annual Average Inflow/Outflow (GL/yr)	Annual Inflow/Outflow normalised to the model domain area (mm/yr)	Annual inflow/outflow as a % of total rainfall across the model domain
	INFLOWS		
Storage (volume released from storage)	70.10	199	28.3%
Constant head	0.36	1	0.1%
Wells	0.00	0	0.0%
Drains	0.00	0	0.0%
ET	0.00	0	0.0%
Head dependent boundaries	9.63	27	3.9%
Recharge	96.71	275	39.1%
Lake seepage	1.40	4	0.6%
TOTAL INFLOWS	**178.2**	**506**	**72%**
TOTAL INFLOWS (excluding storage)	**108.1**	**307**	**44%**
	OUTFLOWS		
Storage (volume going into storage	76.30	217	30.9%
Constant head	5.16	15	2.1%
Wells	49.16	140	19.9%
Drains	4.26	12	1.7%
ET	4.63	13	1.9%
Head dependent boundaries	21.92	62	8.9%
Recharge	15.67	45	6.3%
Lake seepage	1.11	3	0.4%
TOTAL OUTFLOWS	**178.2**	**506**	**72%**
TOTAL OUTFLOWS (excluding storage)	**101.9**	**289**	**41%**
Change in storage	**6.2**	**18**	**3%**

The net recharge rate across the model domain is 32.8%. However, it is more informative to consider the recharge rates for each land use rather than for the entire model domain. It is difficult to calculate average annual recharge rates from the model when there are areas with changing land use, therefore the recharge rates applied to the model for each land use type are presented in Table 22.

Table 22: Recharge rates for each land use type

Recharge zone code	Land use	Depth to groundwater	Annual recharge rate (mm/yr)	Annual recharge rate as a % of ave annual rainfall over the calibration period	Type of recharge
RZ1	Pasture / cleared pine / under construction (i.e., areas where there are several or large cleared areas not yet developed	-	287	40.2%	Gross rate as EVT package applied
RZ2	Banksia - low density/ rural residential blocks	<9 m	133	18.5%	Quasi net recharge[1]
RZ3	Banksia - low density/ rural residential blocks	>9 m	119	16.6%	Quasi net recharge[1]
RZ4	Banksia medium density	>9 m	0	0%	Net
RZ5	Pine - low density	<18 m	215	30.1%	Quasi net recharge[1]
RZ6	Pine – med/high density	<18 m	-2	-0.2%	Quasi net recharge[1]
RZ7	Urban	-	461	64.5%	Net
RZ8	Commercial/Industrial	-	485	67.9%	Net
RZ9	Lakes		714.7	100%	Gross

[1] Quasi net recharge to account for rooting depth, but the EVT package is applied with excess PET (to prevent double accounting of PET), in the event groundwater rises to within 1.5m of the ground surface.

6.7. Calibration summary

The East Wanneroo groundwater model is well calibrated and suitable to use for future scenario simulations. In summary:

- Calibrated pilot point parameters are generally within the expected range of parameter values or considered acceptable.
- Seasonal and annual measured and simulated hydrographs are well matched, with different trends matched in different parts of the model domain.
- The calibration statistics indicate a good calibration has been achieved and any further improvement in calibration statistics is likely to result in overfitting of the parameters.
- The calibration water balance generally matches the conceptual water balance model data provided in Section 4.2.

7. Future scenario modelling

As groundwater level management is critical for the sustainable development of the EWDSP area, future scenario modelling was carried out to inform the conceptual design of the groundwater management system. The future scenario models were selected to indicate:

- The groundwater rise that could occur post-development.
- The required extent of subsoil drainage infrastructure.
- The areas unlikely to be impacted by rising groundwater.
- Indicative subsoil drainage flow rates and annual subsoil drainage volumes to inform the concept design of the groundwater management scheme.
- Indicative post-development lake levels, to further understand potential infrastructure requirements of the water management scheme.

It should be noted that the future scenarios are not predictive.

7.1. Future scenario input variables

Several variables become a consideration when looking at potential future scenarios, including:

- Future climate
- Changes in land use
- Changes in public and private abstraction
- Lake augmentation
- Staging of the land use changes
- The extent and elevation of subsoil drainage
- The return of any subsoil drainage water at surface water bodies
- Leakage from the Superficial Aquifer into the underlying Leederville Aquifer.

Furthermore, there is significant inherent uncertainty with each of these variables, including the following:

- There is a recognised drying climate in the south-west of Western Australia, which is captured in the proposed future climate scenarios, however there is significant variability between the average annual rainfall and the magnitude of peak rainfall and peak drying periods between the different scenarios which will significantly impact the modelling results.
- The DSP indicates potential land use changes, but the timing of the land use change is highly uncertain and depends on several factors including the transient demand for housing, the willingness of landholders to sell to developers and planning direction from government organizations.
- Significant Water Corporation abstraction currently occurs in the vicinity of the DSP area, however the future abstraction rates from these bores is uncertain and could change depending on several factors such as the age and performance of the bores, the climate, water demand and the impacts of abstraction on the surrounding area.
- The return subsoil drainage volume depends on the future climate being simulated. Furthermore, the volume that can be returned to one of the major surface water bodies at a time depends on the water level and available storage volume at that time. We note that this is a coupled surface water-groundwater interaction which cannot be well simulated in a groundwater model requiring simplifying assumptions to be made.

7.2. Future scenario simulations

There are numerous potential permutations of the future scenario variables, however it is impractical to simulate all possible permutations. A selection of scenarios has been identified to inform the concept design of the groundwater management scheme by providing an indicative range of subsoil drainage flow rates, annual subsoil drainage volumes, and lake and groundwater levels.

The following climate and development scenarios were assessed:

- Four different climate scenarios, referred to as Wet 1, Wet 2, Dry 1 and Int 1 scenarios, as described in Section 3.6.1.

- Four development options, including 'no development', 'full-build out', 'staged development' and 'short term staged development to the end of 2039'.

Details of the data used in the future scenario models, including the climate scenario data, future land use changes which that determine future recharge and PET, and simulated future abstraction and leakage rates are presented in Section 3.6.

For all future scenario models:

- The calibrated model was extended from August 2021 to the end of 2022 using measured data where possible or assumed data based on an average of the last 3 years of model calibration data.
- All future data was applied from January 2023 onwards.
- For the no development and full-buildout scenarios, the dates presented in the results correspond to the date of the applied climate scenario and are not associated with any staging.
- Lake augmentation was not included in the future scenario models from January 2023 onwards, as it was not possible to only include lake augmentation when required.

7.2.1. Model design overview for selected development options

The models were carried out in sets based on each development option, with up to four climate scenarios assessed in each set depending on the required model outcomes.

The four different development options were designed, and setup as follows:

- 'No development' simulations:
  - Designed to simulate the conditions that would occur in the future (after the 2028 abstraction reductions) if there is no development in the East Wanneroo DSP area.
  - Designed to be a baseline for comparison with the development scenarios, so that the impacts of development can be assessed.
  - For the 'no development' scenarios:
  - Future recharge and PET rates for the climate scenario being simulated were applied to the model from January 2023 to December 2099 based on land uses at the end of the calibration period.
  - Future abstraction rates were applied in the model from 2023 onwards, including the assumed reductions described in Section 3.6.6.
  - Leakage and fixed/general head boundary conditions were applied until December 2099 based on average monthly values over the last 3 years of model calibration.
  - Future lake data were applied through until December 2099 based on the future climate scenario being simulated.
- 'Full buildout' simulations:
  - Designed to simulate expected conditions at the end of the development period (2072) when there is full buildout of the East Wanneroo DSP area, over a range of different climate scenarios.
  - For the 'full buildout' scenarios:
  - Future recharge and PET rates for the climate scenario being simulated were applied to the model from January 2023 to December 2099, based on assumed final land uses at the end of development (2072) over the East Wanneroo DSP area.
  - Future abstraction rates at the end of development were applied from 2023 onwards. The rates were adjusted as discussed in Section 3.6.6.
  - Leakage and fixed head/general head boundary conditions were extended until December 2099 based on average monthly values over the last 3 years of model calibration.
  - Subsoil drainage was applied where required across the DSP area, except when assessing the spatial extent of subsoil drainage.
  - Future lake data were applied through until December 2099 based on the future climate scenario being simulated.
- 'Staged' simulations:
  - Designed to simulate development staging through to full buildout (shown in Figure 33) across the East Wanneroo DSP area, over the selected range of different climate scenarios. The data was staged based on 5 year period.
  - For the 'staged' scenarios:

    - Staged future climate scenario data (recharge and PET) were applied from January 2023 to December 2079 based on the staged development land use changes described in Section 3.6.2.
    - Future abstraction rates were applied from 2023 onwards, accounting for changes in Water Corporation abstraction, licensed and unlicensed abstraction as discussed in Section 3.6.6.
    - Leakage and fixed head/general head boundary conditions were extended until December 2099 based on average monthly values over the last 3 years of model calibration.
    - Subsoil drainage was staged in the model where required within the DSP area.
    - Future lake data were applied through until December 2099 based on the future climate scenario being simulated.

- ‘Staged to 2040 simulations:
  - Designed to simulate development staging until the end of 2039 with no subsoil drainage, with the model run until the end of 2099 to assess the impact of different climates on the partial development area.
  - This development option was designed to assess the impacts of initial development in areas where subsoil drainage infrastructure is not required.
  - For the ‘staged to 2040’ scenarios:
    - Staged future climate scenario data (recharge and PET) were applied from January 2023 to December 2039 based on the staged development land use changes described in Section 3.6.2. The land use recharge and PET were then applied based on the 2039 land use for the remainder of the model simulation period.
    - Future abstraction rates were applied from 2023 to 2039, accounting for changes in Water Corporation abstraction, licensed and unlicensed abstraction as discussed in Section 3.6.6. The 2039 abstraction rates were then continued until December 2099.
    - Leakage, fixed head and general head boundary conditions were extended until December 2099 based on average monthly values over the last 3 years of model calibration.
    - Subsoil drainage was not included in the model.
    - Future lake data were applied through until December 2099 based on the future climate scenario being simulated.

A summary of the future scenario simulations is presented in Table 23.

Table 23: Summary of future scenario simulations carried out to inform the concept design of the groundwater management scheme

Sim ID	Land use staging	Future climate	Subsoil drainage	Abstraction	Leakage	Purpose of simulation	Model File Name
a	No development	Wet_1	None	Future Water Corporation, licensed and unlicensed abstraction, as described in Section 3.6	Assumed to be the average of the last 3 years of the model calibration period (an average of ~14.5 GL/yr)	To provide a baseline of information to use for comparison with the development scenarios	a_EW_ND_W1.gwv
b		Wet_2					b_EW_ND_W2.gwv
c		Dry_1					c_EW_ND_D1.gwv
d		Int_1					d_EW_ND_I1.gwv
1	Full buildout	Wet_1	None	Future Water Corporation, licensed and unlicensed abstraction, as described in Section 3.6		To indicate the required maximum extent of subsoil drainage, based on areas that could be impacted by post-development groundwater rise (i.e, areas where the depth to maximum post-development groundwater level is less than 2 m when no subsoil drainage is installed)	1_EW_FB_W1.gwv
2		Wet_2					2_EW_FB_W2.gwv
3	Full buildout	Wet_1	Maximum practicable subsoil depth of 2.5 m			To determine the upper and lower bound subsoil drainage flow rates and annual subsoil drainage volumes for a conservative maximum practicable subsoil drain installation depth (2.5 mbgl)	3_EW_FB_W1_SS.gwv
4		Wet_2					4_EW_FB_W2_SS.gwv
5		Dry_1					5_EW_FB_D1_SS.gwv
6		Int_1					6_EW_FB_I1_SS.gwv
7	Full buildout	Wet_1	Maximum practicable subsoil depth of 2.0 m, no drainage of Lake Mariginiup and Lake Jandabup			To assess the sensitivity of the subsoil drainage flow rates and annual subsoil drainage volume to a less conservative maximum practicable subsoil drain installation depth (2.0 mbgl)	7_EW_FB_W1_SS_DR2.gwv
8		Wet_2					8_EW_FB_W2_SS_DR2.gwv
9		Dry_1					9_EW_FB_D1_SS_DR2.gwv
10		Int_1					10_EW_FB_I1_SS_DR2.gwv
11	Staging of entire DSP area, as described in Section 3.6.2	Wet_1	Maximum practicable subsoil depth of 2.0 m, no drainage of Lake Mariginiup and Lake Jandabup			To assess the impact of staging on annual subsoil drainage volumes and lake water levels	11_EW_ST_W1_SS.gwv
12		Wet_2					12_EW_ST_W2_SS.gwv
13		Dry_1					13_EW_ST_D1_SS.gwv
14		Int_1					14_EW_ST_I1_SS.gwv
15	Staged development to 2040	Wet_1	No subsoil drainage simulated across DSP area			To assess the impact of development on groundwater levels in areas expected to be developed over the next 15 to 20 years.	15_EW_ST2_W1_noSS.gwv
16		Wet_2					16_EW_ST2_W2_noSS.gwv
17		Int_1					17_EW_ST2_I1_noSS.gwv
S1	Full buildout	Wet_1	As for Scenario 7	As for Scenario 7	No leakage	To assess the impact of no leakage from the Superficial Aquifer	S1_FB_W1_SS_DR2_nolk.gwv
S2	Full buildout	Wet_1		No Water Corporation abstraction	As for Scenario 7	To assess the impact of no Water Corporation abstraction	S2_FB_W1_SS_DR2_noWC.gwv
S3	Full buildout	Wet_1		As for Scenario 7	As for Scenario 7	To assess the sensitivity of the model to an increased boundary condition head elevation	S3_FB_W1_SS_DR2_inc_BC.gwv
18	Full buildout	Wet_1	As for Scenario 7, with subsoil drainage directed into major wetlands	As for Scenario 7	As for Scenario 7	To assess the response of lakes and groundwater levels to additional water inflows from subsoil drainage	
19		Wet_2					
20		Dry_1					
21		Int_1					
22	Full buildout	Wet_1	As for Scenario 7, with subsoil drainage directed into major wetlands and district water transfer scheme	As for Scenario 7	As for Scenario 7	To assess the feasibility of pumping between lakes and need for offsite discharge	
23		Wet_2					
24		Dry_1					
25		Int_1					
26	Staged development to 2040	Wet_1	As for Scenario 7, with subsoil drainage directed into Lake Mariginiup and Jandabup	As for Scenario 7	As for Scenario 7	To assess the response of lakes and groundwater levels to additional water inflows from subsoil drainage in areas expected to be developed over the next 15 to 20 years.	
27		Wet_2					
28		Int_1					
29	Staged development to 2040	Wet_1	As for Scenario 7, with subsoil drainage directed into Lake Mariginiup and Jandabup, and pumped transfer from Mariginiup to Jandabup	As for Scenario 7	As for Scenario 7	To assess the feasibility of pumping between the two major lakes in areas expected to be developed over the next 15 to 20 years.	
30		Wet_2					
31		Int_1					

7.3. Future scenario simulation results

The future scenario results for no development scenarios a to d, and subsoil extent scenarios 1 and 2, are presented and discussed in the following sections. Predictive scenarios relating to the development will be presented in series two of this report. It should be noted that the results discussed in the following sections are NOT predictive (in terms of representing timing of events) as the simulated future climates are synthetic and the timing and distribution of rainfall is not known. Rather, the future scenarios show potential high and low water levels across the DSP area and the potential range of subsoil drainage flow rates and annual flows that could occur due to the different development options assessed.

The future scenario results discussed in the following sections are indicative NOT predictive – due to future climate uncertainty.

7.3.1. 'No development' scenarios (Simulations a to d)

The 'no development' simulations were designed to simulate future groundwater levels if the EWDSP area was not developed. 'No development' simulations were run for the four climate scenarios to provide baseline groundwater levels and lake water levels for comparison with the future development scenarios so that the impacts of development can be assessed.

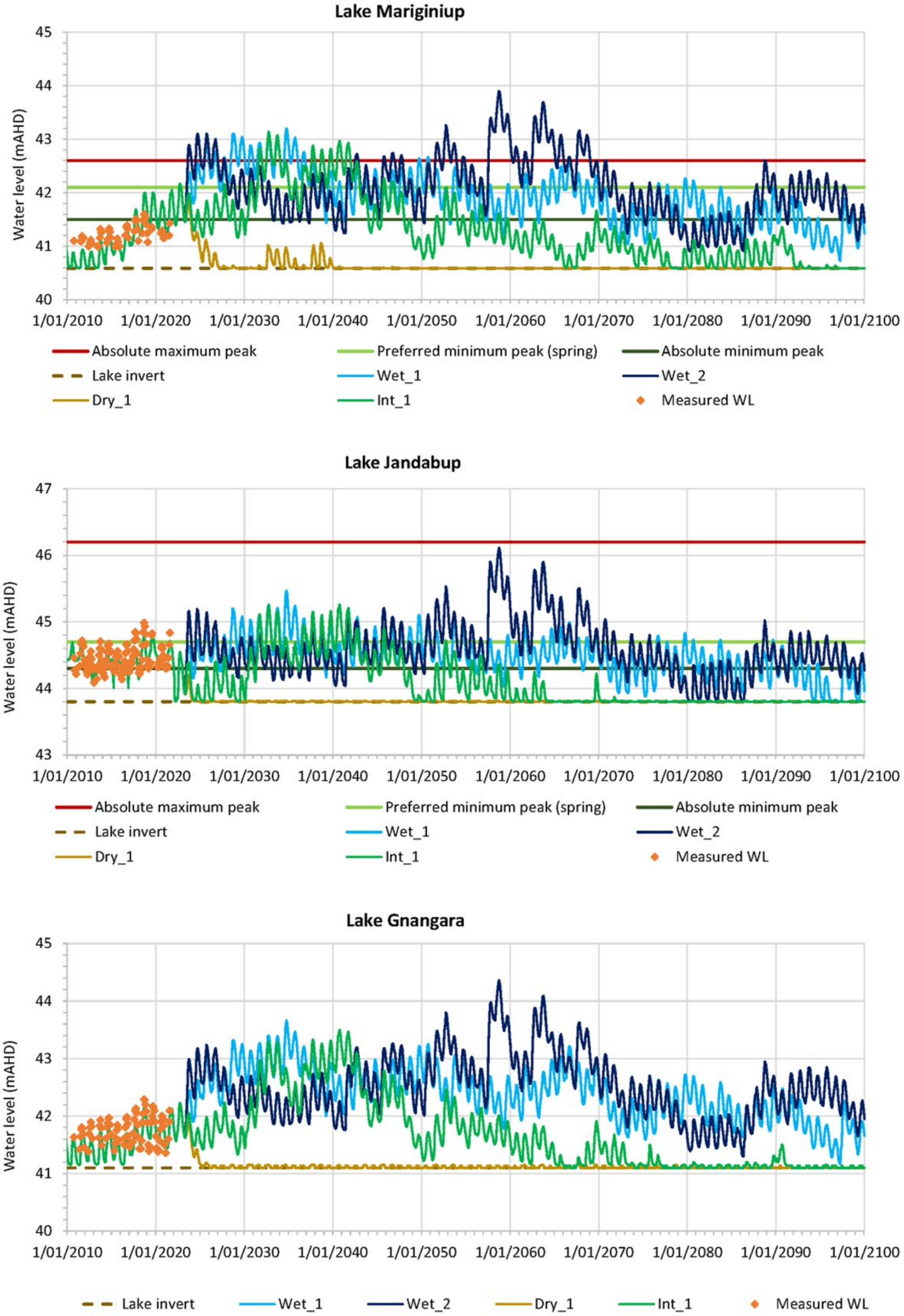
7.3.1.1. Lake water levels

Lake water levels for the 'no development' simulations are presented in Figure 57. These results indicate:

- Future 'no development' lake water levels are higher than calibration levels under the wetter future climates (Wet_1, Wet_2 and the early part of Int_1), especially in Lake Gnangara and Lake Mariginiup. This is likely due to the higher annual rainfalls and reduced future abstraction rates applied in the model from 2023 as follows:
  - Reduced Water Corporation abstraction rates (as indicated in Table 13)
  - Reduced private licensed abstraction (10% licence reductions)
  - Reduced unlicensed abstraction (30% reduction due to a reduced number of irrigation days for unlicensed bore owners).
  - It should be noted that the reduced abstraction rates were assumed to apply from 2023 onwards to allow the 'no development' simulations to be compared to 'full buildout' simulations.
- Lake Mariginiup and Lake Jandabup water levels may exceed the absolute maximum peak during the higher rainfall years.
- A drier future climate with a significant drying climate trend (indicated by the later decades of Int_1 and Dry_1) could result in all the simulated lakes becoming dry, even with the reduced abstraction rates.
- The Wet_2 climate scenario, which has the wettest month, wettest year and highest 2 year moving average of annual rainfall, had significantly higher peaks during the highest rainfall period, whereas similar peak groundwater levels occurred for both the Int_1 and Wet_1 climate scenarios.

7.3.1.2. Maximum groundwater levels

Maximum groundwater level (MGL) surfaces for the four 'no development' scenarios are presented in Figure 58. The differences in groundwater elevation between the four climate scenarios appear relatively minor at the vertical scale of the MGL figures. However, an inspection of the contours shows MGLs for the Dry_1 scenario are up to 2 m lower across the EWDSP area than for the Wet_2 scenario. However, the MGL surfaces for the 'no development' simulations are useful for comparison against future simulation MGL surfaces to assess development impacts on MGLs.



Note: the dates on these figures are not predictive but indicate potential future elevations

Figure 57: Lake water levels for the 'no development' simulations using the four selected climate scenarios (Simulations a to d)

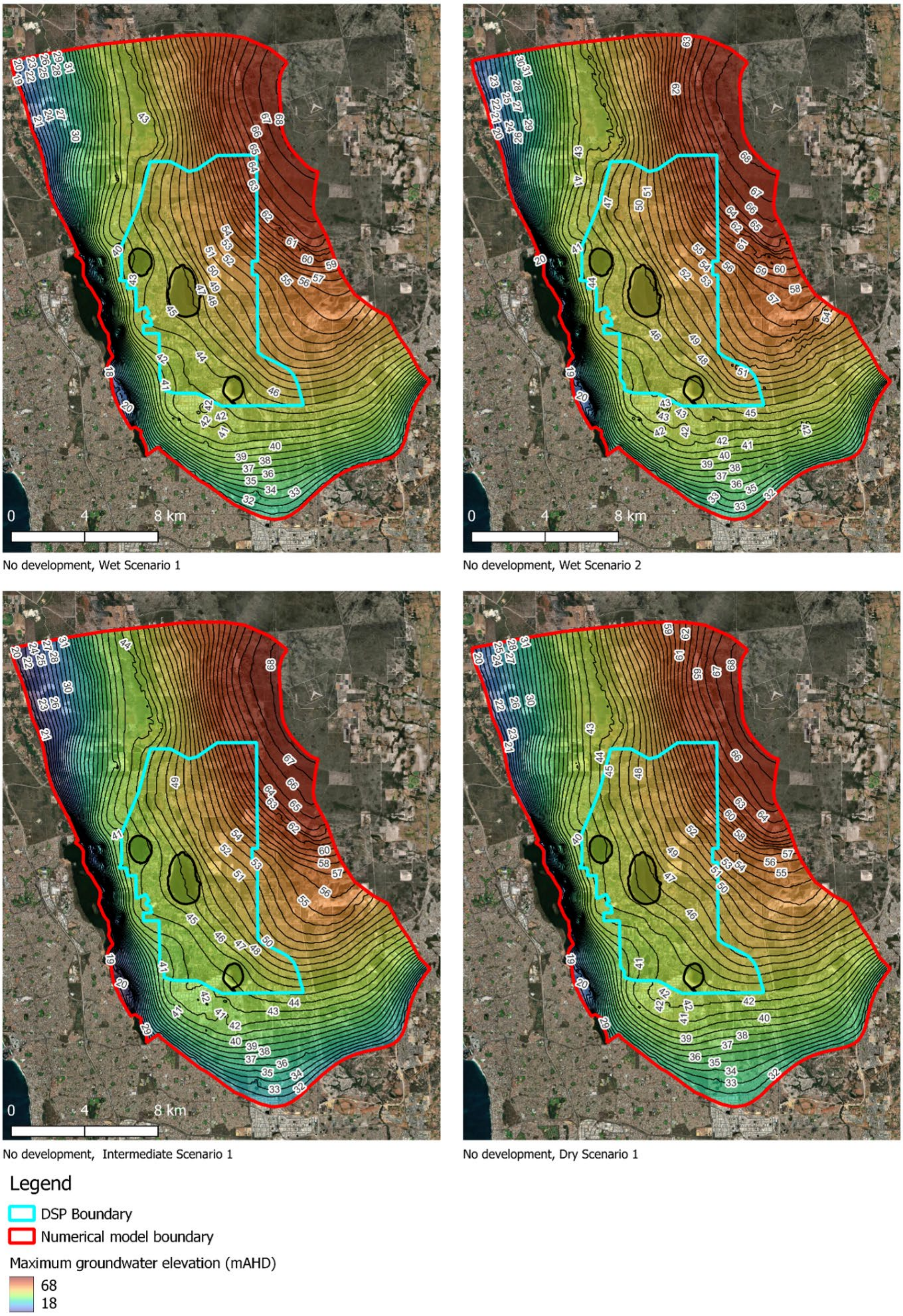


Figure 58: Maximum groundwater level surface from the 'no development' future scenarios

Hydrographs for the 'no development' simulations are presented in Appendix D. Groundwater levels typically vary by up to about 4m between the wetter and intermediate climate scenarios (Wet_1, Wet_2 and Int_1), however the dry climate (Dry_1) has a strong drying trend resulting in groundwater levels more than 12m lower than the wetter scenario levels towards the end of the simulation period. These results highlight the uncertainty in future groundwater levels due to the high degree of uncertainty in the future climate, even when no development occurs across the East Wanneroo DSP area.

The results of the 'no development' simulations are useful for comparison with the future development scenarios to assess the impacts of development.

7.3.2. Subsoil drainage extent - indicated from full-buildout scenarios with no subsoil drainage (Simulations 1 and 2)

Subsoil drainage will be required across the DSP area in urban development areas where the maximum future groundwater surface (without subsoil drainage) is expected to rise to within 2 m of the existing ground surface. For the purpose of this modelling, it is assumed that any future earthworks cut and fill will not increase the area of less than 2m clearance to the AAMGL when compared to the existing ground surface. A preliminary earthworks assessment completed by JDSi supports this. Subsoil drains will be installed as follows:

- At the controlled groundwater level (CGL), where the depth from the post development ground surface to CGL is less than the maximum practicable subsoil installation depth, or
- At the maximum practicable subsoil installation depth, assumed to be 2m bgl (m below ground level) for this investigation.

Using the assumption of a 2 m subsoil drainage installation depth, the potential spatial extent of subsoil drainage was estimated as follows:

- Two full buildout development scenarios were carried out using the Wet_1 and Wet_2 climate scenarios with no subsoil drainage (Scenarios 1 and 2).
- The maximum transient groundwater level (MGL) surface from the two simulations were identified.
- The difference between the pre-development topographic surface (obtained from LiDAR data) and the MGL surface were calculated to give the depth to MGL (below ground level).
- Areas where the depth to MGL is less than 2 m bgl were identified as potential areas requiring subsoil drainage (Figure 59).

Subsoil drainage will be installed in areas of urban development with potentially shallow groundwater and will exclude buffered wetland areas. Potential subsoil drainage areas were included in the groundwater model and are shaded blue in Figure 60.

Based on the modelling results, the required extent of subsoil drainage across the DSP area is shown in in Figure 60 as the area where the depth to MGL is less than 2 m bgl intersects areas of urban development, excluding buffered wetland areas. This subsoil extent was used in predictive development scenarios.

Modelled subsoil drainage flow rates and annual subsoil drainage volumes are presented for the future scenarios below. Subsoil drainage and surface water flows are likely to be managed jointly, so subsoil drainage flow rates were obtained for the surface water catchment areas outlined in the DWMS that had active subsoil drainage. The catchments are shown in Figure 61, along with subsoil drainage extent. Subsoil drainage locations that are isolated from major wetland features will require pumping infrastructure to connect to the regional system. This will be discussed further in a future concept engineering report.

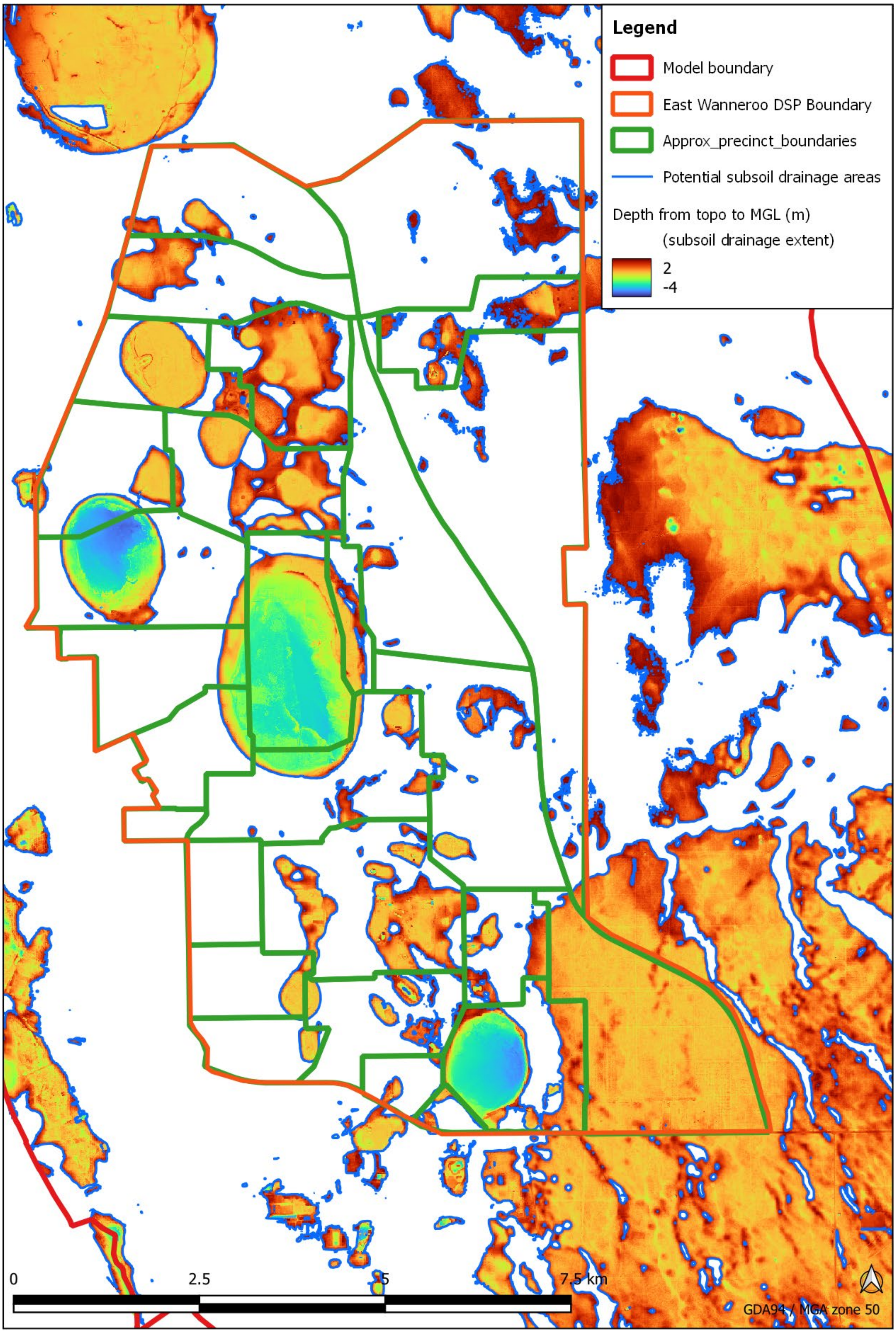


Figure 59: Areas where the depth to MGL is less than 2m below ground level

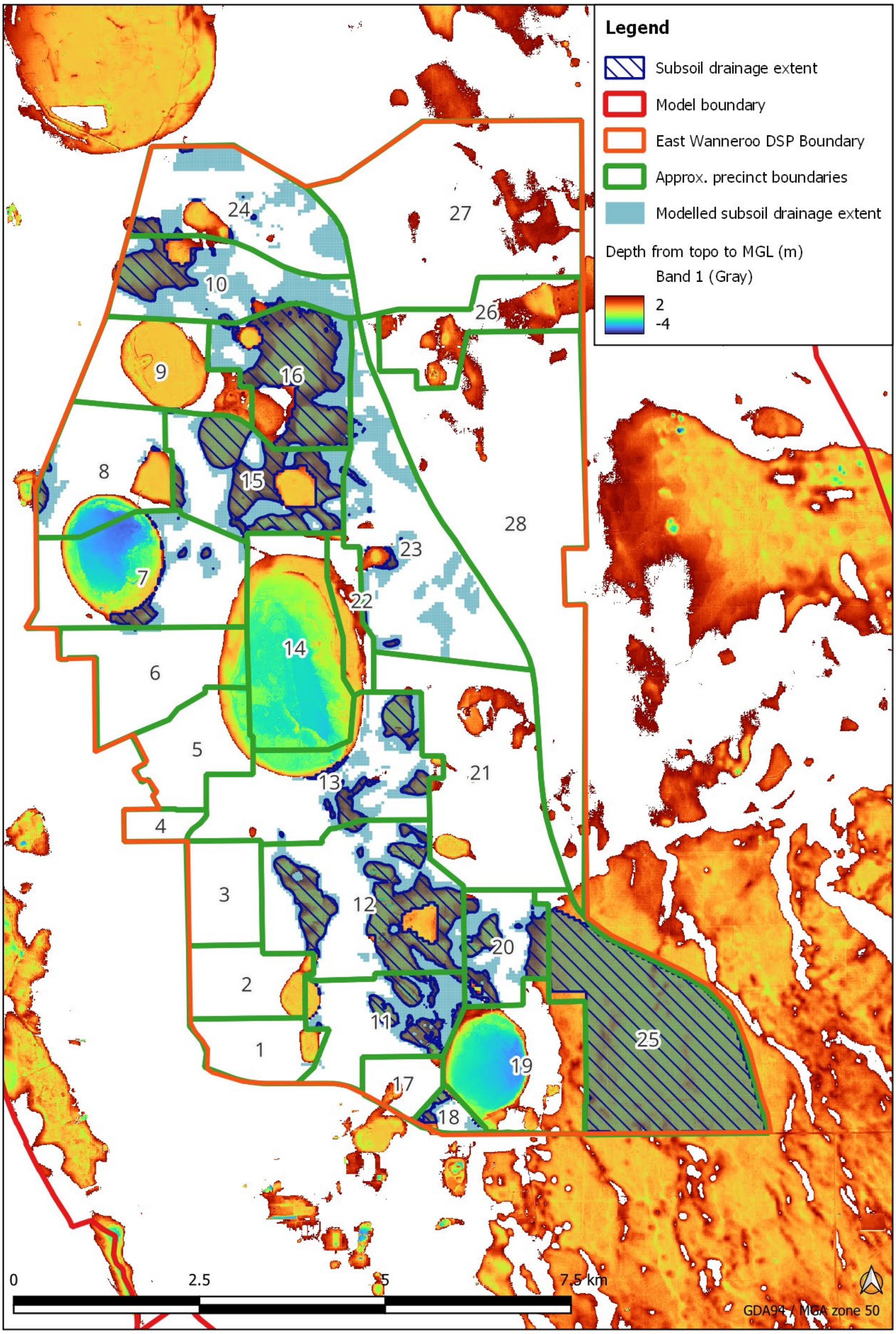


Figure 60: Spatial extent of subsoil drainage (hashed area) as indicated by intersection of modelled drainage area and areas where the depth to MGL is less than 2m below ground level

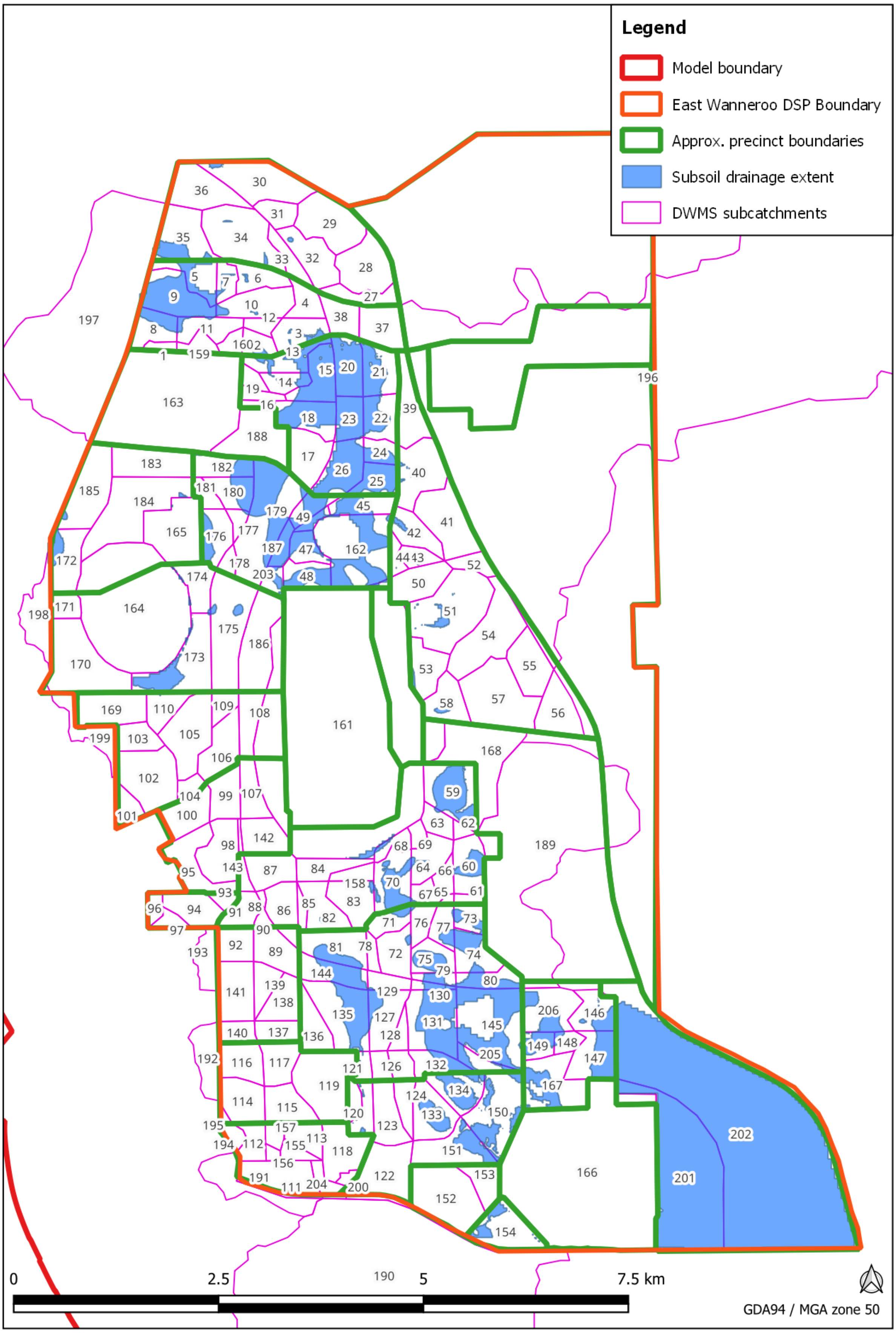


Figure 61: Surface water catchments from the DWMS

7.3.3. Full buildout development scenarios with subsoil drainage at a maximum depth of 2.5m (Simulations 3 to 6)

Full buildout simulations were carried out corresponding with the four selected climate scenarios (Simulations 3 to 6), and subsoil drainage included to a maximum depth of 2.5 m bgl. This maximum subsoil drainage depth is higher than practicable, but the purpose of these simulations was to obtain a conservative estimate of annual subsoil drainage flows and to allow for an assessment of the sensitivity of annual drainage flows to the maximum subsoil drainage elevation.

7.3.3.1. Annual subsoil drainage flow volumes

Total annual flow rate statistics from the four simulations for subsoil drainage across the East Wanneroo DSP area (Figure 62) indicate a large range of subsoil drainage volumes could be generated year to year, ranging from less than 1 GL/yr in a dry future climate to 35 GL/yr in the wettest year of a wet future climate. These results highlight the potential variability in annual subsoil drainage volumes and indicate harvesting of subsoil drainage water in the East Wanneroo DSP area is unlikely to be commercially viable at this stage.

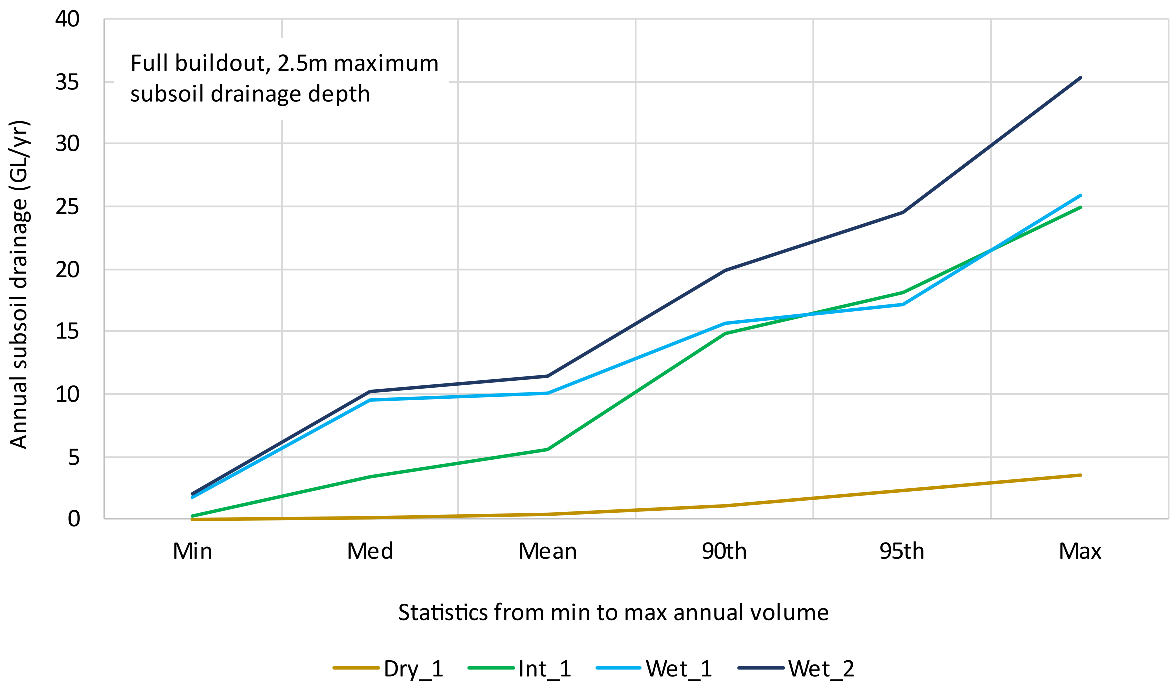


Figure 62: Total annual subsoil drainage volume statistics across the DSP area for the full buildout future scenario simulations with subsoil drainage at a maximum depth of 2.5 m bgl

The cumulative distribution of total annual flows for the four climate scenarios (Figure 63) indicate:

- 50% of the time annual subsoil drainage volumes will be 10 GL or less
- 80% of the time, the annual subsoil flow volume will be less than 15 GL
- Under very wet rainfall years, the annual subsoil drainage volume could be in excess of 30 GL/yr
- Under a drier climate, subsoil drainage volumes may be less than 1 GL/yr for the majority of the time.

The total annual flow rates from these four scenarios (Simulations 3 to 6) provide conservative estimates of the annual subsoil drainage volumes to be managed and show the uncertainty in groundwater volumes to be managed due to uncertainty in the future climate.

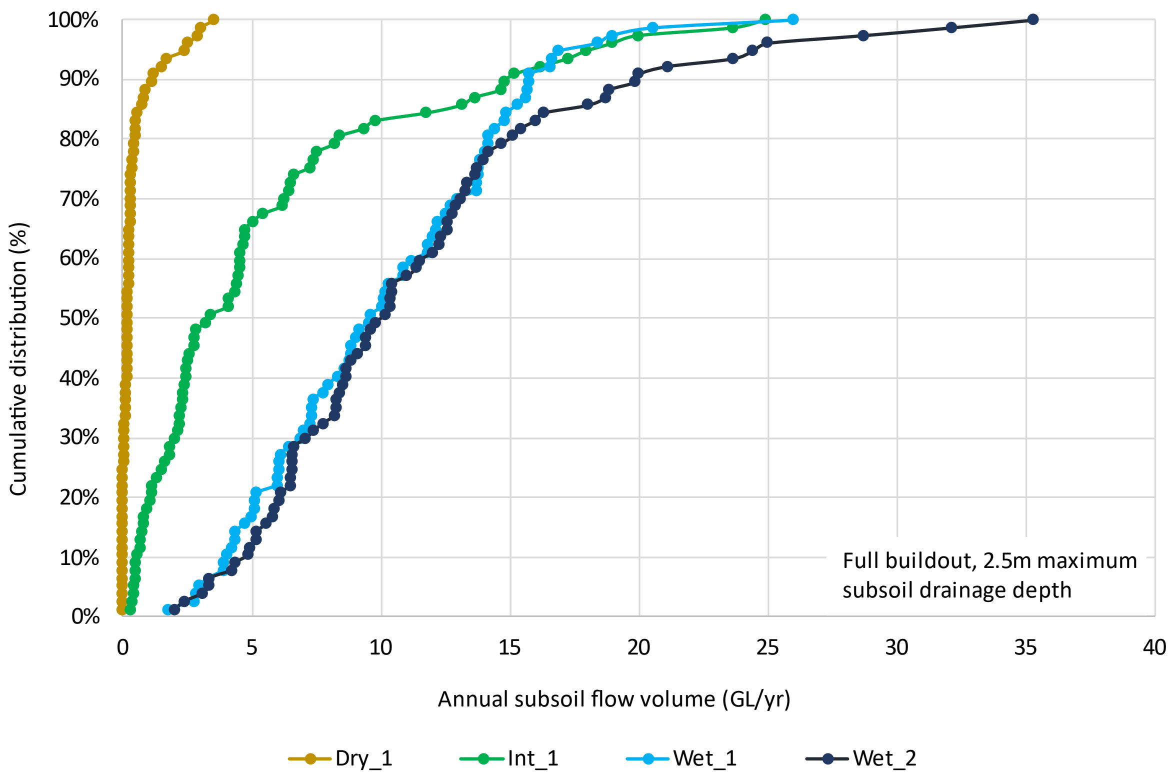


Figure 63: Cumulative distribution of annual subsoil drainage flow volume for the full buildout future scenario simulations with subsoil drainage at a maximum depth of 2.5 m bgl

Further analysis of these results indicated lake water levels were suppressed in the model simulations by the conservatively assumed maximum subsoil drainage depth of 2.5 m bgl. As absolute drainage elevations are required to assess the absolute lake water levels and groundwater elevations, all further simulations were carried out with a maximum subsoil drainage depth of 2.0 m, which is a conservative but more practicable installation depth.

No further analysis of the deeper subsoil drainage simulation results will be presented in this report.

7.3.4. Full buildout development scenarios with subsoil drainage at a maximum depth of 2.0m (Simulations 7 to 10)

Model simulations were carried out for the four climate scenarios with development at full buildout and subsoil drainage at a maximum depth of 2.0 m bgl (Simulations 7 to 10). The purpose of these simulations was to obtain maximum subsoil drainage flow rates, annual subsoil drainage volumes, along with lake water levels and maximum ground water levels to assess development impacts.

7.3.4.1. Subsoil drainage flow rates and annual subsoil drainage flow volumes

For each surface catchment (Figure 61) with active subsoil drainage, subsoil drainage flow rates for each model timestep are shown as box and whisker plots in Appendix E, and tabulated statistics for each catchment are given in Appendix F.

Maximum drainage flow rates are required to inform the concept design for the water management infrastructure and can be summarised as follows:

- The highest drainage flow rates, exceeding 100 L/s, occurred in catchments 9, 59, 145, 162, 179, 201 and 202.
- Catchments 201 and 202 had very high peak flow rates of 270 L/s and 756 L/s, respectively. Some fill may be required in these areas to increase the subsoil drainage elevation, to reduce these drainage flow rates.

- 95% of the drainage flow rates for all catchments were less than 44 L/s, except for Catchment 202 which had a 95th percentile drainage flow rate of 132 L/s.

The total annual drainage flow volume statistics from the East Wanneroo DSP area for the four full buildout simulations with a maximum subsoil drainage depth of 2 m are presented in Figure 64 and Figure 65. These results show:

- A significant difference between simulated minimum and maximum total annual subsoil drainage volumes, both within and between climate scenarios, with annual volumes ranging from less than 1 GL/yr to 30.7 GL/yr.
- The peak annual drainage volume only reduced by about 13%, from 35.3 GL/yr to 30.7 GL/yr when the maximum subsoil drainage installation depth was reduced from 2.5 m to 2.0 m bgl.
- As for the full buildout simulations with a deeper subsoil drainage depth, these simulations indicate subsoil drainage volumes are highly variable and harvesting is unlikely to be commercially viable at this stage.
- Total annual subsoil drainage flow volumes were less than 13 GL/yr for 80% of the years simulated and less than 9 GL/yr for half of the years simulated.

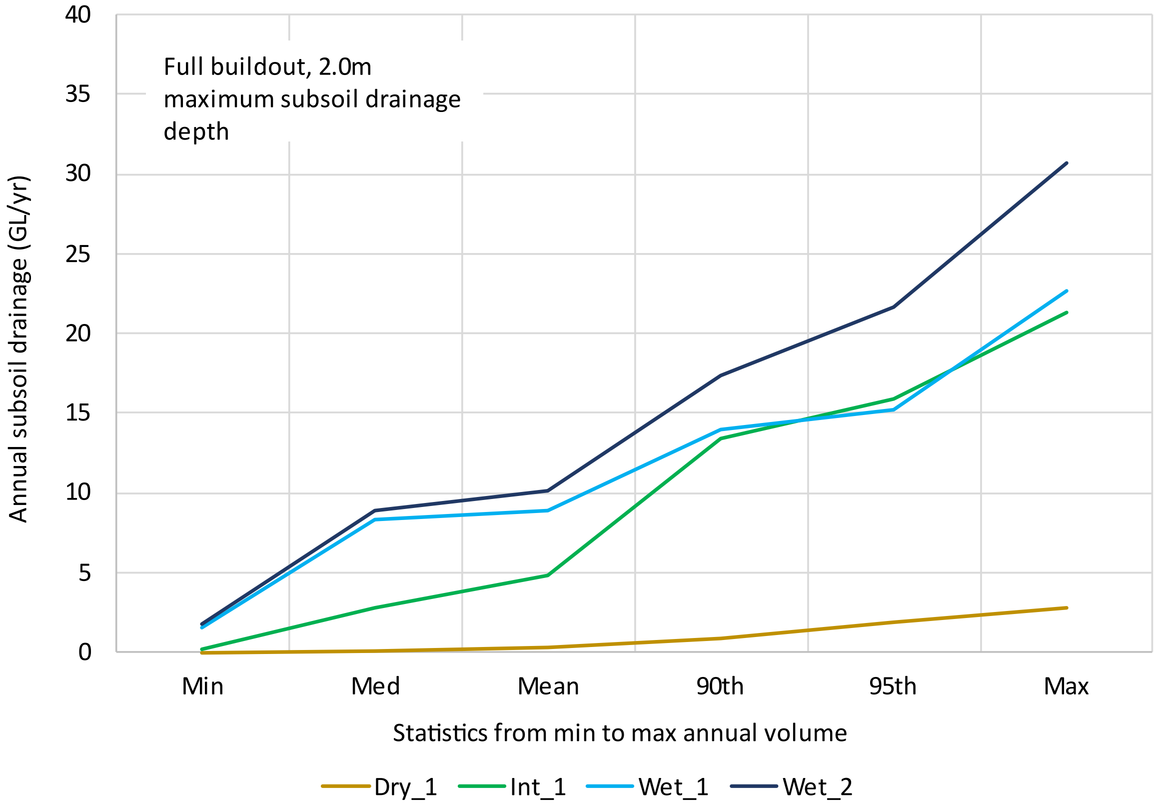


Figure 64: Total annual subsoil drainage volume statistics for the full buildout future scenario simulations with subsoil drainage at a maximum depth of 2.0 m bgl

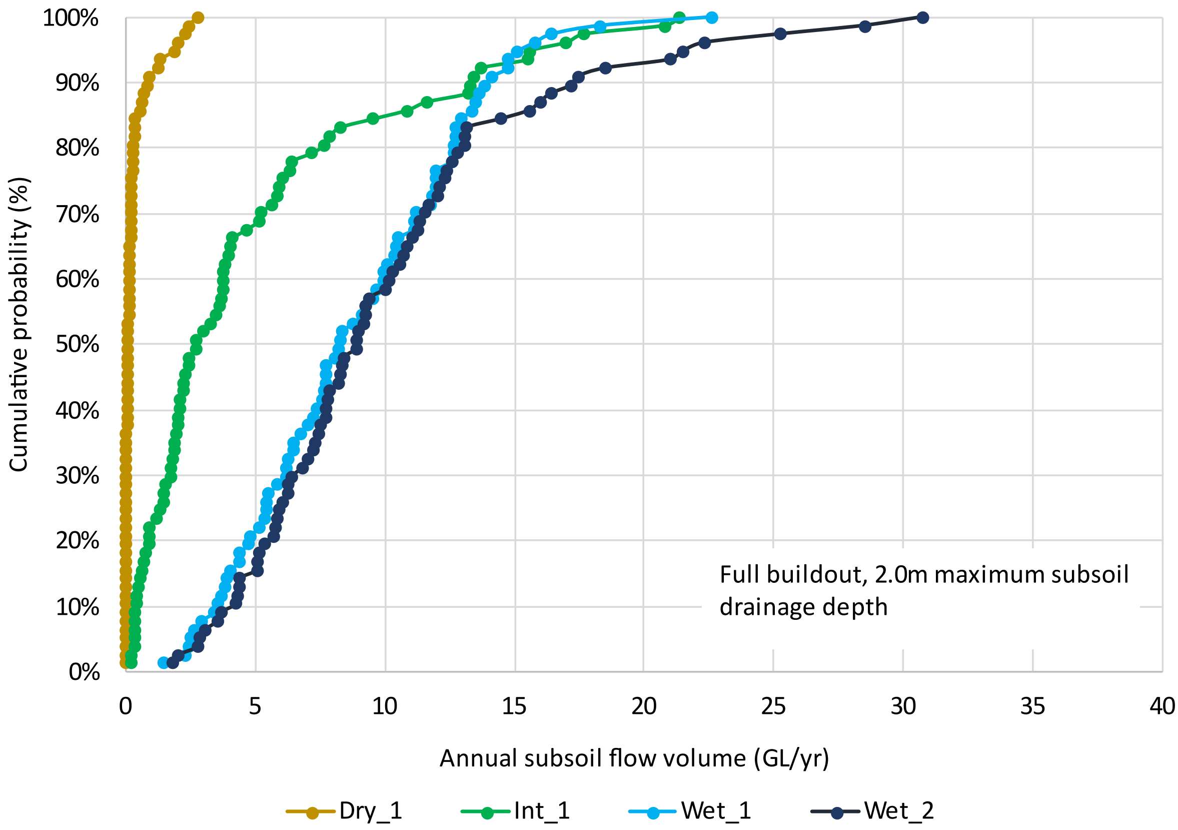


Figure 65: Cumulative distribution of annual subsoil drainage flow volume for the full buildout future scenario simulations with subsoil drainage at a maximum depth of 2.0 m bgl

7.3.4.2. Lake water levels

The groundwater flow modelling results allow for the assessment of development impacts on lake water levels. Lake water levels for the four full buildout simulations are presented in Figure 66, and a comparison between simulated lake water levels for the Wet_1 and Dry_1 climate scenarios at full buildout and with no development is given in Figure 67. The lake water level figures indicate the following:

- Lake water levels are likely to be higher post-development than they would be with no development.
- With development, simulated water levels in Lake Mariginiup were high, exceeding the absolute maximum lake water level. This indicates that management of the lake water levels will be required following development in the area.
- The model results indicate Lake Jandabup appears to have capacity for storage of excess water (e.g. surface water runoff, subsoil drainage water and/or excess water from Lake Mariginiup). However, under wetter climate conditions, simulated Lake Jandabup water levels exceeded the absolute maximum water level following development of the East Wanneroo area, so a discharge option is likely to be required if the future climate follows the trends of the wetter climate scenarios.
- With the expected drying climate trend, urban development across the East Wanneroo area is likely to cause higher water levels in the lakes than would occur with no development, potentially preventing the lakes from going dry or reducing the amount of augmentation required.

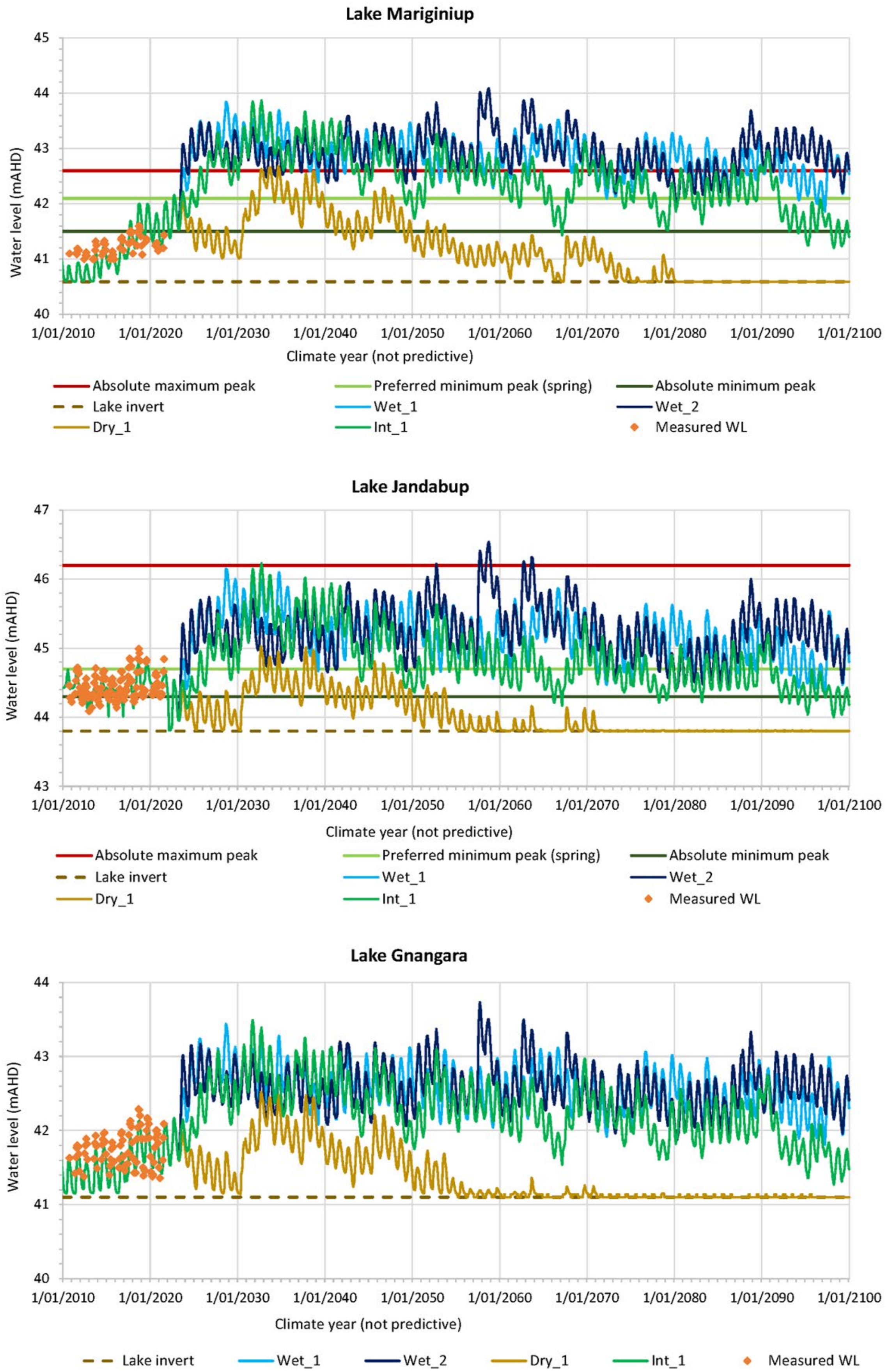


Figure 66: Lake water levels for the full buildout simulations and four climate scenarios, with subsoil drainage at 2 mbgl (Simulations 7 to 10)

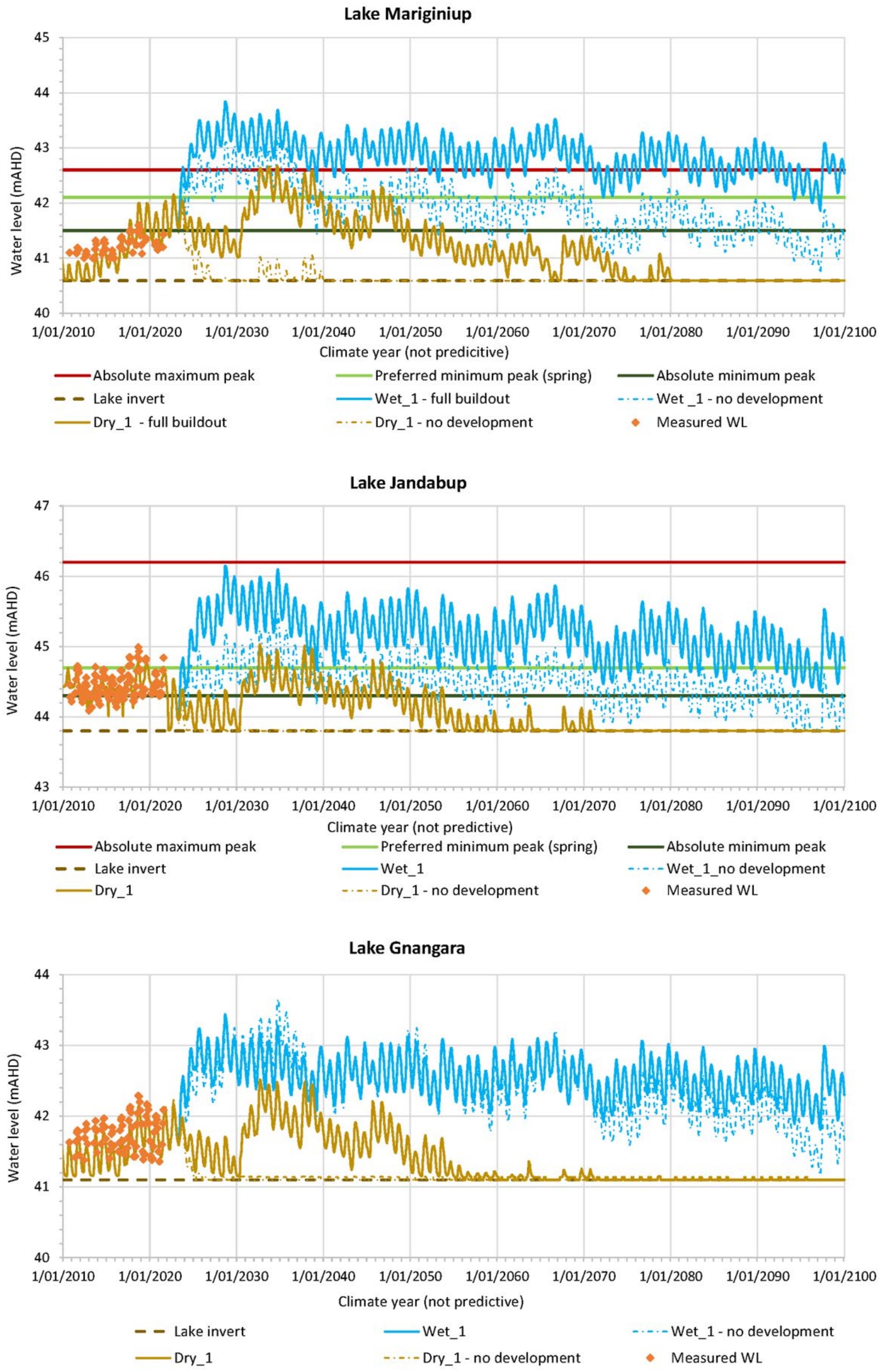


Figure 67: A comparison of the lake water levels for no development and full buildout under the Wet_1 and Dry_1 climate scenarios (Simulations a, c, 7 and 9)

7.3.4.3. Maximum groundwater levels

Maximum groundwater levels (MGLs) for the full buildout simulations with drainage at 2.0 mbgl are presented in Figure 68. As for the ‘no development’ scenarios, the MGL surfaces for the four different climate scenarios appear to show relatively minor differences at the vertical scale of the figures, although the Dry_1 scenario does show lower maximum water elevations than the wetter simulations, particularly through the DSP area.

To assess the impact of development on peak groundwater levels, the difference between the full buildout and ‘no development’ MGL surfaces was evaluated for each climate scenario, as shown in Figure 69. The resulting depth to MGL, overlain by contours of drawdown resulting from the development (to enable visualisation of areas of change from pre-development conditions), is shown in Figure 70. These comparison maps show the following:

- With urban development across the DSP area, groundwater appears to have mounded above the ‘no development’ MGL surface on the western side of the DSP area. In this area urban development is simulated to occur but there is no requirement for subsoil drainage, as this area has adequate clearance to groundwater. The simulated mounding above the ‘no development’ surface is therefore attributed to the increased recharge that occurs with urbanisation.
- The ‘full buildout’ MGL surface is simulated to be up to 2.5 m higher than the ‘no development’ (within the East Wanneroo DSP area) MGL surface on the western side of the DSP area.
- Development is simulated to cause a slight increase in maximum groundwater level (up to 0.5 m) in the vicinity of Lake Mariginiup and Lake Jandabup due to development of the East Wanneroo DSP area, primarily in areas where subsoil drainage is not required.
- Maximum groundwater levels are lower post development for the wet and intermediate climate scenarios (Wet_1, Wet_2, and Int_1 simulations) over parts of the DSP area where the future groundwater is high enough to be intercepted by the subsoil drainage system. This is particularly evident in the vicinity of the catchments with high maximum subsoil drainage flow rates (i.e., Catchments 9, 59, 145, 162, 179, 201 and 202).

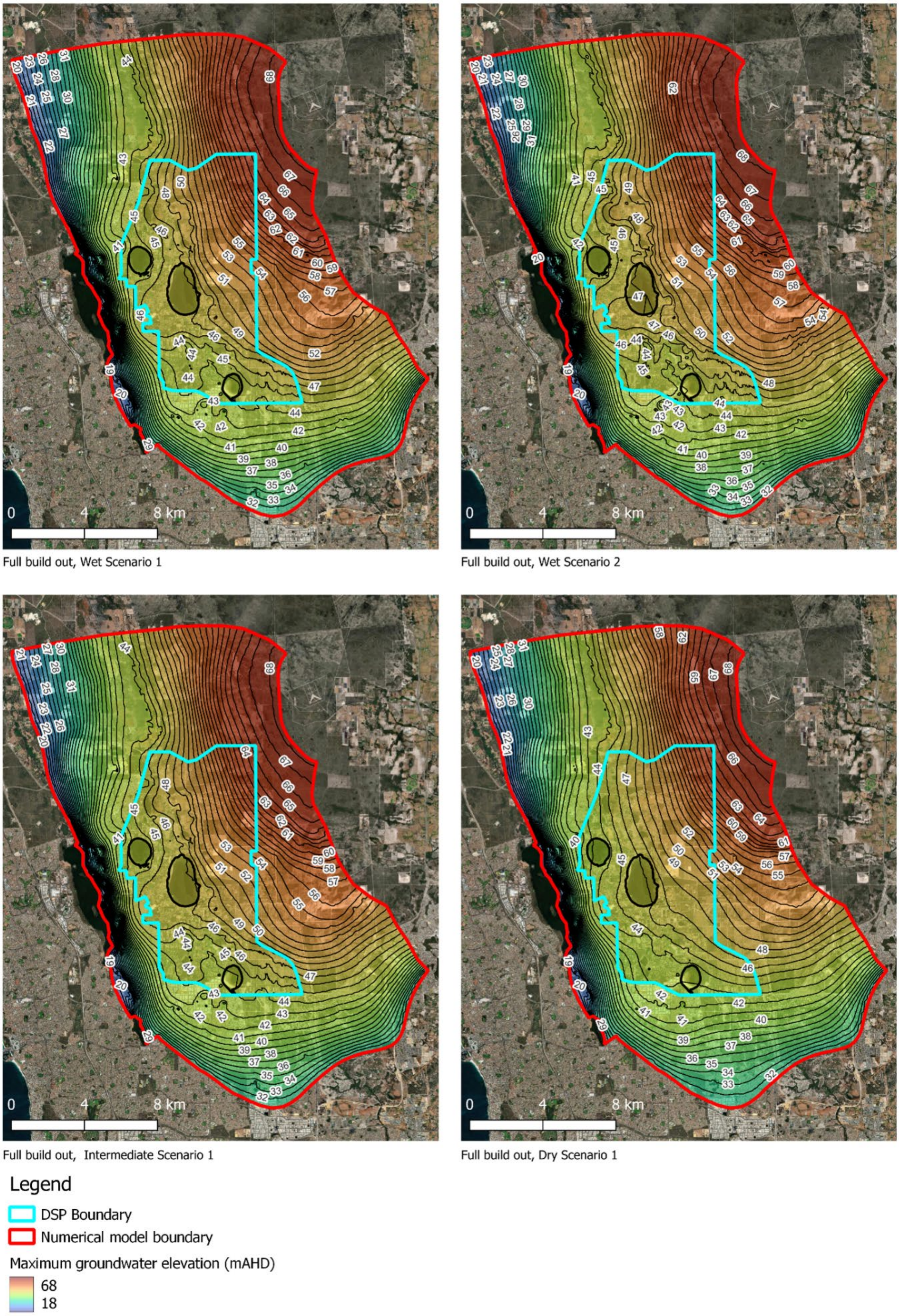


Figure 68: MGL surface for the full buildout simulations with subsoil drainage at 2m bgl, under the four selected climate scenarios

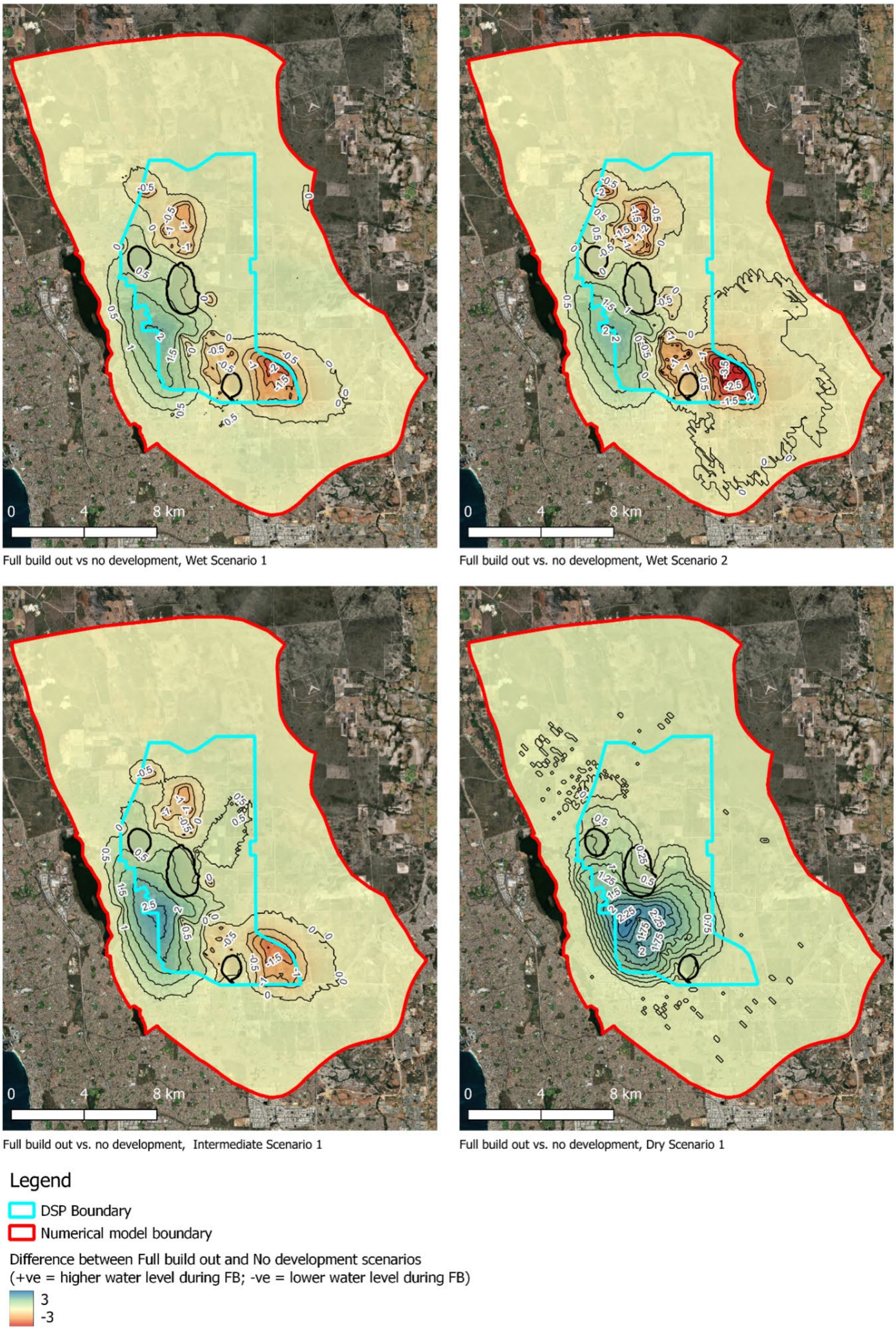


Figure 69: Comparison of the full buildout MGL surface with the no development MGL surface

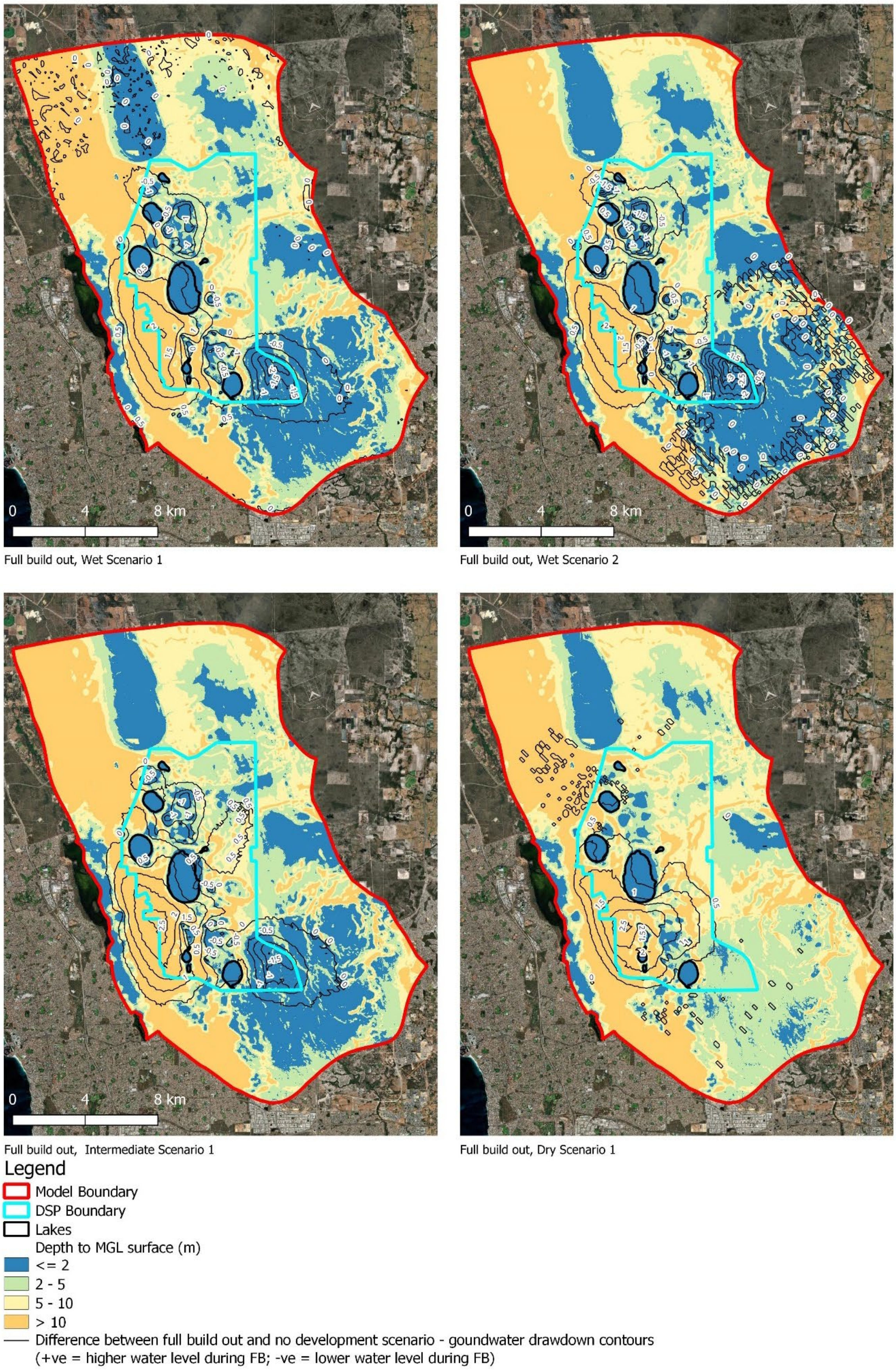


Figure 70: Depth to MGL surface with contours of relative change due to development (full buildout)

7.3.4.4. Annual outflow volumes from the western constant head boundary (Lake Joondalup to Lake Goollelal inclusive)

Annual outflow volumes from the constant head boundary (which runs from the northern end of Lake Joondalup to the southern end of Lake Goollelal on the western side of the model domain as shown in Figure 44), were assessed for both the full buildout with subsoil drainage at 2mbgl simulations (Simulations 7 to 10) and the 'no development' simulations (Simulations a to d). The annual outflow volumes for both simulations are presented in Figure 71 and Table 24. Although not the direct inflow into Lake Joondalup, this boundary outflow volume indicates potential impacts of the future climate scenarios on the discharge into Lake Joondalup. It should be noted, however, that boundary effects could be impacting the results, so they are indicative at best.

This assessment indicates the following:

- Outflow volumes are only slightly higher at full buildout than they are with no development across the DSP area for the wetter climate scenarios.
- In a wetter future climate, maximum outflow volumes from the constant head boundary at full buildout are higher than pre-development outflows but are similar to the 'no development' outflows.
- The average outflows (for no development and full buildout of the DSP area) are similar no more than 5% higher than the predevelopment outflows and are lower for the Int_1 and Dry_1 climate scenarios.
- These results indicate that discharge into Lake Joondalup is not expected to significantly increase with development across the DSP area but will be highly dependent on the future climate.

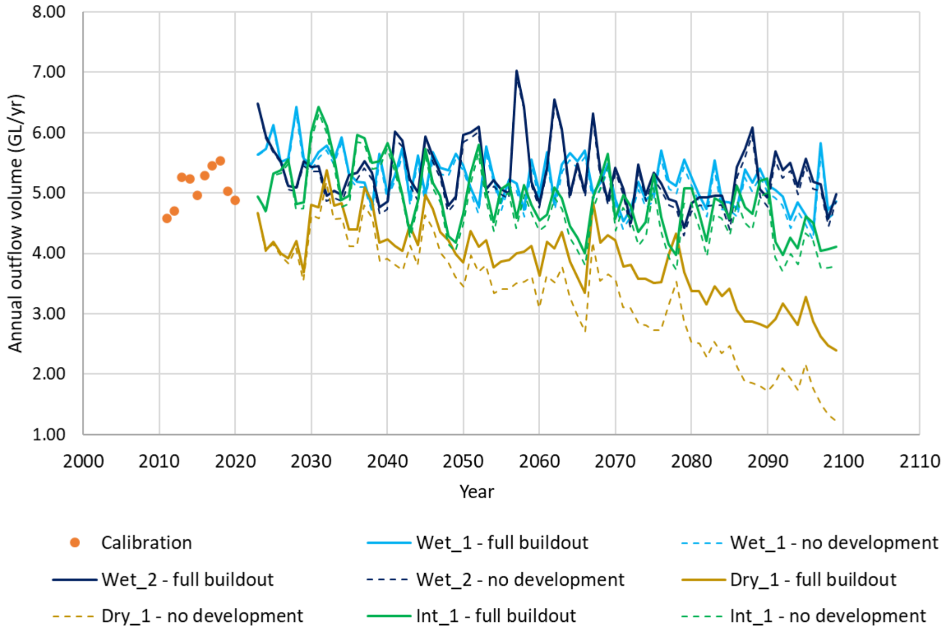


Figure 71: Annual outflow volumes to the constant head boundary condition

Table 24 Annual outflow volumes (from constant head boundary condition) for pre-development, no development and post development (GL/yr)

Statistic	Pre-development (calibration)	No development (simulations a to d)				Post-development (full buildout simulations 7 to 10)			
Statistic		Wet_1	Wet_2	Int_1	Dry_1	Wet_1	Wet_2	Int_1	Dry_1
Min	4.6	4.2	4.3	3.7	1.2	4.4	4.4	4.0	2.4
Ave	5.1	5.1	5.2	4.7	3.3	5.3	5.3	4.9	3.9
Max	5.5	6.4	6.9	6.3	5.2	6.4	7.0	6.4	5.4

7.3.4.5. Model water balance and future climate recharge rates

Average annual model water balances for the four full buildout simulations with drains at 2m bgl are presented in Table 25. The water balance results show average annual recharge rates for the two wetter future scenarios are similar to the average recharge rates for the calibration period. This indicates that the increase in recharge rates due to urbanisation within the DSP area are offset by the drying trends evident in the future climate scenarios.

The breakdown of recharge rates for each land use type over the four selected future climate scenarios, given in Table 26, indicate:

- The Wet_1 and Wet_2 recharge rates (in mm) are similar but lower than those obtained over the model calibration period which is expected as the annual average rainfall for the future scenarios are lower due to drying climate trends.
- Although the Wet_1 and Wet_2 future climates have a similar average annual rainfall, the average annual recharge percentages are higher for Wet_2 due to the increased rate of recharge that occurs with higher rainfall events.
- The Int_1 scenario and Dry_1 scenarios show recharge rates and the recharge percentages generally decreasing from the Wet_1 and Wet_2 recharge percentages. This reduction is expected and consistent with the information presented by Davies (2022), and is implicit in the recharge function which provides improved recharges estimates compared to a straight percentage of rainfall.
- The formulation of the recharge function when groundwater is within the rooting depth of the wooded areas has resulting in significant negative recharge rates and percentages for the drier climate scenarios. Further investigation of recharge rates is required to assess whether these negative rates are realistic or whether they are causing groundwater levels to fall excessively in the model simulations.

7.3.4.6. Significance of results

The full buildout development scenarios, with subsoil drainage included at a depth of 2.0 mbgl, inform the concept design for the groundwater management scheme by:

- Providing maximum catchment flow rates for infrastructure design
- Providing indicative subsoil drainage volumes that will require management on an annual basis, and the potential range in annual subsoil drainage volumes.
- Indicating the potential capacity of the major lakes for short term water storage following full-buildout of the East Wanneroo DSP area.
- Identifying the requirement for ongoing lake water level management at Lake Mariginiup following full buildout,
- Identifying the requirement for lake water management at Lake Jandabup during higher rainfall years following full buildout of the DSP area.

Table 25: Average annual model water balance during full buildout simulations with subsoil drainage at 2m bgl (Simulations 7 to 10)

Parameter	Annual Average Inflow/Outflow (GL/yr)			
	Wet_1	Wet_2	Int_1	Dry_1
INFLOWS				
Storage (volume released from storage)	65.9	68.4	59.2	47.6
Constant head	0.4	0.4	0.4	0.5
Wells	0.0	0.0	0.0	0.0
Drains	0.0	0.0	0.0	0.0
ET	0.0	0.0	0.0	0.0
Head dependent boundaries	9.2	8.7	11.0	16.7
Recharge	96.7	100.8	80.3	45.3
Lake seepage	1.7	1.8	1.5	0.4
TOTAL INFLOWS	173.9	180.2	152.5	110.6
TOTAL INFLOWS (excluding storage)	108.0	111.7	93.2	63.0
OUTFLOWS				
Storage (volume going into storage	66.0	68.8	56.9	37.5
Constant head	5.3	5.4	5.0	3.9
Wells	33.4	33.4	33.4	33.4
Drains	17.1	19.3	10.6	2.2
ET	7.6	8.1	6.3	2.8
Head dependent boundaries	24.4	25.3	21.0	12.1
Recharge	14.4	14.3	14.7	17.5
Lake seepage	5.7	5.7	4.6	1.2
TOTAL OUTFLOWS	173.9	180.2	152.5	110.6
TOTAL OUTFLOWS (excluding storage)	107.9	111.4	95.6	73.0
Change in storage	0.1	0.4	-2.3	-10.1

Table 26: Recharge rates for the 8 different land use types over the four selected future climate scenarios

Zone	Zone description	Recharge rate (mm)				Recharge as a % of annual rainfall			
		Wet_1	Wet_2	Int_1	Dry_1	Wet_1	Wet_2	Int_1	Dry_1
Ave. ann. rainfall (mm/year)		684	685	594	431				
1	Pasture / cleared pine / under construction	269	280	220	113	39.4%	40.9%	37.1%	26.2%
2	Banksia - low density/ rural residential blocks (dtgw[1] < 9m)	106	120	52	-76	15.5%	17.5%	8.8%	-17%
3	Banksia – low density/ rural residential blocks (dtgw[1] > 9m)	108	126	71	23	15.8%	18.4%	12%	5.3%
4	Banksia medium density (dtgw[1] > 9m)	7.0	25	4	0.3	1.0%	3.7%	0.7%	0.1%
5	Pine - low density (dtgw[1] < 18m)	193	205	142	25	28.2%	30.0%	23.9%	5.7%
6	Pine – med/high density (dtgw[1] < 18m)	-35	-19	-93	-240	-5.1%	-2.8%	-15.7%	-55.7%
7	Urban	415	426	360	226	60.7%	62.2%	60.7%	52.5%
8	Commercial/Industrial	435	445	380	242	63.6%	65.0%	64.0%	56.1%

[1] Depth to groundwater

7.3.5. Staged development scenarios with subsoil drainage at a maximum depth of 2.0m (Simulations 11 to 14)

Staged development simulations with subsoil drainage at a maximum depth of 2.0 mbgl were carried out for the four selected climate scenarios (Simulations 11 to 14). These simulations provide an indication of the impacts of staging on the lake and groundwater level.

7.3.5.1. Lake water levels

It should be recognised that staged future scenario modelling outcomes are dependent on the future climate imposed through each stage and are not representative of the range of potential staged flows or the range of absolute staged lake and groundwater levels that could occur under a range of climate conditions. However, staged lake water levels, can be compared to the equivalent full buildout scenario lake water levels to understand the general effects of staging on lake water levels, and to some extent on groundwater elevations as the lakes are surface expressions of the groundwater table.

Staged lake water levels are shown in Figure 72, and a comparison between staged and full development lake water levels for the critical wetter climate scenarios (Wet_1 and Wet_2) are shown in Figure 73. These figures indicate:

- Staging results in maximum water levels up to about 1 m lower than at full buildout over the initial 3 decades of development (until 2050).
- After 2050, there is little difference between the staged and full-buildout water levels.

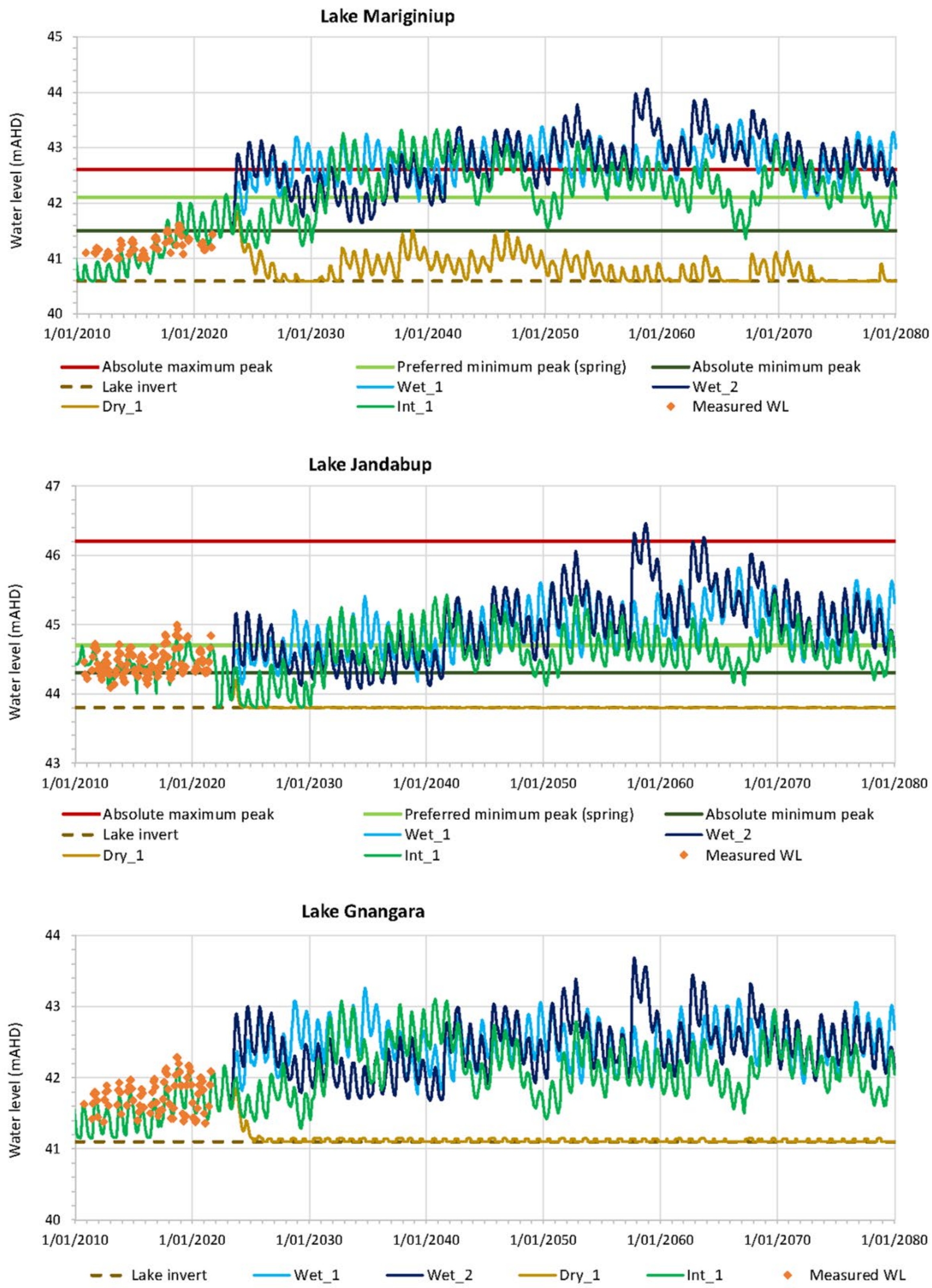
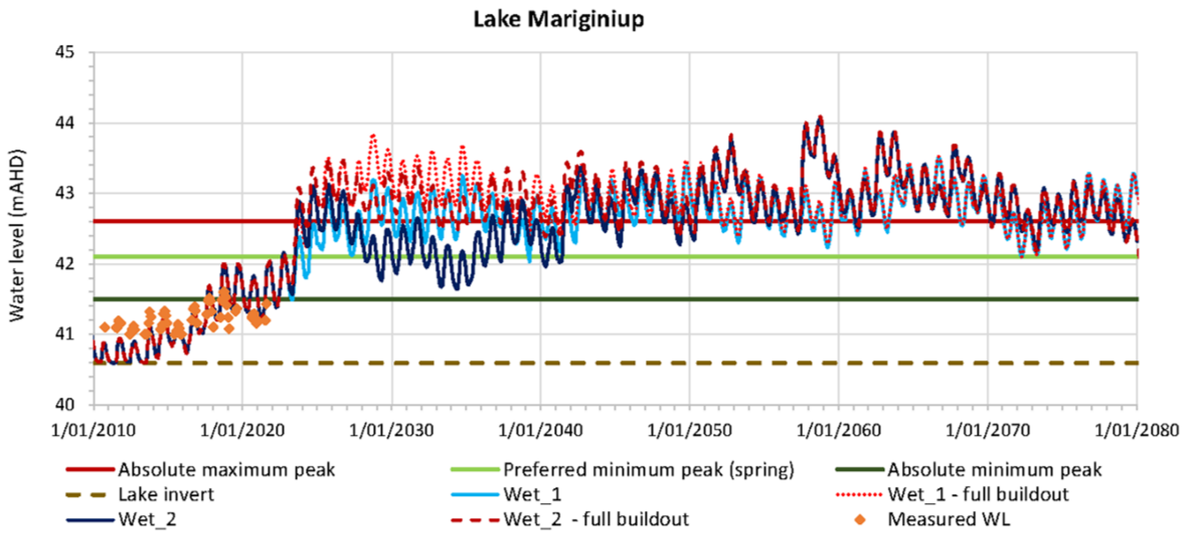
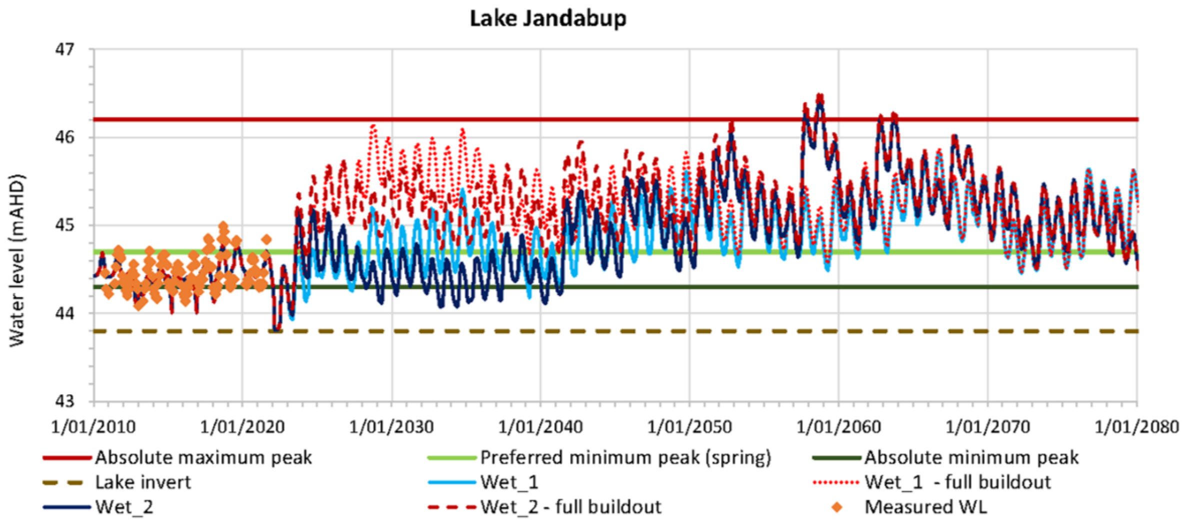


Figure 72: Lake water levels for the staged development simulations and four climate scenarios, with subsoil drainage at 2 m bgl (Simulations 11 to 14)





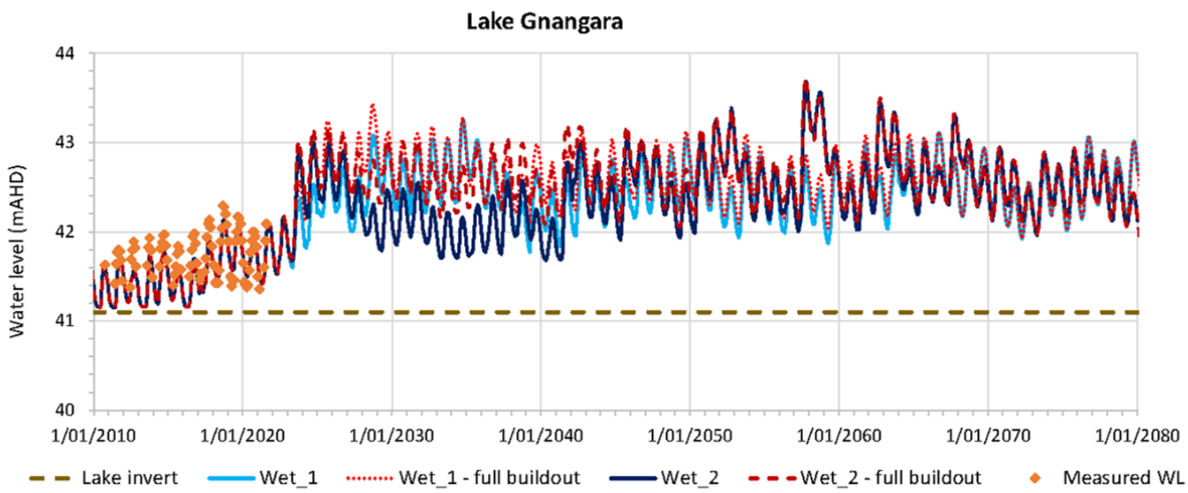


Figure 73: Comparison of the staged and full buildout lake water levels for the wetter climate scenarios (Wet_1 and Wet_2 only)

7.3.6. 'Staged to 2040' development option with no subsoil drainage (Simulations 15 to 17)

'Staged to 2040' simulations were carried out to assess the impacts of development on the western side of the DSP area, primarily in areas that do not require subsoil drainage infrastructure as there is adequate clearance to groundwater. The 'staged to 2040' scenarios were carried out for the three wetter climate scenarios (Wet_1, Wet_2 and Int_1) to assess lake and groundwater level impacts if 'Staged to 2040' development was developed ahead of the groundwater management infrastructure. For these simulations, the model was run with staging included until the end of 2039. The model was then allowed to run to the end of 2099 with no further change in land use or abstraction rates. No subsoil drainage was included in the model.

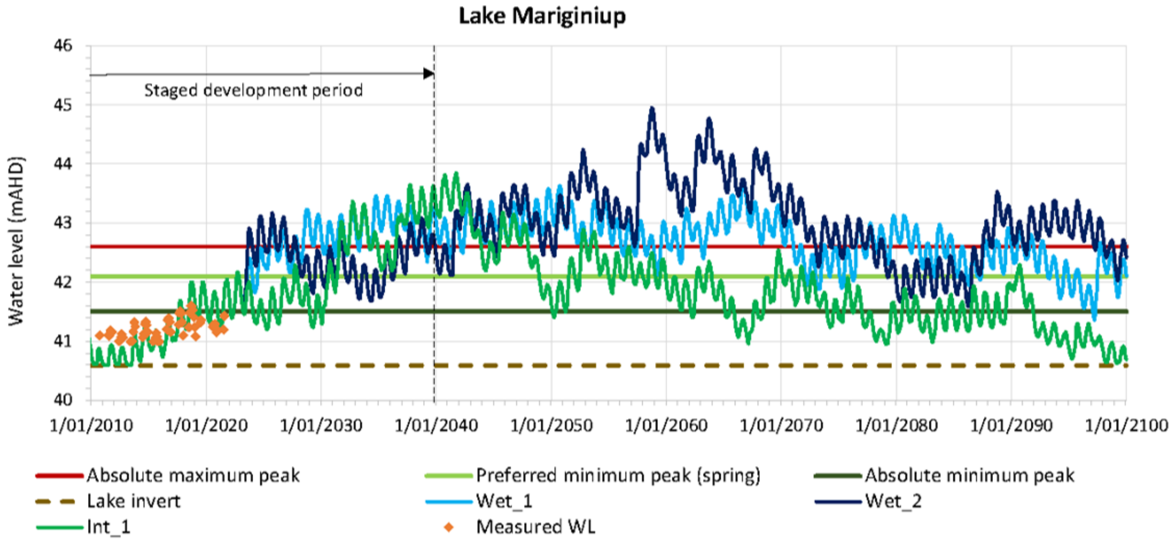
7.3.6.1. Lake water levels

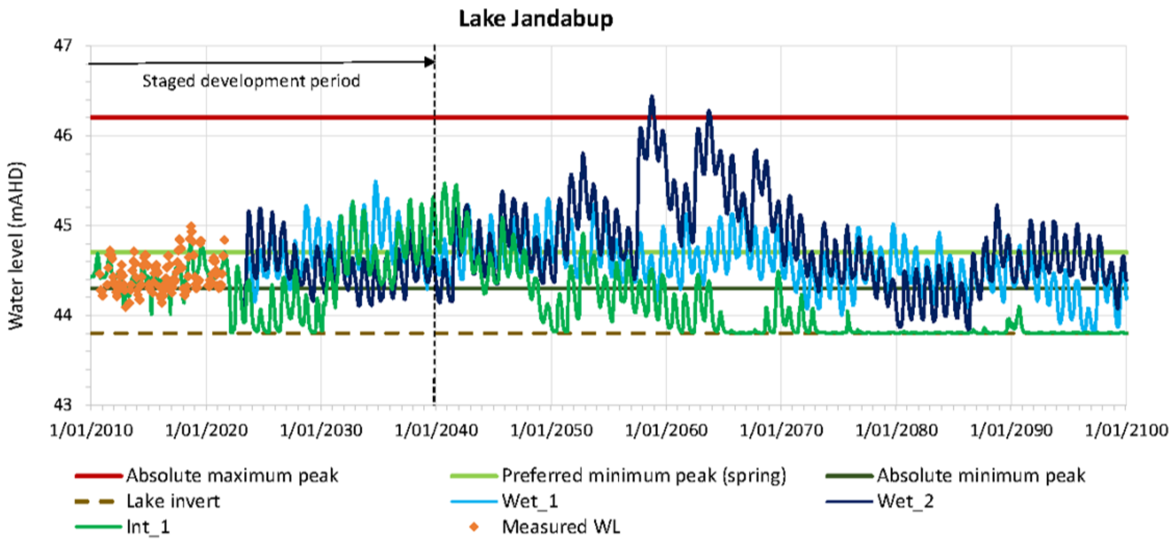
Lake water levels for the 'staged to 2040' simulations are presented in Figure 74. The Wet_1 and Wet_2 lake water levels for the 'staged to 2040' simulations were also compared to the lake water levels from the full buildout with subsoil drainage at 2.0 m bgl simulations (Simulations 7 and 8) in Figure 75, and to the 'no development' simulations (a and b) in Figure 76

The lake water levels figures show:

- Simulated water levels in Lake Mariginiup exceeded the absolute maximum peak during high rainfall events/years during the development staging period (i.e., prior to 2040) and following the end of the staged development (after 2040)
- Simulated Lake Mariginiup water levels for the 'staged to 2040' development option were:
  - Generally lower than the full buildout water levels through the development period (up to 2040).
  - Similar or higher than the full buildout lake water levels during high rainfall events, following the staged development (after 2040), when subsoil drainage is not included in the model to control higher groundwater levels.
  - Higher for the 'staged to 2040' simulations than the levels simulated for no development goes ahead in the East Wanneroo DSP area.
- The simulation results indicate peak water levels in Lake Mariginiup will be controlled to some extent by subsoil drainage infrastructure (indicated by the full buildout simulation results that include subsoil drainage).
- During staging and at full buildout, water levels in Lake Mariginiup will need to be monitored and managed through a discharge system to ensure maximum water levels are controlled.
- Simulated Lake Jandabup water levels, differed to those in Lake Mariginiup, as follows:
  - The full buildout simulated water levels with subsoil drainage were generally higher than the 'staged to 2040' simulations both during and after the 'staged to 2040' development.
  - The higher simulated full buildout water levels for Lake Jandabup are likely due to the increased area of urban development around Lake Jandabup compared to the reduced staged development area for the 'staged to 2040' simulation. The increased urban development would have groundwater levels in the vicinity of the lake and higher lake levels as the major lakes are expression of the groundwater table.
  - The staged water levels were generally higher than the 'no development' levels, but generally by less than 0.5m.
- 'Staged to 2040' simulated water level trends in Lake Gnangara differed from the other two major lakes, as follows:
  - The staged water levels and full buildout water levels were similar and followed the same trends, but the staged development had higher peaks and lower troughs than the full buildout development.
  - The lower amplitude water levels for the full buildout development is interpreted as being due to the higher water levels with urban development around Lake Gnangara but with the levels constrained by subsoil drainage, reducing the water level fluctuations.

- The ‘staged to 2040’ and ‘no development’ lake water levels were very similar, indicating staging to 2040 is likely to have a negligible impact on Gnangara Lake water levels.





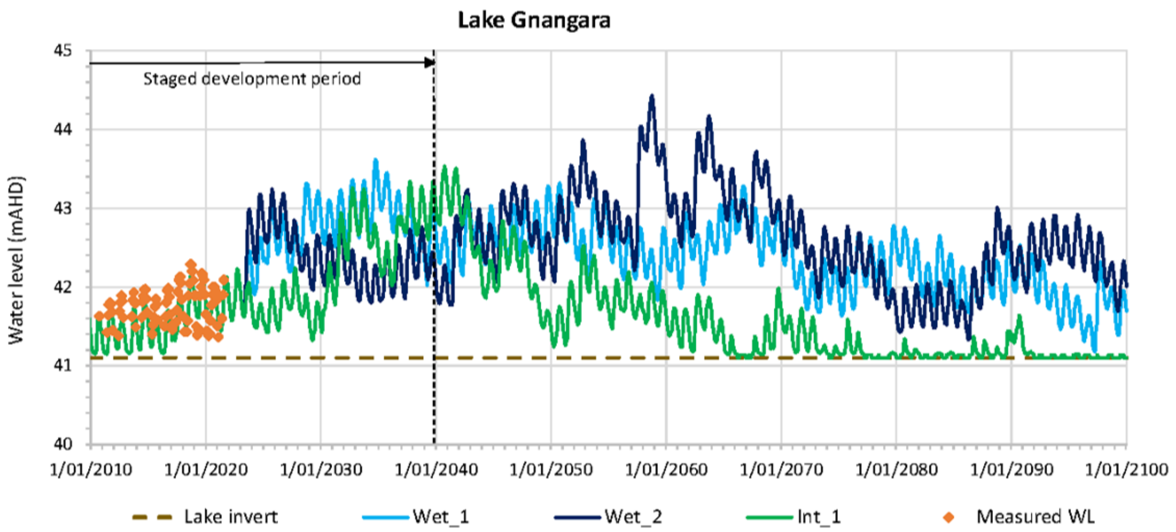


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Figure 74: Lake water levels for 'staged to 2040' simulations with no subsoil drainage, under three climate scenarios (Simulations 11 to 14)

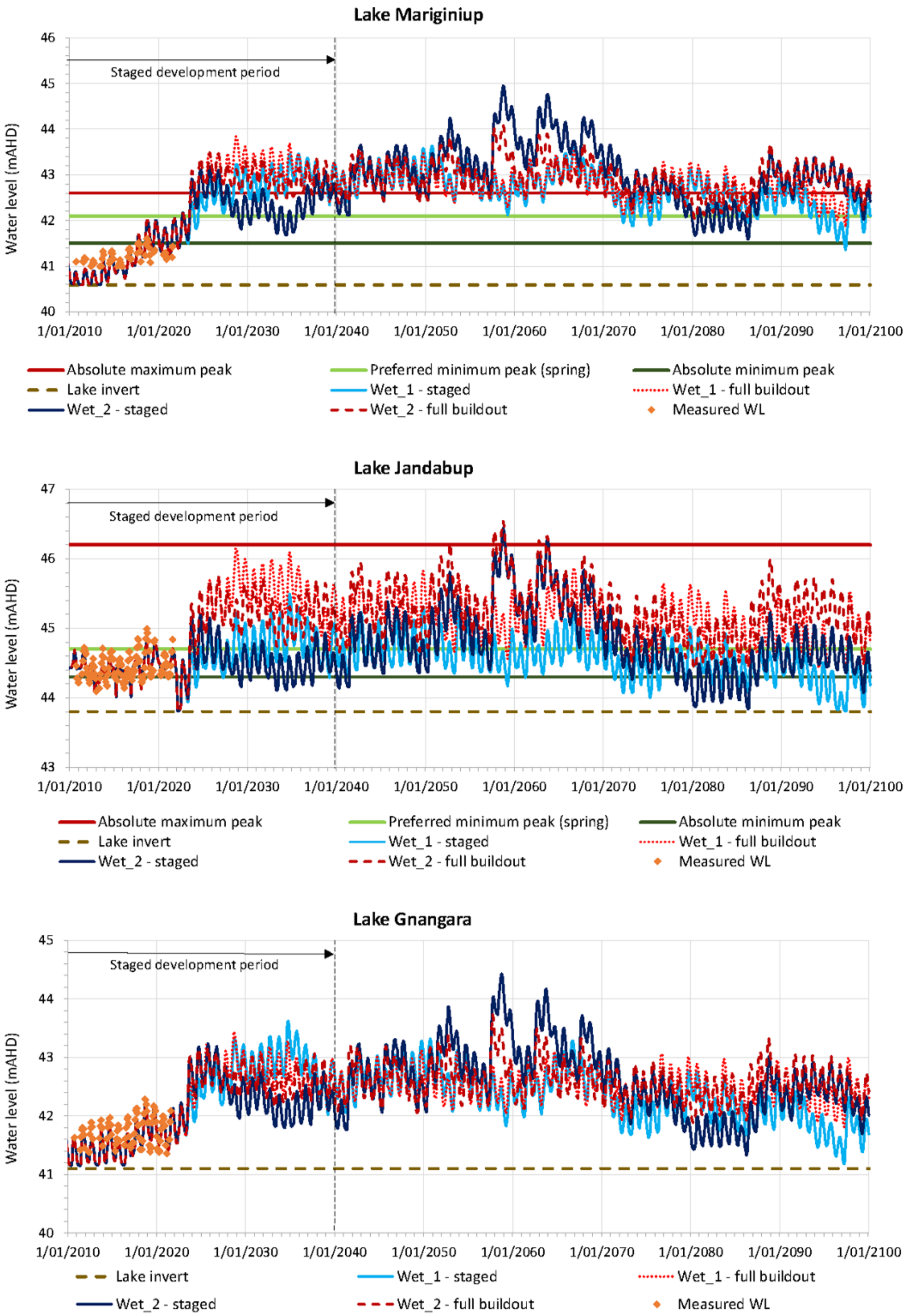
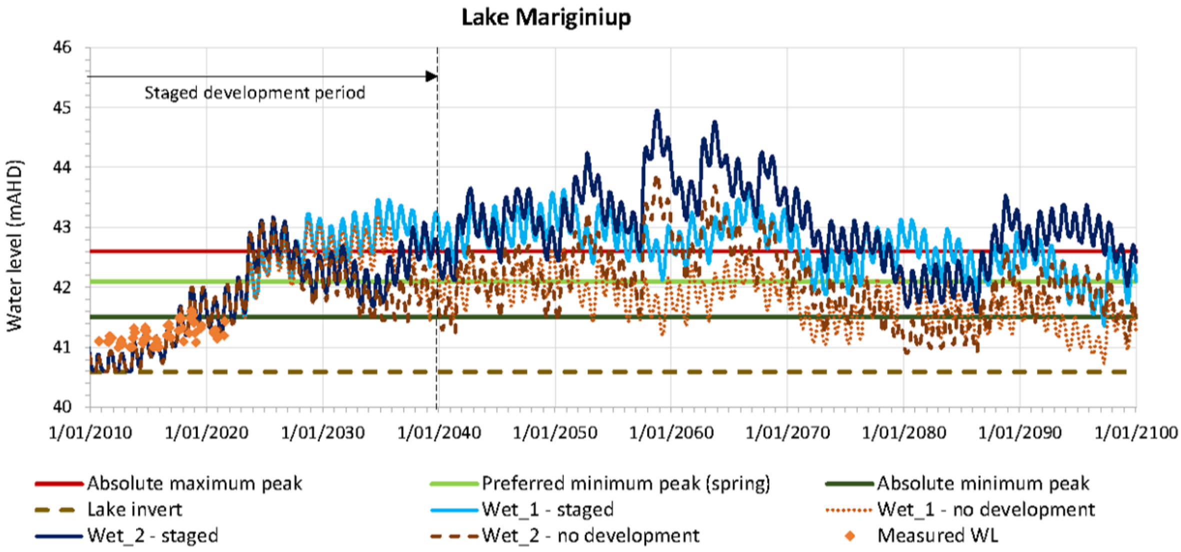
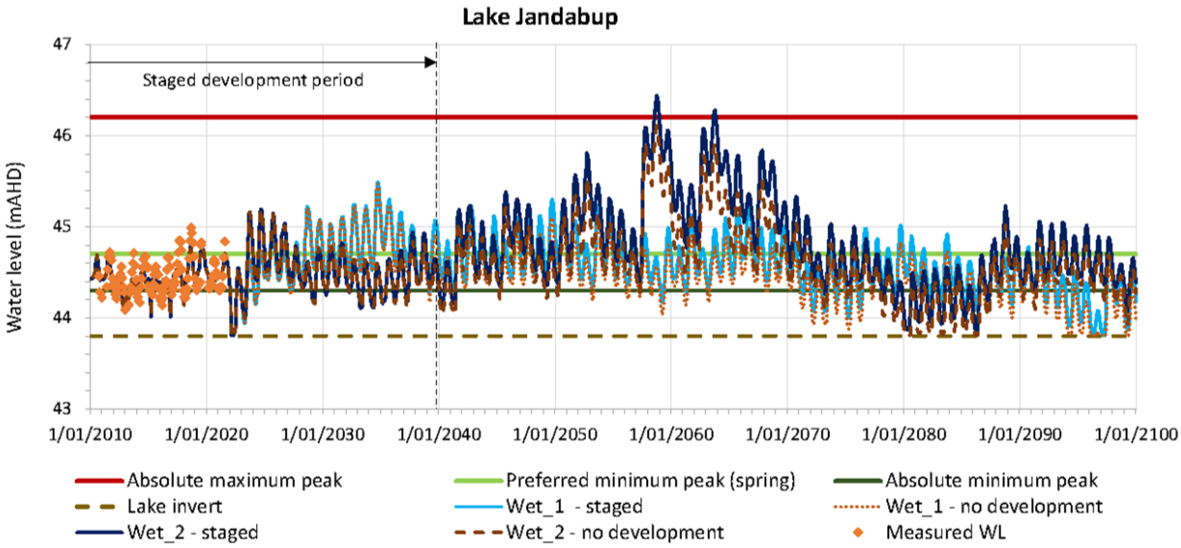


Figure 75: Comparison of the staged development (to 2040) and full buildout (with subsoil drainage) lake water levels for the wetter climate scenarios (Wet_1 and Wet_2 only)





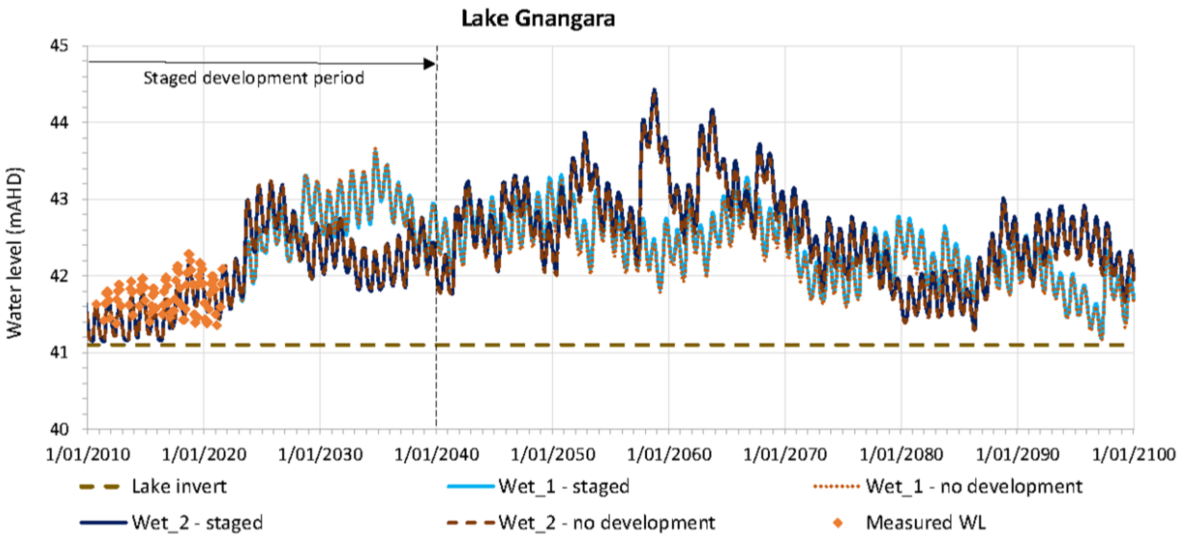


Figure 76: Comparison of the staged development (to 2040) and 'no development' lake water levels for the wetter climate scenarios (Wet_1 and Wet_2 only)

7.3.6.2. Maximum groundwater levels

Maximum groundwater levels for the 'staged to 2040' (with no subsoil drainage) simulations are presented in Figure 77. As for previous simulations, the MGL surfaces for the Wet_1, Wet_2 and Int_1 climate scenarios appear to show relatively minor differences at the vertical scale of the figures.

The impact on maximum groundwater levels of staged development to 2040 with no subsoil drainage is shown in Figure 78. This figure presents the difference between the simulated 'staged to 2040' MGL surface and the corresponding MGL surface for no development of the East Wanneroo DSP area. The resulting depth to MGL is shown in Figure 79. The comparison maps show the following:

- Groundwater is likely to mound above the 'no development' MGL surface along the western side of the DSP area where urban development is simulated to occur. As no subsoil drainage is included in the model, the mounding occurs due to the increased recharge that is simulated to occur with urbanisation.
- The staged MGL surface mounds up to about 1m above the 'no-development' MGL surface for the Wet_2 climate scenario. Mounding of up to about 0.4 m and 0.75 m above the 'no development' MGL surface occurs for the Wet_1 and Int_1 scenarios, respectively.
- Staged development to 2040 with no subsoil drainage primarily impacts maximum groundwater levels on the western side of the DSP area, extending towards the western side of Lake Jandabup, with minimal impacts around Lake Gnangara.

7.3.6.3. Significance of results

The 'staged to 2040' development simulations indicate:

- Staged development on the western side of the East Wanneroo DSP area is likely to increase maximum groundwater levels, by up to 1m, but the effects are localised to the western side of the DSP area, extending towards the western side of Lake Jandabup.
- Lake Mariginiup water levels will need to be monitored and will likely require adaptive management as model simulations indicate rising groundwater levels due to development will cause Lake Mariginiup water levels to rise above the absolute maximum peak in wetter rainfall years.

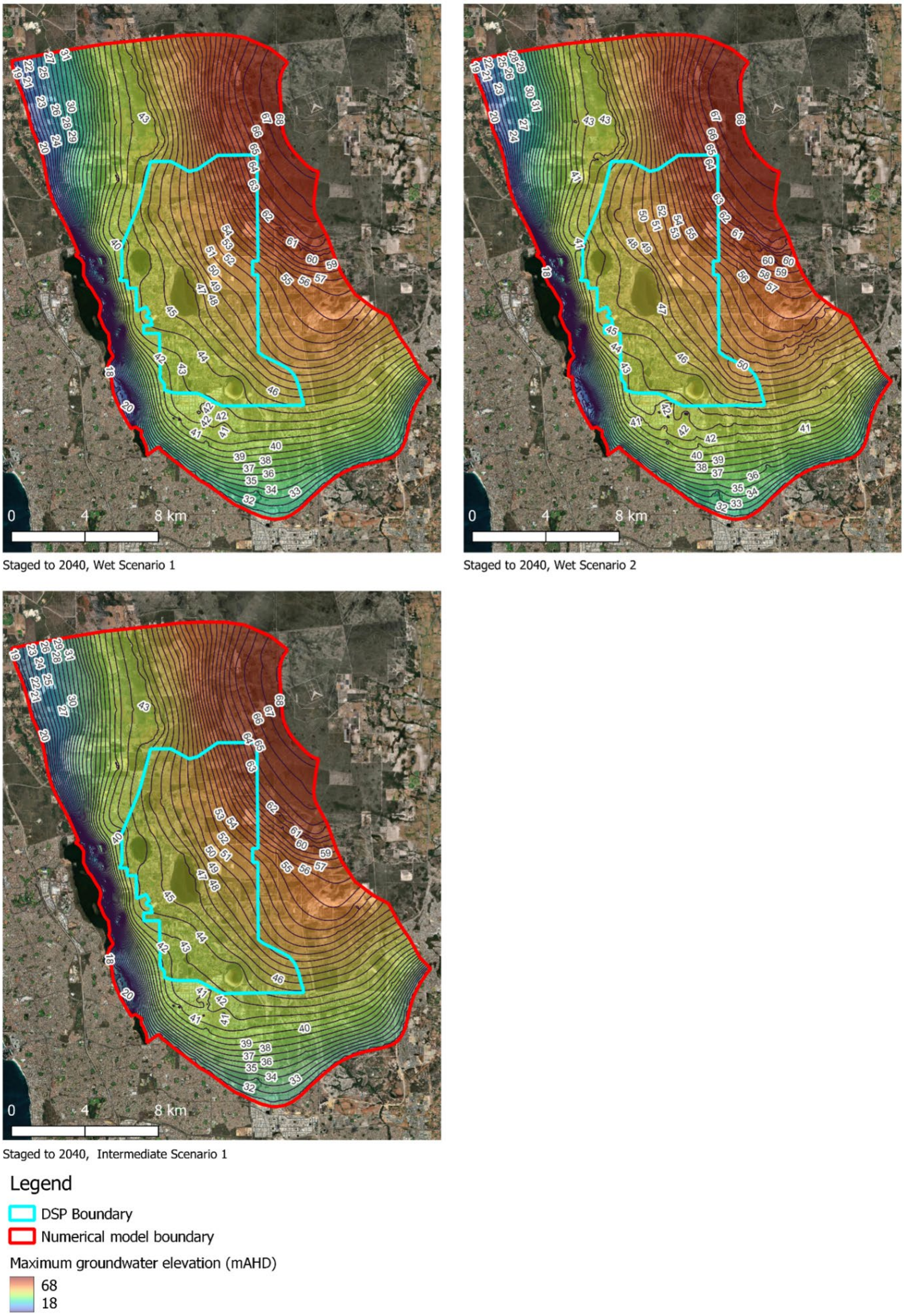
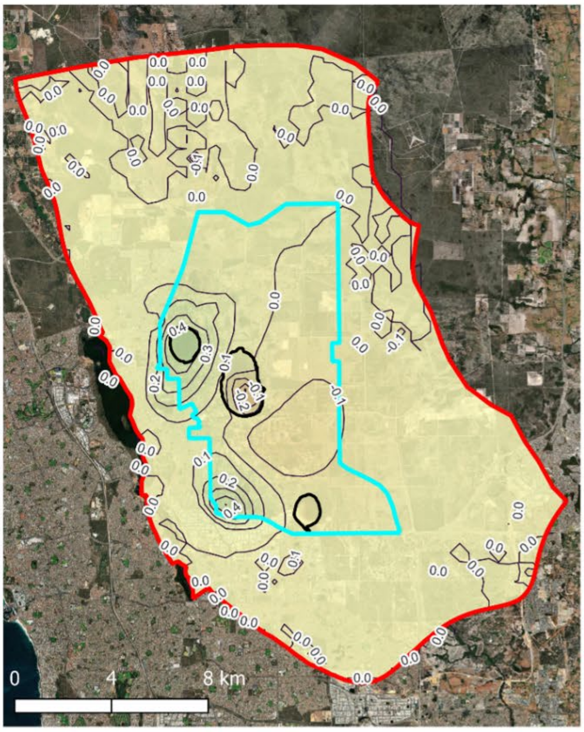
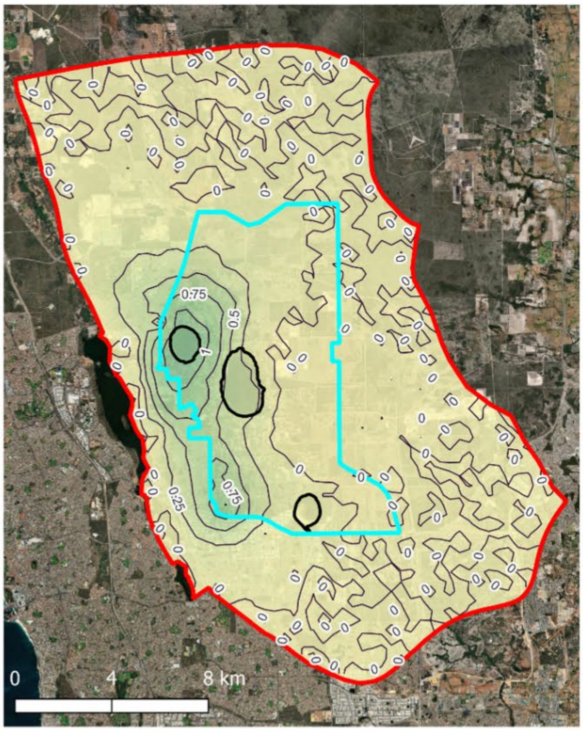


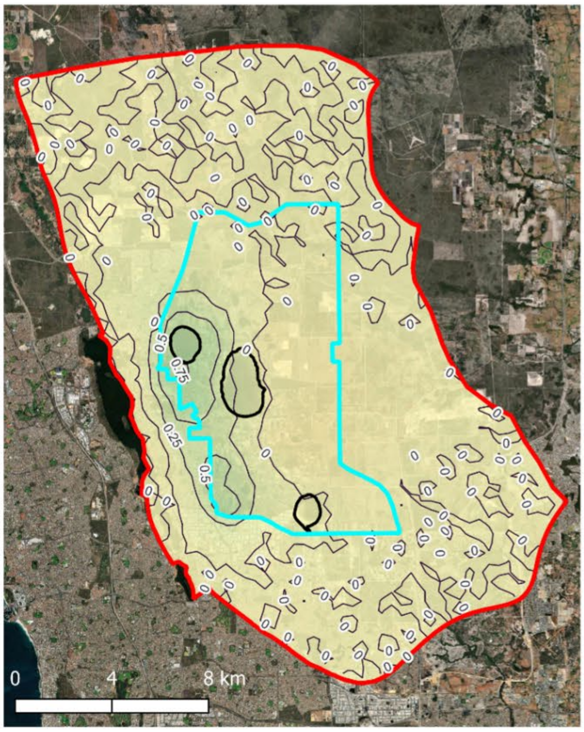
Figure 77: MGL surface for the ‘staged to 2040’ simulations with subsoil drainage at 2 m bgl, under the three wetter climate scenarios (Wet_1, Wet_2 and Int_1)



Staged development vs No development, Wet Scenario 1



Staged development vs No development, Wet Scenario 2



Staged development vs No development, Intermediate Scenario 1

Legend

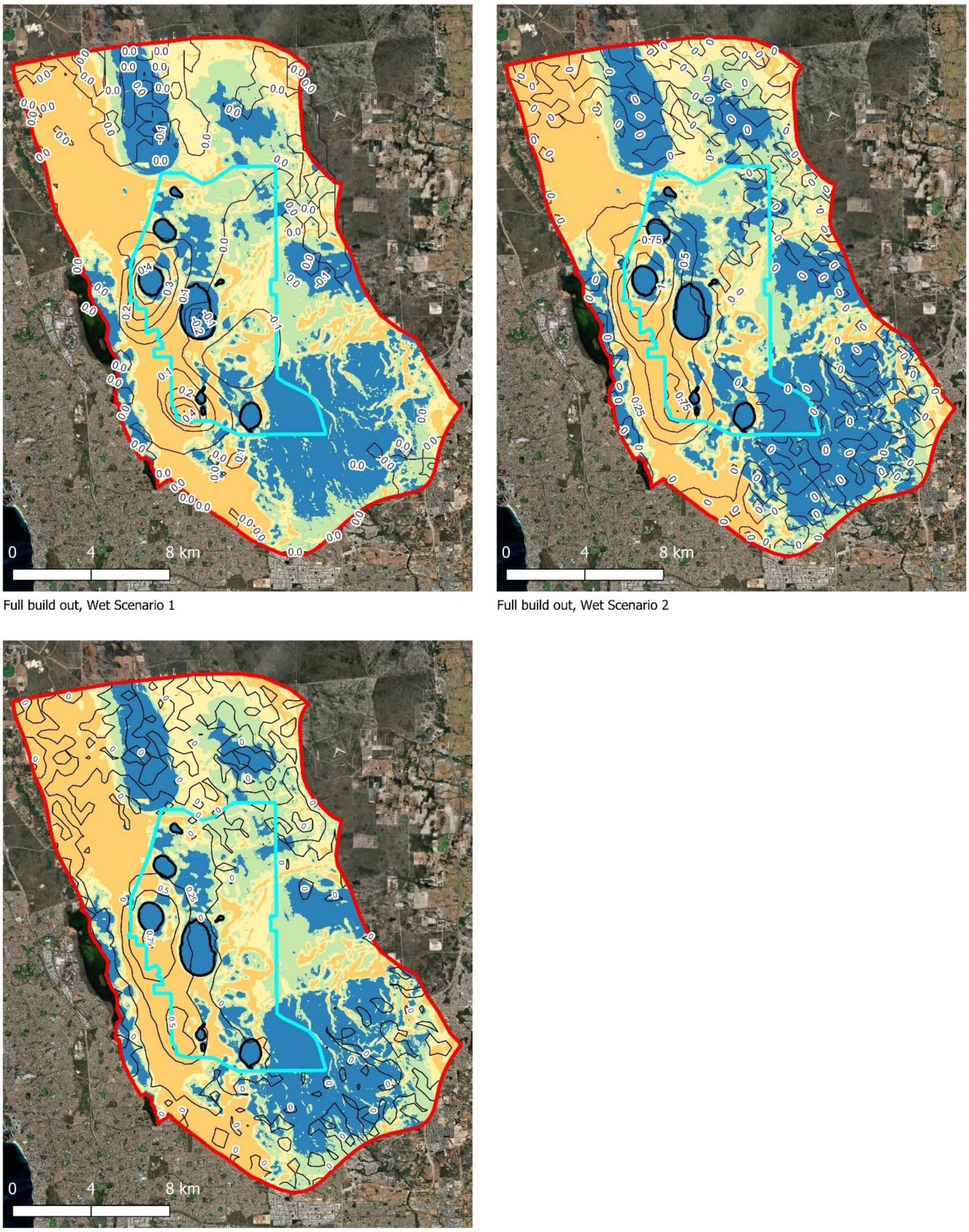
DSP Boundary

Numerical model boundary

Staged Development vs No Development
(+ve = higher water level during SD; -ve = lower water level during SD)

2
-2

Figure 78: Comparison of the 'staged to 2040 MGL surface for the three wetter climate scenarios (Wet_1, Wet_2 and Int_1) with the no development MGL surface



Legend
- Model Boundary
- DSP Boundary
- Lake

Depth to MGL surface (m)
- <= 2
- 2 - 5
- 5 - 10
- > 10
- Difference between build out to 2040 and no development scenario - groundwater drawdown contours (-ve = higher water level during staged development, -ve = lower water levels during staged development).

Figure 79: Depth to MGL surface with contours of relative change due to development (staged to 2040)

8. Model sensitivity

Pentium's experience and advice from DWER have indicated that climate is likely to have the greatest impact on modelled water levels and subsequent subsoil flow volumes. The effect of climate variability has been tested for each of the model scenarios. The impact of subsoil depth and extent has also been tested in the various scenarios by comparing the results of subsoils based at a depth of 2.5m below ground surface, 2.0m below ground surface, and the effect of temporal subsoil installation under the staged scenarios. The results indicated that the extent and timing of subsoil installation does not have a significant impact on the results, with climate related differences being the dominant driver of model uncertainty.

The sensitivity of the groundwater model was further assessed by varying key input parameters against a base model. Simulation 7, which is a full buildout model with subsoil drains at a maximum depth of 2 m bgl model under the Wet_1 climate scenario was selected as the base model. Based on discussions with DWER, three key input parameters were varied to generate three sensitivity models, as follows:

- Sensitivity 1 (S1) – no leakage:
  - leakage was removed from the base case model from January 2023 onwards (i.e., at the start of the future simulation period) so that there was no future leakage from the Superficial aquifer.
- Sensitivity 2 (S2) – no Water Corporation abstraction:
  - Water Corporation abstraction was removed from the base case model from January 2023 onwards.
- Sensitivity 3 (S3) – boundary conditions increased by 1m:
  - Boundary conditions on the western and southern boundary were increased by 1m from January 2023 onwards.

The following modelling results are presented to illustrate model sensitivity:

- Lake water levels for the three sensitivity simulations and base case simulation (Figure 80).
- MGL surfaces from the base case (Simulation 7) and each sensitivity model simulation (S1, S2 and S3), along with the difference between the two MGL surfaces (Figure 81, Figure 82 and Figure 83).
- Total annual subsoil drainage across the EWDSP area for the three sensitivity simulations and base case simulation (Figure 84)
- Annual subsoil drainage for all subsoil drainage catchments (Appendix G).

The results from each sensitivity model simulation are discussed in the following sections.

8.1. 'No Leakage' simulation (Simulation S1)

The first sensitivity simulation (S1) assessed no leakage from the Superficial Aquifer following full buildout across the DSP area. The results of the sensitivity simulation are as follows:

- The difference between the MGL surfaces for the base case model and the S1 sensitivity model (Figure 81) indicates that MGLs increased when no leakage was included in the model, particularly in the northern parts of the model domain where leakage rates are higher. With no leakage, maximum groundwater levels increased by more than 1.75 m in the northern parts of the model domain, and by up to about 0.7 m across the north-eastern quadrant of the DSP area.
- With leakage removed from the model causing higher groundwater levels, drainage flow rates increased. With no leakage, the total annual subsoil drainage volume from the DSP area (Figure 80) increased from 22.6 GL/yr for the base case to 24.6 GL/yr, an increase of about 9%.
- A review of the total annual subsoil drainage volumes for each catchment (Appendix G) shows:
  - Catchments to the north of the DSP area, such as Catchments 2 and 9, had greater impacts from the removal of leakage with annual subsoil drainage volumes increasing

  - by more than 20% in high rainfall years, and by an even greater percentage in lower rainfall years.
  - Catchment 59 on the eastern side of Lake Jandabup showed an increase in annual subsoil drainage volume of 10 to 15% in higher rainfall years.
  - Catchments at the southern end of the DSP area (such as catchments 130, 144 and 201) have similar annual subsoil drainage volumes with or without leakage included in the model.
- There was no significant change to lake water levels when leakage from the Superficial Aquifer was removed at full buildout of the DSP area (as shown in Figure 80), which is expected as the lakes are largely south of the area of impact shown in (Figure 81) and increases in groundwater levels around the lakes are being managed through subsoil drainage.

The 'no leakage' simulation indicates that subsoil drainage volumes and flow rates are sensitive to changes in leakage from the Superficial Aquifer, particularly subsoil drainage in the north half of the DSP area.

Lake and groundwater levels are less sensitive to the changes in leakage because:

  - The greatest impacts on groundwater level are localised to northern and north-western parts of the model domain, outside of the DSP boundary, where the Kardinya Shale confining layer is absent and there are higher rates of leakage from the Superficial Aquifer into the Leederville Aquifer
  - Groundwater levels are largely controlled by subsoil drainage across much of the development area that would be impacted by the removal of leakage.

8.2. 'No WC abstraction' simulation (Simulation S2)

The second sensitivity simulation (S2) assessed the impact of no Water Corporation abstraction occurring within the model domain in the Superficial Aquifer. The results of the S2 sensitivity simulation are as follows:

- The difference between the MGL surfaces for the base case model and the S2 sensitivity model (Figure 82) indicates that groundwater levels increased locally to the east and south of the DSP area where the Water Corporation bores were active in the base case. Without Water Corporation abstraction, simulated water levels increased by up to 0.75 m on the eastern boundary of the DSP area, but much of the area impacted by groundwater level rise in excess of 0.25 m will remain as State Forest (as shown in Figure 1).
- With no Water Corporation abstraction, the higher groundwater levels resulted in increased drainage flow rates. The total annual subsoil drainage volume from the DSP area (Figure 80) increased from 22.6 GL/yr for the base case to 24.0 GL/yr, an increase of about 6%.
- The total annual subsoil drainage volumes for each catchment (Appendix G) shows:
  - Catchments to the north of the DSP area, such as Catchments 2, 5 and 9, had similar annual subsoil drainage volumes with or without Water Corporation abstraction.

    Catchment 59 on the eastern side of Lake Jandabup was impacted by the removal of Water Corporation abstraction with annual subsoil drainage volumes increasing by more than 10% in the high rainfall years, and Catchment 202 at the south-eastern corner shows about a 5% increase in the total annual subsoil drainage volume.
  - Largely internal catchments south of Lake Mariginiup and Lake Jandabup (e.g., 130, 144 and 201) have negligible changes in annual subsoil drainage volume when there is no leakage.
- There was no significant change to lake water levels with no Water Corporation abstraction from the Superficial Aquifer (as shown in Figure 80), which is expected as the lakes are west of the area of impact shown in Figure 82.

The 'no WC abstraction' simulation indicates that subsoil drainage volumes and drain flow rates increase in catchments on the eastern side of the DSP area when there is no Water Corporation abstraction from the Superficial Aquifer.

Lake and groundwater levels area not sensitive to the changes in the Water Corporation abstraction rates.

8.3. Boundary conditions increased by 1m simulation (Simulation S3)

The third sensitivity simulation (S3) assessed the impact of increasing by 1 m, the specified transient head boundary condition on the western and southern boundary. The results of the S3 sensitivity simulation are as follows:

- The difference between the MGL surfaces for the base case model and the S3 sensitivity model (Figure 83) indicates that groundwater levels increased locally around the western and southern boundaries, but the increases did not extend to within the DSP area.
- Based on the total annual subsoil drainage volumes from the DSP area, increasing the BC elevation by 1 m only resulted in a 1% increase to the maximum total subsoil drainage volume across the DSP area.
- The total annual subsoil drainage volumes for each catchment (Appendix G) also show there is minimal impact on subsoil drainage volumes at the catchment scale, when the boundary conditions are increased by 1 m.
- There was no measurable change to lake water levels when the boundary conditions are increased by 1m (Figure 80).

Subsoil drainage flow rates and total flow volumes and lake water levels were not sensitive to the increased head elevation across the western and southern boundaries.

8.4. Recharge

Recharge was not explicitly assessed through a sensitivity analysis, but the simulation of different climate scenarios ranging from a very dry (Dry_1) to very wet scenario (Wet_2) indicates that subsoil drainage flow rates, subsoil drainage flow volumes and lake and groundwater levels are sensitive to recharge over the expected range of likely recharge rates obtained from the future climate scenarios.

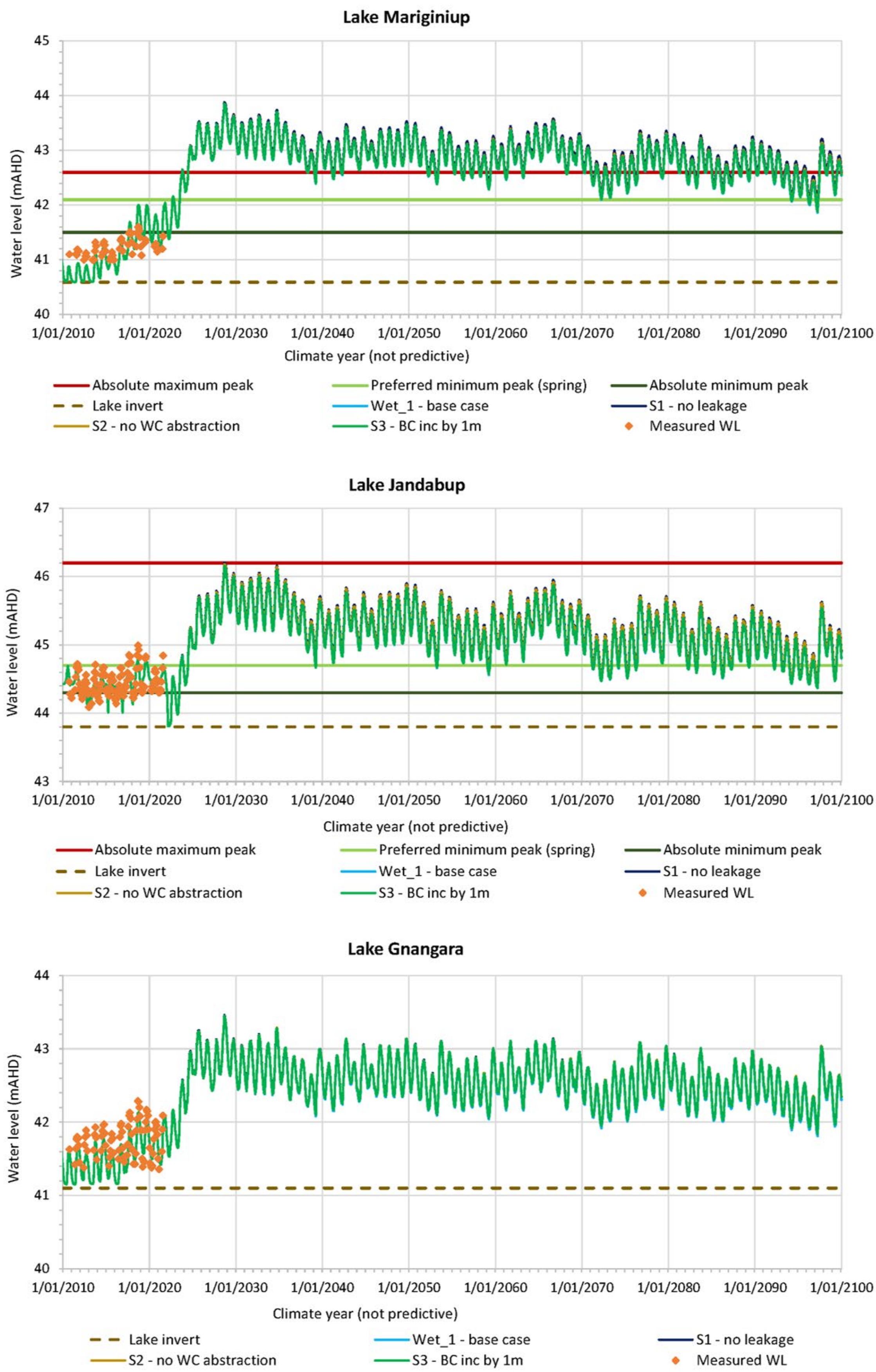


Figure 80: Lake water levels for three sensitivity simulations (S1 to S3) against the Wet_1 full buildout base case simulation (Simulation 7)

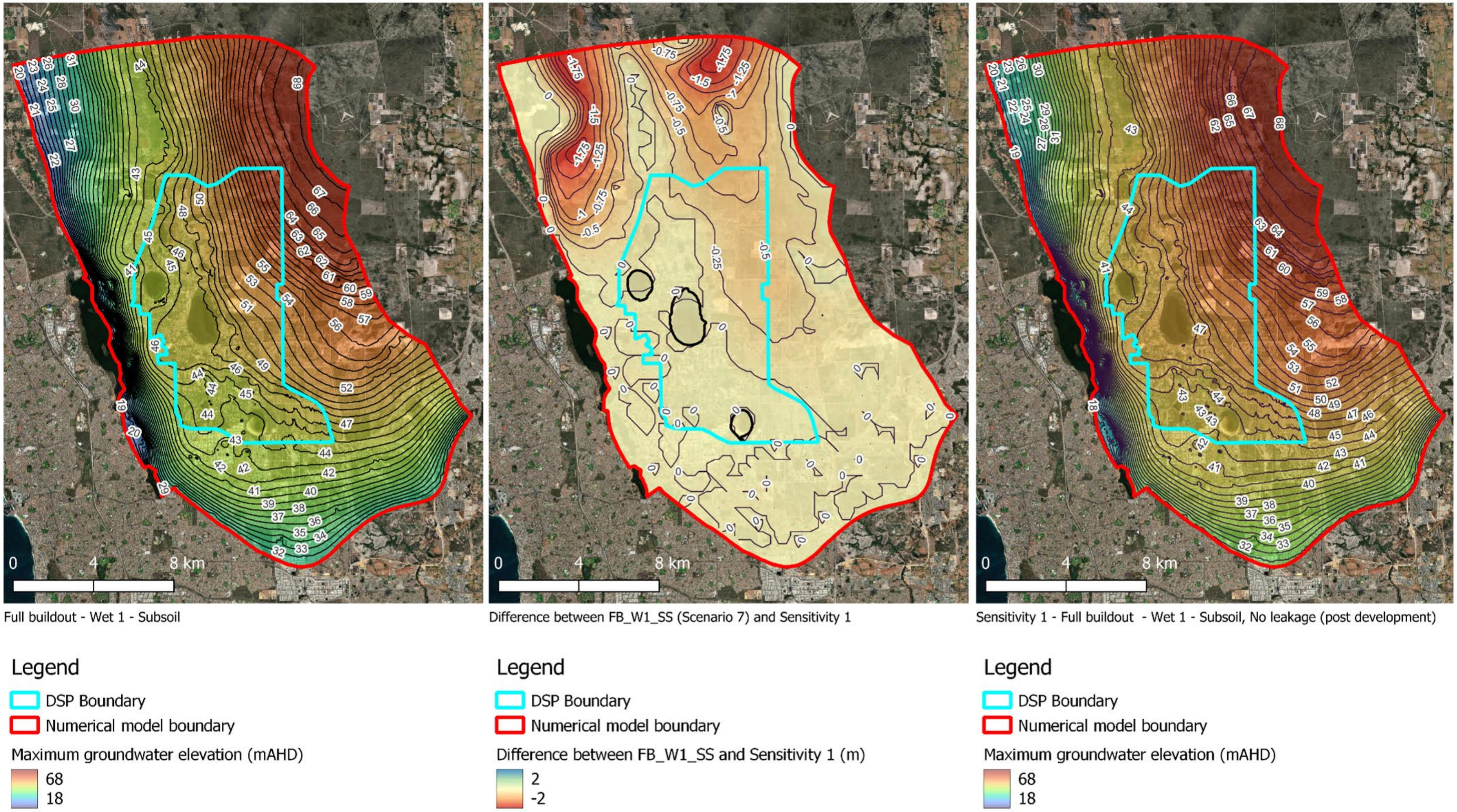


Figure 81: MGL surface for the base case (left), the 'S1 – no leakage' sensitivity model simulation (right) and the difference between the two MGL surfaces (centre)

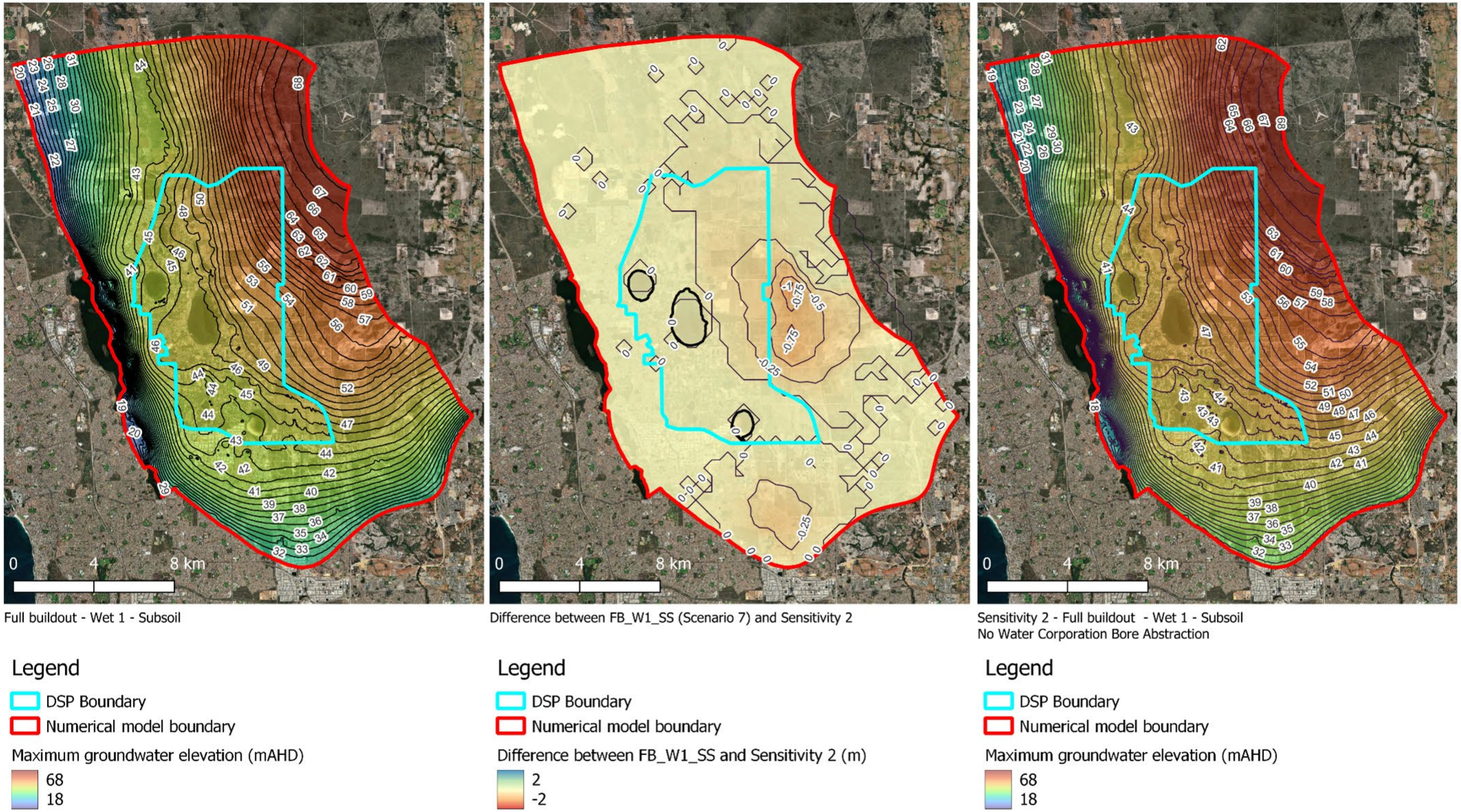


Figure 82: MGL surface for the base case (left), the 'S2 – no WC abstraction' sensitivity model simulation (right) and the difference between the two MGL surfaces (centre)

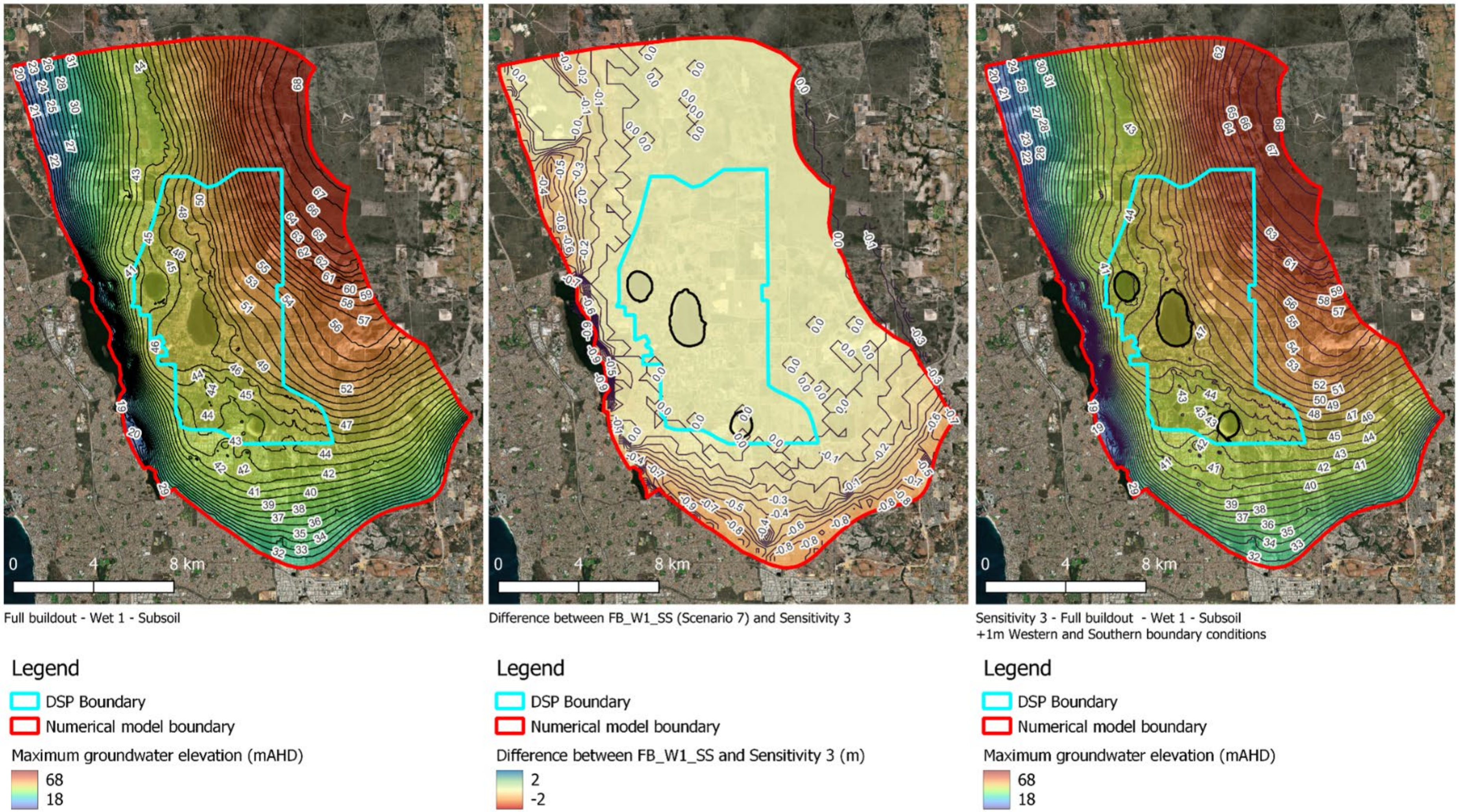


Figure 83: MGL surface for the base case (left), the 'S3 – BC inc by 1m' sensitivity model simulation (right) and the difference between the two MGL surfaces (centre)

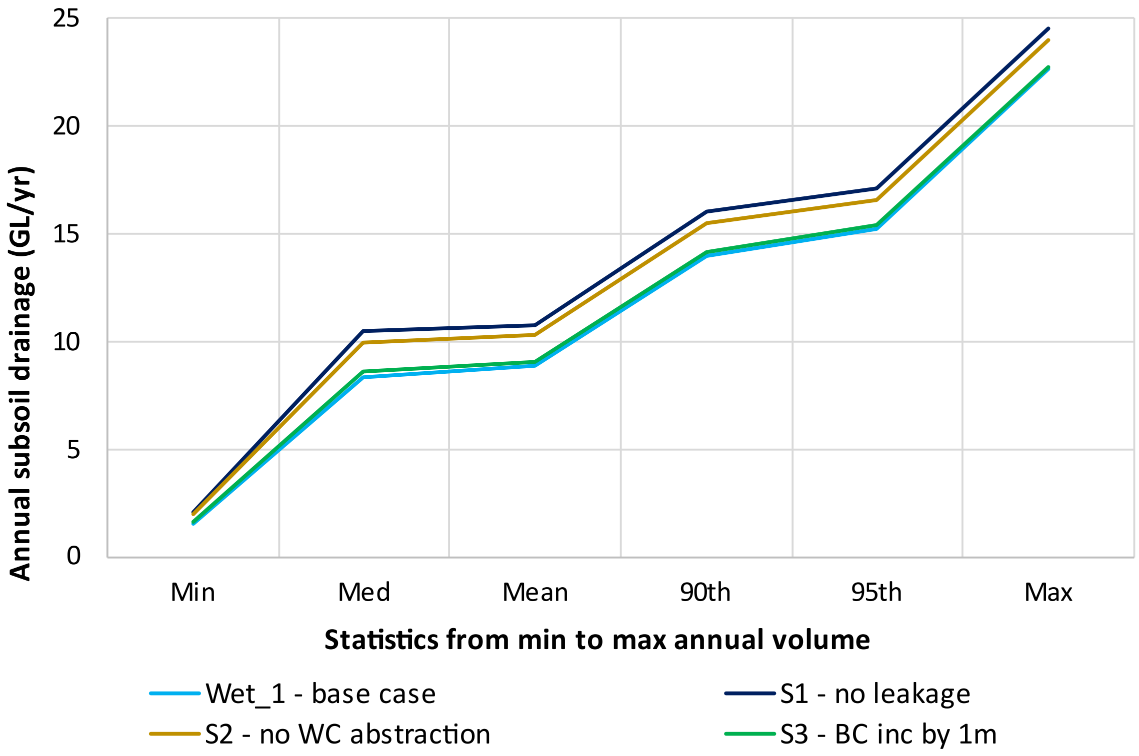


Figure 84: Total annual subsoil drainage volume statistics for the base case (Simulation 7) and three sensitivity simulations

9. Lake level management concept simulations

The future simulations presented in Section 7 relate to the controlling of groundwater across the DSP area including subsoil extent and estimates of subsoil flow. The model simulations effectively remove water captured by the subsoils (using the MODFLOW Drain package) from the model and do not return the drainage water into the model domain. This is a typically sound assumption in most urban settings where subsoils discharge to free-flowing outlets (typically linear surface drainage features) and are then conveyed away from the site.

However, due to the topography of the DSP area and presence of interdunal wetlands, most of the DSP area is centrally draining with no outlet to a drainage feature able to transmit water away from the proposed development areas. The DWMS proposes to gravity drain subsoil and stormwater to major wetlands were possible (via constructed treatment basins located external to the natural wetlands). Local trapped catchments (i.e. those that do not drain towards the major wetlands under natural conditions) are proposed to have infrastructure adjoining drainage basins with water pumped to the closest major wetland.

Due to the potential for high volumes of drainage water under wet climates and/or large rainfall events, coupled with the likely coincidence of high groundwater levels, the lakes may not have adequate capacity to store all the drainage water under these conditions. Therefore, an artificial mechanism to transfer water between the lakes and/or out of the DSP area is required to manage lake and groundwater levels across the DSP. The combination of local drainage collection points (precinct scale) and lake transfer pumping systems (district scale) form the proposed East Wanneroo Groundwater Management Scheme (EWGWMS). This section considers the feasibility of the EWGMS in terms of lake water level response to receiving water via either direct rainfall, subsoil drainage or stormwater inflows (as described in the DWMS) and the required pumping of surplus water between lakes and out of the DSP.

9.1. Model updates

In order to undertake a more detailed assessment of the lake levels in response to proposed water management, several updates were made to the numerical groundwater model in order to simulate the proposed EWGWMS (pumping and discharge of water into, out of, and between lakes). These include:

- Conversion of the model to MODFLOW-6 (MF6). The lake package in MF6 remains an active part of the regional groundwater model solution, whereas all earlier versions of MODFLOW (including MPDFLOW-USG - the solver for the original model) “deactivate” lake model cells from the regional model, requiring lake input and outputs to be manually and iteratively updated in successive model runs. MF6 is currently the only MODFLOW solver capable to couple the transient lake inputs and outputs with the operations of other boundary conditions within the same groundwater model solution.
- As the lake cells remain active in the MF6 numerical model, hydraulic properties representing a “void” are required to produce water levels reflecting those simulated in Section 7.3. A hydraulic conductivity of 1000 m/day and a specific yield of 1 were applied to cells representing the lake boundary condition.
- The Multi-aquifer Well (MAW) package was used to represent pumping of water out of the lakes, with pump switch on-off level set as the Absolute Minimum Peak level (see Table 27) to ensure the lake was not pumped below the minimum environmental threshold. The Automatic Flow Reduction option was used to reduce the flow rate as the lake level approached the pump on-off level, such that pumping rates fluctuated between the maximum applied abstraction rate and zero abstraction as required based on the simulated lake level. In reality, a shorter-term on-off cycle would likely be applied, however this degree of control is not possible to include in the model with monthly stress periods.
- The MF6 Water Mover (WMV) package was used to direct subsoil flows (from the Drain package) into lakes based on the overall wetland catchment areas (i.e. includes trapped catchment flows pumped from local catchments and gravity flows that are free flowing to wetlands) shown in Figure 85. Any water removed by the MAW package from lakes Mariginiup, Gnangara, Adams, Coogee Swamp, Badgerup and Little Badgerup were transferred into Lake Jandabup using the modelled fluxes within the current simulation. Water removed from Lake Jandabup was not redirected, as the proposed discharge location is outside of the model domain, and was considered removed from the model

water balance. Water from catchments 172 and 185 are directed outside of the DSP to an existing wetland at Da Vinci Park (not simulated in the model) and catchments 201 and 202 were excluded from the water management system as these are planning investigation areas with low probability of development.

- Surface water flows are not explicitly included in the updated groundwater model. Recharge of stormwater at infiltration basins under average rainfall conditions is captured in the modelled urban recharge. Allowance for rapid transfer of storm events has been considered in the lake management by determining a critical freeboard level to allow for a 24hr 1% Annual Exceedance Probability (AEP) peak rainfall event as discussed further in Section 9.2.

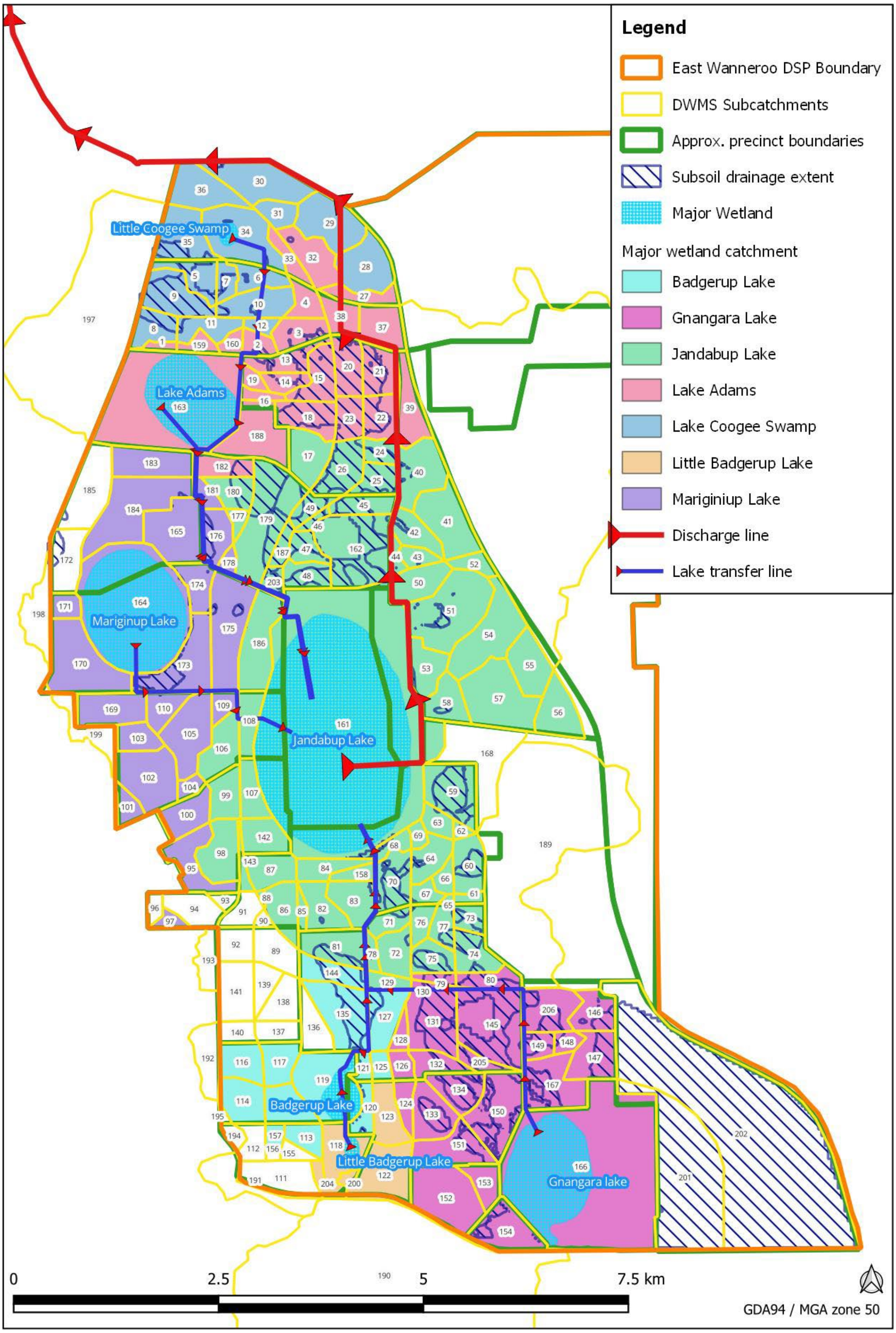


Figure 85: Subsoil drainage catchments of major wetlands and proposed EWGMS

9.2. Key lake reference levels

Pentium Water used published literature to set specific lake water management design criteria in this assessment and the EWGMS concept engineering design. Environmental minimum and maximum peak levels are based on existing contemporary surveys (Kavavos et al., 2020) and Gnangara Mound Ministerial Statement criteria (DoW, 2004) at Lake Jandabup and Mariginiup. The other lakes in East Wanneroo do not appear to have contemporary wetland vegetation surveys and assessments to determine critical environmental water requirements or preferred levels. Inferred levels have been determined using aerial imagery and LiDAR to provide an indicative range for simulated pump operation.

Engineering levels (critical spill level and critical freeboard level) have been estimated from LiDAR data. The spill level represents the height at which water level will meet the topographic elevation of existing infrastructure including roads and buildings based on a visual analysis of the LiDAR and aerial imagery data. This analysis relates to the current setting and has not considered the post-development road and building levels that are likely to be higher. The critical freeboard level is the spill level minus the amount of rise that would occur after stormwater is directed into the lakes during a 1% AEP 24hr rain event.

Table 27: Summary of key environmental and engineering levels (in mAHD) used in lake water level assessments

		Environmental thresholds			Engineering thresholds	
Wetland	**Lake invert**	**Absolute min peak (spring)**	**Min desired annual peak (spring)**	**Absolute max peak (short term)**	**Critical spill level#**	**Critical freeboard level#**
Jandabup	43.8	44.3*	44.7*	46.2^	47.5	47.0
Mariginiup	40.6	41.5*	42.1*	42.6*	45.5	45.1
Gnangara#	41.1	41.5	42	43	45	44.5
Adams#	43	43.2	44	45	46	45.4
Coogee#	46.1	46.5	47.5	49	49.5	
Badgerup#	40.3	40.7	41.5	42	43	42.3
Little Badgerup#	40.3	40.5	41.5	42	43	

*Gnangara Mound (2004) ministerial condition
^Kavazos et al 2020
Inferred by Pentium from aerial imagery and LiDAR

9.3. Full buildout development scenarios with subsoils discharged to lakes

Model simulations 18 to 21 were carried out for the four climate scenarios with development at full buildout and subsoil drainage at a maximum depth of 2.0 m bgl (as for Simulations 7 to 10) with the further addition of return of subsoil drainage water into the relevant major wetland. The purpose of these simulations was to assess the response of the lake levels to the input of subsoil drainage water and assess the lakes capacity to contain water associated with urban drainage, while earlier simulations relate to the control of groundwater mounding resulting only from the land use change.

Importantly, the results of these scenarios are not considered representative. The MODFLOW Drain package used to represent subsoils assume free draining conditions and therefore control the water levels around the lakes to the specified drain invert level (CGL), whereas in reality these subsoils would not be able to drain under such conditions due to inundation. Consequently, the modelled subsoil flows are higher than reasonable due to water overspilling from the lakes, being collected by the subsoils (drain package), and recirculating into the lakes in the model, which further increases lake levels. Conversely, while the simulated maximum groundwater level is high compared to other scenarios, it is lower than would occur in reality due to the simulated subsoils controlling down water levels (when in actuality they wouldn't be able to drain). To overcome this limitation, detailed subsoil designs (layout, pipe diameter and invert levels) would need to be explicitly represented in the model such that drain flows were restricted to the maximum pipe flow capacity. This fine scale of detail is well beyond the level of complexity able to be included in this regional model. However, what these simulations do serve is to indicate that the lakes have limited additional capacity to contain the urban drainage water, and that active management of lake levels is likely essential in the wetter climate scenarios to ensure water levels do not exceed threshold levels (engineering and/or environmental).

9.3.1. Subsoil drainage flow rates and annual subsoil drainage flow volumes

The total annual drainage flow volume statistics from for the four full buildout simulations with subsoil drainage discharging to wetlands are presented in Figure 86 and Figure 87. These results show:

- A significant increase (approximately a 300%) in subsoil drainage volumes when compared to Simulations 7 to 10 (which don't include subsoil discharge to lakes). The Wet2 maximum annual discharge rate increases from 30.7 GL/yr to 92.2 GL/yr.

While discharging subsoils to the lakes would result in a rise in lake levels and regional groundwater levels resulting in an increase in subsoil flows, the flows estimated here are considered to be excessive due to recirculation in the model at the edge of the lakes. It is not recommended that these values be used for engineering design.

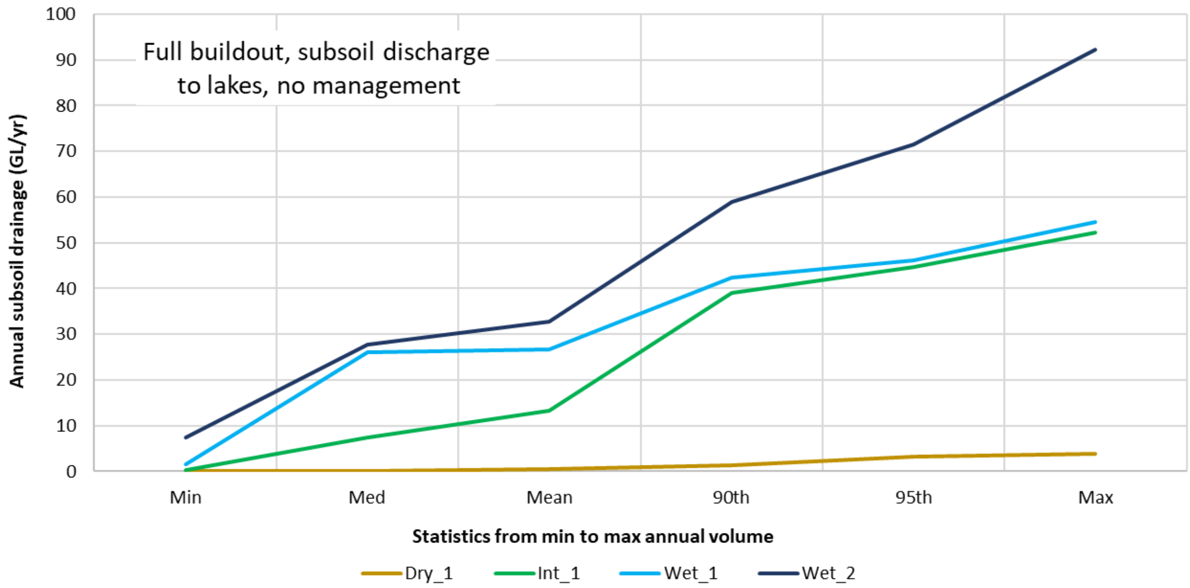


Figure 86: Total annual subsoil drainage volume statistics for the full buildout future scenario simulations with subsoils discharging to lakes

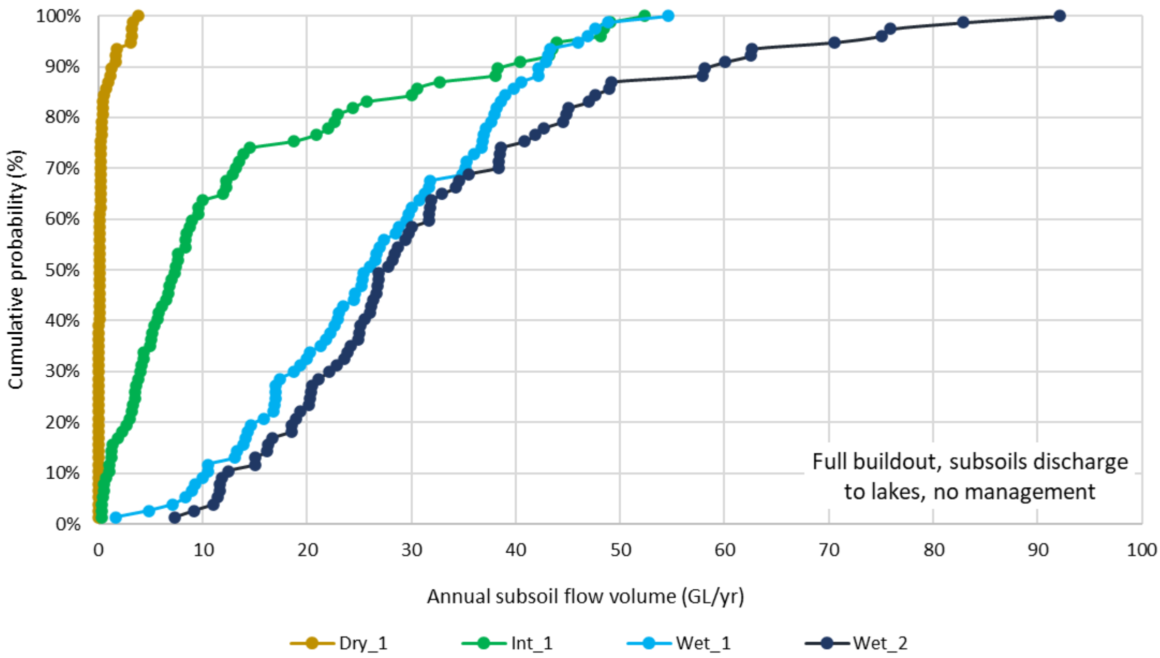


Figure 87: Cumulative distribution of annual subsoil drainage flow volume for the full buildout future scenario simulations with subsoils discharging to lakes

9.3.2. Lake levels

Lake water levels for the four full buildout simulations with subsoils discharging into lakes are presented in Figure 88, and a comparison between simulated lake water levels for the extreme Wet_2 and Dry_1 climate scenarios at full buildout and with no development is given in Figure 89 and the Wet_1 and Int_1 climates in Figure 90. The lake water level figures indicate the following:

- With development inclusive of subsoil discharge to lakes, simulated water levels in all lakes exceed the lake spill level (and consequently all lower threshold levels) in all climates except the Dry_1 climate (where environmental thresholds are breached).
- Lake water levels are likely to be substantially higher (up to 5.5m under the Wet_2 climate, and up to 5m under the Wet_1 and Int_1 climates) post-development with subsoil discharge to lakes than they would be with no development.

While lake levels are likely over-estimated due to model re-circulation of subsoil drainage, these results indicate that there is not sufficient capacity to contain urban drainage in the lakes and that subsoils (set at CGL level) would not be able to drain freely. Active management of the lake water levels will be required to enable full-buildout development.

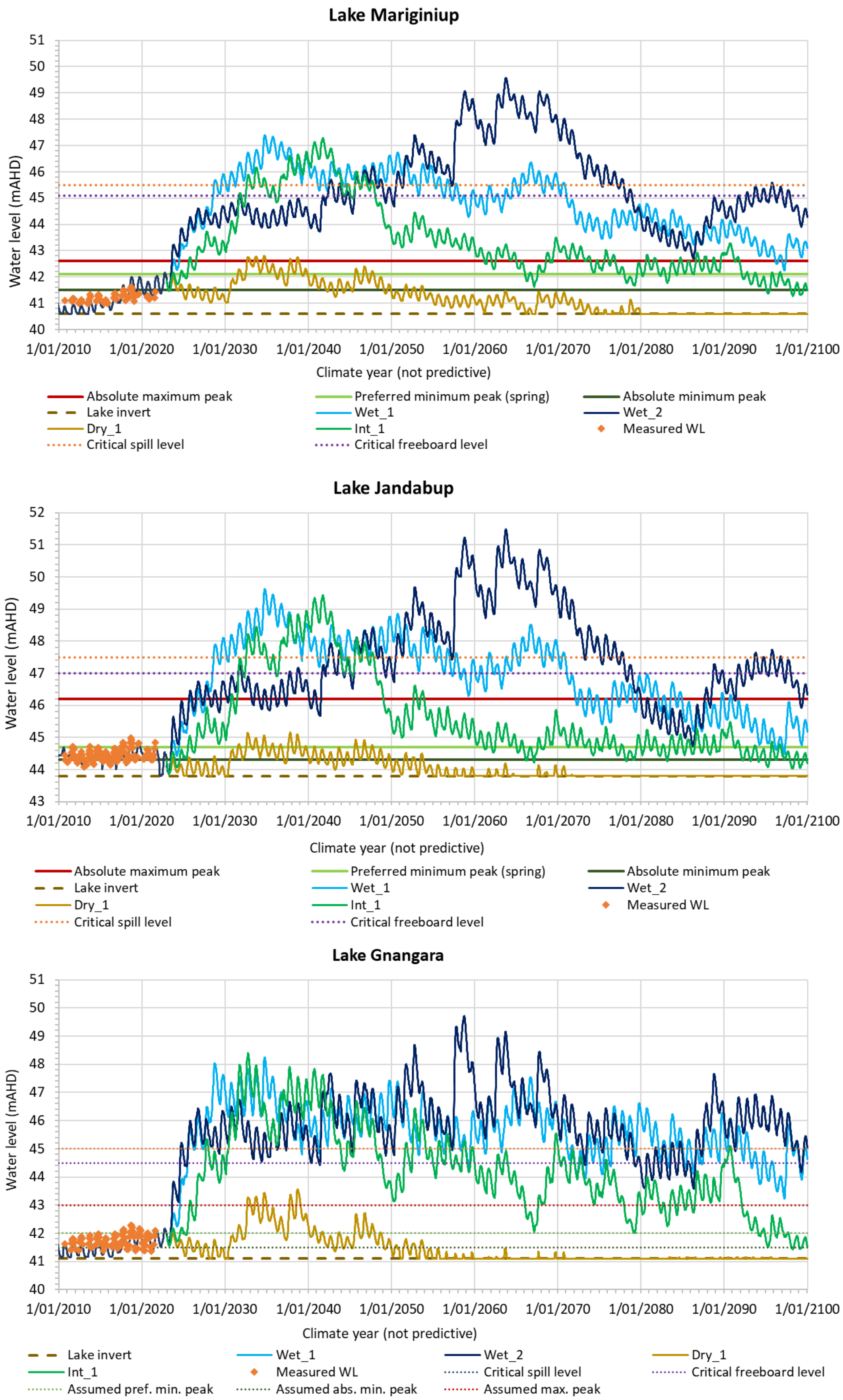


Figure 88: Lake water levels for the full buildout simulations and four climate scenarios, with subsoils discharging to lakes (Simulations 18 to 21)

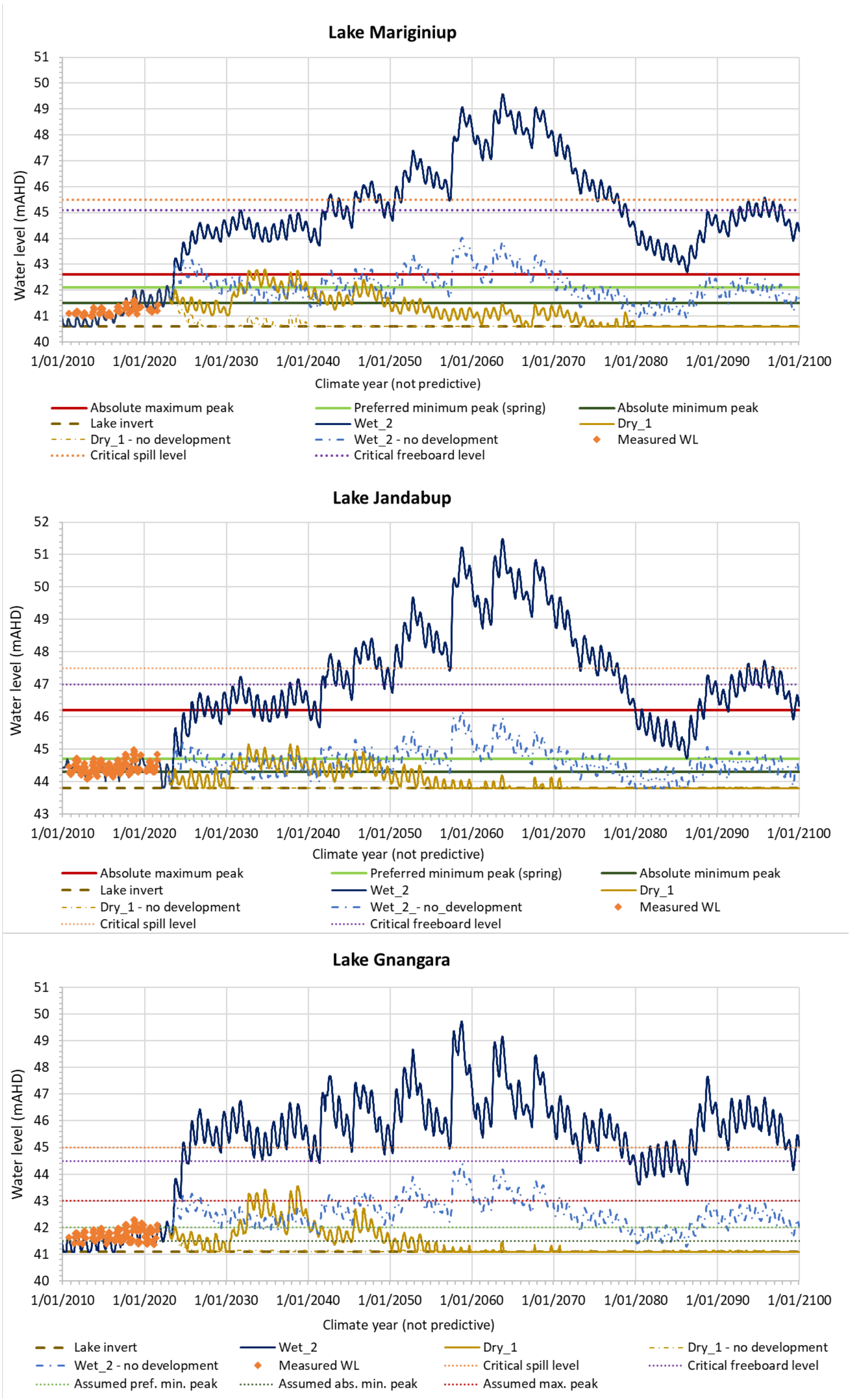


Figure 89: A comparison of the lake water levels for no development and full buildout under the extreme Wet_2 and Dry_1 climate scenarios (Simulations b, c, 19 and 20)

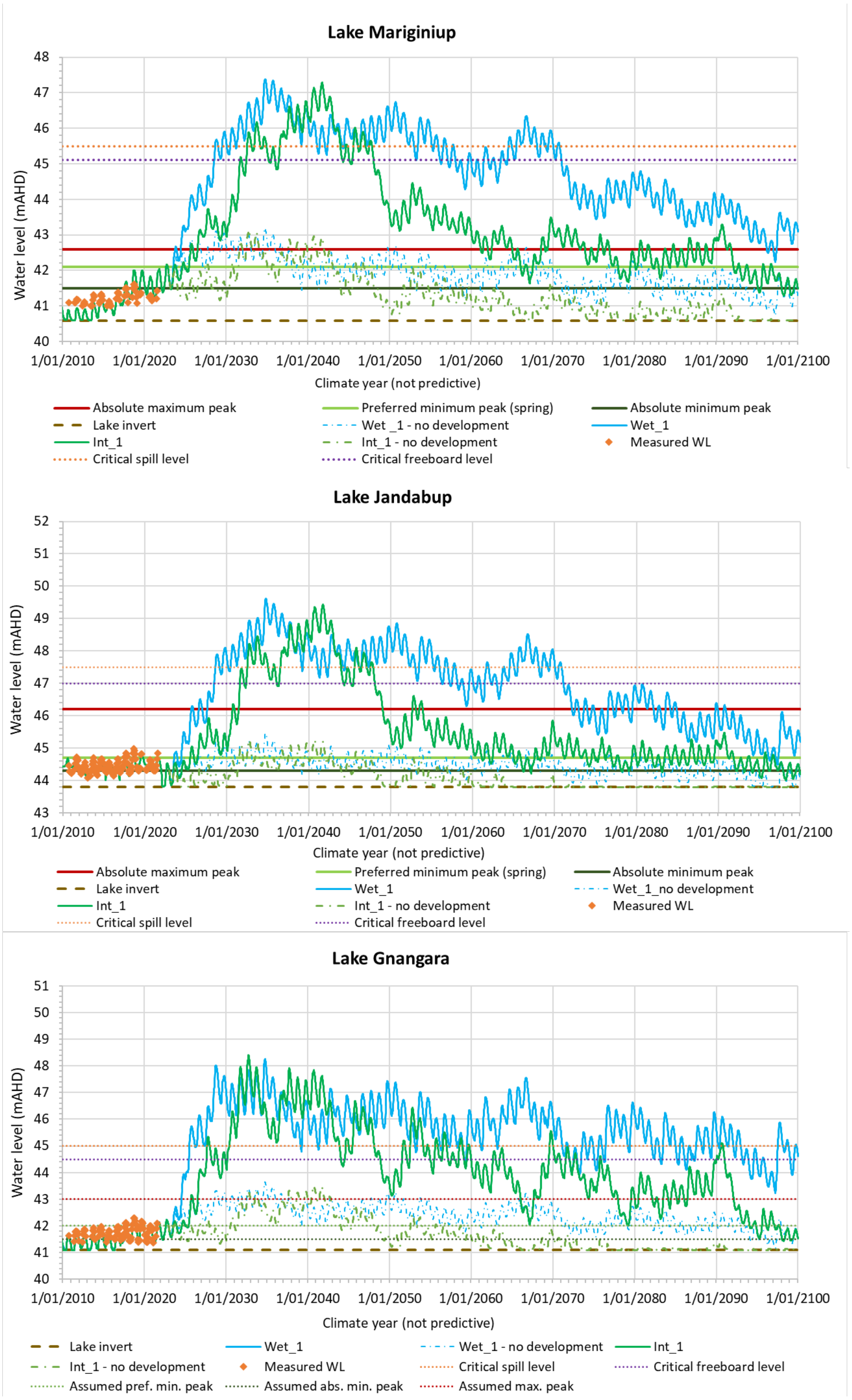


Figure 90: A comparison of the lake water levels for no development and full buildout under the less extreme Wet_1 and Int_1 climate scenarios (Simulations a, d, 18 and 21)

9.3.3. Maximum groundwater levels

Maximum groundwater levels (MGLs) for the full buildout simulations with subsoils discharging into the lakes are presented in Figure 91 and compared to the ‘no development scenarios in Figure 92. The depth to MGL is shown in Figure 93. These comparison maps show the following:

- Groundwater mounding due to the development is significant, with localised peak water levels at the wetlands receiving subsoil drainage water and extending downgradient to the western model boundary (Lake Joondalup).
- Development is simulated to cause an increase in maximum groundwater level (up to 5.5 m) at the perimeters of Lake Mariginiup, Jandabup and Gnangara due to lakes overspilling, noting that there is a steep gradient away from the lakes due to modelled subsoils.
- The ‘full buildout’ MGL surface is simulated to be up to 4.5 m higher than the ‘no development’ (within the East Wanneroo DSP area) MGL surface on the western side of the DSP area, however depth to groundwater remains sufficient and no impacts due to shallow water are expected.
- Maximum groundwater levels are lower post development for the wet and intermediate climate scenarios (Wet_1, Wet_2, and Int_1 simulations) over parts of the DSP area where the future groundwater is high enough to be intercepted by the subsoil drainage system, although in reality these locally lowered areas are not likely to readily drain under such elevated regional groundwater conditions.

9.3.4. Significance of results

The full buildout development Simulations 18 to 21 inclusive of subsoil discharge into the wetlands indicate that there is insufficient capacity for the lakes to contain urban drainage. Lake water level management will be required to enable full-buildout development of the East Wanneroo DSP area.

Estimated subsoil drainage volumes for these simulations are higher than estimated under Simulations 7 to 10, however the volumes predicted by Simulations 18 to 21 are considered excessive due to re-circulation of subsoil drainage. The modelled lake levels (overtopping lakes) simulated in these scenarios cannot be permitted to occur as significant infrastructure damage will result and drainage systems will fail. Therefore, assuming appropriate artificial control of the lake levels, sizing subsoil drainage to the volumes estimated here would result in significant oversizing. It is therefore not recommended to use these values in infrastructure design, as will be further validated in Section 9.4.2

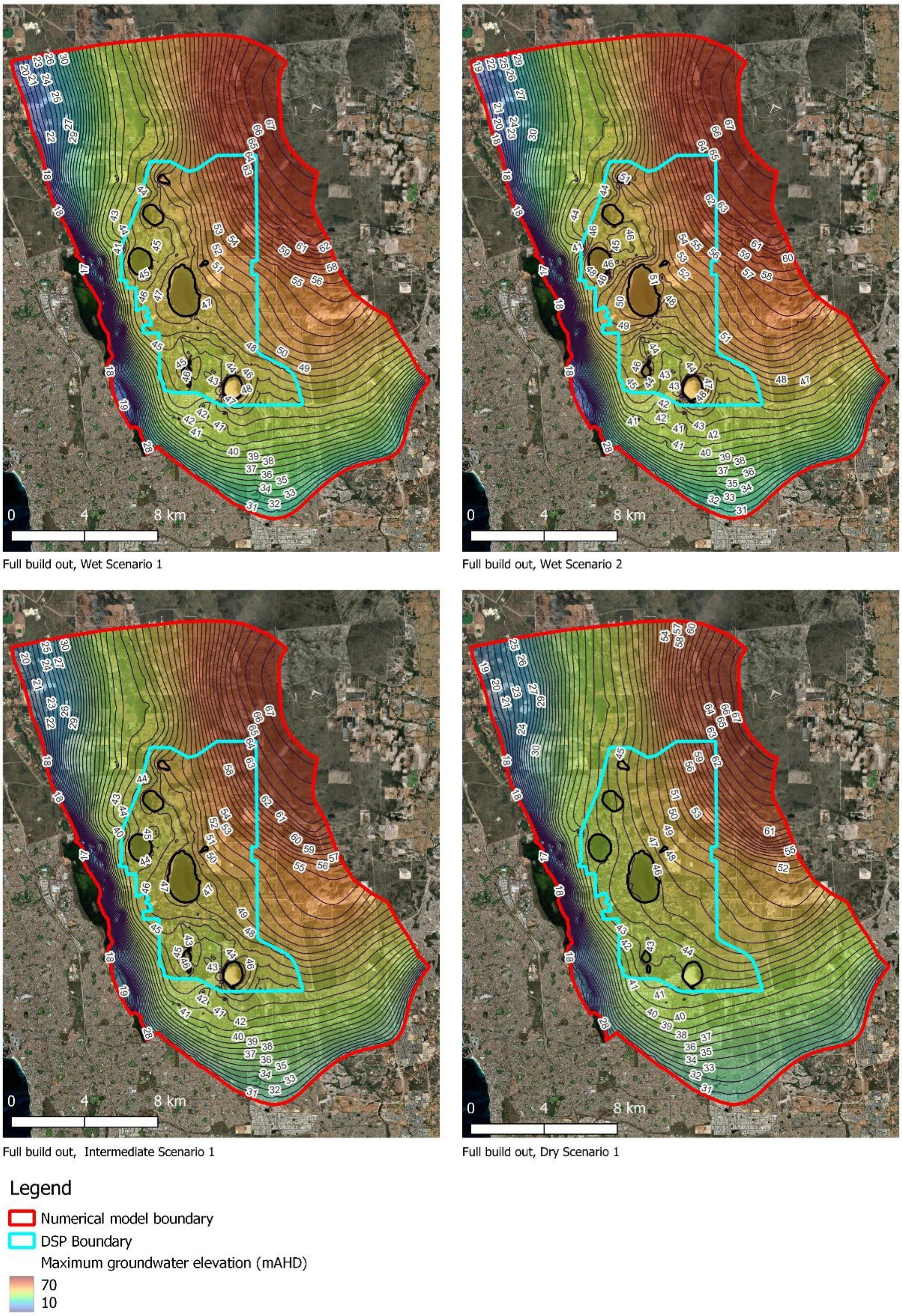


Figure 91: MGL surface for the full buildout simulations with subsoil drainage discharging into lakes, under the four selected climate scenarios

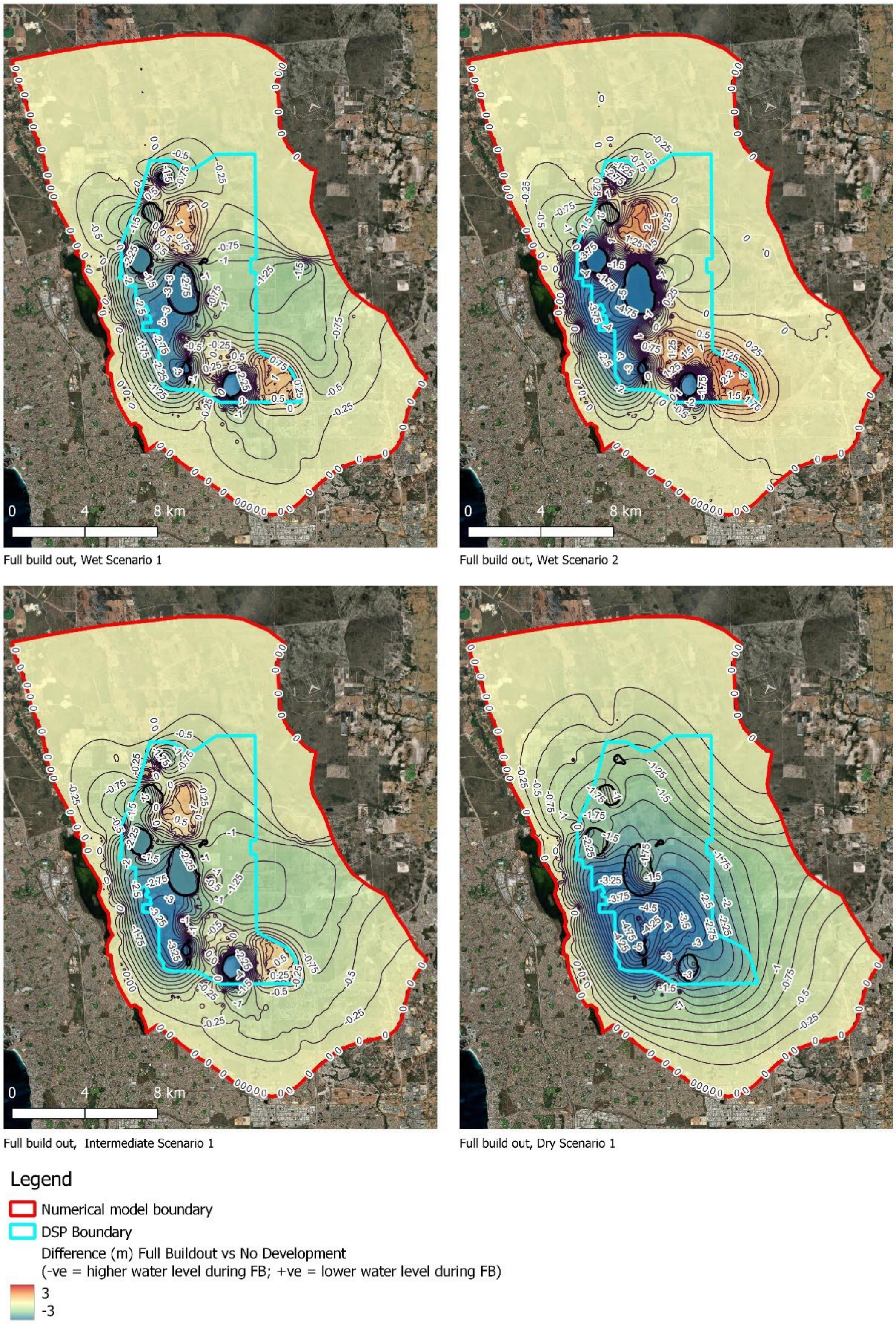


Figure 92: Comparison of the full buildout simulations with subsoil drainage discharging into lakes MGL surface with the no development MGL surface

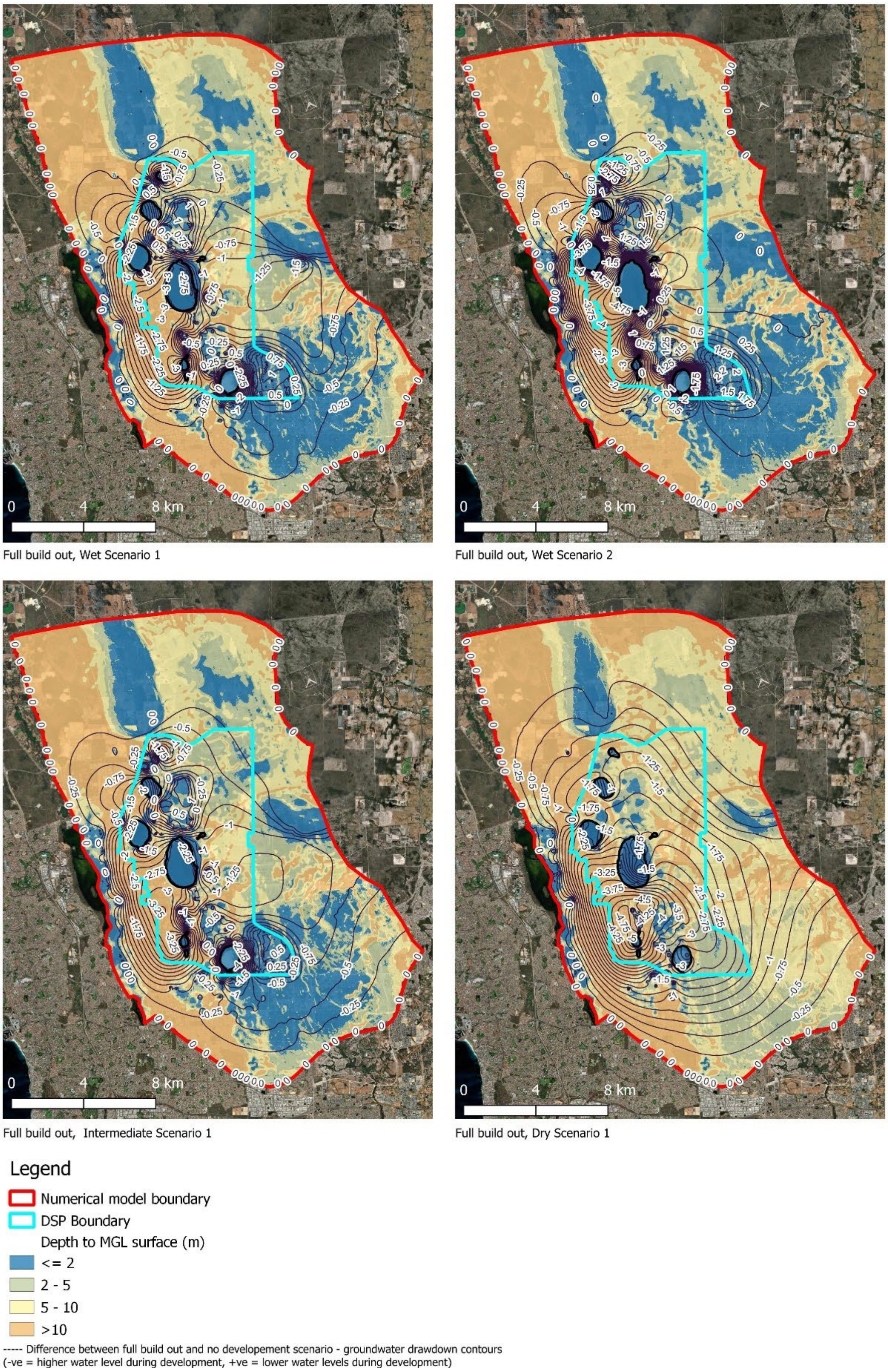


Figure 93: Depth to MGL surface with contours of relative change due to development (full buildout simulations with subsoil drainage discharging into lakes)

9.4. Full buildout development scenarios with subsoils discharged to lakes and lake level management via pumping transfer

In order to manage the excessively high lake levels presented in Section 9.3 pumping out water out of the lakes was tested in Simulations 22 to 25 (using Simulations 18 to 21 as the base). Water was pumped from each of lakes Mariginiup, Gnangara, Adams, Coogee Swamp, Badgerup and Little Badgerup into Lake Jandabup, which was used as a buffer storage due to its central location and having the greatest capacity. An arterial discharge line was simulated via high-rate pumping to remove the combined excess from Lake Jandabup to an offsite location (outside of the model domain).

The groundwater modelling and associated analysis of lake water levels for Simulations a to d indicate that under all bar a very dry climate, the future lake water levels will exceed the existing absolute maximum water level (environmental threshold level) at Lake Mariginiup with or without urban development. Given this fact, it is not appropriate to prohibit (through management actions) exceedance of the absolute maximum peak but rather adopt an adaptive management approach to potential future high lake water levels that prevents lake water levels rising and presenting a flood risk, while reasonably minimising the occurrence of exceedances of environmental thresholds.

Pumping was simulated in the model from each of the major wetlands with the pump switch on-off level set as the Absolute Minimum Peak level (see Table 27). This aimed to ensure the lake was not pumped below the minimum environmental threshold where the no-development conditions would have been above for any given climate. The maximum pumping rate applied at each wetland for these simulations are presented in Table 28. This maximum rate was applied consistently for each climate scenario, however the use of the Automatic Flow Reduction option reduced the flow rate as the lake level approached the pump on-off level, such that pumping rates fluctuated between the maximum applied abstraction rate and zero abstraction as required based on the simulated lake level.

Table 28: Maximum pumping rates from each wetland

Wetland	Max lake transfer pumping rate (L/sec)
Mariginiup	100
Gnangara	150
Jandabup	1500
Adams	100
Coogee	100
Badgerup	50
Little Badgerup	50

9.4.1. Full buildout lake pumping rates statistics

The statistics for the modelled pumping rates from each wetland are presented in Table 29 to Table 32. Pumping reaches the maximum applied pumping rates for all lakes in all climates (bar Dry_1) except Lake Jandabup, where the 1500 L/sec is only required for the Wet_2 climate, and 1085 L/sec being the second highest maximum rate required in the wettest year (2028) of the Int_1 climate. This variability indicates that the water management requirements are highly dependant on the future climate and options to up and or down/scale management as required should be built in as part of an adaptive management plan.

Table 29: Pumping rate statistics for the Wet_1 scenario (Simulation 22)

Pumping rate (L/sec)	Mariginiup	Gnangara	Jandabup	Adams	Coogee	Badgerup	Liltle Badgerup
Max annual peak	100	150	1029	100	100	50	50
Mean annual peak	99	140	632	89	13	50	34
Mean (all times)	61	72	294	44	2	42	22
Wet year mean	93	123	608	90	35	50	37

Table 30: Pumping rate statistics for the Wet_2 scenario (Simulation 23)

Pumping rate (L/sec)	Mariginiup	Gnangara	Jandabup	Adams	Coogee	Badgerup	Liltle Badgerup
Max annual peak	100	150	1500	100	100	50	50
Mean annual peak	99	143	674	92	21	50	35
Mean (all times)	64	76	320	47	6	42	23
Wet year mean	65	94	601	59	69	41	40

Table 31: Pumping rate statistics for the Dry_1 scenario (Simulation 24)

Pumping rate (L/sec)	Mariginiup	Gnangara	Jandabup	Adams	Coogee	Badgerup	Liltle Badgerup
Max annual peak	100	150	511	88	0	50	50
Mean annual peak	22	18	61	5	0	14	12
Mean (all times)	6	5	18	1	0	7	4
Wet year mean	53	50	170	18	0	35	17

Table 32: Pumping rate statistics for the Int_1 scenario (Simulation 25)

Pumping rate (L/sec)	Mariginiup	Gnangara	Jandabup	Adams	Coogee	Badgerup	Liltle Badgerup
Max annual peak	100	150	1085	100	100	50	50
Mean annual peak	86	105	421	55	9	44	31
Mean (all times)	43	46	181	23	2	32	19
Wet year mean	87	113	565	78	34	49	35

9.4.2. Subsoil drainage flow rates and annual subsoil drainage flow volumes

The total annual drainage flow volume statistics for the four full buildout simulations with subsoil drainage discharge to lakes and pumped water levels management are presented in Figure 94 and Figure 95. These results show:

- A slight reduction (15%) in subsoil drainage when compared to Simulations 7 to 10 (with no subsoil discharge to lakes or lake pumping). The Wet_2 maximum annual discharge rate decreases from 30.7 GL/yr to 27 GL/yr.
- This relative reduction in subsoil flow volumes is a consequence of the pumping management of lake levels reducing the groundwater levels with respect to those of Simulations 7 to 10, and consequently reducing the volume of water intercepted by subsoils.

It is not recommended that these rates are used to form engineering designs as they are subjective to the adopted lake pumping regime and it is more conservative to use rates derived from groundwater mounding scenarios (Simulations 7 to 10) in the absence of further management, the extent of which may be varied as planning progresses.

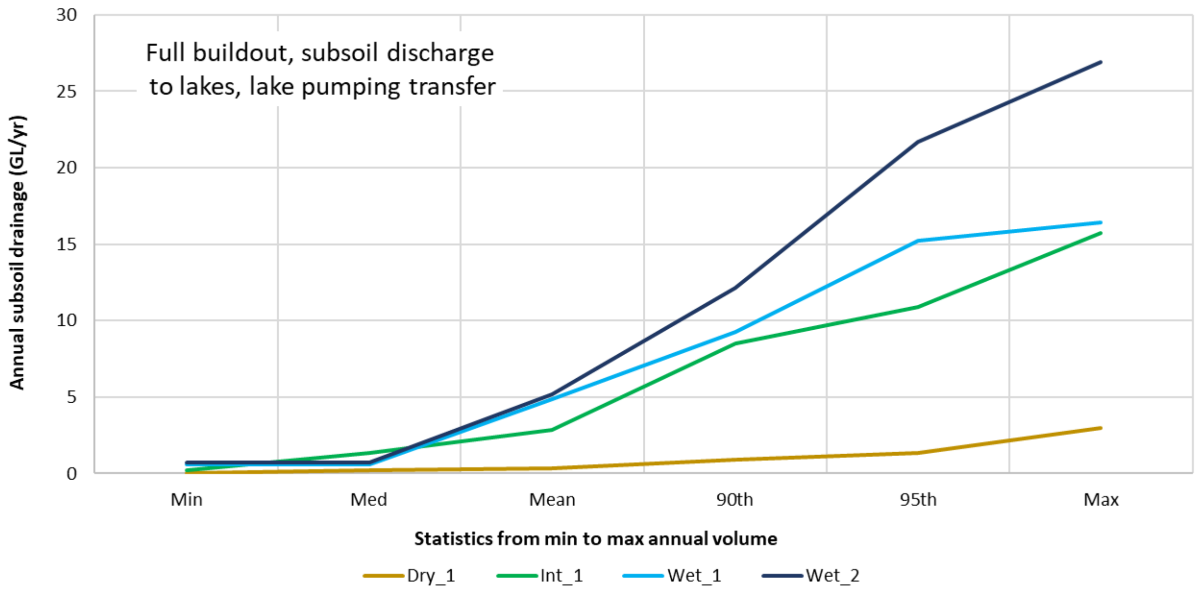


Figure 94: Total annual subsoil drainage volume statistics for the full buildout future scenario simulations with subsoils discharging to lakes

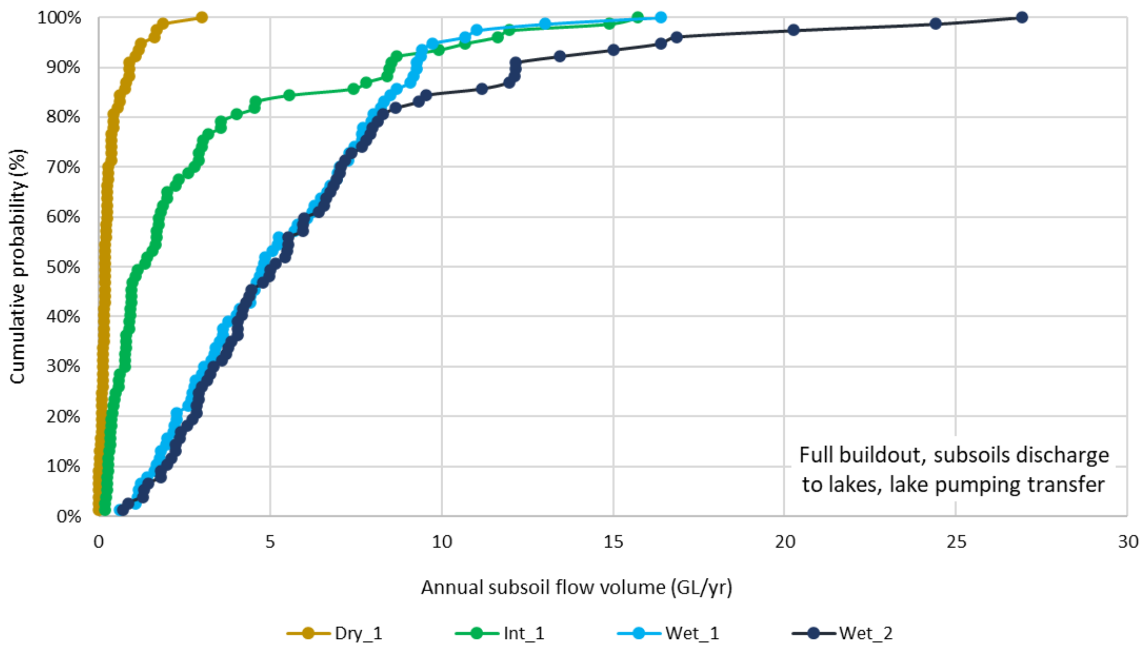


Figure 95: Cumulative distribution of annual subsoil drainage flow volume for the full buildout future scenario simulations with subsoils discharging to lakes

9.4.3. Lake levels

Lake water levels for the four full buildout simulations under the proposed EWGMS are presented in Figure 96, and a comparison between simulated lake water levels for the extreme Wet_2 and Dry_1 climate scenarios at full buildout and with no development is given in Figure 97 and the Wet_1 and Int_1 climates in Figure 98Figure 67. The lake water level figures indicate the following:

- Simulated lake levels are lowered significantly when compared to Simulations 18 to 21.
- Lake levels are able to be managed below the Absolute Max Peak for most years with annual exceedances under very wet conditions.
- Managed lake water levels reduce the magnitude of highs and lows with respect to no development, reducing the probability of exceeding environmental peak limits while maintaining seasonality and helping to increase dry season/dry climate water levels to within preferred environmental ranges.
- Further assessment to determine maximum and minimum allowable lake levels are required for all lakes other than Lake Mariginiup and Lake Jandabup, however the model indicates that lake level reduction via pumped transfer is a physically viable option for management.

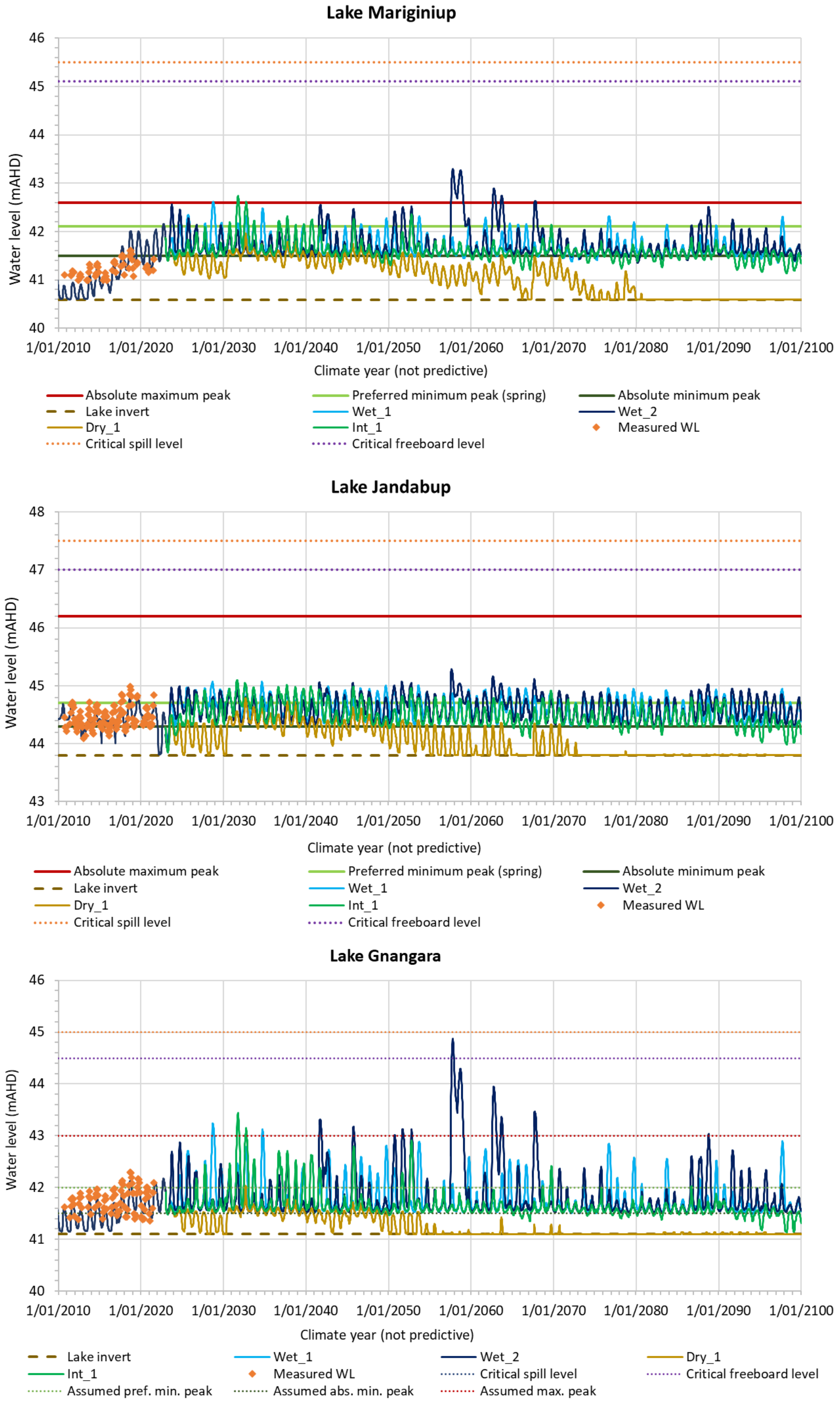
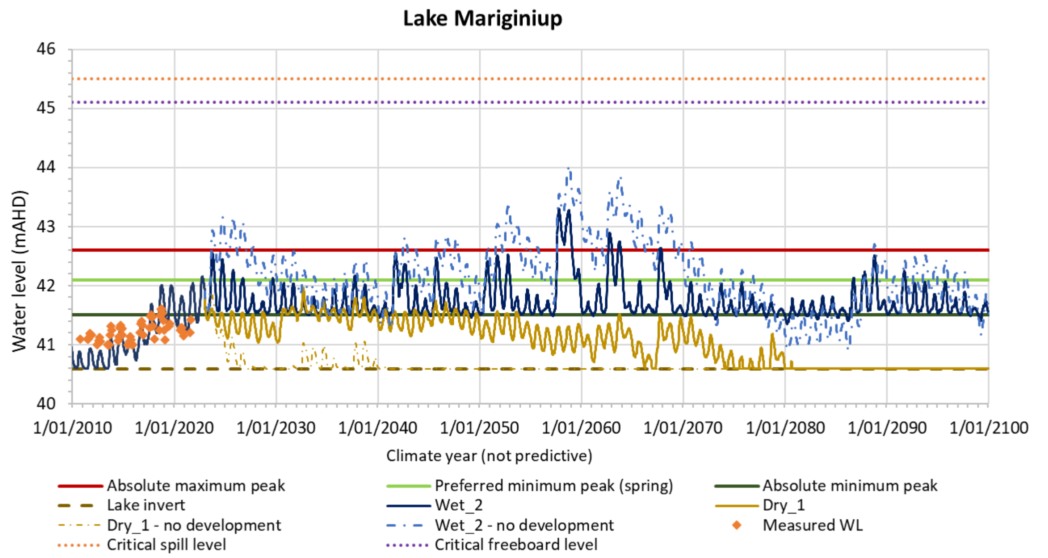
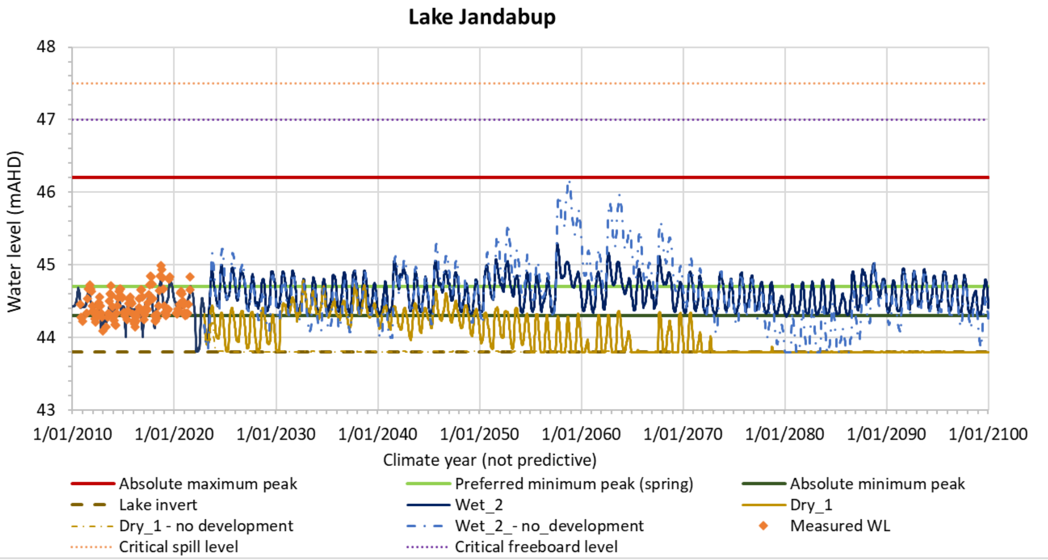


Figure 96: Lake water levels for the full buildout simulations and four climate scenarios, with subsoils discharging to lakes and pumped transfer (Simulations 22 to 25)





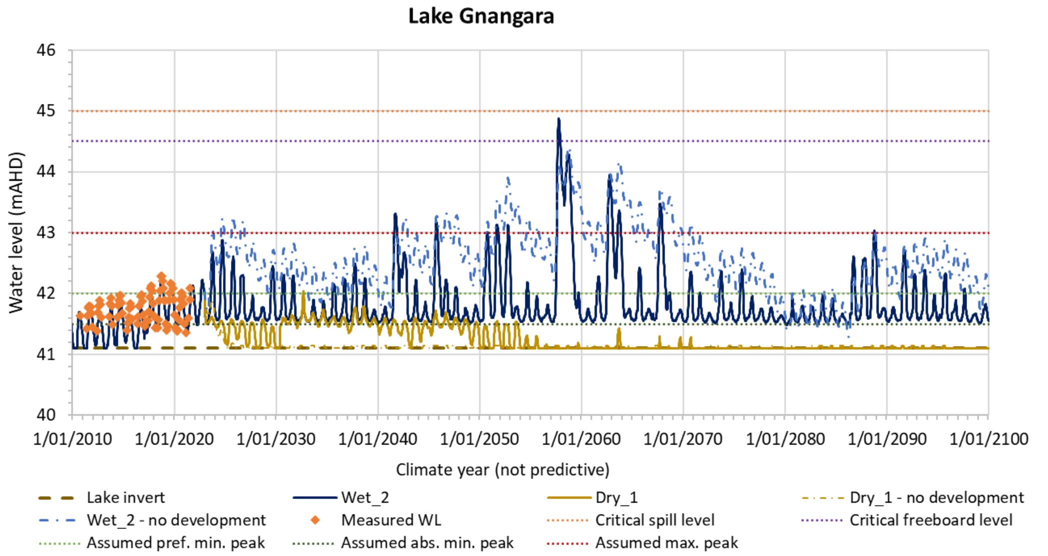


Figure 97: A comparison of the lake water levels for no development and full buildout under the extreme Wet_2 and Dry_1 climate scenarios (Simulations b, c, 23 and 24)

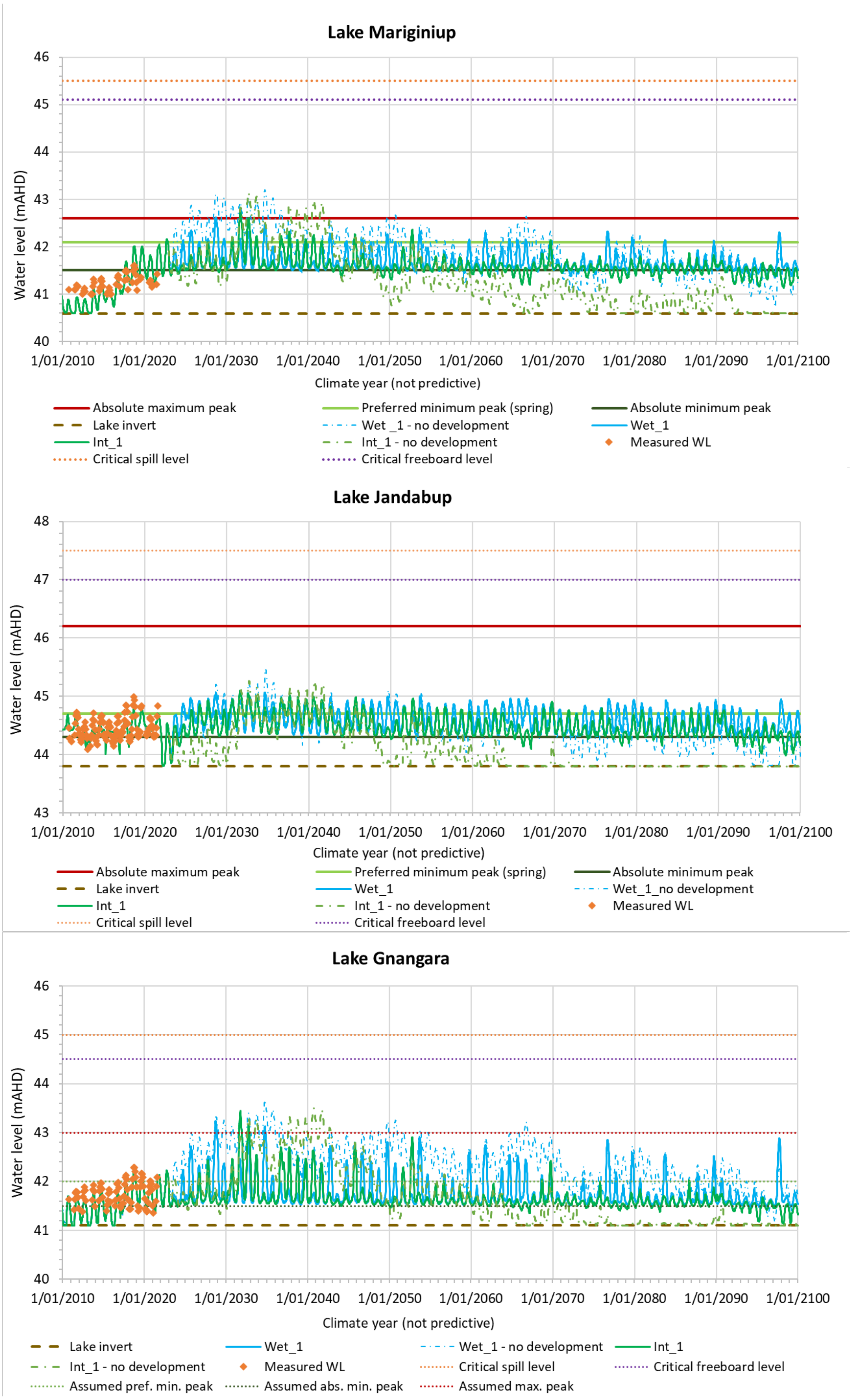


Figure 98: A comparison of the lake water levels for no development and full buildout under the less extreme Wet_1 and Int_1 climate scenarios (Simulations a, d, 22 and 25)

9.4.4. Maximum groundwater levels

Maximum groundwater levels (MGLs) for the full buildout simulations with subsoils discharging into the lakes are presented in Figure 99 and compared to the ‘no development’ scenarios in Figure 100. These comparison maps show the following:

- Maximum groundwater levels are overall reduced from the no development simulations for the Wet1 and Wet_2 climates as a result of reducing the peak lake levels via pumping.
- Maximum groundwater levels remain higher than the no development equivalent for the Dry_1 climate as a result of the additional urban water recharge, but limited groundwater control via subsoils and/or lake pumping as water levels remain below specified management levels.
- Maximum groundwater levels are reduced slightly from those of Simulations 7 to 10 due to lowering of the lake levels.
- Groundwater mounding at the west of the DSP beneath elevated dunes remains for all scenarios due to the additional recharge, however depth to water is significant and no impacts due to shallow water are expected.

9.4.5. Significance of results

The full buildout development Simulations 22 to 25 representing the proposed EWGMS indicate that the proposed pumping transfer scheme is viable to control lake water levels to within engineering thresholds and reasonably maintain levels within environmental level thresholds, with rare exceedances due to very wet conditions, as also expected under no development conditions. Modelled lake pumping rates required to maintain lake levels are highly variable indicating adaptive management will be required with contingency in the design to both increase and reduce pumped volumes as required dependant on future climate.

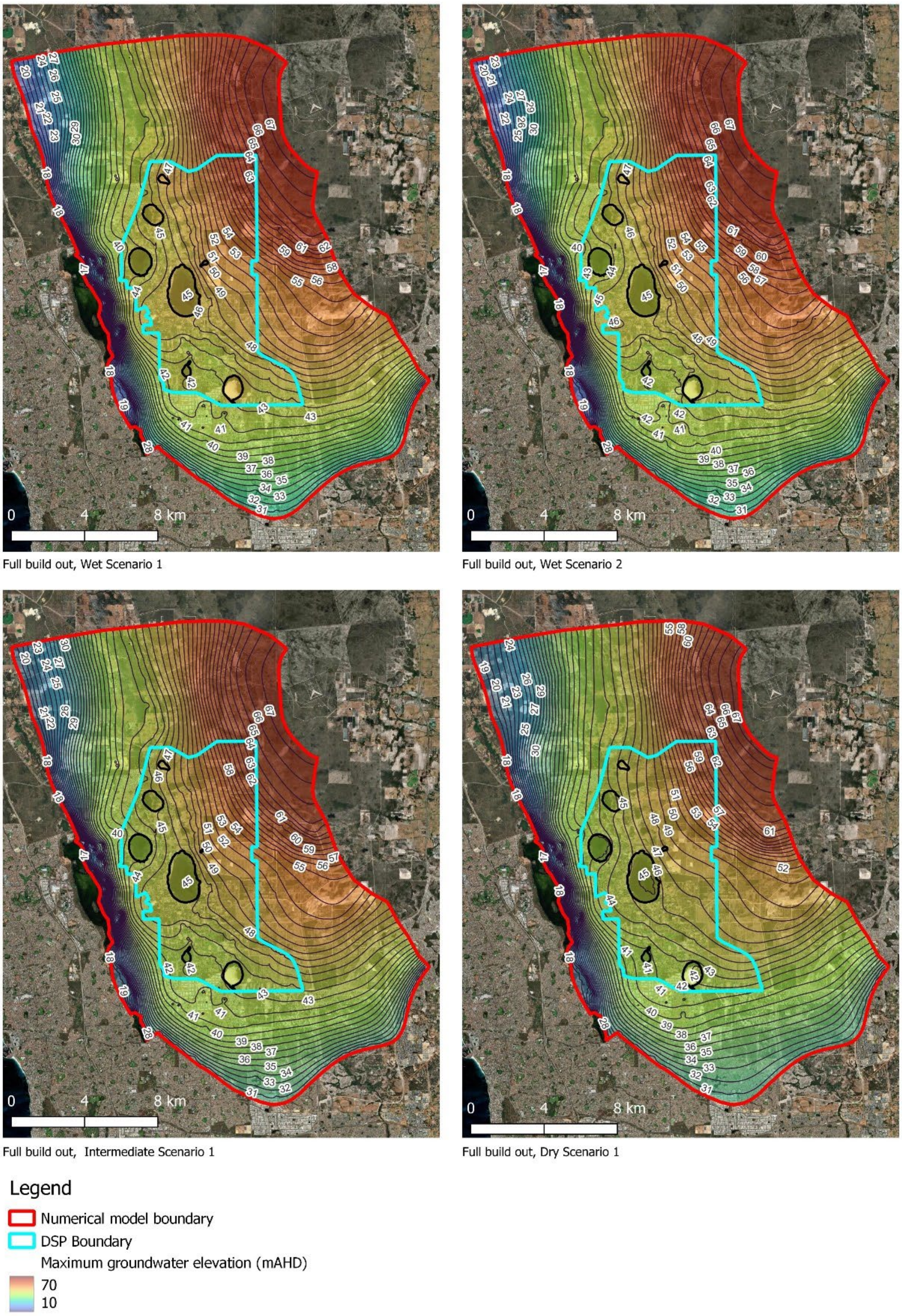


Figure 99: MGL surface for the full buildout simulations with subsoil drainage discharging into lakes and pumping transfer, under the four selected climate scenarios

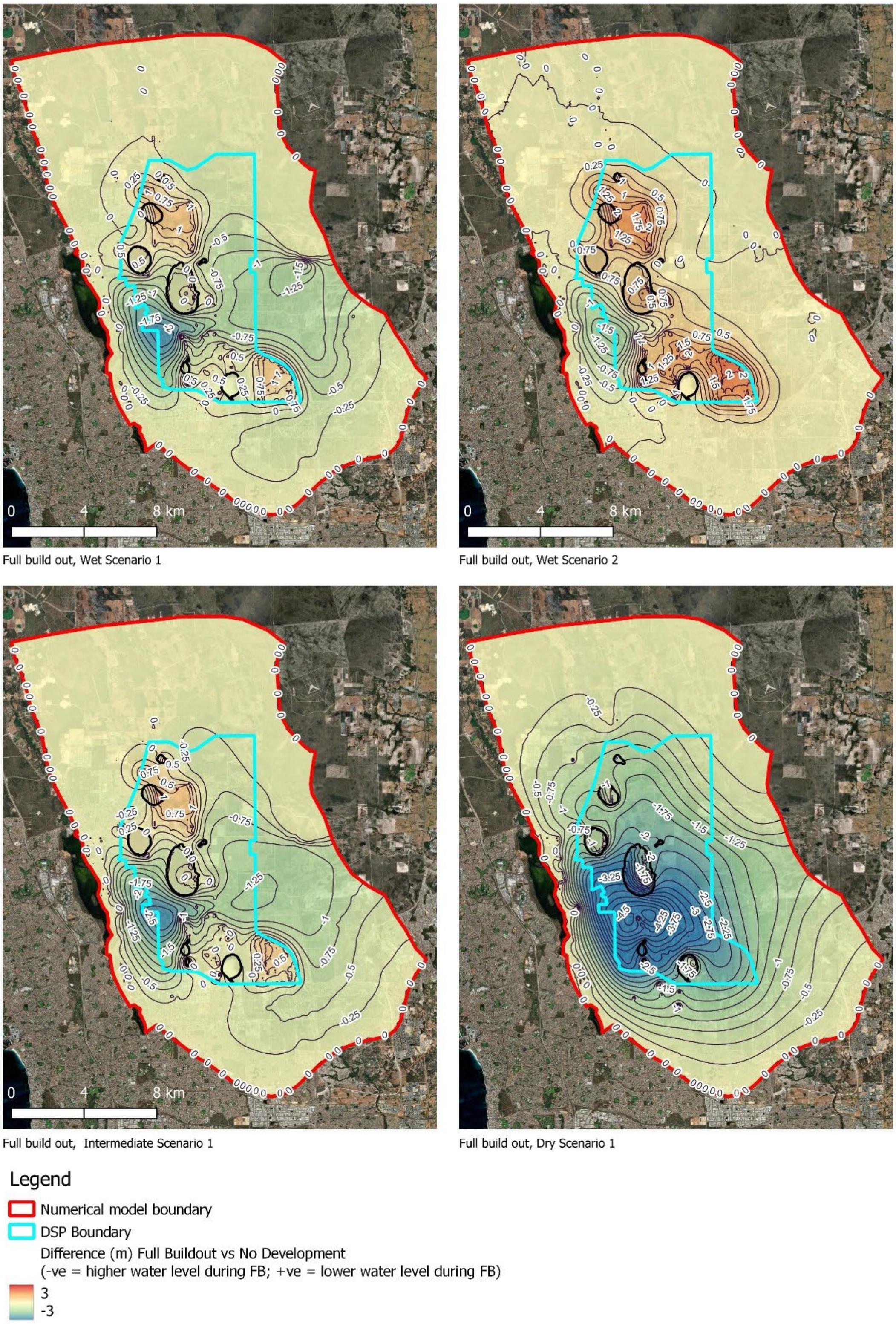


Figure 100: Comparison of the full buildout simulations with subsoil drainage discharging into lakes and pumping transfer with MGL surface with the no development MGL surface

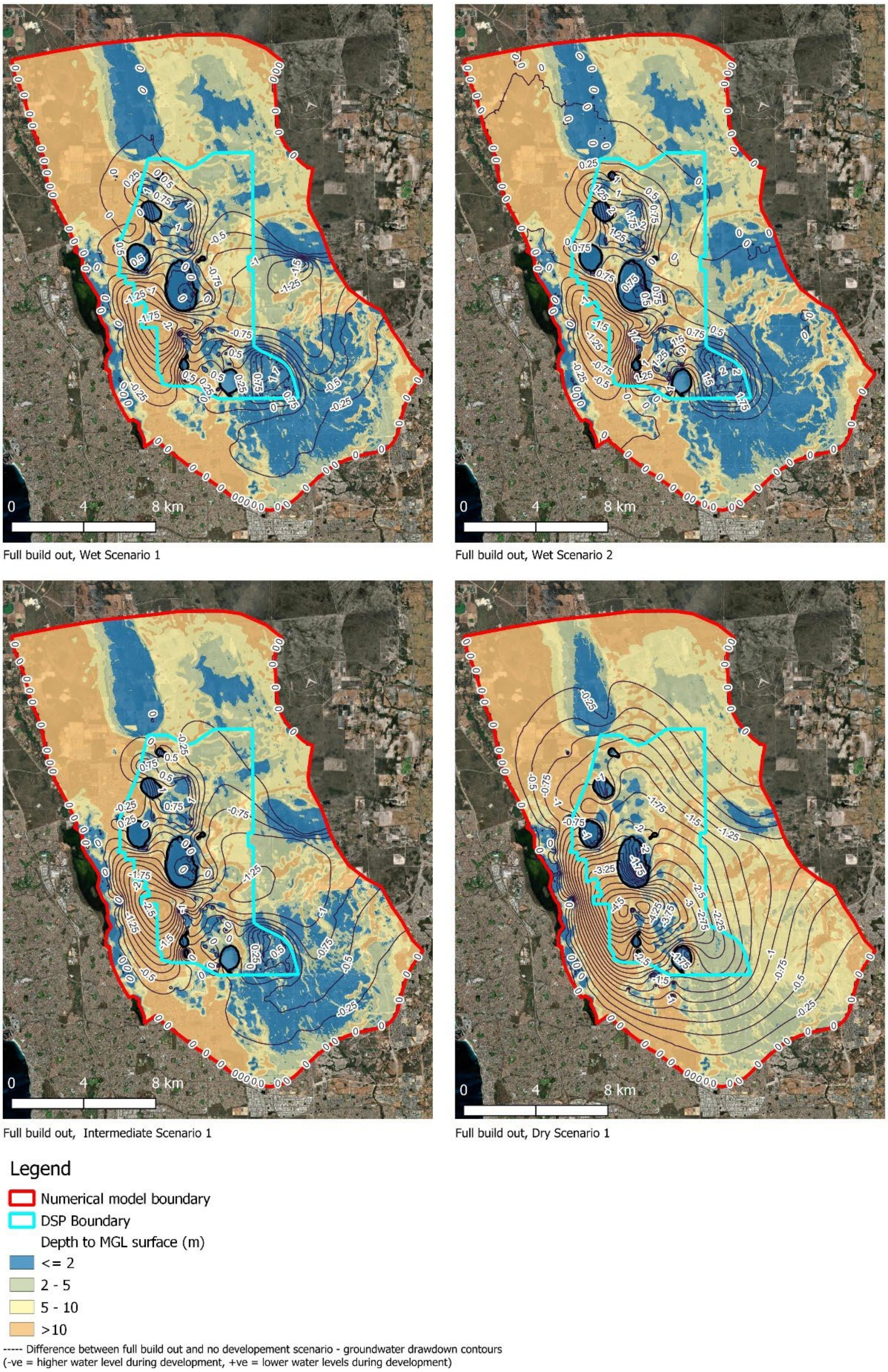


Figure 101: Depth to MGL surface with contours of relative change due to development (full buildout simulations with subsoil drainage discharging into lakes and pumping transfer)

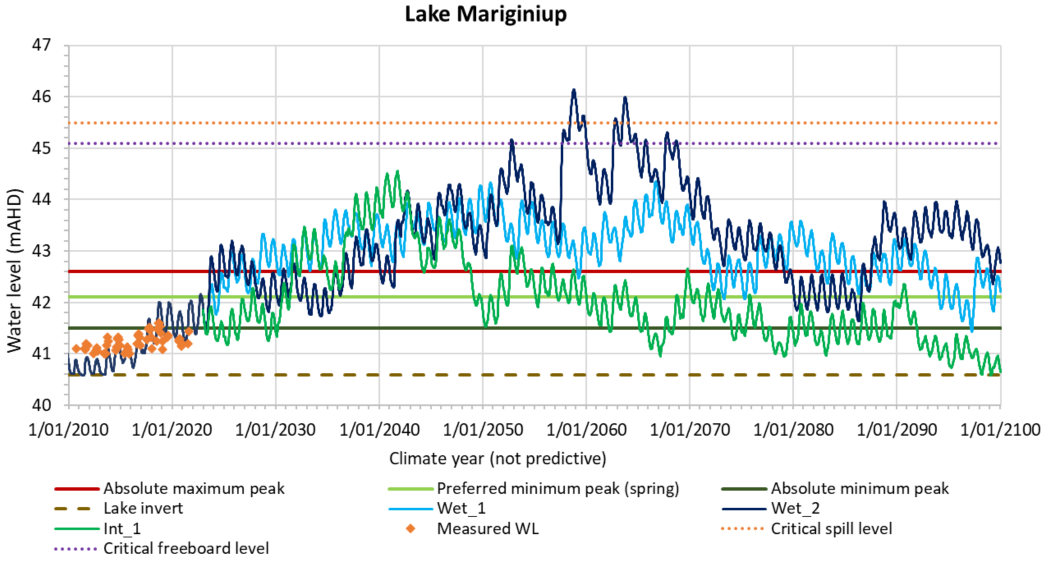
9.5. Staged to 2040 development scenarios with subsoils discharged to lakes (no pumping)

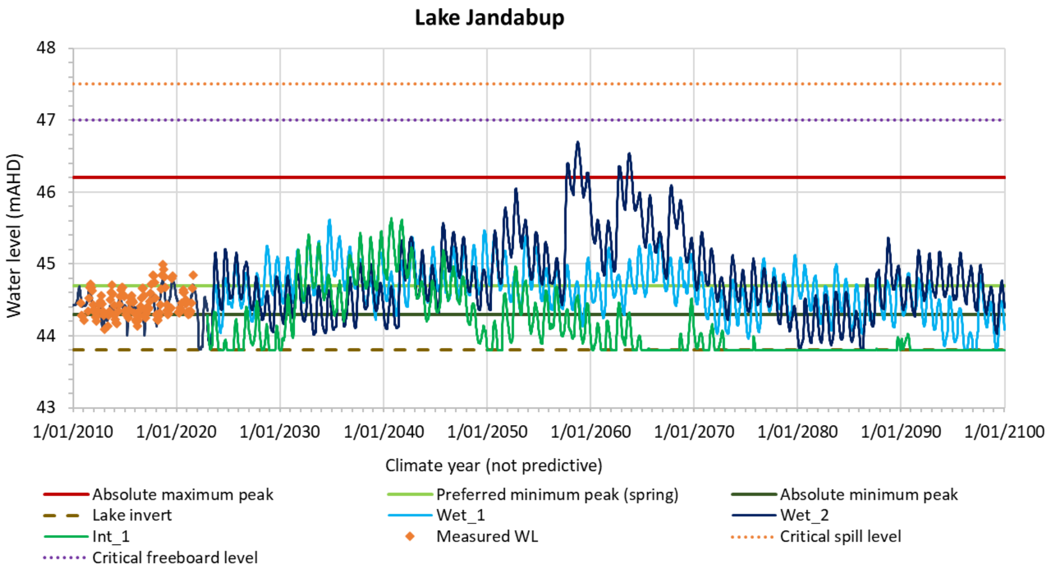
The ‘Staged to 2040’ simulations 15 to 17 were updated to MF6 as per the full buildout simulations, with subsoils included in the ‘Staged to 2040’ development area and discharged to lakes Mariginiup and Jandabup for the three wetter climate scenarios (Wet_1, Wet_2 and Int_1). For these simulations, the model was run with staged development included until the end of 2039. The model was then allowed to run to the end of 2099 with no further change in land use or abstraction rates. These simulations were used to assess whether progressing ‘Staged to 2040’ development (inclusive of areas requiring subsoil drainage) would require implementation of the full or partial EWGMS (in particular a pumped transfer from Lake Mariginiup and/or Lake Jandabup).

9.5.1. Lake Levels

Lake water levels for the ‘Stage to 2040’ simulations with subsoils discharged to lakes are presented in Figure 102, and a comparison between simulated lake water levels for the extreme Wet_2 and Dry_1 climate scenarios at full buildout and with no development is given in Figure 103 and the Wet_1 and Int_1 climates in Figure 104. The lake water level figures indicate the following:

- With ‘staged to 2040’ development, inclusive of subsoil discharge into Lake Mariginiup and Jandabup, simulated water levels in Lake Mariginiup exceed the absolute maximum lake water level across multiple years.
- Simulated seasonal peak levels with subsoil discharge to lakes (from Precinct 7, 8 and western end of Precinct 15) at Lake Mariginiup are in excess of 2m higher than the equivalent peaks simulated for no development conditions under the Wet_2 climate and 1.5m higher under the Wet_1 and Int_1 climates.
- Simulated water levels in Lake Jandabup exceed the absolute maximum lake water level only in the 5 wettest years of the Wet_2 climate.
- Simulated seasonal peak levels with subsoil discharge (from the east side of Precinct 15) to Lake Jandabup are 0.6m higher than the equivalent peaks simulated for no development conditions under the Wet_2 climate, and 0.3m higher under the Wet_1 and Int_1 climates.
- Artificially reducing the lake water levels at Lake Mariginiup via pumping is likely to be required to protect future infrastructure under wet climate conditions, and is very likely to be required to manage water levels at Lake Mariginiup to within current environmental thresholds following development in all bar extreme dry conditions.
- Pumping from Jandabup is not required to protect infrastructure under any climate, noting that pumped water from Mariginiup is not included in these simulations.





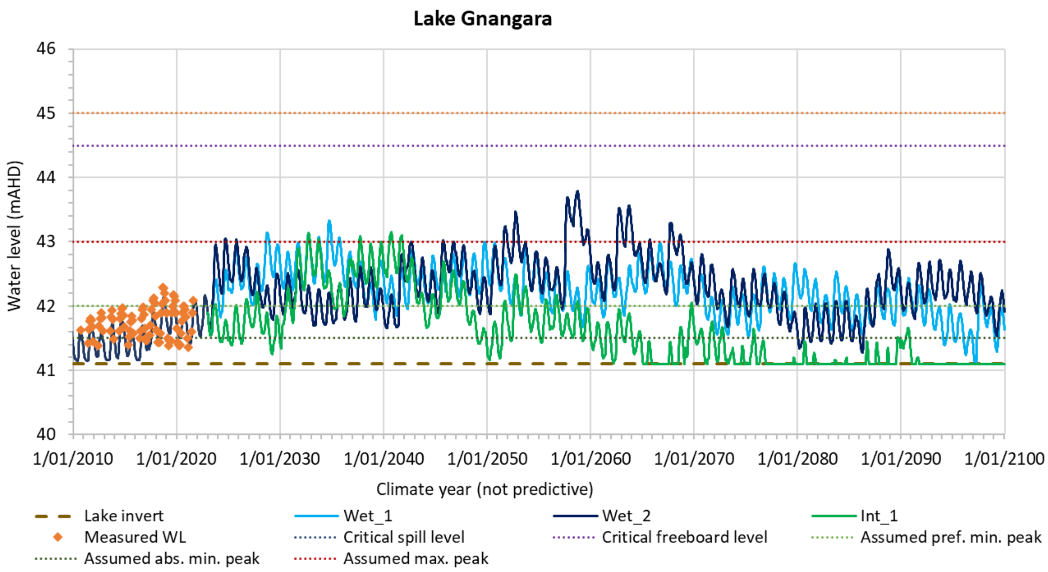


Figure 102: Lake water levels for 'staged to 2040 with subsoil discharge to lakes', under three climate scenarios (Simulations 26 to 28)

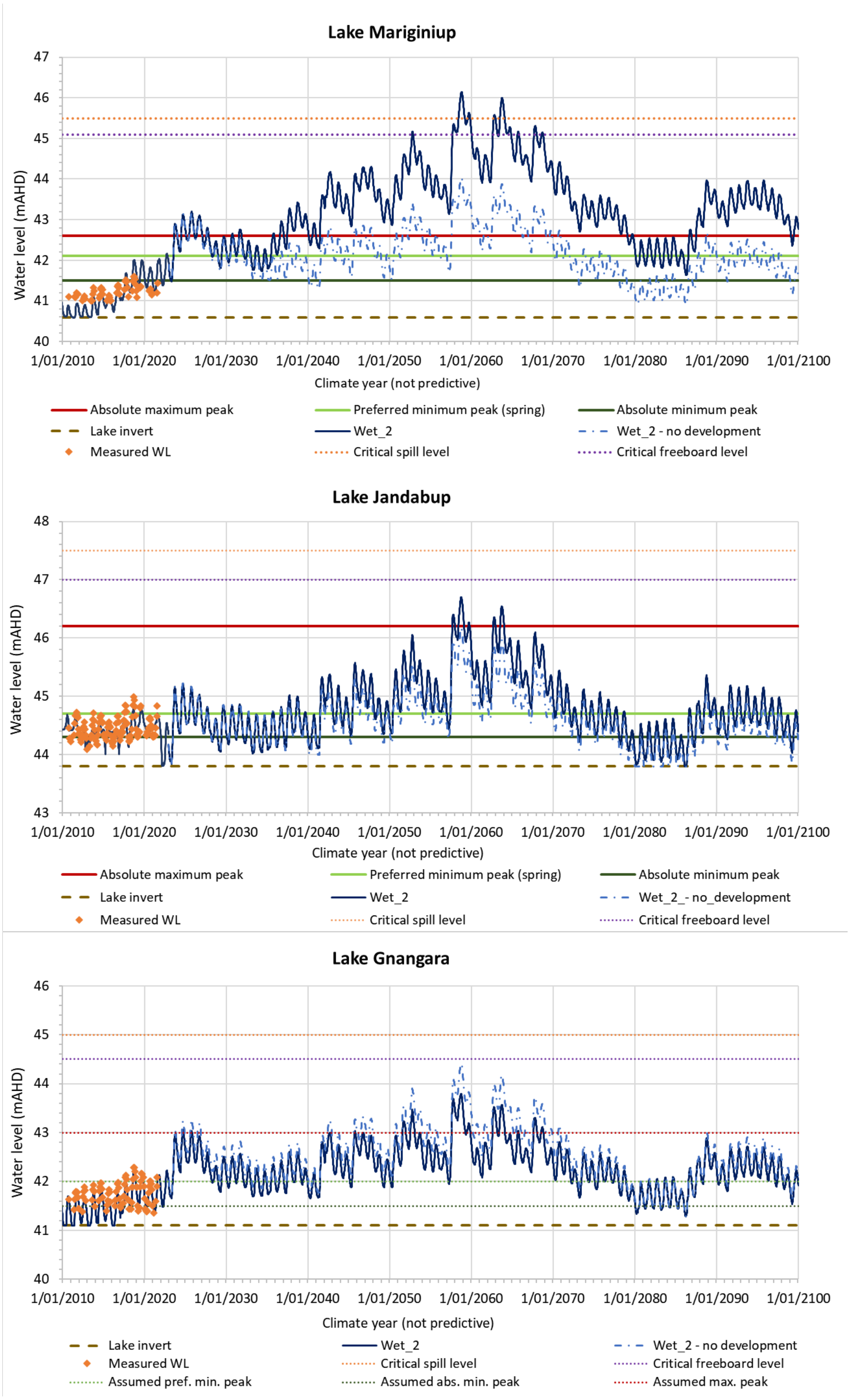


Figure 103: A comparison of the lake water levels for no development and 'staged to 2040' under the extreme Wet_2 climate scenarios (Simulations b and 27)

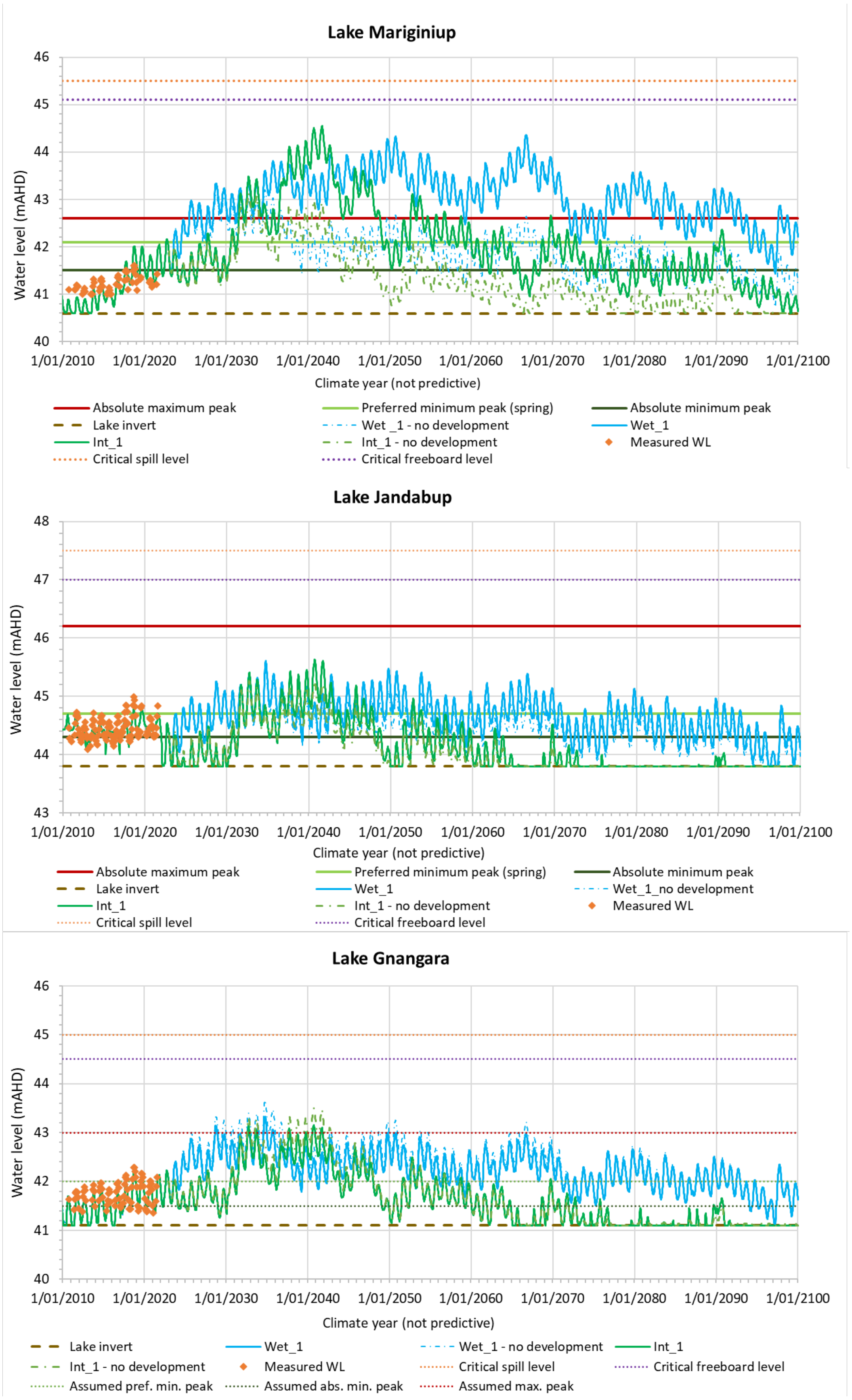


Figure 104: A comparison of the lake water levels for no development and 'staged to 2040' under the Wet_1 and Int_1 climate scenarios (Simulations a,c, 26 and 28)

9.5.2. Maximum groundwater levels

Maximum groundwater levels (MGLs) for the full buildout simulations with subsoils discharging into the lakes are presented in Figure 105 and compared to the 'no development' scenarios in Figure 106. The depth to MGL is shown in Figure 107. These comparison maps show the following:

- Groundwater mounding when compared to no development is centred over Lake Mariginiup (due to receiving the most subsoil drainage), with increased groundwater levels of up to 2.5m in the Wet_2 climate.
- Slight mounding also occurs at Lake Jandabup, with increased levels of up to 0.75m at the western edge of Jandabup under the Wet_2 climate.
- Increased groundwater levels extend to the western DSP boundary, but significant depth to water remains.
- Areas upgradient of Lake Mariginiup and Jandabup have slightly reduced maximum groundwater levels due to the downgradient subsoils lowering water levels.

9.5.3. Significance of results

Simulations 26 to 28 representing Staged development to 2040 inclusive of subsoil discharge to Lakes Mariginiup and Jandabup indicate that Lake Mariginiup water levels are likely to require management via pumping to avoid breaching engineering thresholds and to reduce the likelihood of breaching environmental thresholds. Development to 2040 is unlikely to be of material consequence to water levels at Jandabup (assuming no water is transferred from Lake Mariginiup).

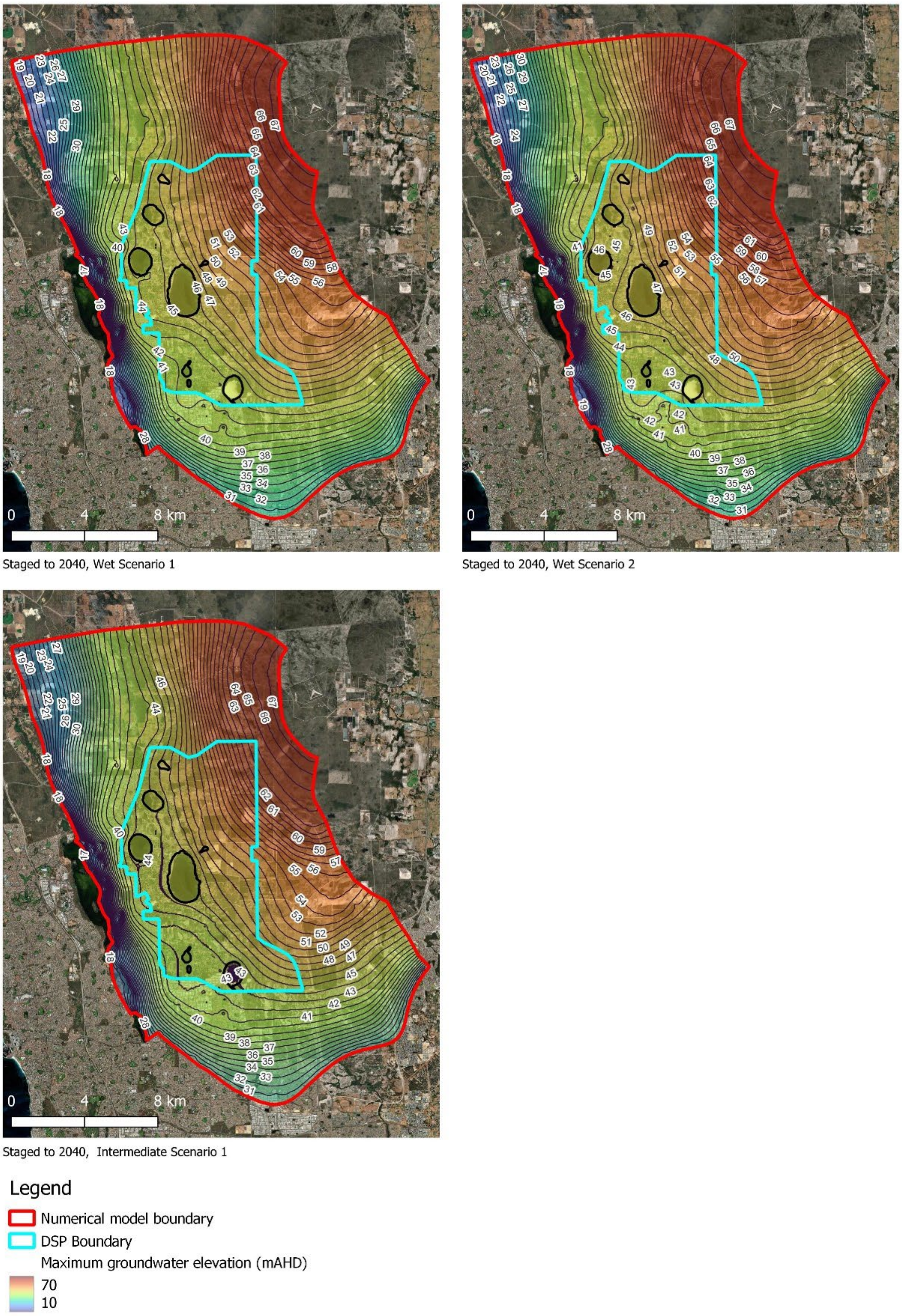


Figure 105: MGL surface for the staged to 2040 simulations (subsoil drainage discharging into lakes), under the three selected climate scenarios

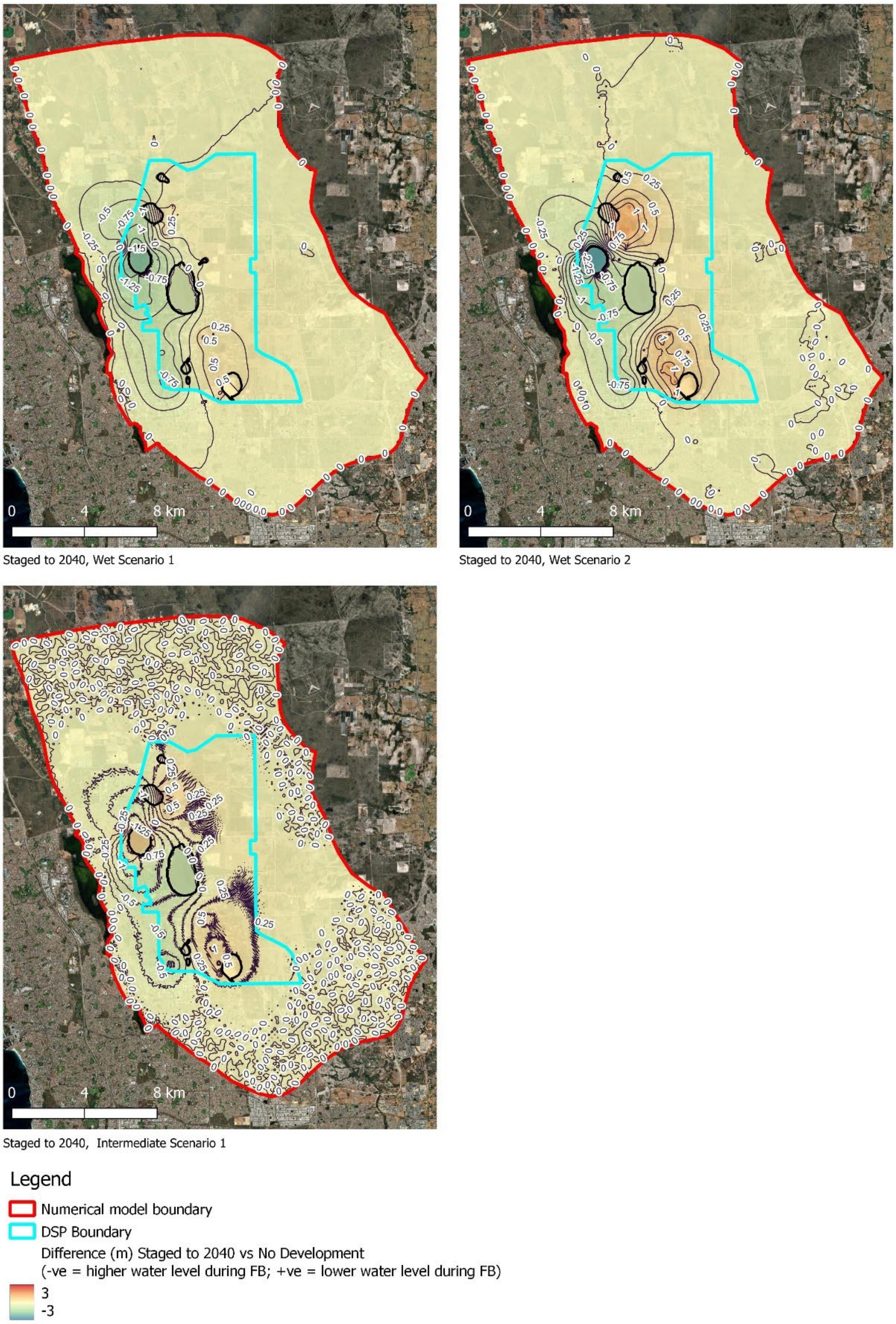


Figure 106: Comparison of the staged to 2040 simulations (subsoil drainage discharging into lakes) with MGL surface with the no development MGL surface

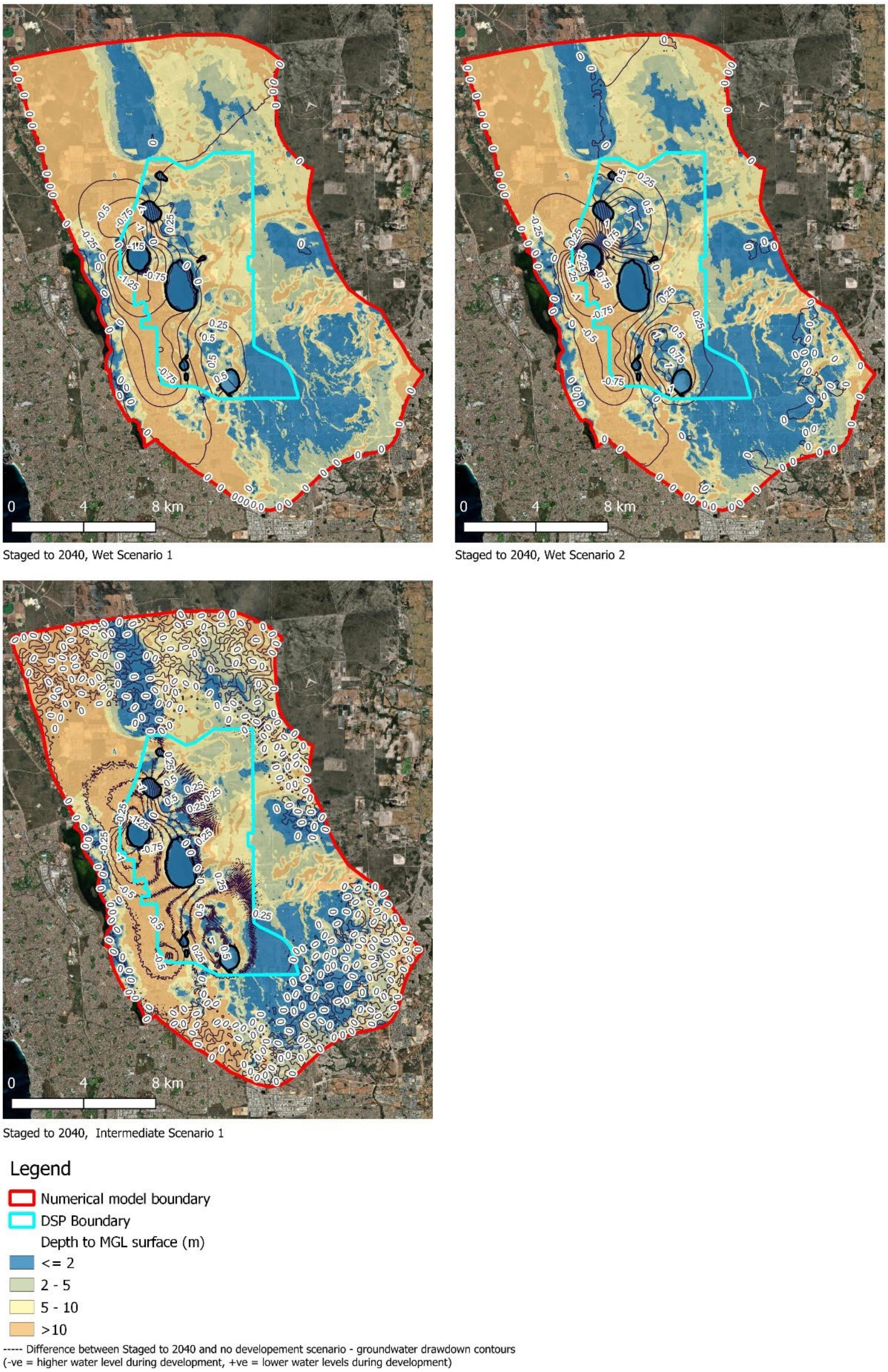


Figure 107: Depth to MGL surface with contours of relative change due to development (staged to 2040 simulations with subsoil drainage discharging into lakes)

9.6. Staged to 2040 development scenarios with subsoils discharged to lakes (with pumping from Mariginiup)

Simulations 29 to 31 include subsoils from the 'Staged to 2040' development area discharged to lakes Mariginiup and Jandabup and the pump transfer of up to 100L/sec from Lake Mariginiup to Jandabup for the three wetter climate scenarios (Wet_1, Wet_2 and Int_1). These simulations were used to assess whether progressing 'Staged to 2040' development (inclusive of areas requiring subsoil drainage) would be achievable by managing only the water levels in Lake Mariginiup without the need for a pumped outlet from Lake Jandabup. Pumping from Lake Mariginiup was only active in the model when water levels in the lake were greater than 41.5 mAHD (the absolute minimum peak). When water levels dropped below this level the pumping between lakes in the model ceased and only restarted if/when lake water levels exceeded 41.5 mAHD to maintain seasonality in the lake levels.

9.6.1. Lake Levels

Lake water levels for the 'Stage to 2040' simulations with subsoils discharged to lakes and pumping from Mariginiup to Jandabup are presented in Figure 108, and a comparison between simulated lake water levels for the extreme Wet_2 and Dry_1 climate scenarios at full buildout and with no development is given in Figure 109 and the Wet_1 and Int_1 climates in Figure 110. The lake water level figures indicate the following:

- Pumping of up to 100 L/sec from Lake Mariginiup to Lake Jandabup when water levels are above the absolute minimum peak is simulated to be sufficient to maintain the post-development lake water level to below the no-development equivalent for each climate, with the absolute maximum peak only breached under very wet years as would occur under existing land use.
- The Wet_1 and Int_1 climates simulation outputs show Lake Mariginiup water levels do not breach the absolute maximum lake level with pumping of up to 100 L/sec.
- The model results indicate Lake Jandabup generally has adequate capacity for receiving the excess water from Mariginiup in terms of not breaching engineering thresholds.
- The results of the Wet_2 climate simulation indicate Lake Jandabup water levels exceed the absolute maximum peak water level following development of the East Wanneroo Staged to 2040 development. A discharge option from Lake Jandabup may be required if the future climate follows the trends of the wetter climate scenarios and environmental values are to be protected.
- Additionally, modelling of the Wet_2 climate also indicates infrastructure may be at risk in the event of a very wet year (>1200mm) and concurrent 1% AEP storm event if Lake Jandabup is used as storage of excess water from Mariginiup without the means to also remove water from Jandabup.

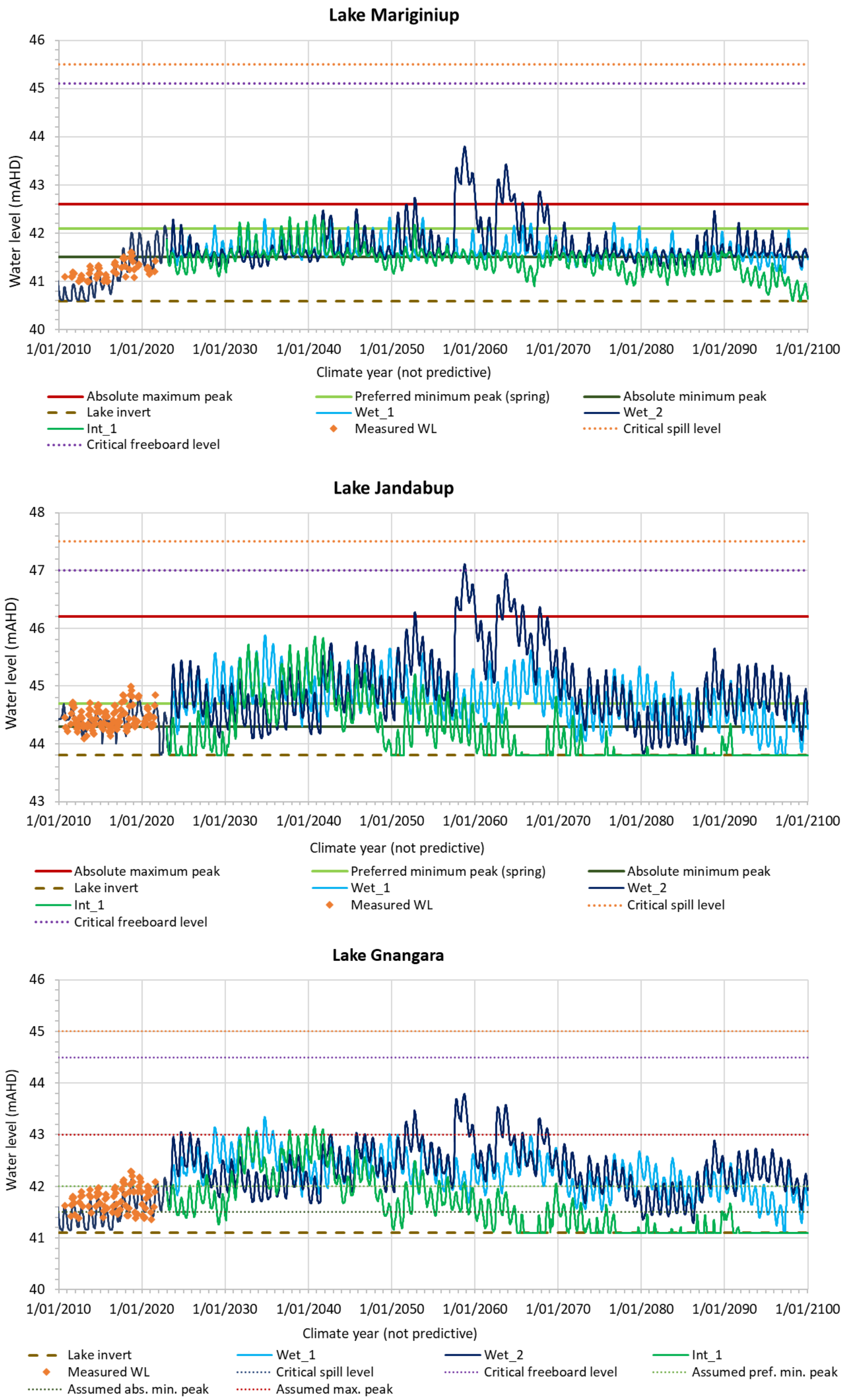


Figure 108: Lake water levels for 'staged to 2040' with subsoil discharge to lakes and pumping from Lake Mariginiup to Jandabup, under three climate scenarios (Simulations 29 to 31)

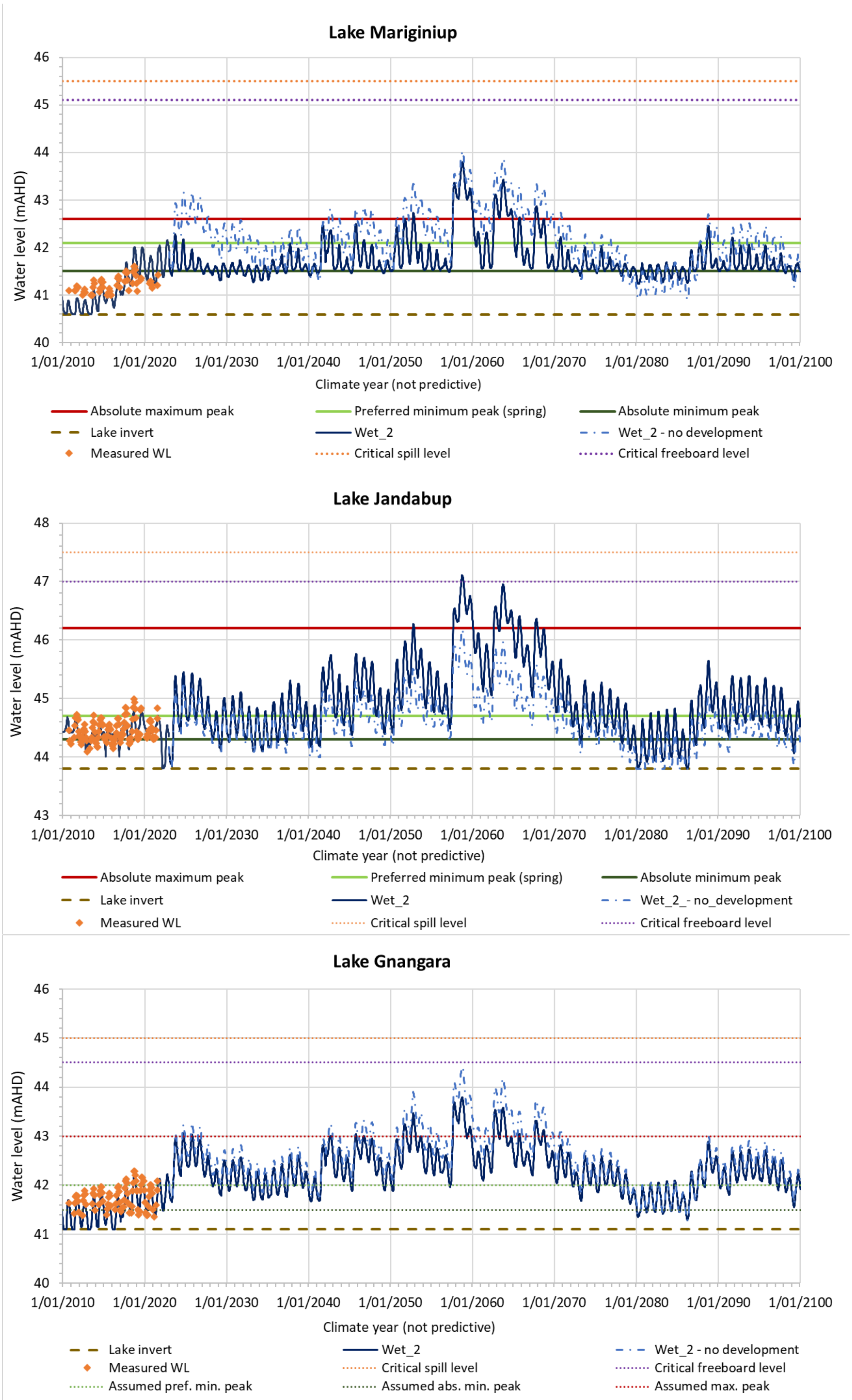


Figure 109: A comparison of the lake water levels for no development and for 'staged to 2040' with subsoil discharge to lakes and pumping from Lake Mariginiup to Jandabup, under the extreme Wet_2 climate scenarios (Simulations b and 30)

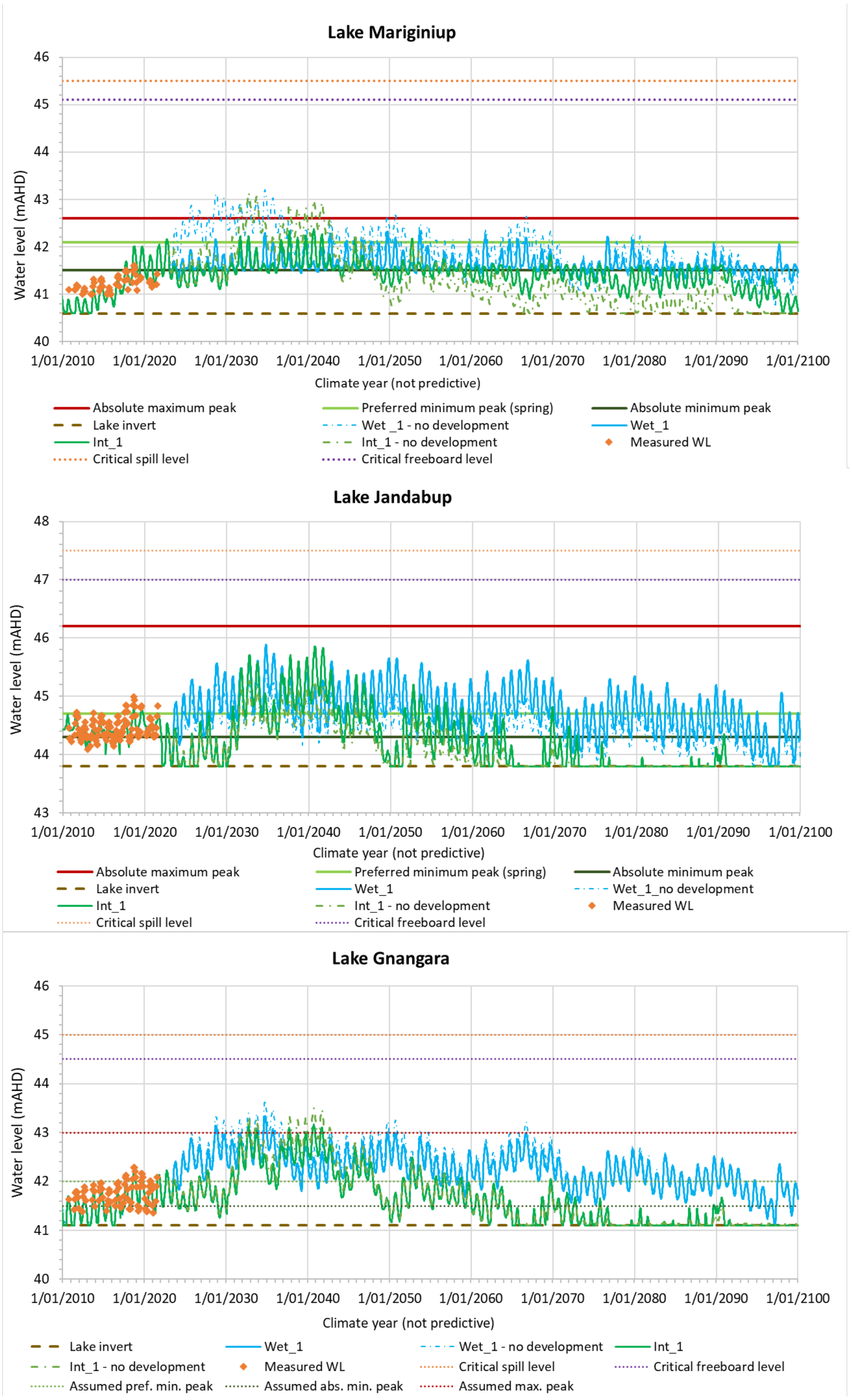


Figure 110: A comparison of the lake water levels for no development and for 'staged to 2040' with subsoil discharge to lakes and pumping from Lake Mariginiup to Jandabup, under the Wet_1 and Int_1 climate scenarios (Simulations a,c,29 and 31)

9.6.2. Maximum groundwater levels

Maximum groundwater levels (MGLs) for the full buildout simulations with subsoils discharging into the lakes and pumping of up to 100 L/sec from Lake Mariginiup to Jandabup are presented in Figure 111 and compared to the 'no development' scenarios in Figure 112. The depth to MGL is shown in Figure 113. These comparison maps show the following:

- Groundwater mounding of up to 1m when compared to no development is centred over Lake Jandabup in the Wet_2 climate.
- Maximum water levels are reduced at Lake Mariginiup by up to 0.5m when controlled by pumping when compared to no development.
- Increased groundwater levels extend to the western DSP boundary, but significant depth to water remains.
- Areas upgradient of Lake Mariginiup and Jandabup have slightly reduced maximum groundwater levels due to the downgradient subsoils lowering water levels.

9.6.3. Significance of results

Simulations 29 to 31 representing "Staged development to 2040" inclusive of subsoil discharge to Lakes Mariginiup and Jandabup with pumped transfer of up to 100 L/sec from Lake Mariginiup to Lake Jandabup indicate that Lake Mariginiup can be managed using pumping and Lake Jandabup has adequate capacity to receive this water in all bar very wet climate, where there is some risk that a storm event occurring simultaneously with peak lake3 levels may result in lake overtopping. It is recommended that if 'staged to 2040' development progresses inclusive of subsoils discharging to lakes and prior to the development of the district scale EWGMS, that a contingency option is readily available to remove water from Lake Jandabup in the event of very high water levels. Nominally, the use of the Absolute Maximum Peak as a trigger to start removing water from Lake Jandabup (for the management of early development only) would appear to be reasonable, but this has not been assessed in the groundwater model.

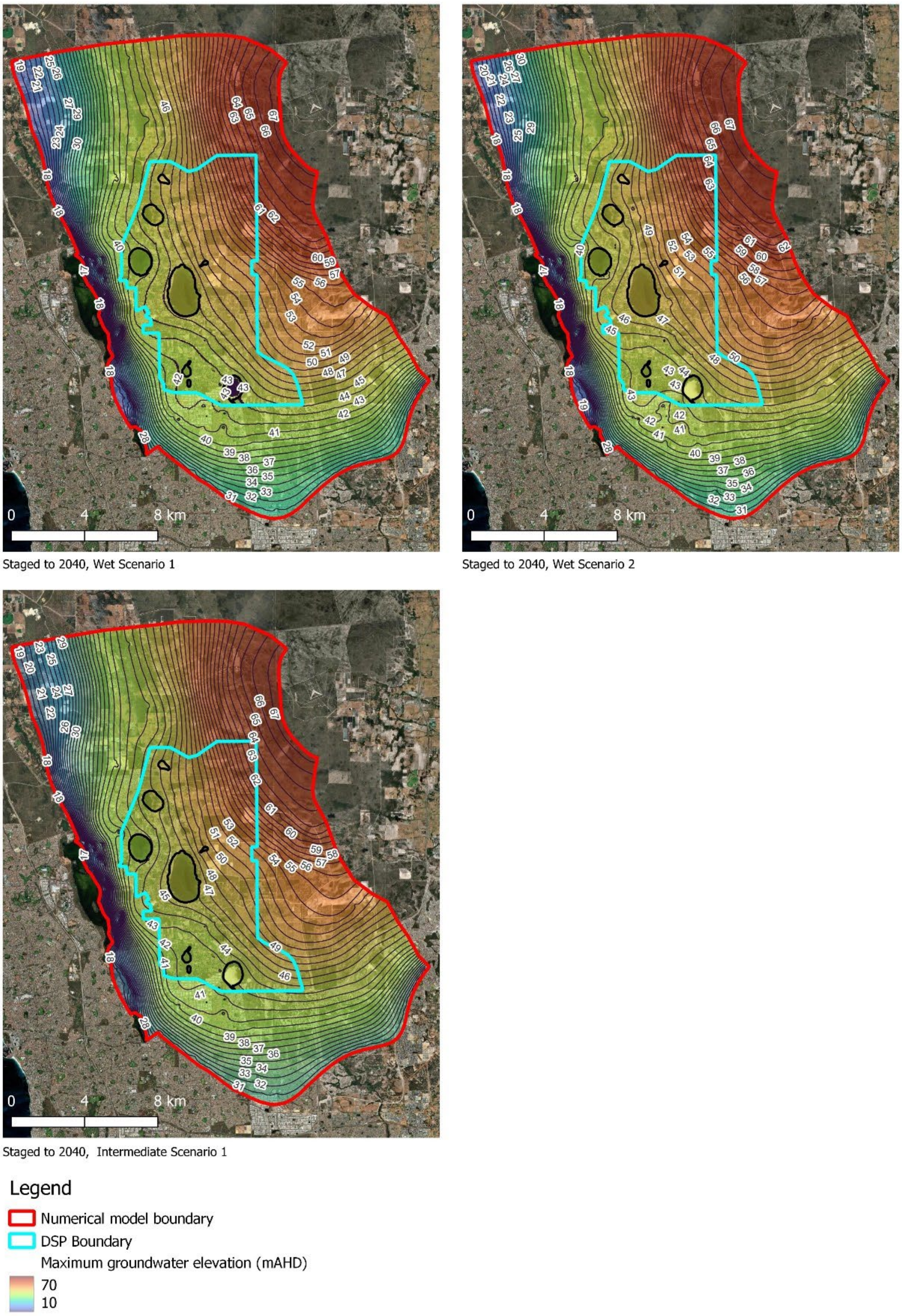


Figure 111: MGL surface for the staged to 2040 simulations (subsoil drainage discharging into lakes and pumping from Lake Mariginiup to Jandabup), under the three selected climate scenarios

Figure 112: Comparison of the stage to 2040 simulations (subsoil drainage discharging into lakes and pumping from Lake Mariginiup to Jandabup) with MGL surface with the no development MGL surface

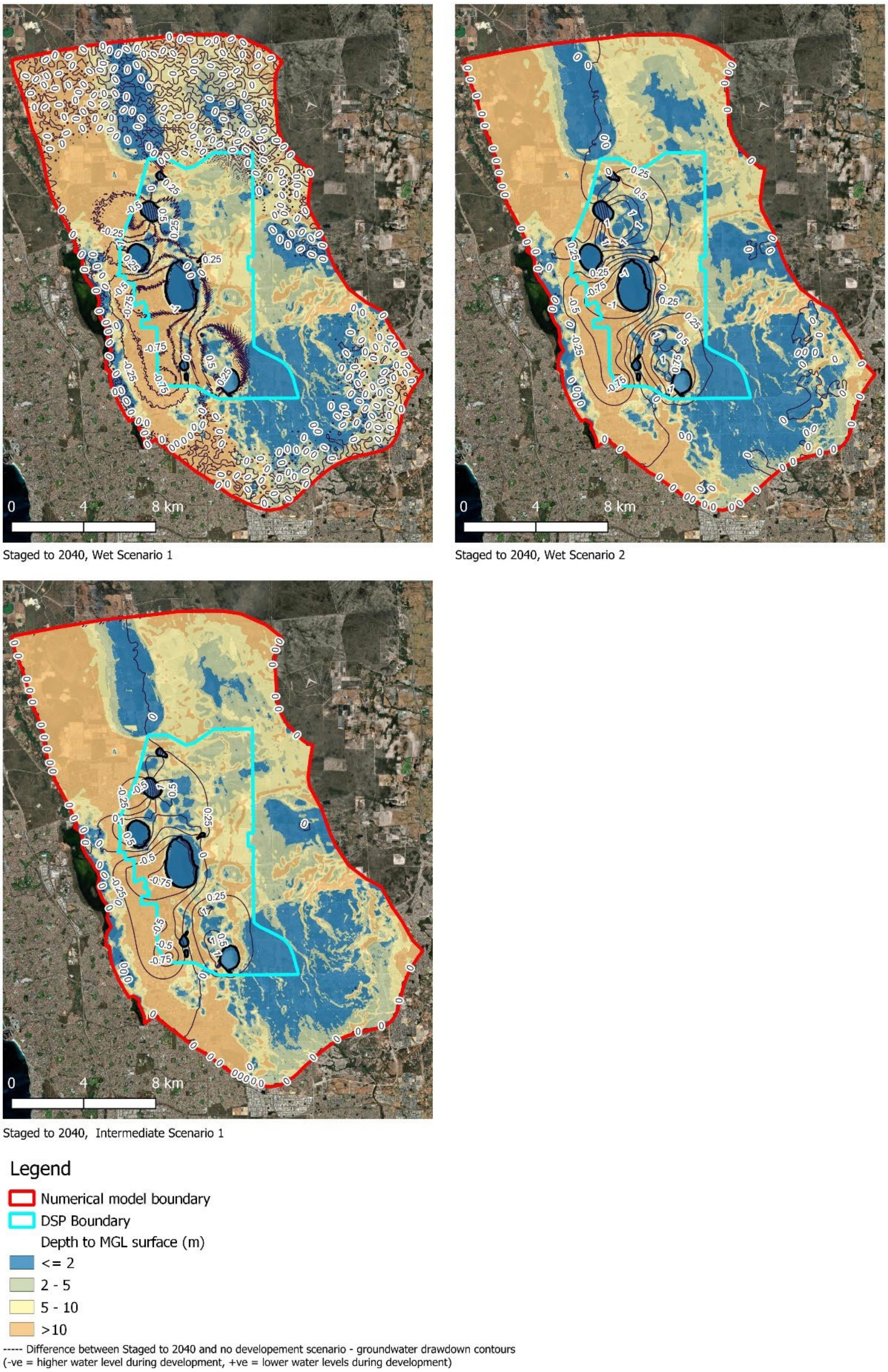


Figure 113: Depth to MGL surface with contours of relative change due to development (staged to 2040 simulations with subsoil drainage discharging into lakes and pumping from Lake Mariginiup to Jandabup)

10. Model limitations

Interpreting the results of a groundwater model always requires caution. There is an inherent compromise between the complexity of the actual hydrogeological system and the relative simplicity of a computer model. This modelling was undertaken based on reports and/or raw data that were made available to Pentium, including unpublished and publicly accessible sources.

Key limitations of the model include:

- Poor calibration on the western side of the model domain
  - There was poor calibration of the groundwater model through the area of steep hydraulic gradient on the western side of the model domain extending to the western side of the East Wanneroo DSP area. The poor calibration is evident in simulated water levels higher than measured water levels towards the end of the calibration period, with the groundwater level trends not well matched across all bores. This discrepancy may be causing higher future water levels to be simulated on the western side of the model domain.
- Recharge function constraints
  - The recharge function is a bucket type model which is a compromise between the complexity of a fully coupled unsaturated/saturated zone model and the simplicity of assumed linear recharge rates. Given the model is uncoupled, the change in recharge with depth to groundwater is not being simulated in the East Wanneroo groundwater model Furthermore, recharge rates and the applicability of the recharge function over the extremes of the climate being simulated, particularly during the very dry and very wet rainfall periods, has not been examined. It is anticipated that in particular the Dry_1 climate water levels may be too low towards the end of the simulation, but for the purposes of this work the implications of this are not important for engineering design.
- Geological simplification
  - Aquifer properties were assumed to apply over the full depth of the aquifer. The presence of different permeability layers, such as low permeability clay lenses, has not been considered. Given the sensitivity of the model to leakage which depends on vertical flow perpendicular to sedimentary layering, the assumption of one set of aquifer properties over the full model depth may be influencing the model results.
- Post development landform
  - No post development earthworks were available for the DSP at the time of modelling, therefore future scenarios use current topography to represent ground level. The use of Modflow drains to control ground water rise in areas of low clearance to groundwater minimises the need for a specific post development land surface to be represented in the model. The groundwater modelling assumes that the for the post-development landform, any areas of cut won't lower the existing surface to within 2m of CGL. This is supported by an earthworks assessment undertaken by JDSi across the entire DSP area which concluded no cut would occur in areas of shallow clearance to groundwater. However, consideration of proposed earthworks at local planning stage may require some refinement of the required subsoil extent.
  - Additionally, where the post-development landform incorporates significant areas of fill to raise clearance to groundwater and does not employ a mechanism for groundwater control, adjacent areas that have not yet had drainage controls in place may be impacted by rising groundwater levels were there is low existing clearance to groundwater. This should be assessed at local planning stage and an engineering control placed as required,
- Subsoil drainage simplification
  - The simulation of subsoil drainage has been applied in the model using a drainage "plain" set at the 1986 – 1995 AAMGL (assigned as the CGL) with the Modflow Drain package, which assumes all drains are able to rapidly convey any intercepted water to a suitable discharge location and that water level will not rise above the drain invert level. The depth of subsoils modelled (set at CGL at depths up to 2m below ground level) is conservative and accounts for likely mounding between subsoil drains, however this does not preclude the need for more detailed assessment of drainage layouts, pipe inverts and outfall elevations at a local planning scale with the appropriate post development landform. This may become particularly important

when considering the effects of discharging drainage water to wetlands and ensuring drainage outlet elevations above peak water levels.

While the model provides a useful tool to assess the potential impacts of the development, the inherent uncertainty resulting from the simplification process in constructing the model and parameterisation, as well as uncertainty in future model stresses (climate, land use, abstraction etc) mean that the results of any predictive scenarios should be considered indicative only and the model should be validated using ongoing groundwater monitoring and updated in a regular basis (nominally 5 to 10 year intervals). A groundwater monitoring program to support this data collection has been committed in the DWMS and forms part of the costing of the DCP.

11. Key implications and future work

- A detailed groundwater flow model has been developed for the East Wanneroo DSP area, as recommended in the DWMS.
- As part of the current project work, the East Wanneroo groundwater model has been used to simulate a select set of future scenarios to inform the concept design of the groundwater management scheme that will be required in low lying parts of the East Wanneroo DSP area.
- Future scenario modelling has provided the following information:
  - The spatial extent of subsoil drainage that will be required within the East Wanneroo DSP area.
  - Maximum subsoil drainage flow rates at the catchment scale for infrastructure design and maximum annual subsoil drainage volumes that will need to be managed.
  - Indicative lake water levels for the 'no development' scenario, staged development, 'staged to 2040' development and at full buildout of the DSP area under a range of climate scenarios.
  - Indicative maximum groundwater levels for no development, staged development and at full buildout of the DSP area.
- Recognising that the results of the models are indicative NOT predictive, key implications from the future scenario modelling are summarised below.

  Lake Mariginiup

  - Without development, Lake Mariginiup water levels are likely to occasionally exceed the absolute maximum peak levels during higher rainfall periods (i.e., wet scenarios).
  - With development, Lake Mariginiup water levels will likely exceed the absolute maximum peak water level and may also overtop in the event that urban drainage is directed into the lakes (as proposed under the DWMS) under all bar extremely dry climate scenarios. Ongoing monitoring and water level management (adaptive management practices) will be required once development commences.
  - A scheme to remove excess water from Lake Mariginiup will likely be required following development in the vicinity of the lake should wetter climates be experienced. Modelling indicates pumping can be used to control lake levels to acceptable maximum.
  - With or without development, in a dry future climate Lake Mariginiup may become dry even with the planned reductions in abstraction rates.

  Lake Jandabup

  - With development, Lake Jandabup water levels will likely exceed the absolute maximum peak water level and may also overtop in the event that urban drainage is directed into the lakes (as proposed under the DWMS) under all bar extremely dry climate scenarios. Ongoing monitoring and water level management (adaptive management practices) will be required once development commences.
  - For 'staged to 2040' development Lake Jandabup appears to have some available (buffer) storage for the management of subsoil drainage water and transfer of excess water from Mariginiup.
  - Adaptive management practices will also be required at Lake Jandabup following development around the lake.
  - An offsite water disposal scheme is likely to be required following development to manage excess water during later stages of development. Modelling indicates pumping can be used to control lake levels to acceptable maximum, with flow rates of up to 1500 L/sec required to discharge water offsite.

  Lake Gnangara

  - Further work is required at this lake to determine key environmental and engineering lake threshold levels. Pentium has estimated lakes for this assessment. With development, Lake Gnangara water levels will likely exceed the absolute maximum peak water level (as estimated by Pentium) and may also overtop in the event that urban drainage is directed into the lakes (as proposed under the DWMS) under all bar extremely dry climate scenarios.
  - Ongoing monitoring and water level management (adaptive management practices) will be required once development commences.

  - Modelling indicates pumping can be used to control lake levels to acceptable maximum.

  Maximum groundwater level observations

  - Development across the East Wanneroo area results in higher simulated maximum groundwater levels than with no development on the western side of the DSP area. These higher levels occur where there is adequate clearance to groundwater and subsoil drainage is not required to manage rising groundwater levels. The increased recharge due to urbanisation therefore causes groundwater to mound in those areas. Maximum groundwater levels were simulated to be up to 2.5 m higher than no development levels during high rainfall periods.
  - Development across the East Wanneroo area results in lower simulated maximum groundwater levels than would occur with no development through parts of the East Wanneroo DSP area because groundwater levels will be managed and controlled through subsoil drainage.

  Annual subsoil drainage volumes

  - There is significant variability in the simulated volume of subsoil drainage water that will be generated following full buildout of the DSP area, with annual subsoil drainage volumes ranging from 2 GL/yr to more than 30 GL/yr in a wetter climate, and from 0 GL/yr to about 3 GL/yr in a dry climate scenario.
  - Due to the uncertainty in the future climate, there is significant variability and uncertainty in potential future subsoil drainage volumes across the DSP area. With this uncertainty, a subsoil drainage harvesting scheme currently does not appear to be commercially viable given this unpredictability.

  Staged development to 2040 without subsoil drainage

  - Simulated staged development on the western side of the DSP area, in areas that do not require groundwater management infrastructure to be installed, increased maximum water levels by up to 1 m in Lake Mariginiup during high rainfall periods, and increased groundwater levels on the western side of the DSP area by up to 1 m. From the modelling, there is a small or negligible impact of this early staged development on water levels in the other major lakes.

- It should be recognised that all groundwater models have limitations and interpreting the results of a groundwater model always requires caution, as there is an inherent compromise between the complexity of the actual hydrogeological system and the relative simplicity of a computer model.
- Despite the ever-present model limitations, the results that have been obtained from the suite of future simulations presented in this report, provide useful data to inform the concept design of the water management system in East Wanneroo.
- The groundwater model has been developed as a design tool and will be available for future studies to further inform decision making processes associated with the development of the East Wanneroo DSP area. The model can be adapted and refined as required to inform local structure planning, but in its current regional scale format should not be used to inform detailed engineering design.
- Detailed subsoil engineering design has not been undertaken to support this assessment. However, at LWMS and preliminary engineering design stage consideration will need to be given to the functionality of subsoil drainage and their free-flowing outlets based on simulated lake water levels.

Further work

A groundwater monitoring program has been committed in the DWMS and forms part of the costing of the DCP. Data obtained from this monitoring should be used to validated/update the groundwater model for both pre- and post-development conditions on a regular basis (nominally 5 to 10 year intervals) to provide greater confidence in predictions and water level response to development.

A number of other additional assessments are necessary to determine acceptable lake management criteria, including but not limited to:

- Ecohydrological studies to assess the ecological water requirements of the environmental values contained by the wetlands, with respect to the required maximum and minimum groundwater levels and hydroperiods (duration of inundation) to maintain these.
- Groundwater and soil water quality impacts arising from both changing water levels and the discharge/transfer of water to/between lakes. Mobilisation of nutrients from historic land uses and/or acidity and heavy metals associated with acid sulfate soils are key risks.

- Setting acceptable environmental trigger criteria and identification of contingency measures if triggers are exceeded for water level and water quality for all wetlands within the East Wanneroo DSP.

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13. List of appendices

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Appendix A: Calibrated pilot point parameter values

Appendix A: Calibrated pilot point parameter values

Pilot Point number	Horizontal hydraulic conductivity, Kx (m/day)	Vertical hydraulic conductivity, Kz (m/day)	Specific yield, Sy
1	5.89	1.00	0.21
2	25.04	1.00	0.20
3	18.33	1.00	0.26
4	1.05	1.00	0.19
5	2.29	1.00	0.21
6	17.90	1.00	0.30
7	6.98	1.00	0.23
8	7.56	0.99	0.22
9	6.20	1.00	0.25
10	4.61	0.81	0.20
11	5.57	0.84	0.21
12	0.56	0.99	0.30
13	3.09	0.98	0.30
14	7.88	0.97	0.30
15	23.32	1.00	0.22
16	27.18	1.00	0.21
17	16.97	1.03	0.20
18	12.64	1.96	0.22
19	13.34	2.02	0.24
20	18.29	2.04	0.26
21	4.04	0.99	0.21
22	2.71	0.96	0.25
23	5.33	0.95	0.25
24	9.98	1.03	0.30
25	44.13	0.98	0.30
26	42.63	1.99	0.30
27	20.25	2.01	0.30
28	31.94	2.00	0.26
29	50.00	2.14	0.25
30	32.69	2.20	0.22
31	21.97	1.99	0.25
32	18.99	2.00	0.25
33	7.47	1.00	0.22
34	13.18	1.00	0.25
35	25.93	2.03	0.30
36	6.85	2.01	0.30
37	35.27	1.94	0.30
38	8.09	2.07	0.28

Pilot Point number	Horizontal hydraulic conductivity, Kx (m/day)	Vertical hydraulic conductivity, Kz (m/day)	Specific yield, Sy
39	22.05	1.97	0.30
40	27.16	1.98	0.30
41	13.55	2.01	0.30
42	4.96	2.06	0.26
43	6.25	2.04	0.24
44	11.37	2.00	0.24
45	12.64	0.96	0.21
46	6.34	0.98	0.22
47	22.62	2.00	0.29
48	20.86	2.00	0.28
49	22.42	2.03	0.30
50	50.00	2.04	0.30
51	37.29	2.00	0.30
52	13.44	2.00	0.30
53	8.50	2.00	0.29
54	13.15	2.00	0.27
55	12.75	2.00	0.25
56	5.61	1.99	0.28
57	11.63	2.00	0.29
58	20.22	1.99	0.27
59	13.07	1.94	0.26
60	16.64	2.00	0.29
61	9.90	1.93	0.29
62	14.30	1.93	0.30
63	18.67	2.03	0.30
64	5.34	2.02	0.30
65	12.78	2.01	0.30
66	31.53	2.00	0.30
67	20.98	2.00	0.25
68	25.50	2.00	0.24
69	50.00	2.00	0.29
70	17.87	2.07	0.26
71	15.39	2.09	0.28
72	13.82	2.01	0.30
73	7.81	1.95	0.30
74	17.24	1.93	0.30
75	46.42	2.02	0.30
76	0.52	2.03	0.30
77	13.59	1.85	0.30
78	50.00	2.00	0.30
79	13.88	2.08	0.28
80	16.33	1.97	0.30

Pilot Point number	Horizontal hydraulic conductivity, Kx (m/day)	Vertical hydraulic conductivity, Kz (m/day)	Specific yield, Sy
81	9.06	1.87	0.30
82	2.98	1.95	0.30
83	21.96	2.02	0.30
84	5.17	1.98	0.29
85	6.85	2.00	0.30
86	24.58	1.99	0.30
87	11.16	2.00	0.30
88	15.94	2.00	0.25

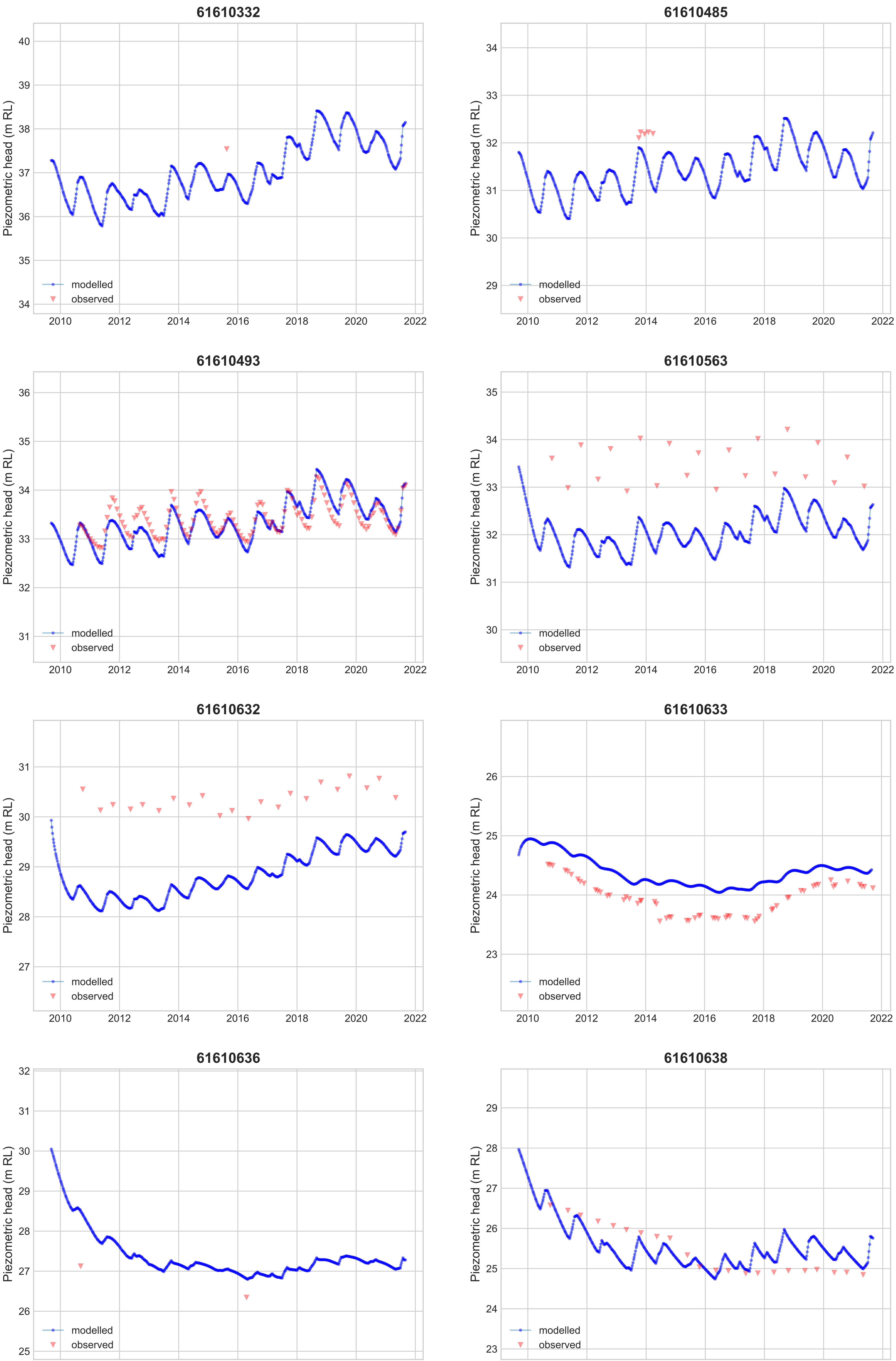
Appendix B: Target time series statistics

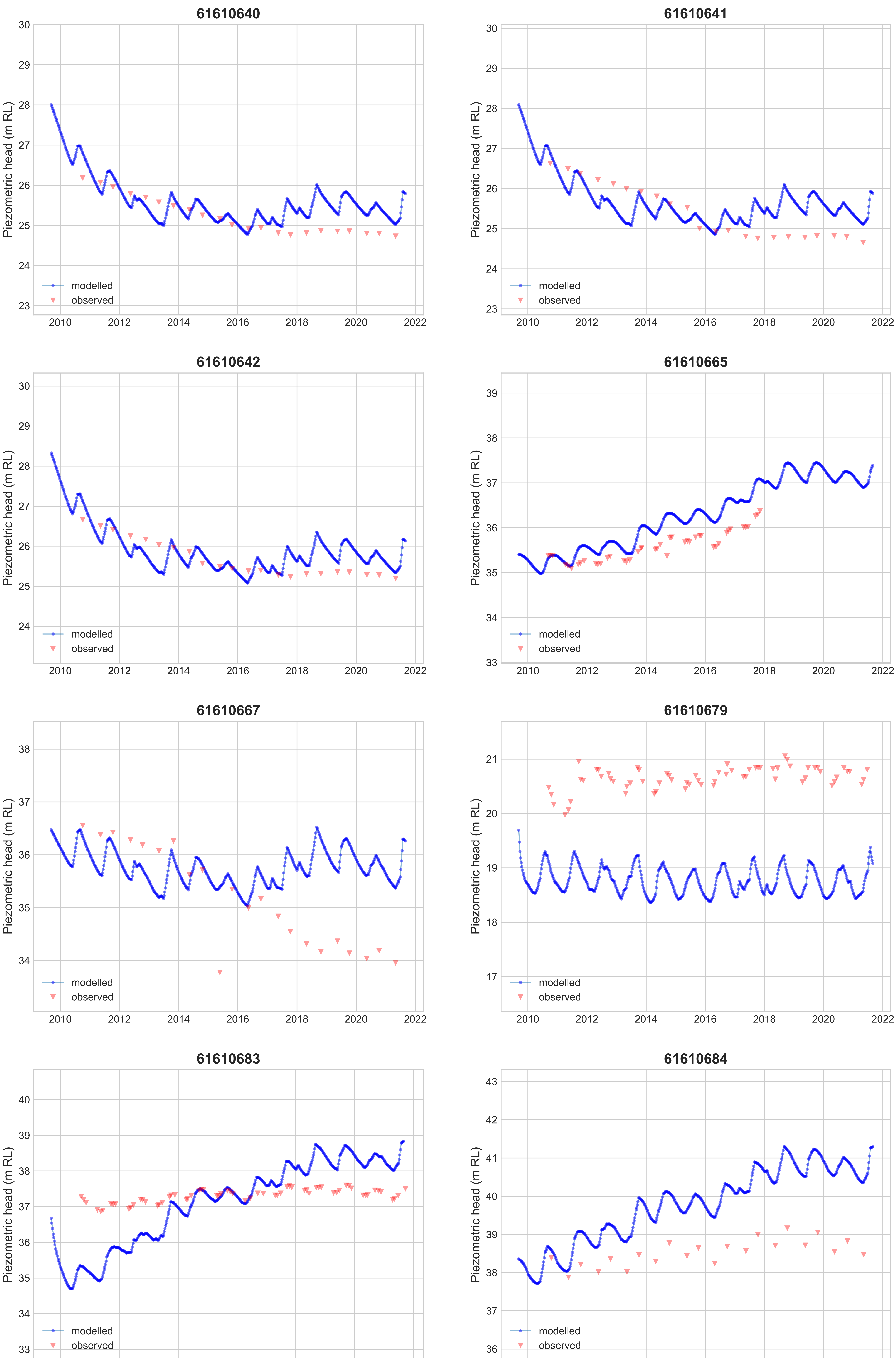
Appendix B: Observed and modelled time series data statistics for the target observation bores (ordered by observation count) and 3 major lakes.

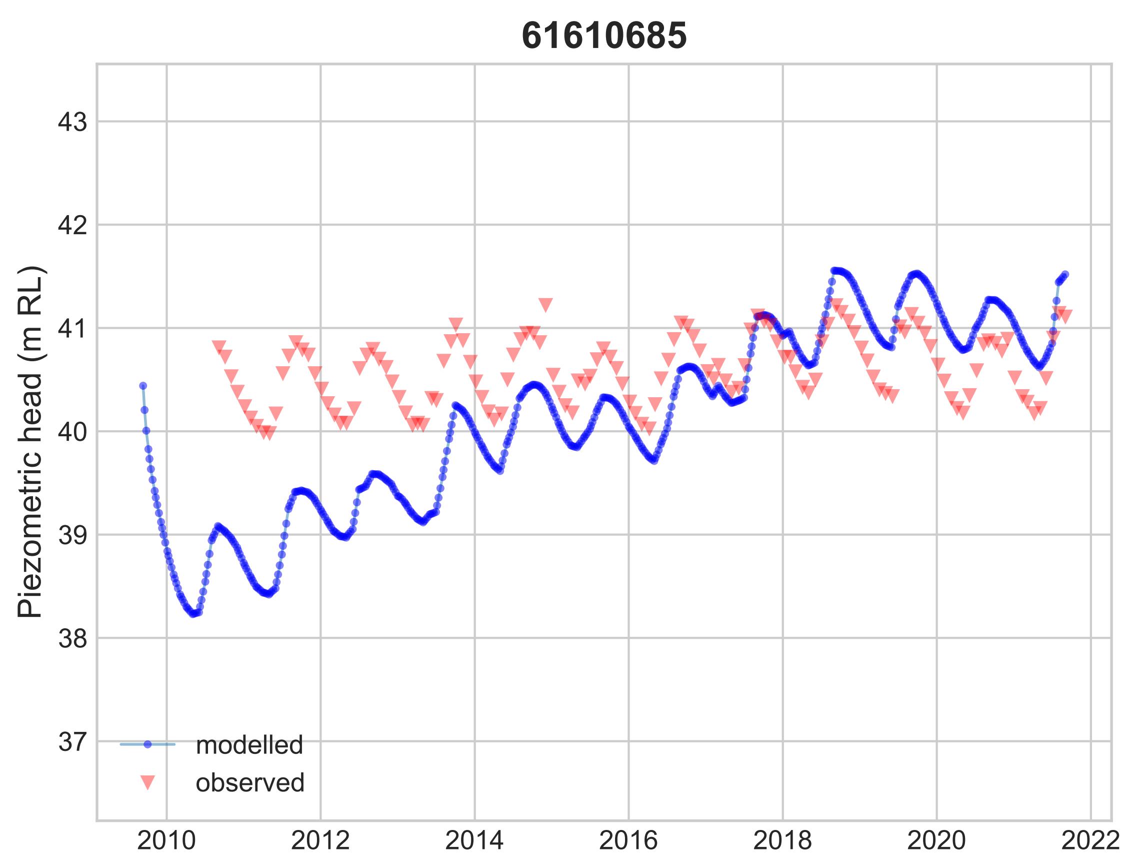
Target	Count of Observations	Observed (mAHD)				Modelled (mAHD)			
		Average	Minimum	Maximum	Range (m)	Average	Minimum	Maximum	Range (m)
61610989	134	43.008	42.187	43.758	1.571	42.539	41.523	43.556	2.033
61610493	133	33.414	32.820	34.269	1.449	33.372	32.492	34.422	1.930
61610743	133	43.199	42.239	44.212	1.973	43.559	42.600	44.618	2.018
61610744	133	43.206	42.244	44.201	1.957	43.558	42.599	44.616	2.017
61610745	133	44.168	43.467	44.963	1.496	43.570	42.606	44.628	2.023
61610764	133	44.444	43.826	45.131	1.305	44.343	43.765	45.007	1.243
61610765	133	44.544	42.948	45.133	2.185	44.339	43.760	45.003	1.243
61610768	133	46.588	46.020	47.399	1.379	46.424	45.675	47.262	1.587
61610769	133	46.666	46.132	47.442	1.310	46.419	45.671	47.257	1.586
61610820	133	45.317	44.900	45.893	0.993	45.610	45.061	46.312	1.252
61610822	133	45.521	45.100	46.101	1.001	45.605	45.055	46.306	1.251
61610835	133	39.888	38.580	41.165	2.585	39.728	38.473	41.141	2.668
61610918	133	39.575	38.650	40.633	1.983	39.291	38.421	40.363	1.942
61610967	133	51.003	50.152	52.017	1.865	50.649	49.963	51.342	1.378
61610978	133	55.620	54.746	56.736	1.990	55.859	55.232	56.564	1.332
61611025	133	35.882	35.344	36.724	1.380	35.876	35.023	36.940	1.917
61618440	133	41.616	40.924	42.288	1.364	41.444	40.707	42.257	1.550
61610685	132	40.585	39.985	41.225	1.240	40.214	38.427	41.553	3.127
61610750	132	43.622	42.640	44.892	2.252	43.966	43.314	44.709	1.395
61610762	132	44.354	43.774	45.187	1.413	43.918	43.243	44.622	1.379
61610789	132	45.052	44.246	46.272	2.026	45.061	43.981	46.242	2.262
61610833	132	54.728	54.045	55.895	1.850	55.090	54.189	56.225	2.037
61610860	132	58.548	57.701	59.733	2.032	58.876	57.927	60.050	2.123
61610933	132	47.194	45.921	48.120	2.199	47.334	46.654	48.099	1.445
61611440	132	40.692	40.040	41.389	1.349	40.376	38.671	41.689	3.018
61613231	132	65.136	64.692	65.527	0.835	63.216	62.449	64.159	1.710
61611034	132	47.941	47.349	49.039	1.690	48.018	47.228	48.720	1.492
61613200	131	47.004	46.446	47.717	1.271	46.878	46.253	47.616	1.363
61613211	131	52.108	51.193	53.274	2.081	52.190	51.129	53.398	2.268
61611010	130	47.942	47.294	48.599	1.305	47.710	47.001	48.413	1.412
61610763	126	44.436	43.862	45.097	1.235	44.377	43.773	45.025	1.252
61610697	118	41.536	40.942	42.457	1.515	41.370	40.760	42.094	1.335
61610843	113	42.009	41.557	42.622	1.065	42.045	41.416	42.786	1.371
61613203	93	44.217	43.570	45.005	1.435	44.273	43.288	45.321	2.033
61610803	67	52.087	51.449	53.127	1.678	51.910	51.150	52.796	1.646
61610864	66	65.543	64.995	66.430	1.435	65.178	64.595	65.791	1.196
61610679	66	20.652	19.979	21.056	1.077	18.801	18.449	19.226	0.777
61610688	65	40.530	39.885	41.125	1.240	40.165	38.395	41.533	3.137
61610794	65	49.577	48.226	51.040	2.814	49.528	48.194	50.826	2.631
61610832	65	55.373	54.330	56.896	2.566	55.653	54.522	56.905	2.383
61610683	64	37.304	36.871	37.605	0.734	37.231	34.945	38.729	3.784
61610734	64	42.004	41.264	42.684	1.420	41.927	40.952	42.936	1.984
61610737	64	42.041	41.305	42.775	1.470	41.940	41.040	42.749	1.708
61610738	64	42.083	41.320	42.893	1.573	41.940	41.040	42.748	1.708
61610884	64	47.314	46.680	47.920	1.240	47.052	46.346	47.609	1.264
61610696	63	40.624	39.667	41.638	1.971	40.429	39.410	41.463	2.053
61610736	63	41.824	41.174	42.376	1.202	41.957	41.044	42.742	1.698
61610845	63	46.629	45.963	47.160	1.197	46.702	45.797	47.473	1.676
61610943	63	64.625	63.435	65.826	2.391	64.345	63.580	65.259	1.680
61611289	63	50.960	50.181	51.616	1.435	51.158	50.012	52.233	2.221
61610901	61	54.175	53.061	54.931	1.870	53.638	52.984	54.301	1.317
61610633	59	23.937	23.560	24.520	0.960	24.348	24.046	24.884	0.839
61610855	57	52.882	52.257	53.454	1.197	52.133	51.114	53.056	1.942
61611001	45	40.551	39.933	41.178	1.245	40.307	39.073	41.284	2.211
61611002	45	40.637	40.019	41.189	1.170	40.313	39.073	41.291	2.218
61610665	44	35.584	35.098	36.374	1.276	35.996	35.161	37.086	1.924
61611003	39	40.708	40.340	41.350	1.010	40.302	39.076	41.295	2.219
61610861	24	61.494	60.277	62.865	2.588	62.344	61.504	63.362	1.857
61610761	23	42.395	42.010	42.735	0.725	41.932	41.109	42.797	1.688

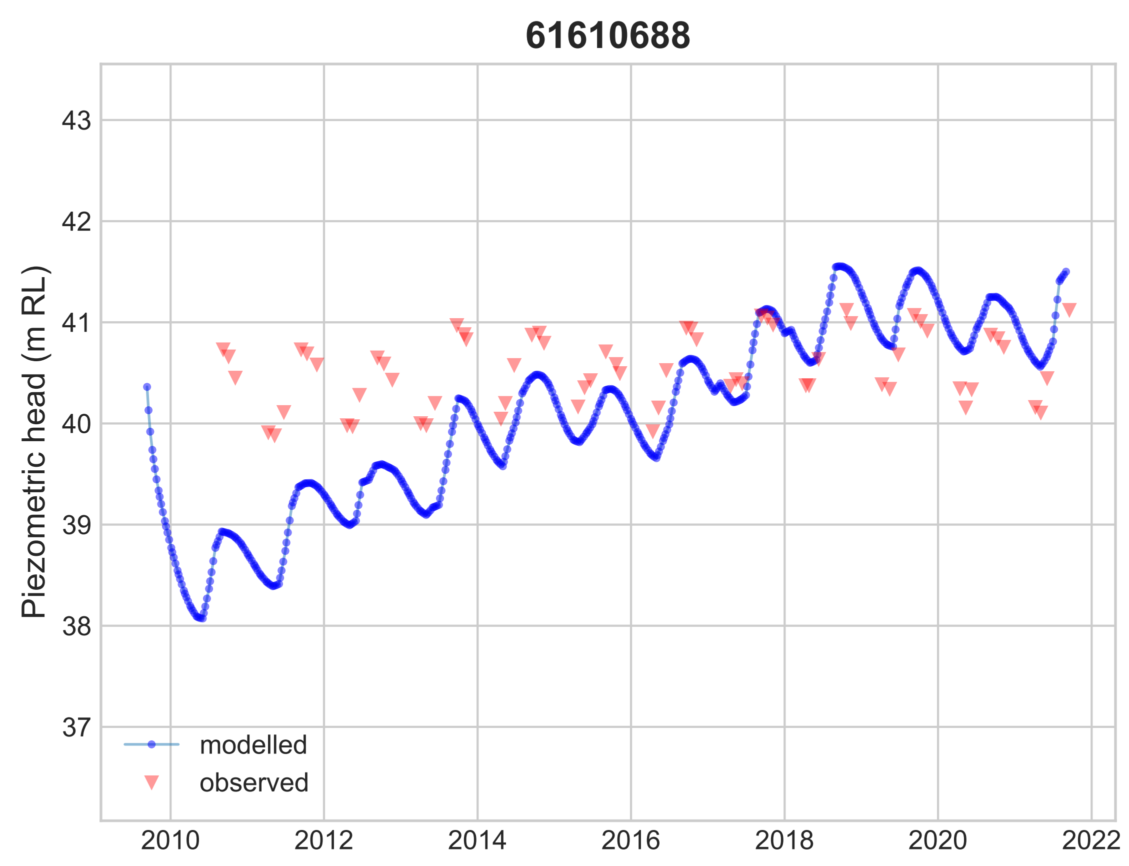
Target	Count of Observations	Observed (mAHD)				Modelled (mAHD)			
		Average	Minimum	Maximum	Range (m)	Average	Minimum	Maximum	Range (m)
61610936	23	65.194	64.744	65.624	0.880	63.398	62.657	64.261	1.604
61610937	23	61.262	60.810	61.905	1.095	63.388	62.649	64.252	1.603
61610938	23	61.478	60.988	62.153	1.165	63.390	62.651	64.253	1.603
61610939	23	62.909	62.394	63.649	1.255	64.081	63.375	64.947	1.572
61610940	23	62.652	62.149	63.404	1.255	64.084	63.377	64.949	1.572
61610941	23	65.431	64.890	66.015	1.125	64.092	63.384	64.957	1.574
61610942	23	62.912	62.415	63.654	1.239	64.090	63.384	64.955	1.571
61610563	22	33.488	32.919	34.217	1.298	32.018	31.345	32.912	1.567
61610632	22	30.353	29.966	30.816	0.850	28.824	28.120	29.625	1.506
61610638	22	25.435	24.851	26.581	1.730	25.421	24.782	26.774	1.992
61610640	22	25.219	24.736	26.186	1.450	25.455	24.814	26.809	1.995
61610641	22	25.396	24.662	26.632	1.970	25.538	24.895	26.896	2.001
61610642	22	25.673	25.198	26.663	1.465	25.768	25.118	27.130	2.012
61610667	22	35.155	33.779	36.557	2.778	35.704	35.086	36.350	1.264
61610684	22	38.524	37.879	39.169	1.290	39.878	38.072	41.212	3.141
61610714	22	36.395	35.680	37.205	1.525	36.513	34.983	37.908	2.925
61610715	22	38.557	37.837	39.260	1.423	38.566	37.211	39.872	2.661
61610718	22	41.329	40.660	41.900	1.240	41.380	40.563	42.309	1.746
61610816	22	42.219	41.555	43.081	1.526	43.390	42.689	44.041	1.352
61610817	22	45.009	44.536	45.565	1.029	44.833	44.289	45.379	1.089
61610907	22	65.159	64.530	66.008	1.478	63.718	62.957	64.689	1.732
61618432	22	27.530	26.910	28.114	1.204	29.509	27.069	31.014	3.945
61611031	22	46.199	45.703	47.038	1.335	45.994	45.427	46.705	1.278
61672191	20	35.728	35.493	35.983	0.490	36.281	36.025	36.571	0.547
61611498	17	35.158	34.589	35.909	1.320	35.465	34.335	36.640	2.305
61611377	17	41.290	40.596	42.181	1.585	41.028	40.367	41.957	1.590
61610716	10	38.951	38.631	39.203	0.572	37.763	37.101	38.397	1.296
61610719	9	41.155	40.690	41.577	0.887	41.131	40.577	41.523	0.945
61610720	9	41.125	40.650	41.562	0.912	41.193	40.622	41.610	0.988
61610485	5	32.190	32.108	32.228	0.120	31.597	31.079	31.898	0.819
61610815	3	40.461	39.941	40.811	0.870	40.380	39.829	40.728	0.898
61618441	3	33.862	33.595	34.085	0.490	34.885	34.364	35.440	1.076
61610636	2	26.740	26.350	27.130	0.780	27.657	26.812	28.503	1.691
61610758	2	41.060	41.060	41.060	0.000	40.429	40.105	40.754	0.649
61610332	1	37.545	37.545	37.545	0.000	36.882	36.882	36.882	0.000
61610695	1	41.246	41.246	41.246	0.000	41.489	41.489	41.489	0.000
61610770	1	46.872	46.872	46.872	0.000	46.780	46.780	46.780	0.000
61610821	1	45.666	45.666	45.666	0.000	46.124	46.124	46.124	0.000
61610873	1	40.041	40.041	40.041	0.000	39.463	39.463	39.463	0.000
61610874	1	41.796	41.796	41.796	0.000	40.908	40.908	40.908	0.000
61610882	1	41.600	41.600	41.600	0.000	40.919	40.919	40.919	0.000
61610954	1	38.240	38.240	38.240	0.000	38.556	38.556	38.556	0.000
61610986	1	40.471	40.471	40.471	0.000	40.314	40.314	40.314	0.000
61610987	1	40.019	40.019	40.019	0.000	40.074	40.074	40.074	0.000
61613204	1	49.367	49.367	49.367	0.000	47.545	47.545	47.545	0.000
Lake Mariginiup	56	41.224	41.000	41.601	0.601	41.291	40.601	42.002	1.401
Lake Jandabup	116	44.450	44.089	44.985	0.896	44.436	44.026	44.775	0.749
Lake Gnangara	90	41.755	41.360	42.290	0.930	41.642	41.153	42.129	0.977

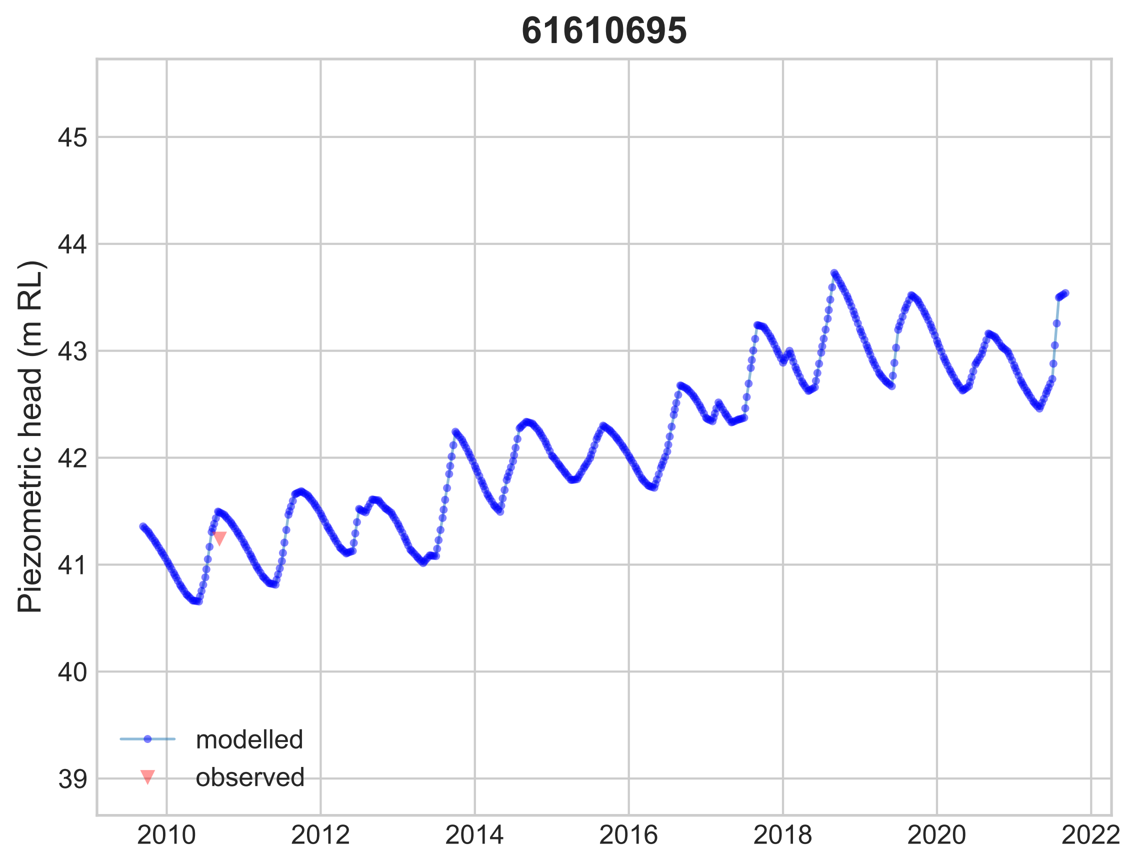
Appendix C: Calibration hydrographs

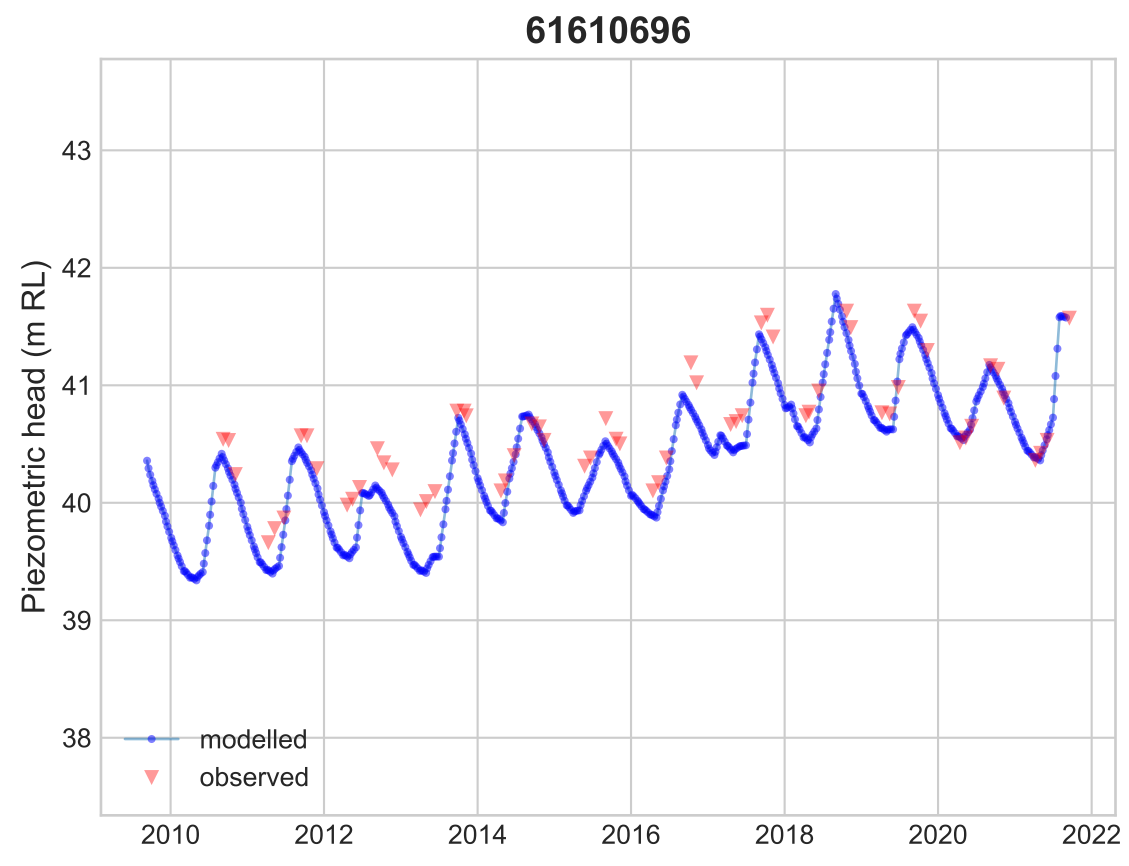

61610332
61610485
61610493
61610563
61610632
61610633
61610636
61610638
Piezometric head (m RL)
modelled
observed
2010
2012
2014
2016
2018
2020
2022

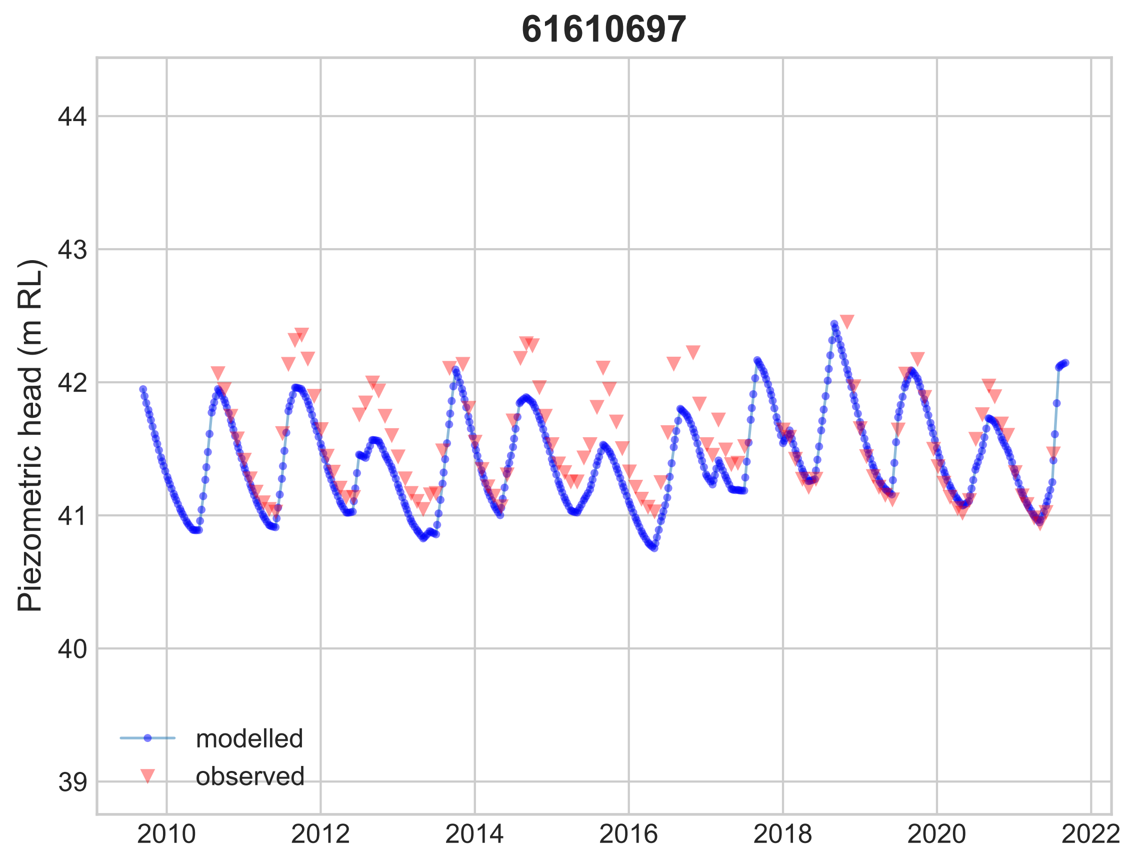

61610640
61610641
61610642
61610665
61610667
61610679
61610683
61610684
Piezometric head (m RL)
modelled
observed
2010
2012
2014
2016
2018
2020
2022

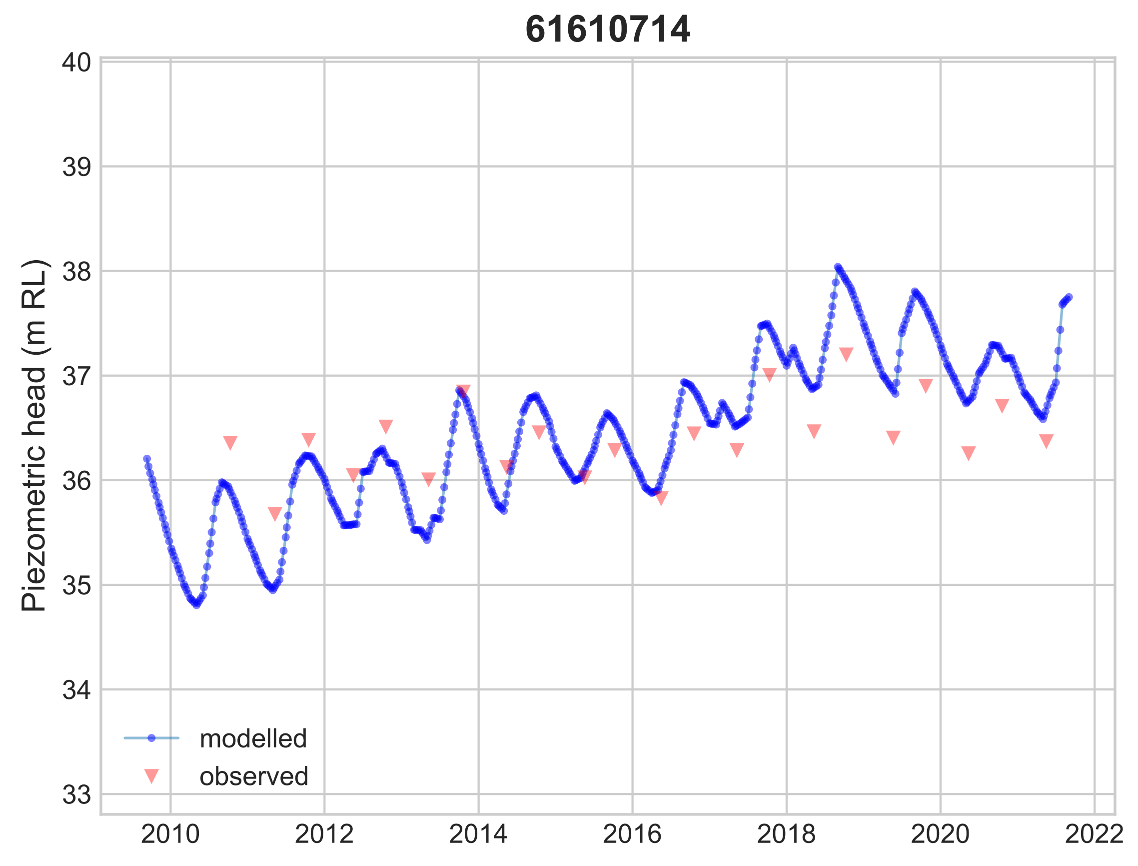

61610685
Piezometric head (m RL)
modelled
observed

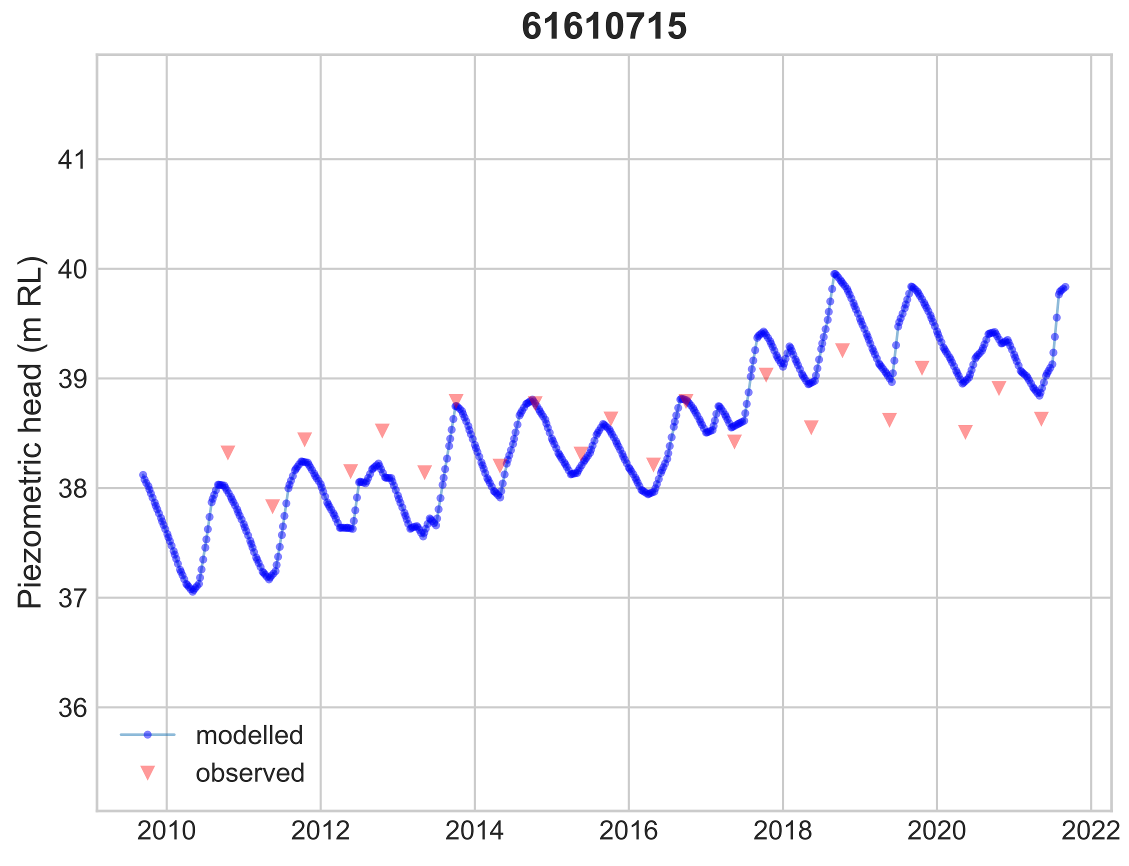

61610688
Piezometric head (m RL)
modelled
observed

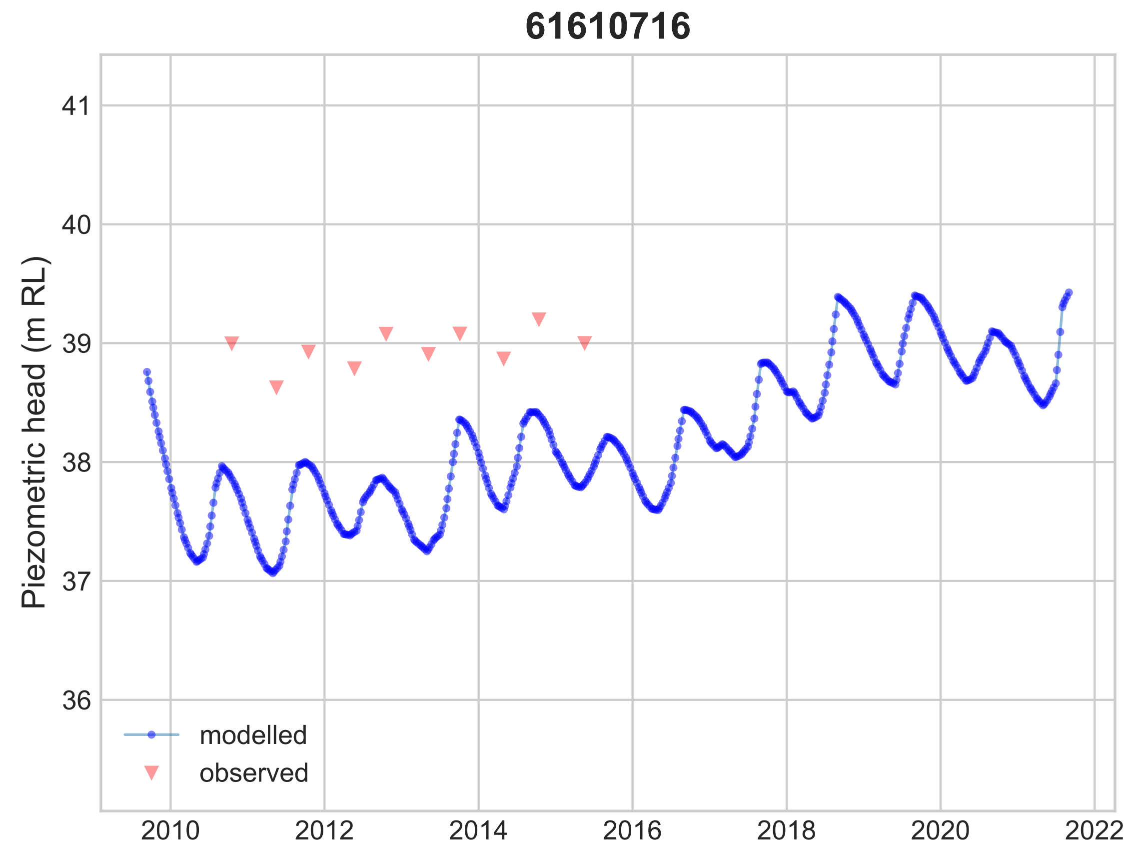

61610695
Piezometric head (m RL)
modelled
observed

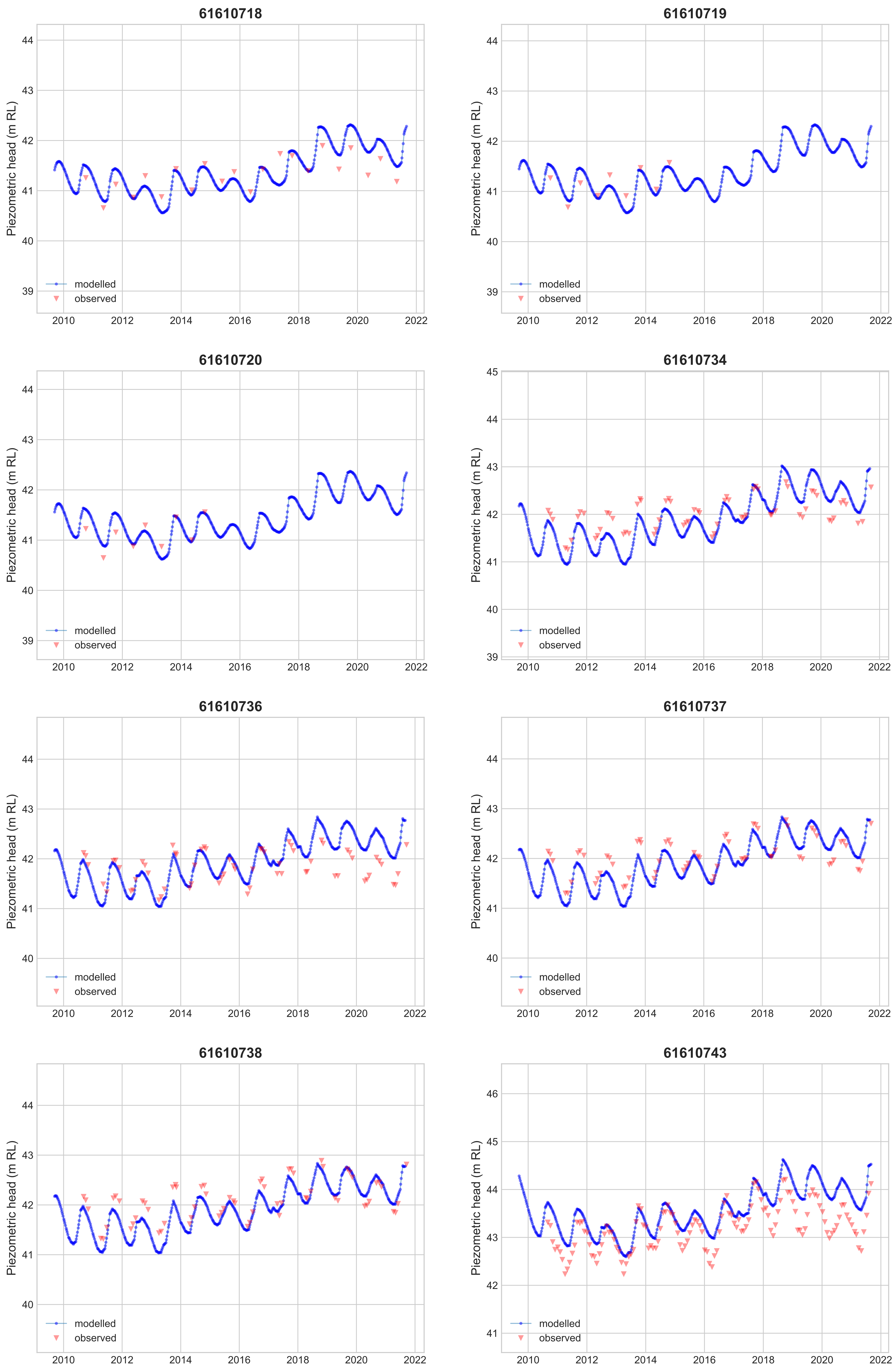

61610696
Piezometric head (m RL)
modelled
observed

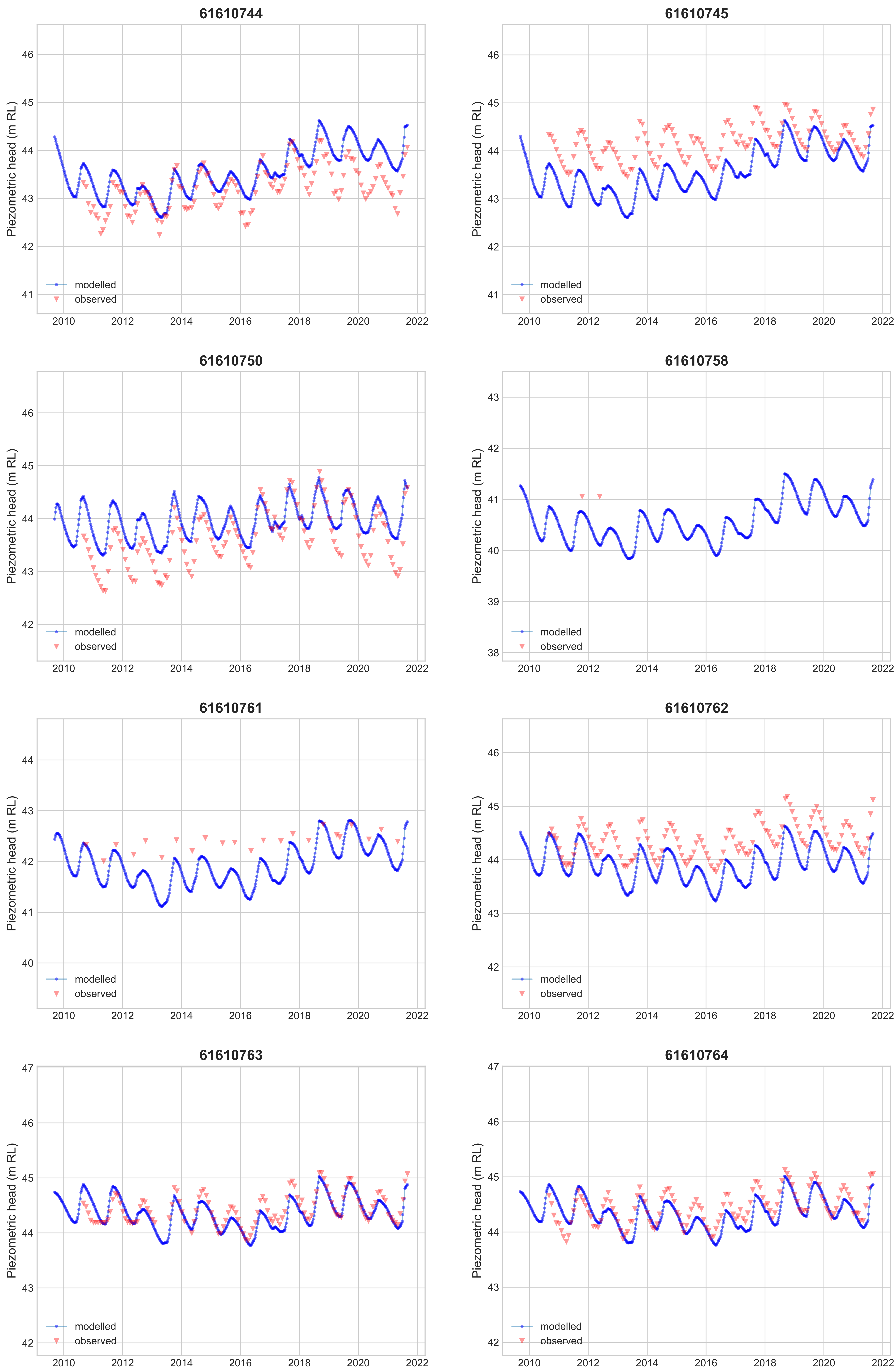

61610697
Piezometric head (m RL)
modelled
observed


61610714
Piezometric head (m RL)
modelled
observed

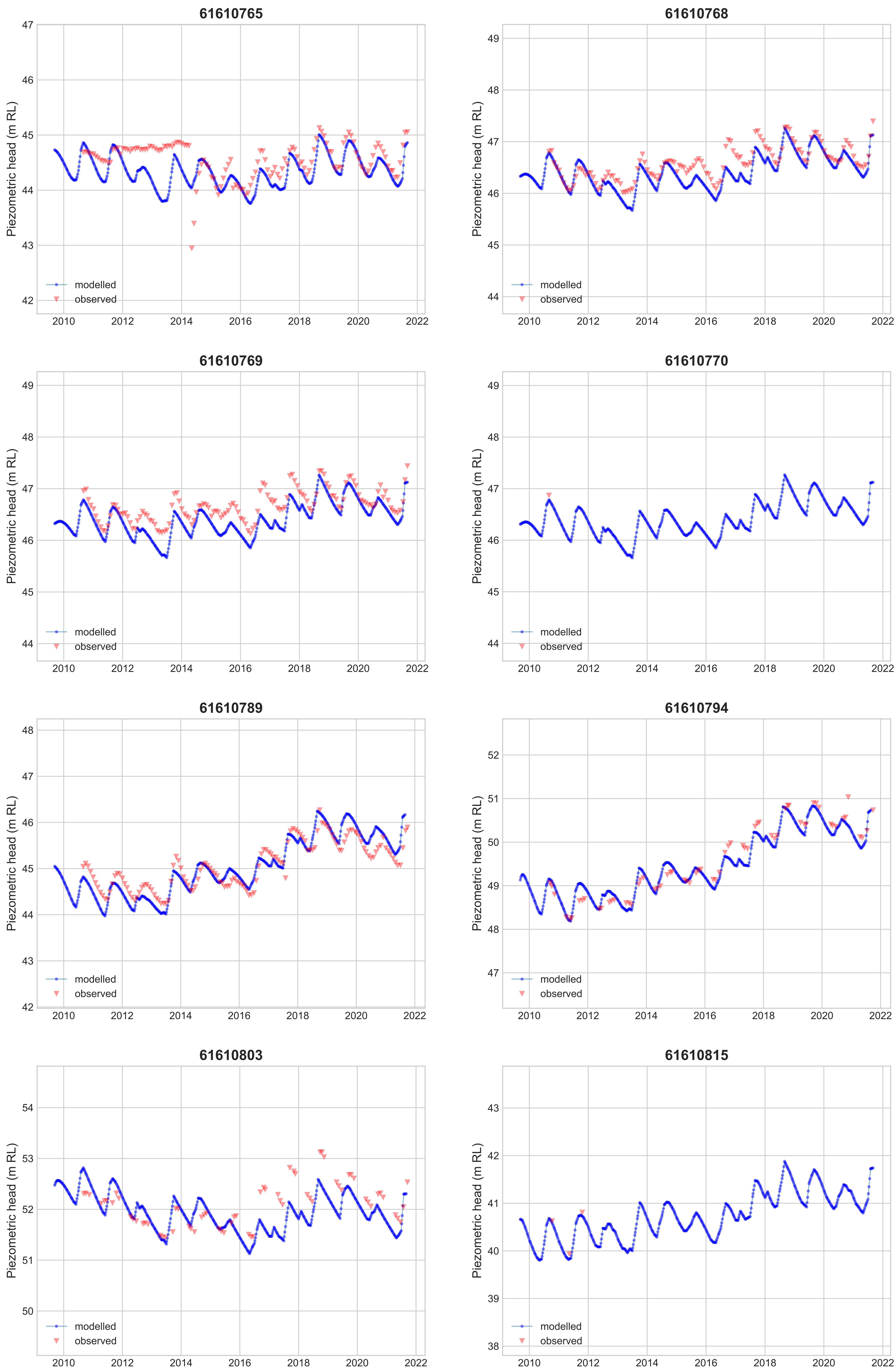

61610715
Piezometric head (m RL)
modelled
observed


61610716
Piezometric head (m RL)
modelled
observed

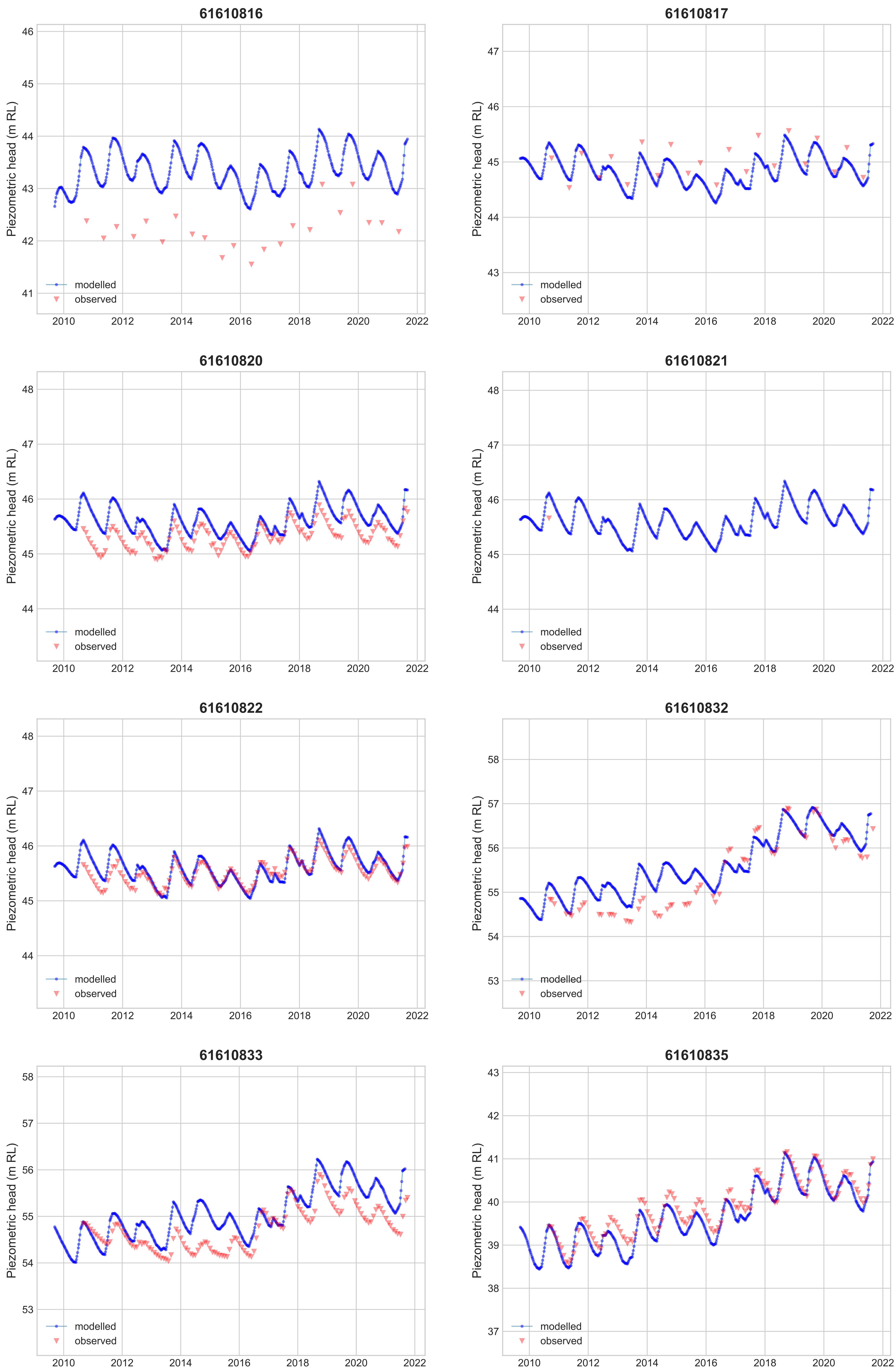

61610718
61610719
61610720
61610734
61610736
61610737
61610738
61610743
Piezometric head (m RL)
modelled
observed
2010
2012
2014
2016
2018
2020
2022

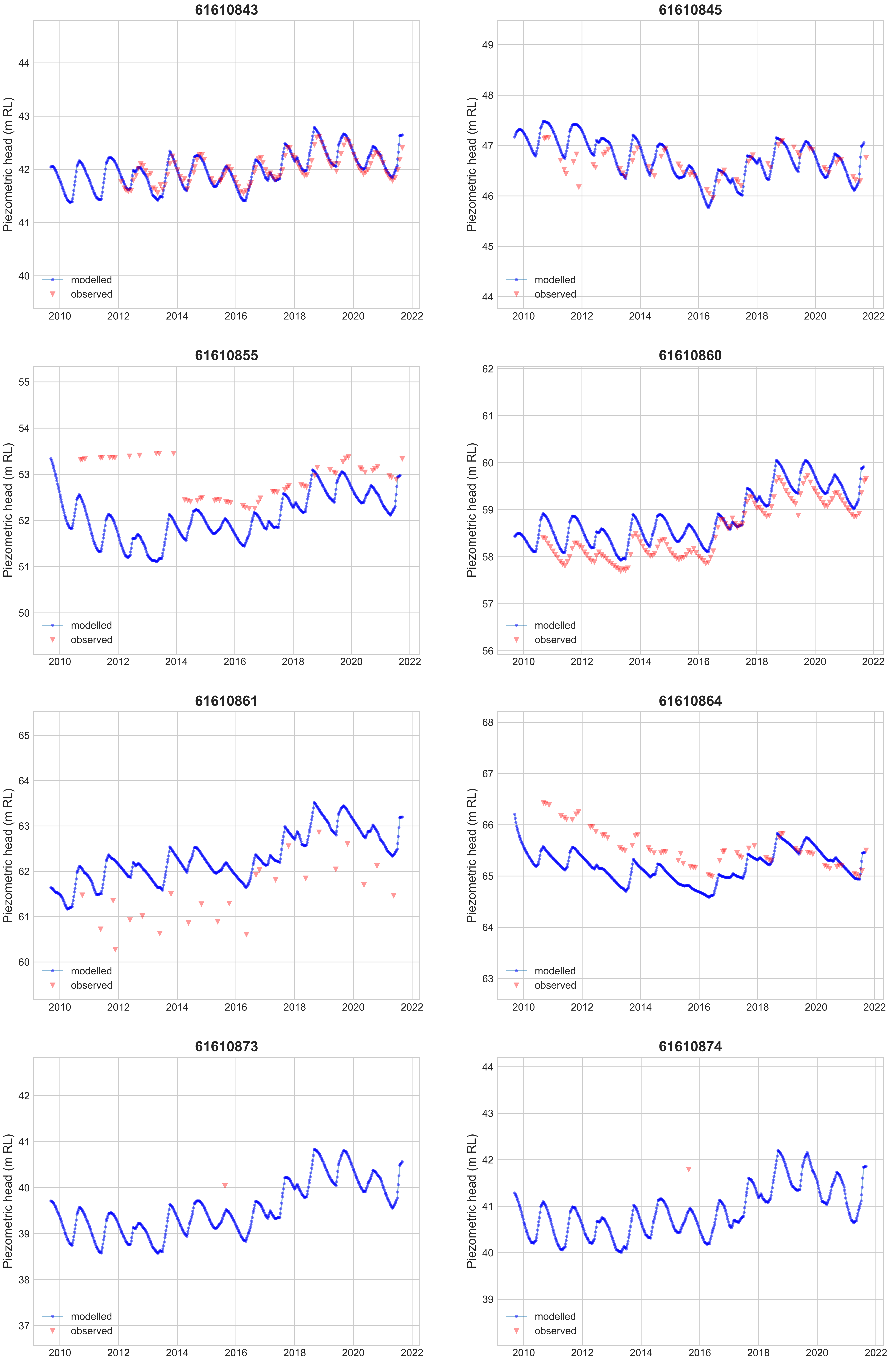


61610744
61610745
61610750
61610758
61610761
61610762
61610763
61610764
Piezometric head (m RL)
modelled
observed
2010
2012
2014
2016
2018
2020
2022

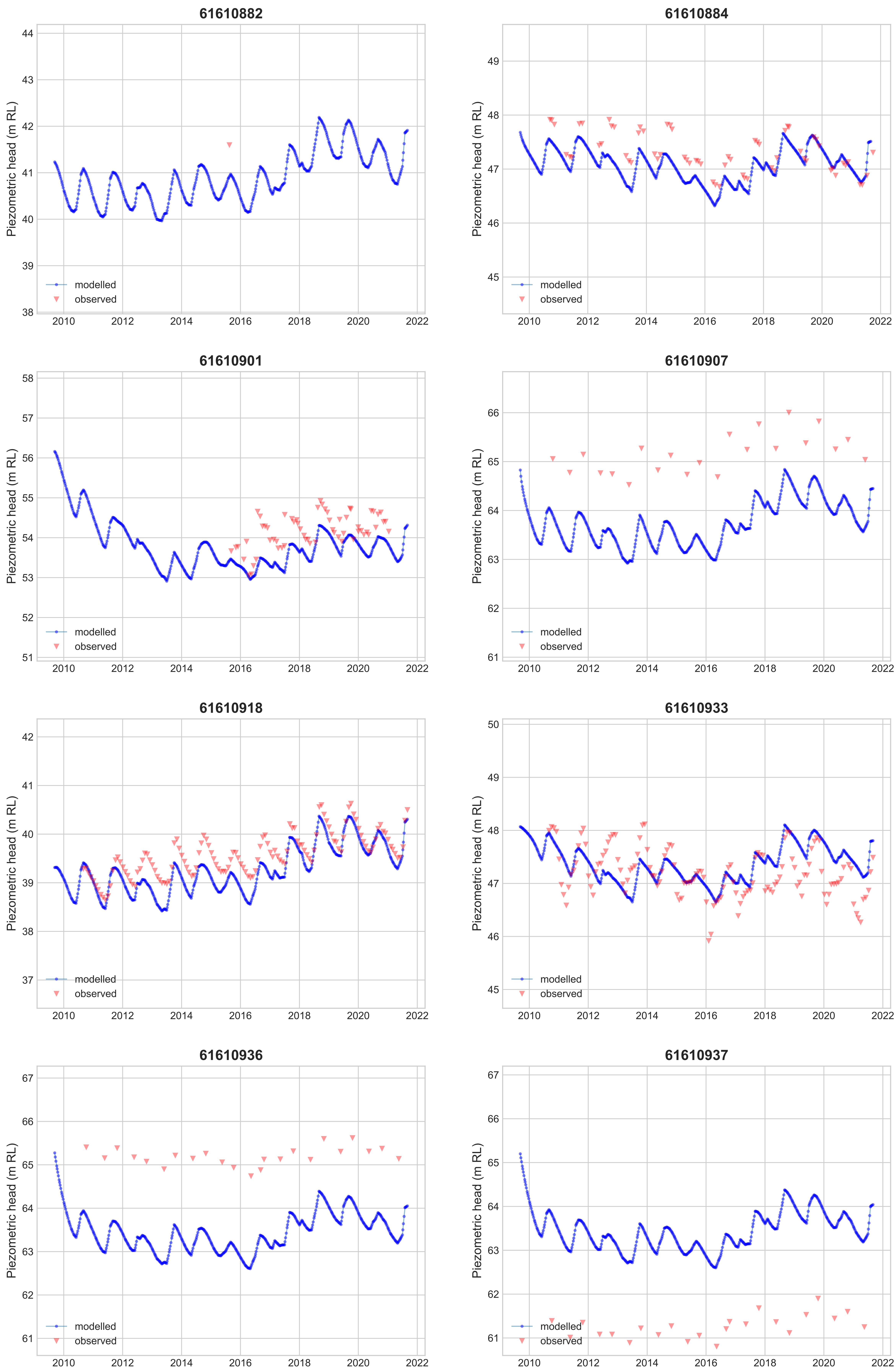


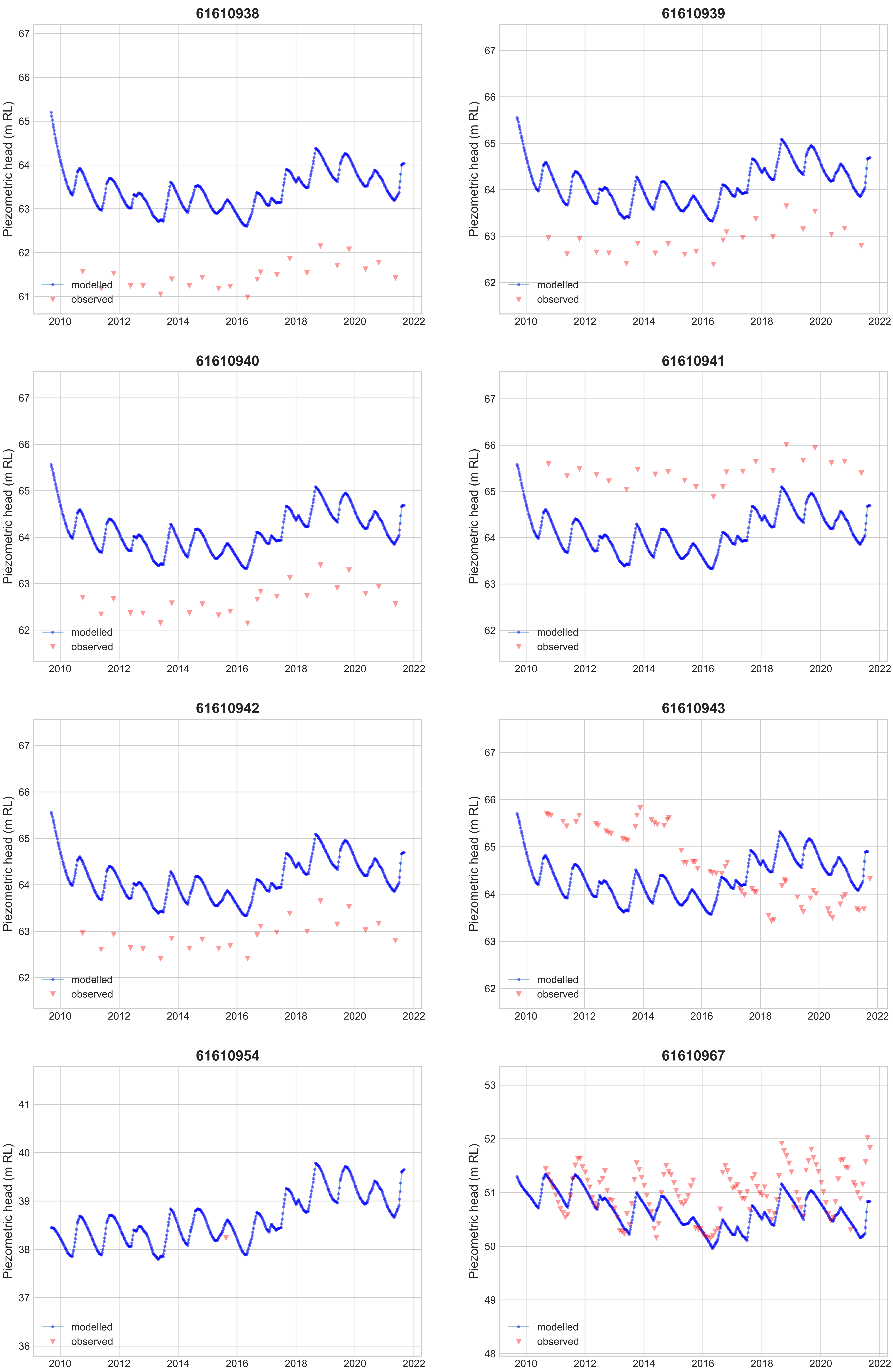
61610765
61610768
61610769
61610770
61610789
61610794
61610803
61610815
Piezometric head (m RL)
modelled
observed
2010
2012
2014
2016
2018
2020
2022

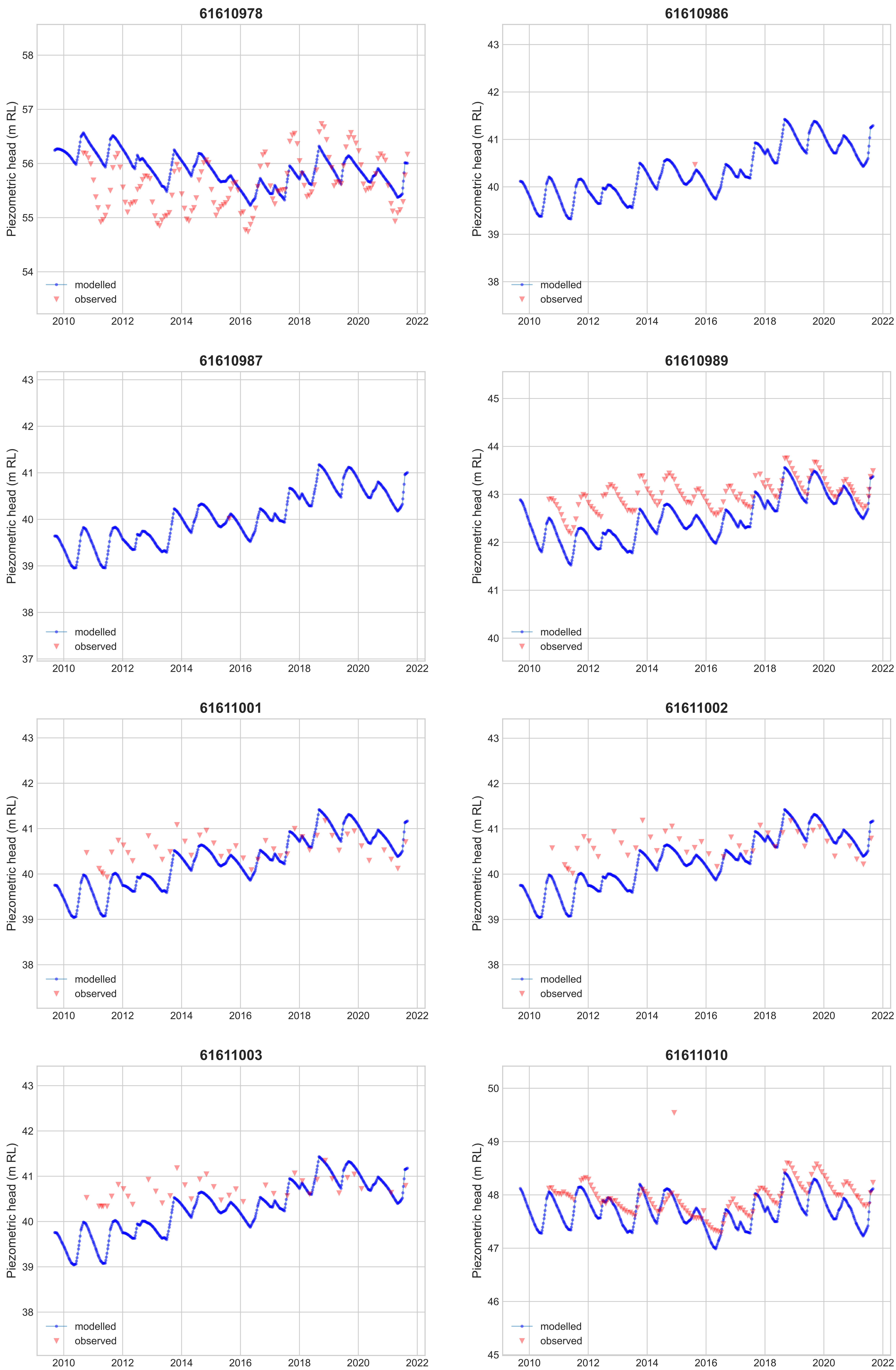

61610816
61610817
61610820
61610821
61610822
61610832
61610833
61610835
Piezometric head (m RL)
modelled
observed
2010
2012
2014
2016
2018
2020
2022



61610843
61610845
61610855
61610860
61610861
61610864
61610873
61610874
Piezometric head (m RL)
modelled
observed
2010
2012
2014
2016
2018
2020
2022


61610882
Piezometric head (m RL)
modelled
observed
61610884
Piezometric head (m RL)
modelled
observed
61610901
Piezometric head (m RL)
modelled
observed
61610907
Piezometric head (m RL)
modelled
observed
61610918
Piezometric head (m RL)
modelled
observed
61610933
Piezometric head (m RL)
modelled
observed
61610936
Piezometric head (m RL)
modelled
observed
61610937
Piezometric head (m RL)
modelled
observed
2010
2012
2014
2016
2018
2020
2022


61610938
61610939
61610940
61610941
61610942
61610943
61610954
61610967
Piezometric head (m RL)
modelled
observed
2010
2012
2014
2016
2018
2020
2022


61610978
61610986
61610987
61610989
61611001
61611002
61611003
61611010
Piezometric head (m RL)
modelled
observed
2010
2012
2014
2016
2018
2020
2022
54
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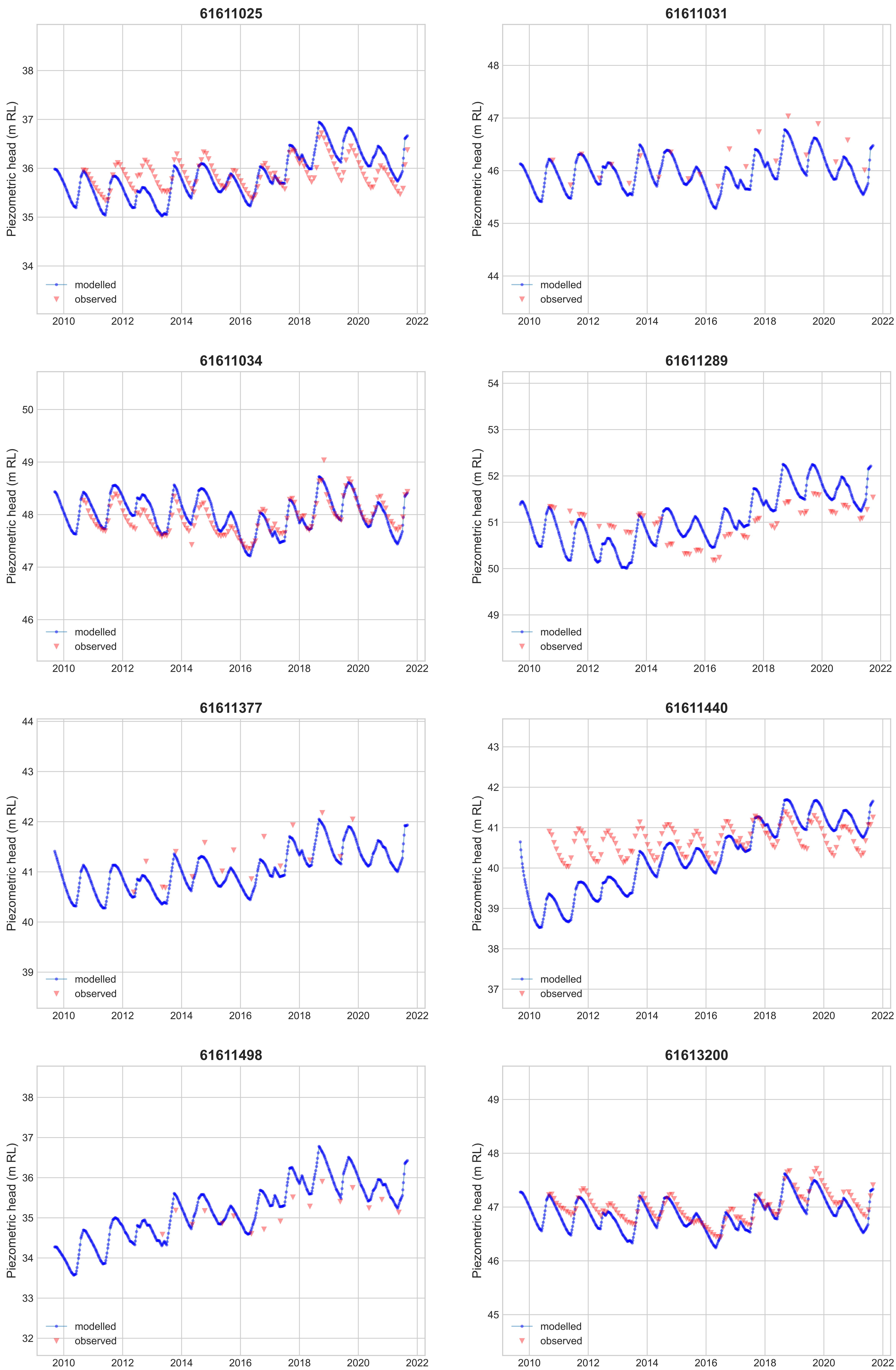
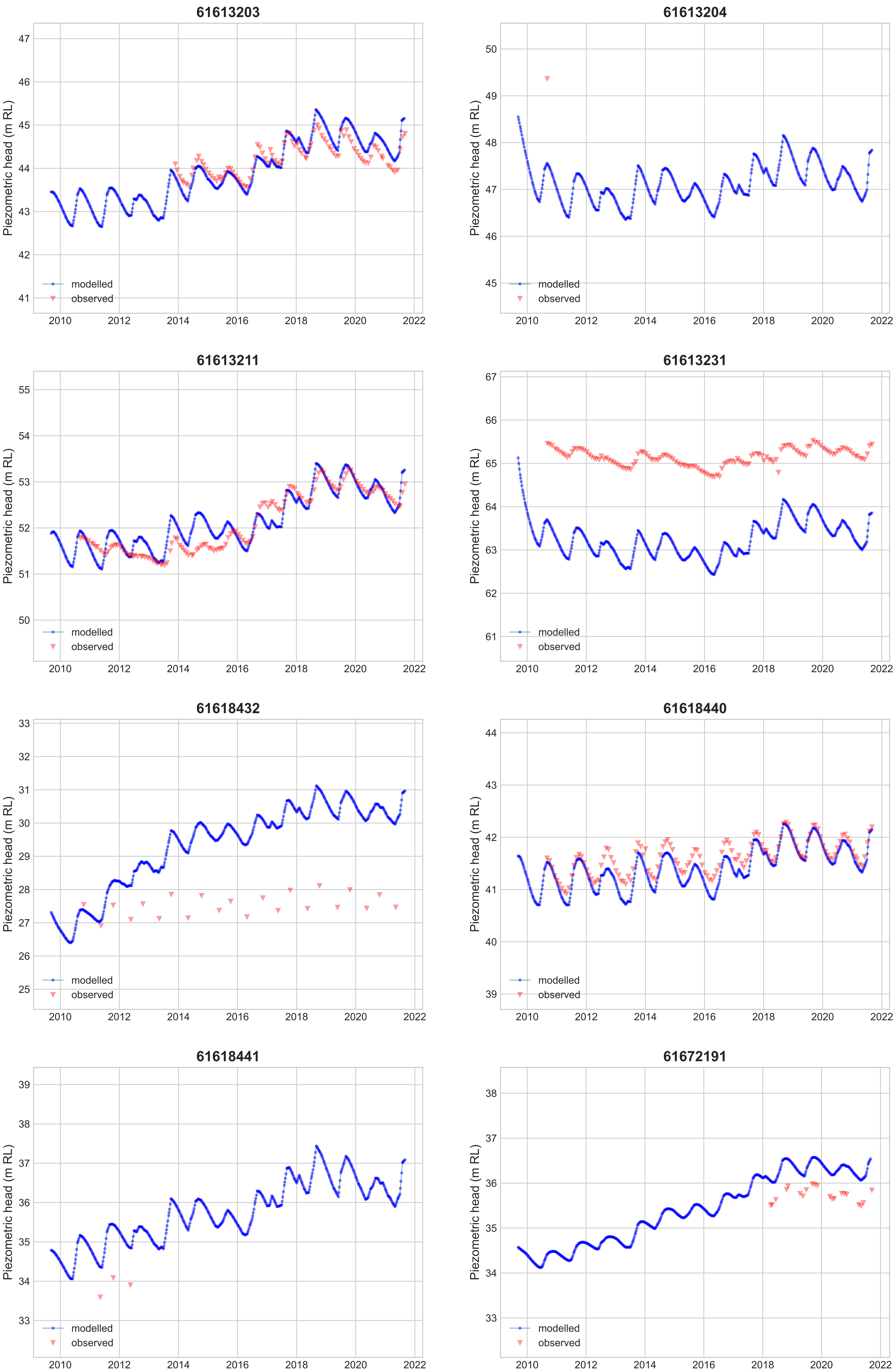
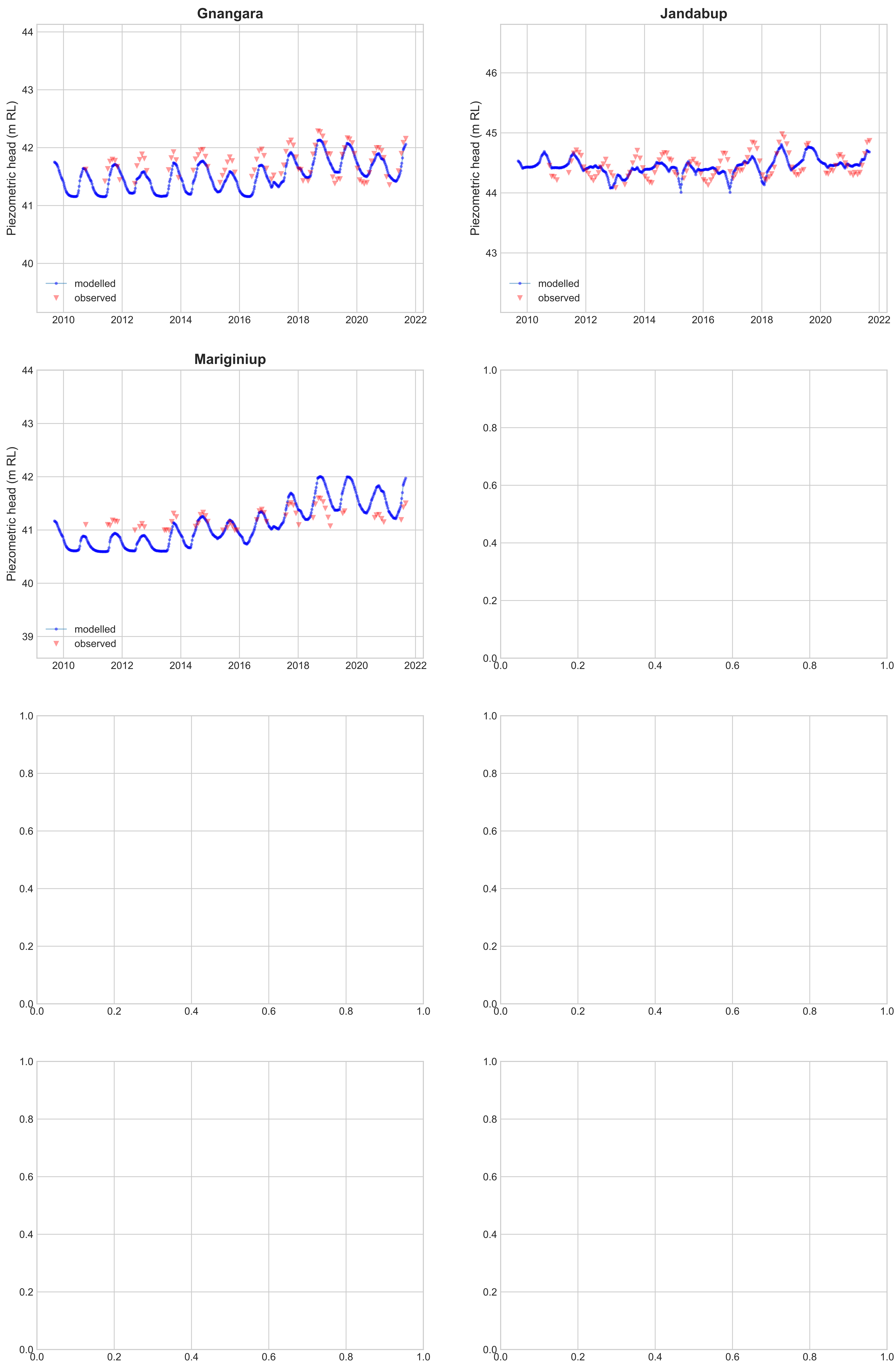
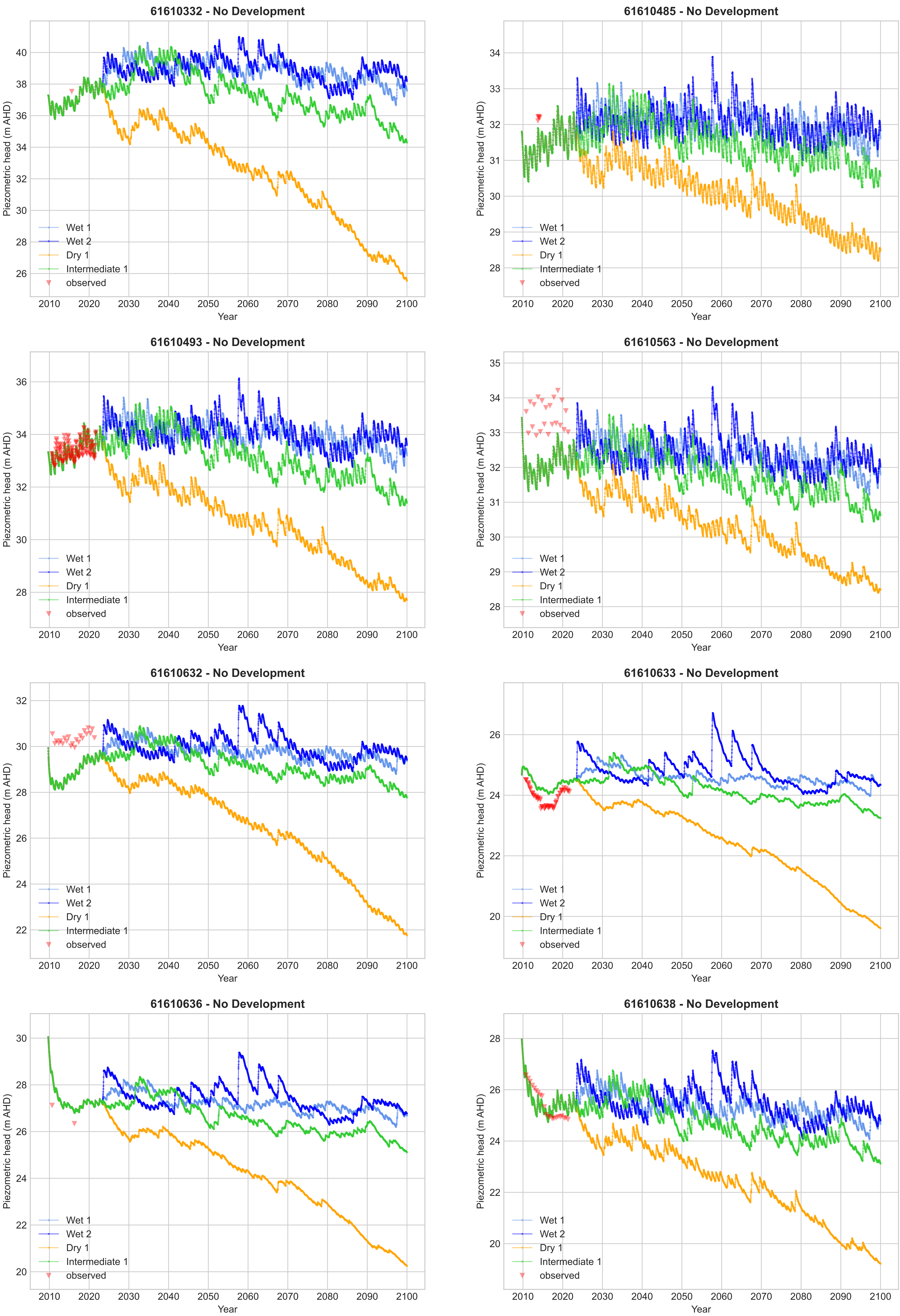
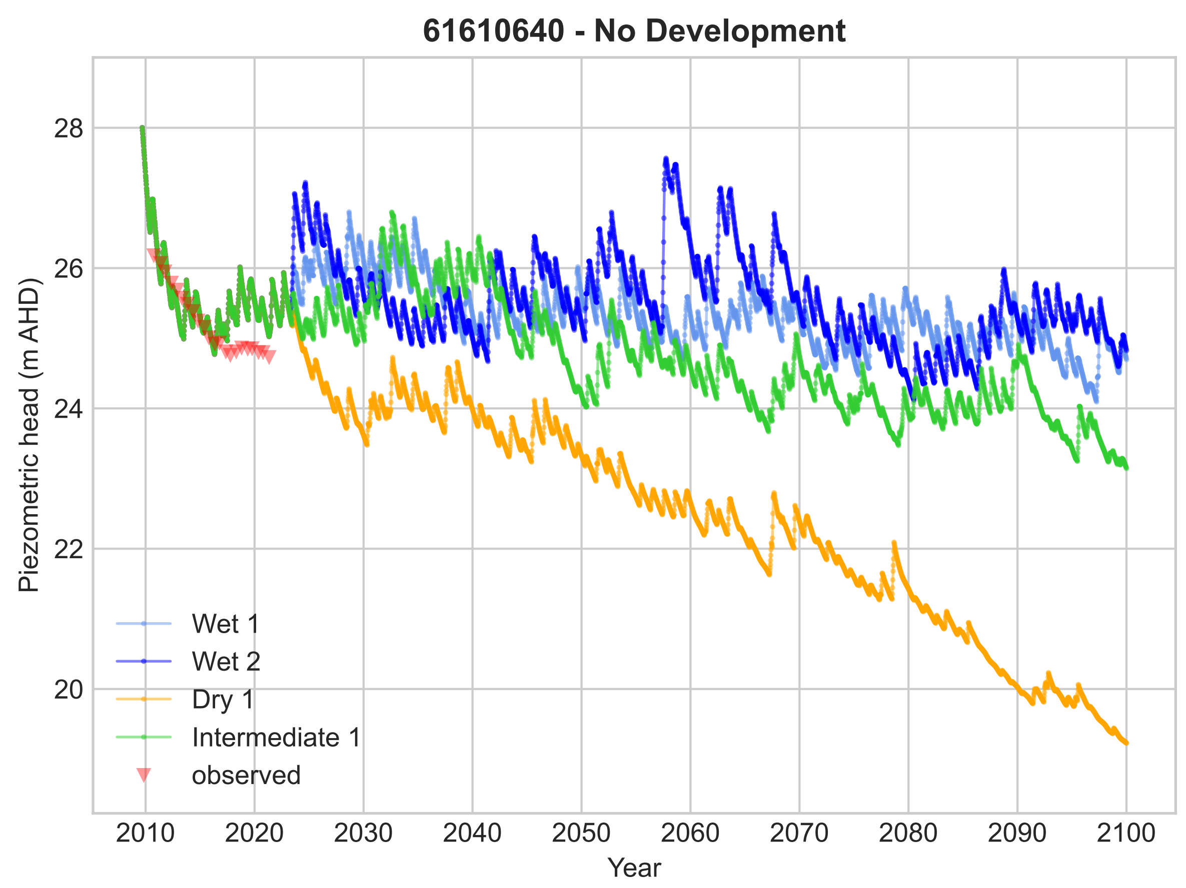

61611025
61611031
61611034
61611289
61611377
61611440
61611498
61613200
Piezometric head (m RL)
modelled
observed
2010
2012
2014
2016
2018
2020
2022

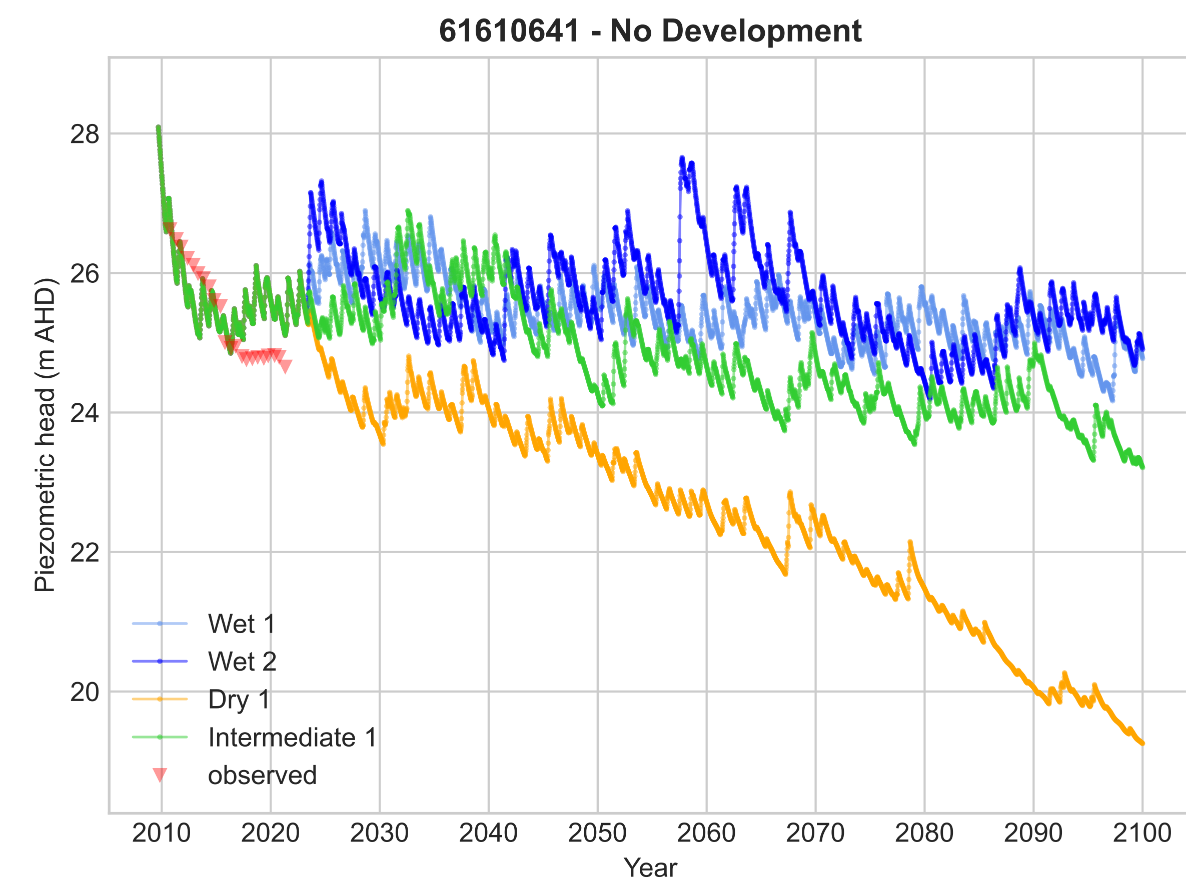

61613203
61613204
61613211
61613231
61618432
61618440
61618441
61672191
Piezometric head (m RL)
modelled
observed
2010
2012
2014
2016
2018
2020
2022

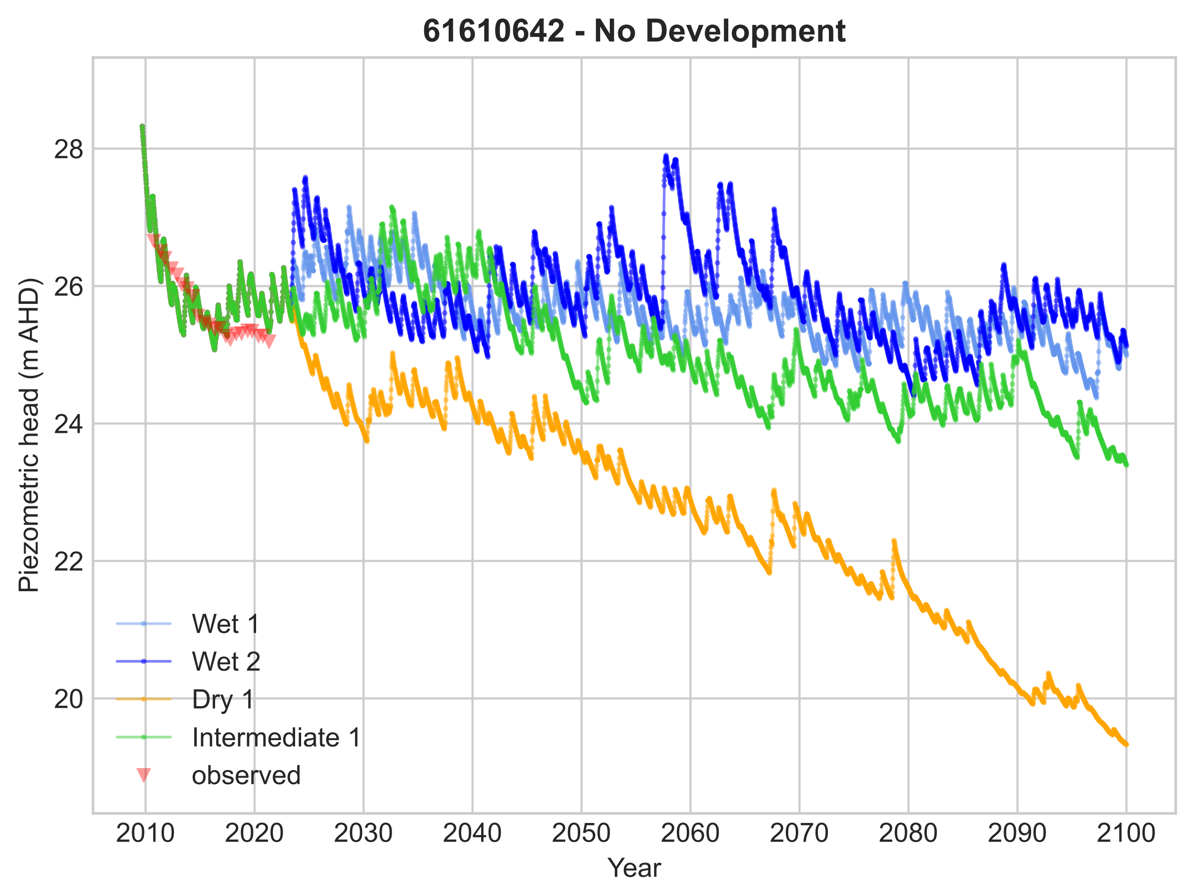

Gnangara
Jandabup
Mariginiup
Piezometric head (m RL)
modelled
observed
2010
2012
2014
2016
2018
2020
2022

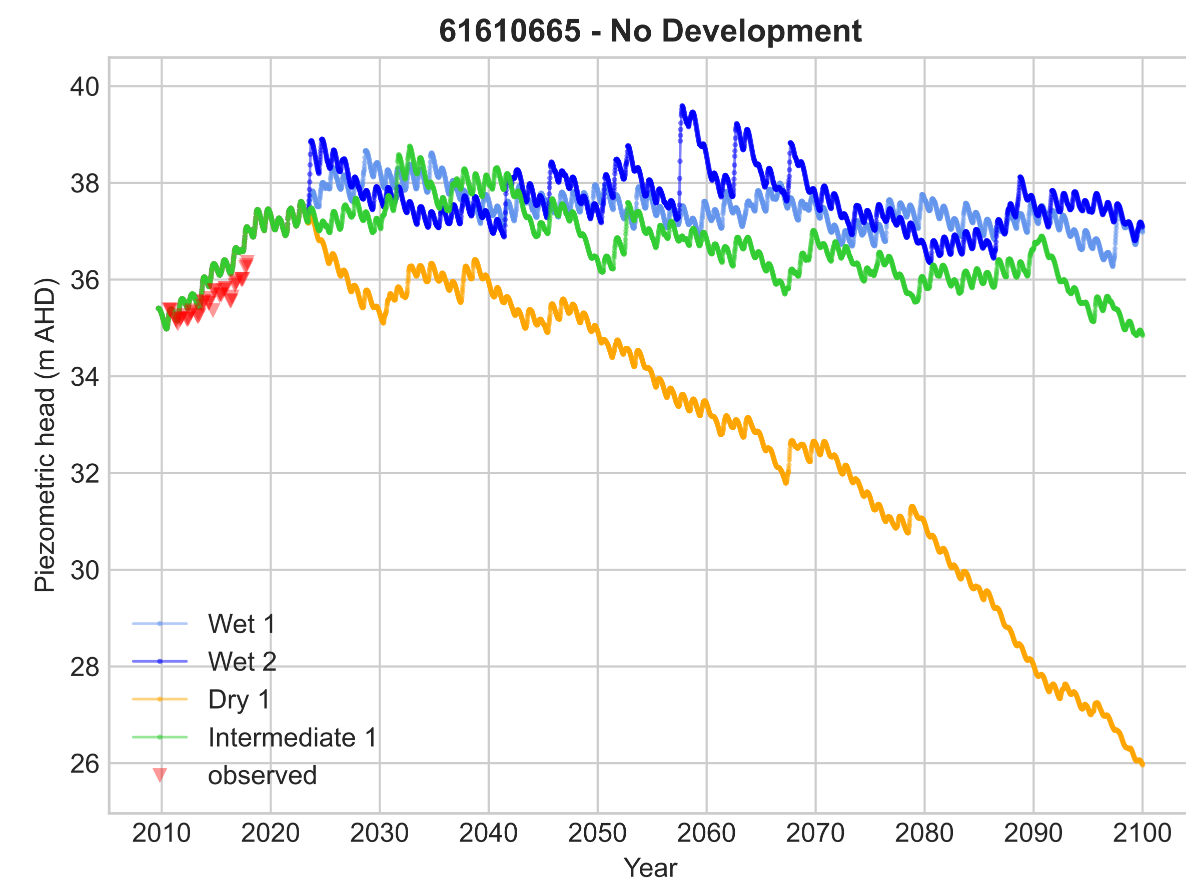
Appendix D: ‘no development’ (baseline) hydrographs

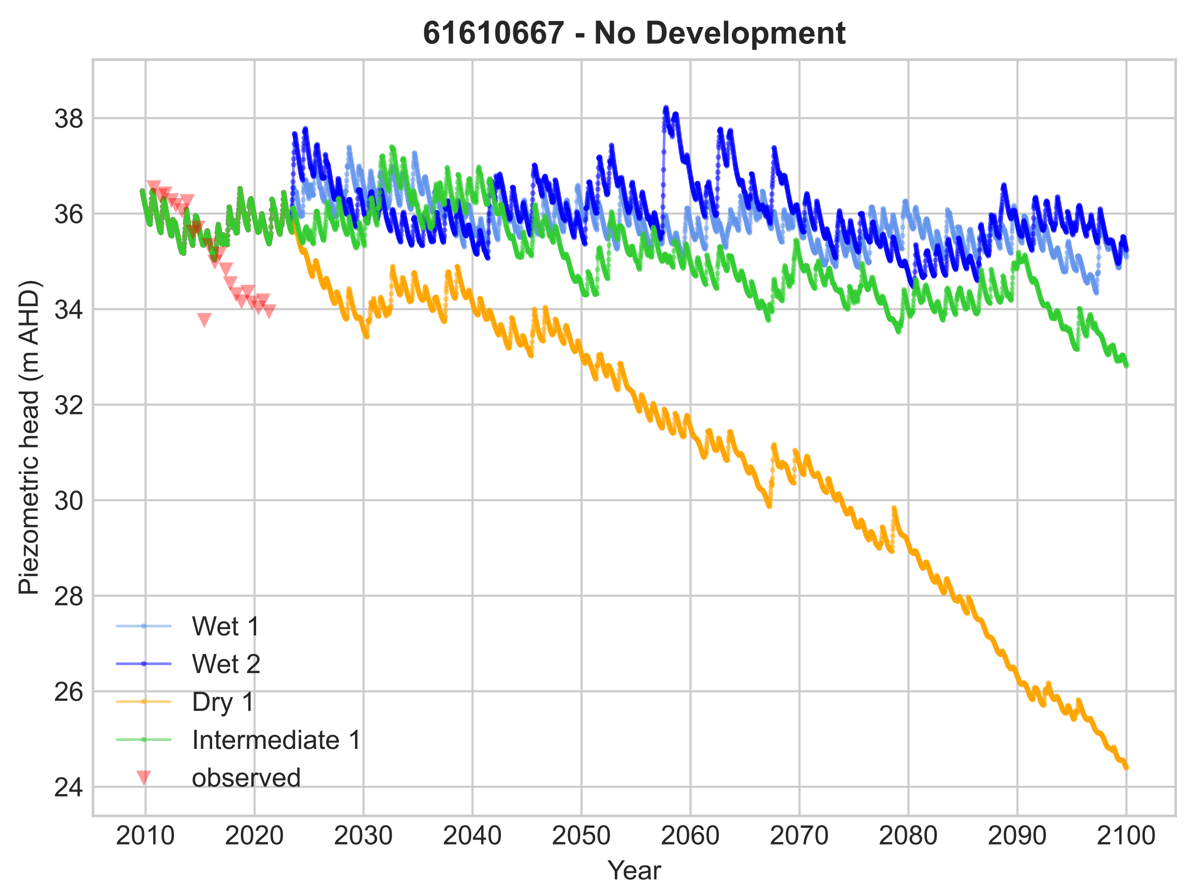

61610332 - No Development
61610485 - No Development
61610493 - No Development
61610563 - No Development
61610632 - No Development
61610633 - No Development
61610636 - No Development
61610638 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

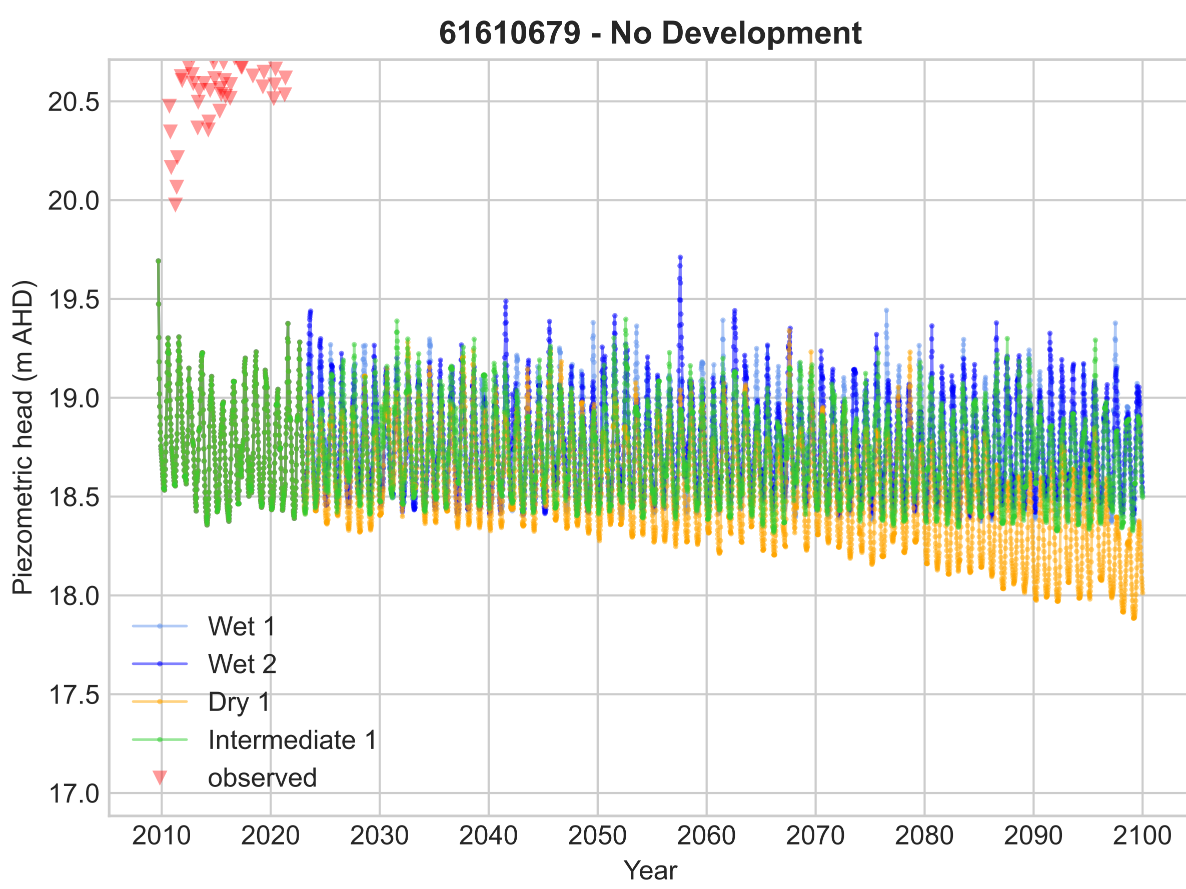

61610640 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

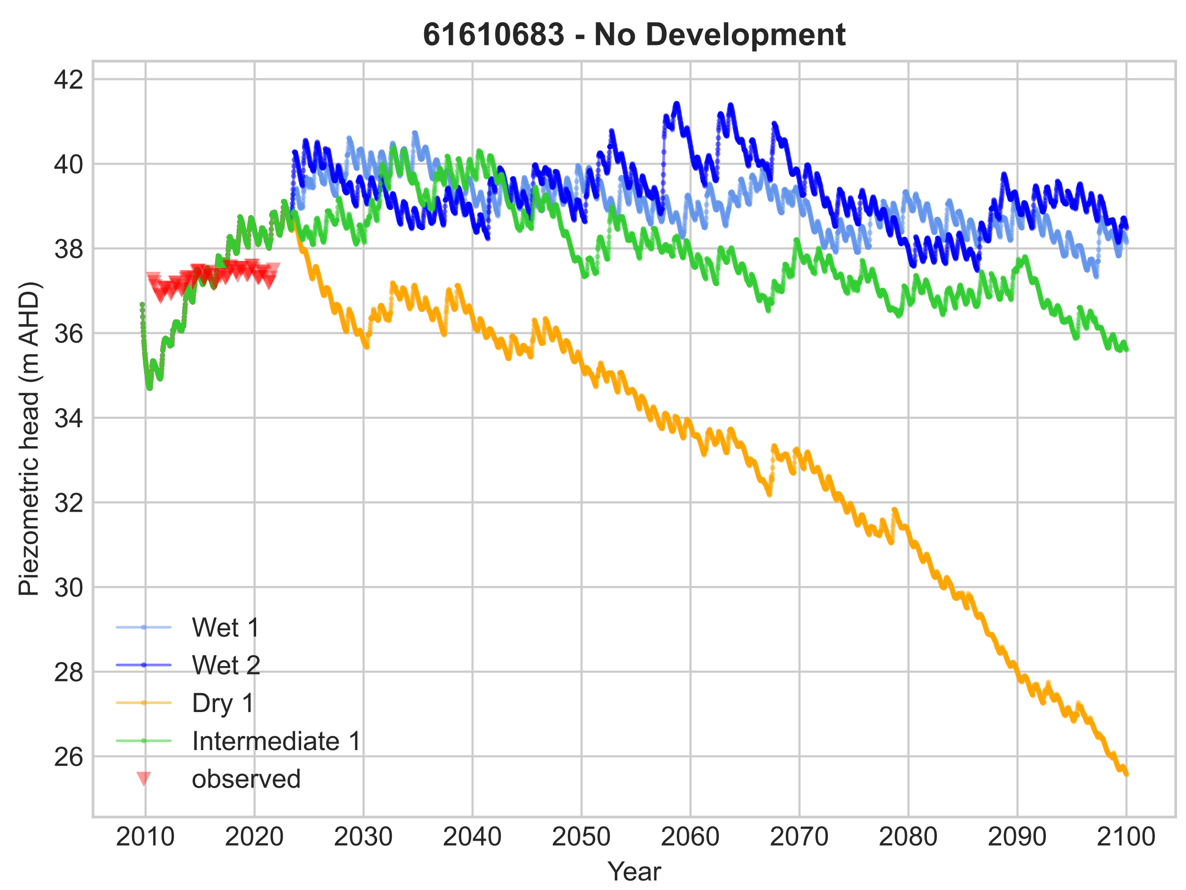

61610641 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

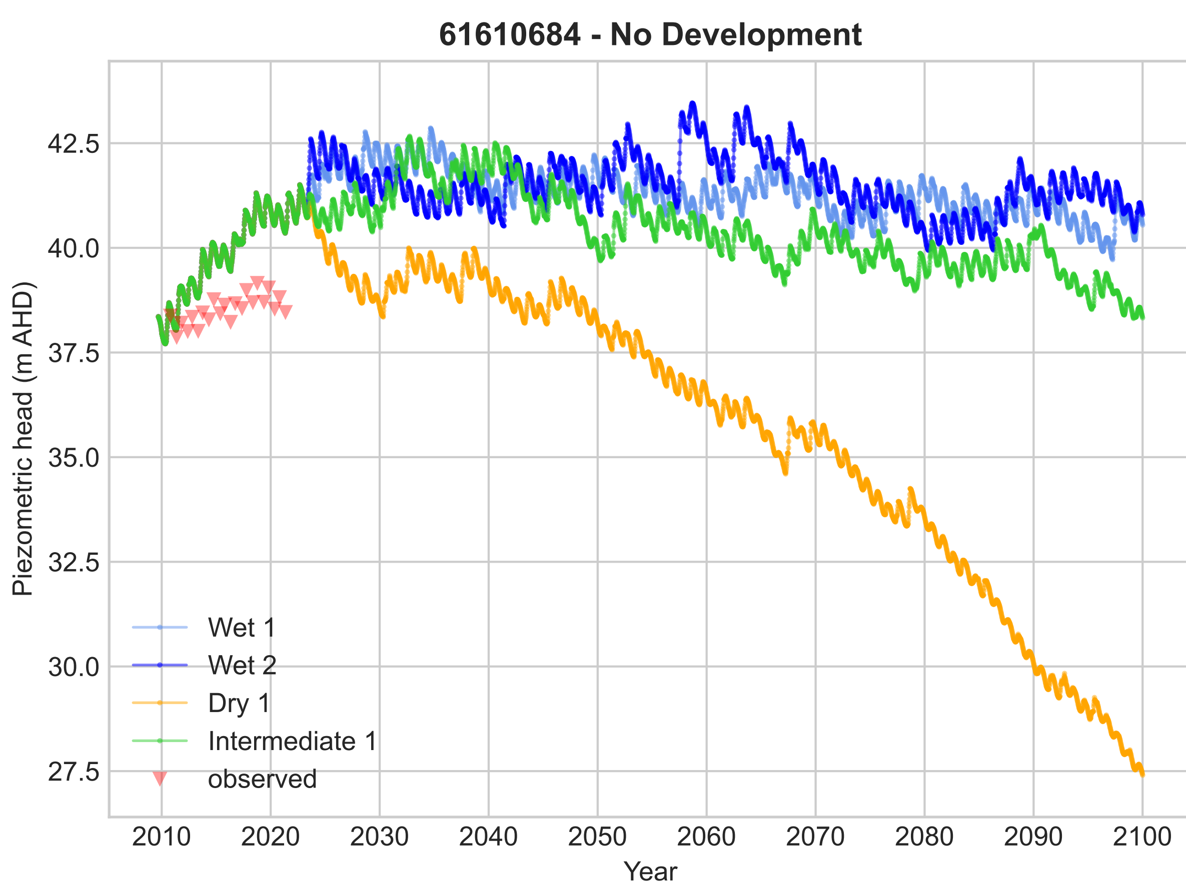

61610642 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

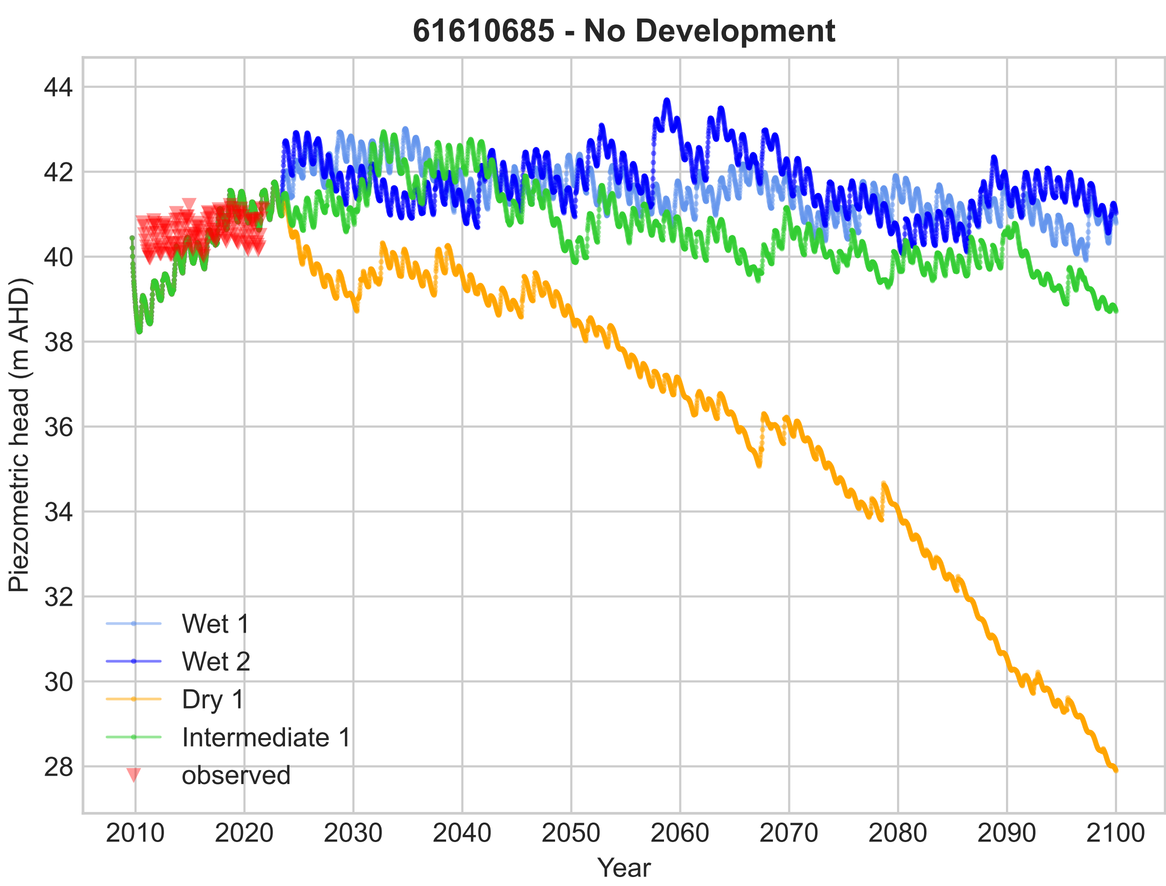

61610665 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

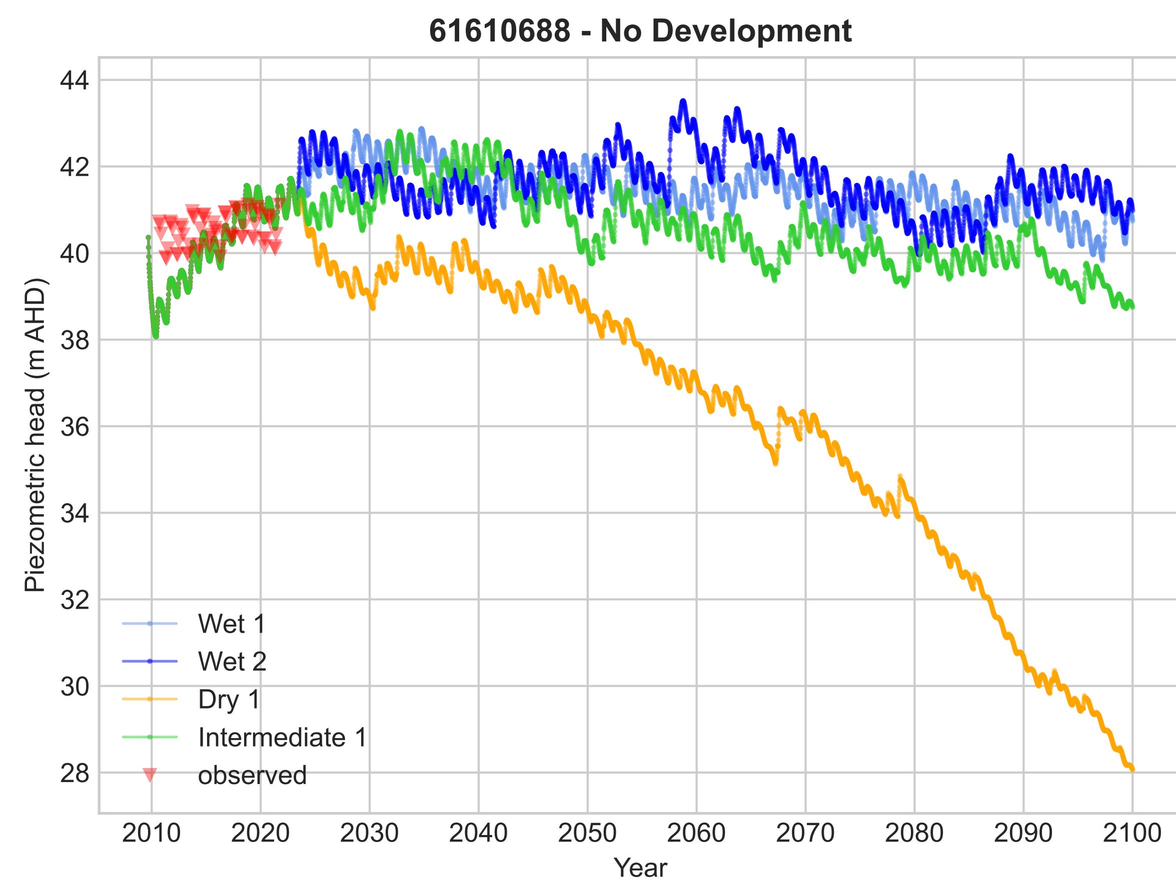

61610667 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

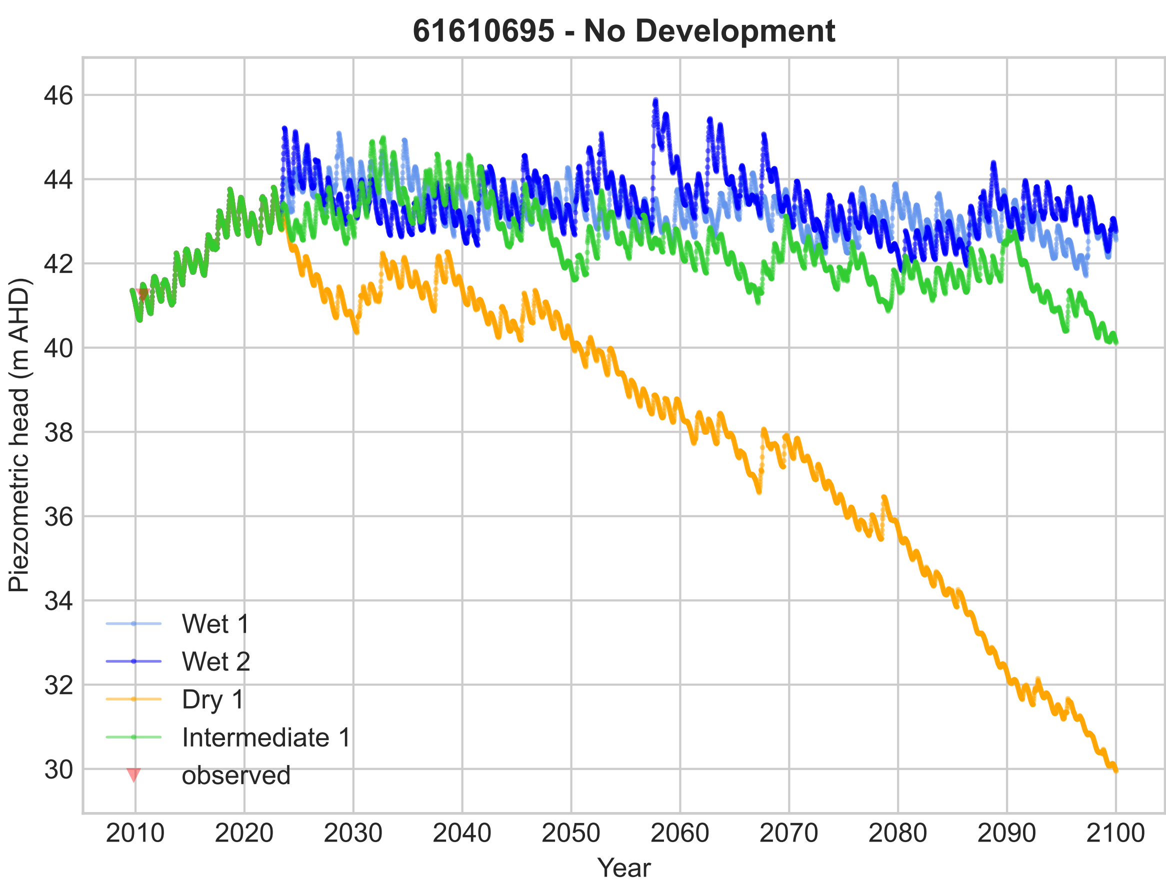

61610679 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

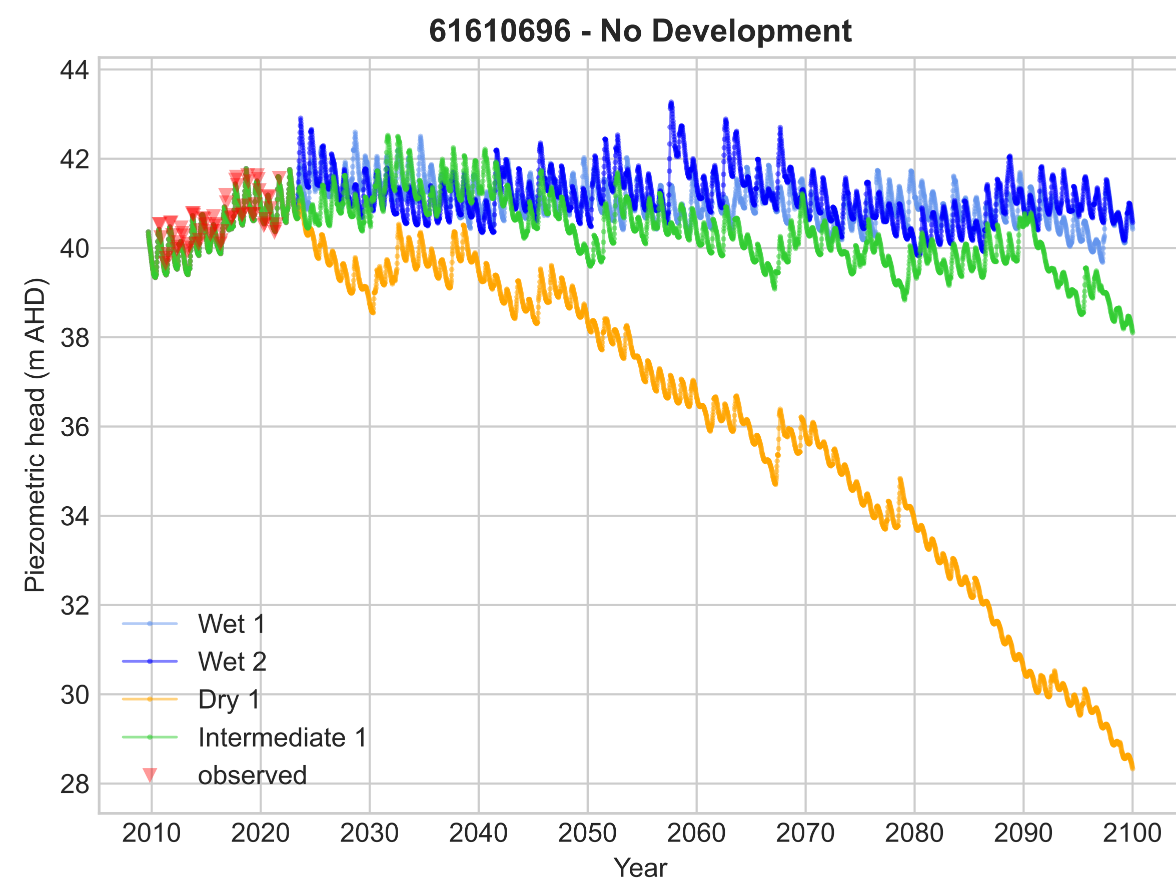

61610683 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

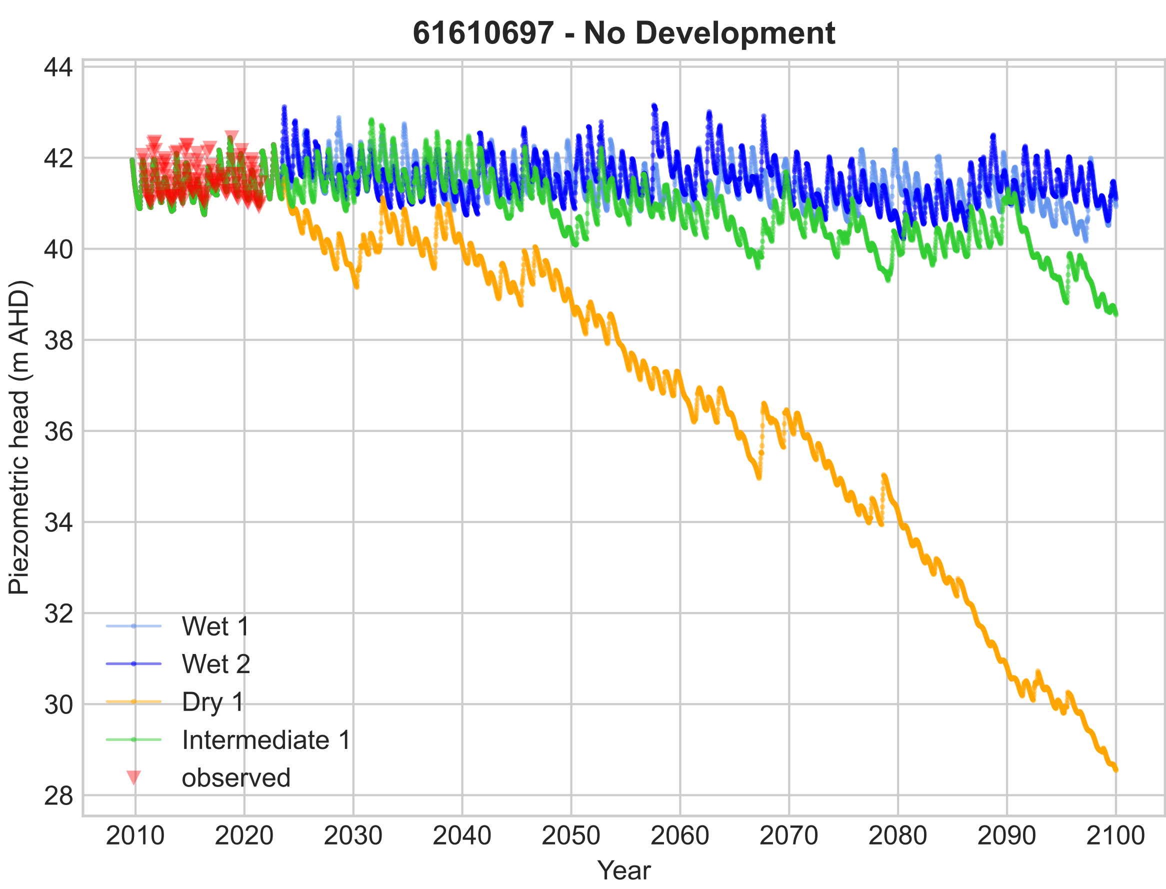

61610684 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

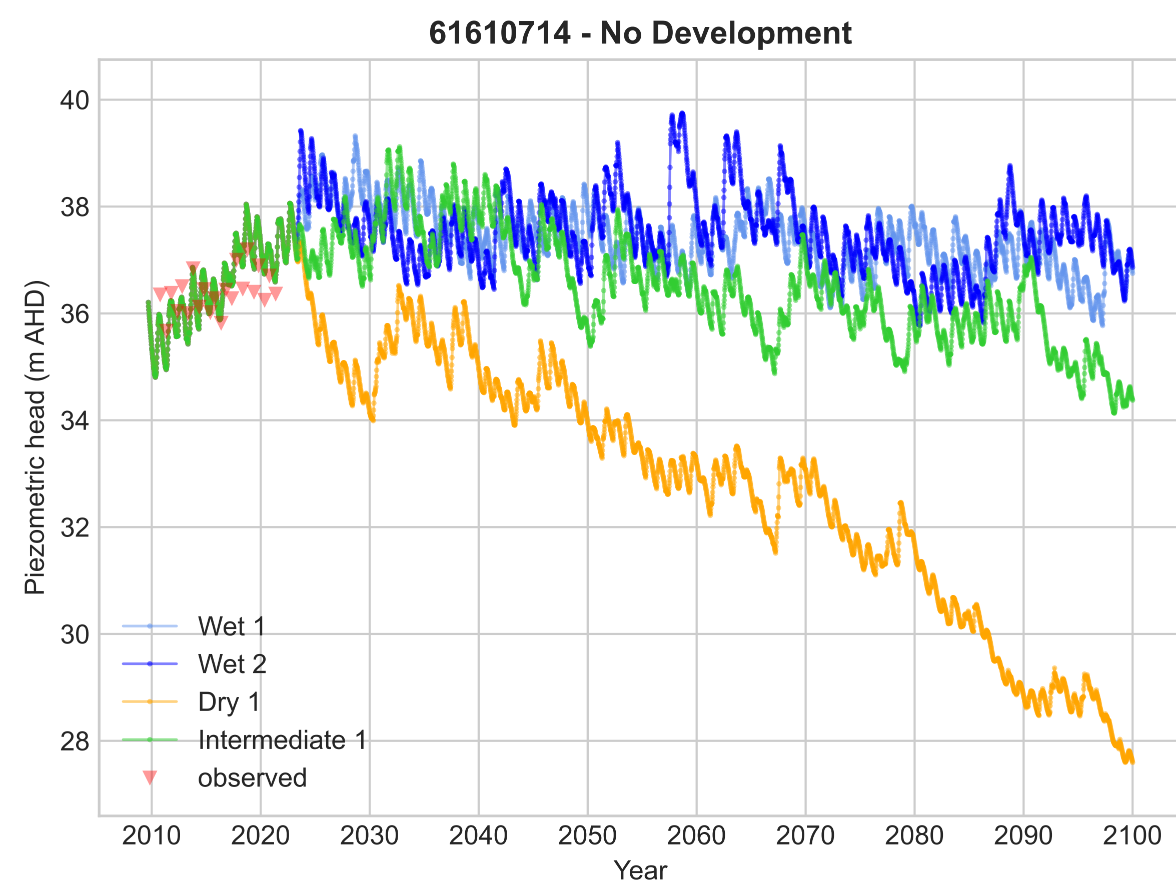

61610685 - No Development
Piezometric head (m AHD)
Year
44
42
40
38
36
34
32
30
28
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

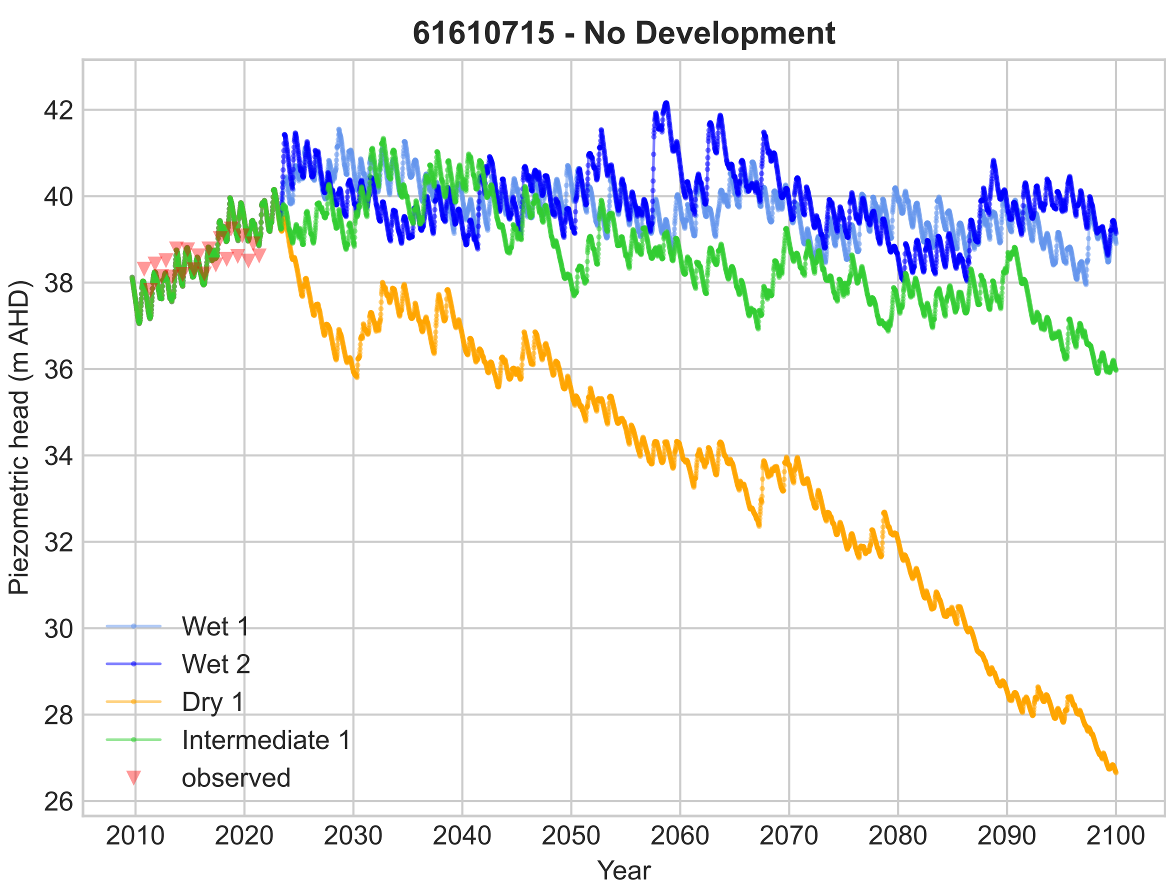

61610688 - No Development
Piezometric head (m AHD)
Year
44
42
40
38
36
34
32
30
28
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

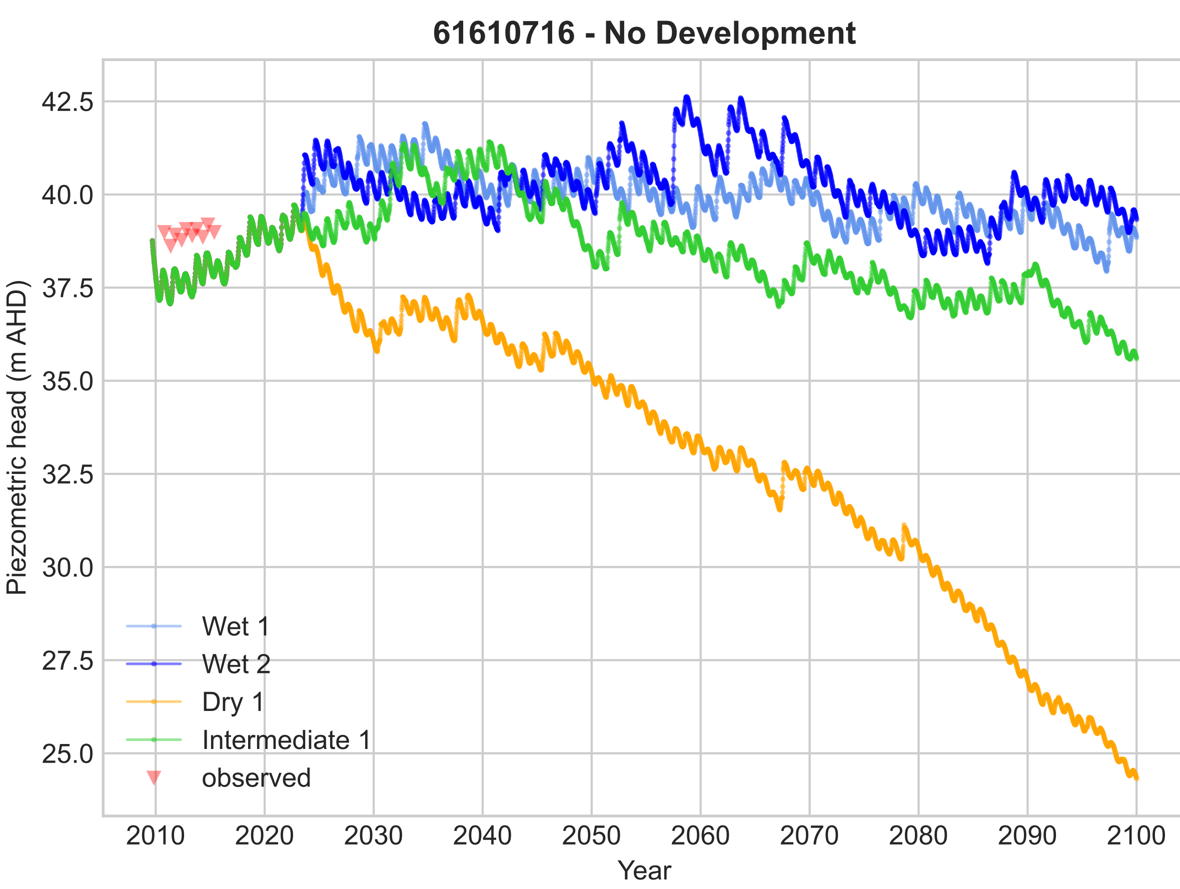

61610695 - No Development
Piezometric head (m AHD)
Year
46
44
42
40
38
36
34
32
30
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

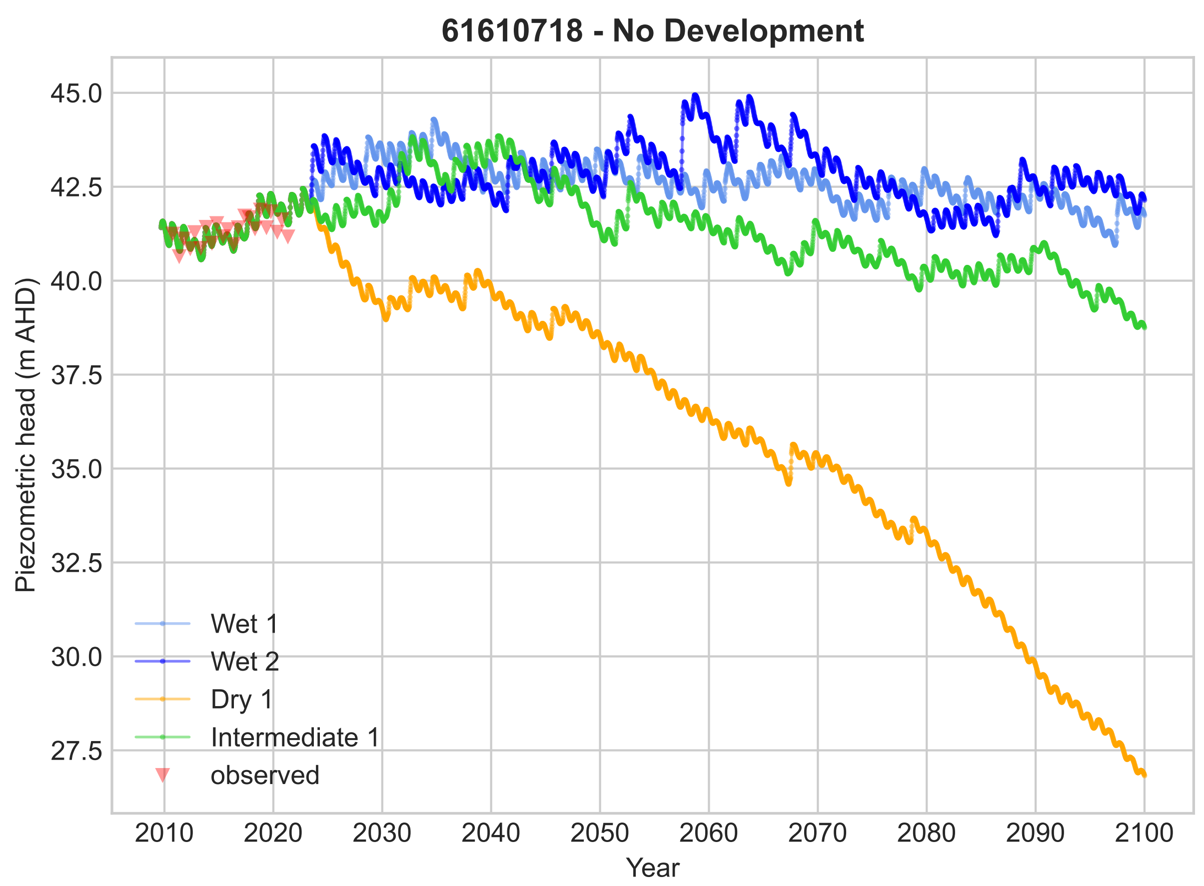

61610696 - No Development
Piezometric head (m AHD)
Year
44
42
40
38
36
34
32
30
28
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

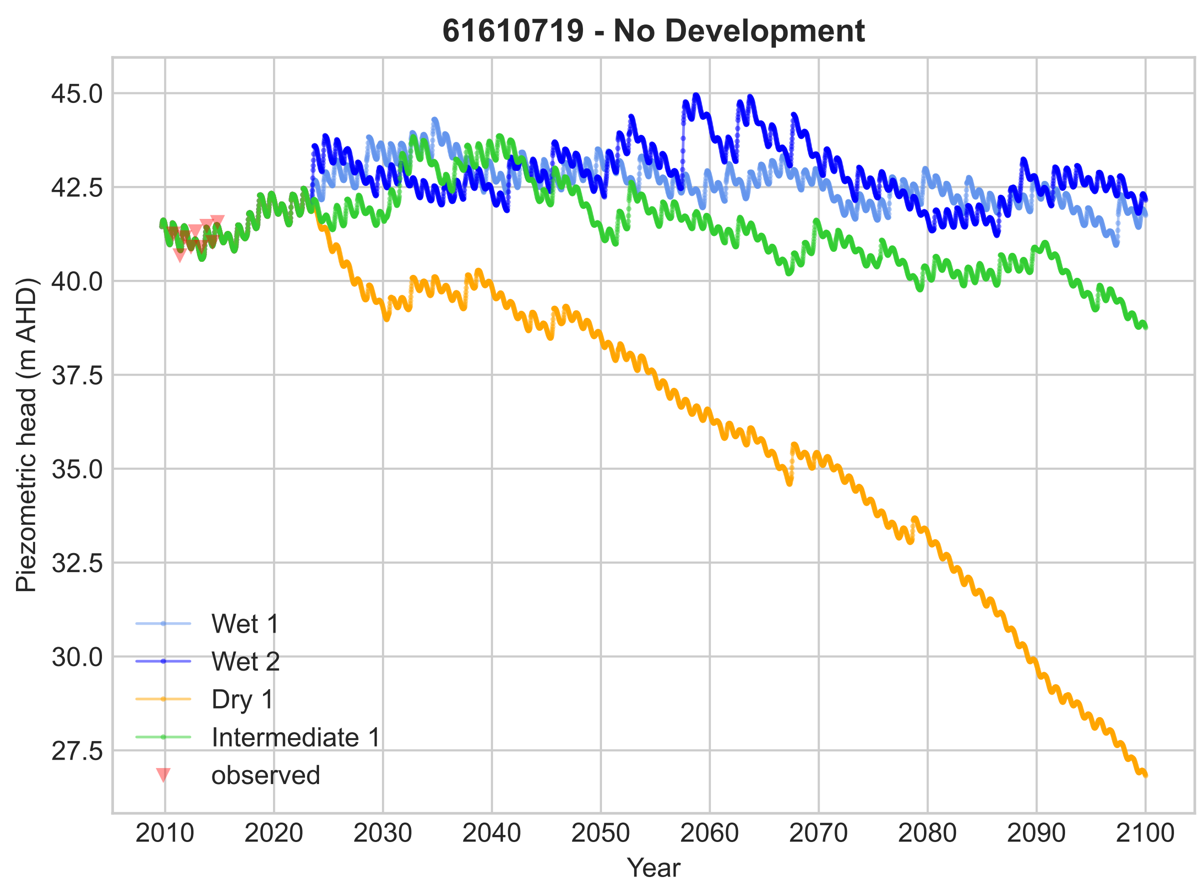

61610697 - No Development
Piezometric head (m AHD)
Year
44
42
40
38
36
34
32
30
28
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

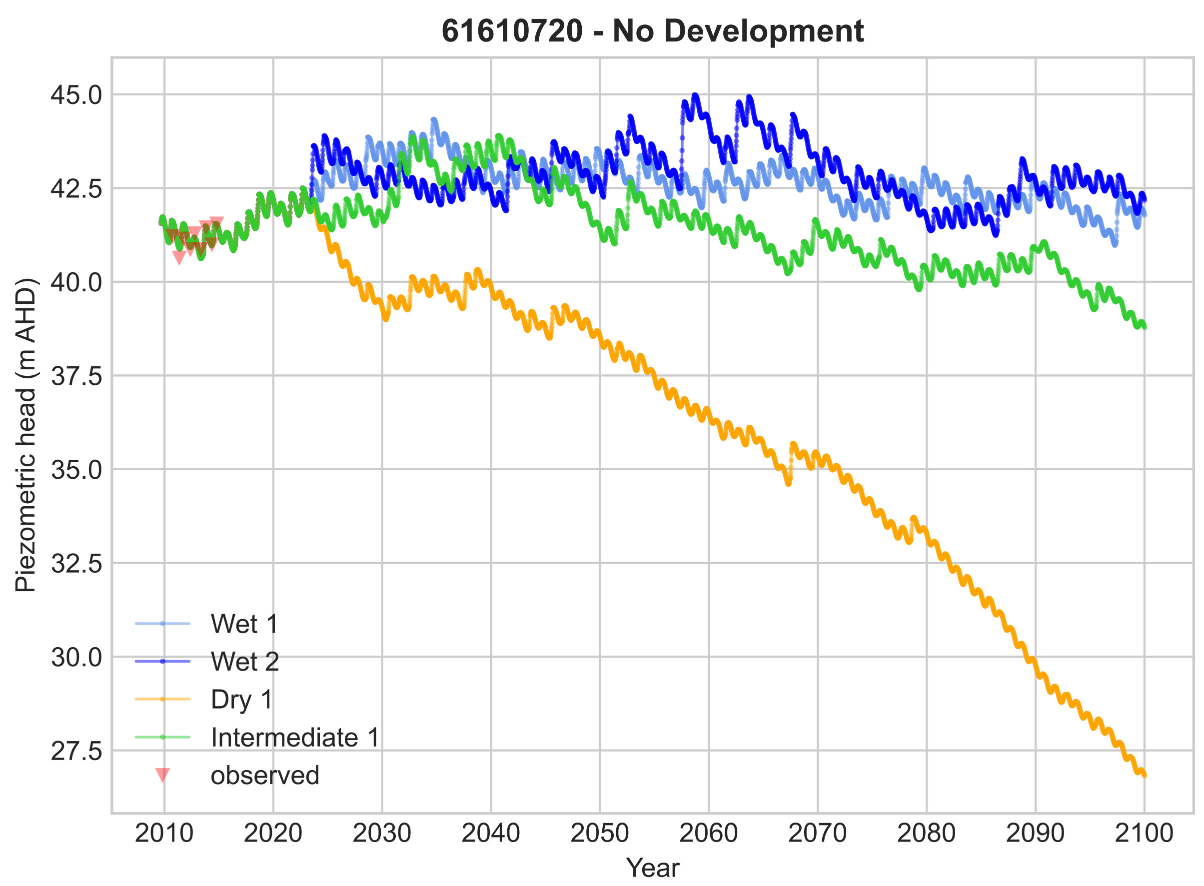

61610714 - No Development
Piezometric head (m AHD)
Year
40
38
36
34
32
30
28
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

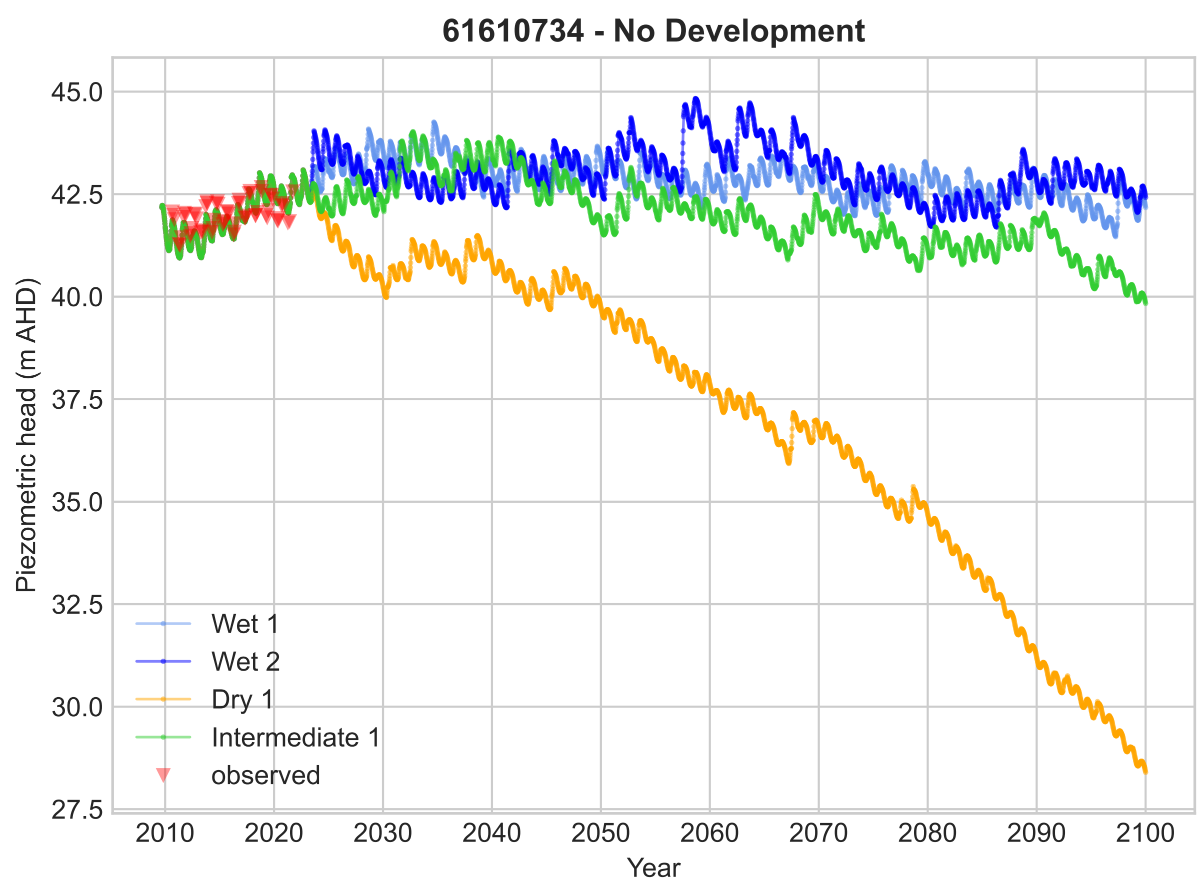

61610715 - No Development
Piezometric head (m AHD)
Year
42
40
38
36
34
32
30
28
26
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

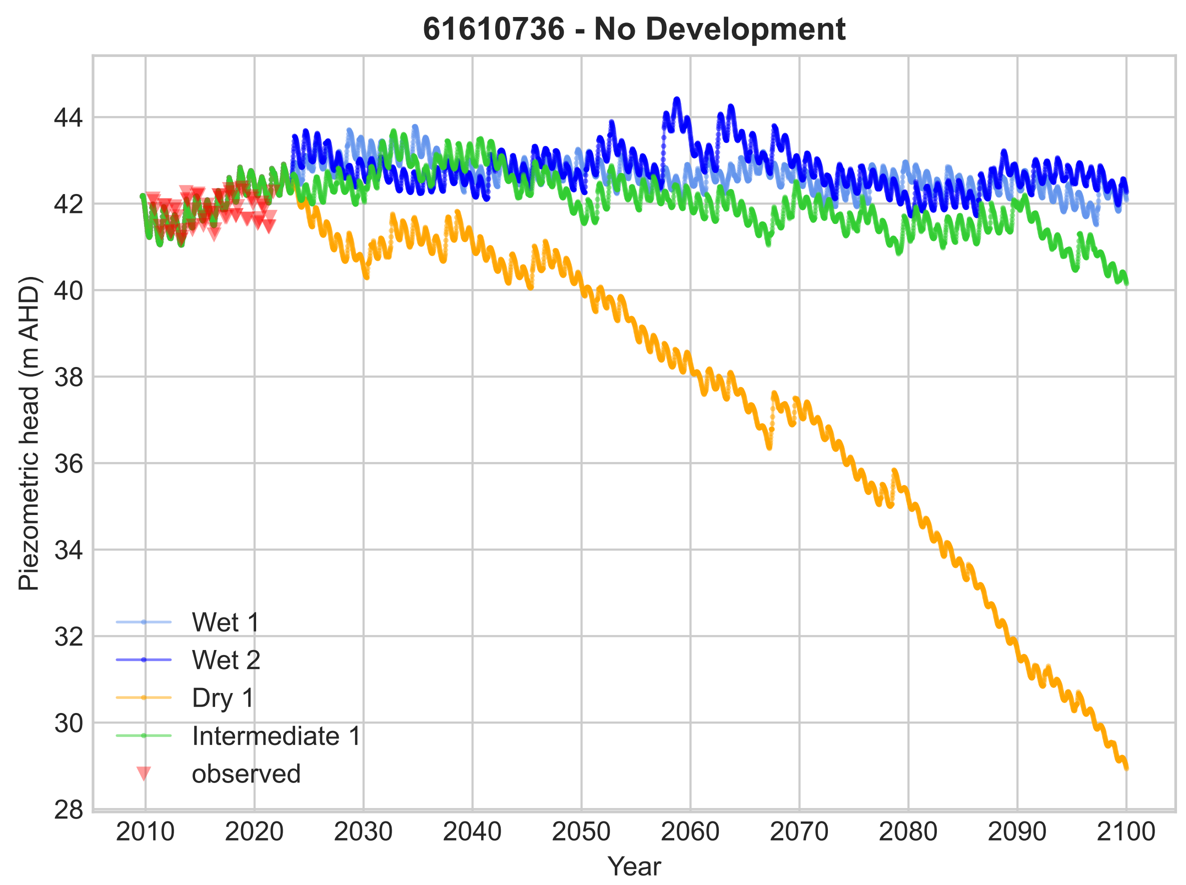

61610716 - No Development
Piezometric head (m AHD)
Year
42.5
40.0
37.5
35.0
32.5
30.0
27.5
25.0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

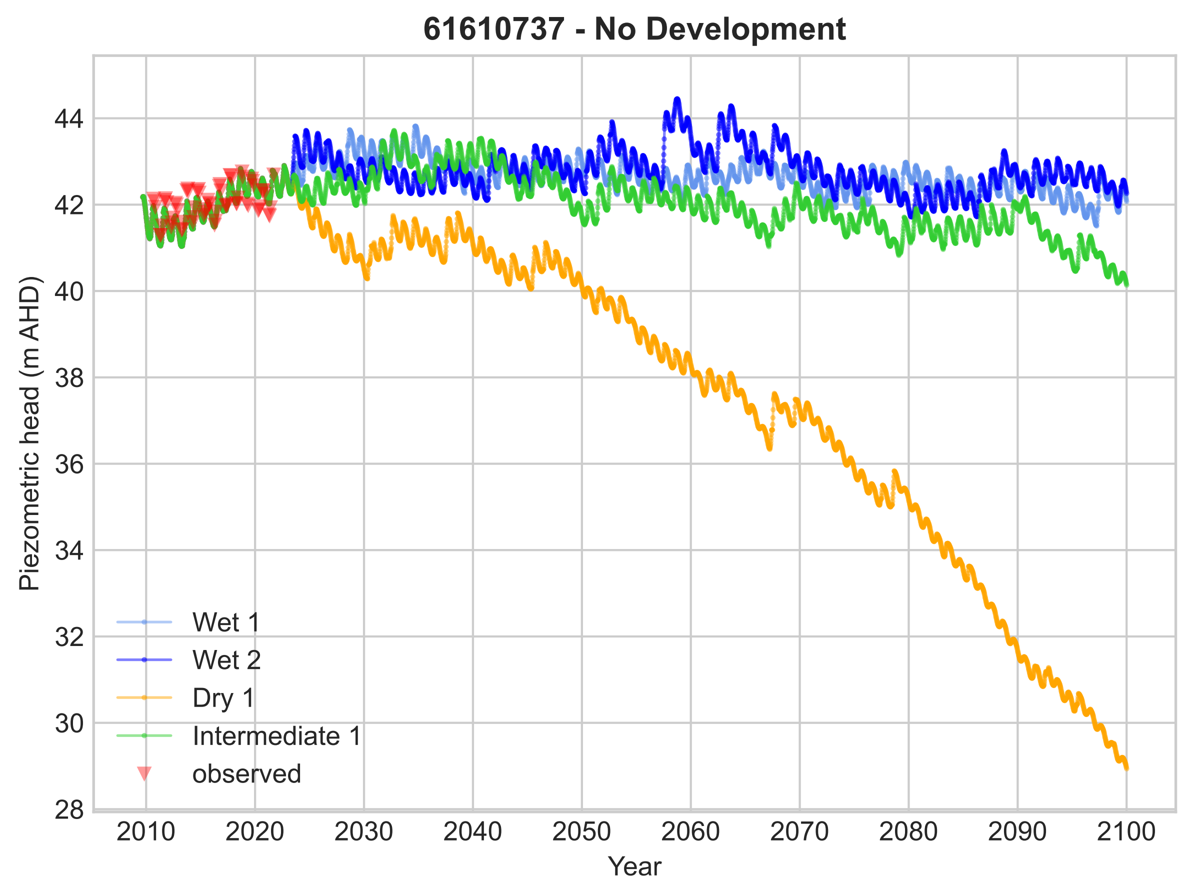

61610718 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

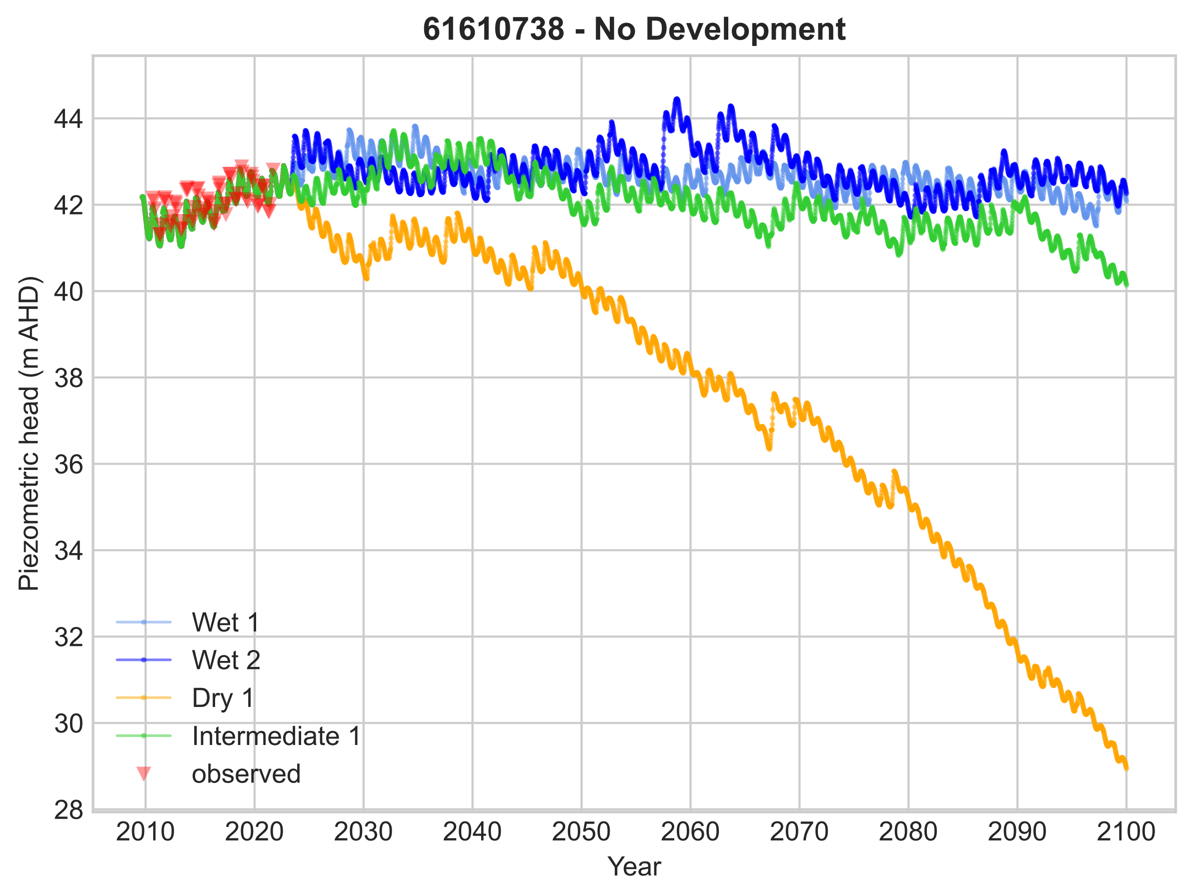

61610719 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

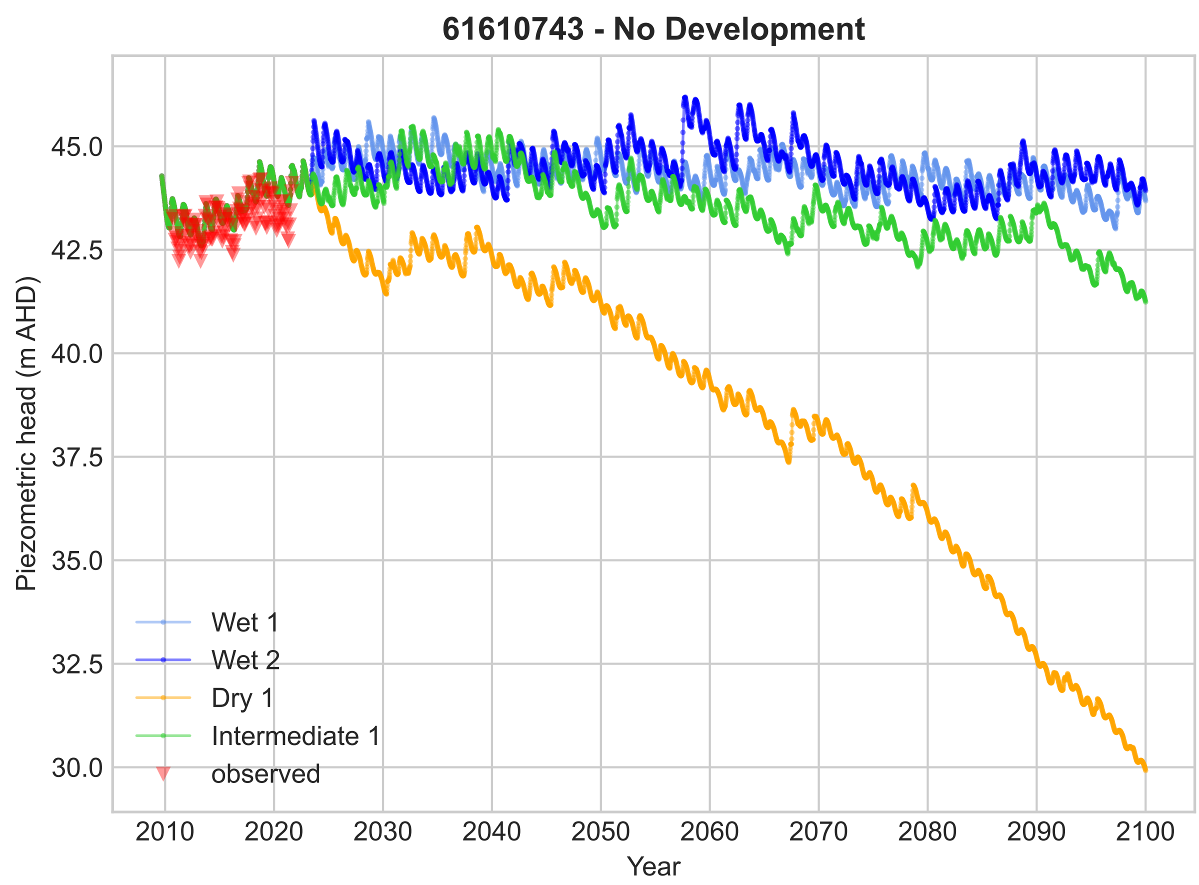

61610720 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

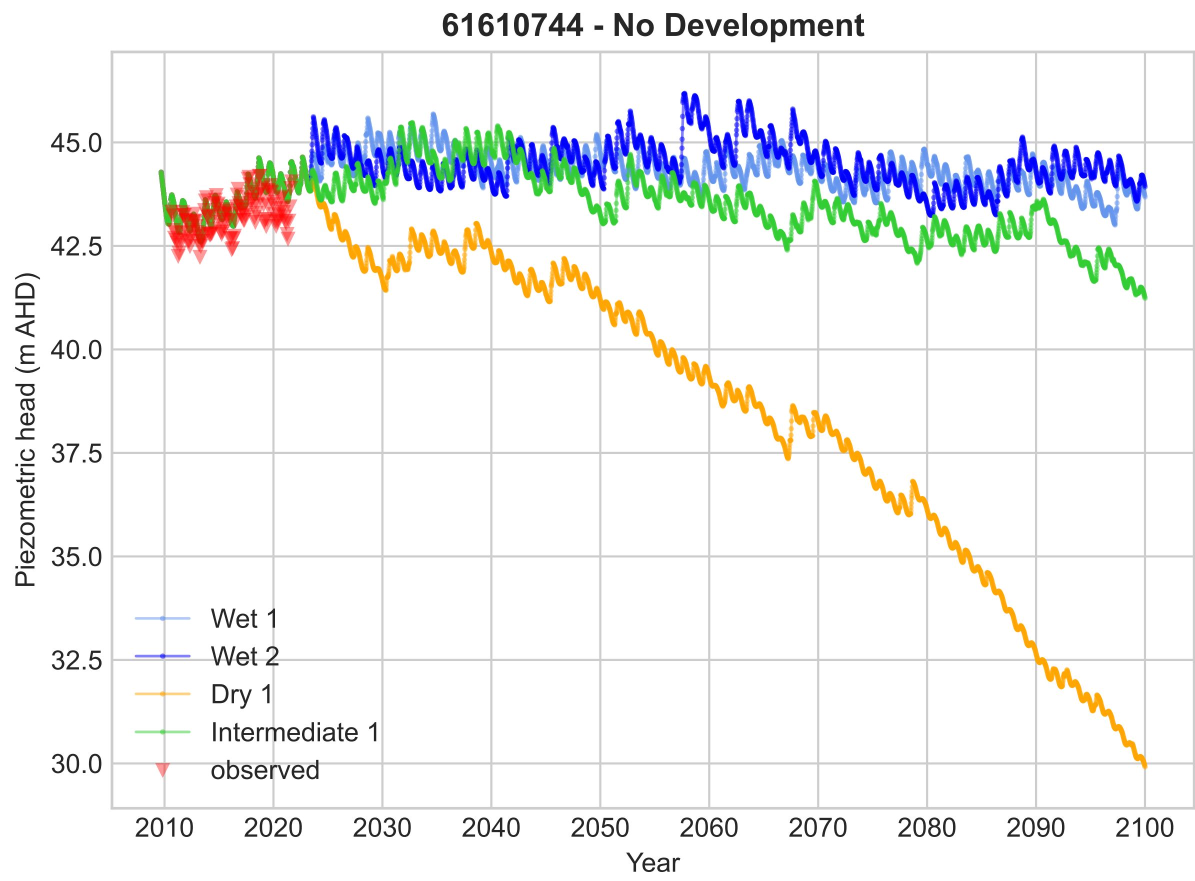

61610734 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

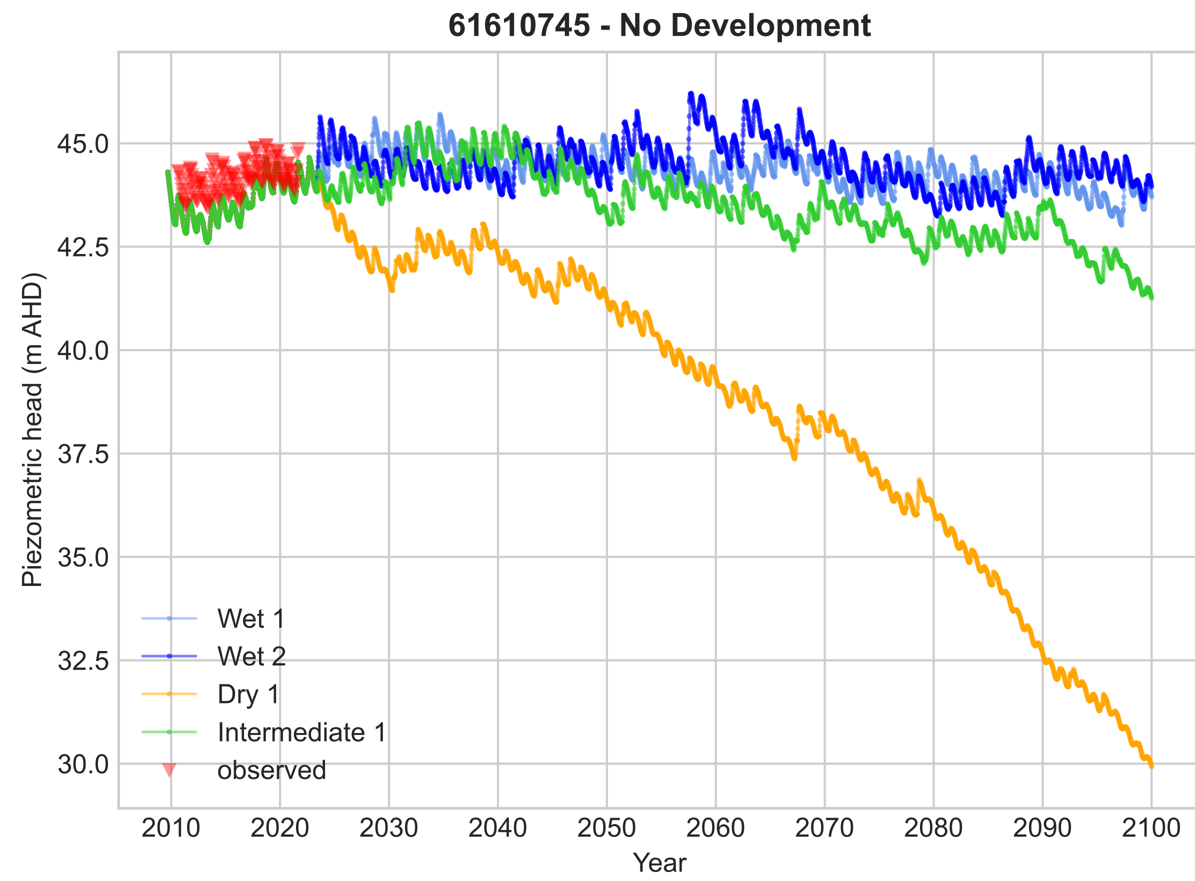

61610736 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

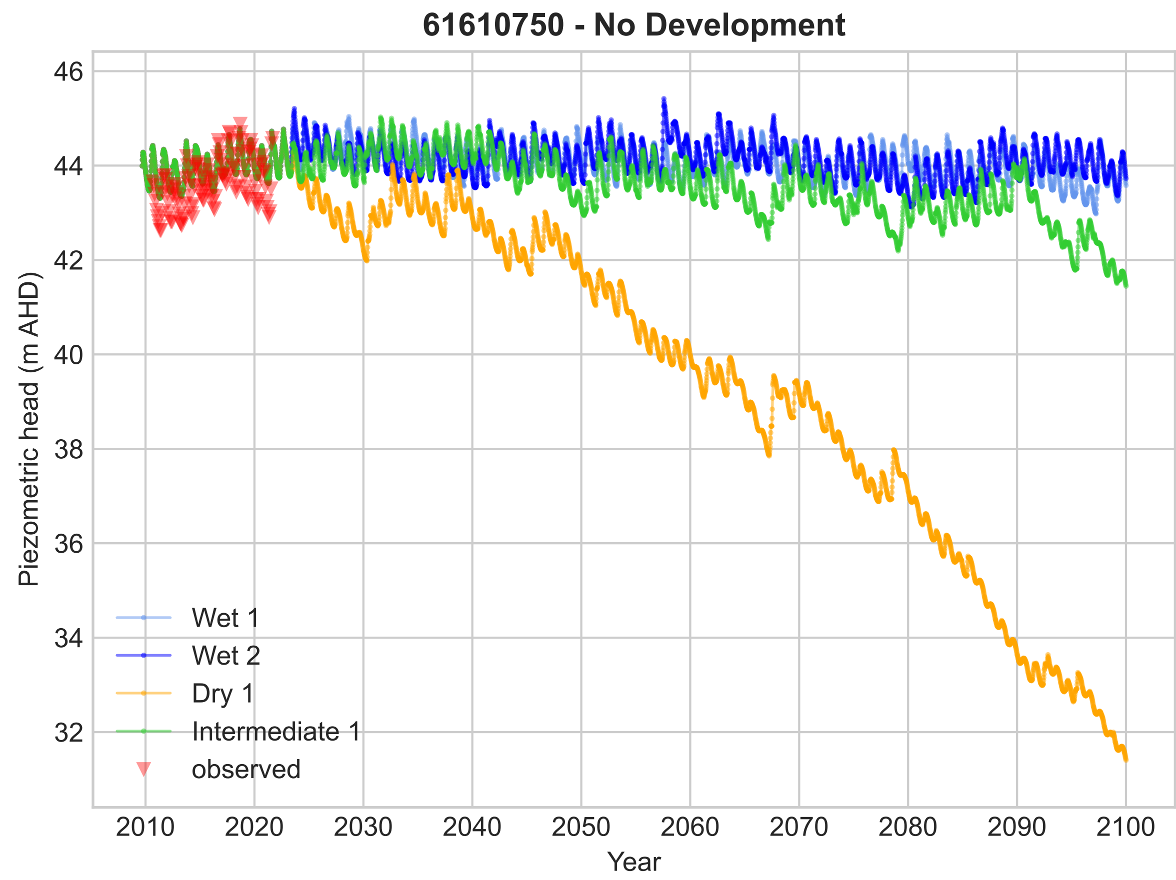

61610737 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

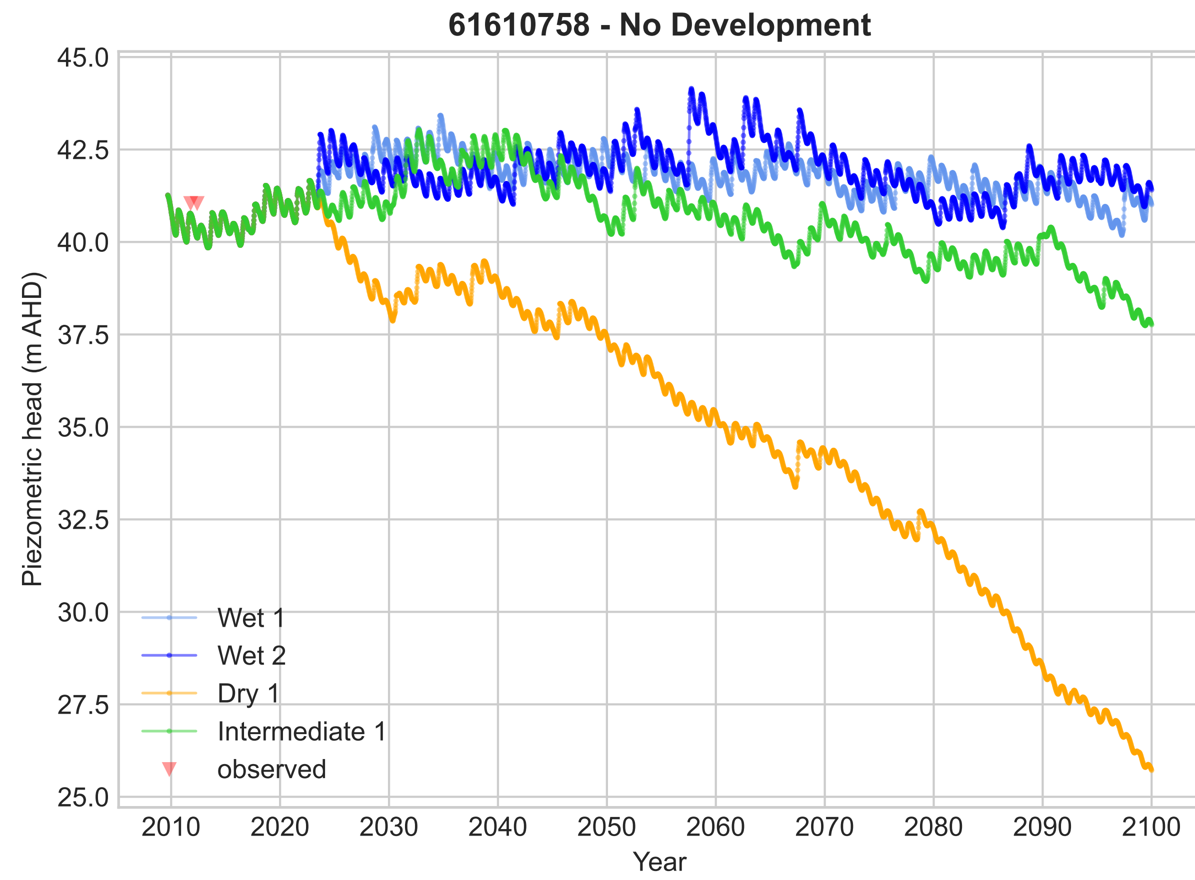

61610738 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

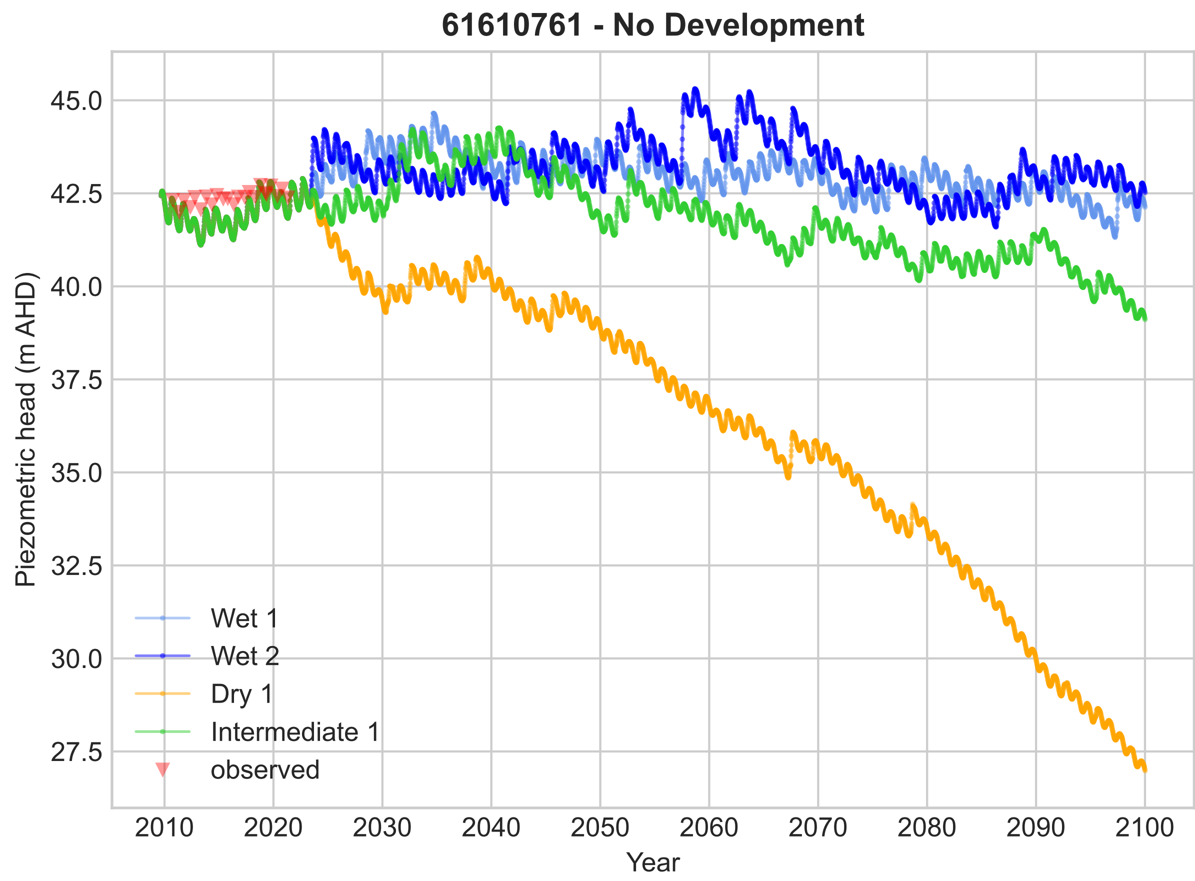

61610743 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

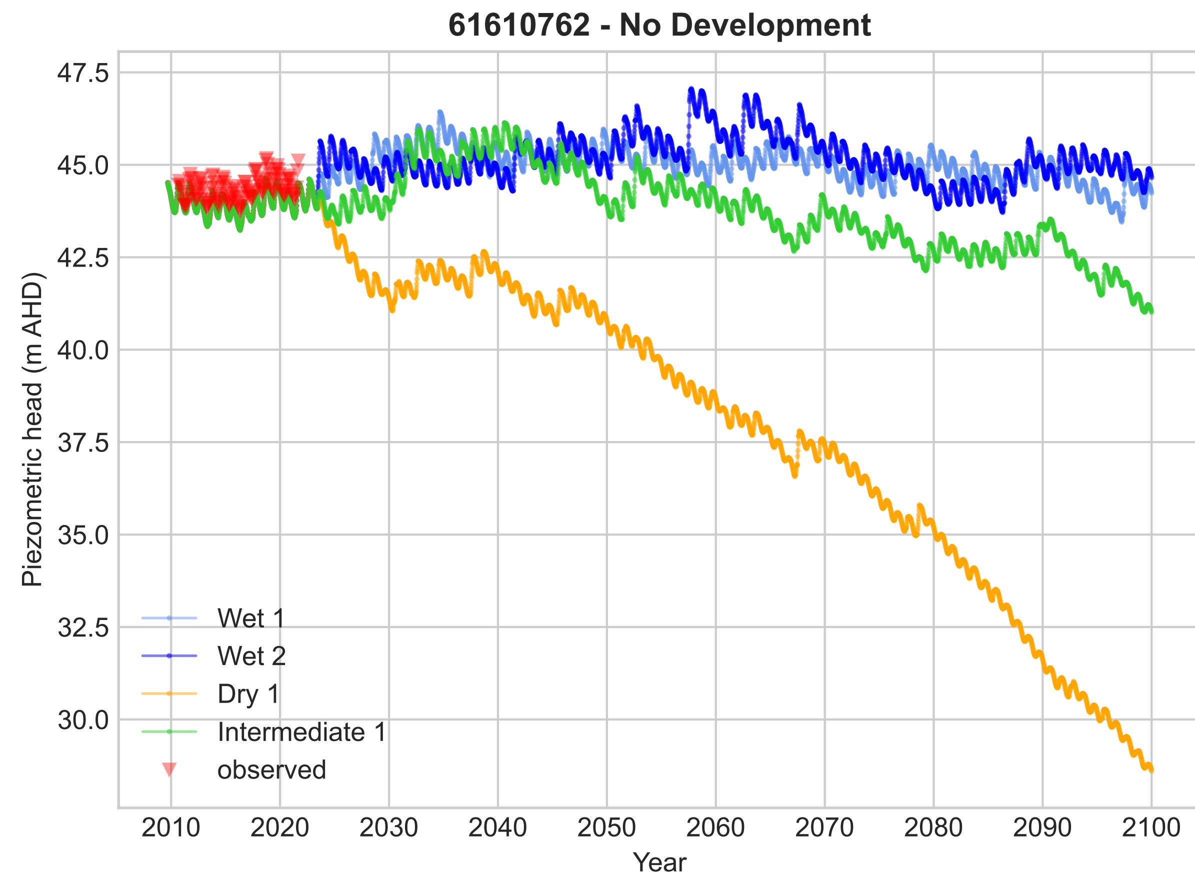

61610744 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

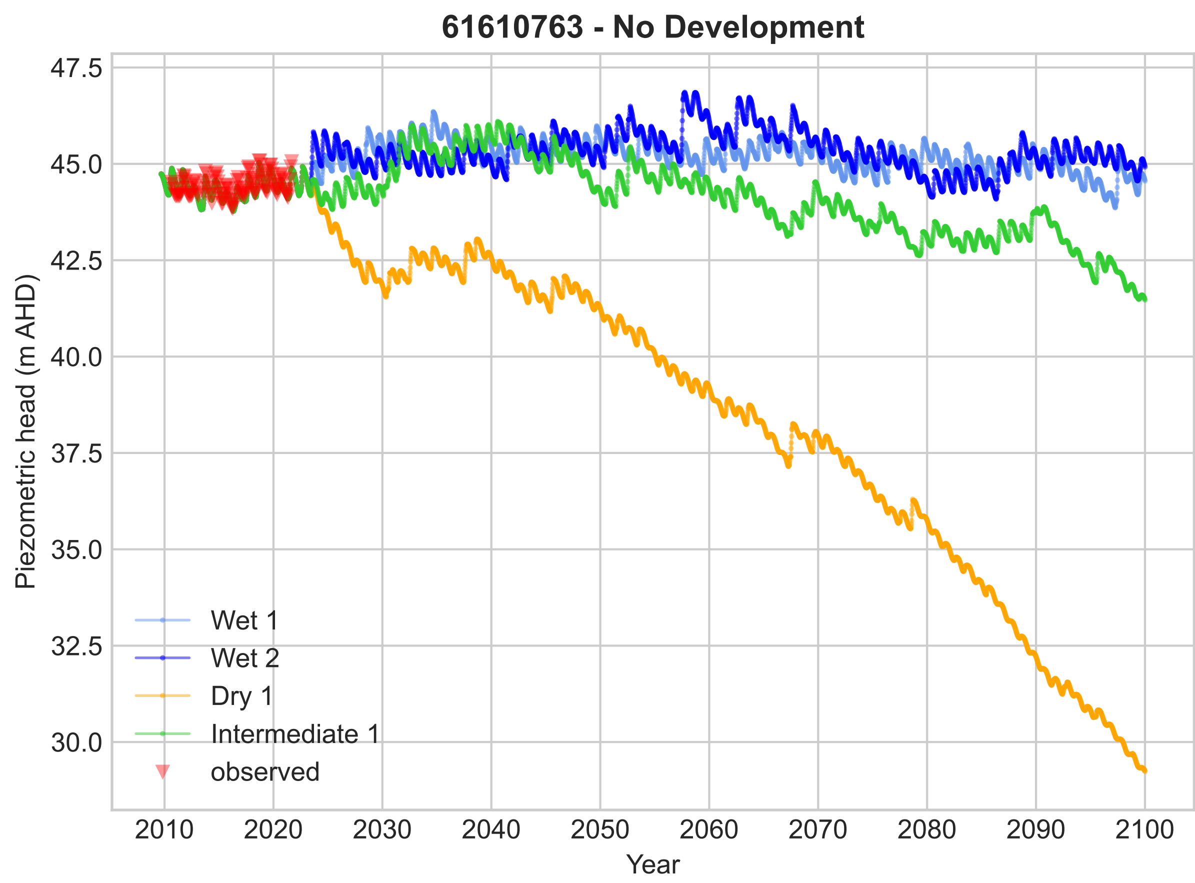

61610745 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

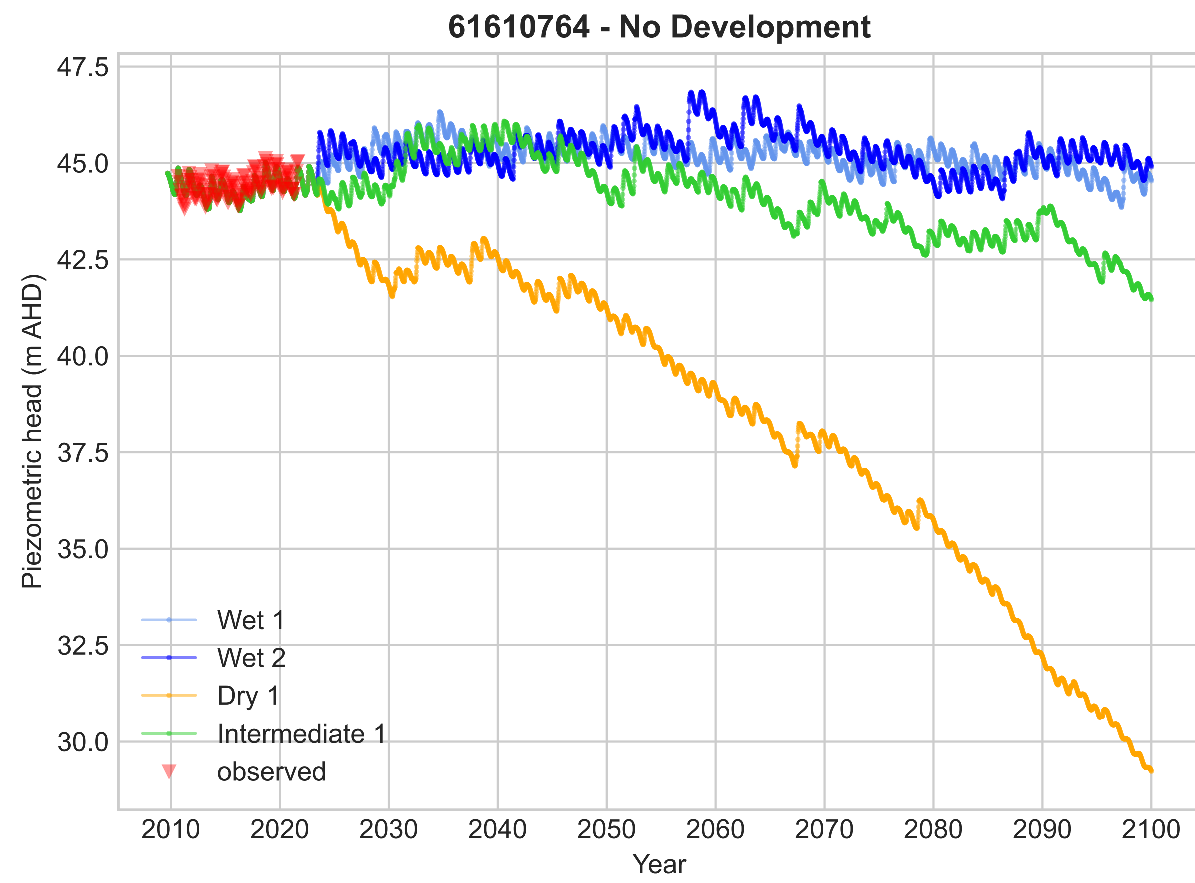

61610750 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

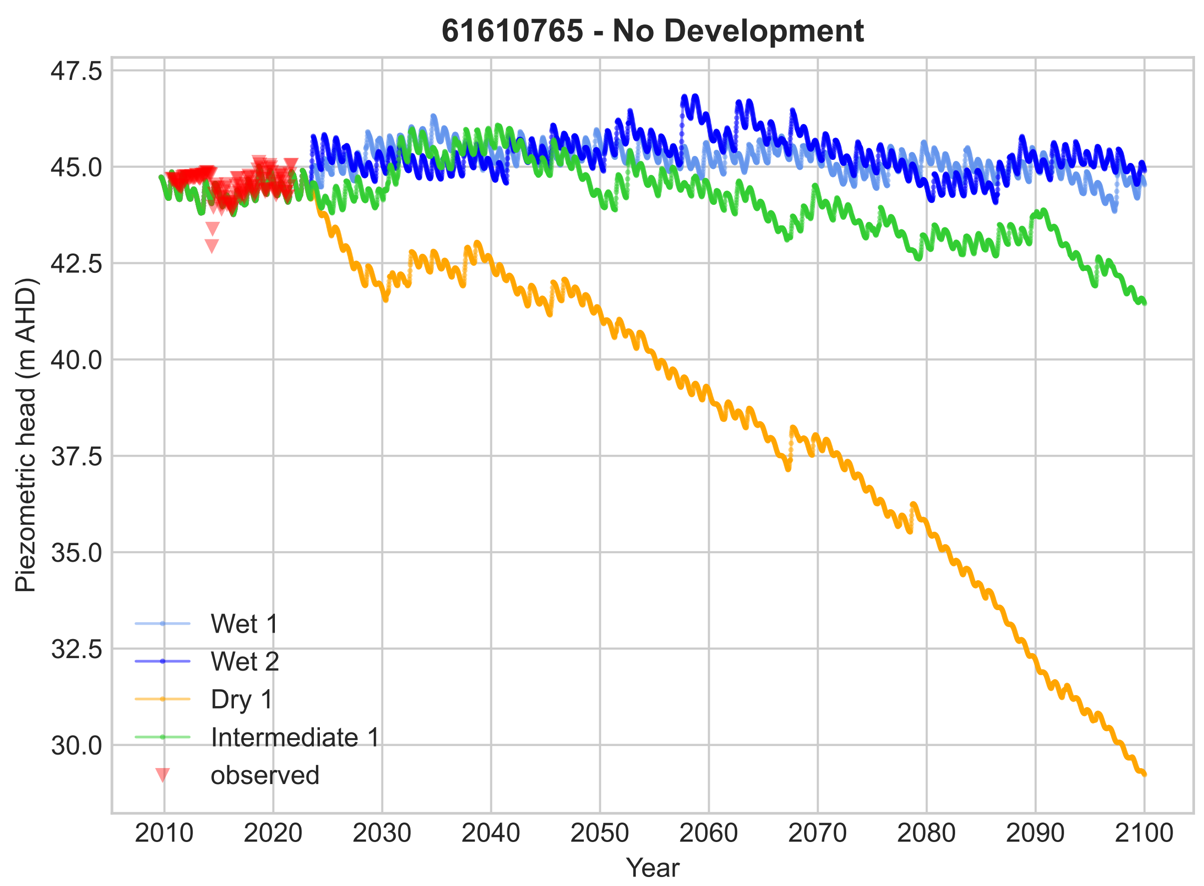

61610758 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

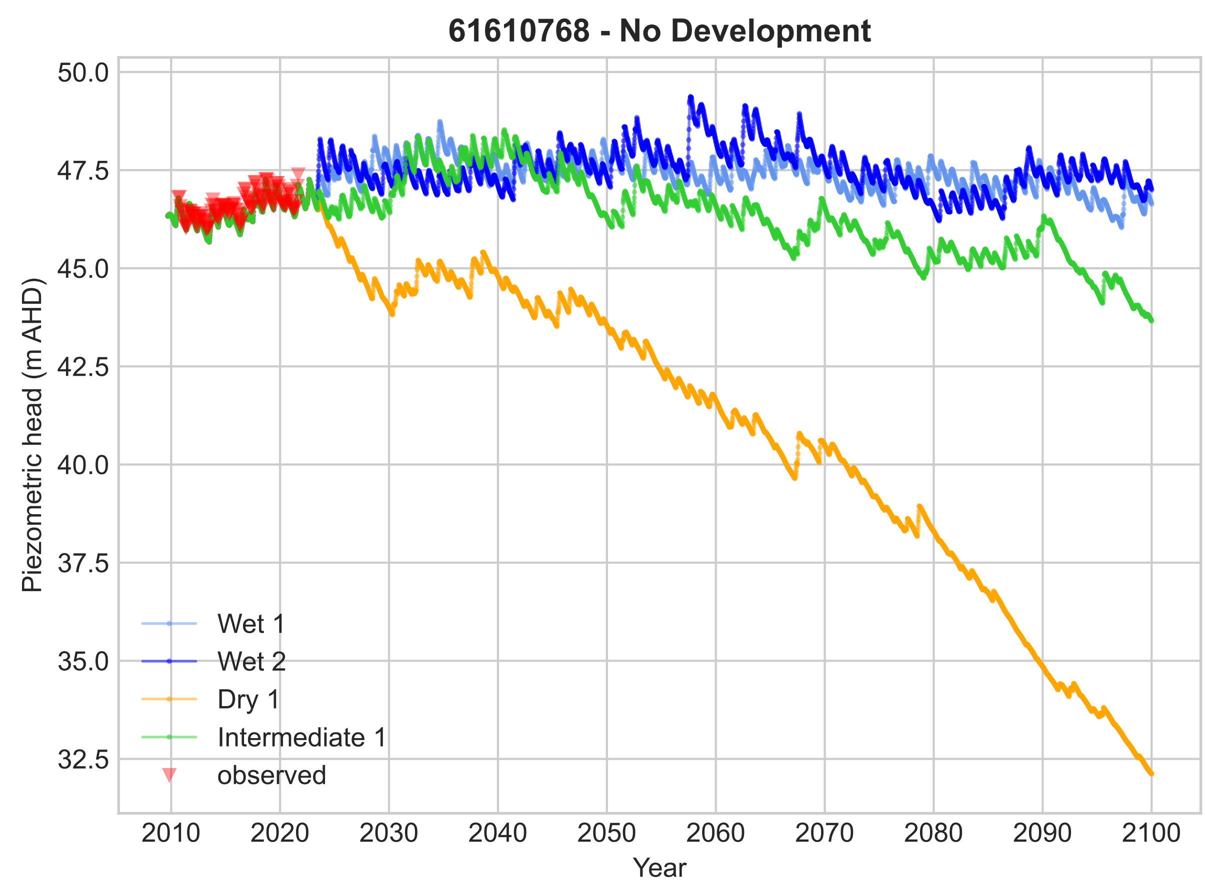

61610761 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

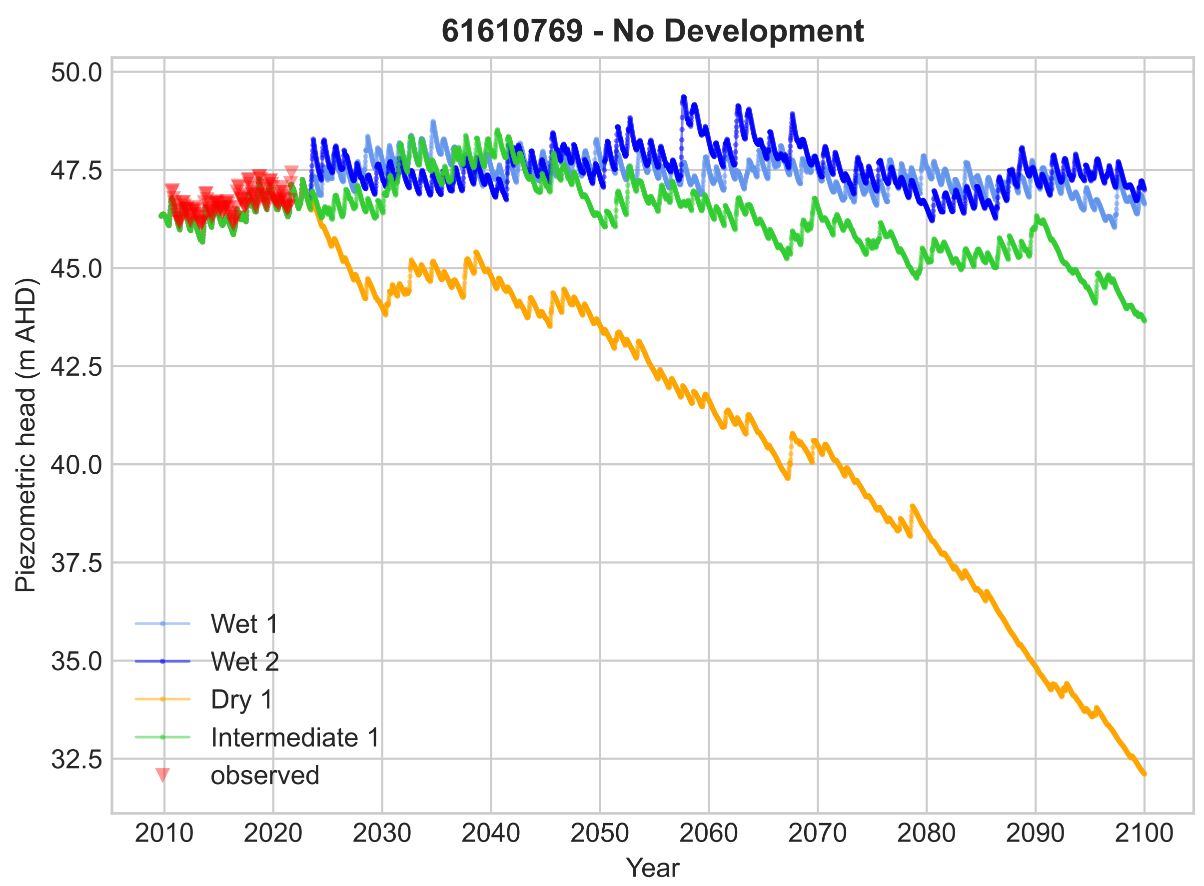

61610762 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

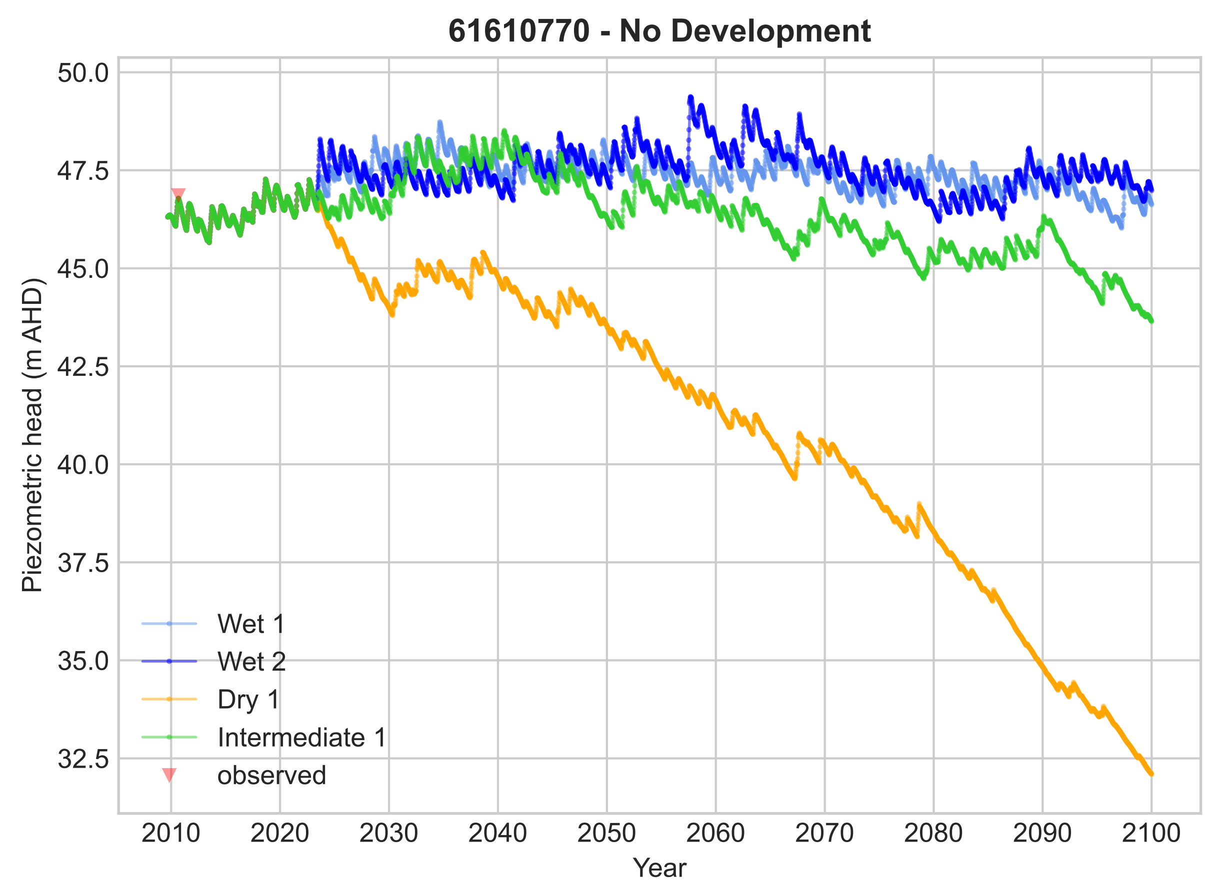

61610763 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

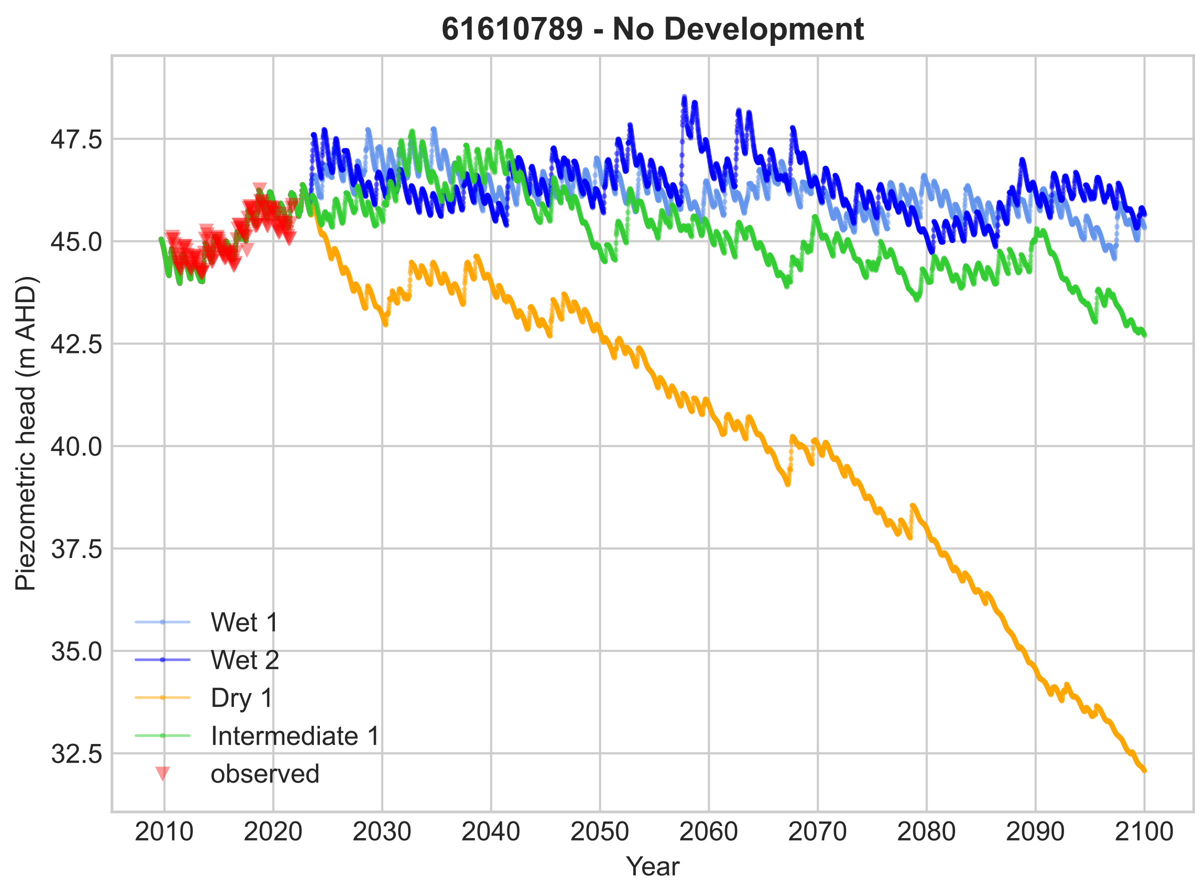

61610764 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

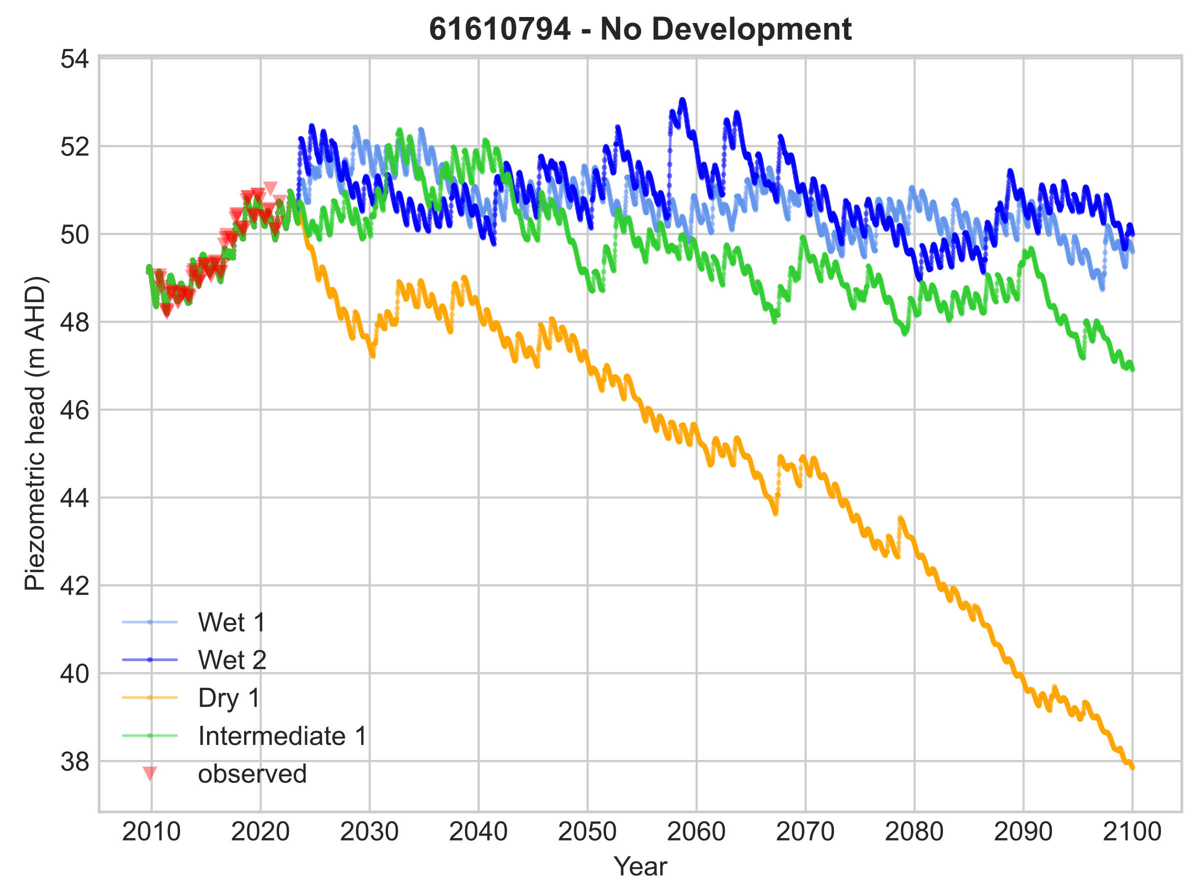

61610765 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

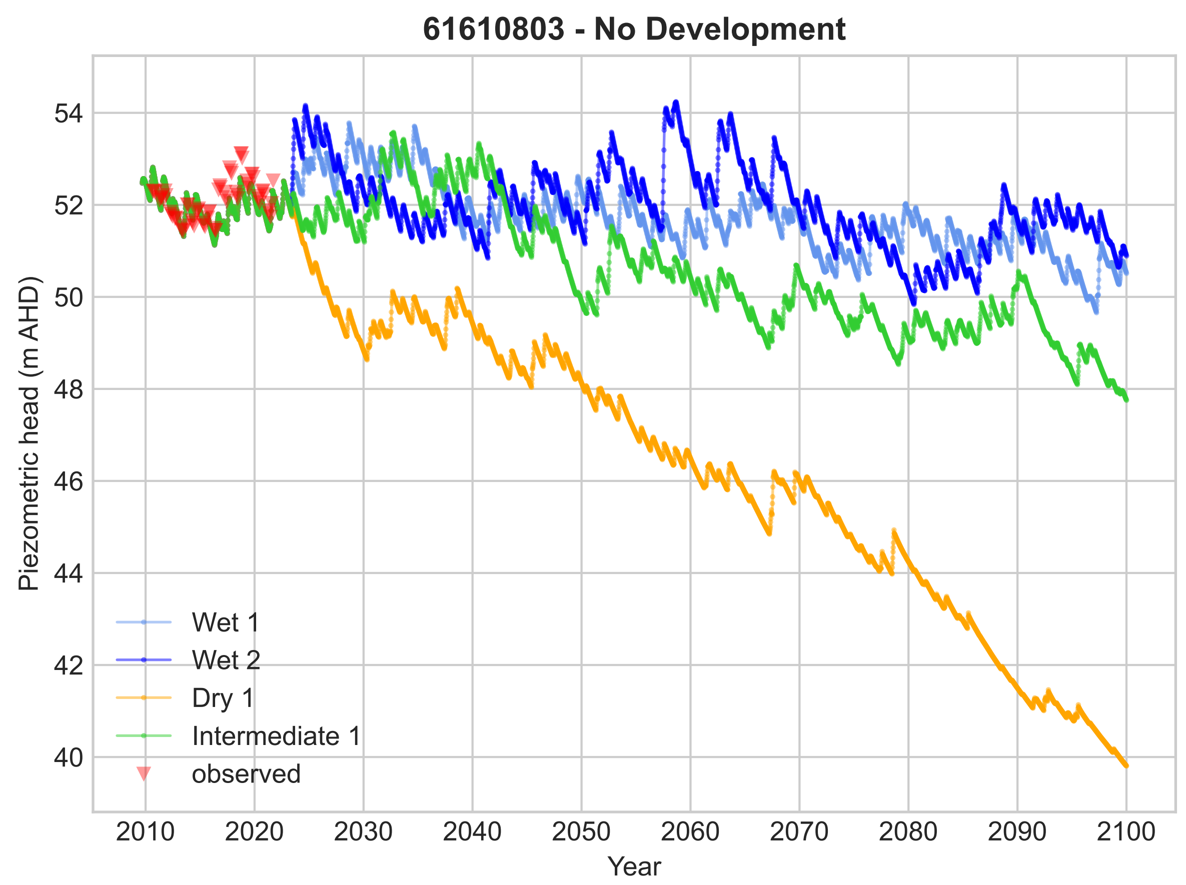

61610768 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

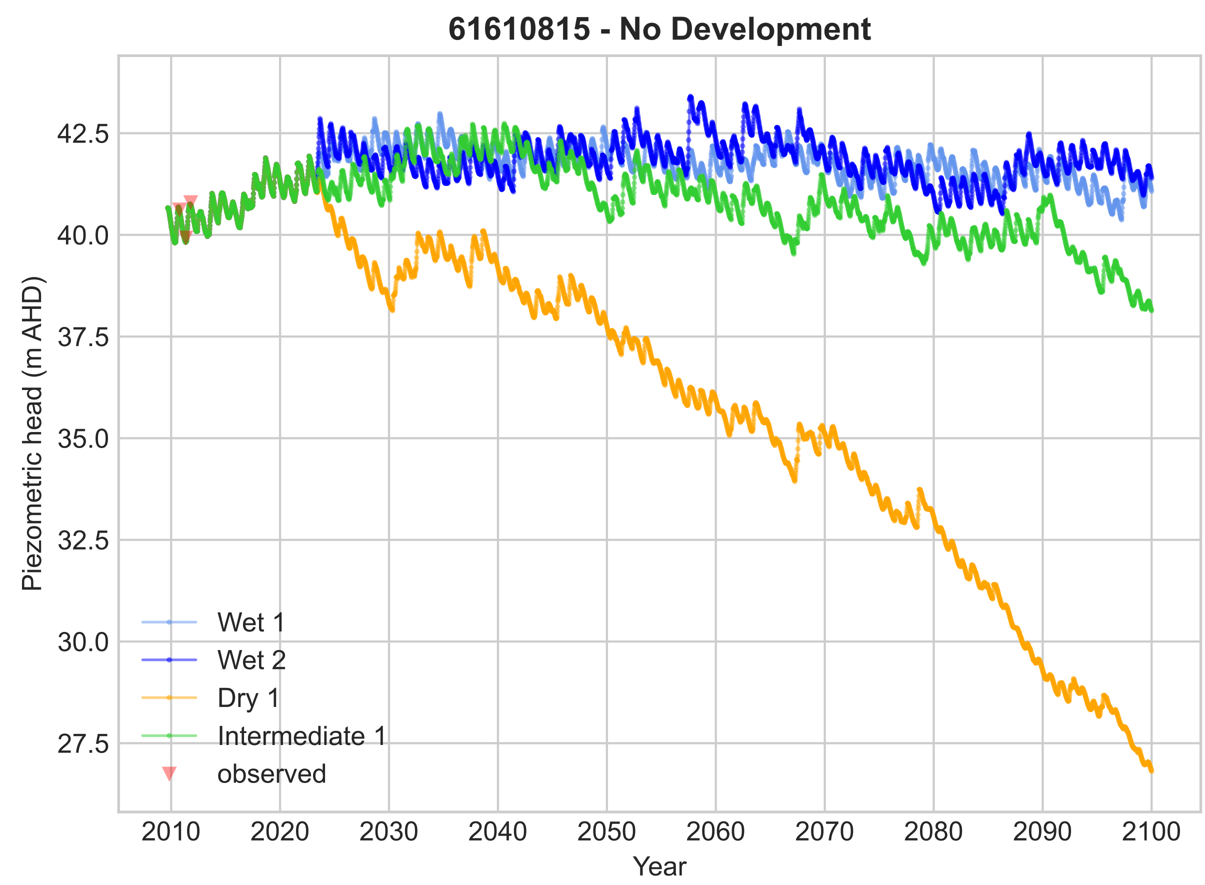

61610769 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

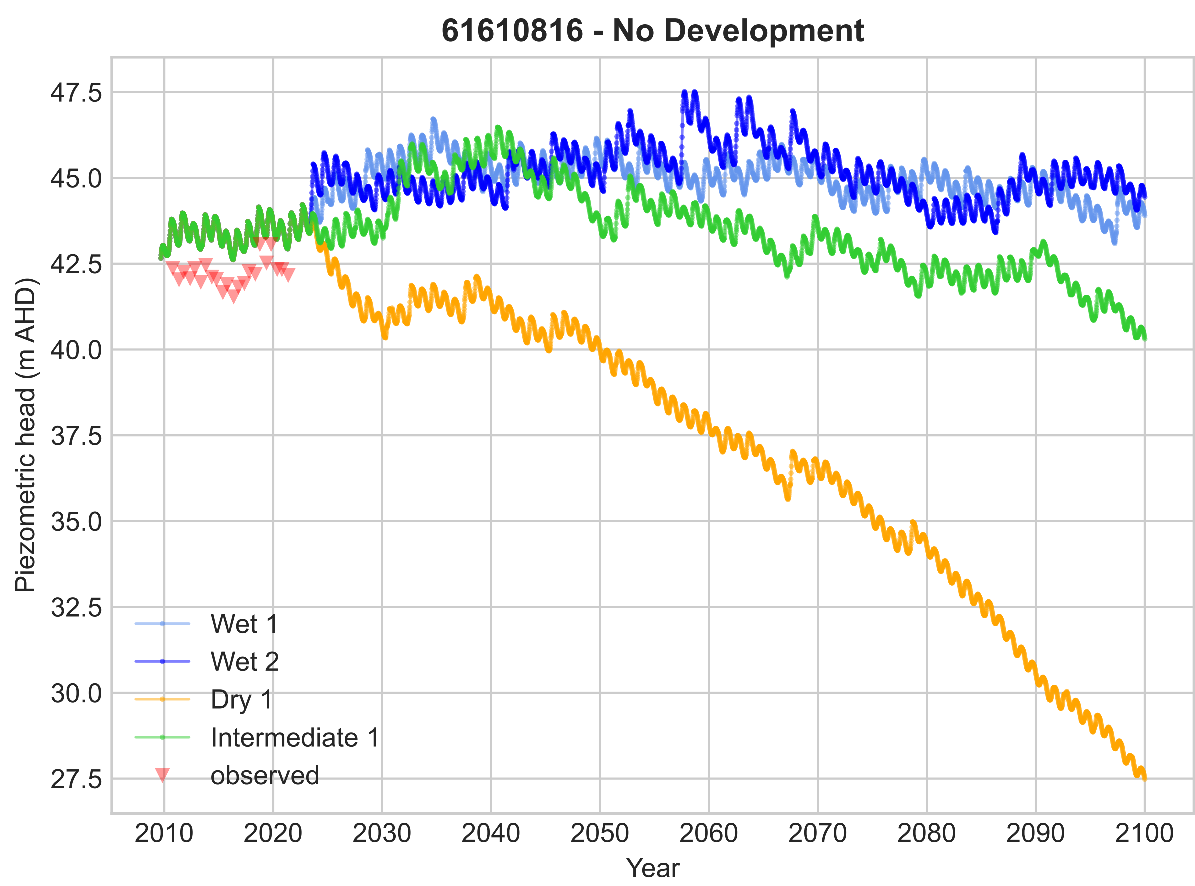

61610770 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

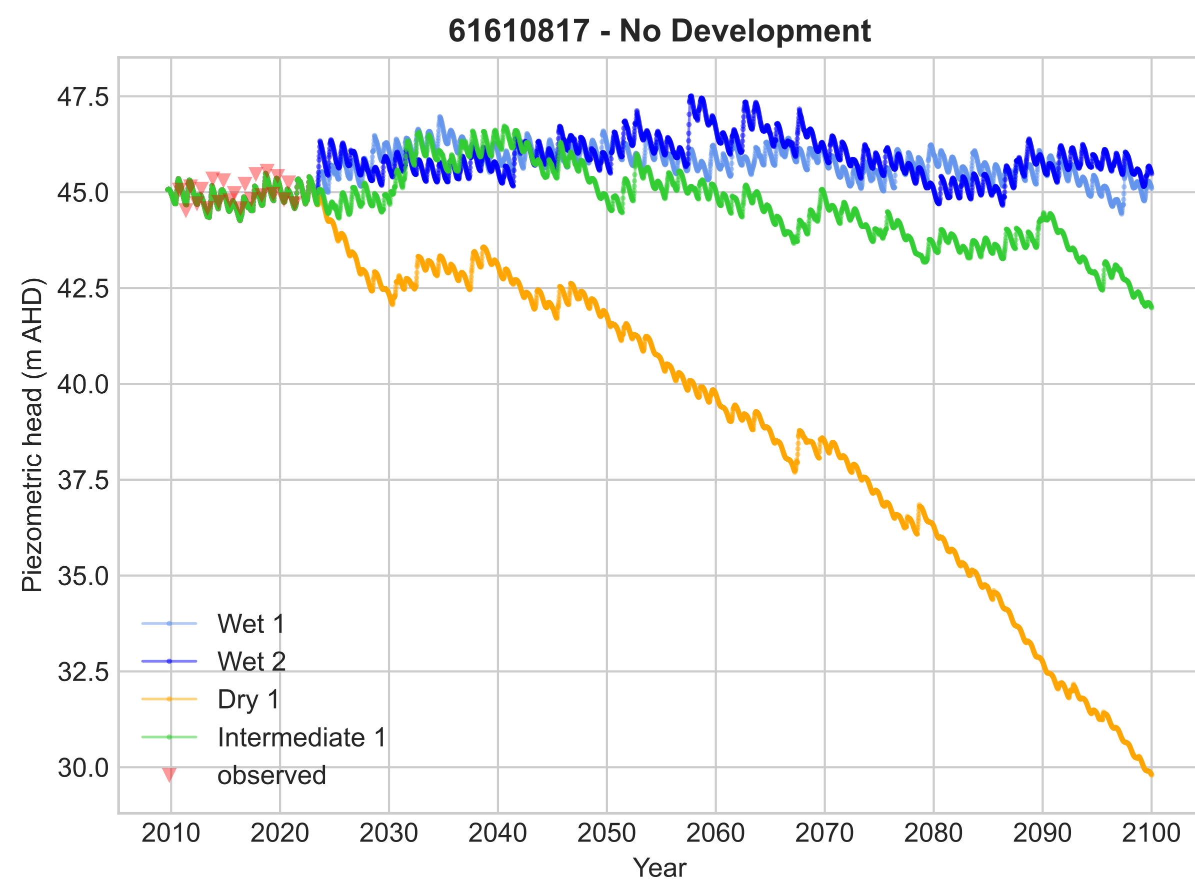

61610789 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

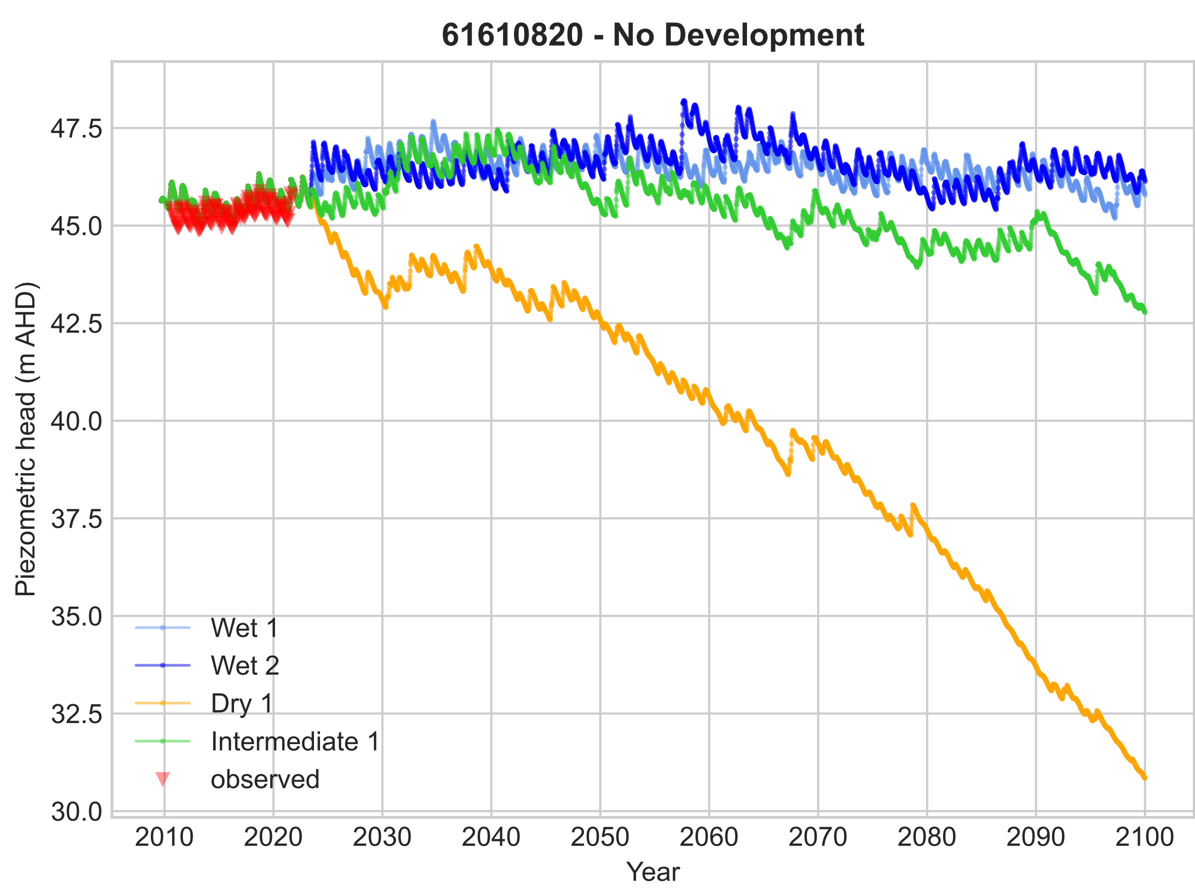

61610794 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

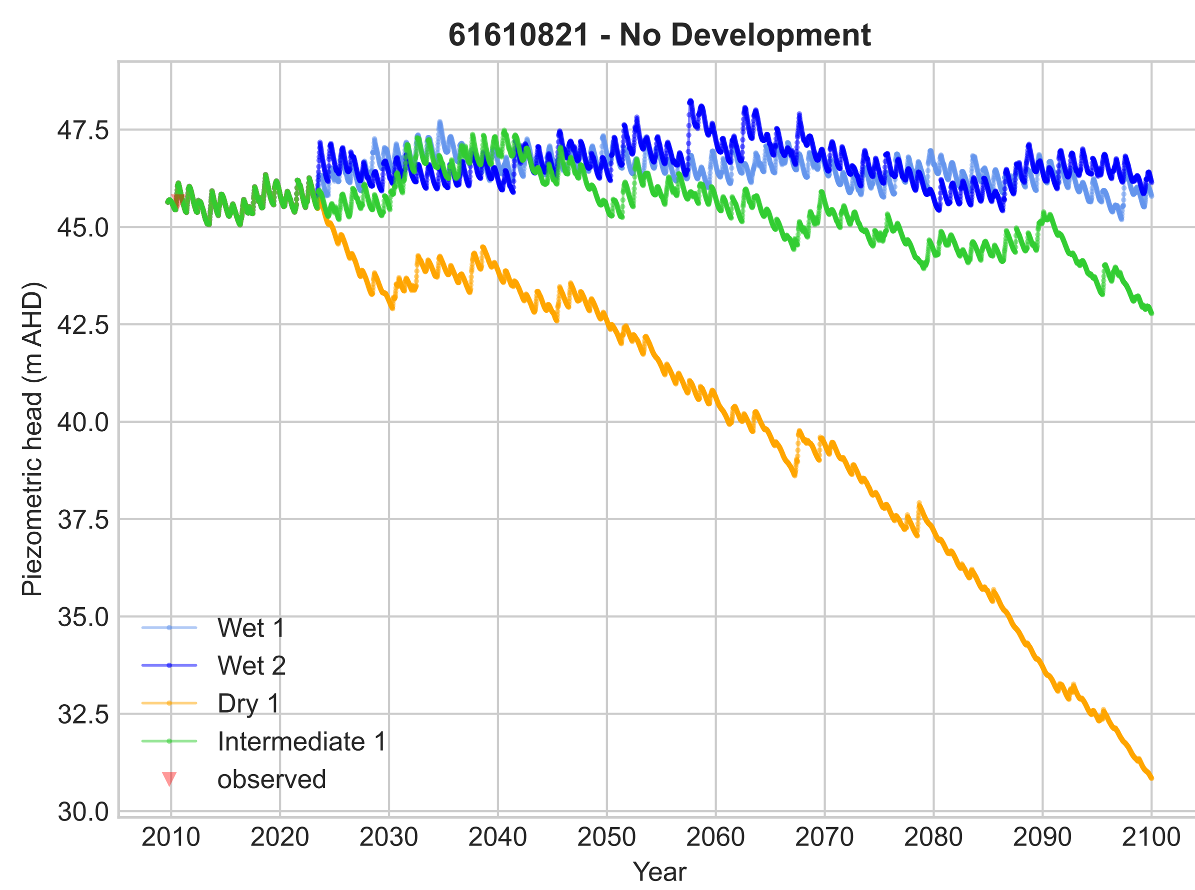

61610803 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

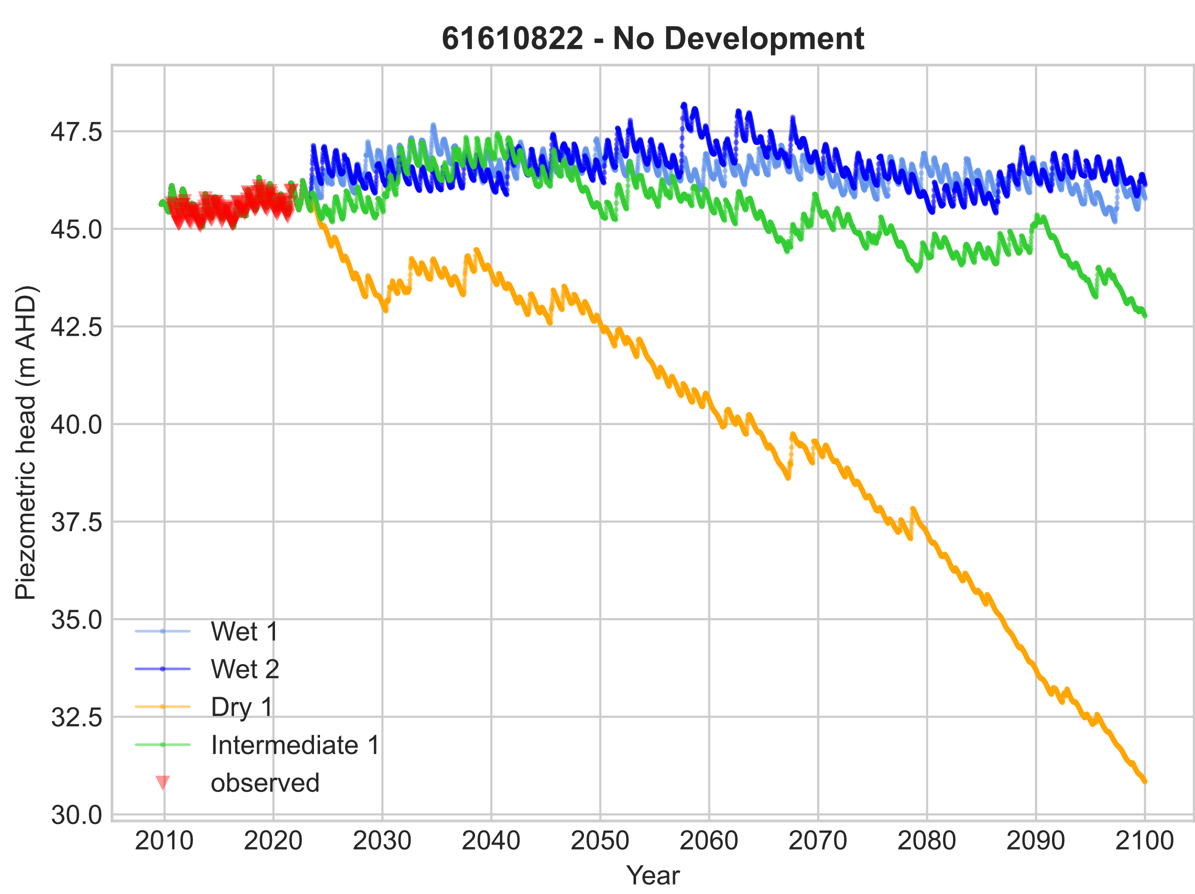

61610815 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

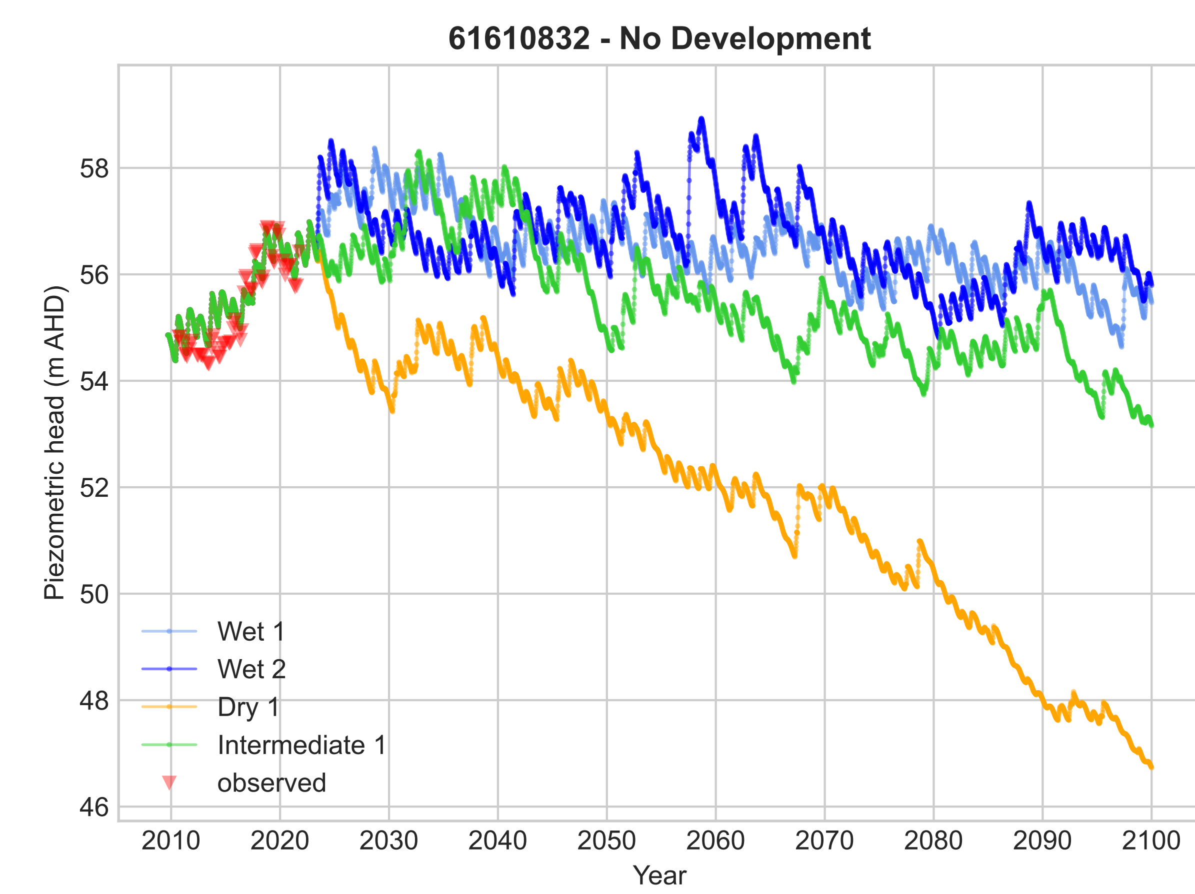

61610816 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

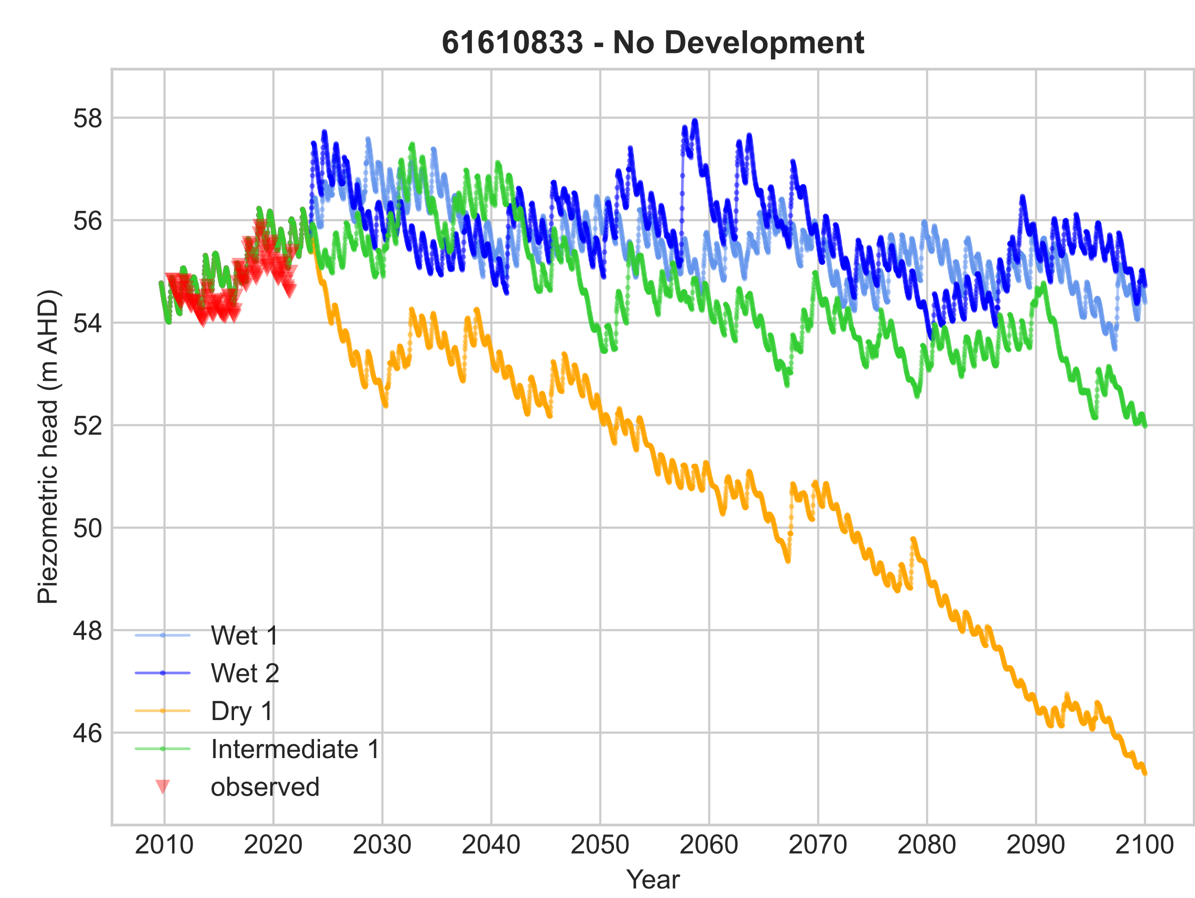

61610817 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

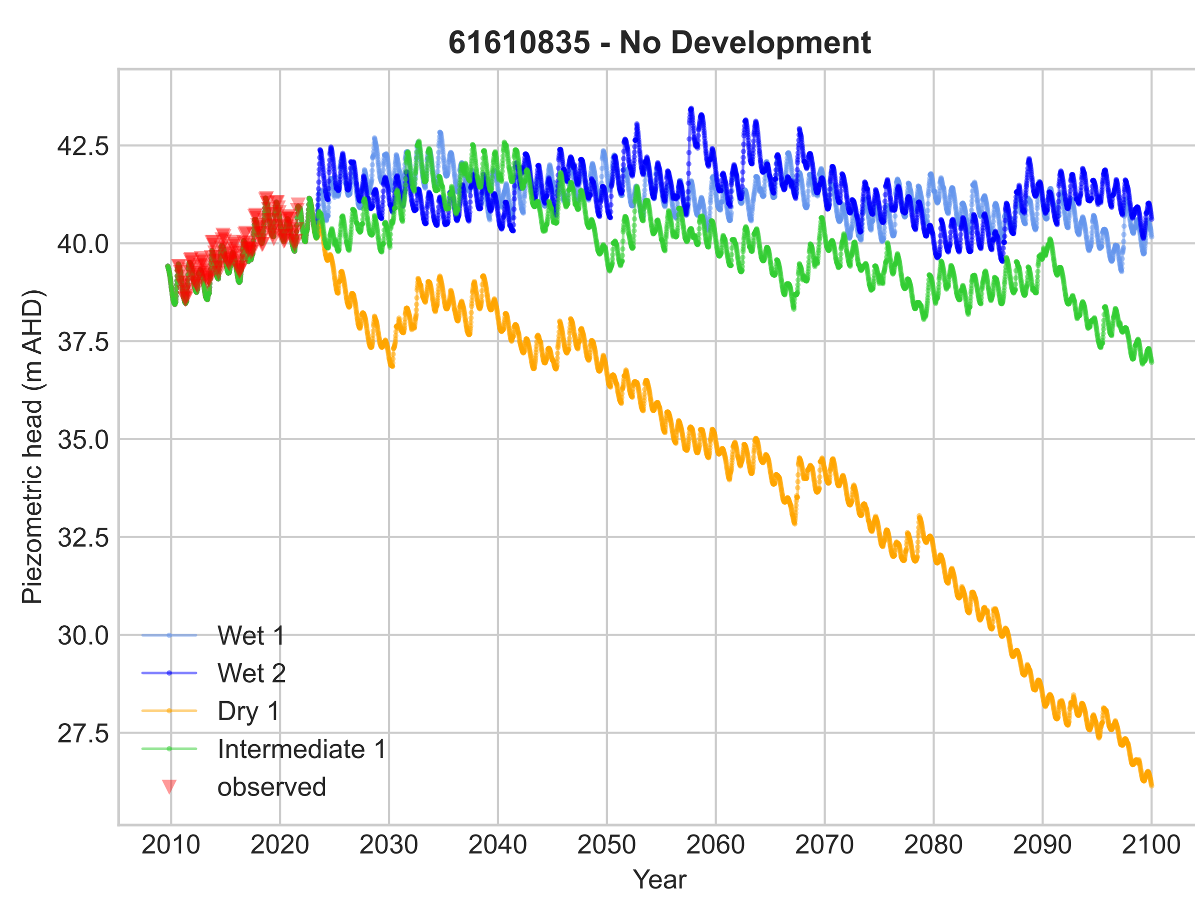

61610820 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

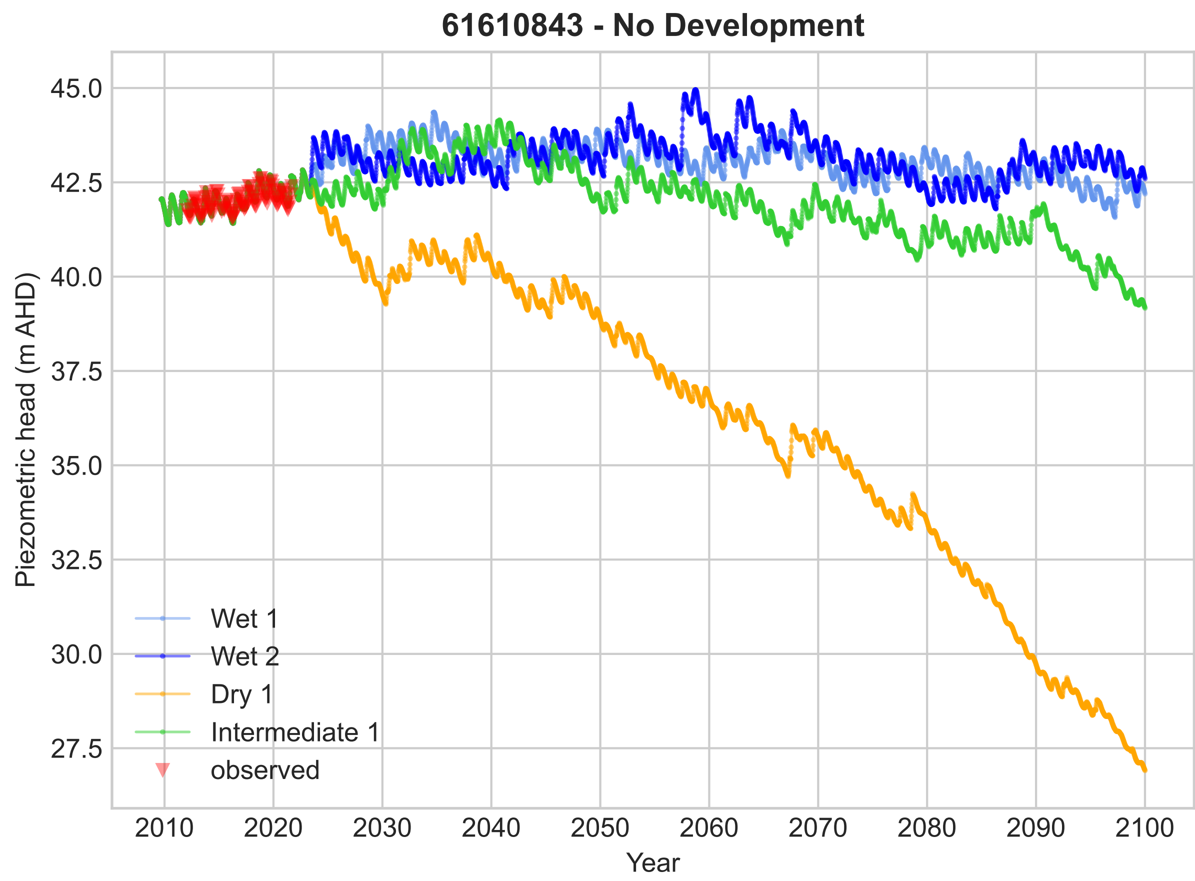

61610821 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

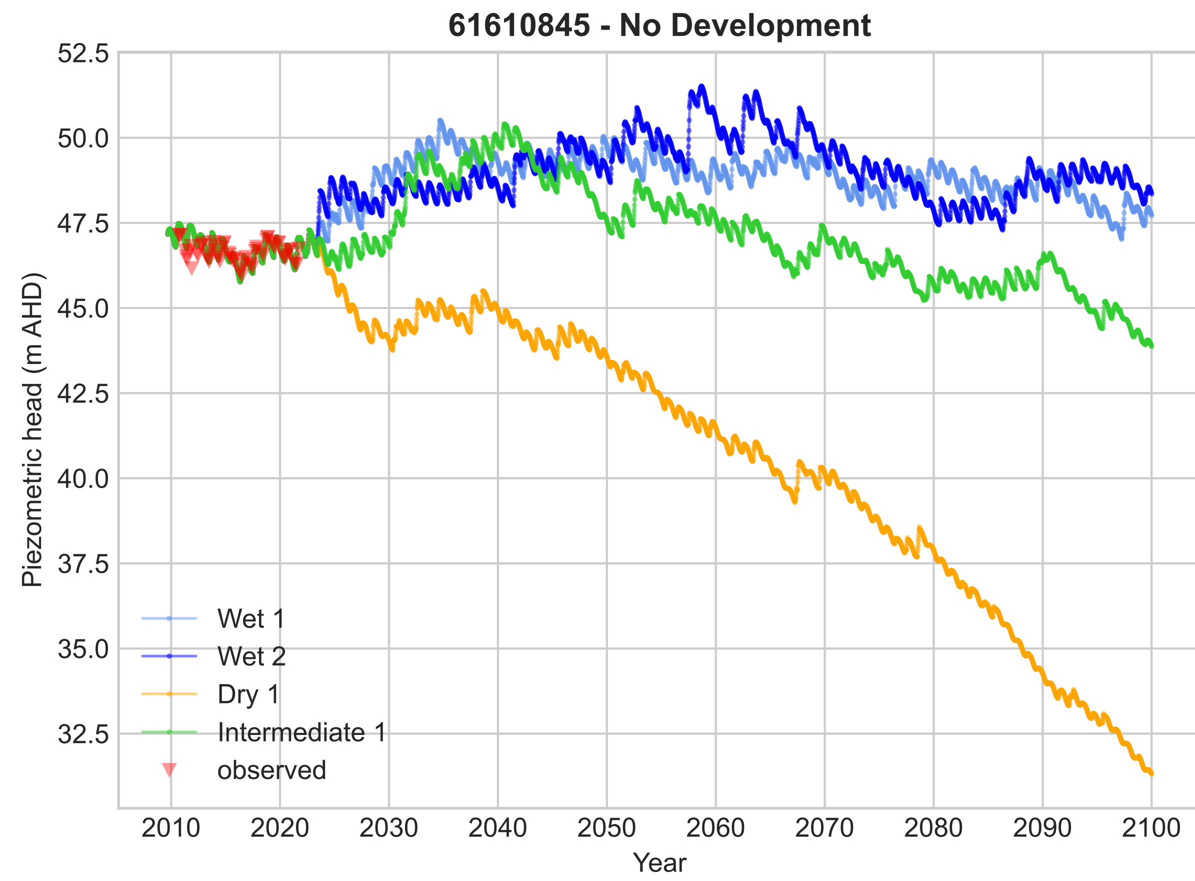

61610822 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

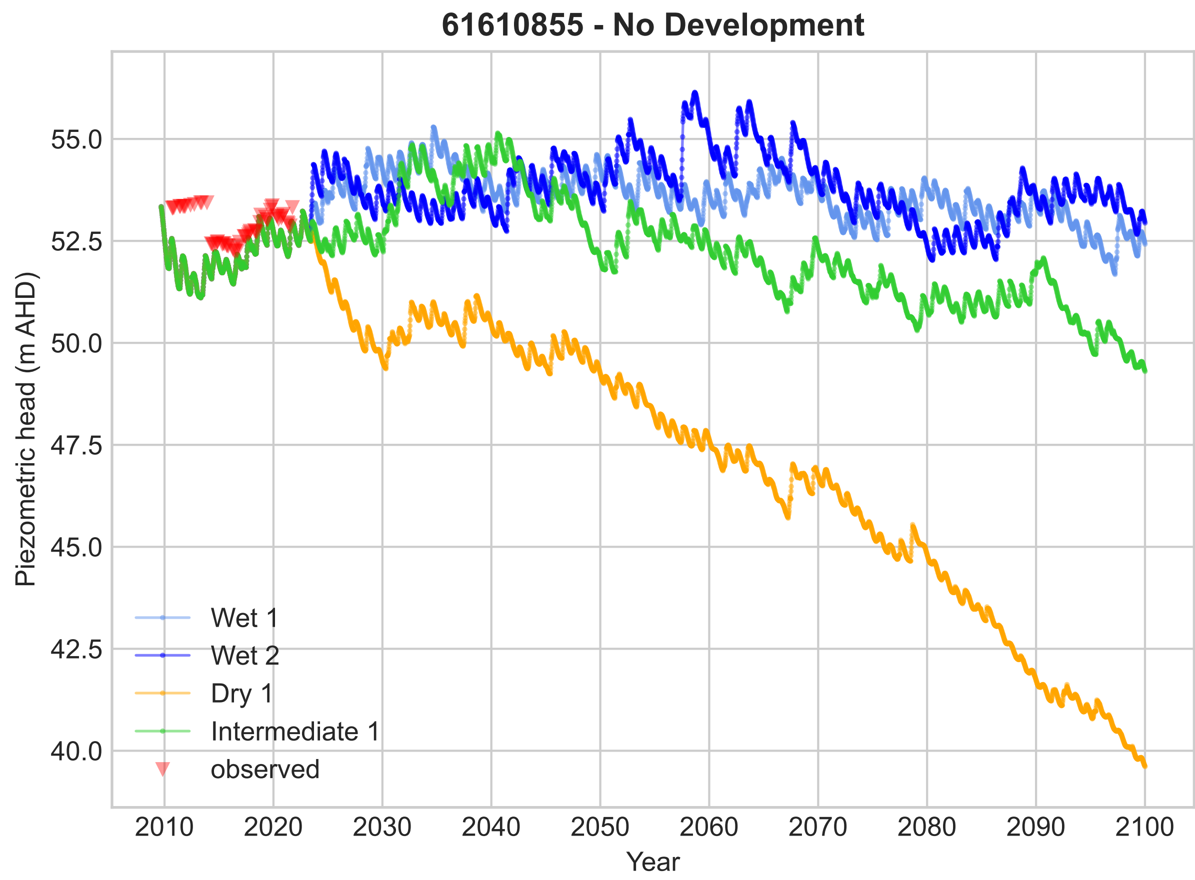

61610832 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

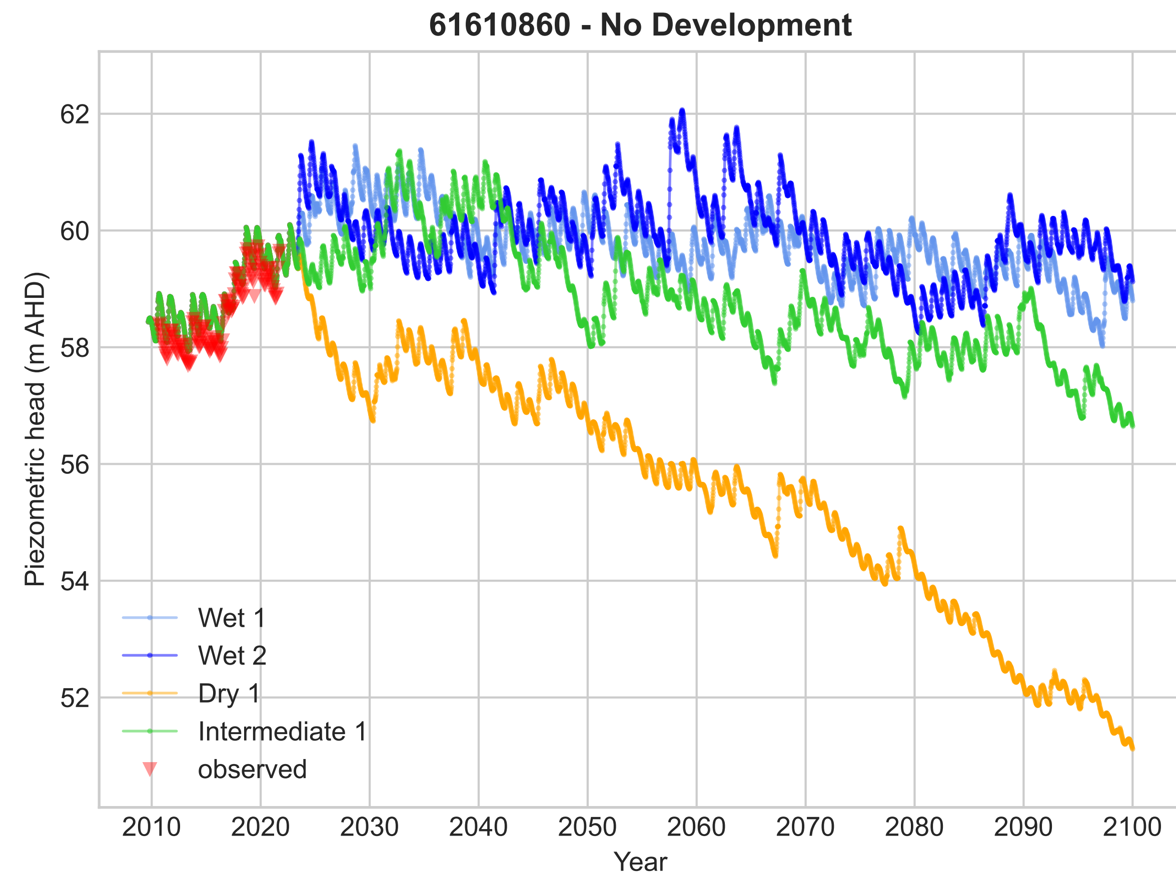

61610833 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

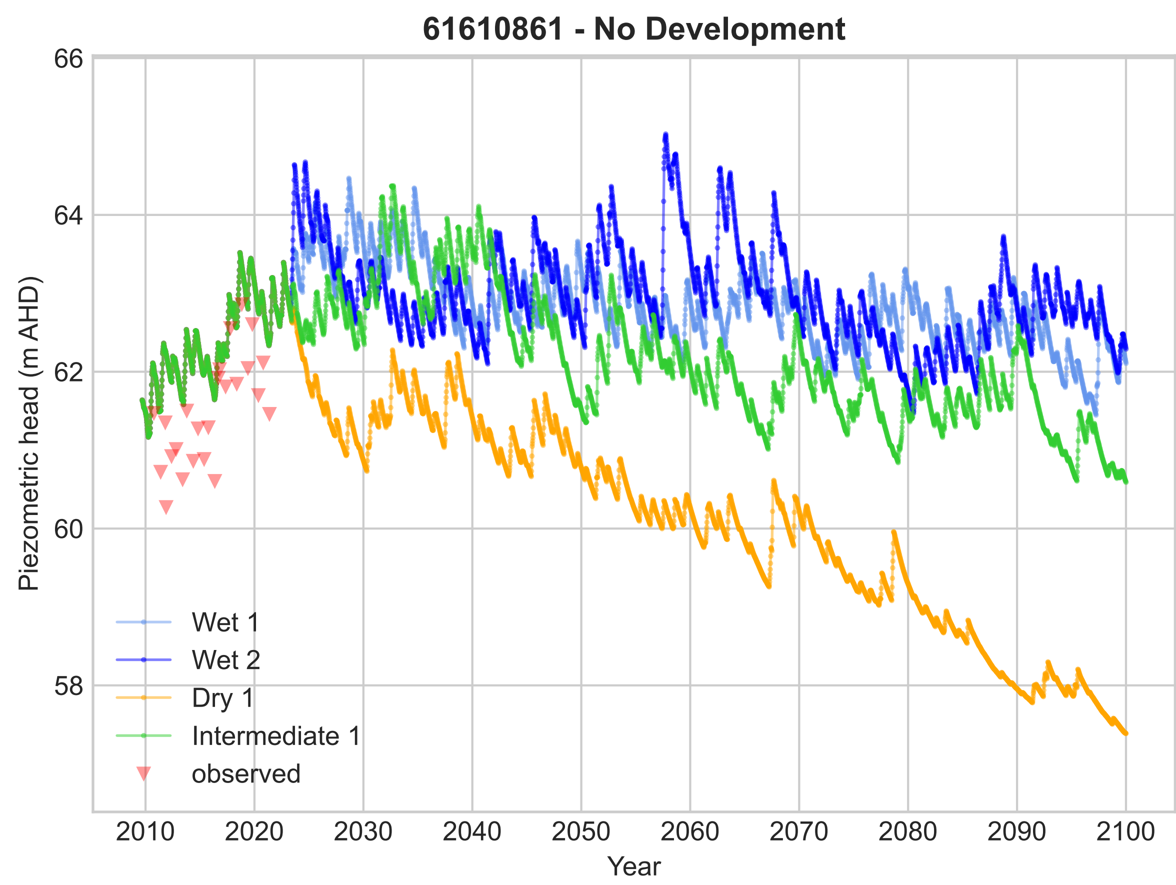

61610835 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

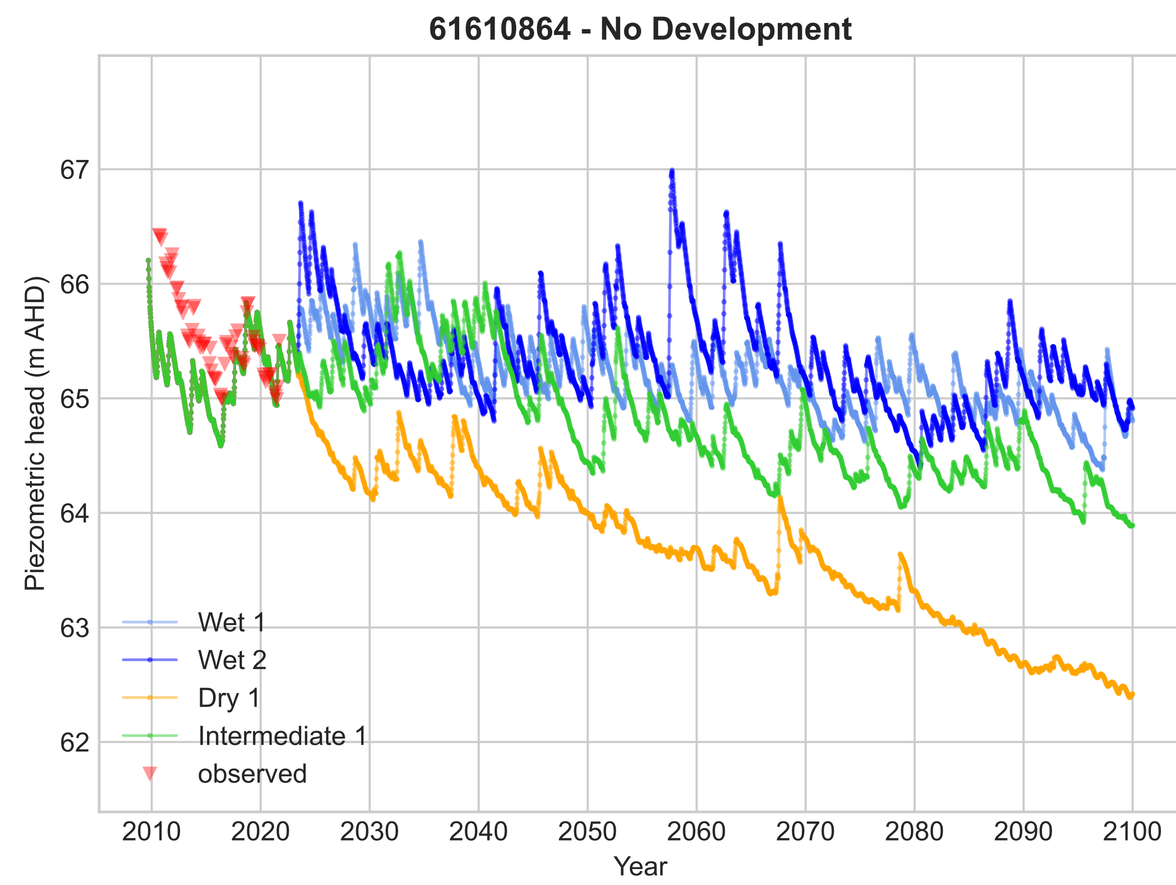

61610843 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

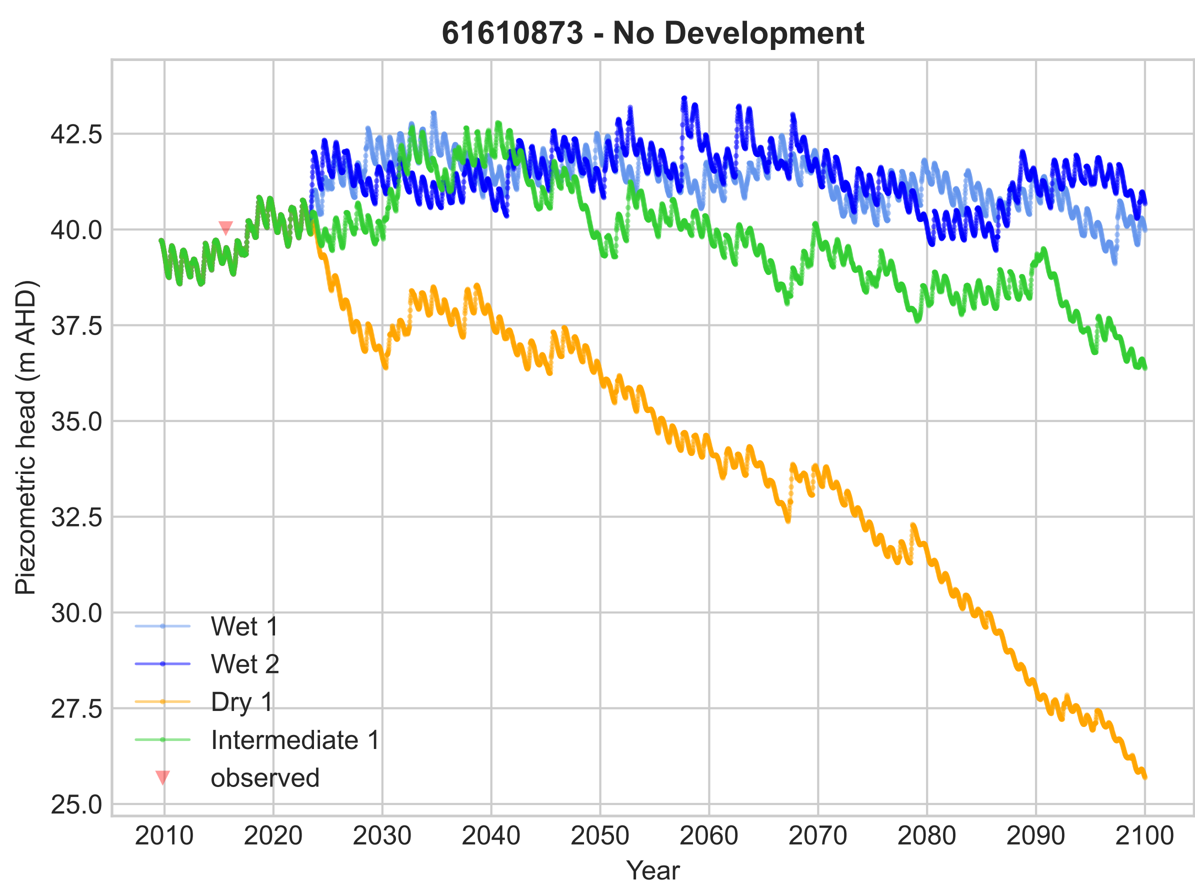

61610845 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

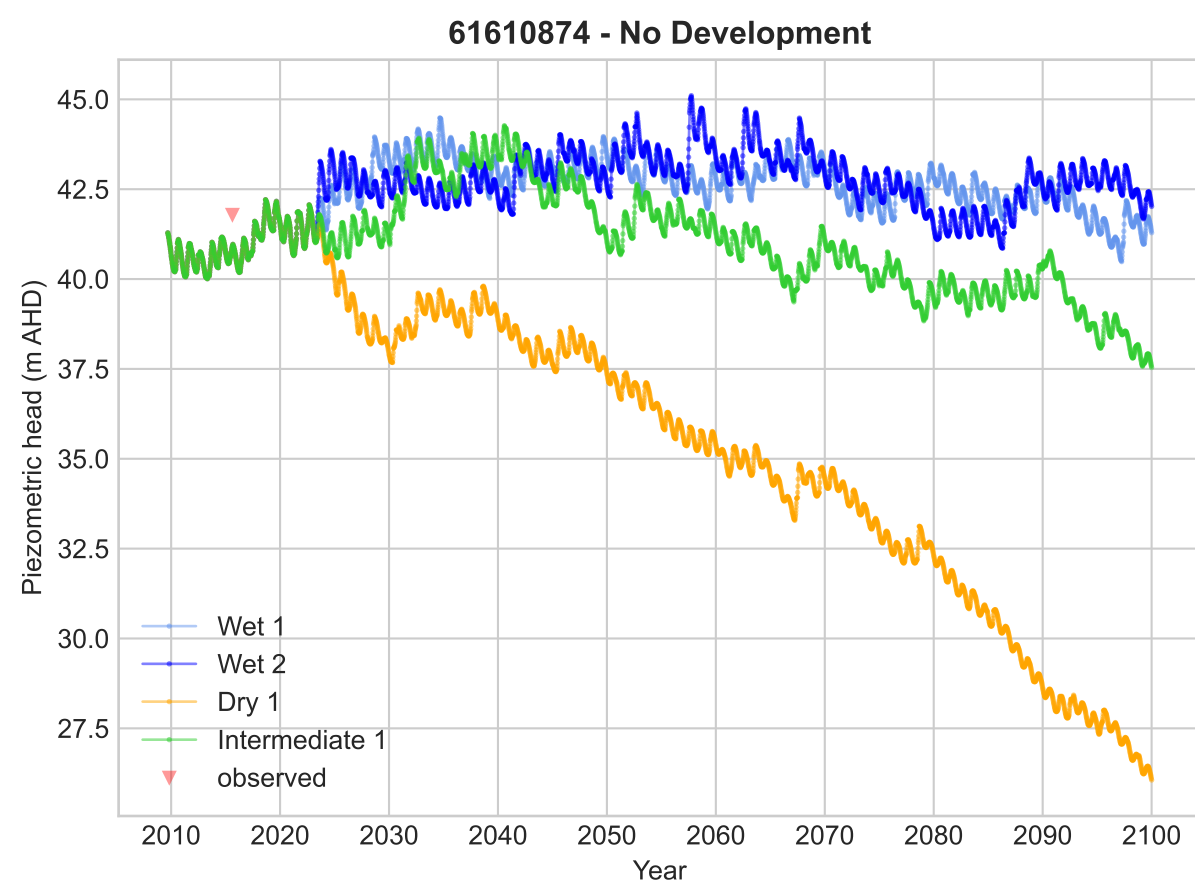

61610855 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

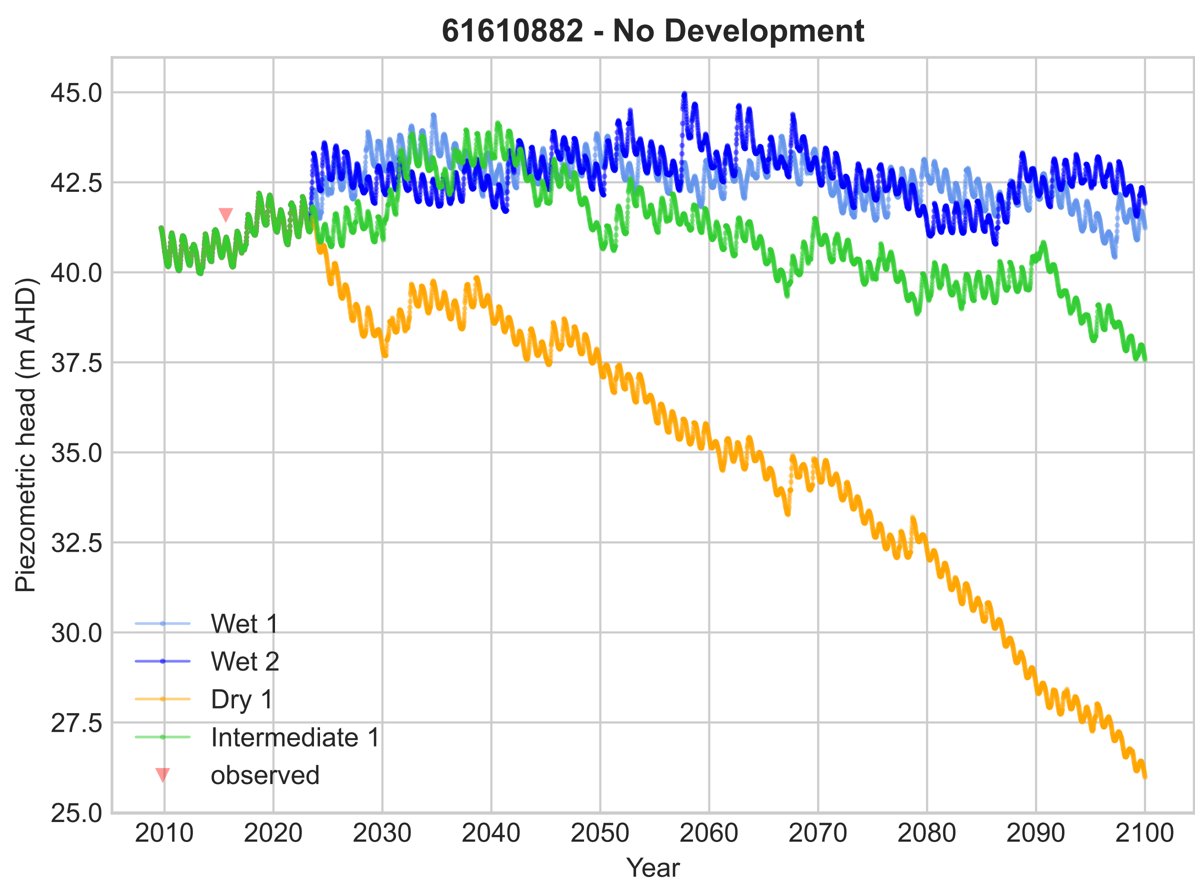

61610860 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

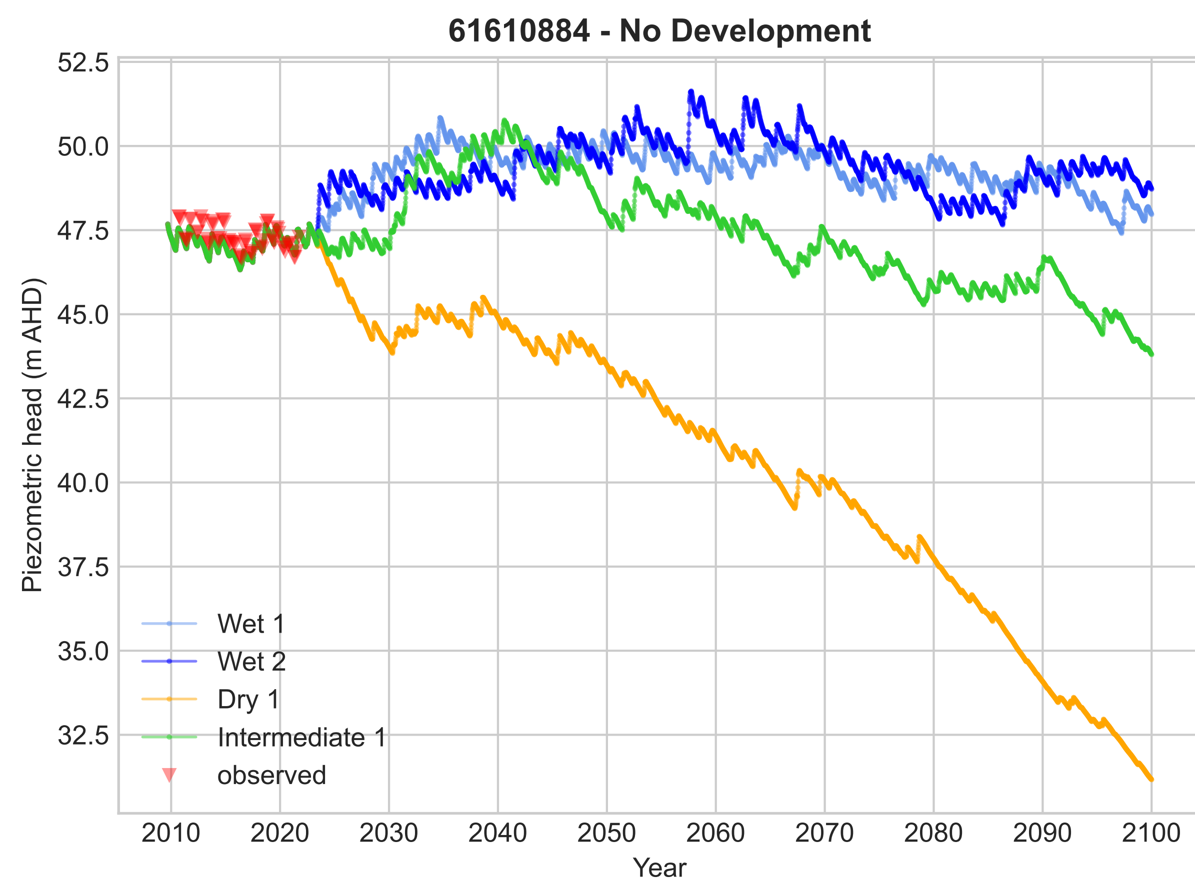

61610861 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

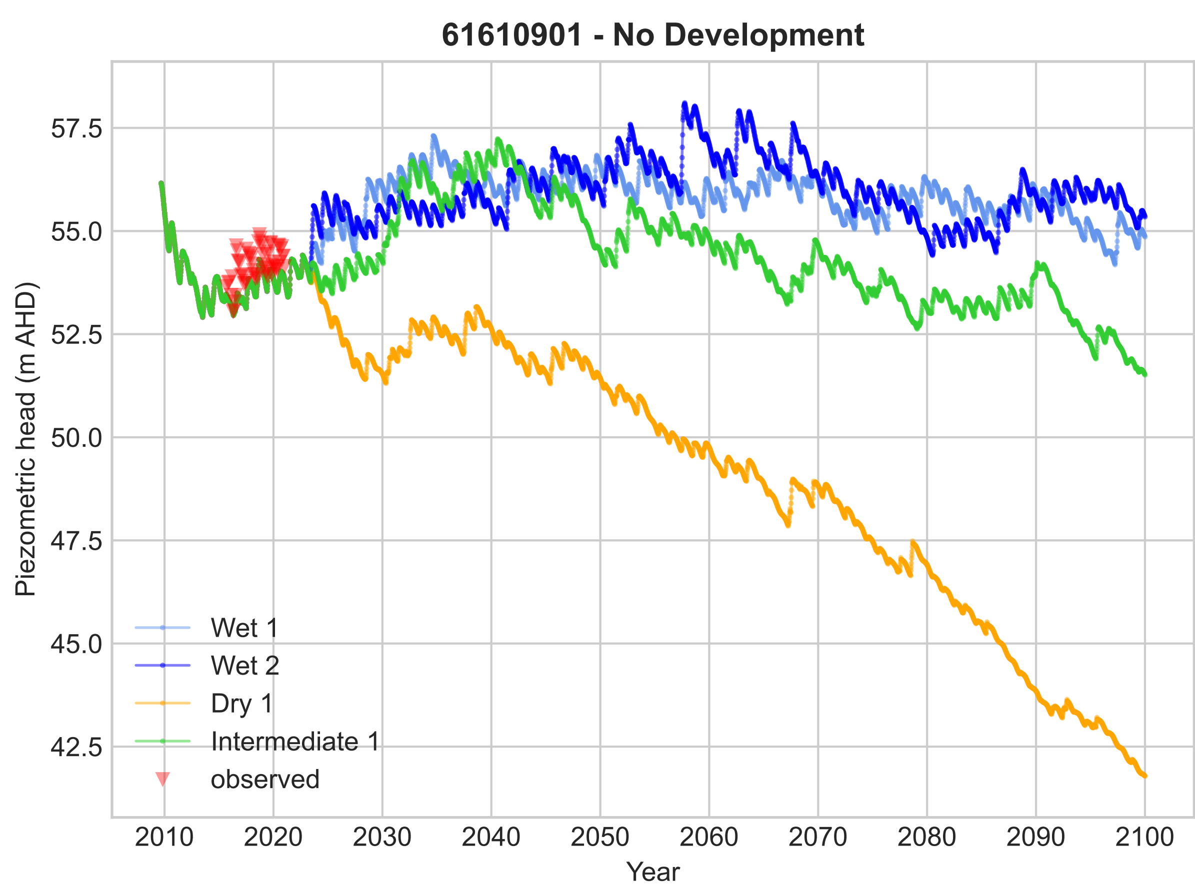

61610864 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

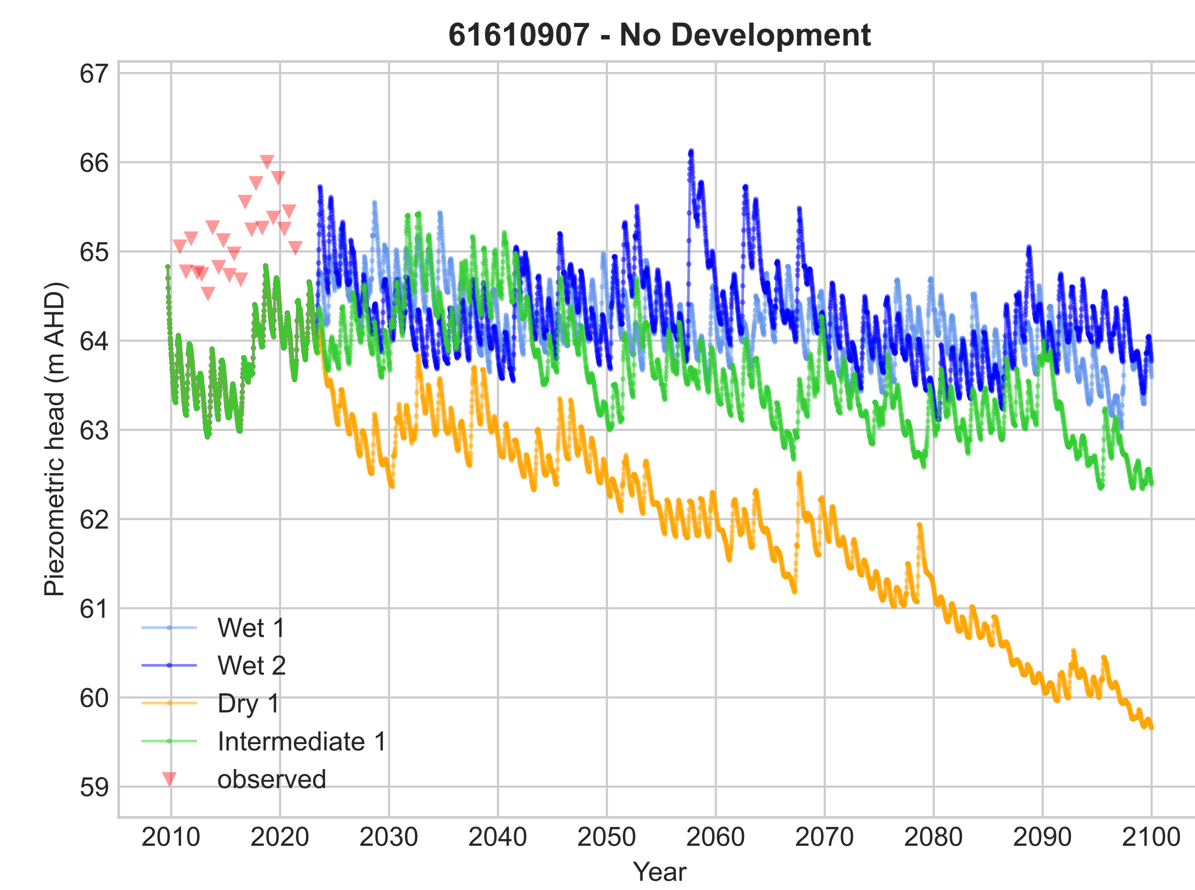

61610873 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

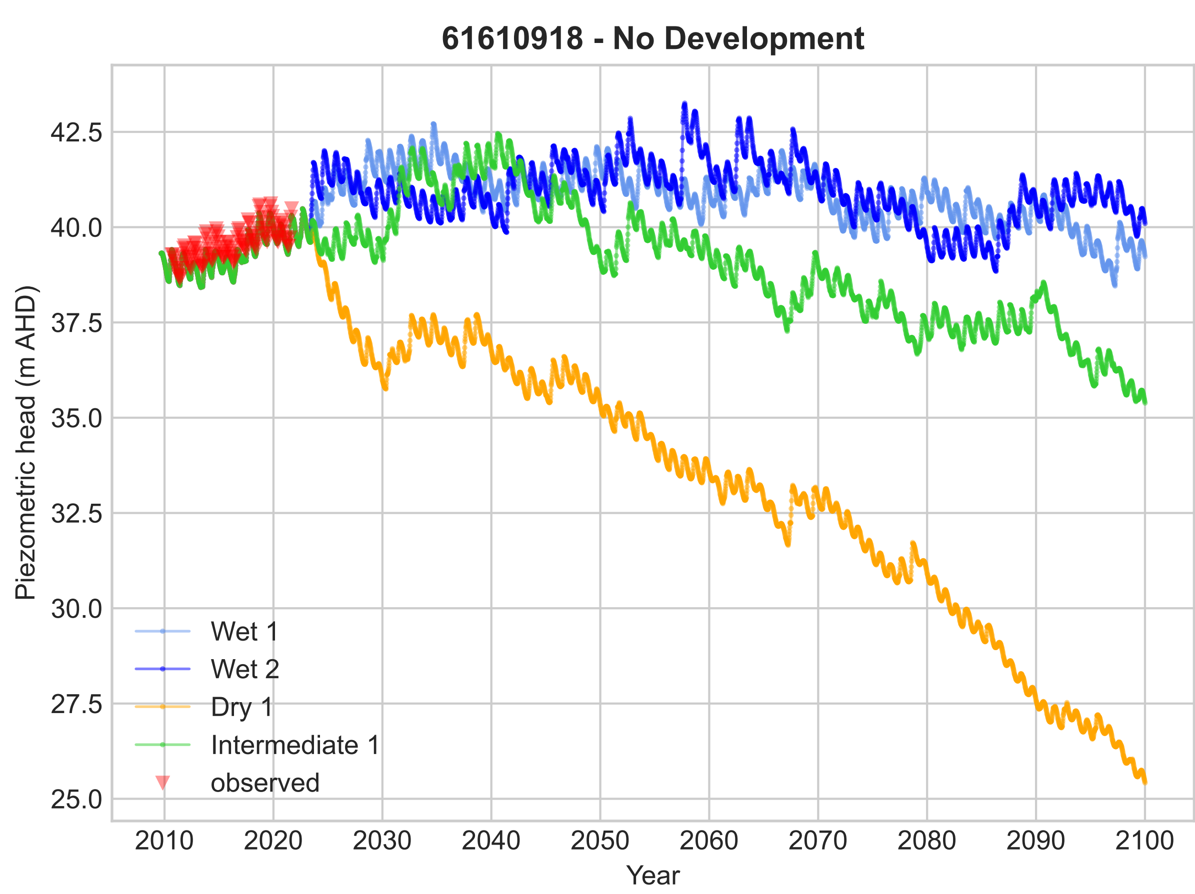

61610874 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

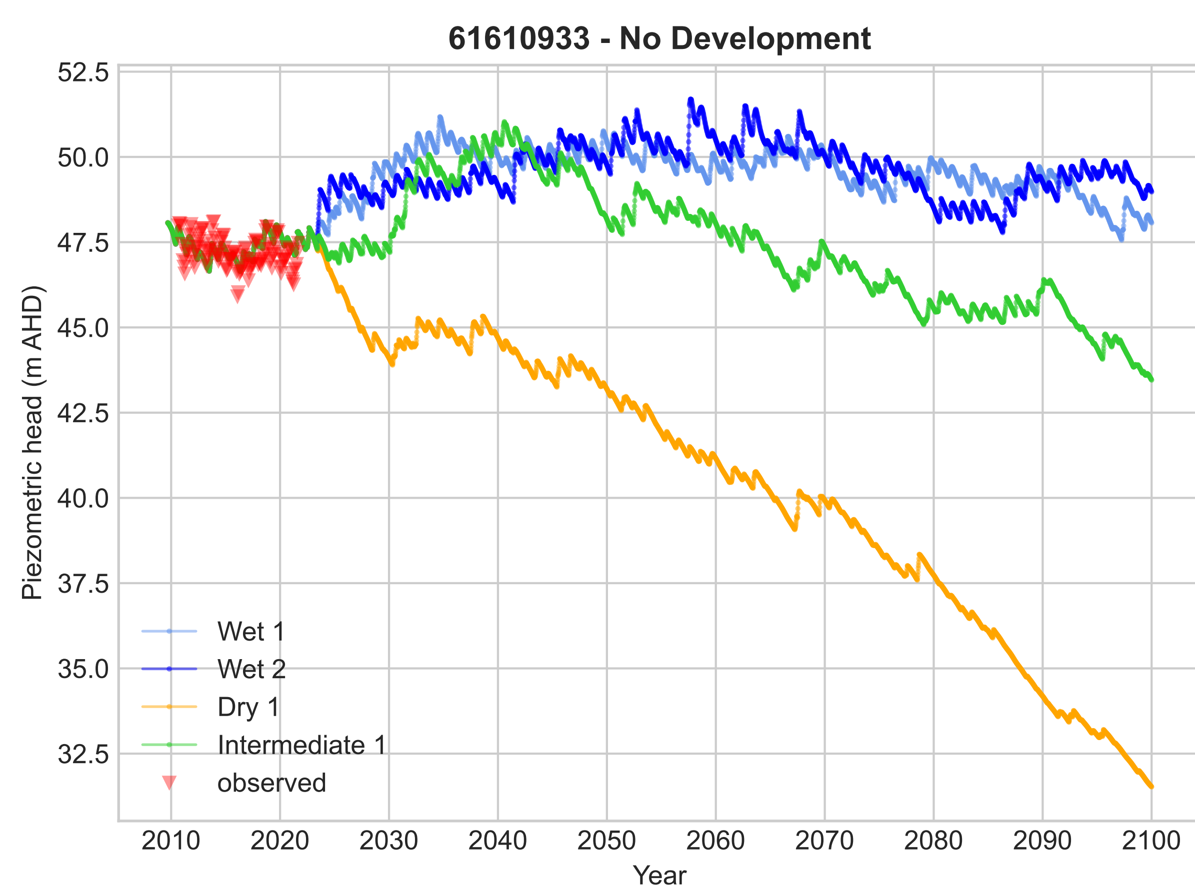

61610882 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

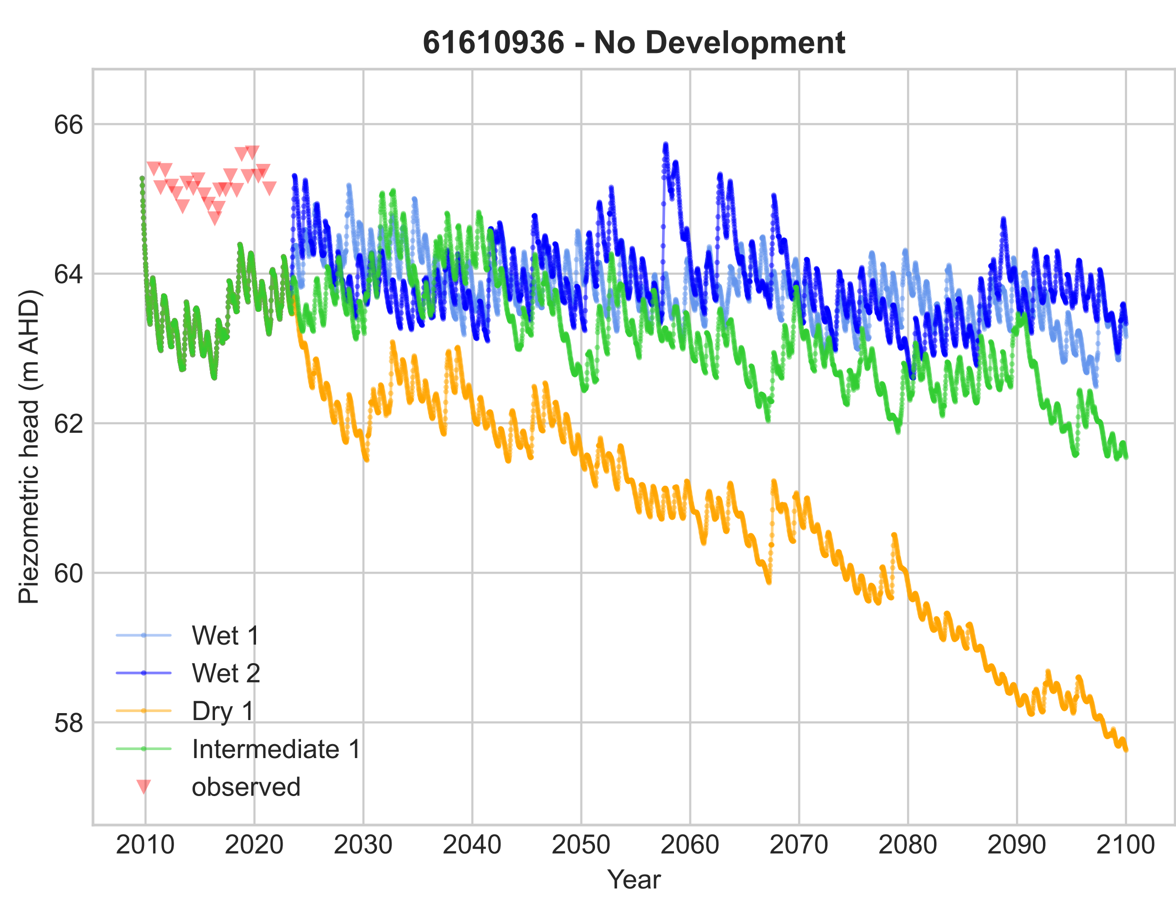

61610884 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

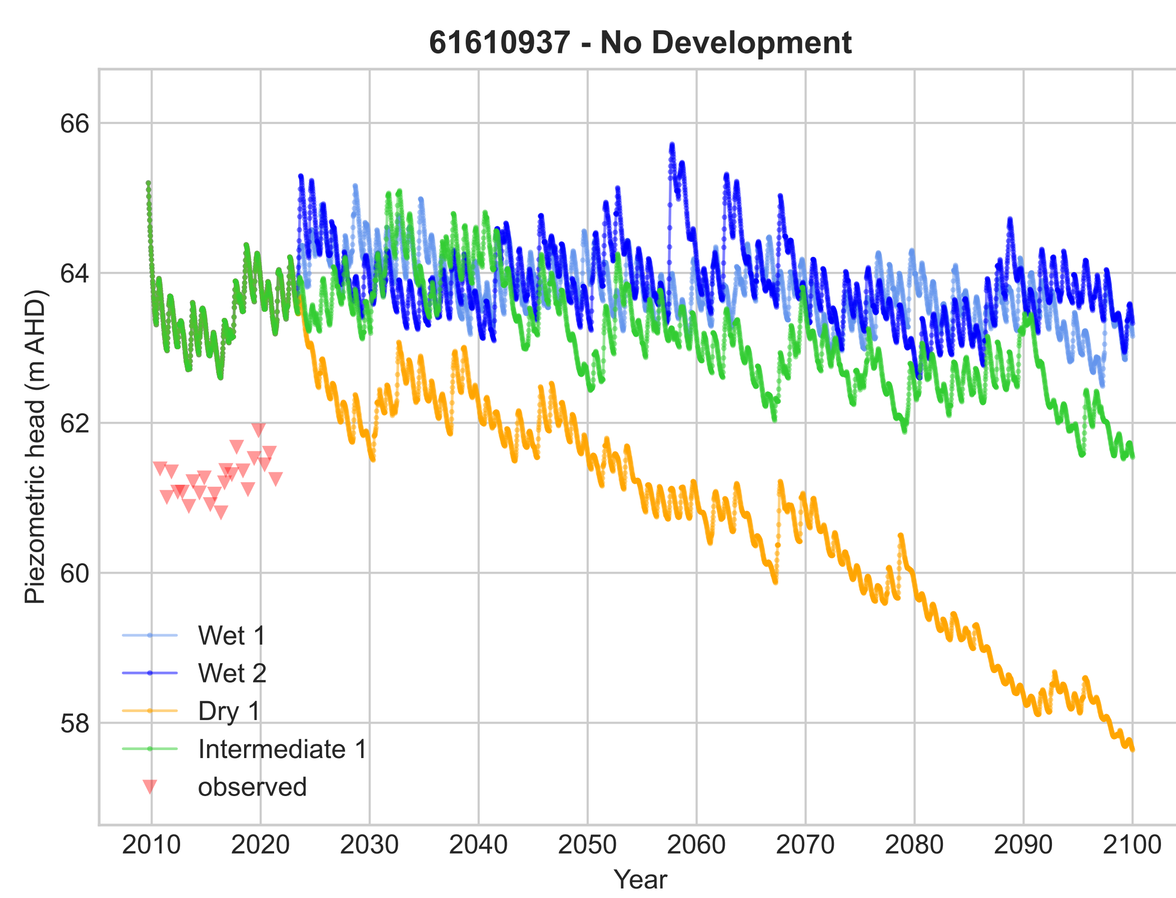

61610901 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

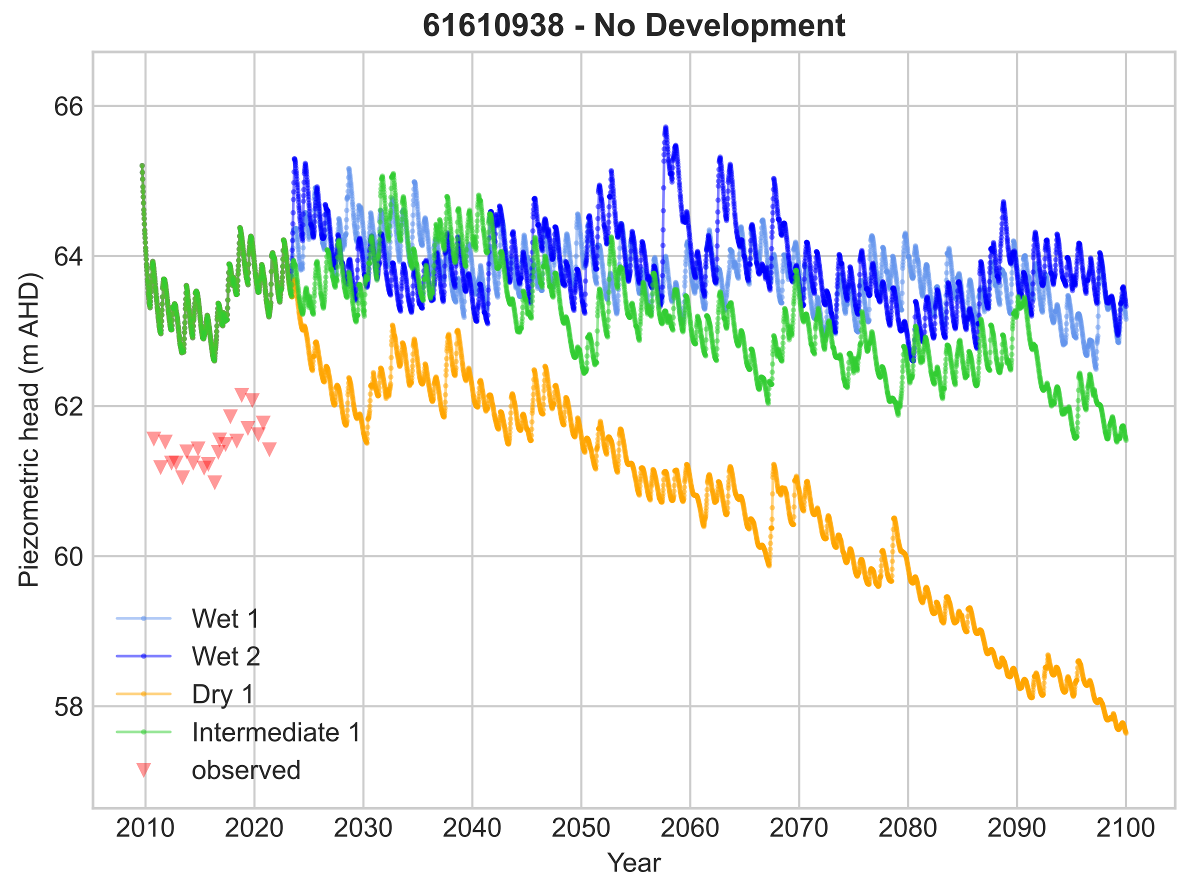

61610907 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

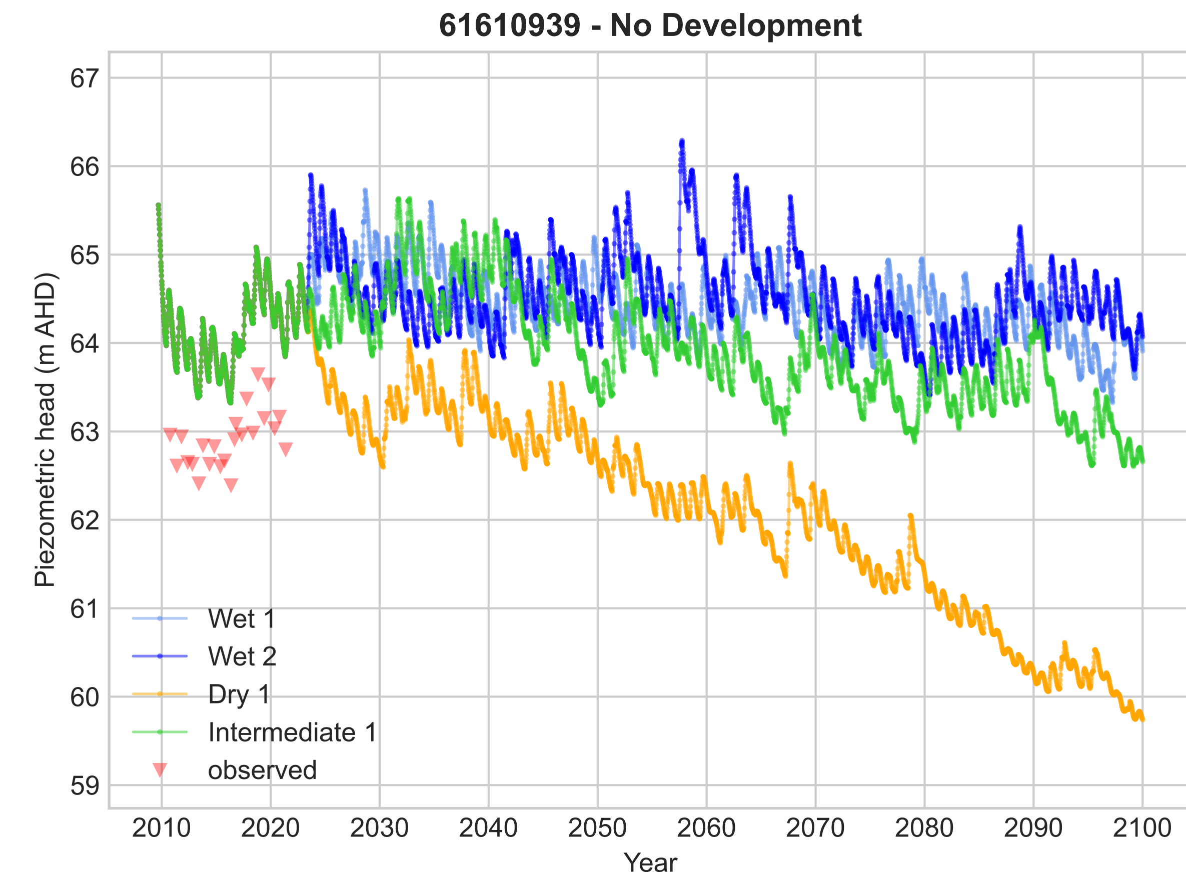

61610918 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

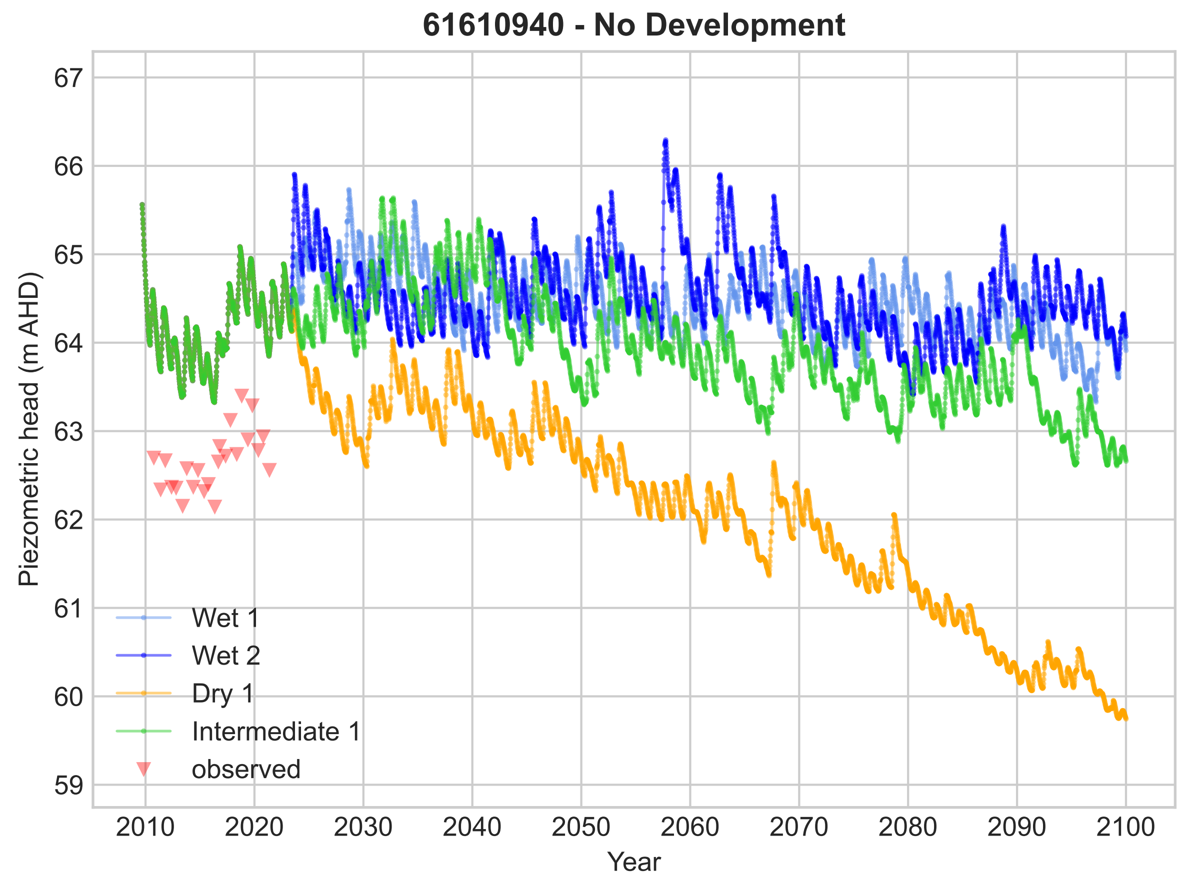

61610933 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

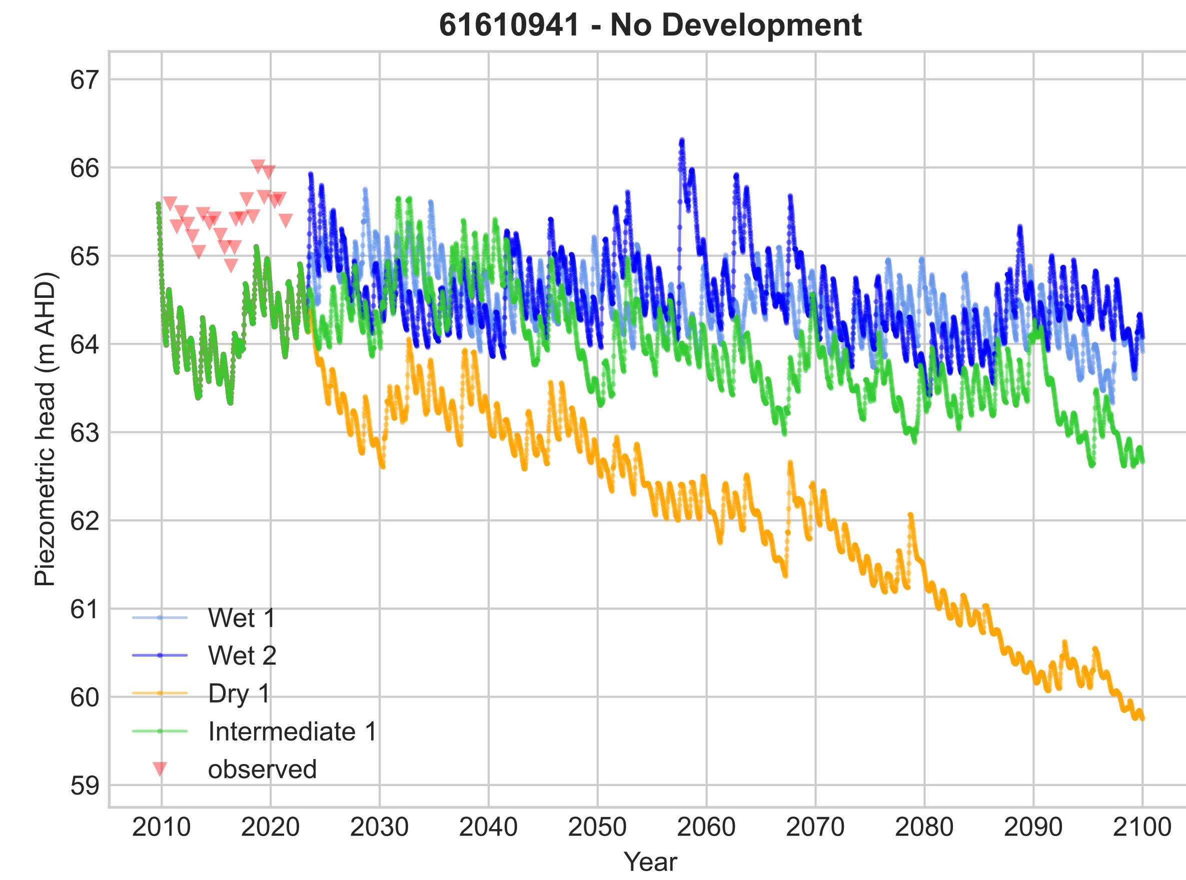

61610936 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

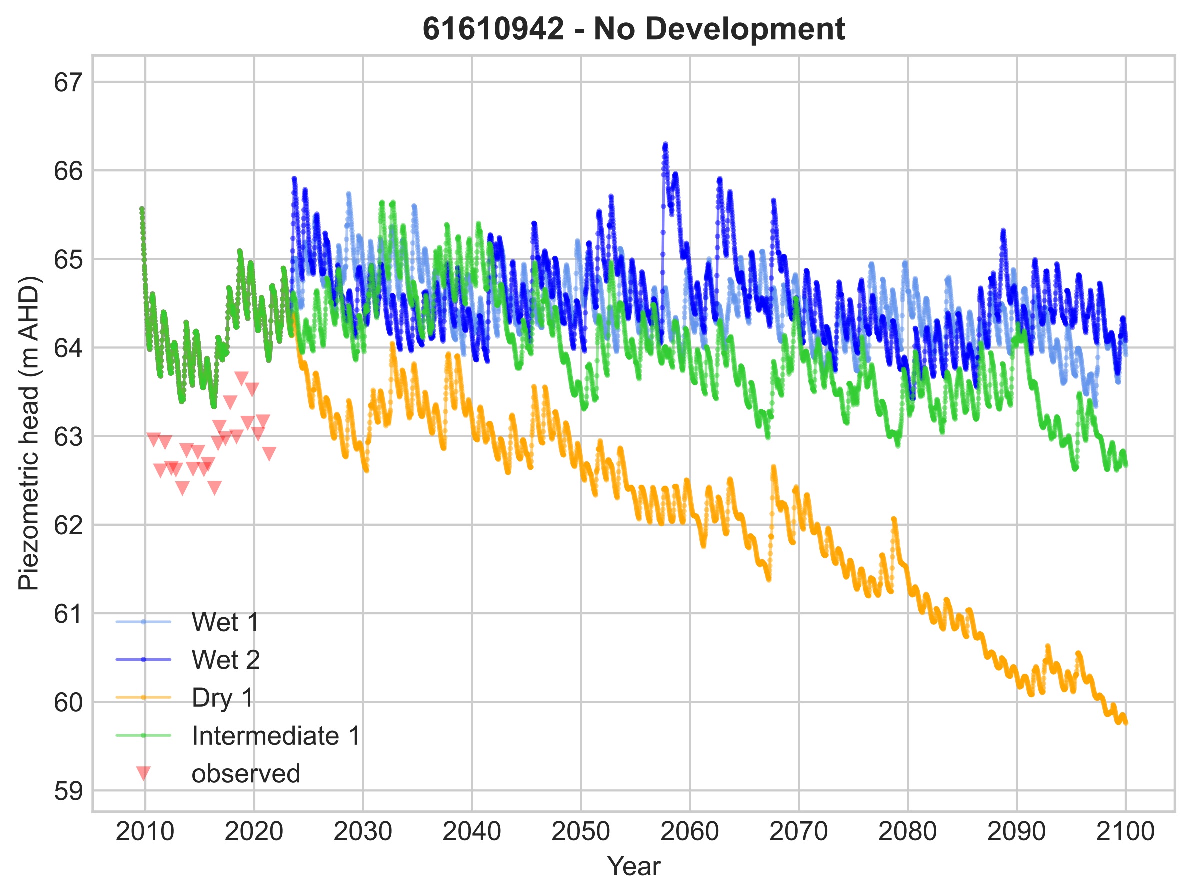

61610937 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

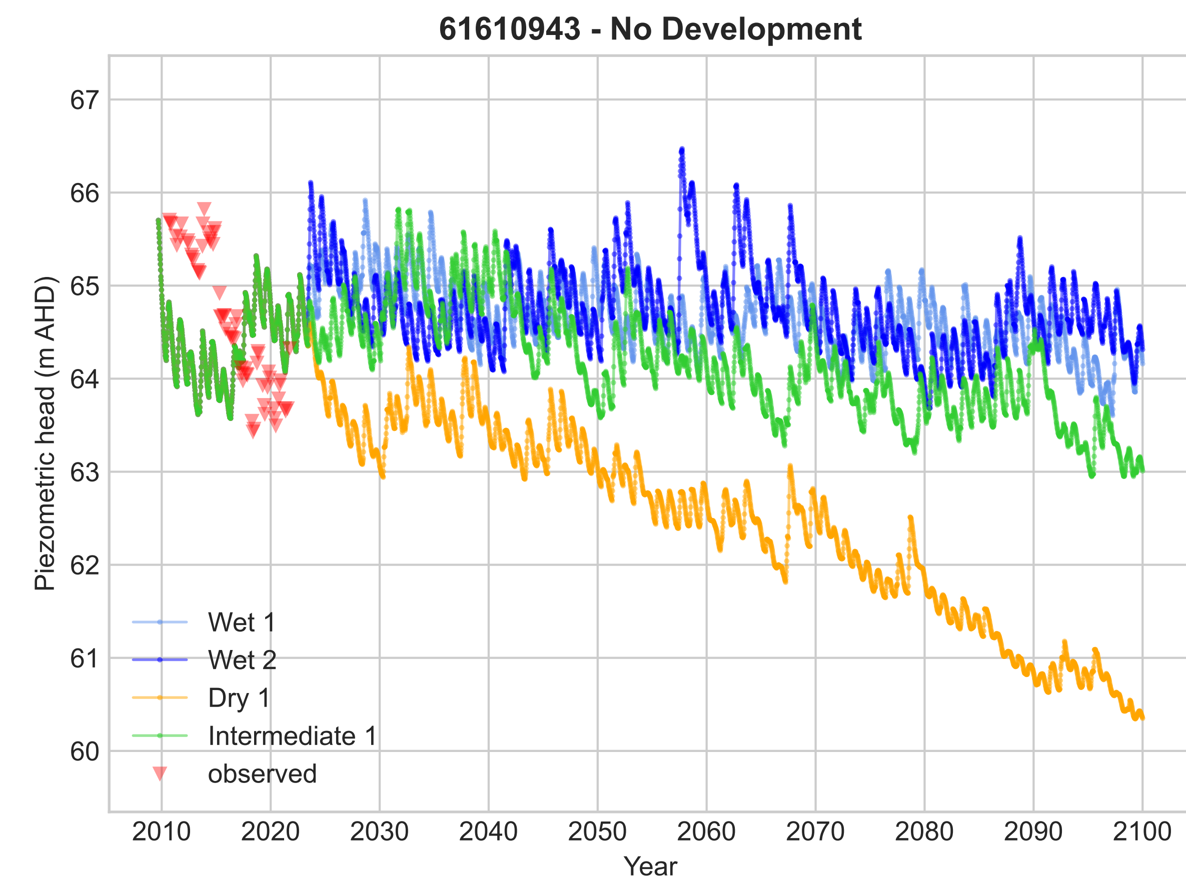

61610938 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

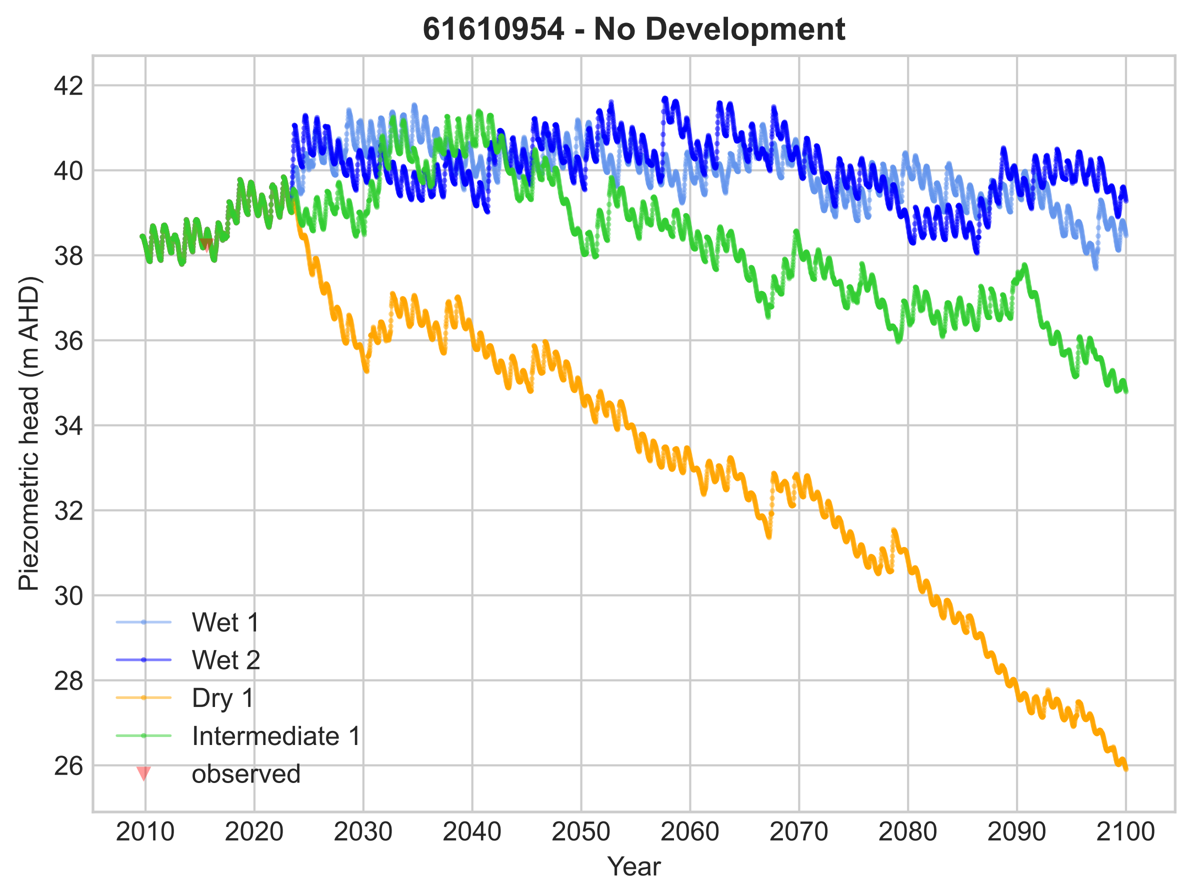

61610939 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

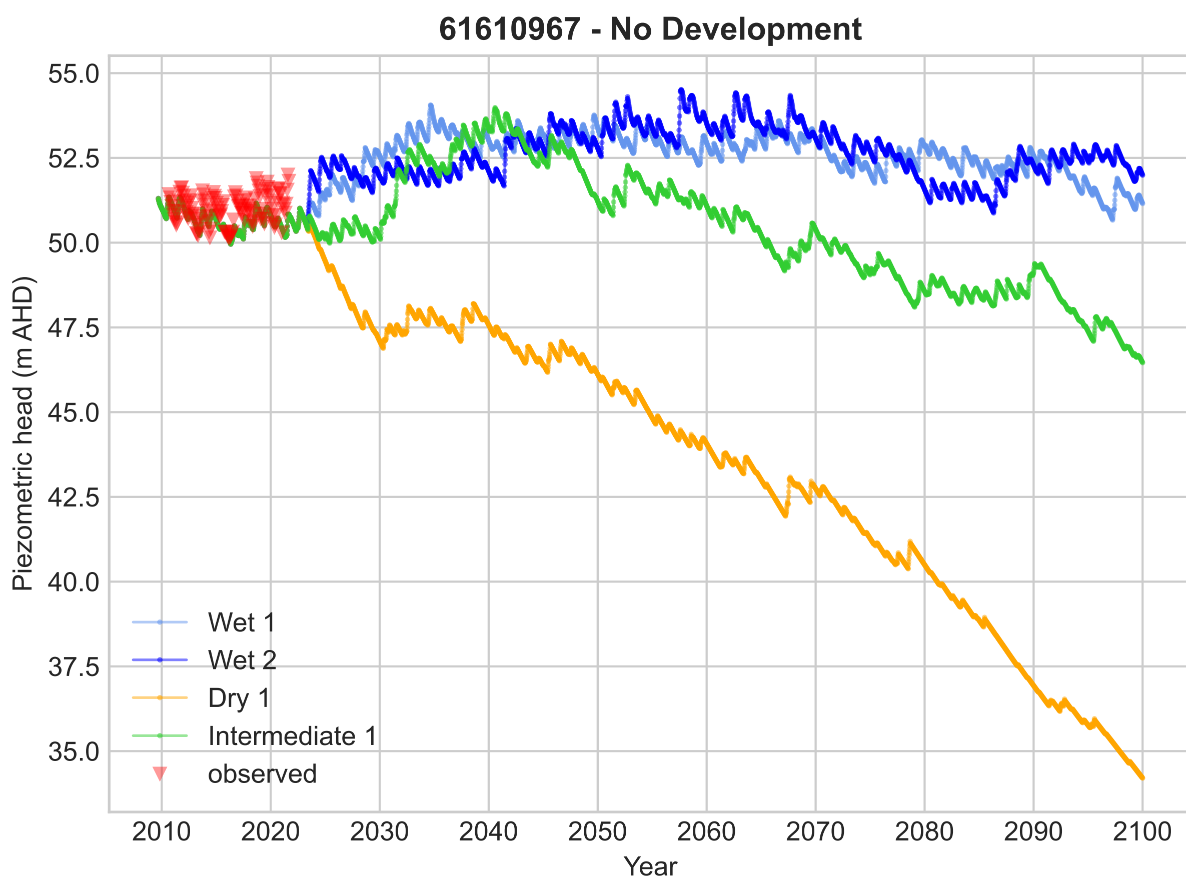

61610940 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

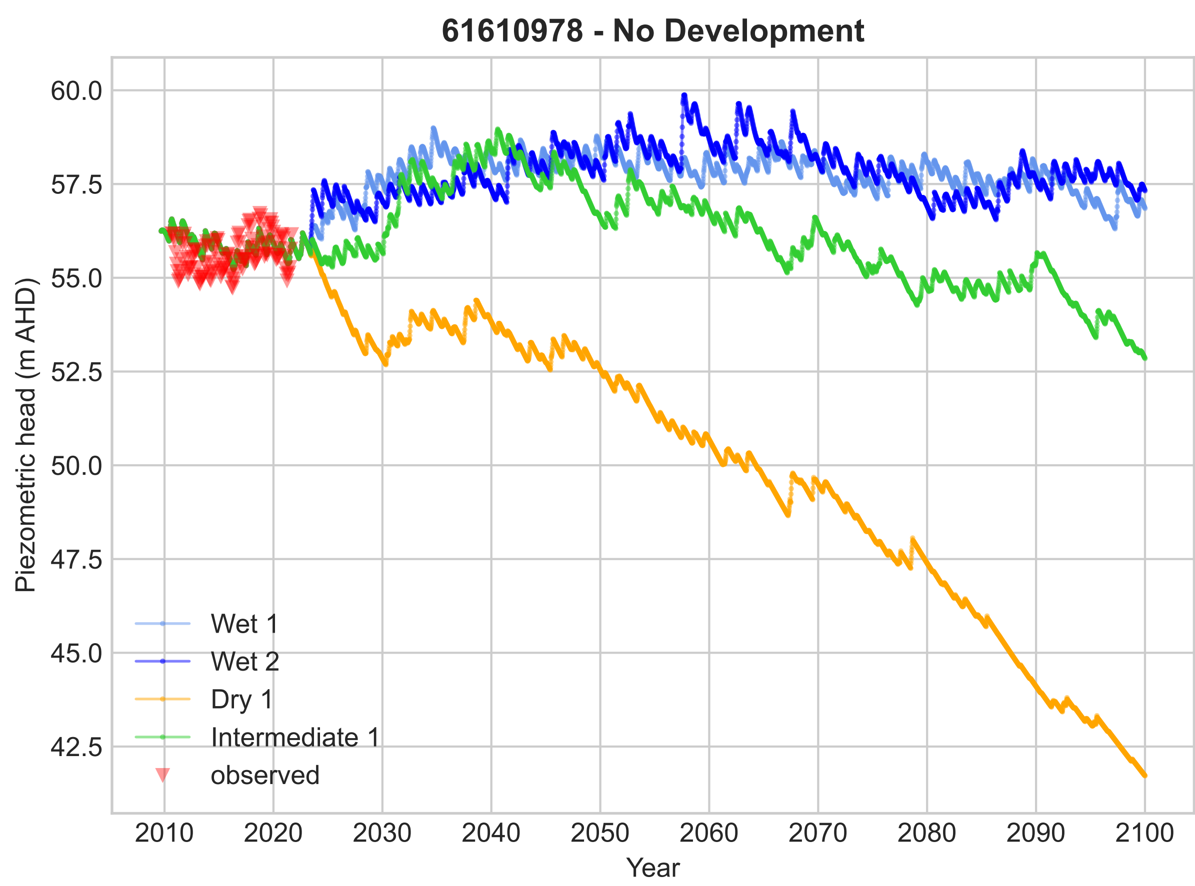

61610941 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

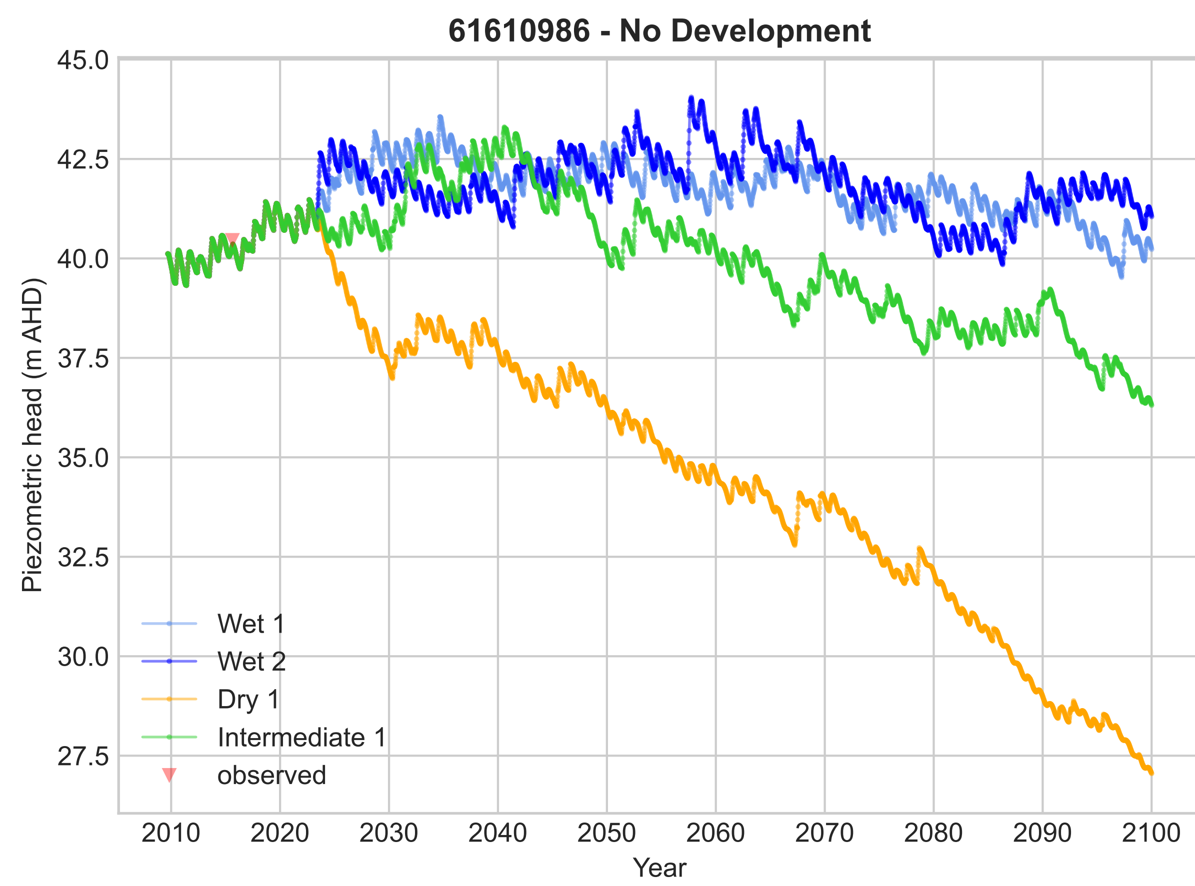

61610942 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

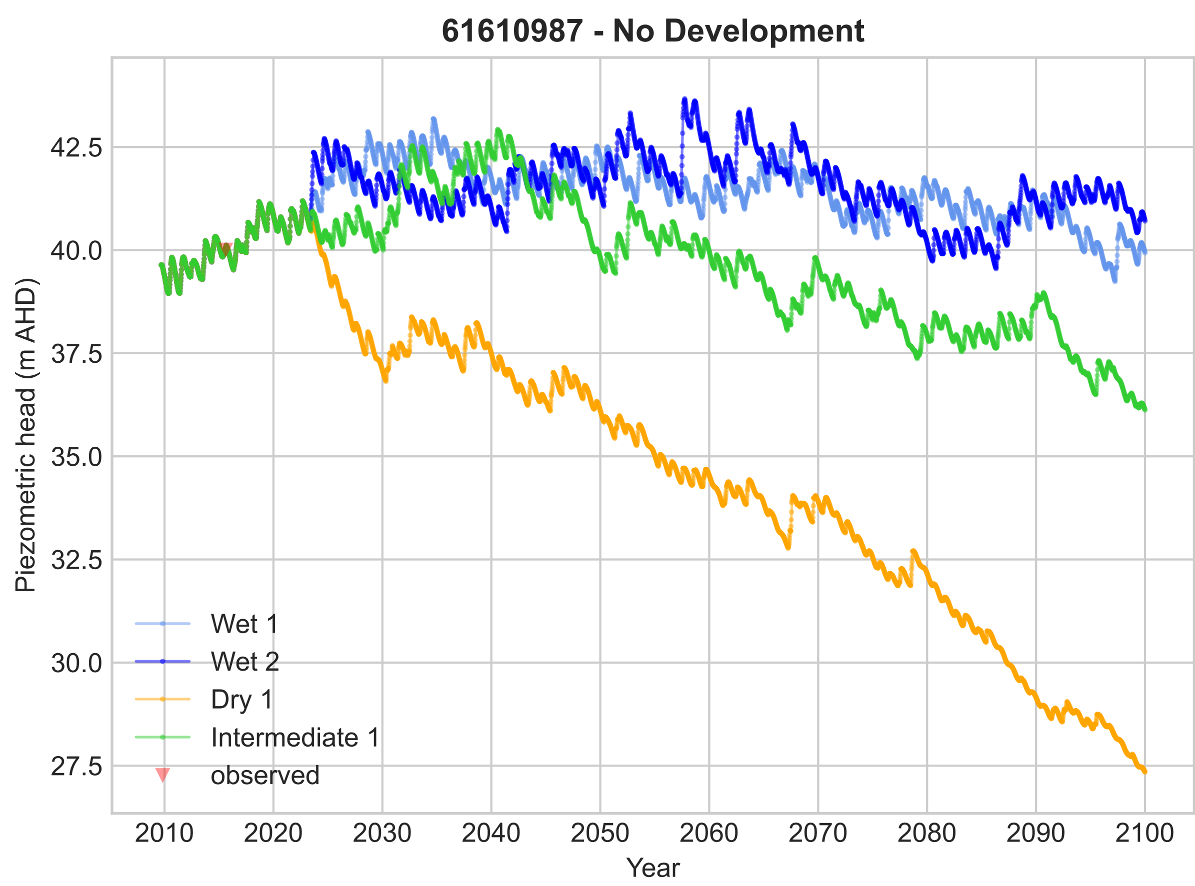

61610943 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

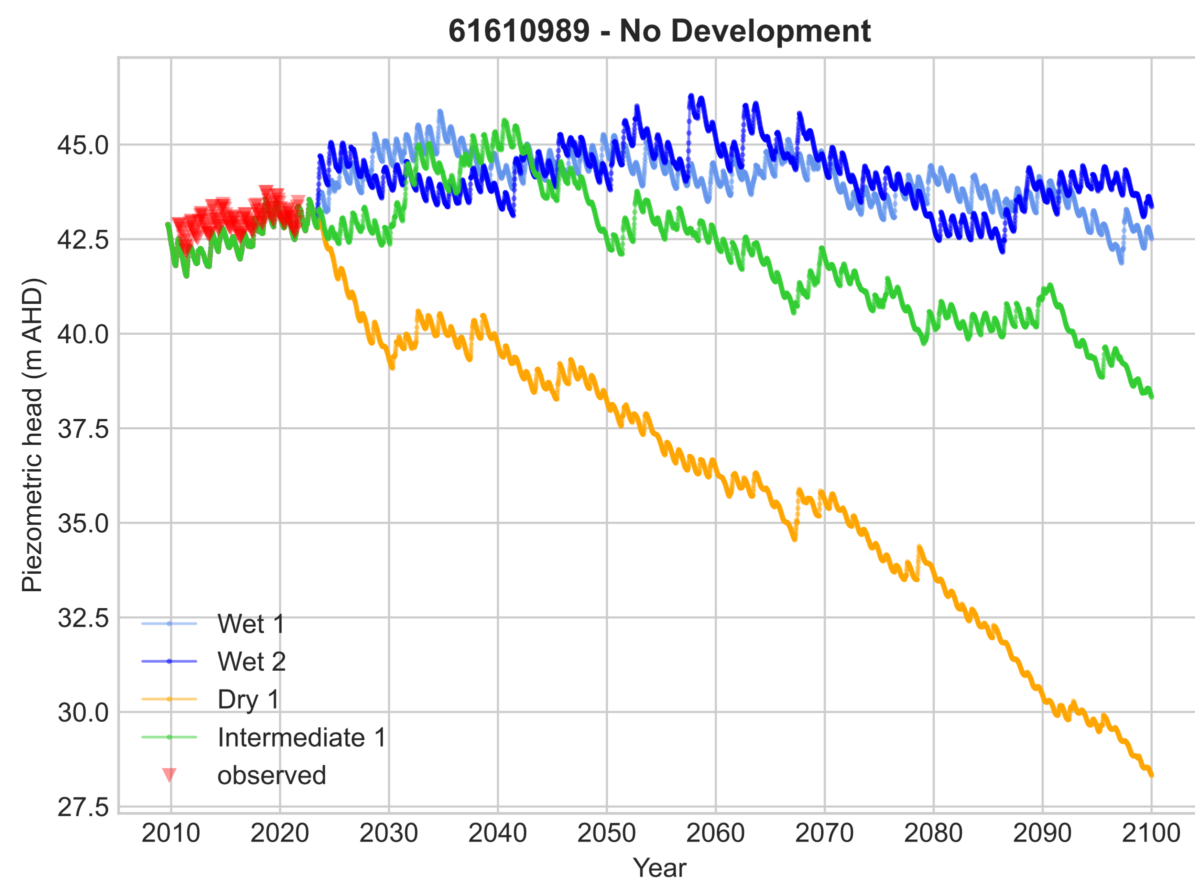

61610954 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

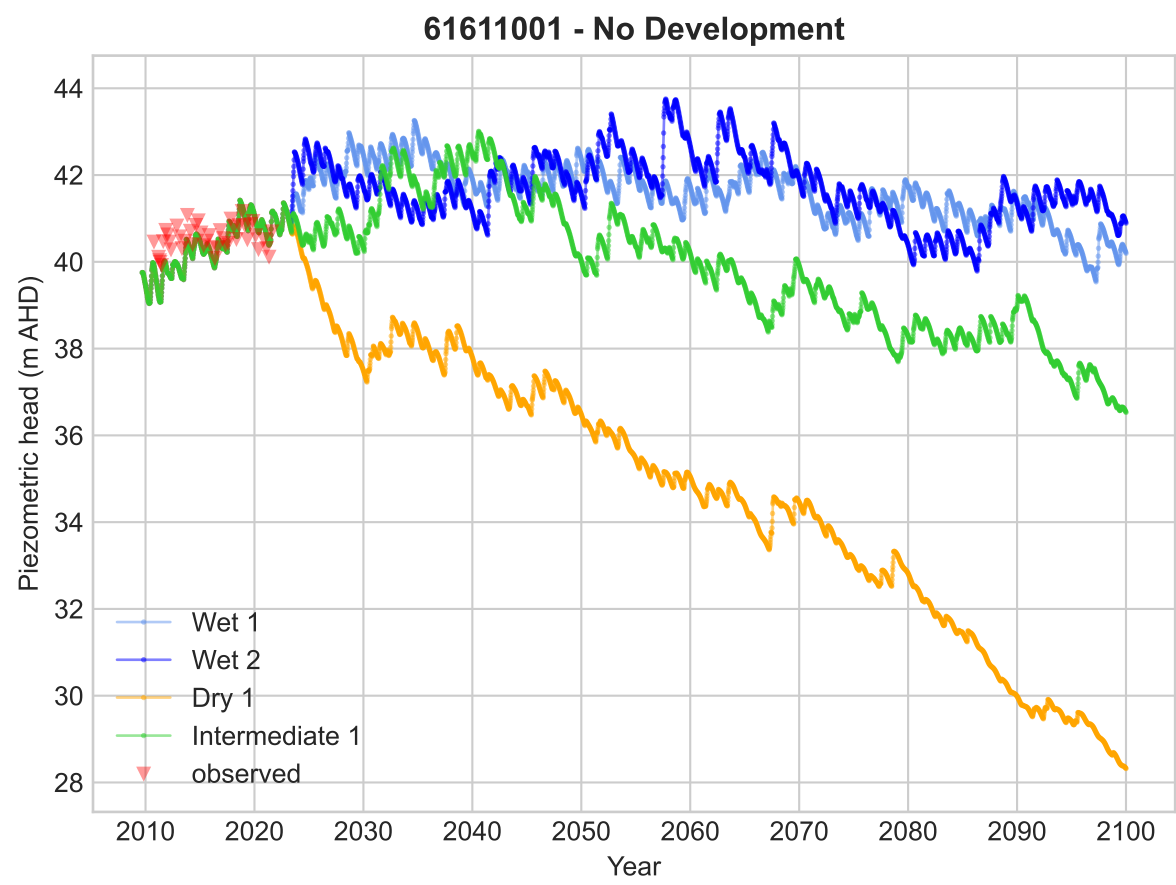

61610967 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

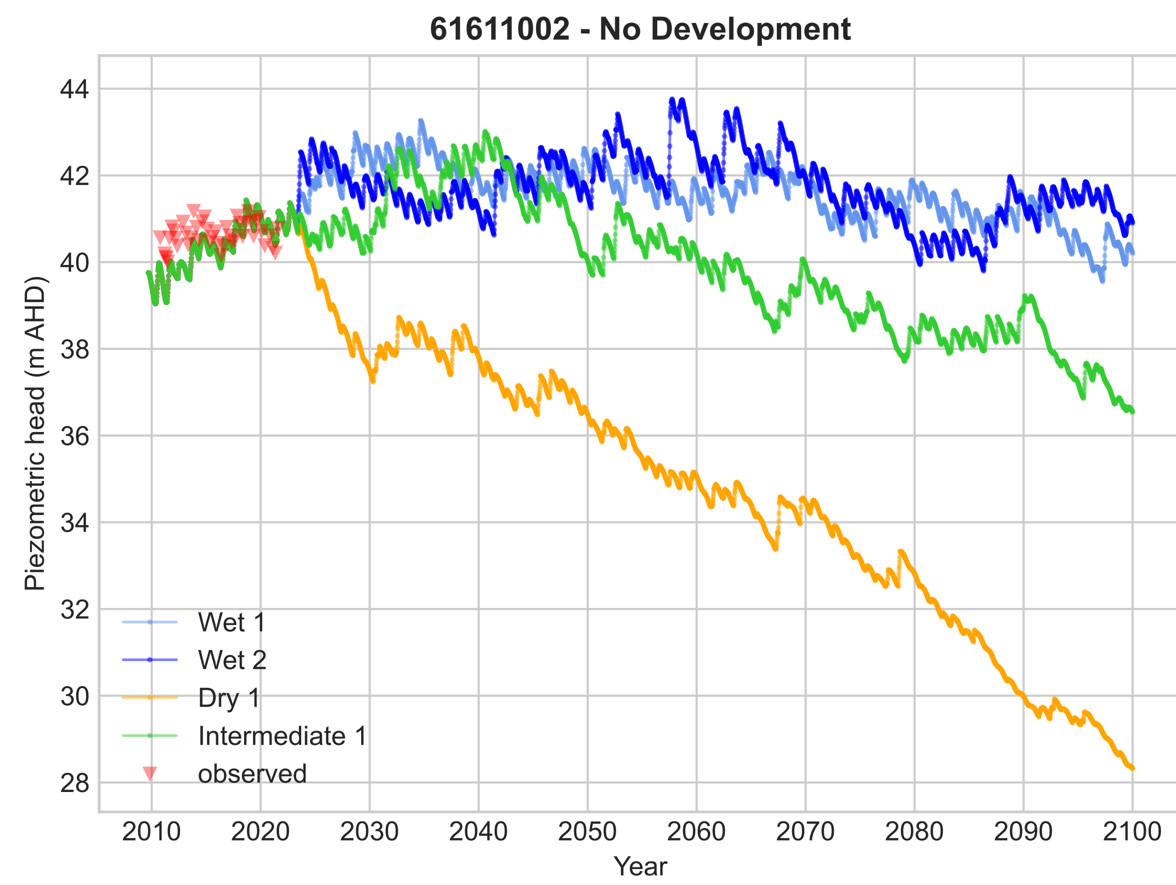

61610978 - No Development
Piezometric head (m AHD)
Year
60.0 57.5 55.0 52.5 50.0 47.5 45.0 42.5
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

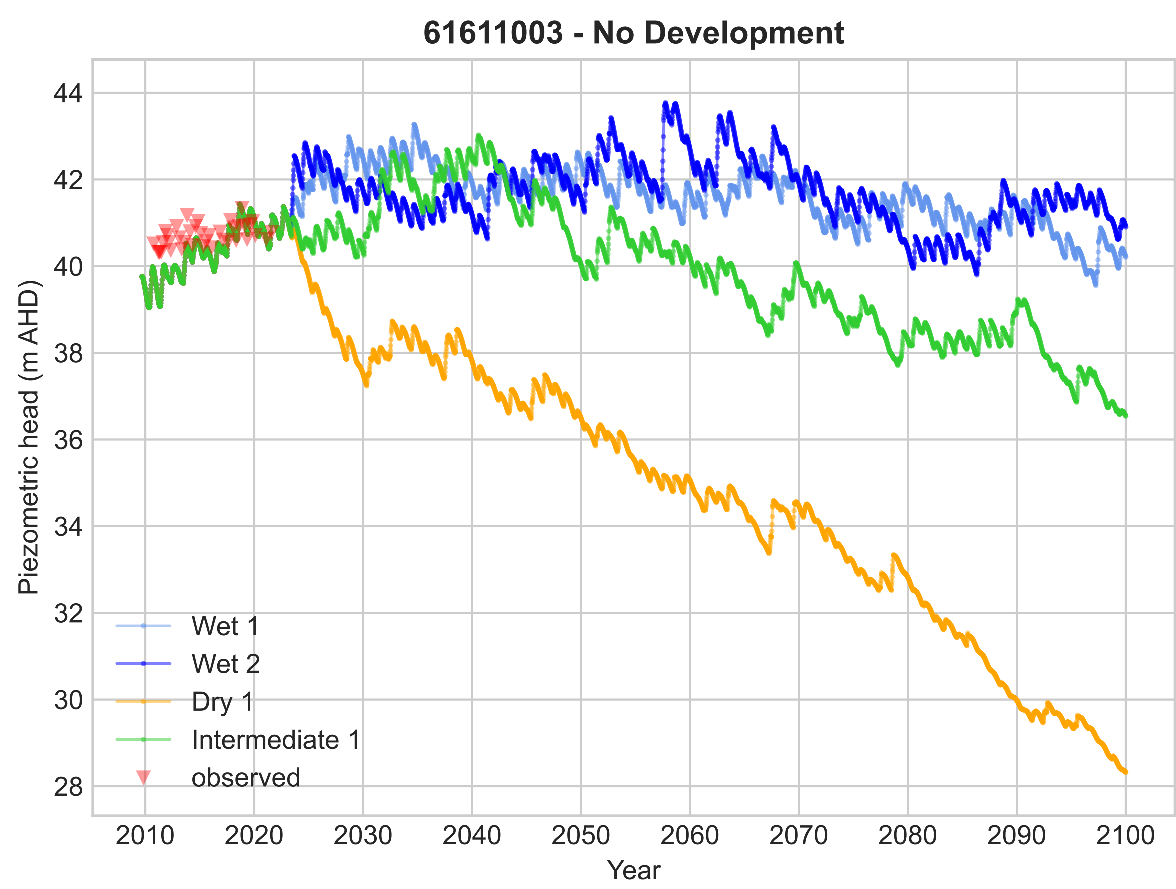

61610986 - No Development
Piezometric head (m AHD)
Year
45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

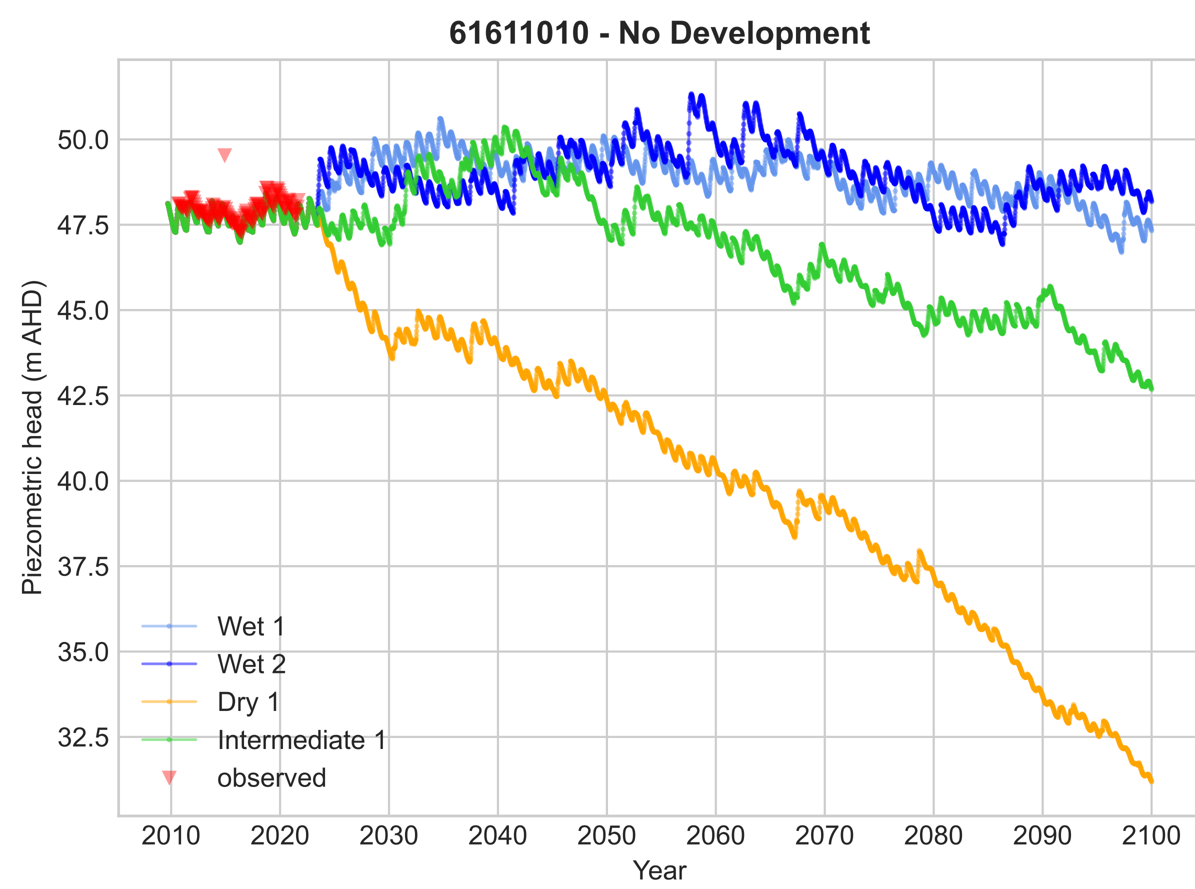

61610987 - No Development
Piezometric head (m AHD)
Year
42.5 40.0 37.5 35.0 32.5 30.0 27.5
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

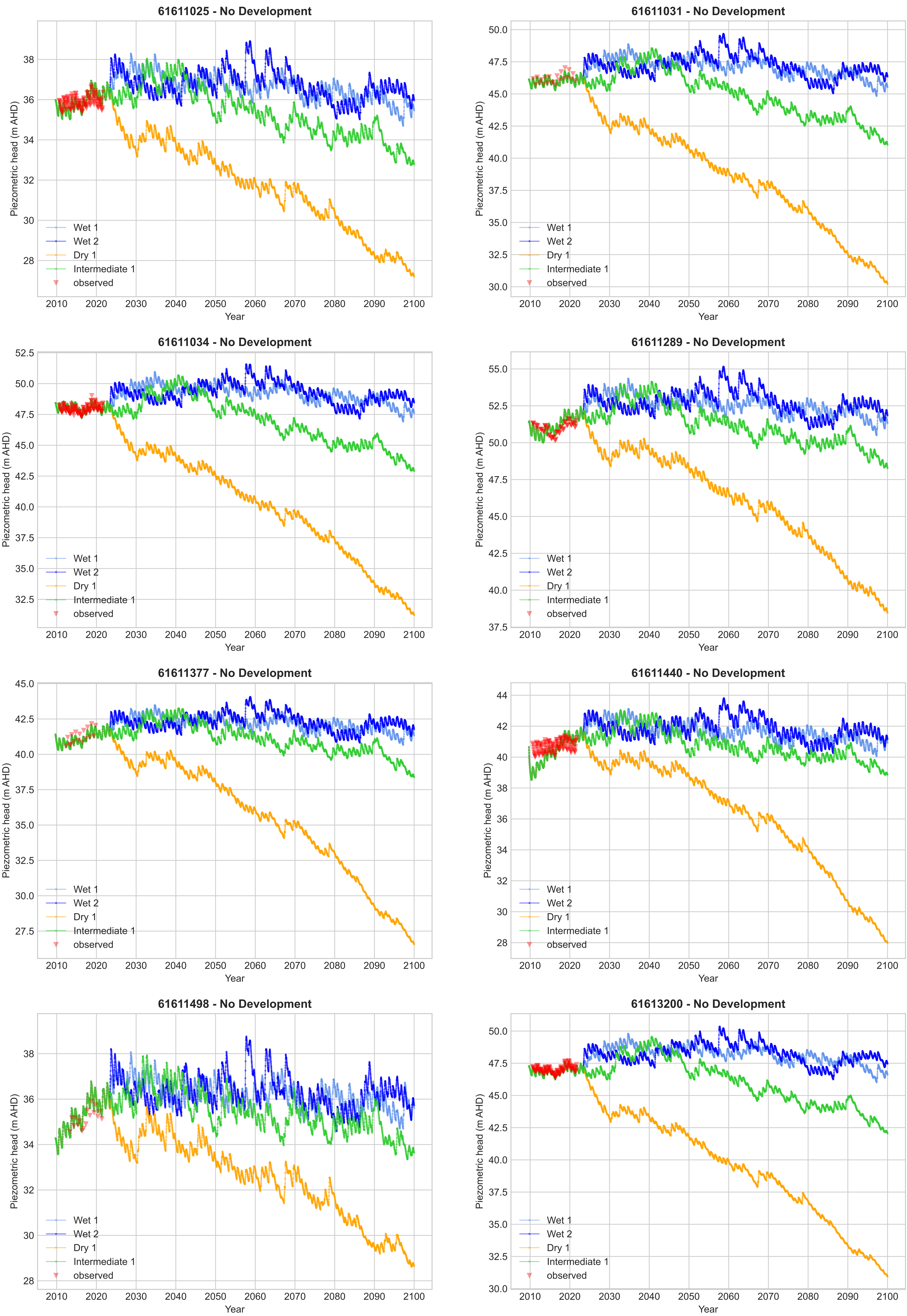

61610989 - No Development
Piezometric head (m AHD)
Year
45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

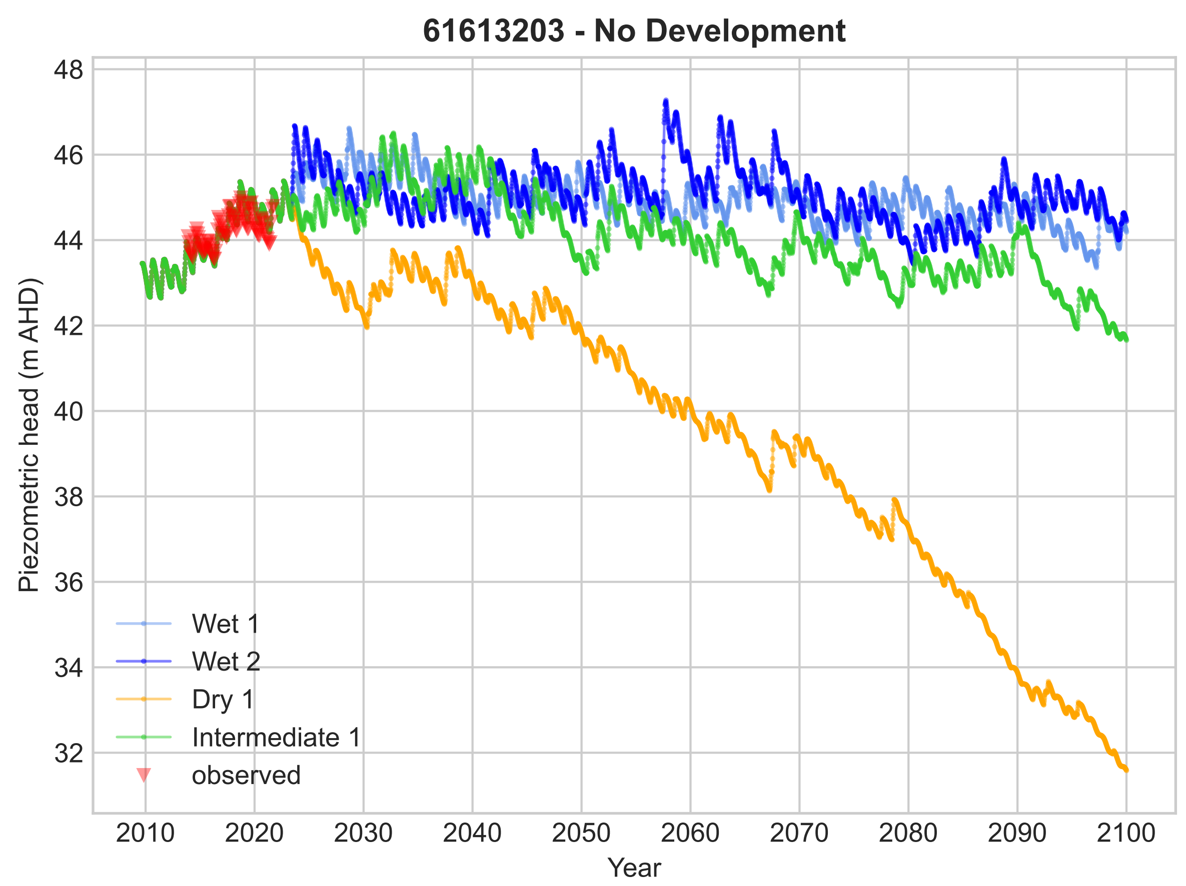

61611001 - No Development
Piezometric head (m AHD)
Year
44 42 40 38 36 34 32 30 28
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

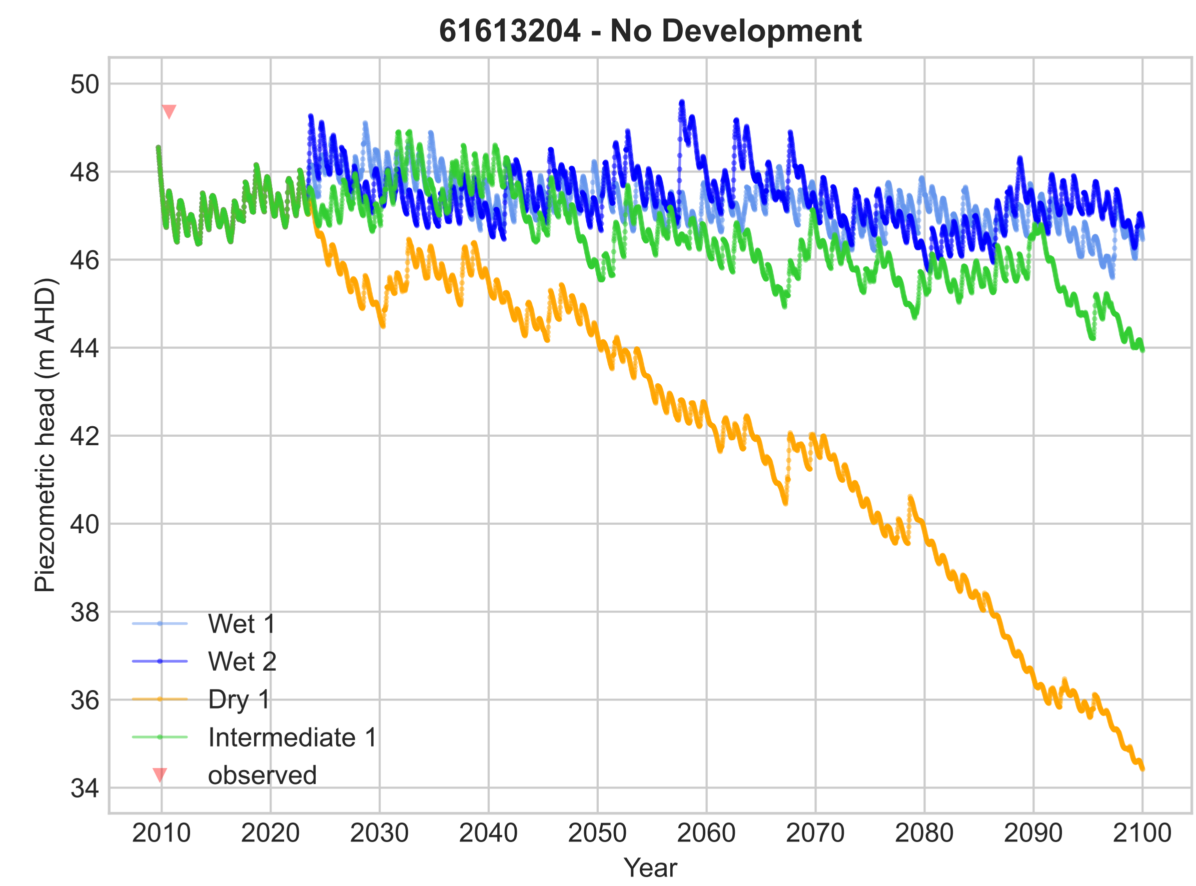

61611002 - No Development
Piezometric head (m AHD)
Year
44 42 40 38 36 34 32 30 28
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

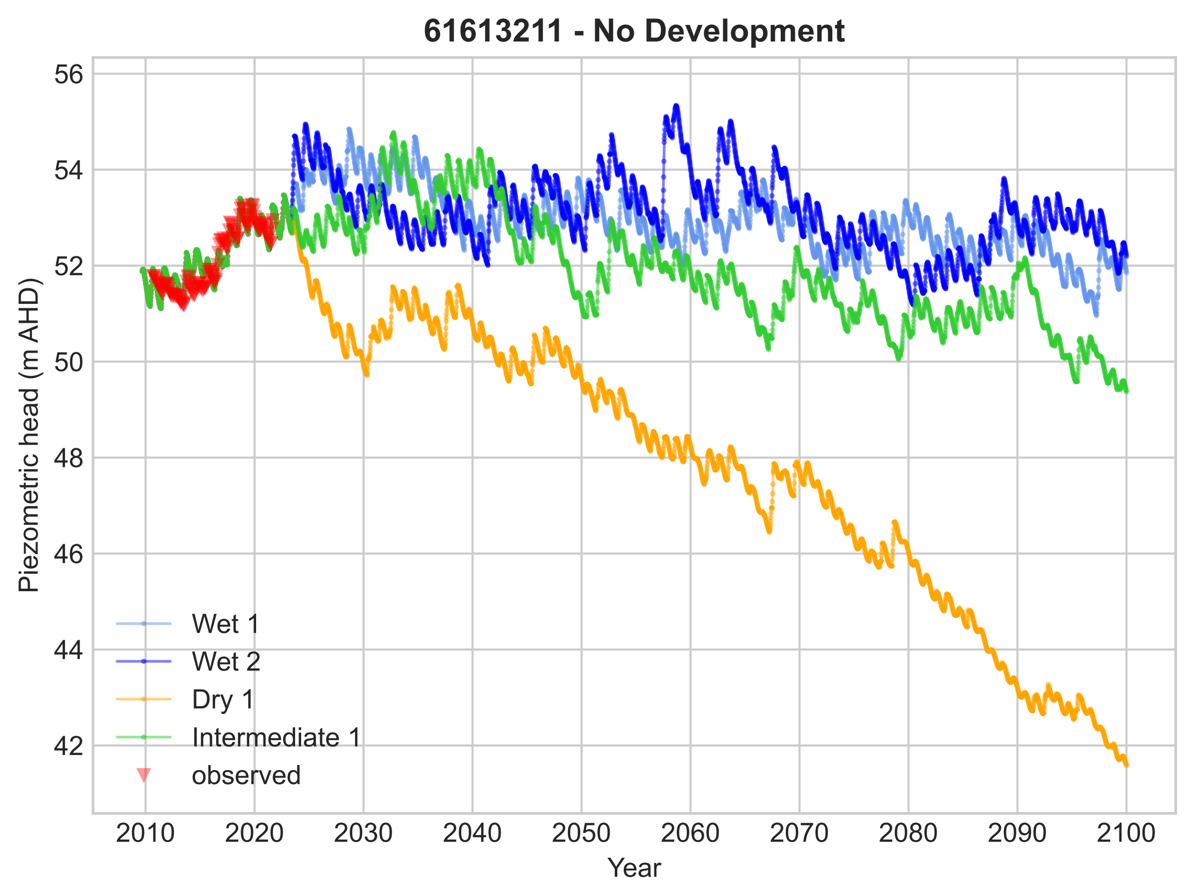

61611003 - No Development
Piezometric head (m AHD)
Year
44 42 40 38 36 34 32 30 28
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

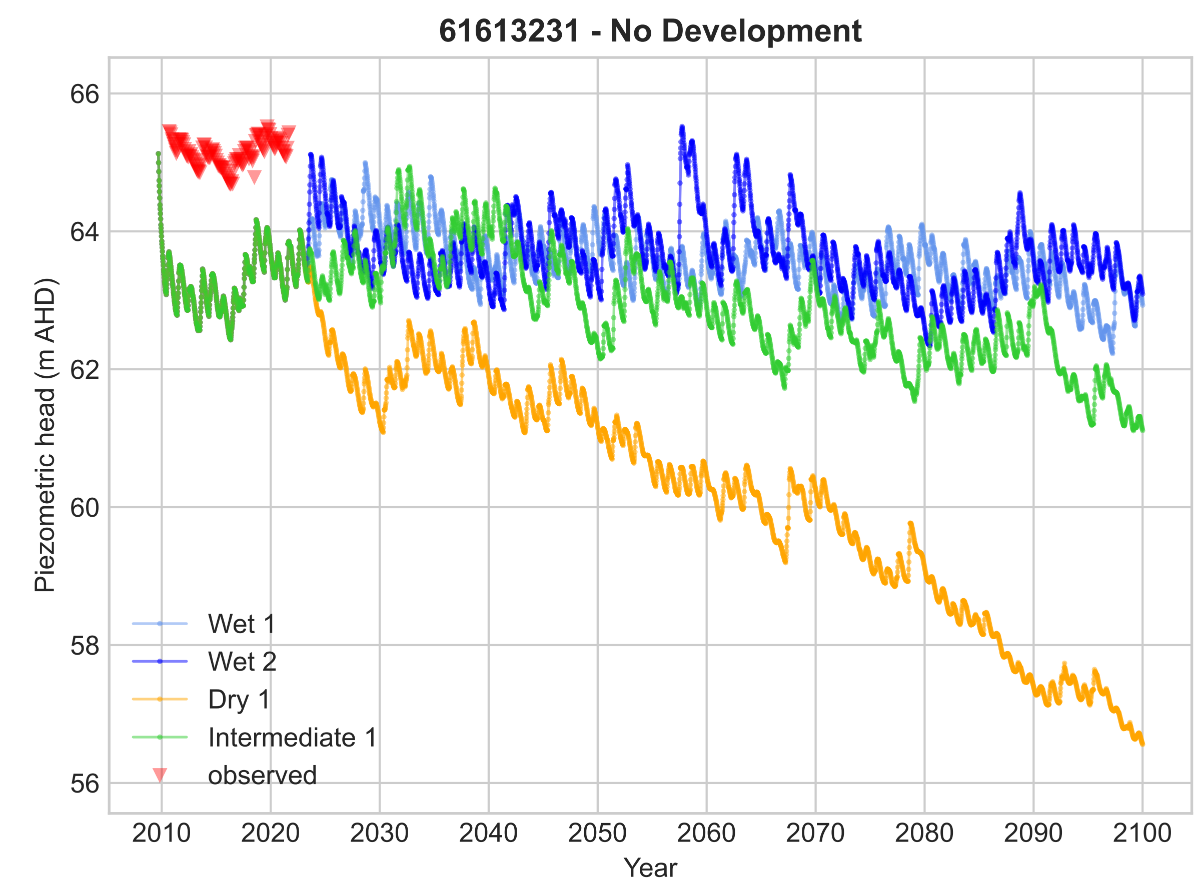

61611010 - No Development
Piezometric head (m AHD)
Year
50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

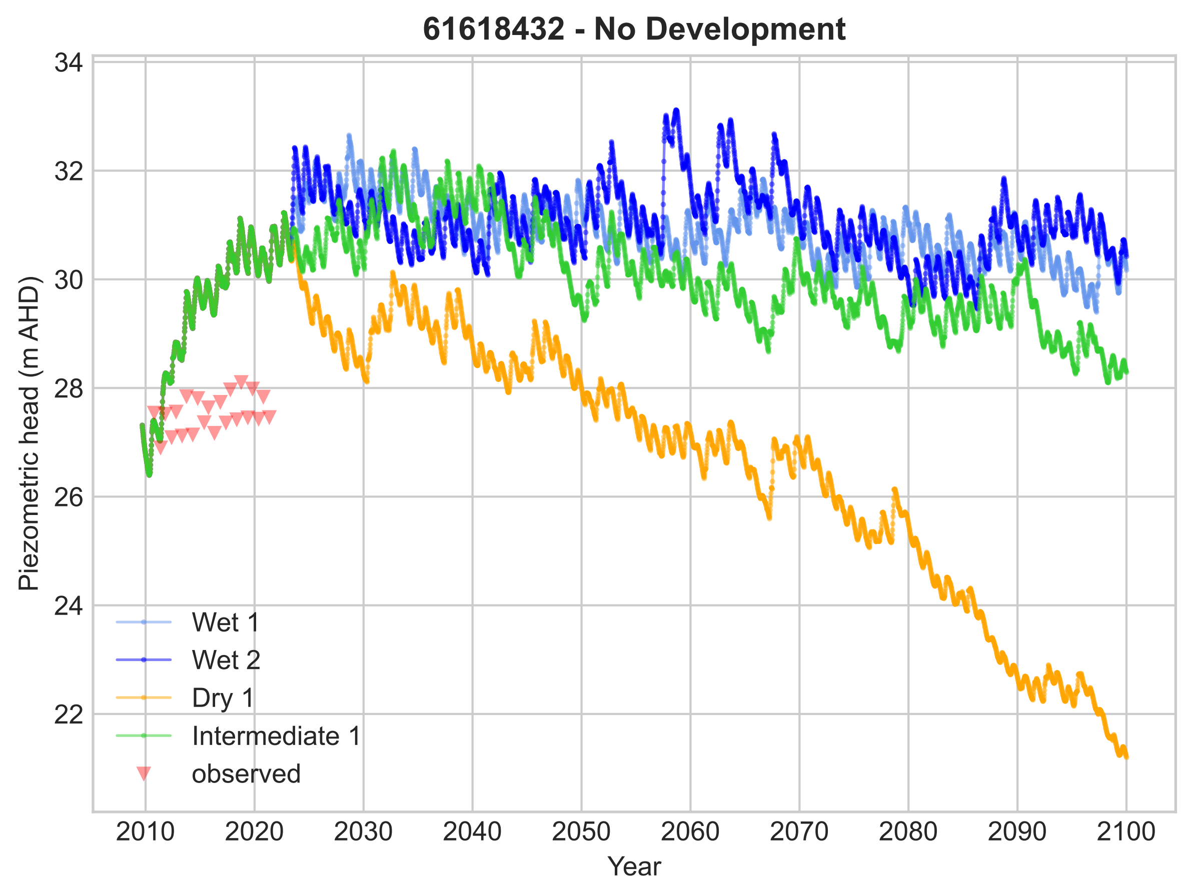

61611025 - No Development
61611031 - No Development
61611034 - No Development
61611289 - No Development
61611377 - No Development
61611440 - No Development
61611498 - No Development
61613200 - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

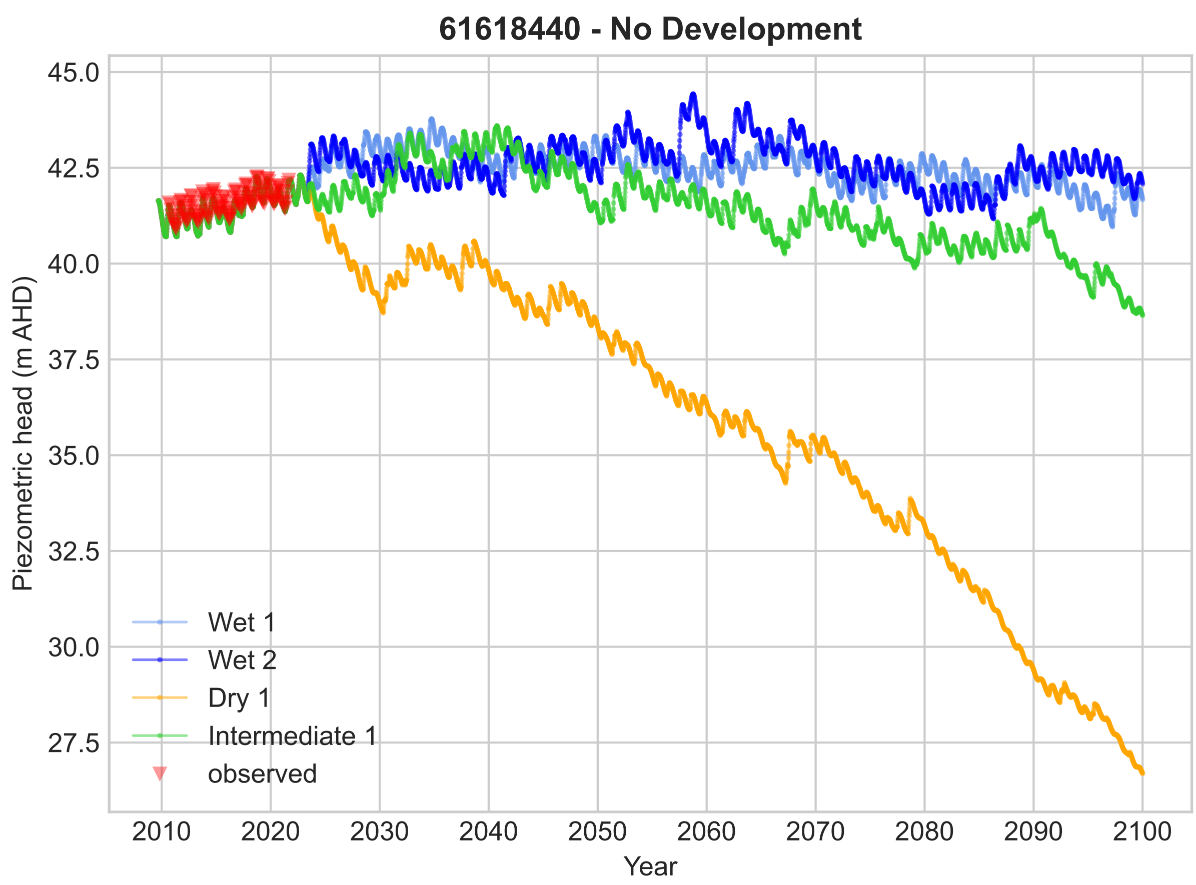

61613203 - No Development
Piezometric head (m AHD)
48 46 44 42 40 38 36 34 32
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

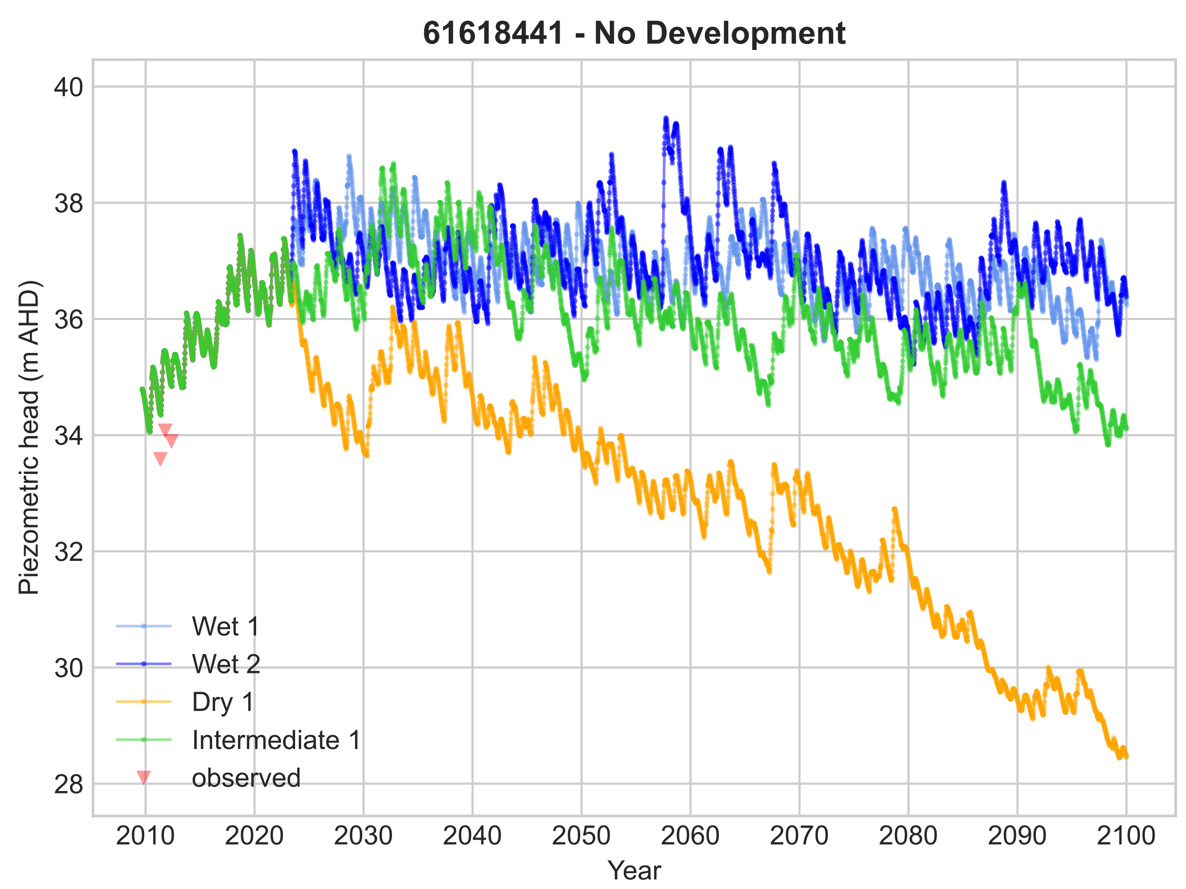

61613204 - No Development
Piezometric head (m AHD)
50 48 46 44 42 40 38 36 34
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

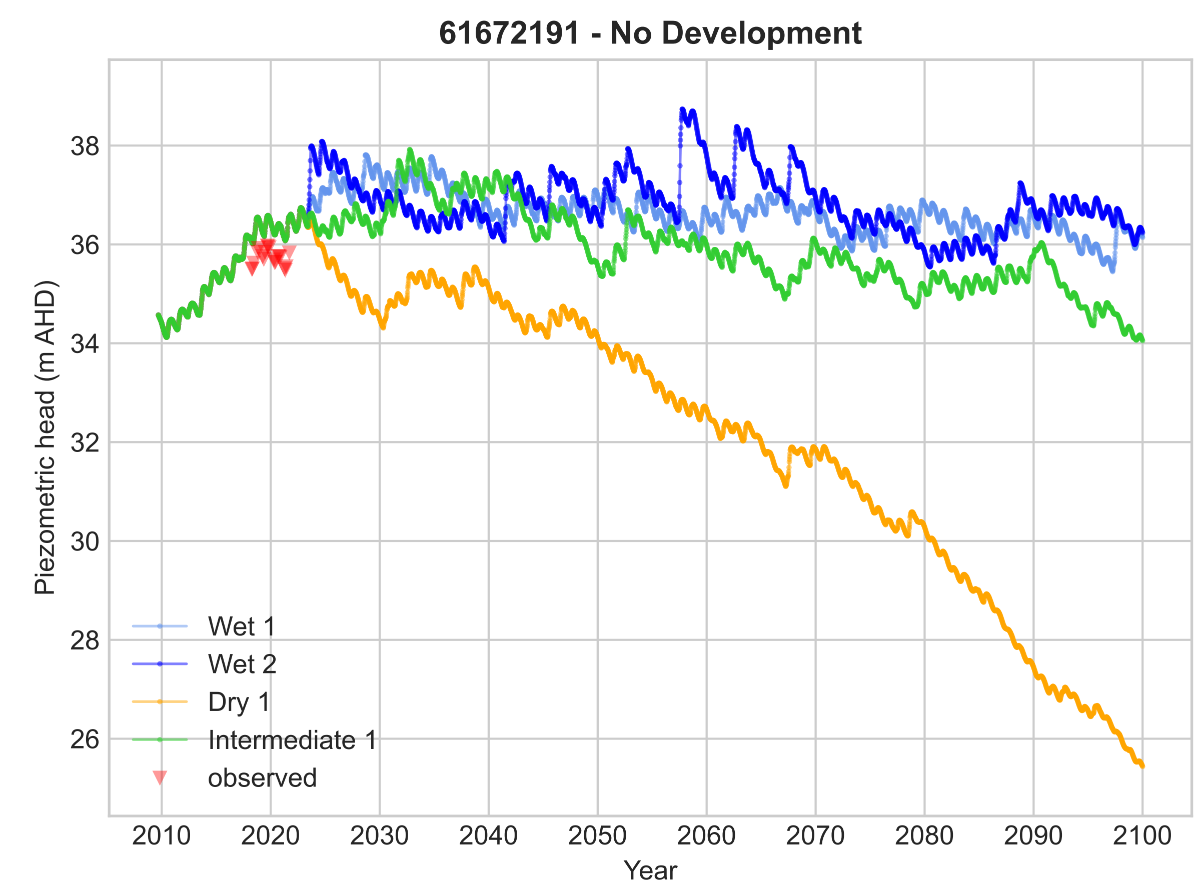

61613211 - No Development
Piezometric head (m AHD)
56 54 52 50 48 46 44 42
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

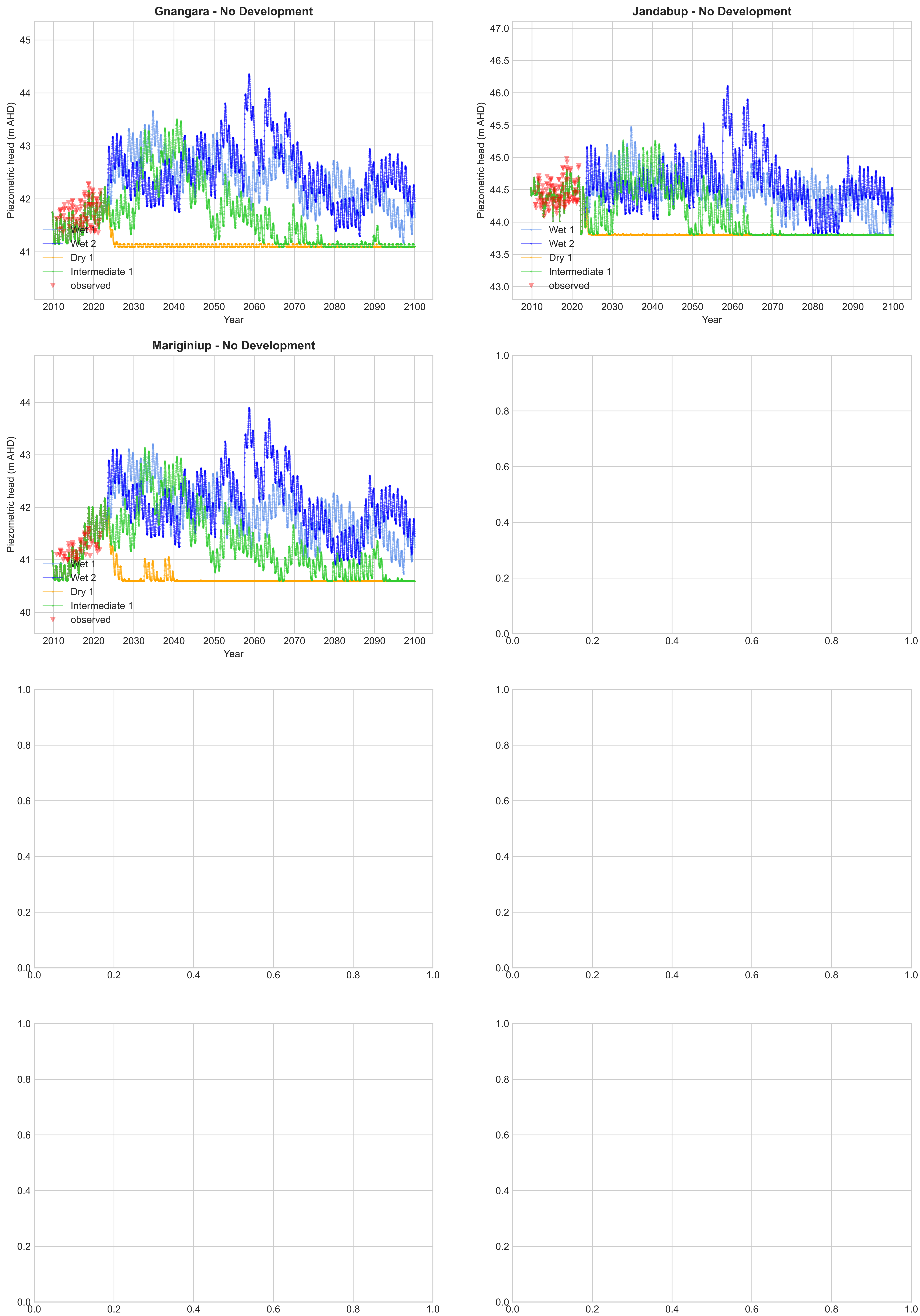

61613231 - No Development
Piezometric head (m AHD)
66 64 62 60 58 56
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed


61618432 - No Development
Piezometric head (m AHD)
34 32 30 28 26 24 22
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed


61618440 - No Development
Piezometric head (m AHD)
45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed


61618441 - No Development
Piezometric head (m AHD)
40 38 36 34 32 30 28
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed


61672191 - No Development
Piezometric head (m AHD)
38 36 34 32 30 28 26
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

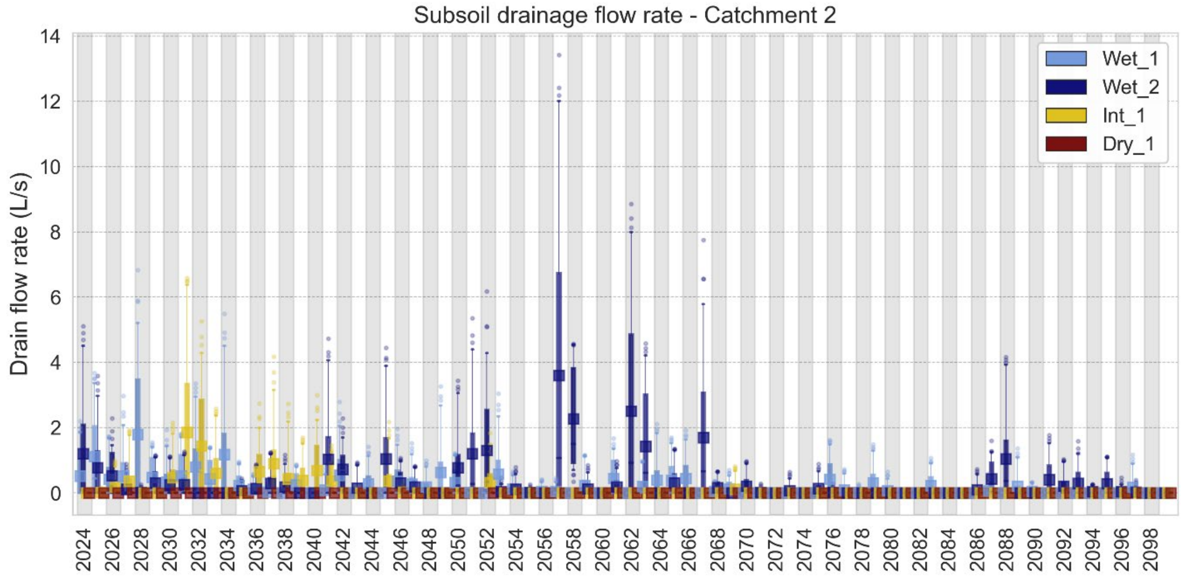


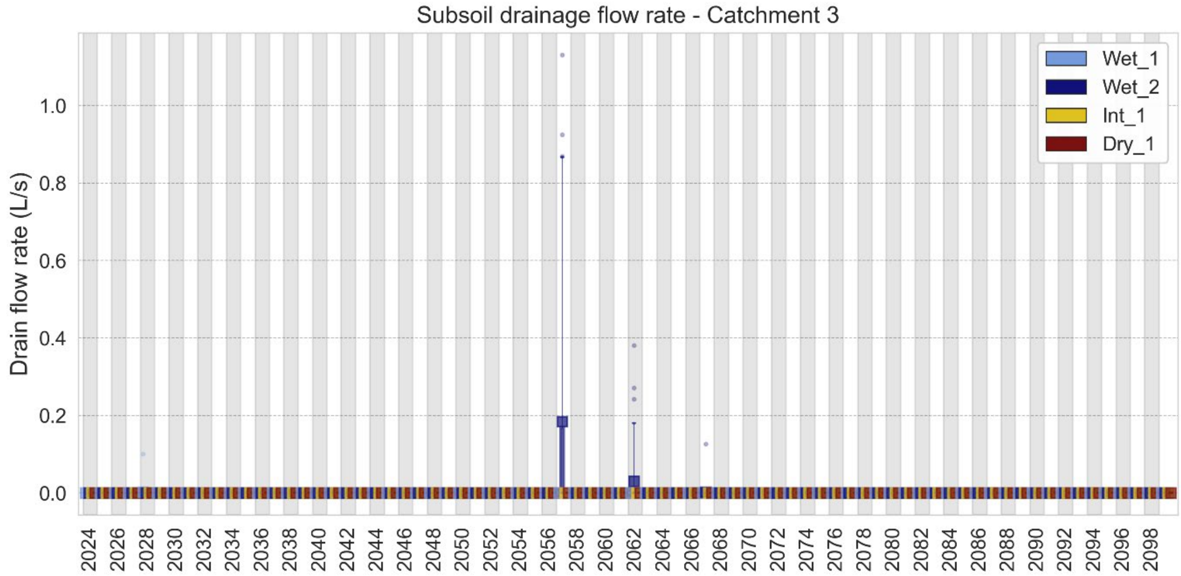
Gnangara - No Development
Jandabup - No Development
Mariginiup - No Development
Piezometric head (m AHD)
Year
Wet 1
Wet 2
Dry 1
Intermediate 1
observed

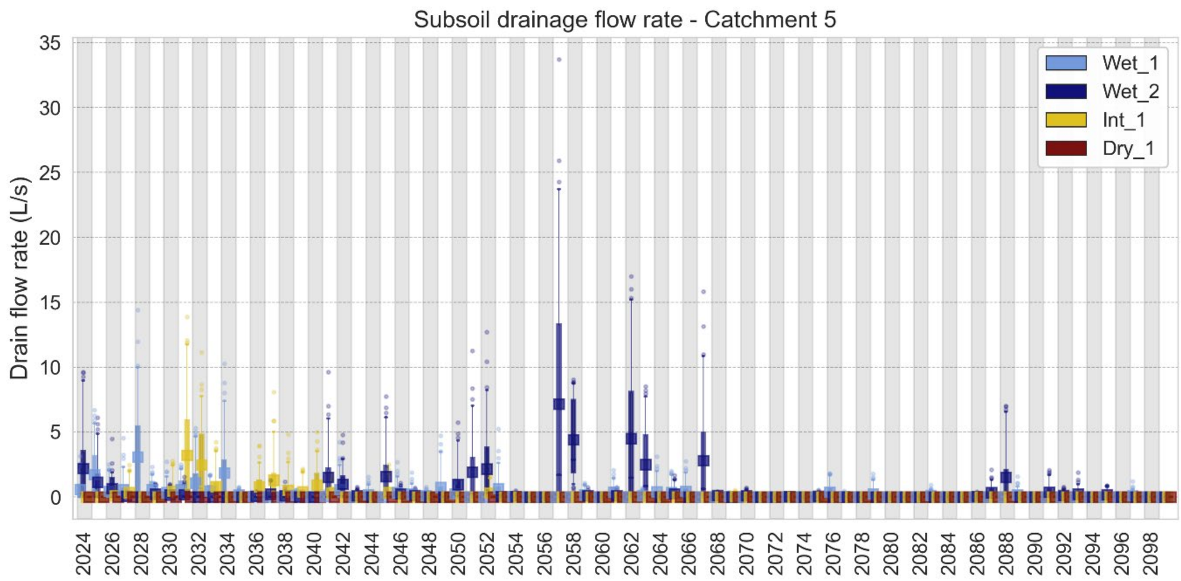
Appendix E: Box and whisker plots of catchment subsoil drainage flow rates

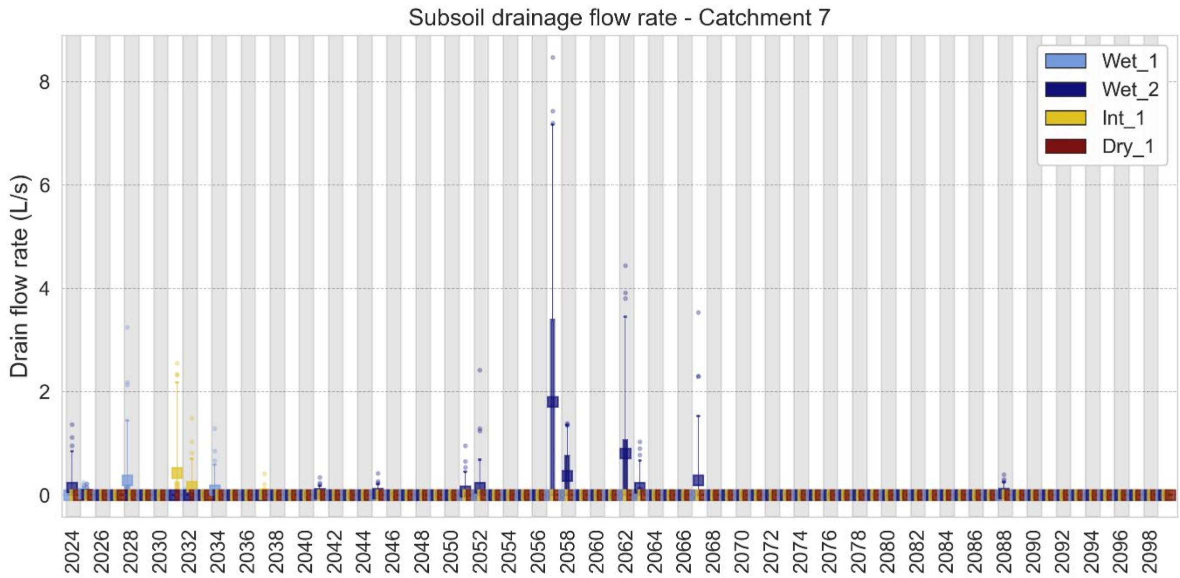
Appendix E: Box and whisker plots of catchment subsoil drainage flow rate

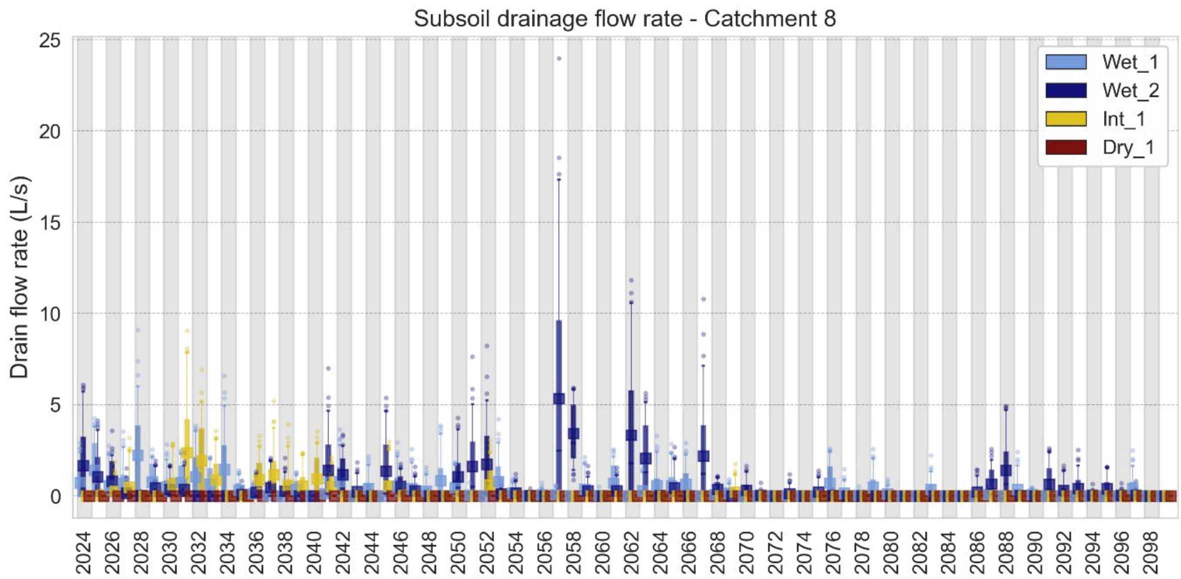
Full buildout, 2.0m max subsoil drainage depth simulations for the four selected climate scenarios

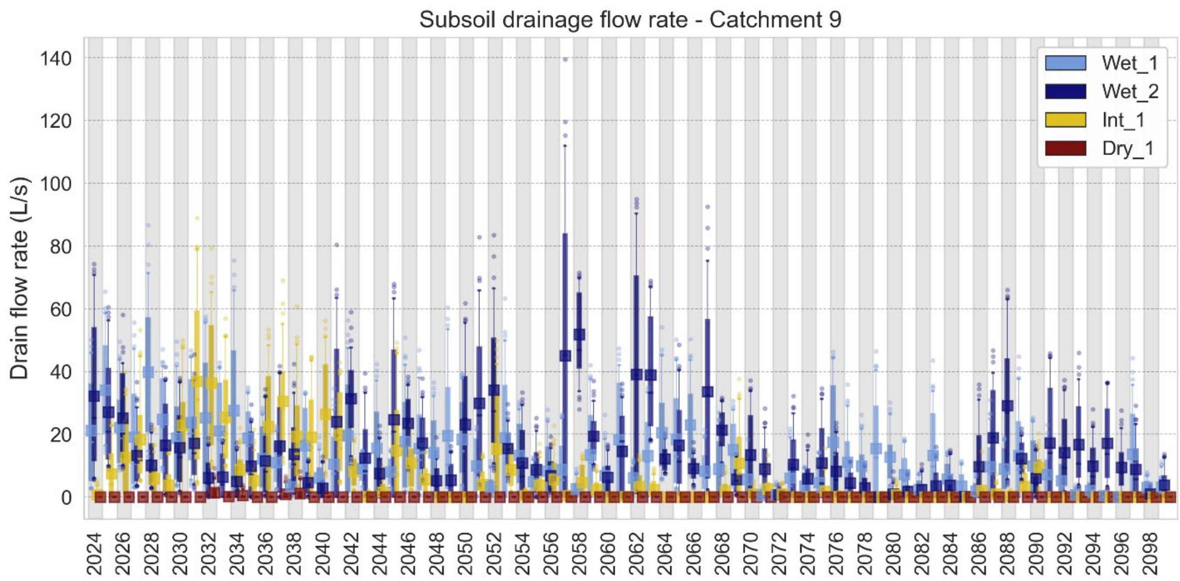


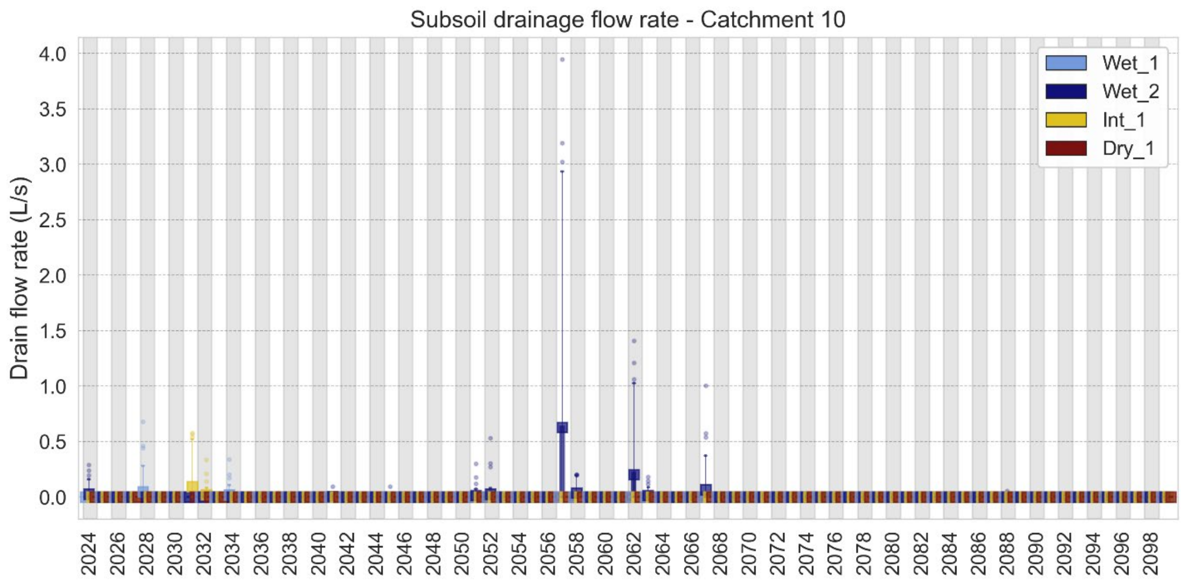


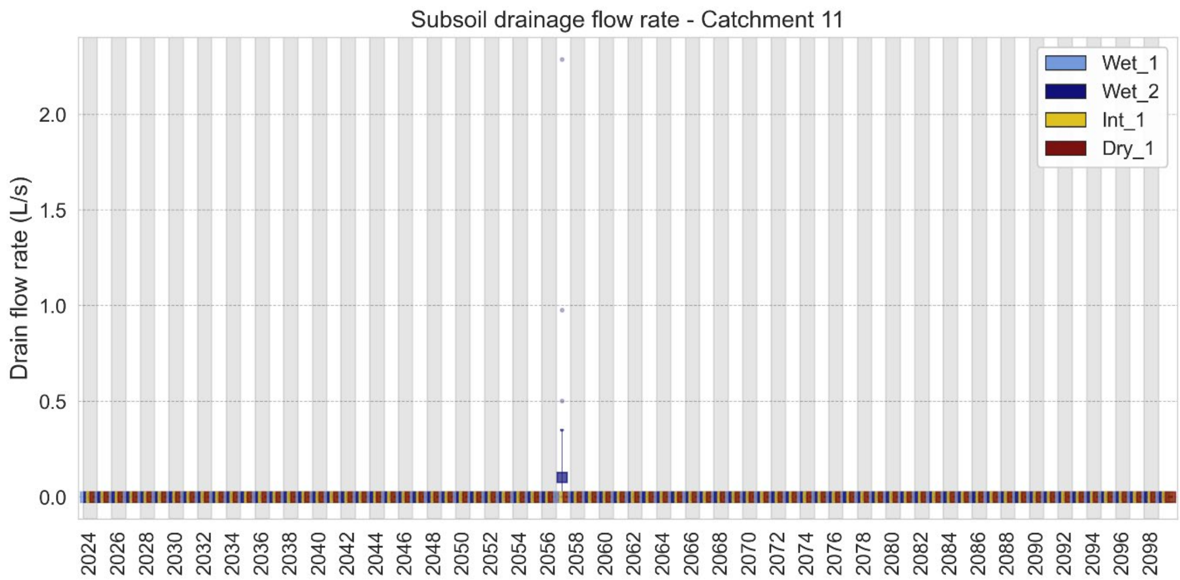

Subsoil drainage flow rate - Catchment 5
Drain flow rate (L/s)
0
5
10
15
20
25
30
35
Wet_1
Wet_2
Int_1
Dry_1
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
2052
2054
2056
2058
2060
2062
2064
2066
2068
2070
2072
2074
2076
2078
2080
2082
2084
2086
2088
2090
2092
2094
2096
2098

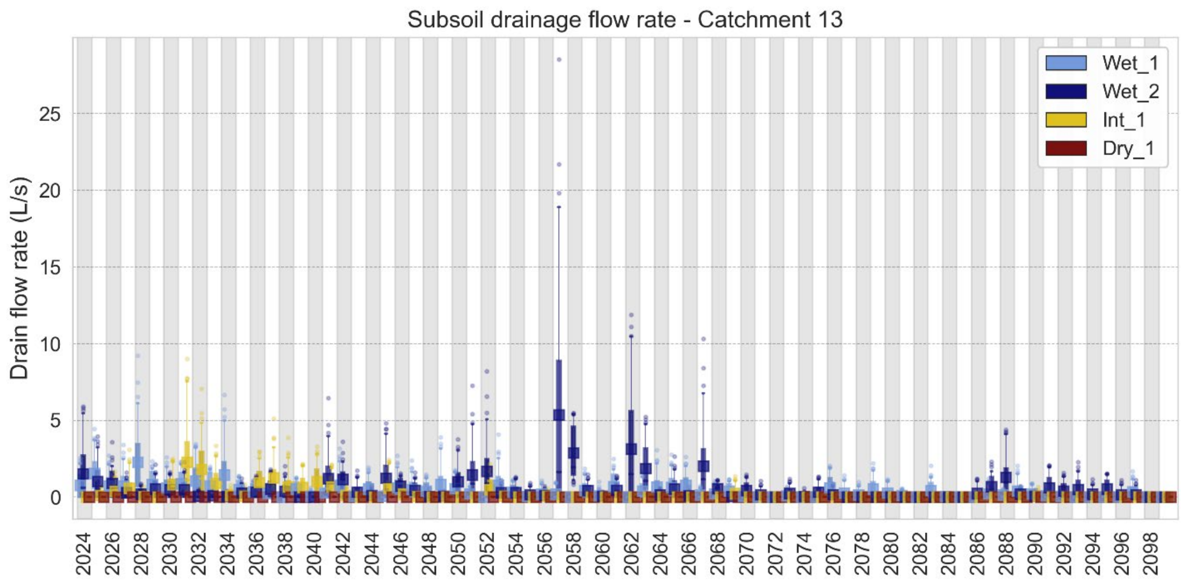

Subsoil drainage flow rate - Catchment 7
Drain flow rate (L/s)
0
2
4
6
8
Wet_1
Wet_2
Int_1
Dry_1
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
2052
2054
2056
2058
2060
2062
2064
2066
2068
2070
2072
2074
2076
2078
2080
2082
2084
2086
2088
2090
2092
2094
2096
2098

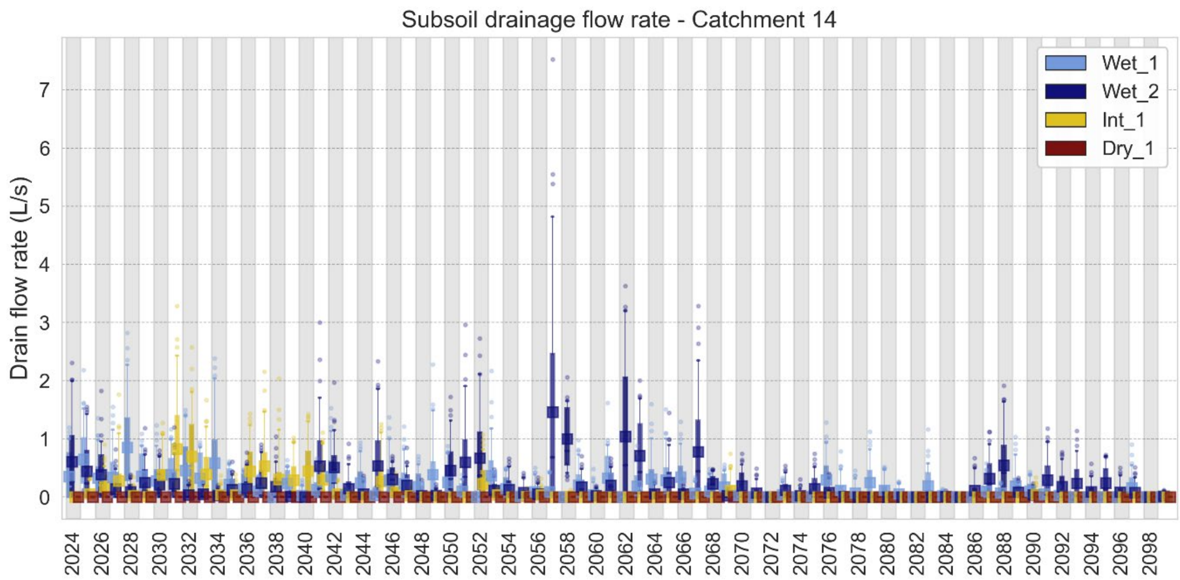

Subsoil drainage flow rate - Catchment 8
Drain flow rate (L/s)
0
5
10
15
20
25
Wet_1
Wet_2
Int_1
Dry_1
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
2052
2054
2056
2058
2060
2062
2064
2066
2068
2070
2072
2074
2076
2078
2080
2082
2084
2086
2088
2090
2092
2094
2096
2098

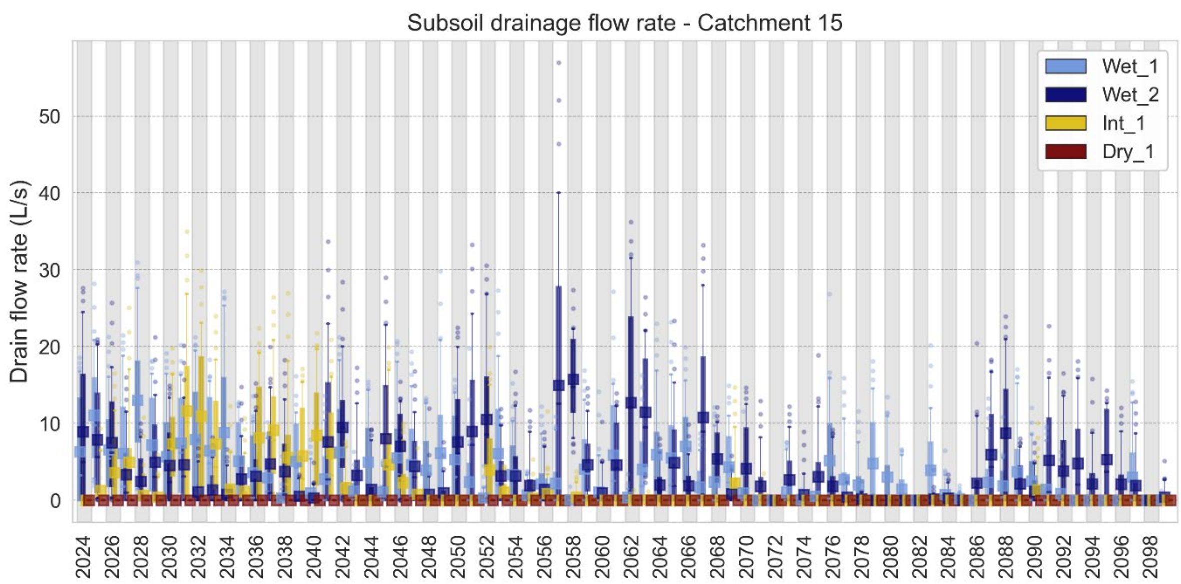

Subsoil drainage flow rate - Catchment 9
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1


Subsoil drainage flow rate - Catchment 10
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

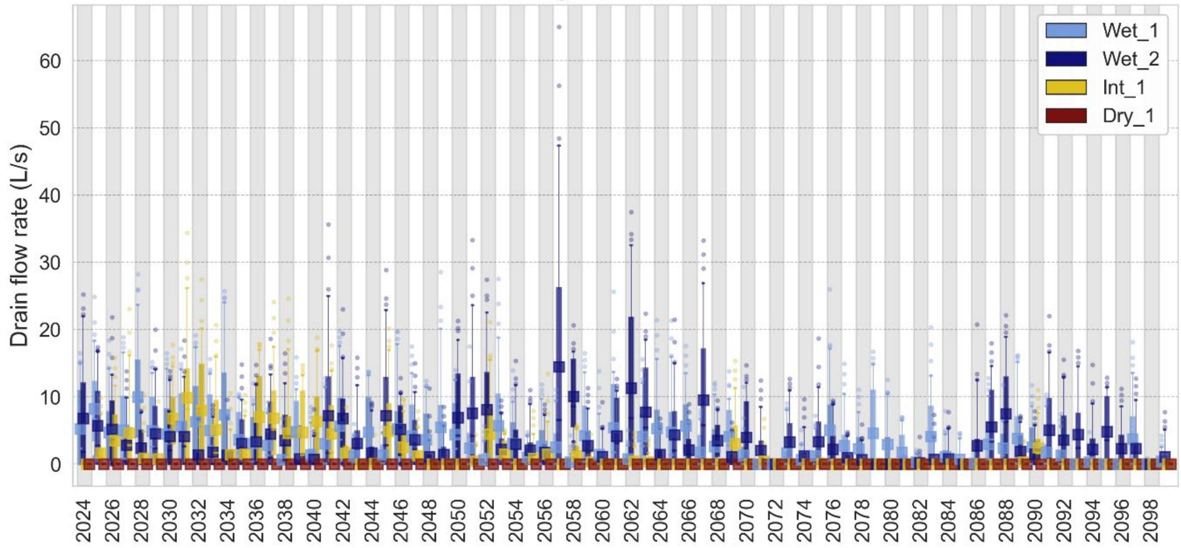

Subsoil drainage flow rate - Catchment 11
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1


Subsoil drainage flow rate - Catchment 13
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

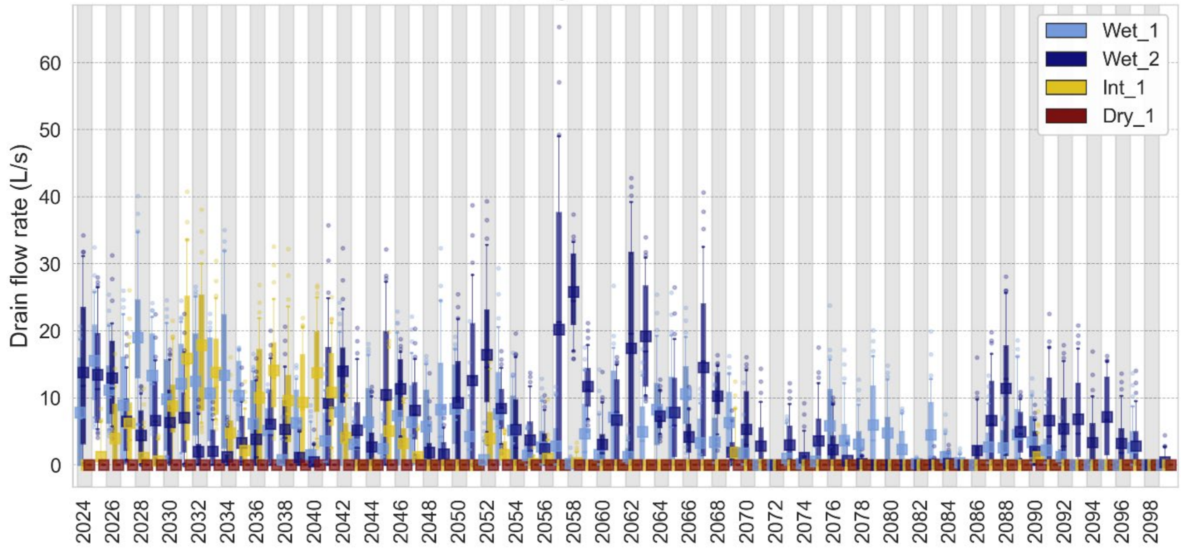

Subsoil drainage flow rate - Catchment 14
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1


Subsoil drainage flow rate - Catchment 15
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

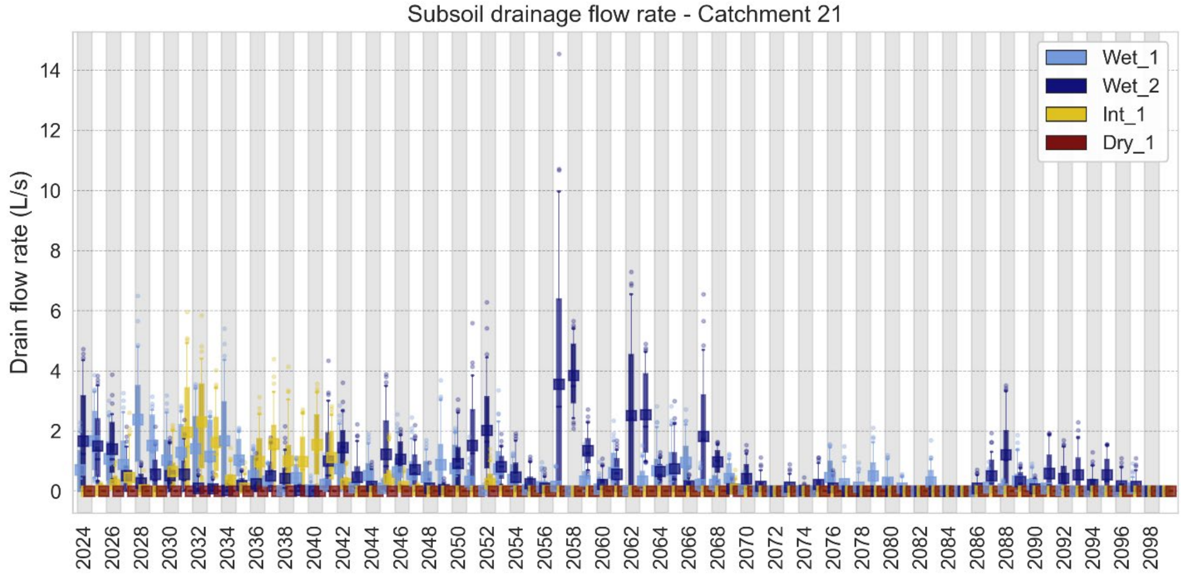
Subsoil drainage flow rate - Catchment 18

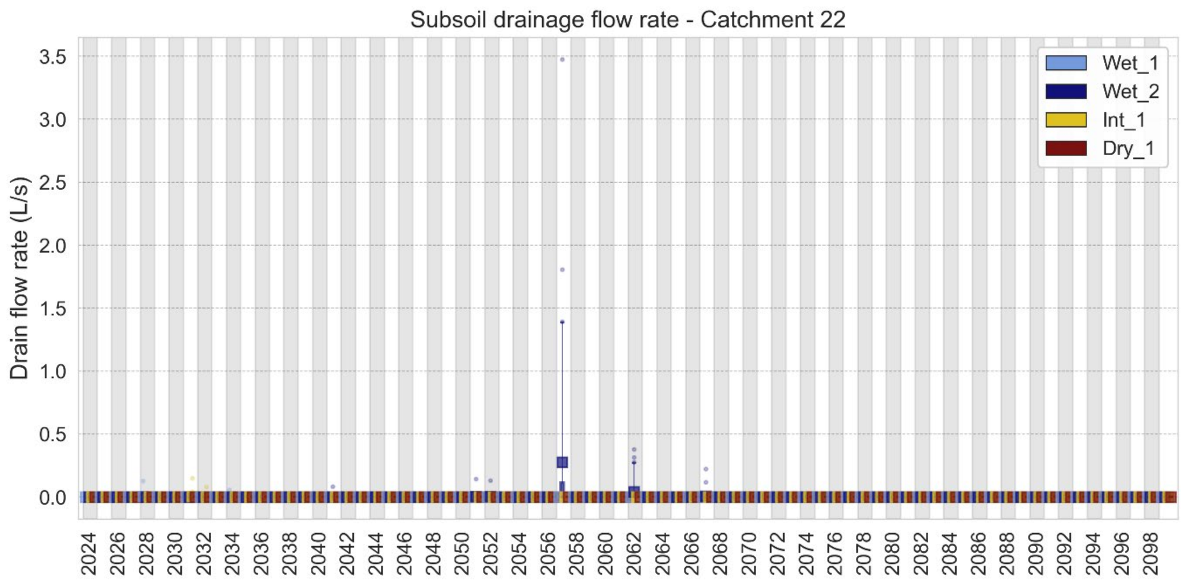


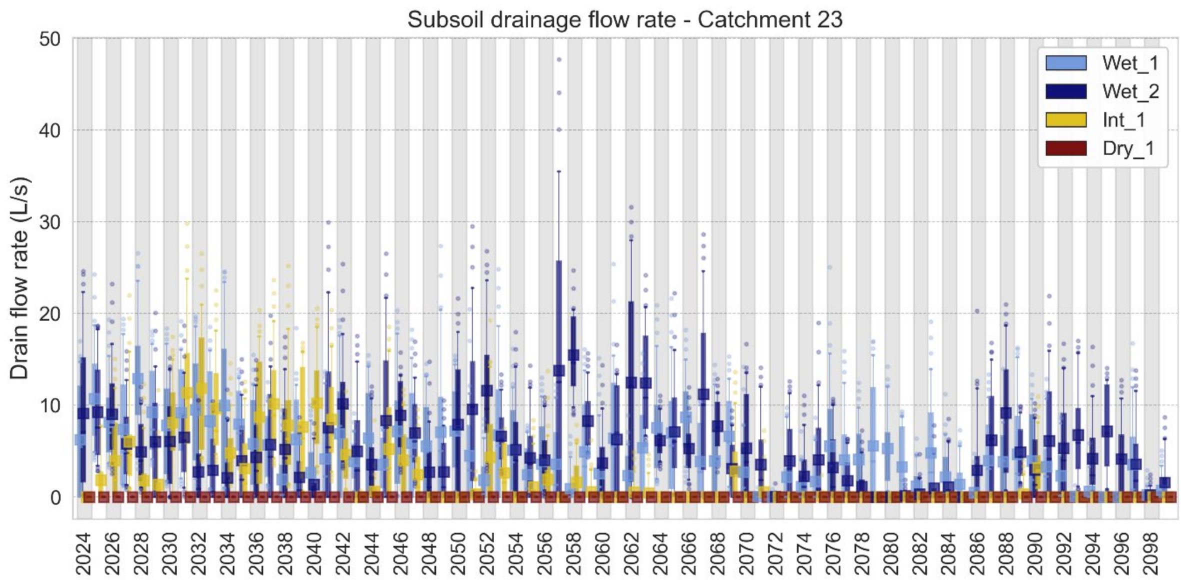
Subsoil drainage flow rate - Catchment 20

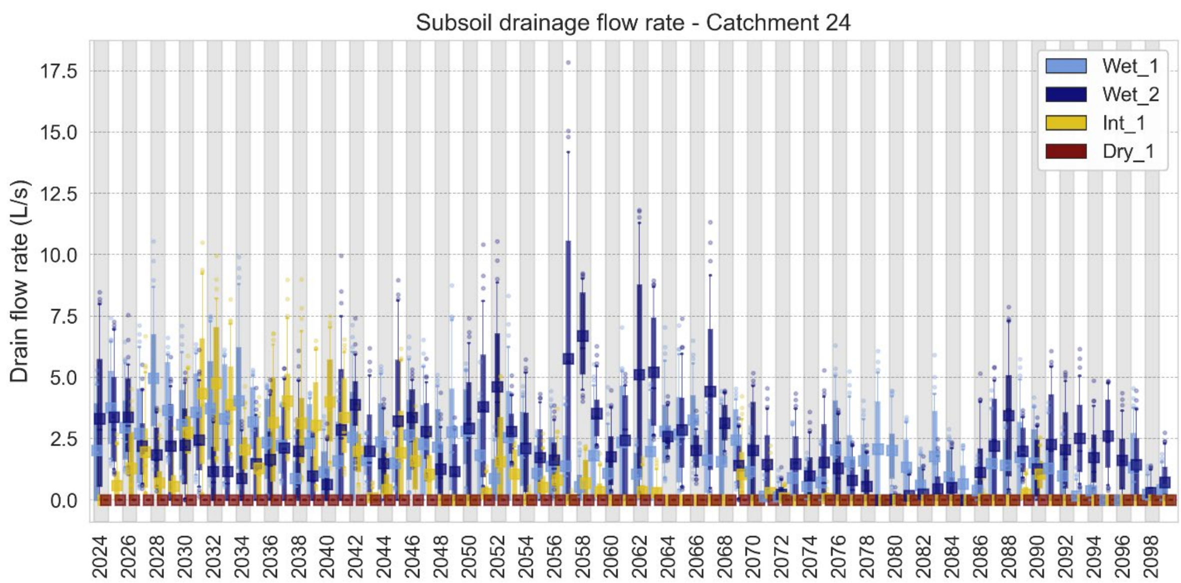


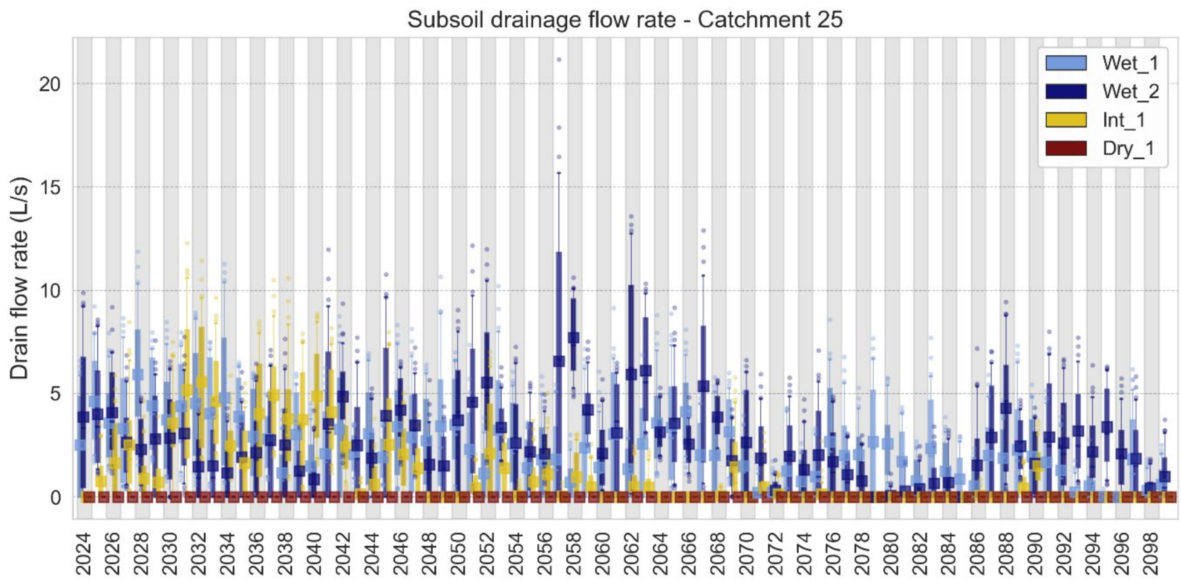
Subsoil drainage flow rate - Catchment 21

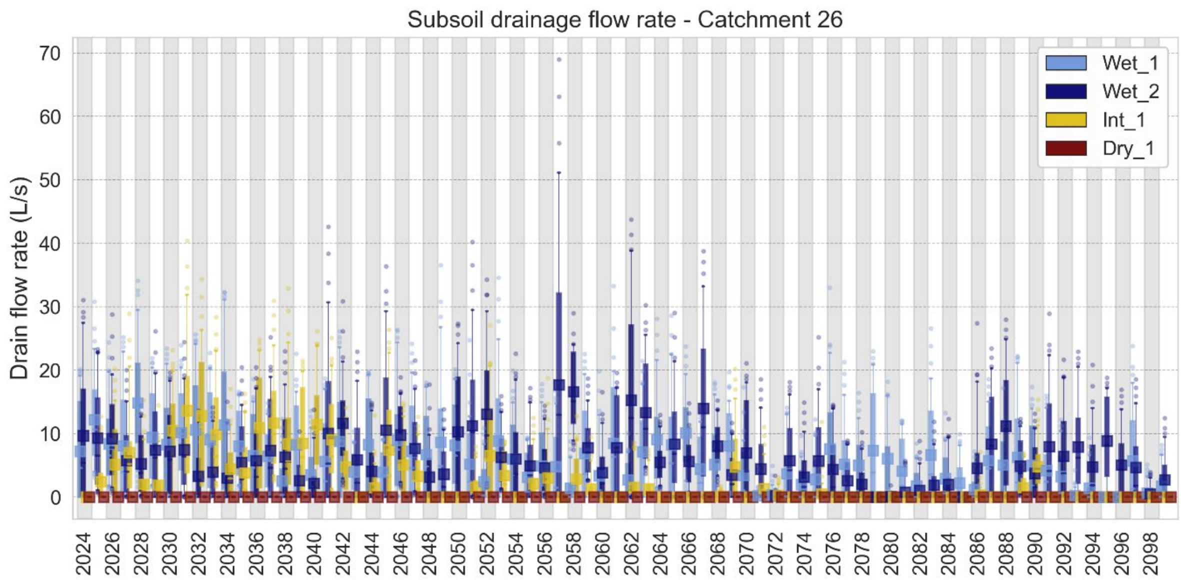


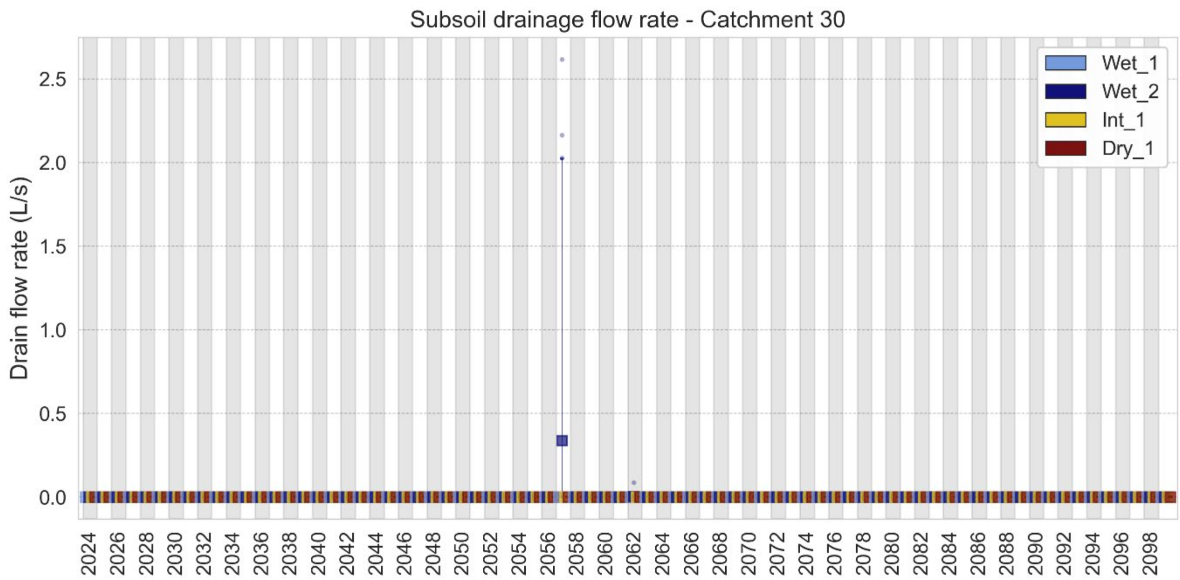

Subsoil drainage flow rate - Catchment 22
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

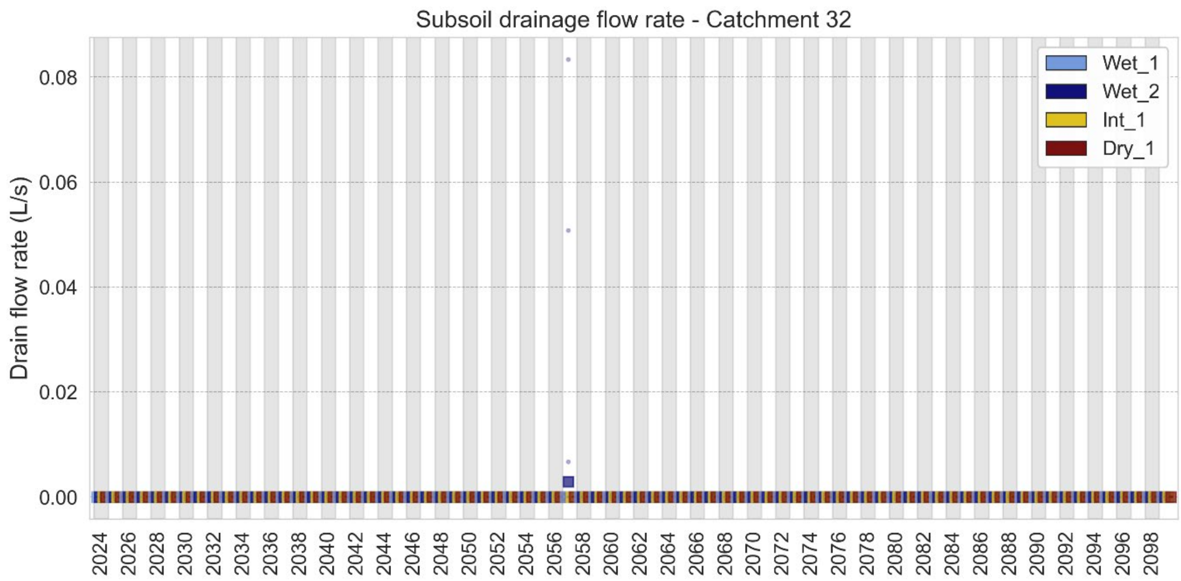

Subsoil drainage flow rate - Catchment 23
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

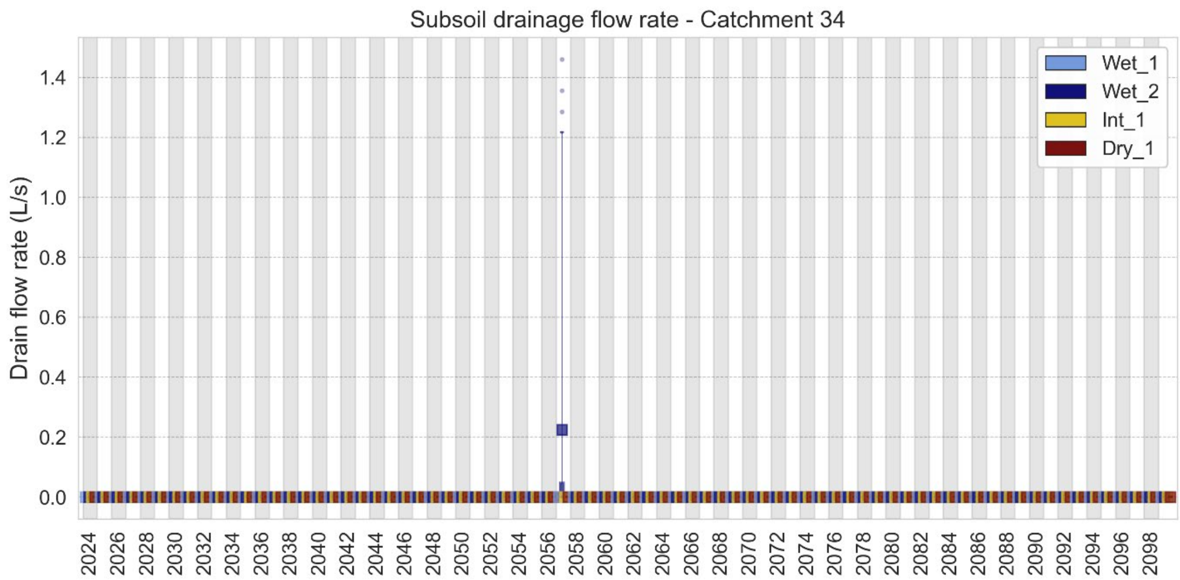

Subsoil drainage flow rate - Catchment 24
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

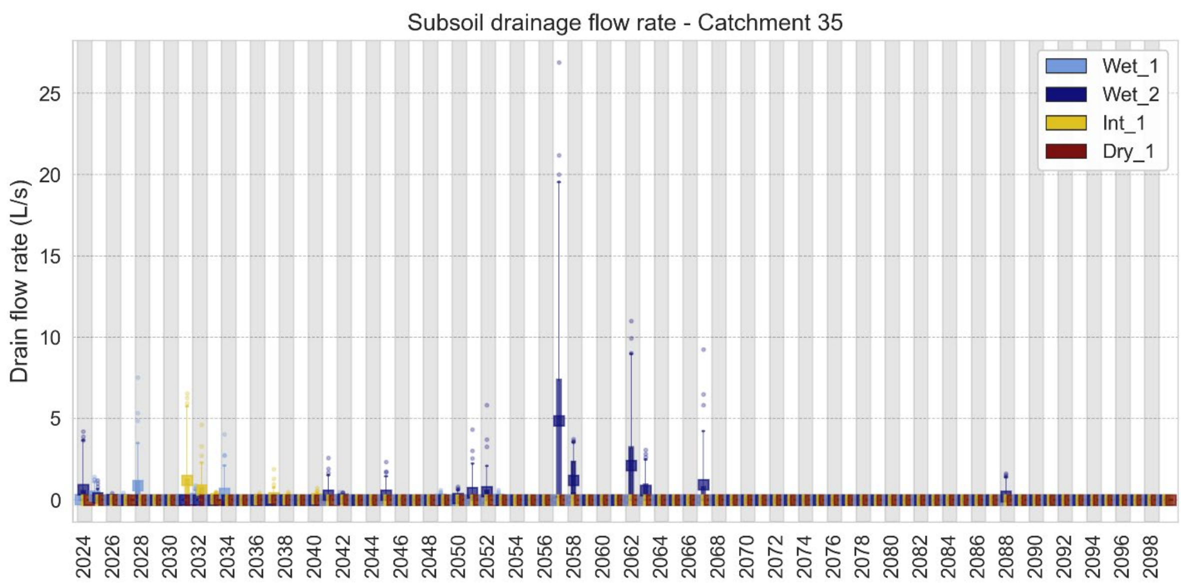

Subsoil drainage flow rate - Catchment 25
Drain flow rate (L/s)
0
5
10
15
20
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

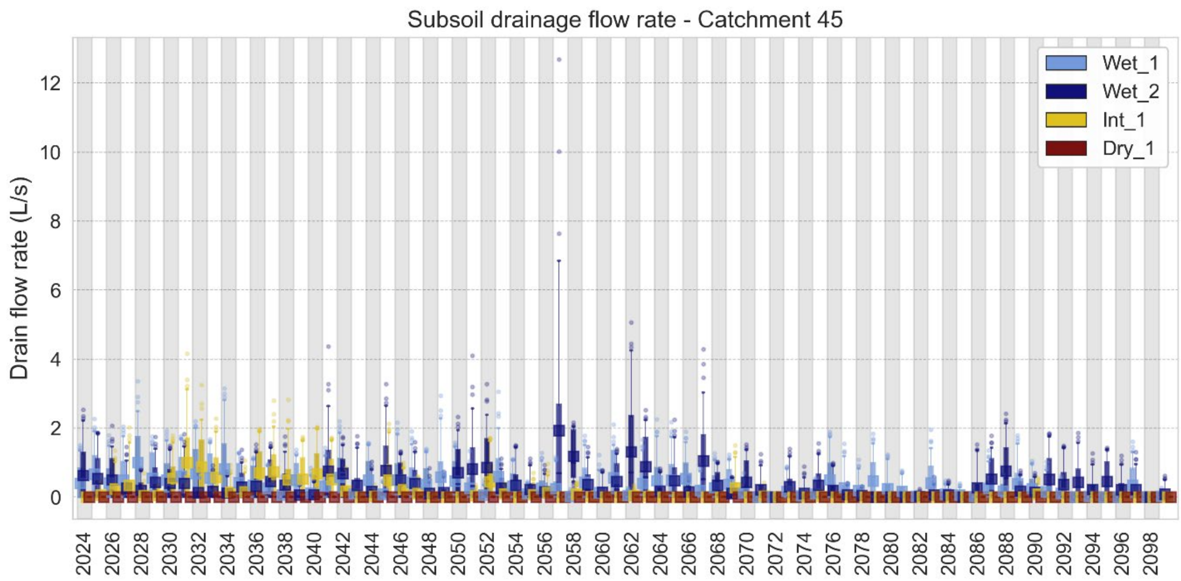

Subsoil drainage flow rate - Catchment 26
Drain flow rate (L/s)
0
10
20
30
40
50
60
70
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

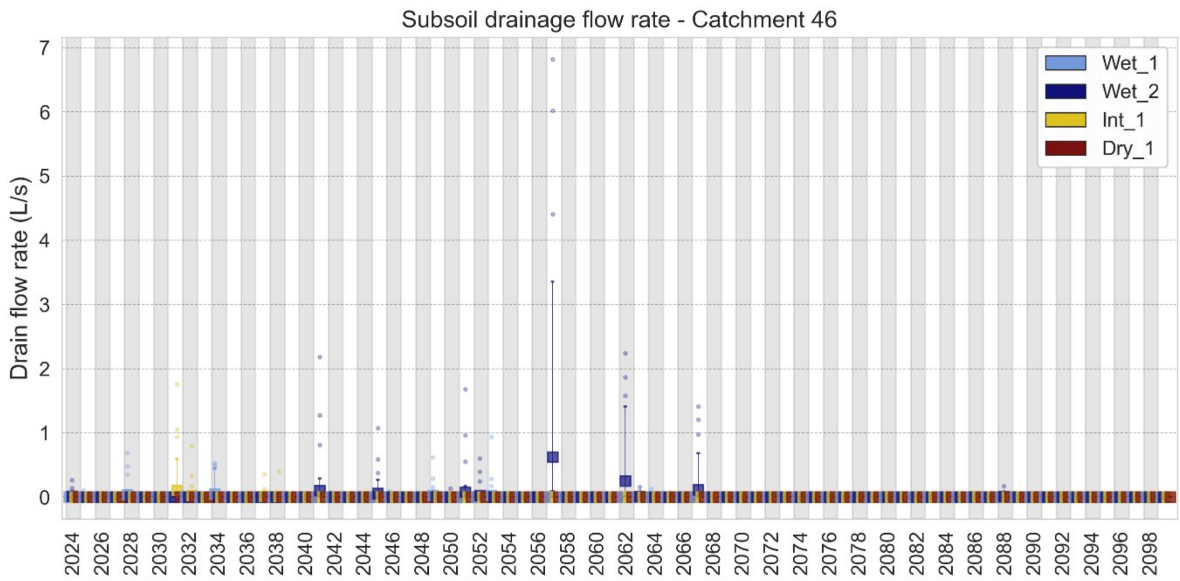

Subsoil drainage flow rate - Catchment 30
Drain flow rate (L/s)
0.0
0.5
1.0
1.5
2.0
2.5
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

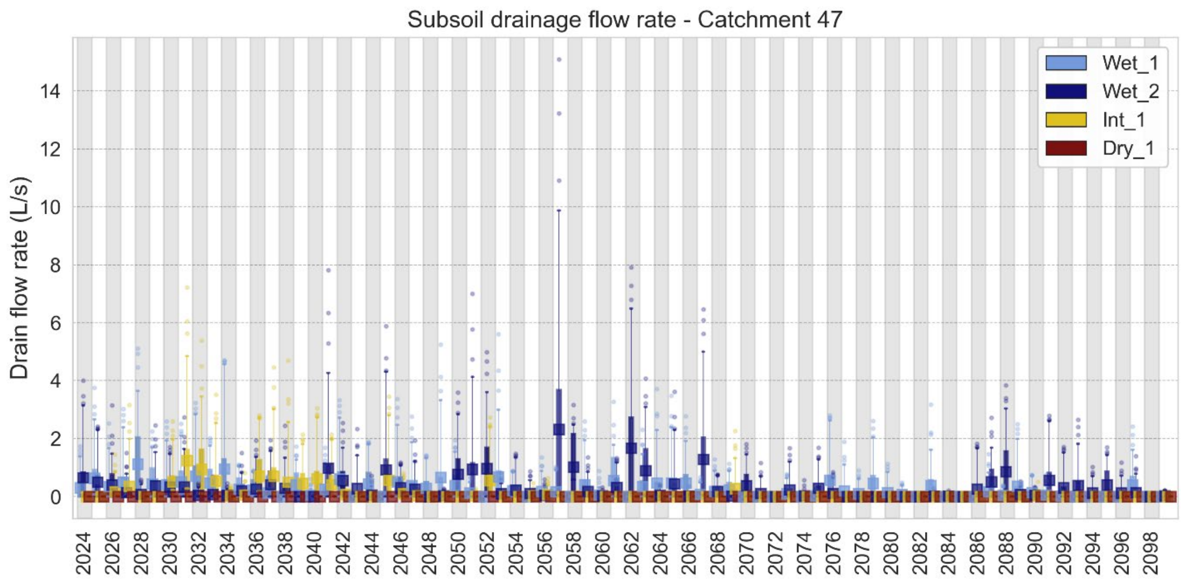

Subsoil drainage flow rate - Catchment 32
Drain flow rate (L/s)
0.00
0.02
0.04
0.06
0.08
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

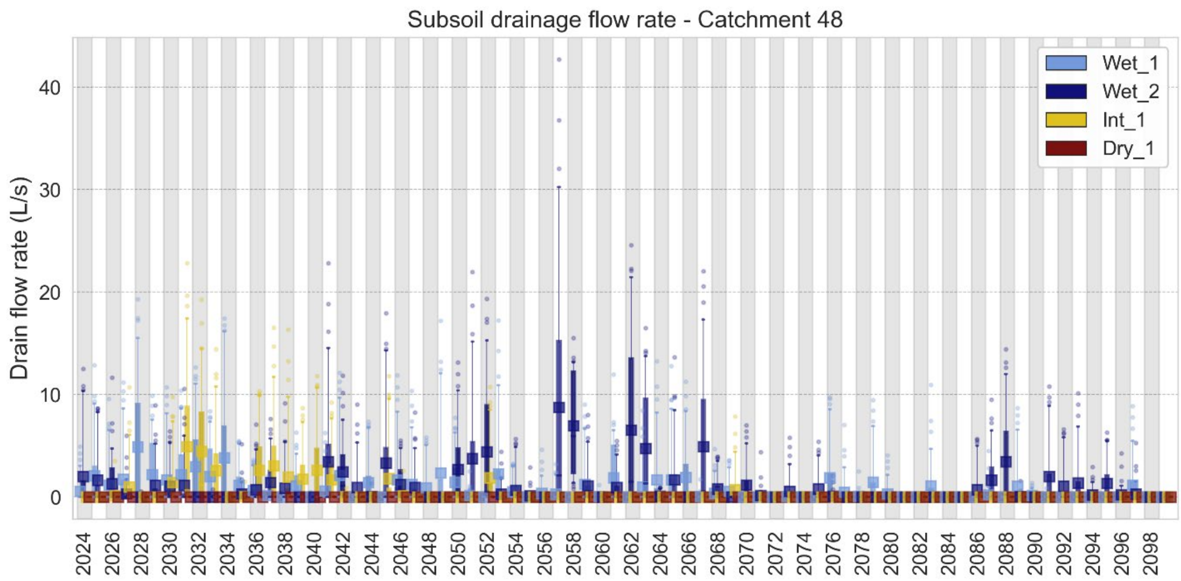

Subsoil drainage flow rate - Catchment 34
Drain flow rate (L/s)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

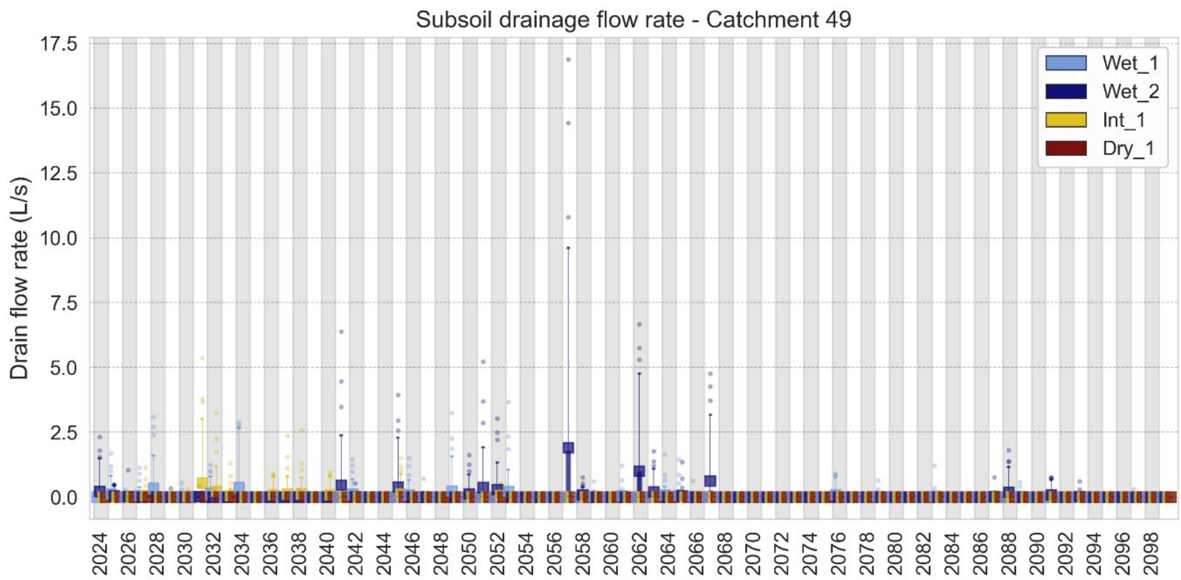

Subsoil drainage flow rate - Catchment 35
Drain flow rate (L/s)
0
5
10
15
20
25
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

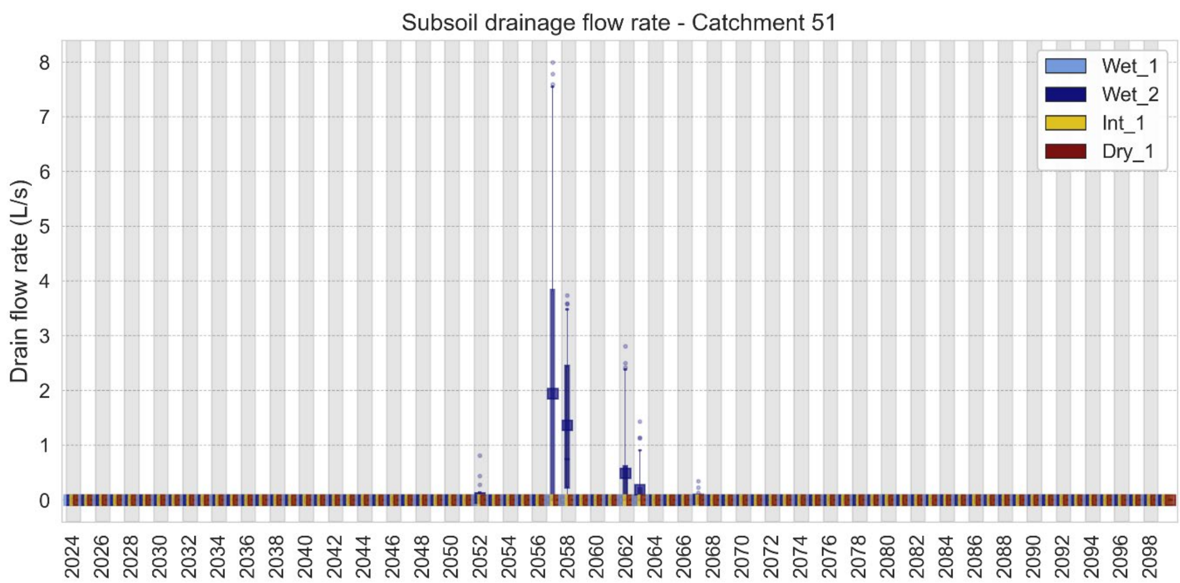

Subsoil drainage flow rate - Catchment 45
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

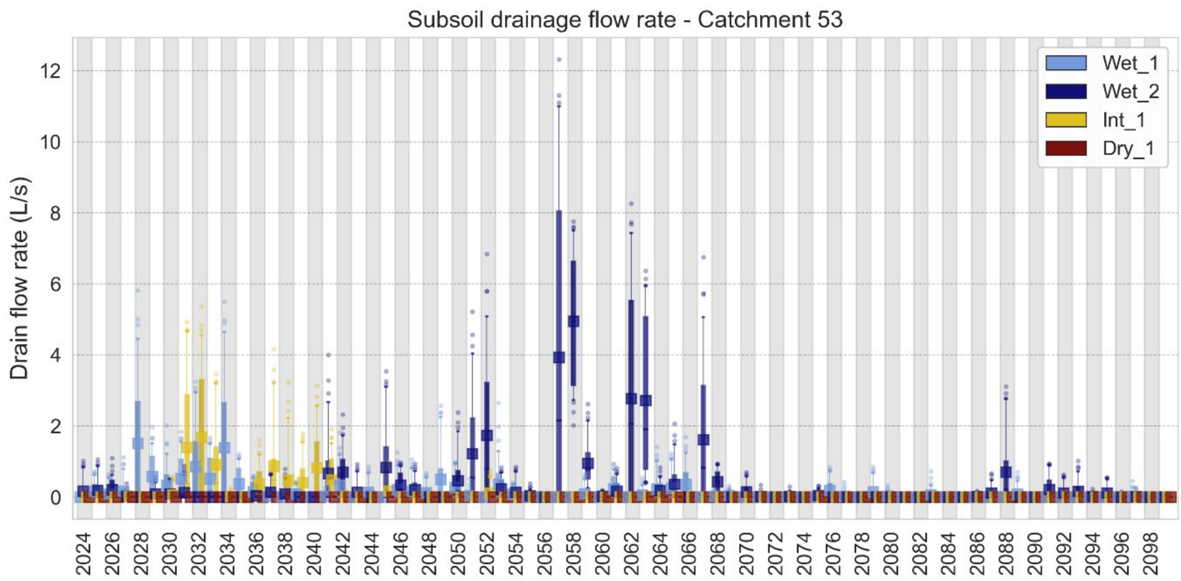

Subsoil drainage flow rate - Catchment 46
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

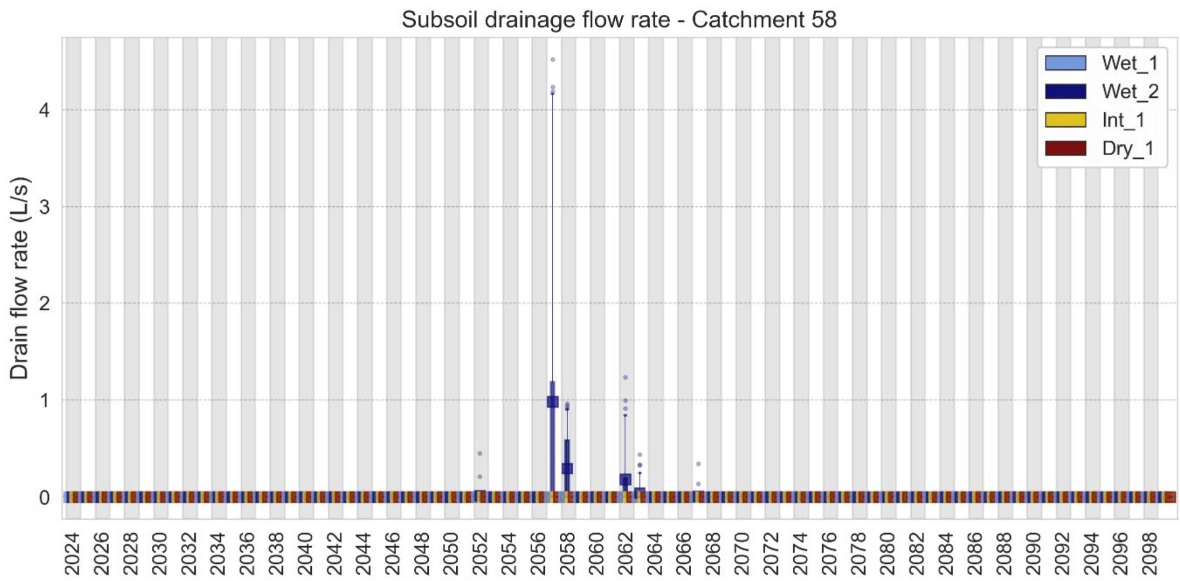

Subsoil drainage flow rate - Catchment 47
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

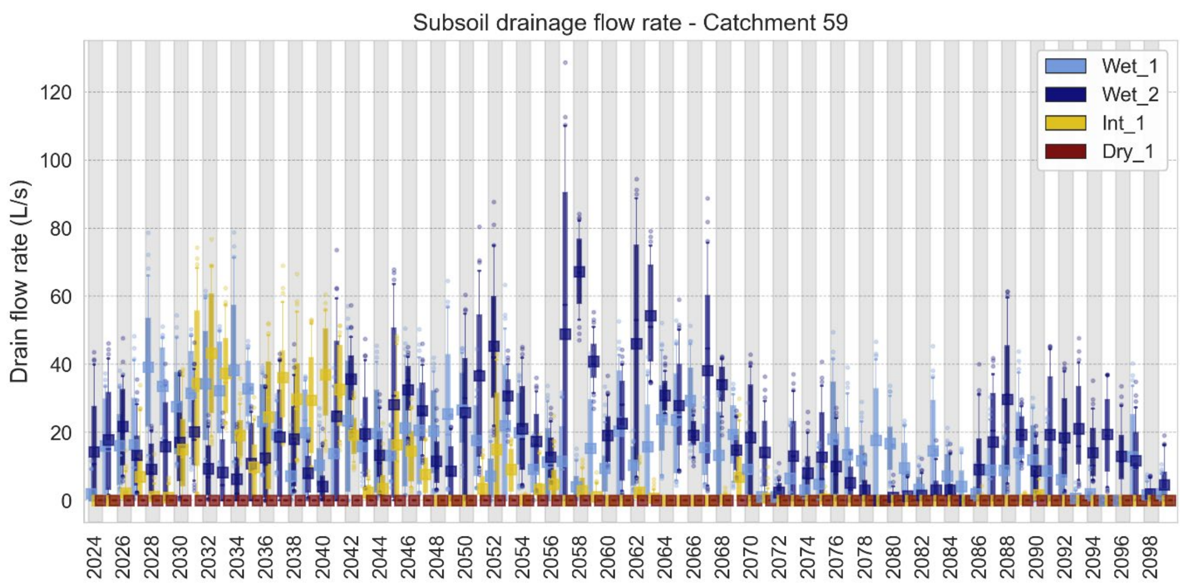

Subsoil drainage flow rate - Catchment 48
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

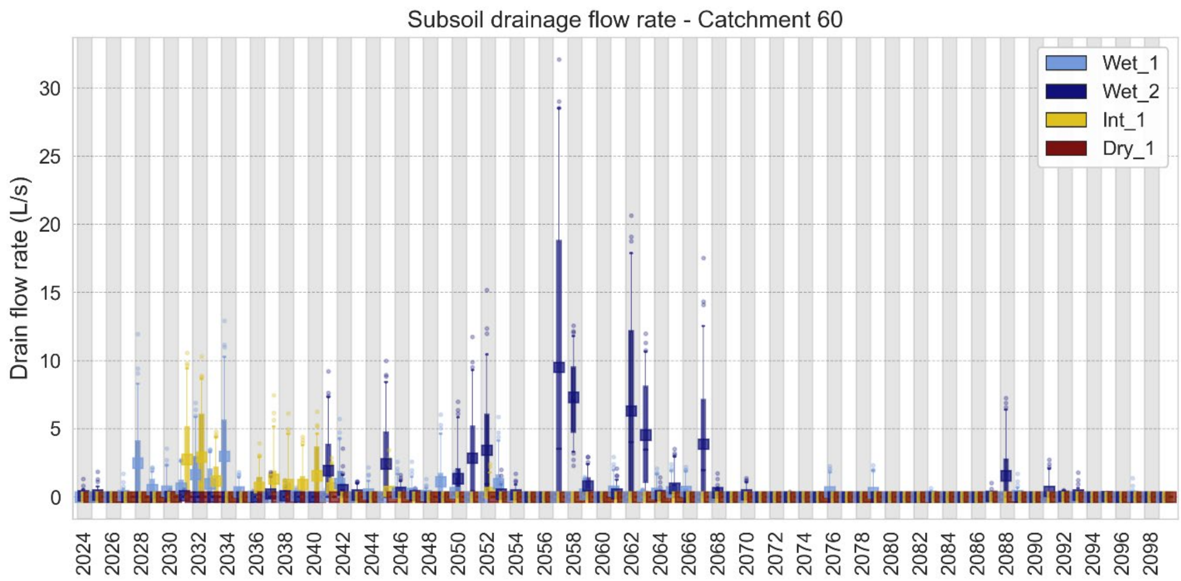

Subsoil drainage flow rate - Catchment 49
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

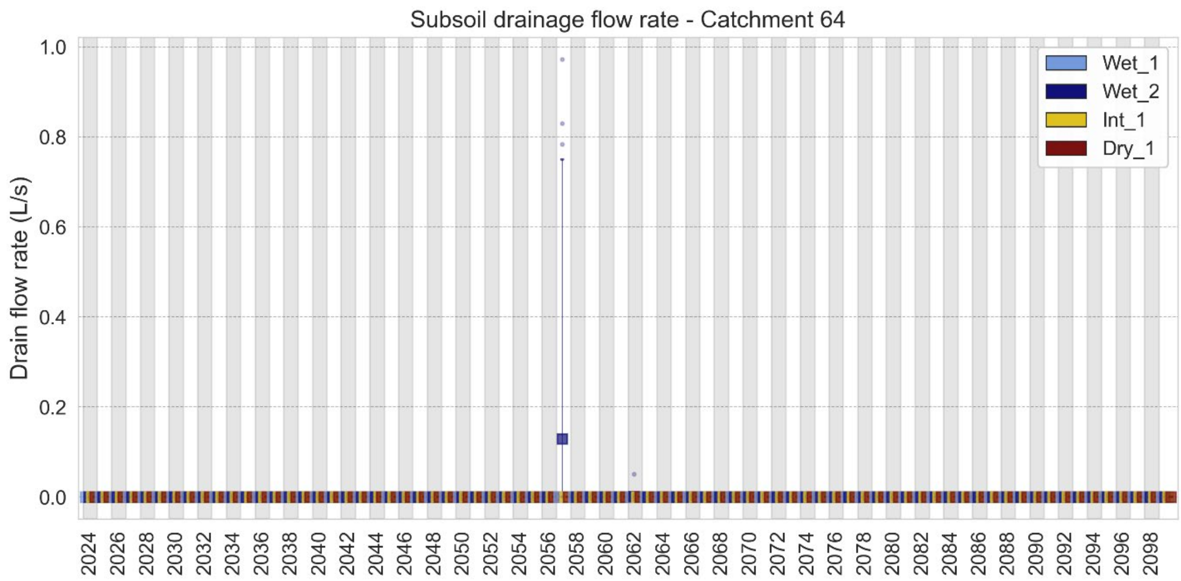

Subsoil drainage flow rate - Catchment 51
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

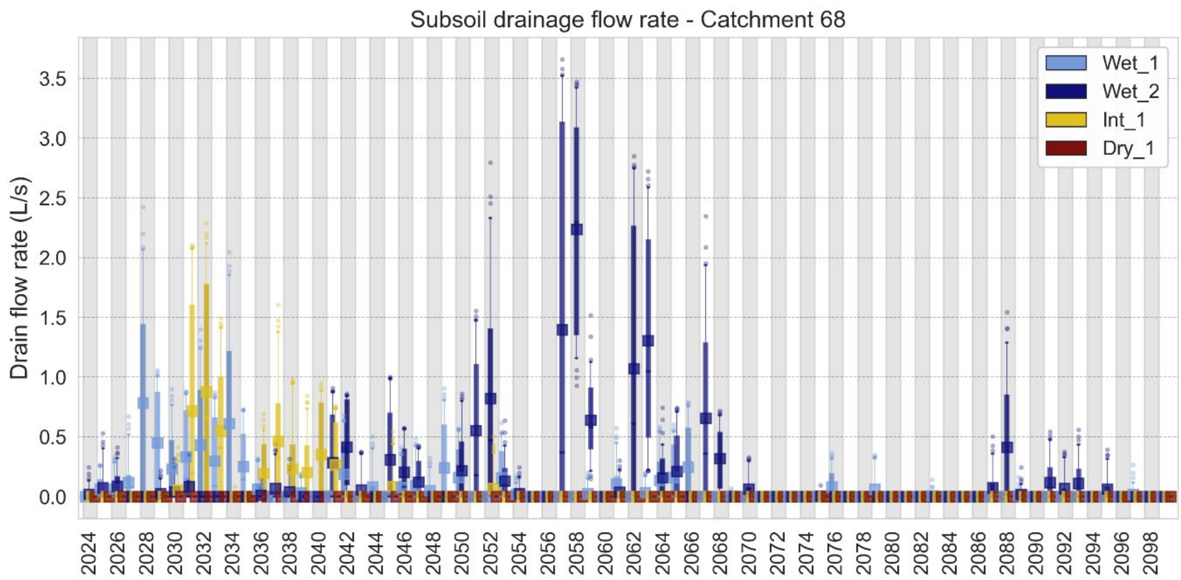

Subsoil drainage flow rate - Catchment 53
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

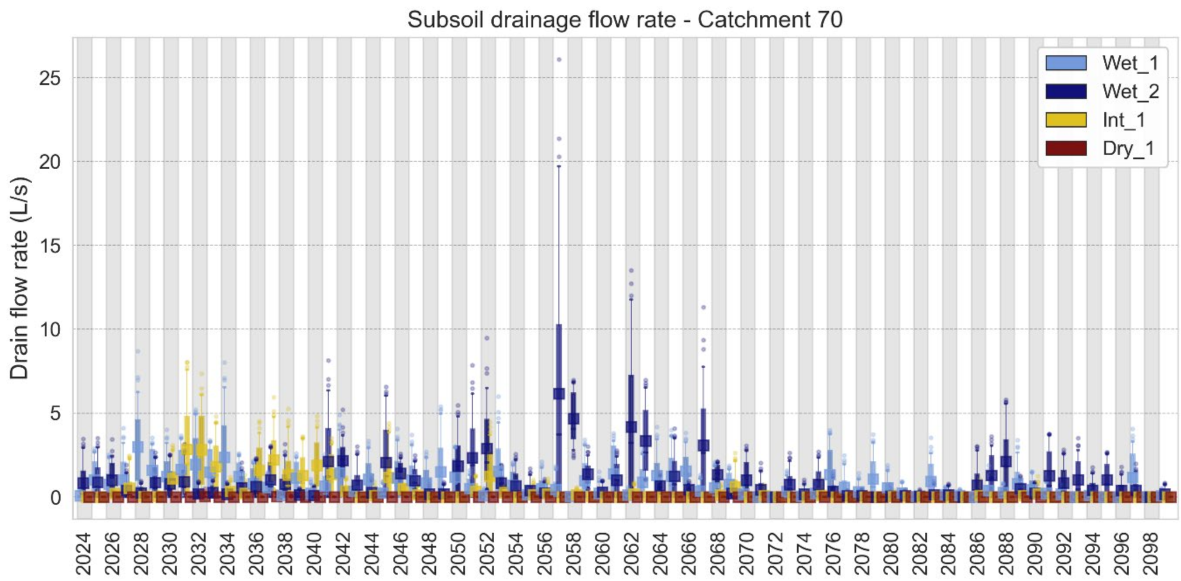

Subsoil drainage flow rate - Catchment 58
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1


Subsoil drainage flow rate - Catchment 59
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

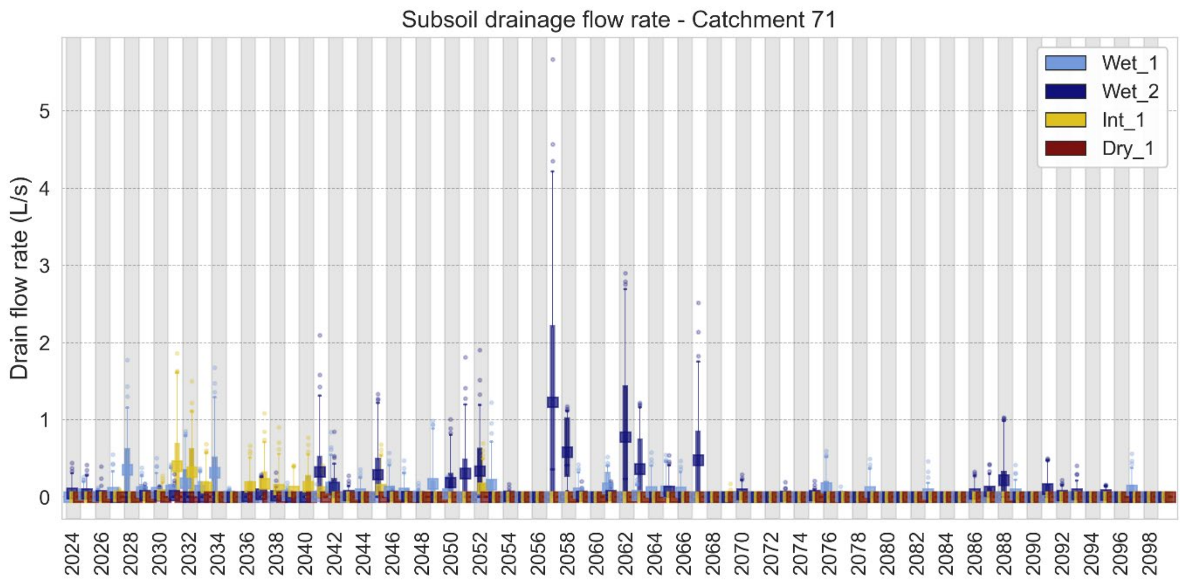

Subsoil drainage flow rate - Catchment 60
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1


Subsoil drainage flow rate - Catchment 64
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

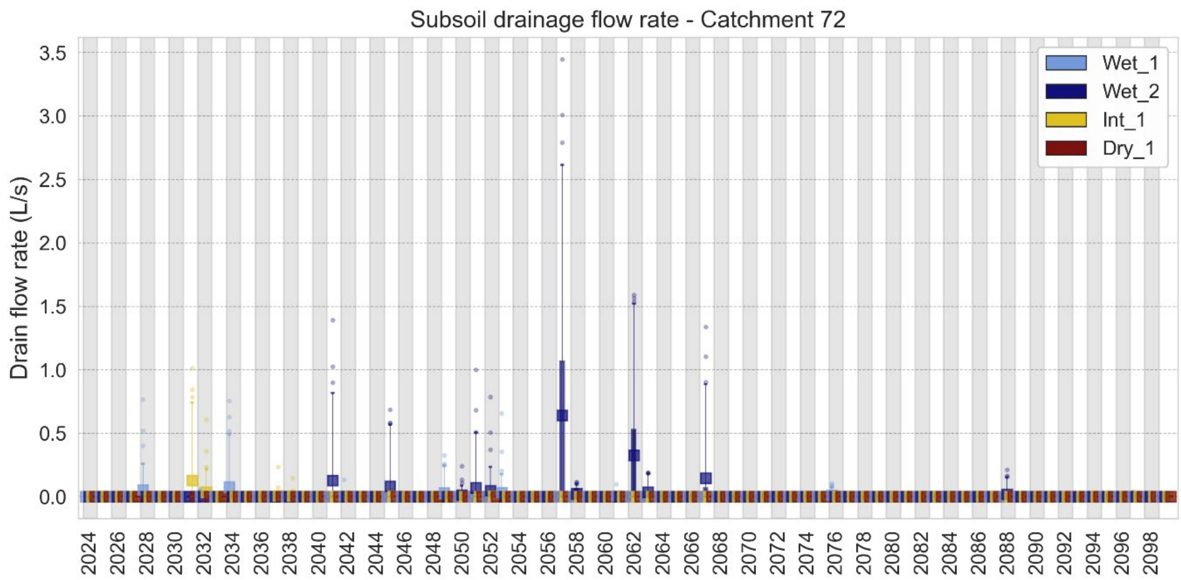

Subsoil drainage flow rate - Catchment 68
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1



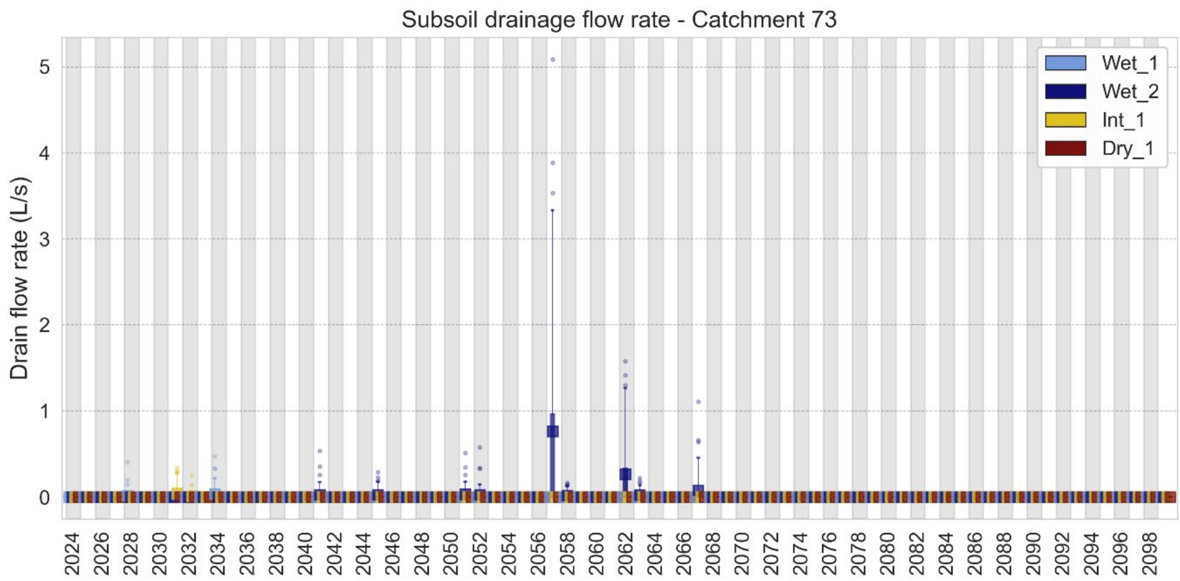
Subsoil drainage flow rate - Catchment 70
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

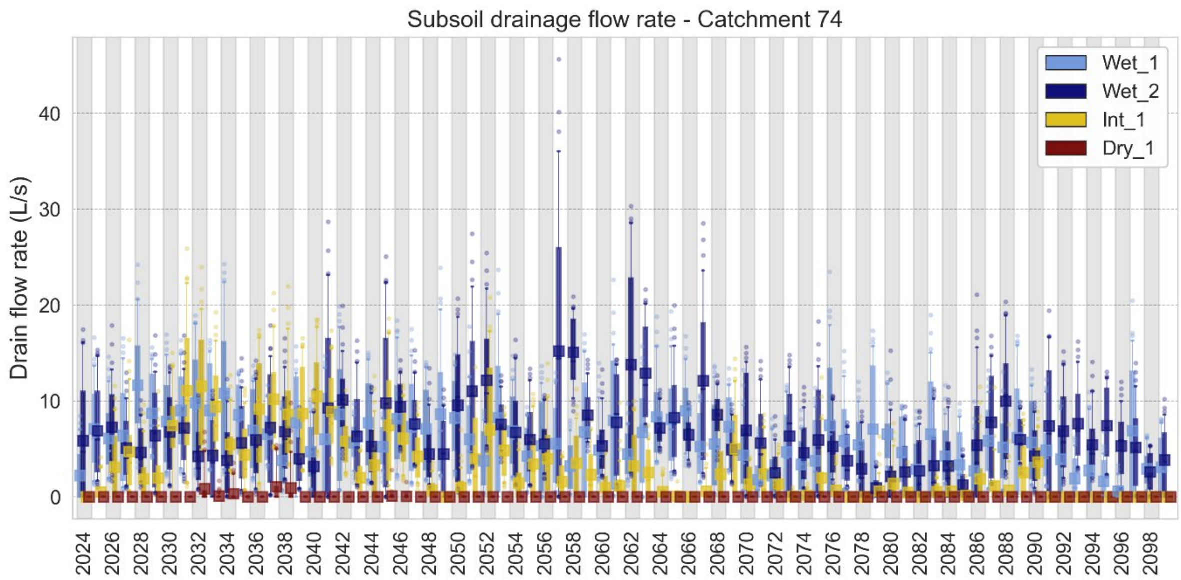


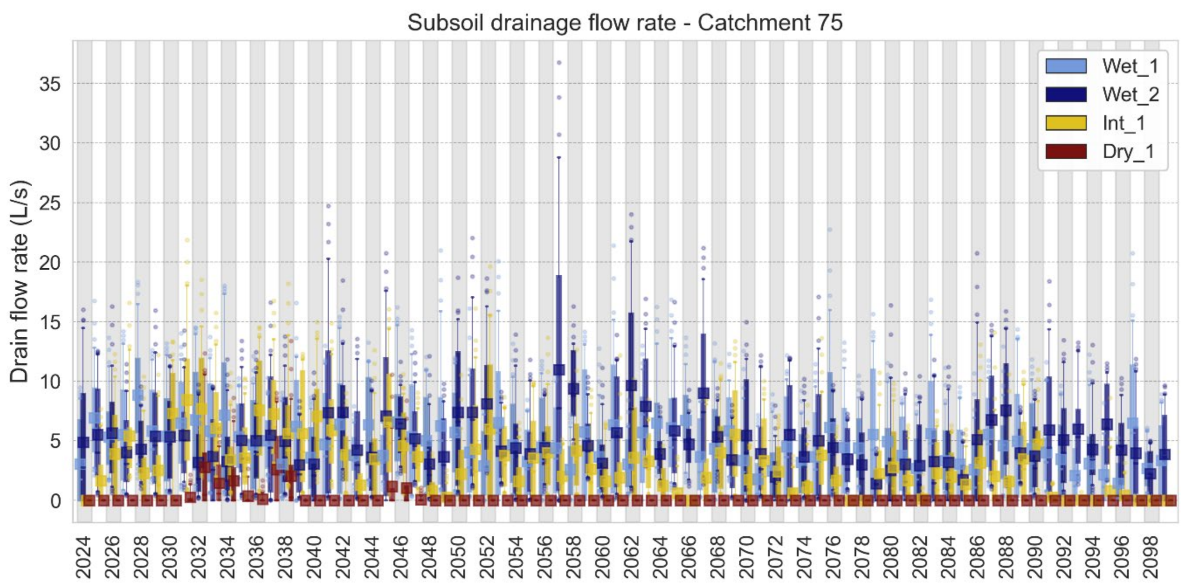
Subsoil drainage flow rate - Catchment 71
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

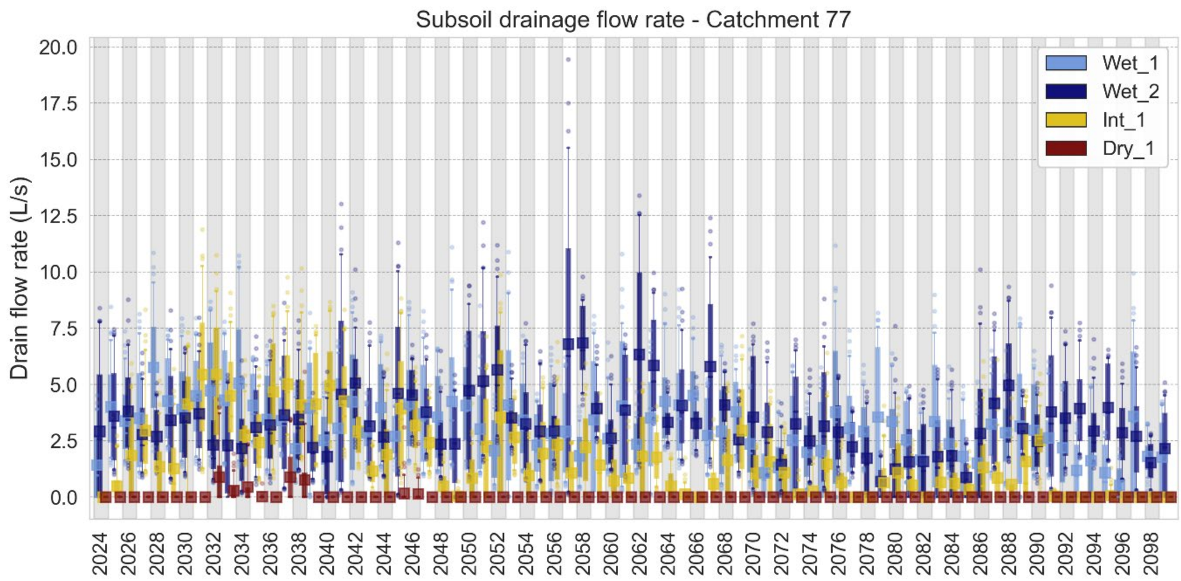


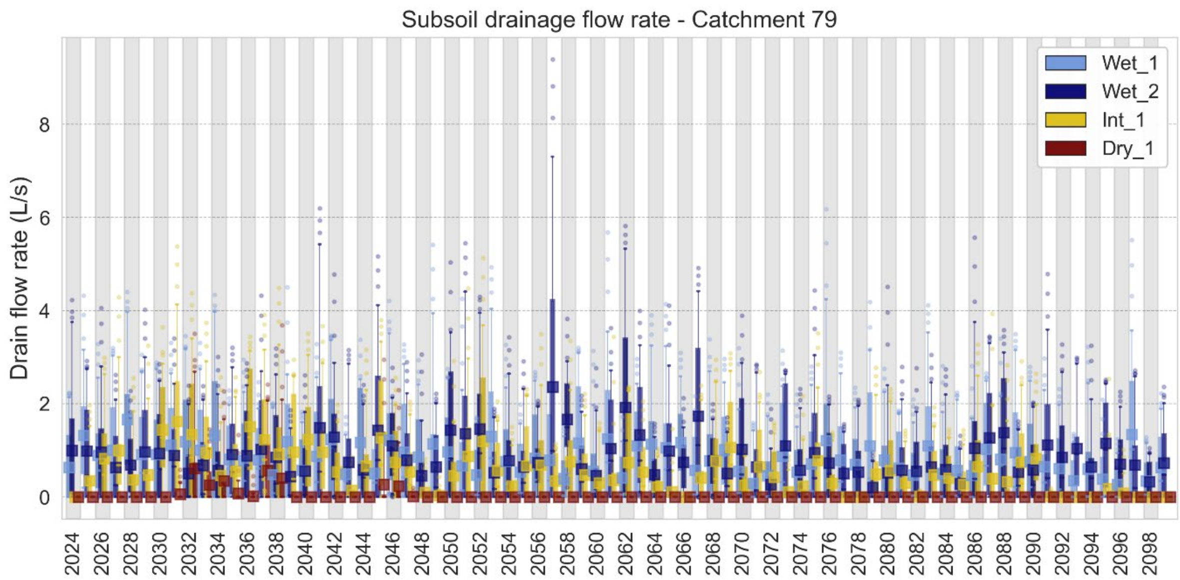
Subsoil drainage flow rate - Catchment 72
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

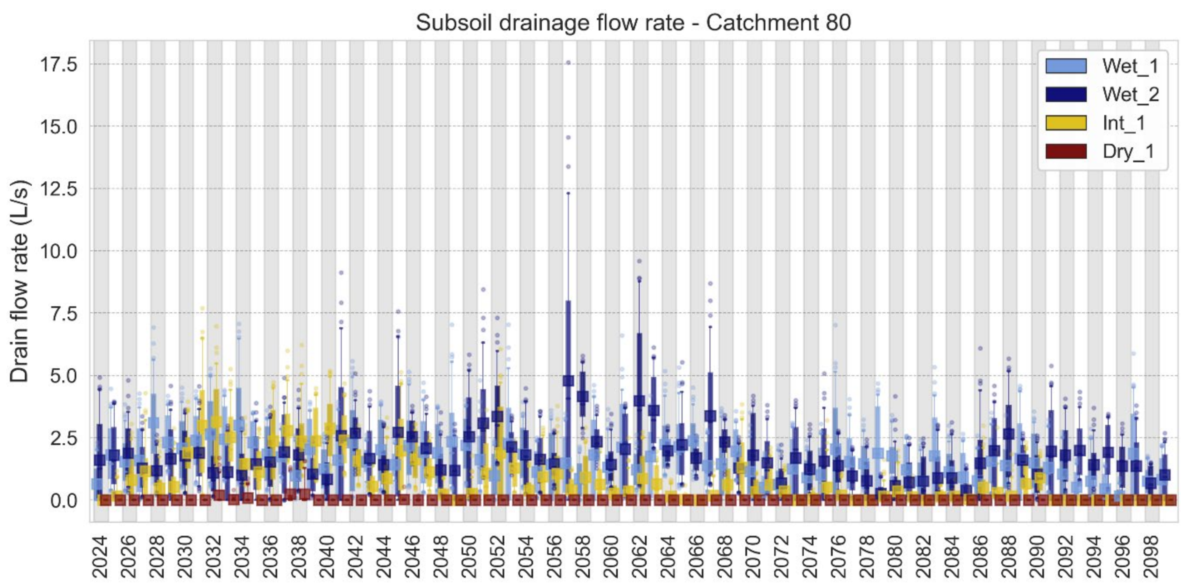

Subsoil drainage flow rate - Catchment 73
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1
0
1
2
3
4
5
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

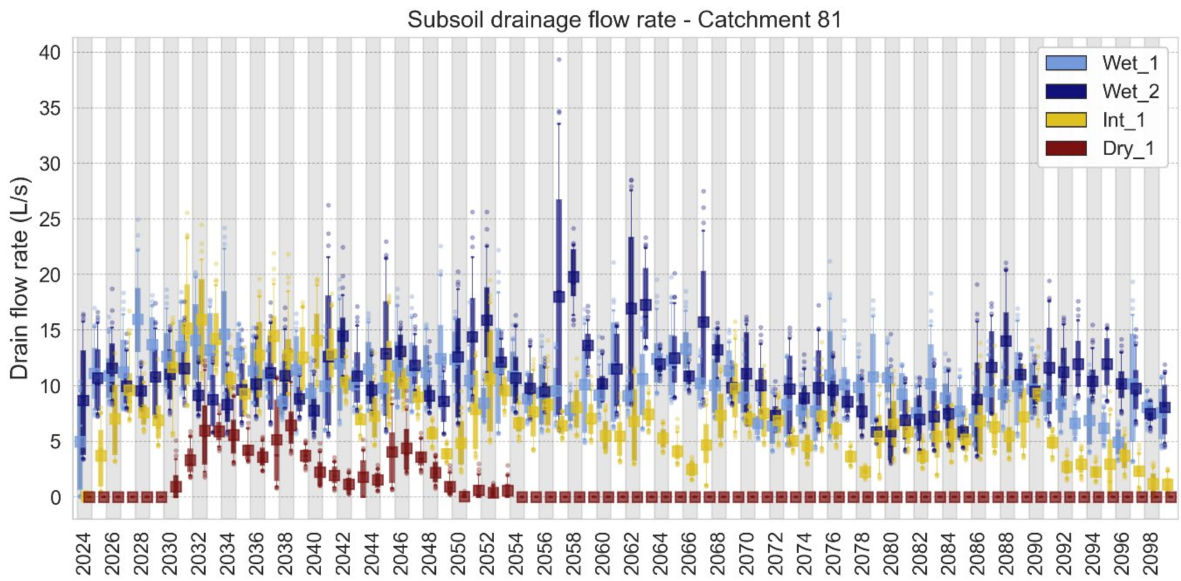

Subsoil drainage flow rate - Catchment 74
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1
0
10
20
30
40
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

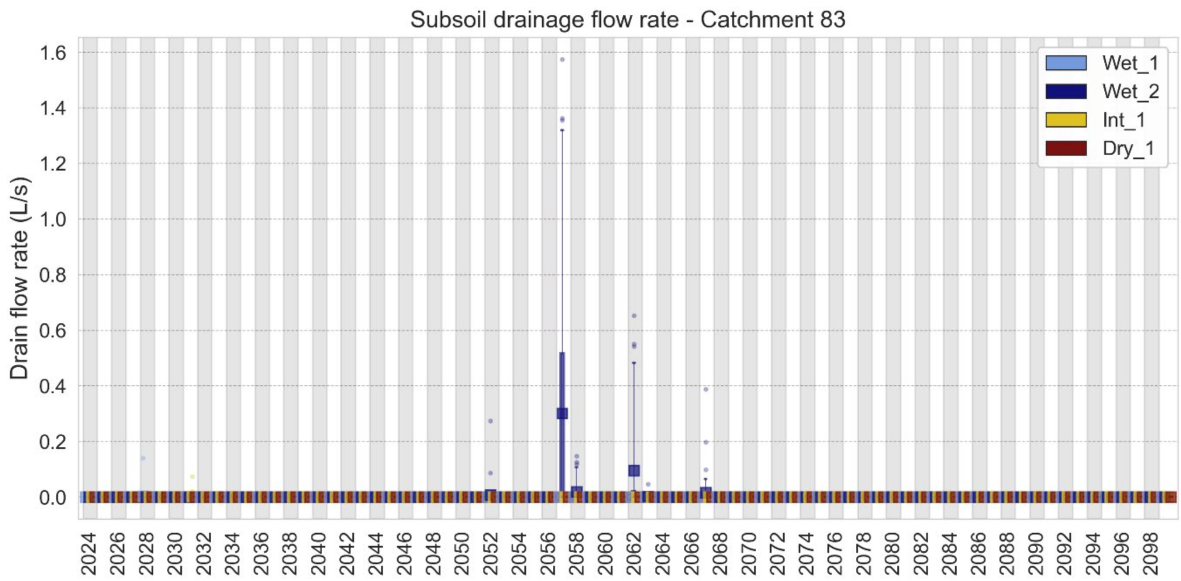

Subsoil drainage flow rate - Catchment 75
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1
0
5
10
15
20
25
30
35
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

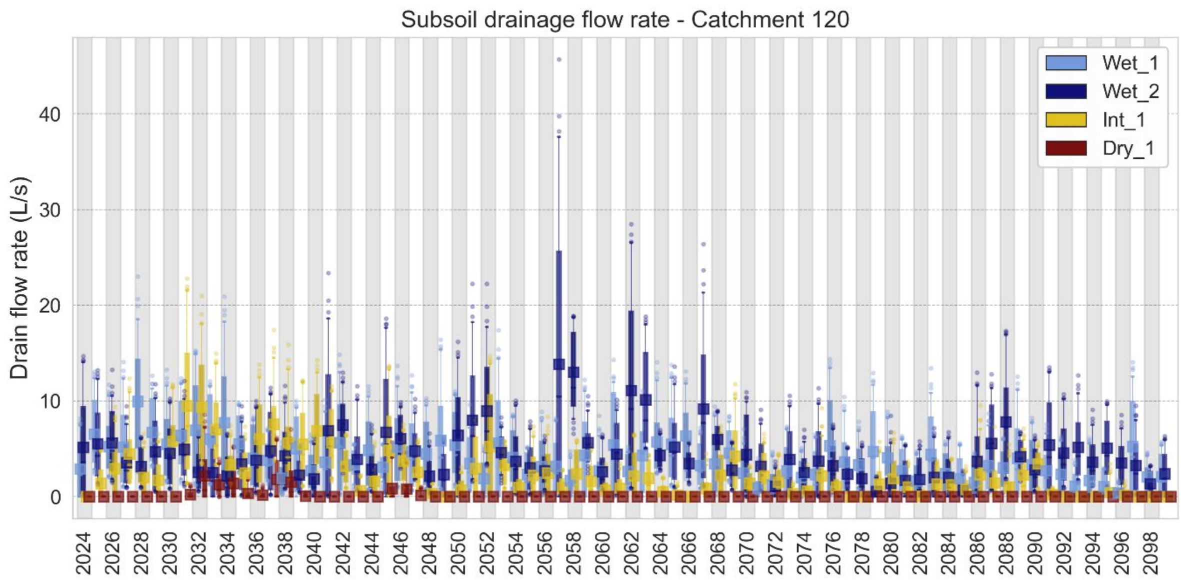

Subsoil drainage flow rate - Catchment 77
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

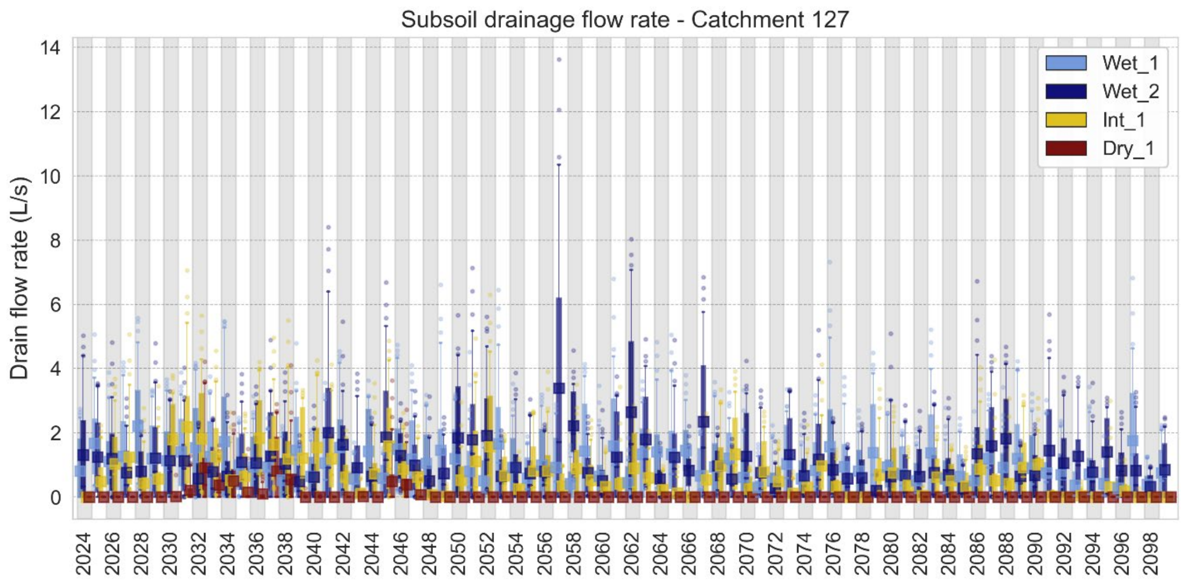

Subsoil drainage flow rate - Catchment 79
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

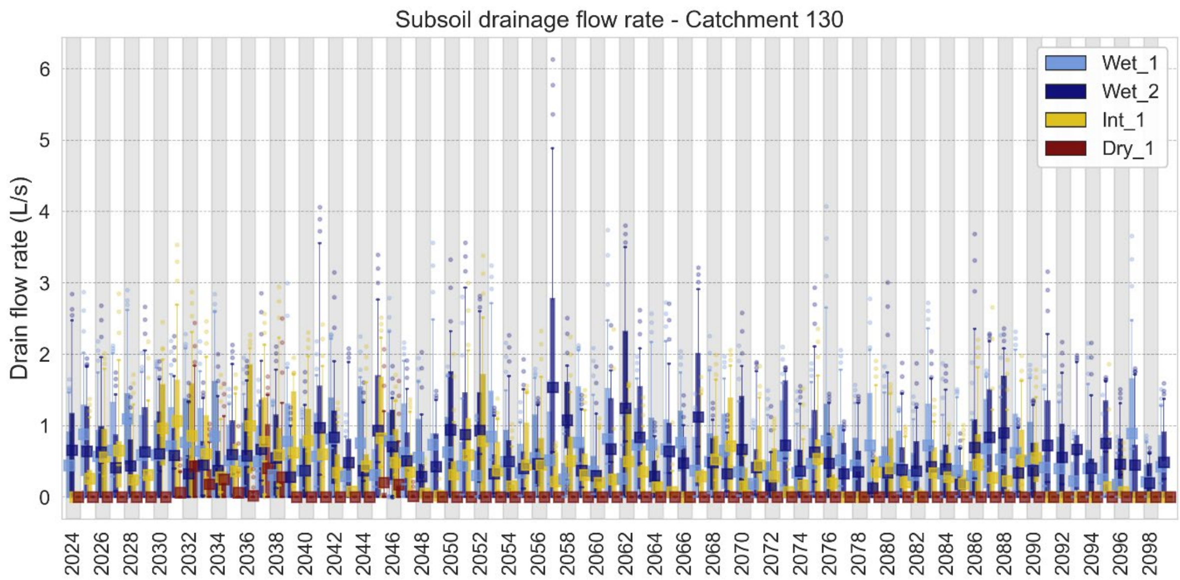

Subsoil drainage flow rate - Catchment 80
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

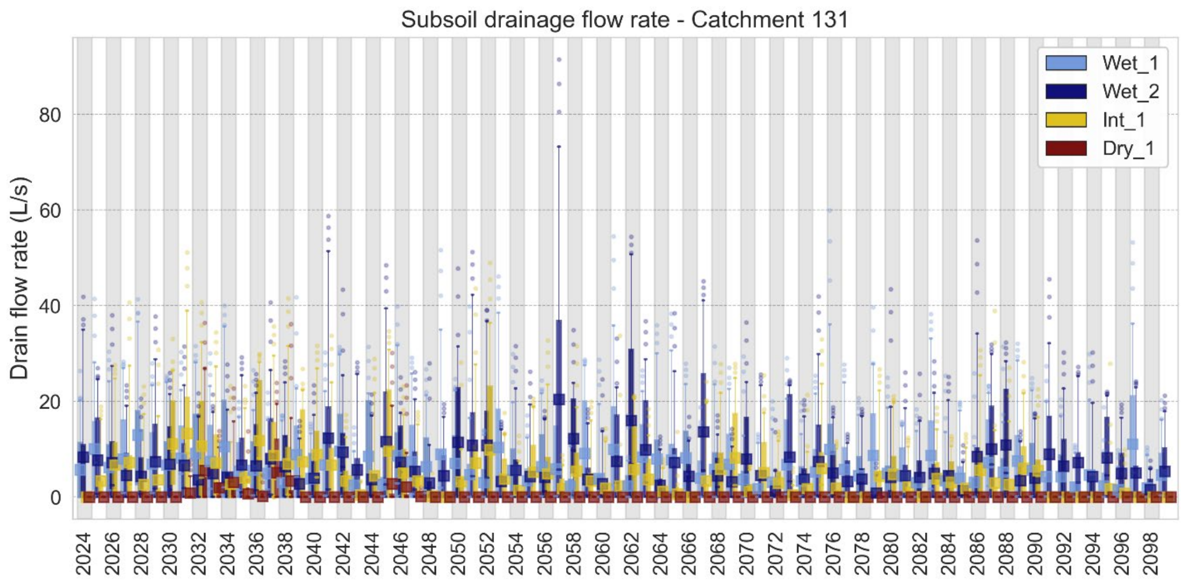

Subsoil drainage flow rate - Catchment 81
Drain flow rate (L/s)
0
5
10
15
20
25
30
35
40
Wet_1
Wet_2
Int_1
Dry_1
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
2052
2054
2056
2058
2060
2062
2064
2066
2068
2070
2072
2074
2076
2078
2080
2082
2084
2086
2088
2090
2092
2094
2096
2098

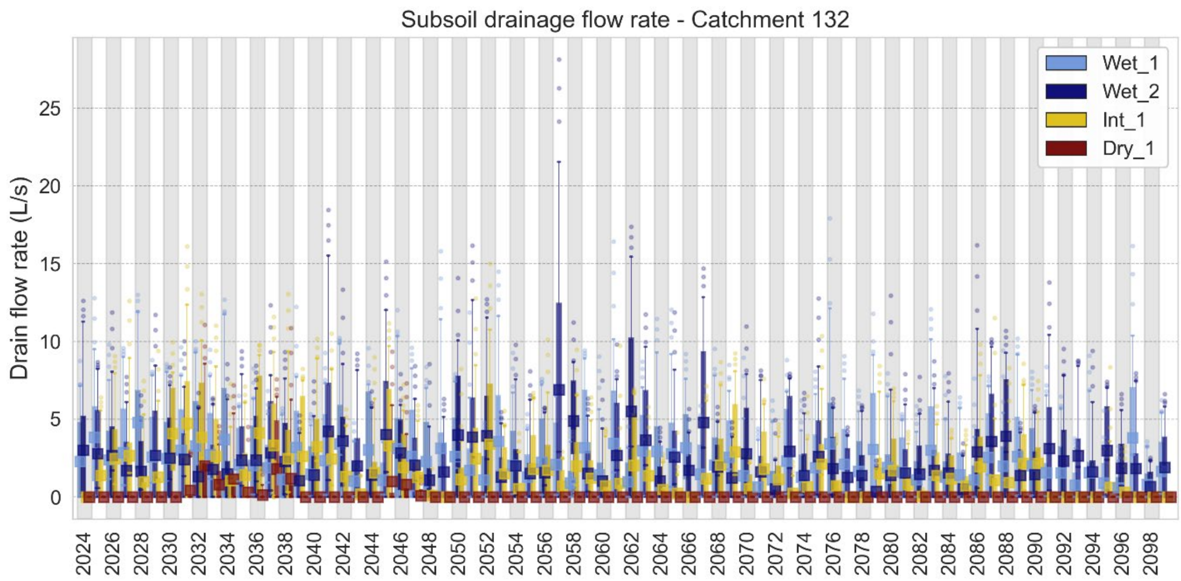

Subsoil drainage flow rate - Catchment 83
Drain flow rate (L/s)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Wet_1
Wet_2
Int_1
Dry_1
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
2052
2054
2056
2058
2060
2062
2064
2066
2068
2070
2072
2074
2076
2078
2080
2082
2084
2086
2088
2090
2092
2094
2096
2098

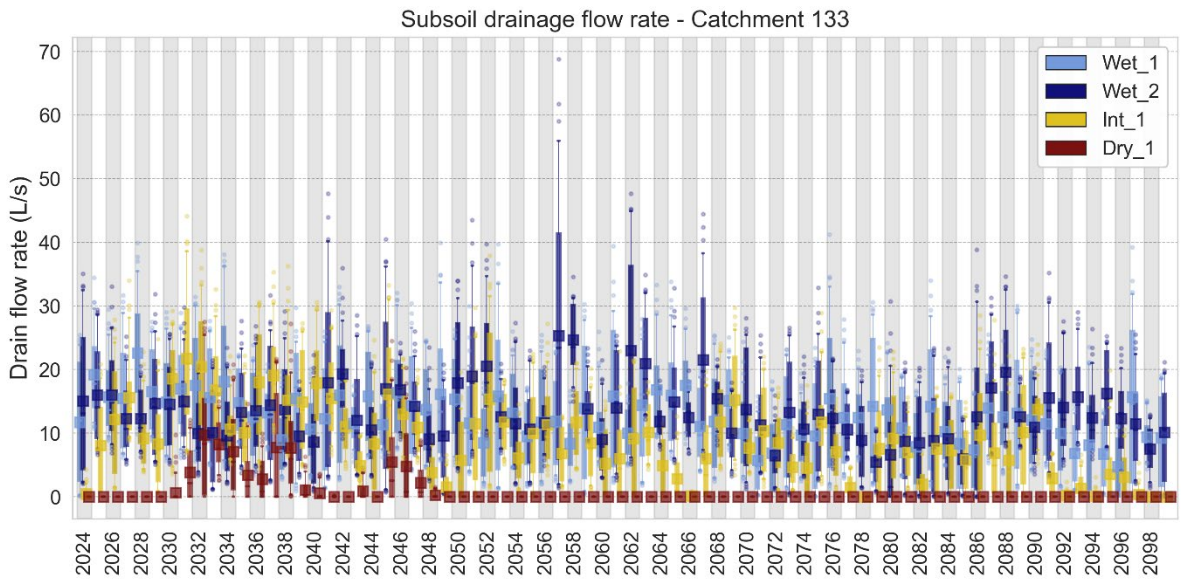

Subsoil drainage flow rate - Catchment 120
Drain flow rate (L/s)
0
10
20
30
40
Wet_1
Wet_2
Int_1
Dry_1
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
2052
2054
2056
2058
2060
2062
2064
2066
2068
2070
2072
2074
2076
2078
2080
2082
2084
2086
2088
2090
2092
2094
2096
2098

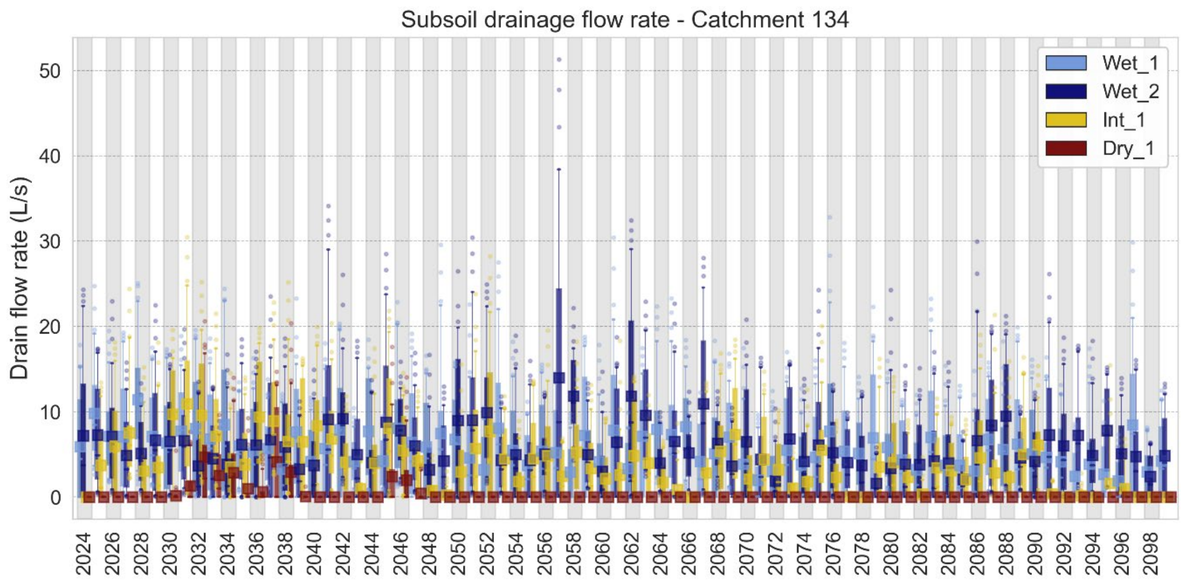

Subsoil drainage flow rate - Catchment 127
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

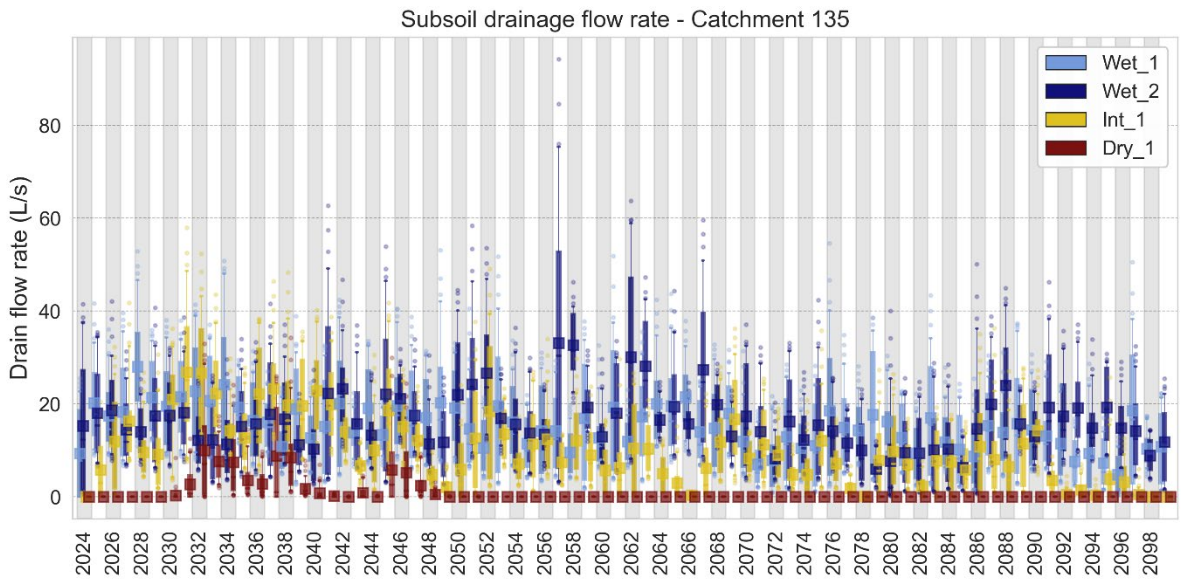

Subsoil drainage flow rate - Catchment 130
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

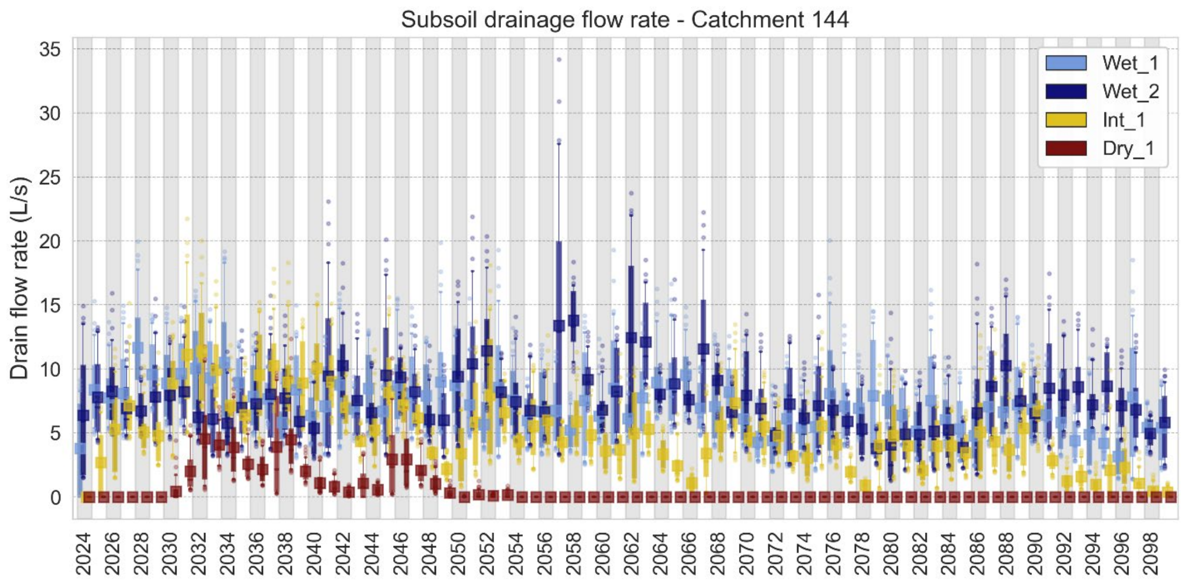

Subsoil drainage flow rate - Catchment 131
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

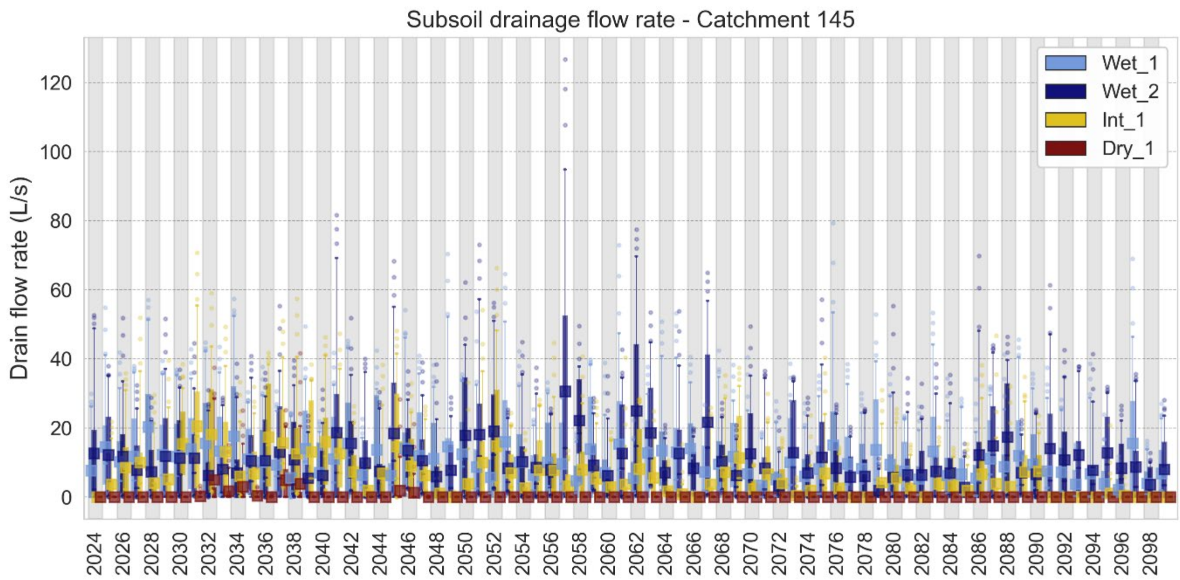

Subsoil drainage flow rate - Catchment 132
Drain flow rate (L/s)
0
5
10
15
20
25
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

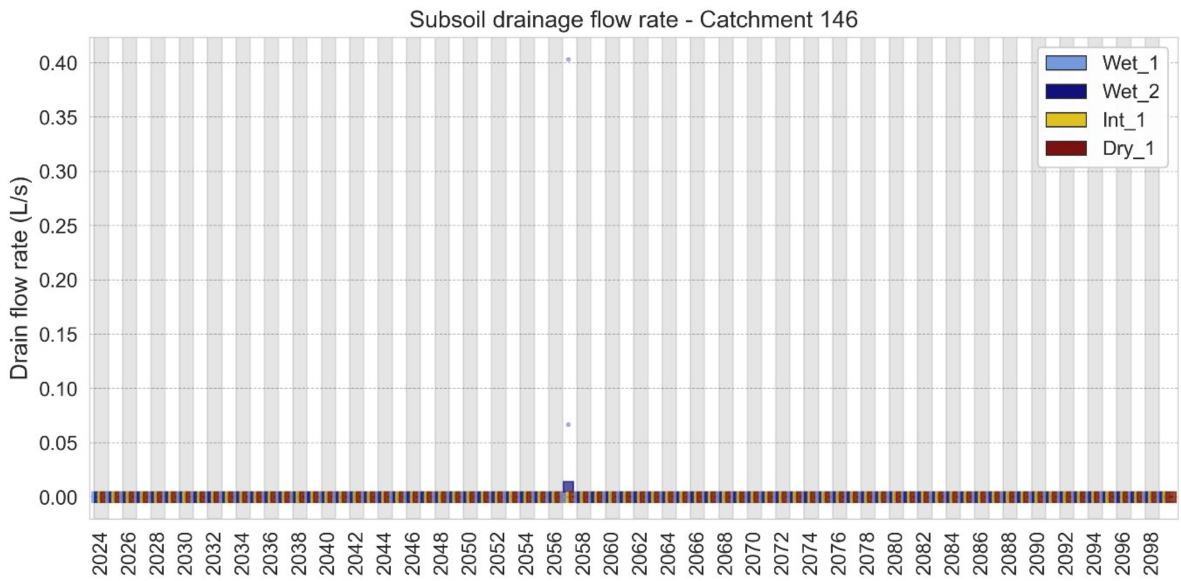

Subsoil drainage flow rate - Catchment 133
Drain flow rate (L/s)
0
10
20
30
40
50
60
70
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

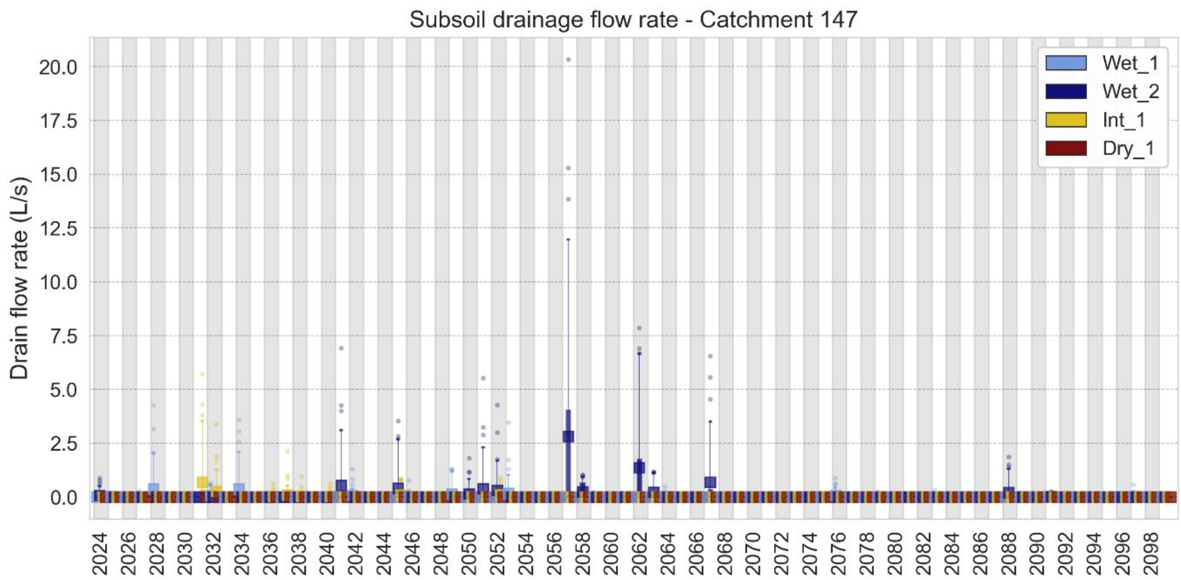

Subsoil drainage flow rate - Catchment 134
Drain flow rate (L/s)
0
10
20
30
40
50
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

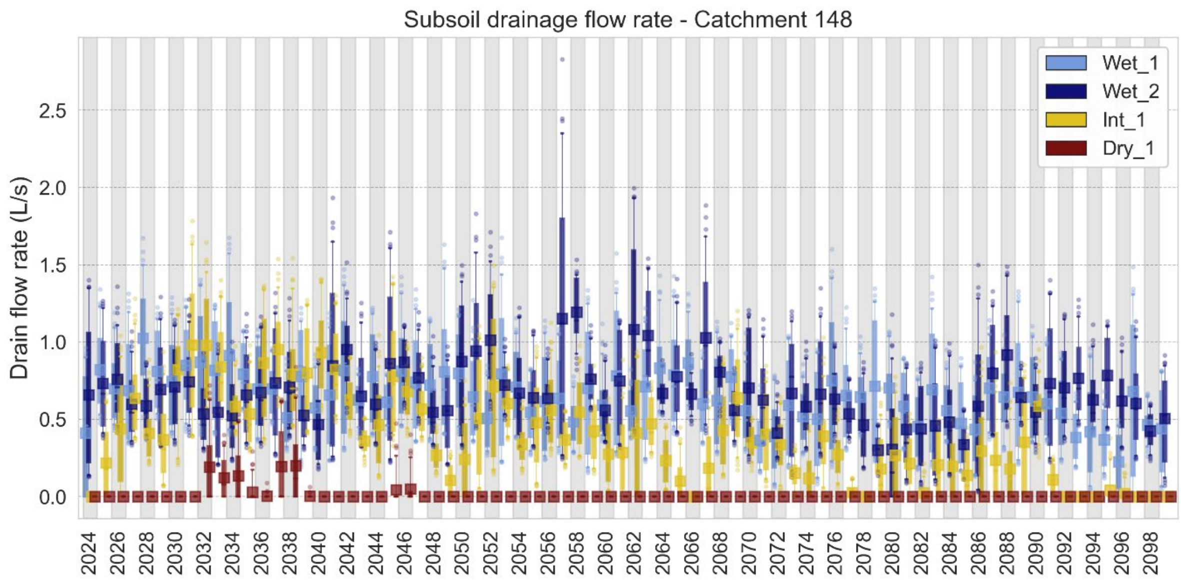

Subsoil drainage flow rate - Catchment 135
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

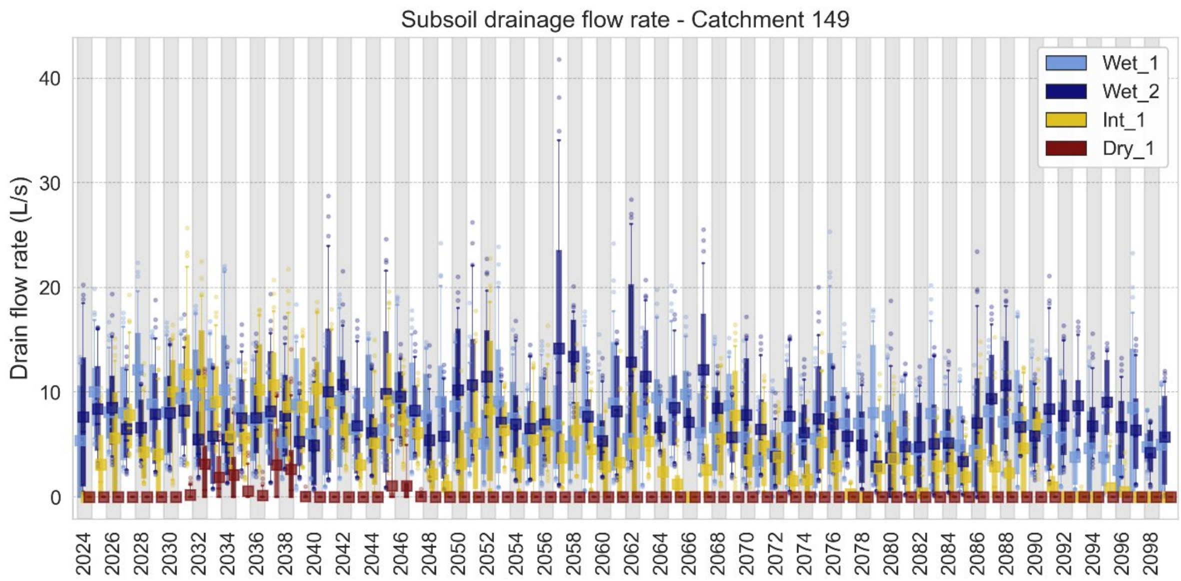

Subsoil drainage flow rate - Catchment 144
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

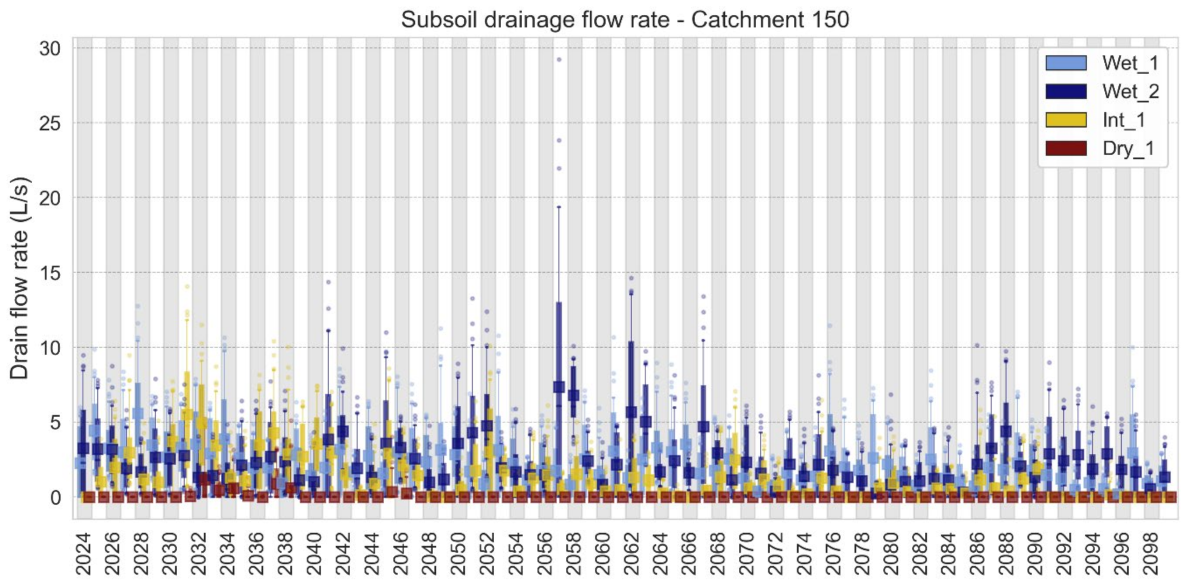

Subsoil drainage flow rate - Catchment 145
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

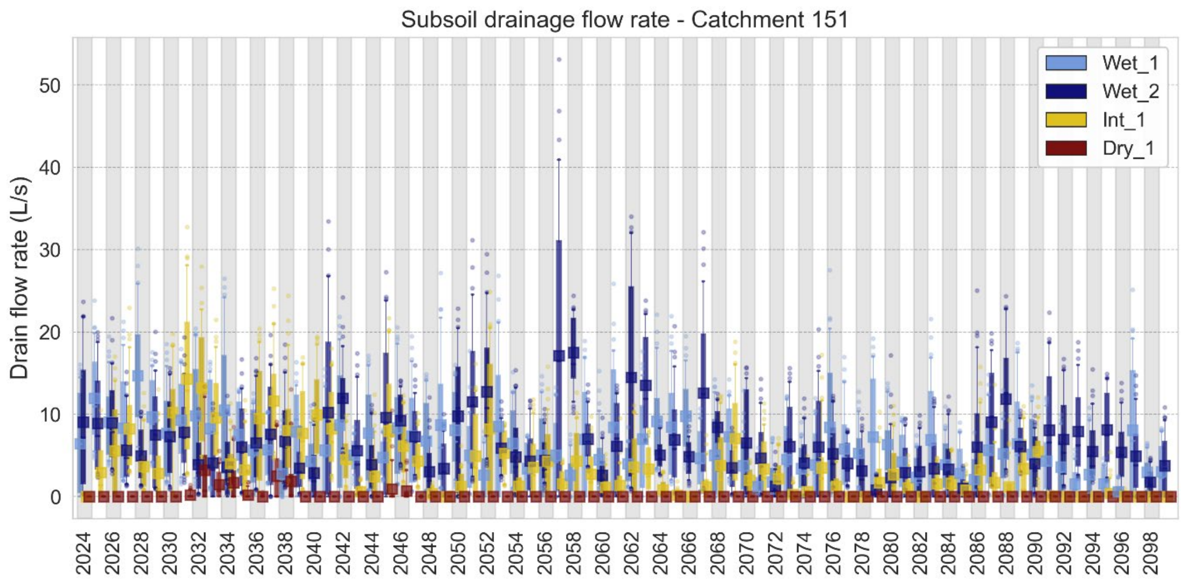

Subsoil drainage flow rate - Catchment 146
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

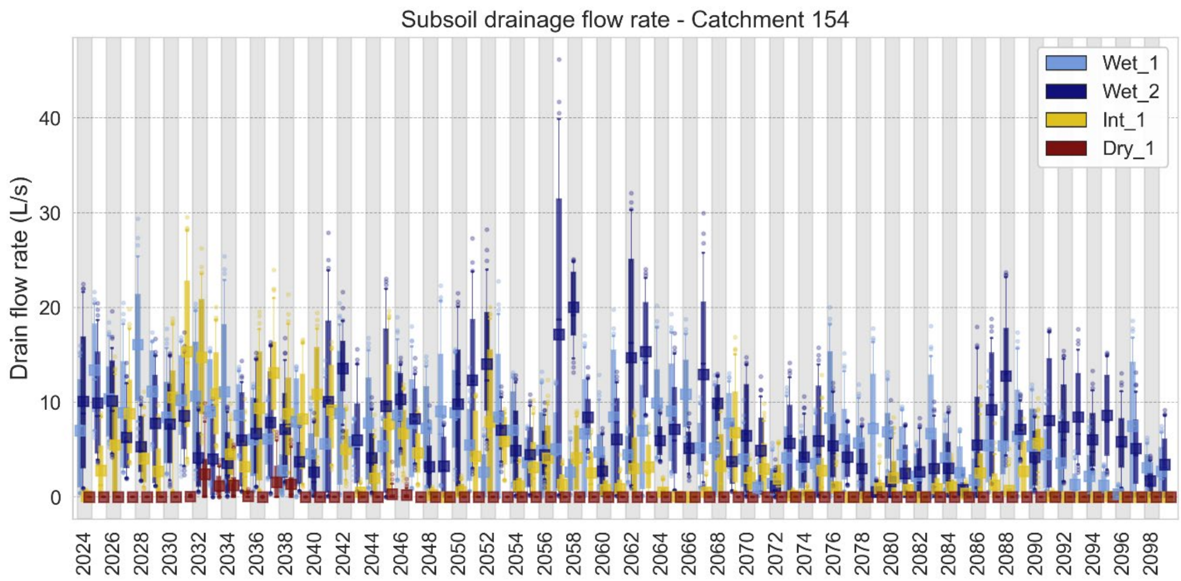

Subsoil drainage flow rate - Catchment 147
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

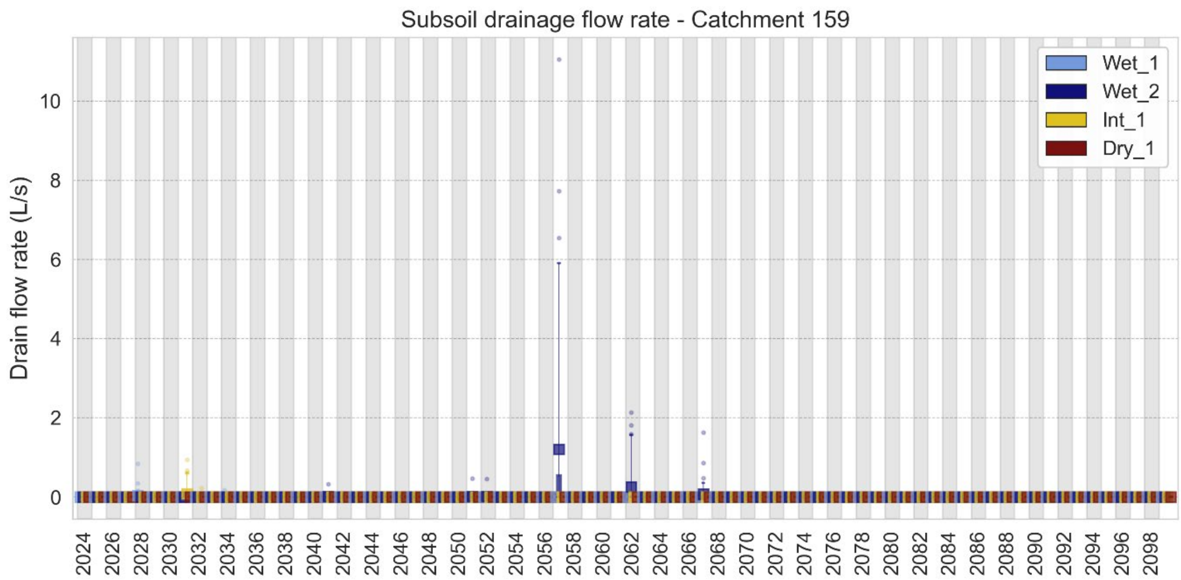

Subsoil drainage flow rate - Catchment 148
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

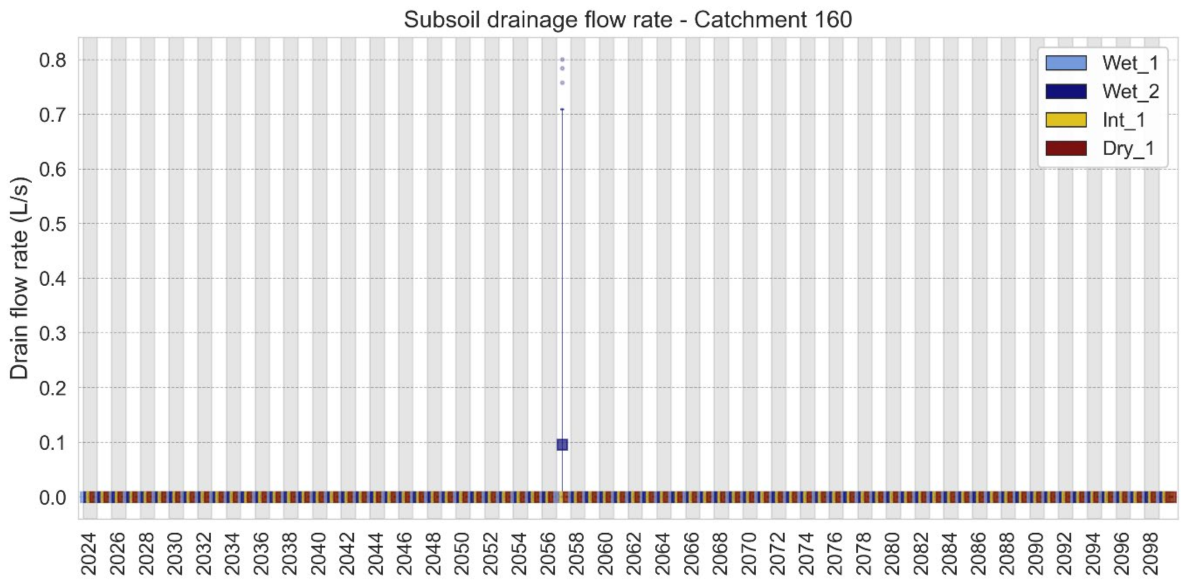

Subsoil drainage flow rate - Catchment 149
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

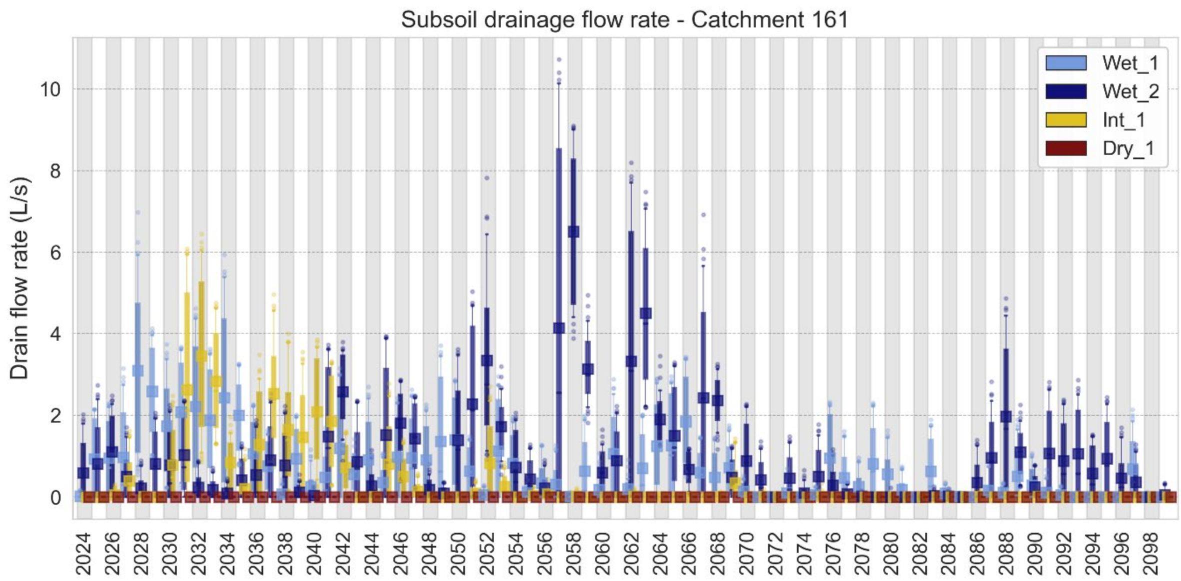

Subsoil drainage flow rate - Catchment 150
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

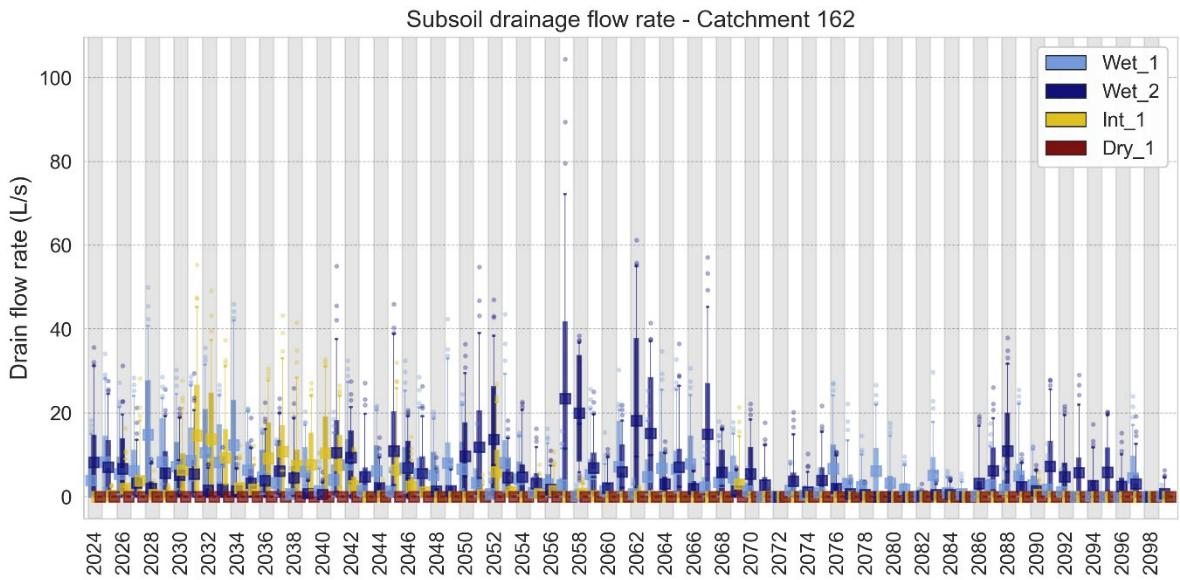

Subsoil drainage flow rate - Catchment 151
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

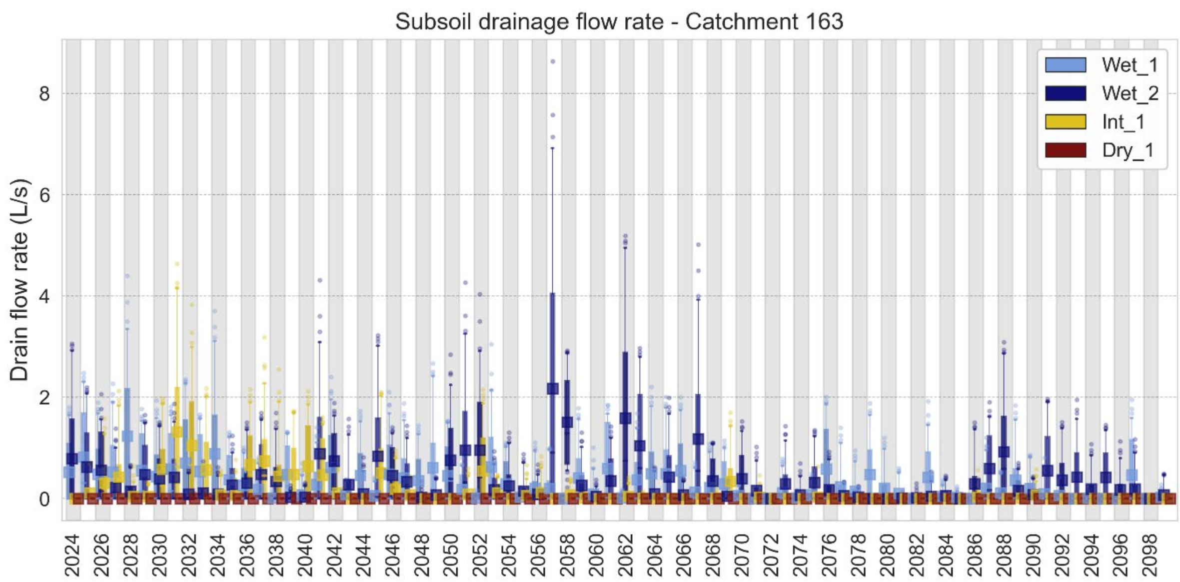

Subsoil drainage flow rate - Catchment 154
Drain flow rate (L/s)
0
10
20
30
40
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

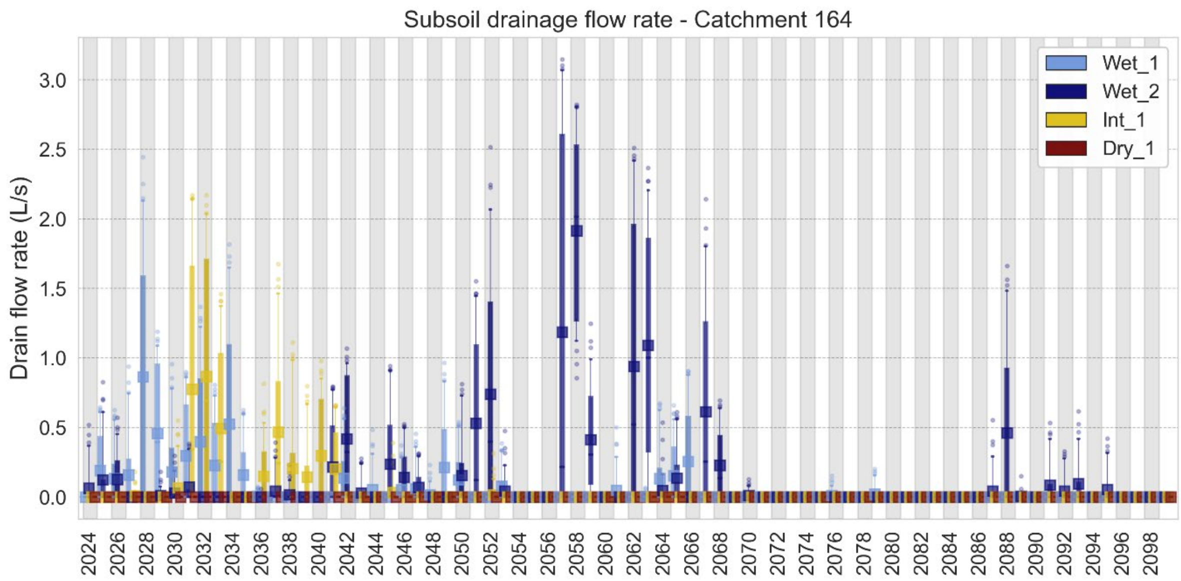

Subsoil drainage flow rate - Catchment 159
Drain flow rate (L/s)
0
2
4
6
8
10
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

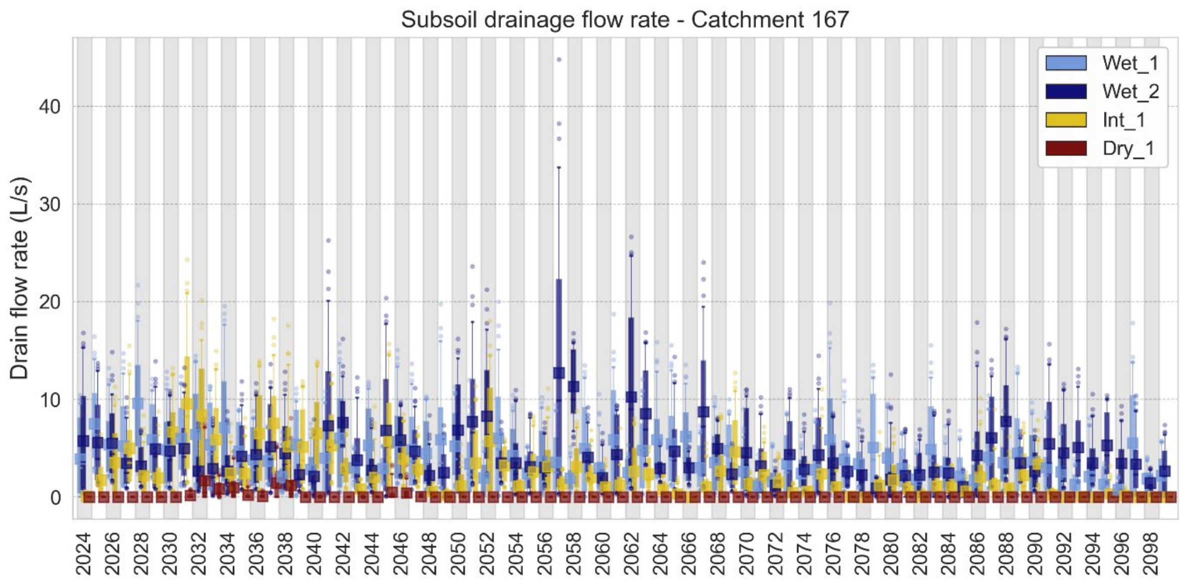

Subsoil drainage flow rate - Catchment 160
Drain flow rate (L/s)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

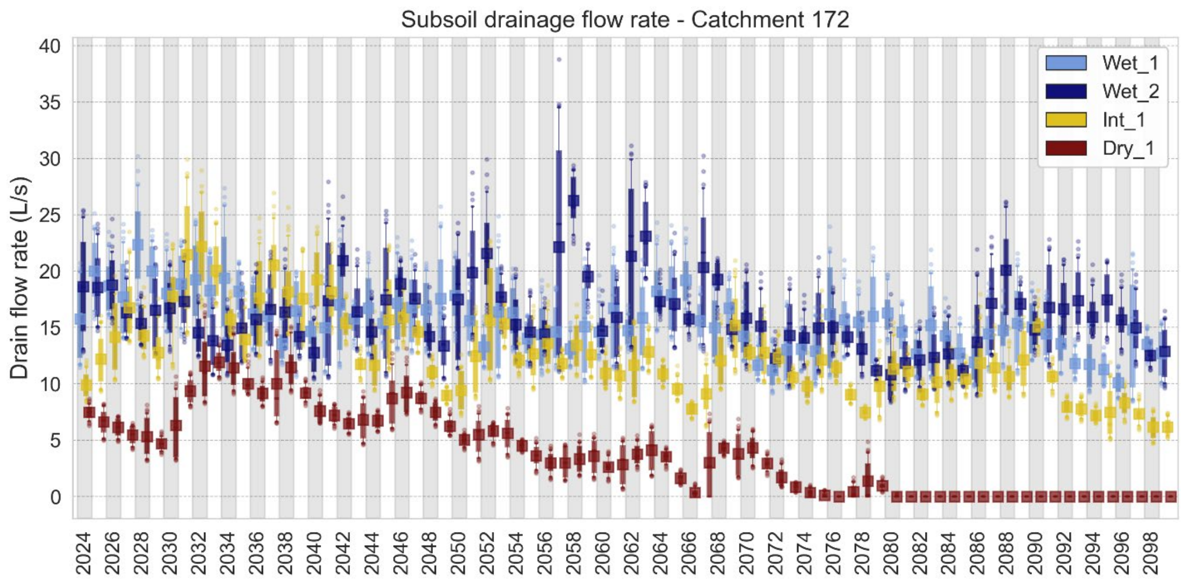

Subsoil drainage flow rate - Catchment 161
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

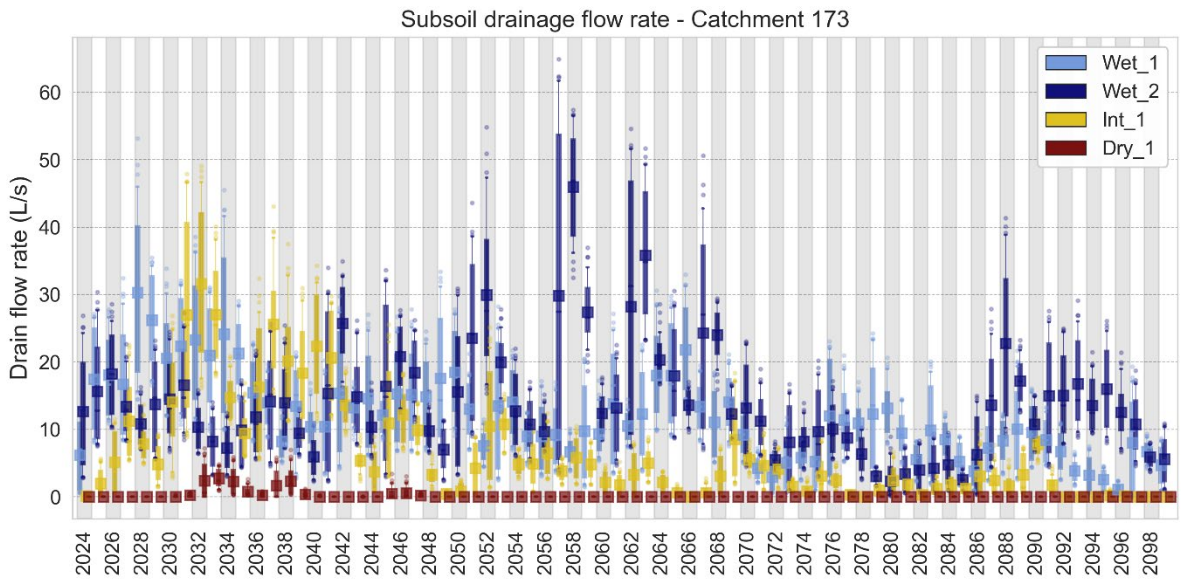

Subsoil drainage flow rate - Catchment 162
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

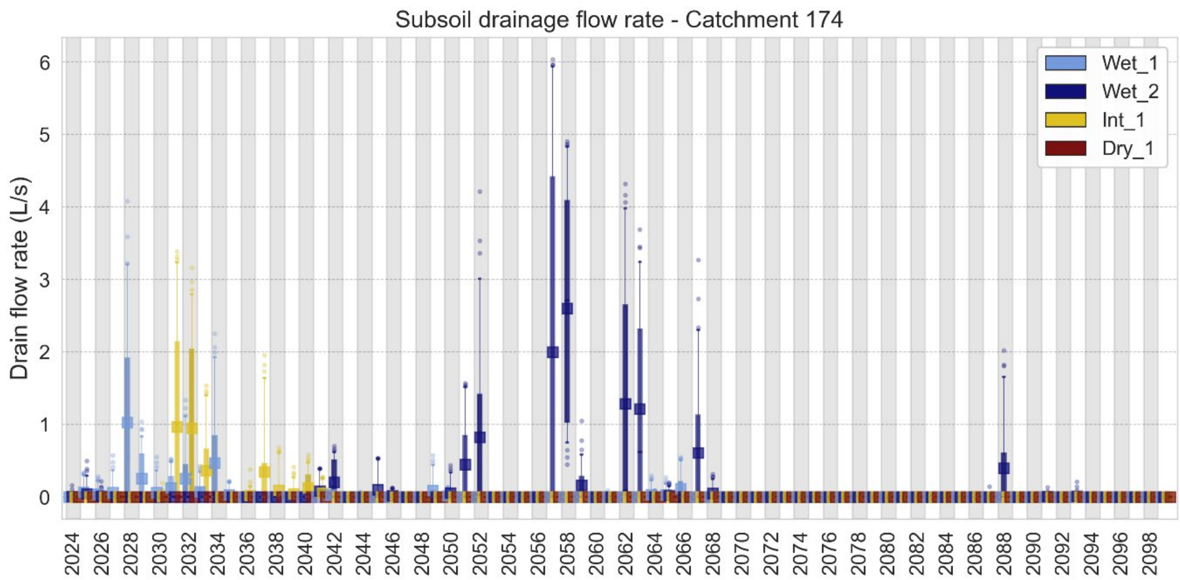

Subsoil drainage flow rate - Catchment 163
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

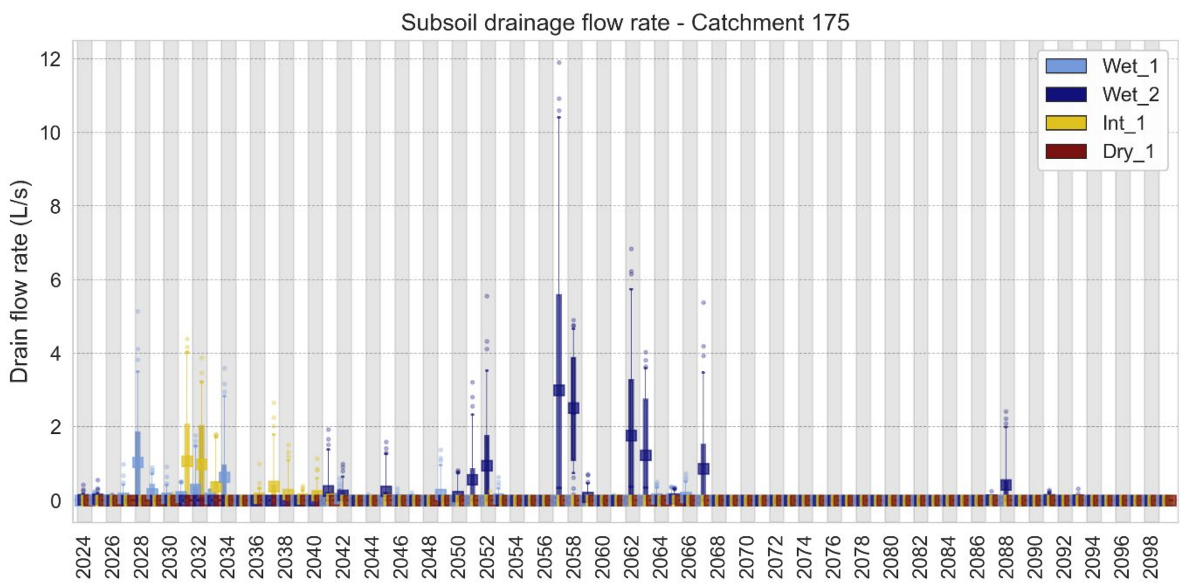

Subsoil drainage flow rate - Catchment 164
Drain flow rate (L/s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

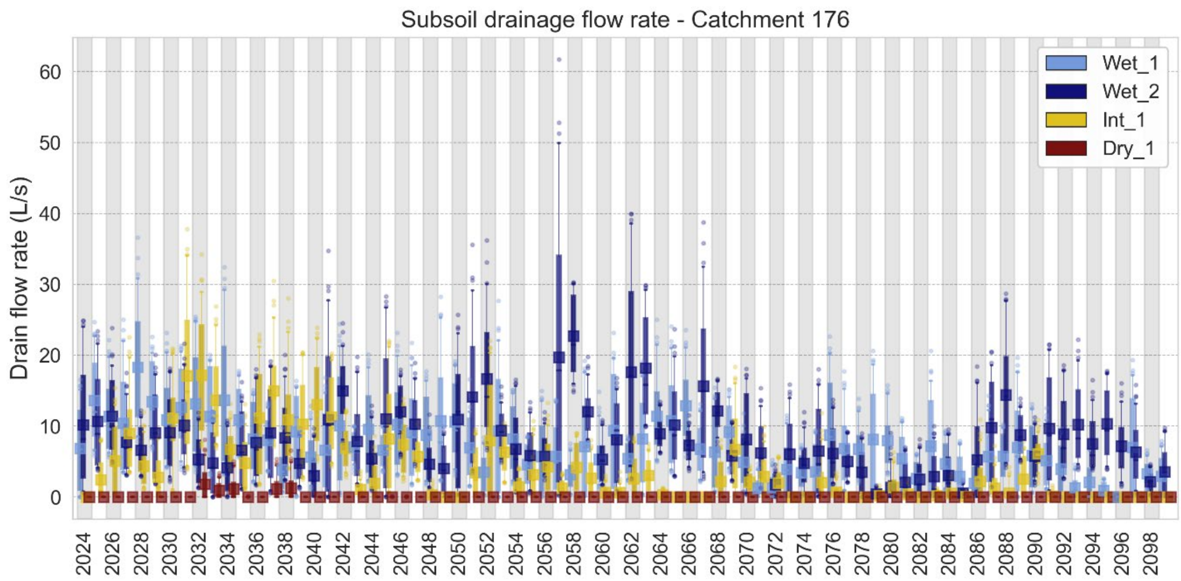

Subsoil drainage flow rate - Catchment 167
Drain flow rate (L/s)
0
10
20
30
40
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

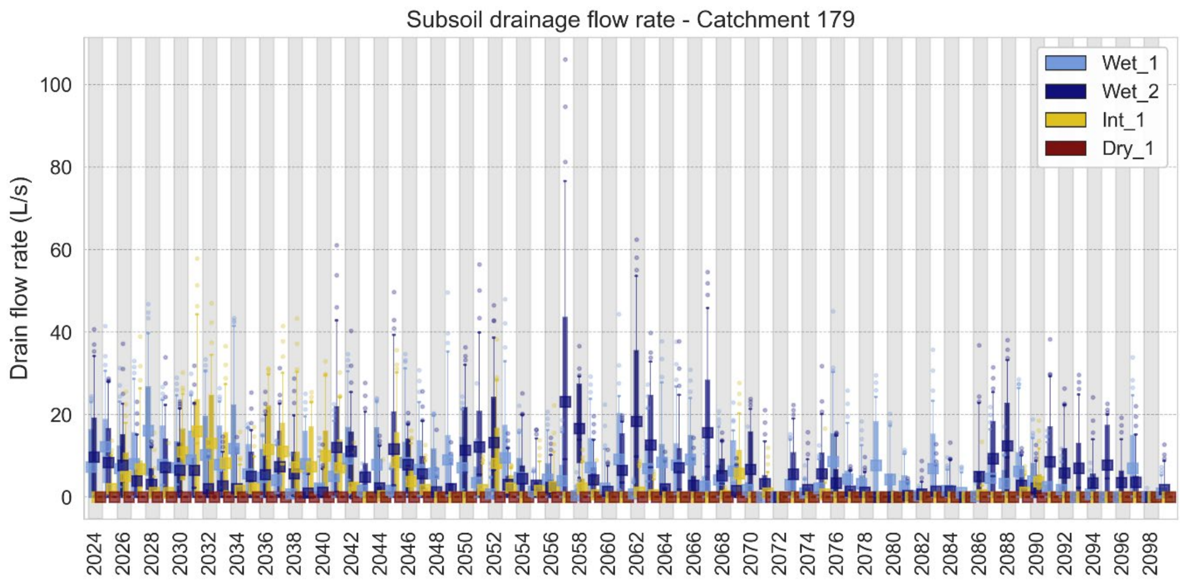

Subsoil drainage flow rate - Catchment 172
Drain flow rate (L/s)
0
5
10
15
20
25
30
35
40
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098

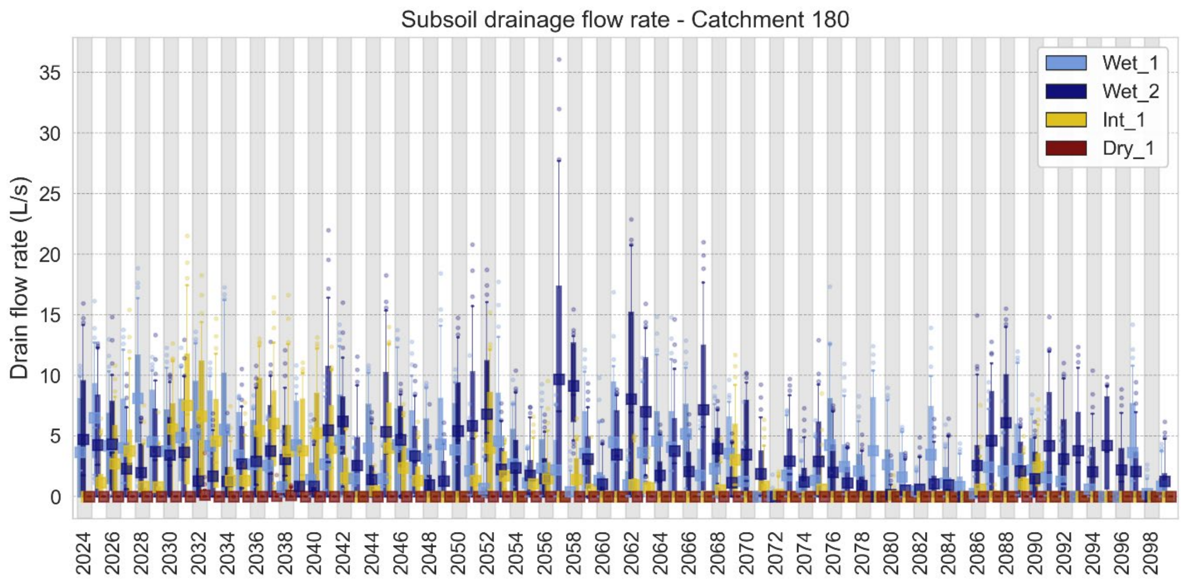

Subsoil drainage flow rate - Catchment 173
Wet_1
Wet_2
Int_1
Dry_1
Drain flow rate (L/s)

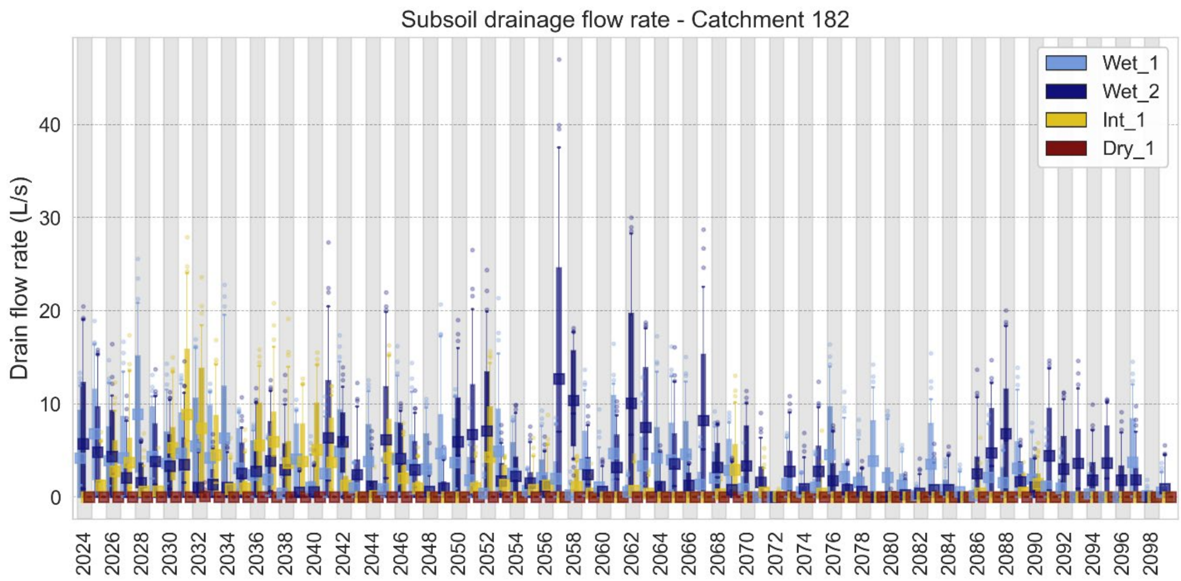

Subsoil drainage flow rate - Catchment 174
Wet_1
Wet_2
Int_1
Dry_1
Drain flow rate (L/s)


Subsoil drainage flow rate - Catchment 175
Wet_1
Wet_2
Int_1
Dry_1
Drain flow rate (L/s)


Subsoil drainage flow rate - Catchment 176
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1


Subsoil drainage flow rate - Catchment 179
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1


Subsoil drainage flow rate - Catchment 180
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1


Subsoil drainage flow rate - Catchment 182
Wet_1
Wet_2
Int_1
Dry_1
Drain flow rate (L/s)
0
10
20
30
40
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
2052
2054
2056
2058
2060
2062
2064
2066
2068
2070
2072
2074
2076
2078
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2082
2084
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2092
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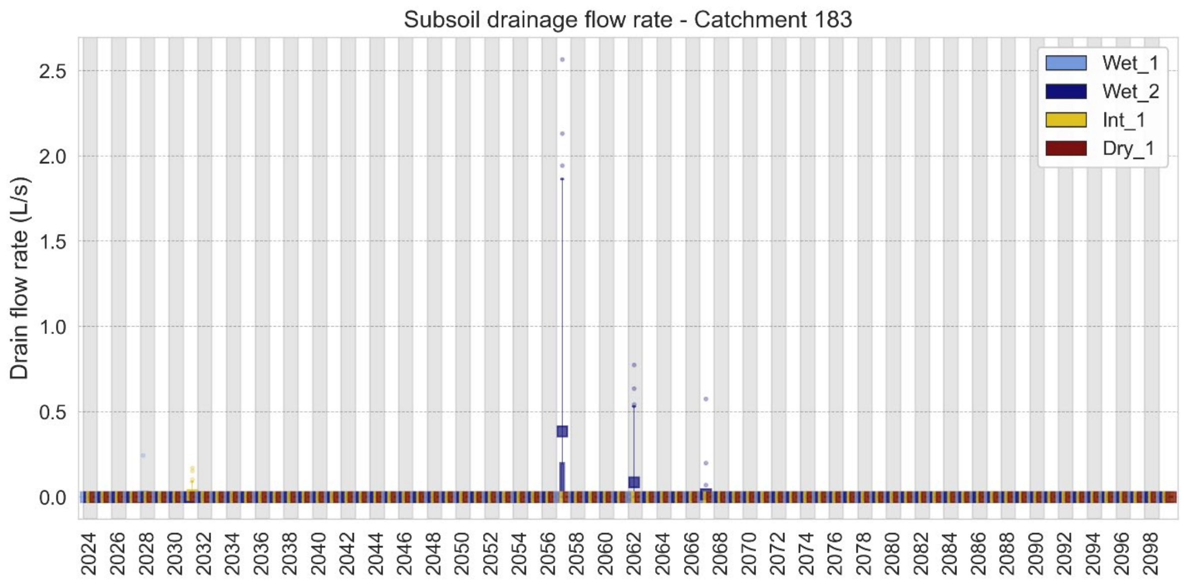
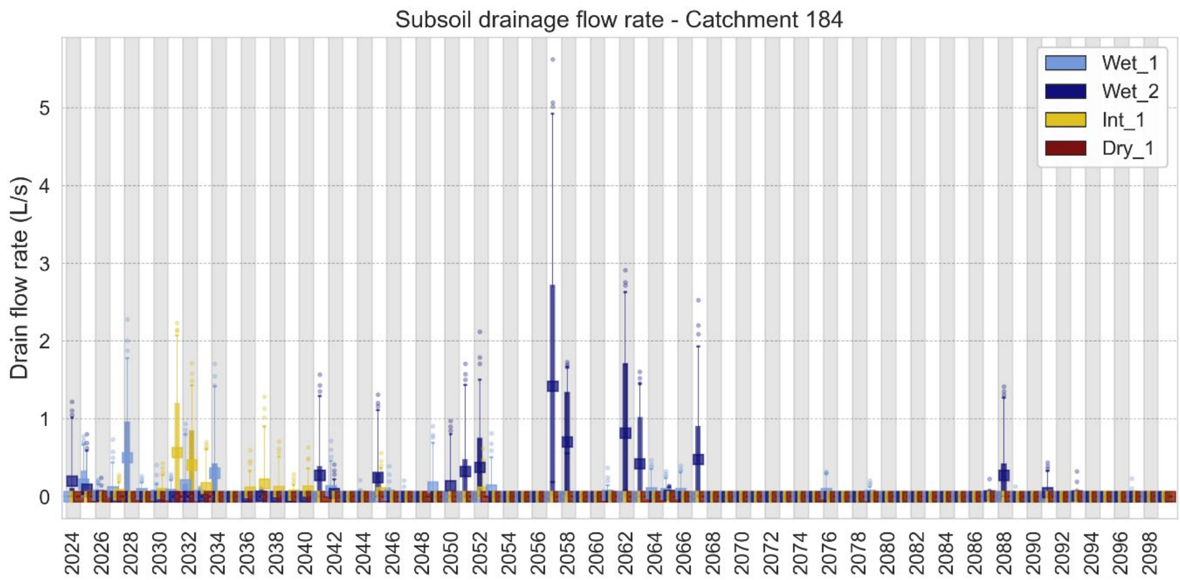
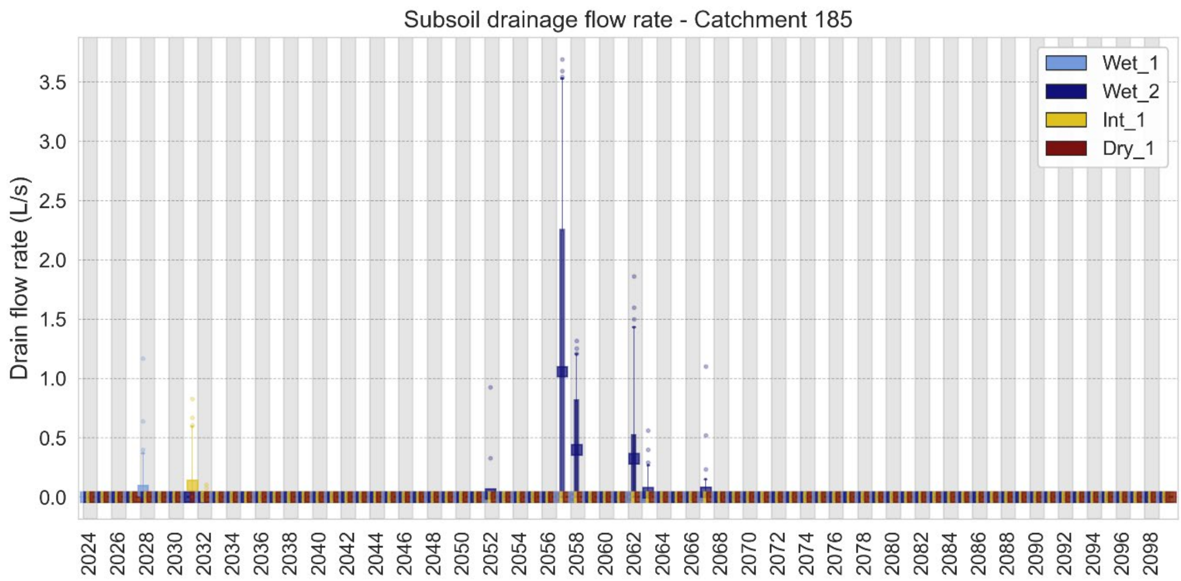
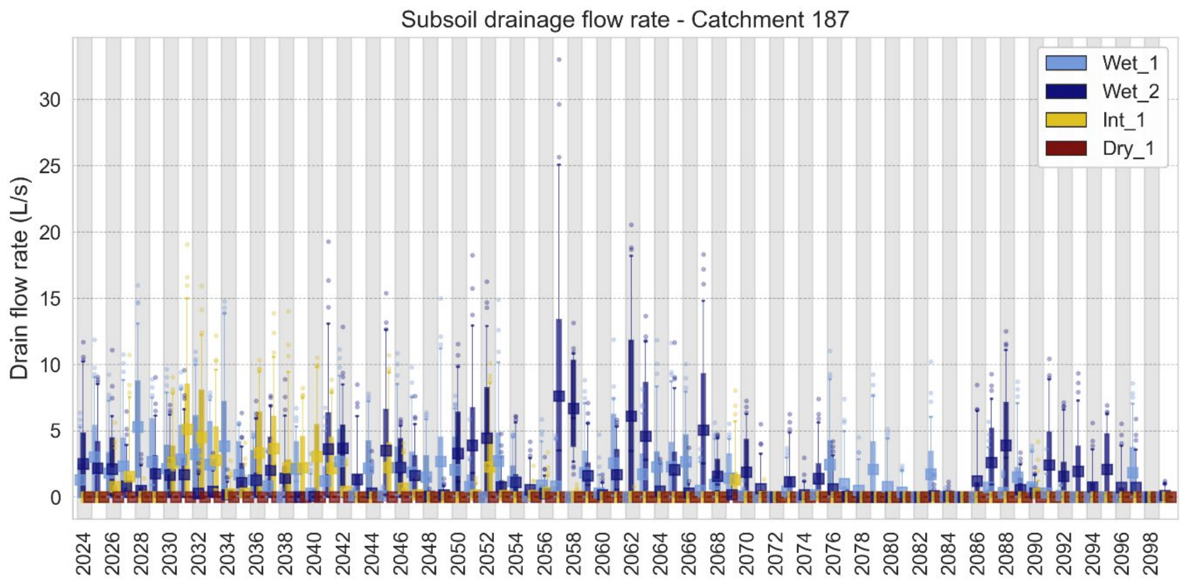
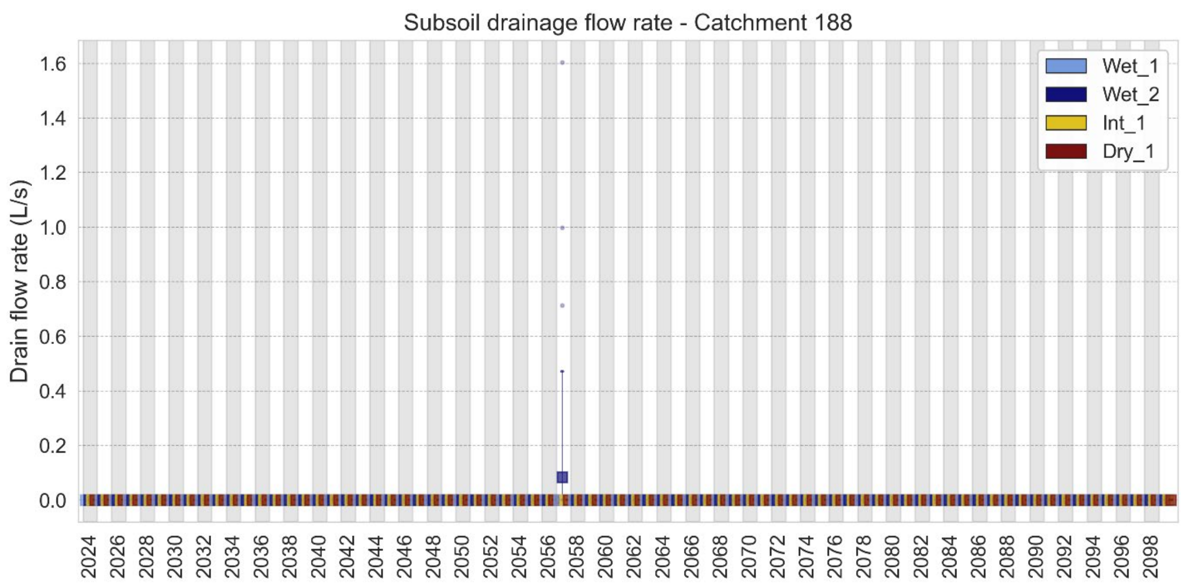
2096
2098

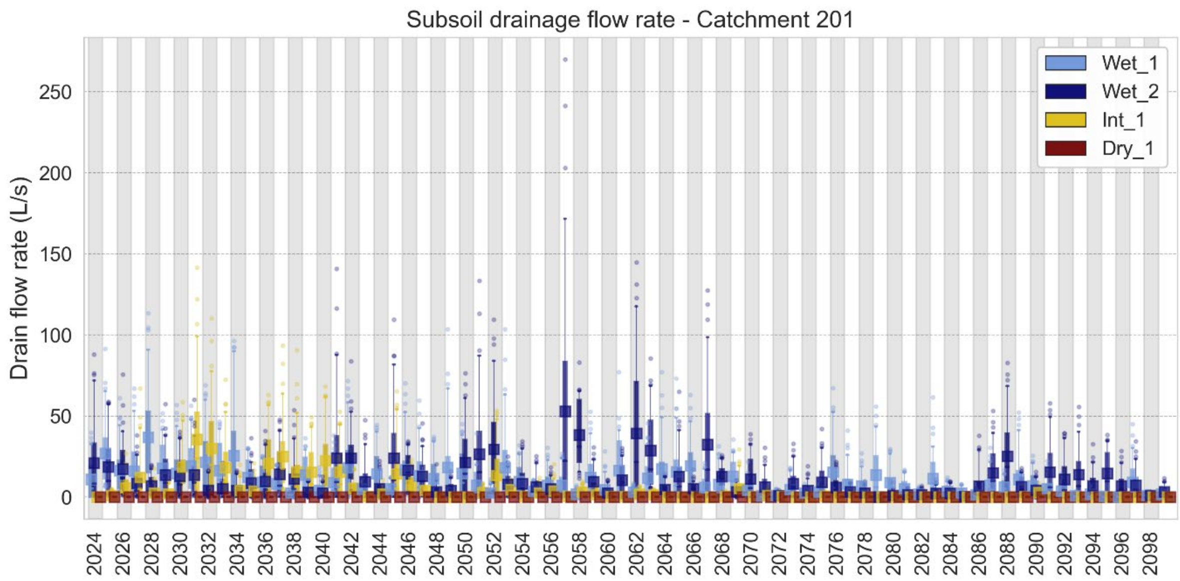

Subsoil drainage flow rate - Catchment 183
Wet_1
Wet_2
Int_1
Dry_1
Drain flow rate (L/s)
0.0
0.5
1.0
1.5
2.0
2.5
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
2052
2054
2056
2058
2060
2062
2064
2066
2068
2070
2072
2074
2076
2078
2080
2082
2084
2086
2088
2090
2092
2094
2096
2098

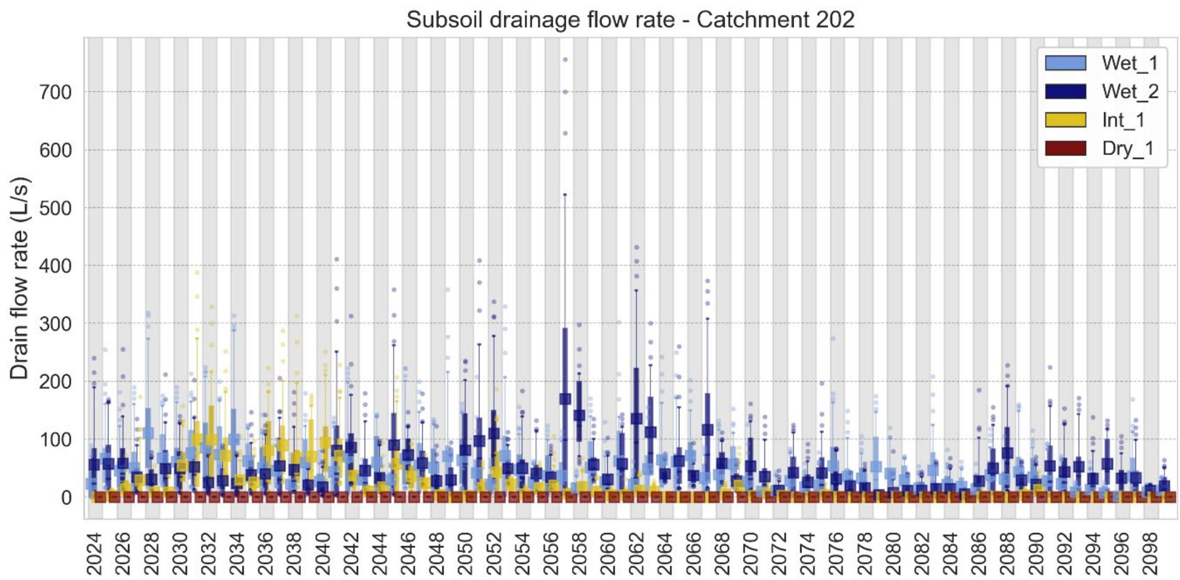

Subsoil drainage flow rate - Catchment 184
Wet_1
Wet_2
Int_1
Dry_1
Drain flow rate (L/s)
0
1
2
3
4
5
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
2052
2054
2056
2058
2060
2062
2064
2066
2068
2070
2072
2074
2076
2078
2080
2082
2084
2086
2088
2090
2092
2094
2096
2098

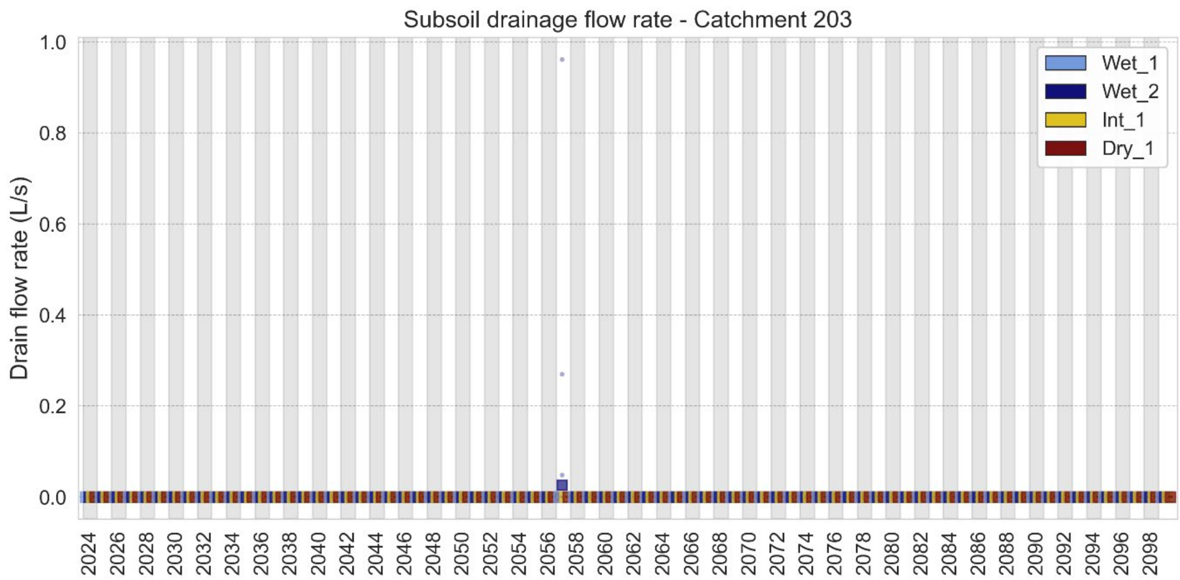

Subsoil drainage flow rate - Catchment 185
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1

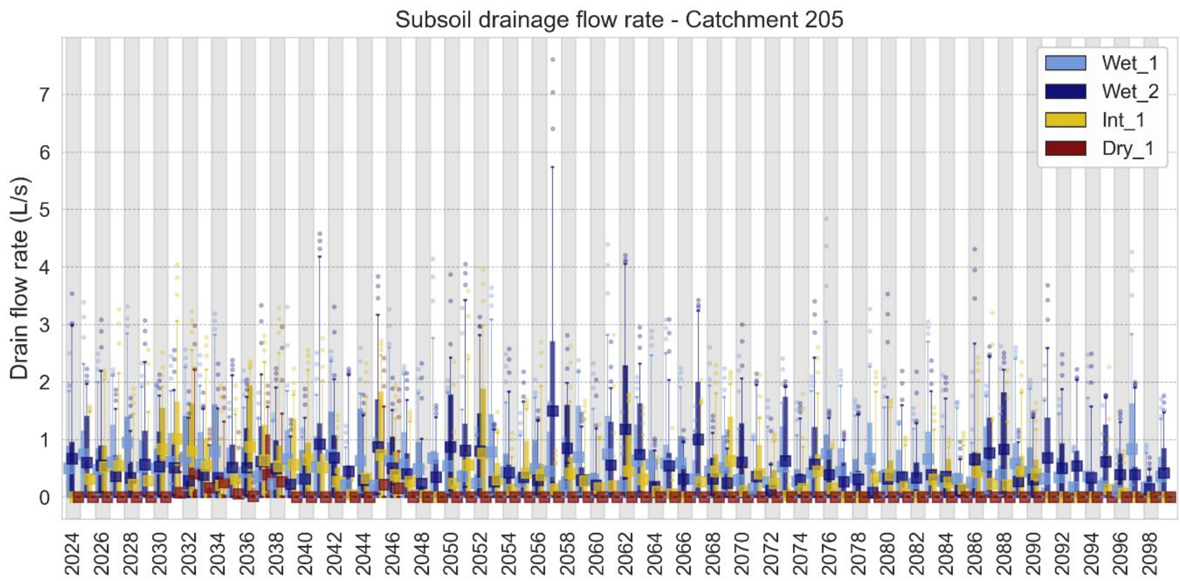

Subsoil drainage flow rate - Catchment 187
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1


Subsoil drainage flow rate - Catchment 188
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1


Subsoil drainage flow rate - Catchment 201
Drain flow rate (L/s)
0
50
100
150
200
250
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098


Subsoil drainage flow rate - Catchment 202
Drain flow rate (L/s)
0
100
200
300
400
500
600
700
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098


Subsoil drainage flow rate - Catchment 203
Drain flow rate (L/s)
0.0
0.2
0.4
0.6
0.8
1.0
Wet_1
Wet_2
Int_1
Dry_1
2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098


Subsoil drainage flow rate - Catchment 205
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1
0
1
2
3
4
5
6
7
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
2052
2054
2056
2058
2060
2062
2064
2066
2068
2070
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2076
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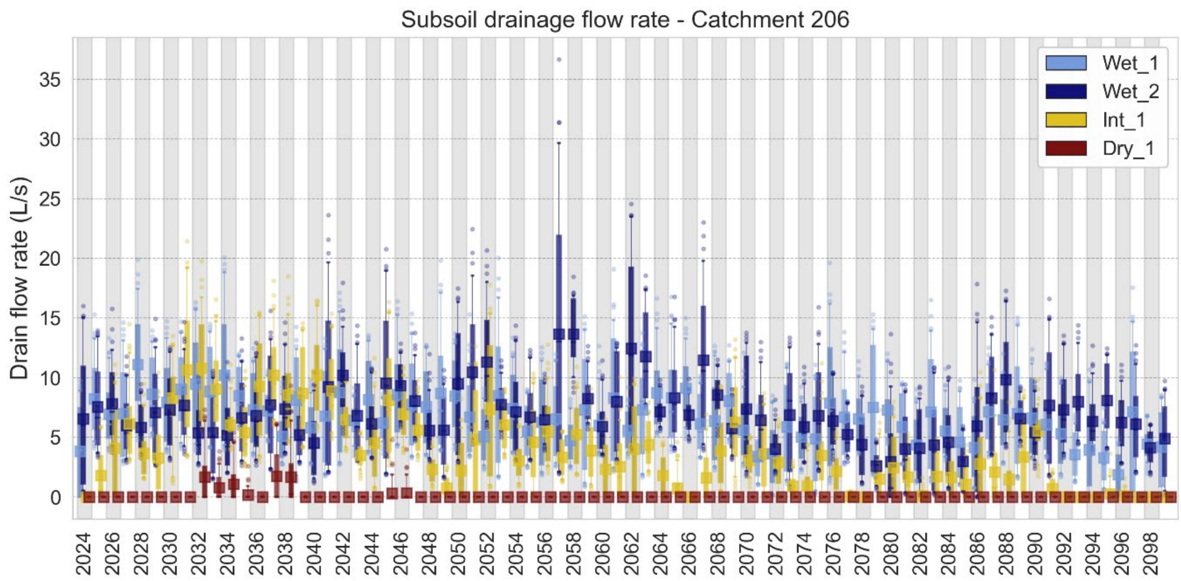
2082
2084
2086
2088
2090
2092
2094
2096
2098


Subsoil drainage flow rate - Catchment 206
Drain flow rate (L/s)
Wet_1
Wet_2
Int_1
Dry_1
0
5
10
15
20
25
30
35
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
2052
2054
2056
2058
2060
2062
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2098

Appendix F: Catchment subsoil drainage flow rate statistics

Appendix F: Catchment subsoil drainage flow rate statistics

Full buildout, 2.0m max subsoil drainage depth simulations for the four selected climate scenarios

Statistics based on maximum monthly timestep flow rates

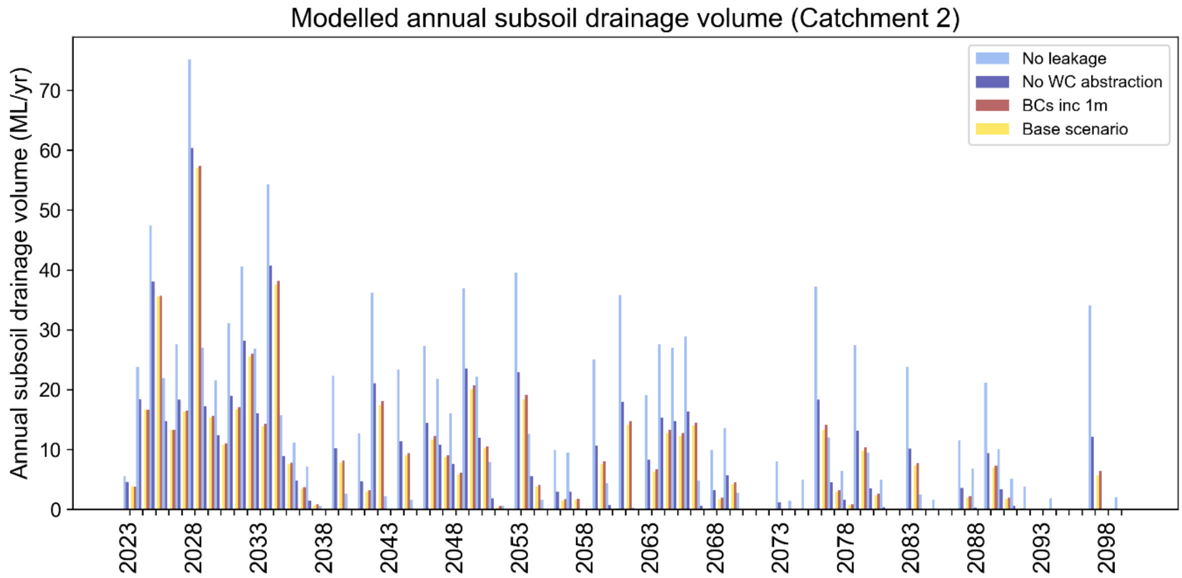
Catchment Number	Minimum L/s	Median L/s	Mean L/s	90th Percentile L/s	95th Percentile L/s	Maximum L/s
2	0.0	0.0	0.2	0.5	1.2	13.4
3	0.0	0.0	0.0	0.0	0.0	1.1
5	0.0	0.0	0.3	0.3	1.4	33.7
7	0.0	0.0	0.0	0.0	0.0	8.5
8	0.0	0.0	0.3	0.7	2.0	24.0
9	0.0	0.0	8.1	27.9	39.8	139.6
10	0.0	0.0	0.0	0.0	0.0	3.9
11	0.0	0.0	0.0	0.0	0.0	2.3
13	0.0	0.0	0.3	1.0	1.7	28.5
14	0.0	0.0	0.1	0.4	0.8	7.5
15	0.0	0.0	2.3	9.6	14.4	57.0
18	0.0	0.0	2.1	8.5	12.8	65.0
20	0.0	0.0	3.3	12.7	17.9	65.3
21	0.0	0.0	0.3	1.1	2.0	14.6
22	0.0	0.0	0.0	0.0	0.0	3.5
23	0.0	0.0	3.0	10.9	14.4	47.7
24	0.0	0.0	1.2	4.0	5.3	17.8
25	0.0	0.0	1.4	5.1	6.6	21.2
26	0.0	0.0	3.7	13.8	18.6	69.0
30	0.0	0.0	0.0	0.0	0.0	2.6
32	0.0	0.0	0.0	0.0	0.0	0.1
34	0.0	0.0	0.0	0.0	0.0	1.5
35	0.0	0.0	0.1	0.0	0.0	26.9
45	0.0	0.0	0.2	0.9	1.4	12.7
46	0.0	0.0	0.0	0.0	0.0	6.8
47	0.0	0.0	0.2	0.6	1.5	15.1
48	0.0	0.0	0.7	1.3	5.6	42.7
49	0.0	0.0	0.1	0.0	0.0	16.9
51	0.0	0.0	0.0	0.0	0.0	8.0
53	0.0	0.0	0.2	0.3	0.9	12.3
58	0.0	0.0	0.0	0.0	0.0	4.5
59	0.0	0.0	9.4	33.4	43.2	128.7
60	0.0	0.0	0.3	0.0	1.4	32.1
64	0.0	0.0	0.0	0.0	0.0	1.0

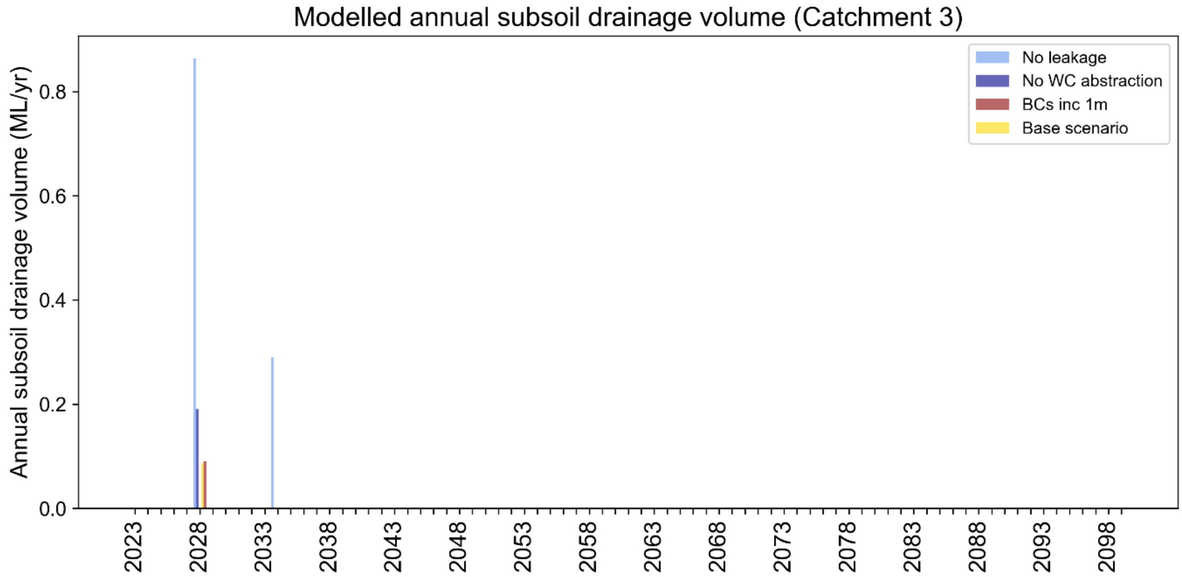
Catchment Number	Minimum L/s	Median L/s	Mean L/s	90th Percentile L/s	95th Percentile L/s	Maximum L/s
68	0.0	0.0	0.1	0.1	0.5	3.7
70	0.0	0.0	0.5	1.8	3.0	26.1
71	0.0	0.0	0.0	0.0	0.3	5.7
72	0.0	0.0	0.0	0.0	0.0	3.4
73	0.0	0.0	0.0	0.0	0.0	5.1
74	0.0	0.4	3.6	11.4	14.2	45.7
75	0.0	1.0	3.1	9.5	11.9	36.8
77	0.0	0.7	1.9	5.6	6.9	19.4
79	0.0	0.0	0.6	2.1	2.8	9.4
80	0.0	0.0	1.0	3.0	3.8	17.6
81	0.0	6.5	6.4	14.1	16.1	39.3
83	0.0	0.0	0.0	0.0	0.0	1.6
120	0.0	0.5	2.6	7.9	10.7	45.7
127	0.0	0.0	0.7	2.4	3.3	13.6
130	0.0	0.0	0.4	1.4	1.8	6.1
131	0.0	0.0	4.3	17.0	23.9	91.5
132	0.0	0.0	1.6	6.0	8.0	28.1
133	0.0	5.7	8.3	22.0	26.3	68.8
134	0.0	0.7	4.0	12.9	16.2	51.3
135	0.0	6.3	9.8	26.5	32.3	94.3
144	0.0	4.1	4.6	10.7	12.7	34.2
145	0.0	0.1	6.9	25.5	35.1	126.7
146	0.0	0.0	0.0	0.0	0.0	0.4
147	0.0	0.0	0.0	0.0	0.0	20.3
148	0.0	0.3	0.4	1.0	1.2	2.8
149	0.0	2.6	4.5	12.6	15.2	41.8
150	0.0	0.0	1.4	4.6	6.1	29.2
151	0.0	1.3	4.1	12.3	16.0	53.1
154	0.0	0.6	4.0	12.4	16.1	46.2
159	0.0	0.0	0.0	0.0	0.0	11.1
160	0.0	0.0	0.0	0.0	0.0	0.8
161	0.0	0.0	0.5	1.9	2.8	10.7
162	0.0	0.0	2.9	11.0	20.0	104.4
163	0.0	0.0	0.6	1.2	2.0	54.3
164	0.0	0.0	0.1	0.0	0.5	3.1
167	0.0	1.2	2.9	8.5	11.1	44.8
172	0.0	11.8	10.6	19.6	21.6	38.8
173	0.0	3.4	7.4	21.2	26.9	64.9
174	0.0	0.0	0.1	0.0	0.1	6.0
175	0.0	0.0	0.1	0.0	0.0	11.9
176	0.0	0.6	4.6	14.3	18.6	61.7
179	0.0	0.0	3.5	13.8	21.8	106.1

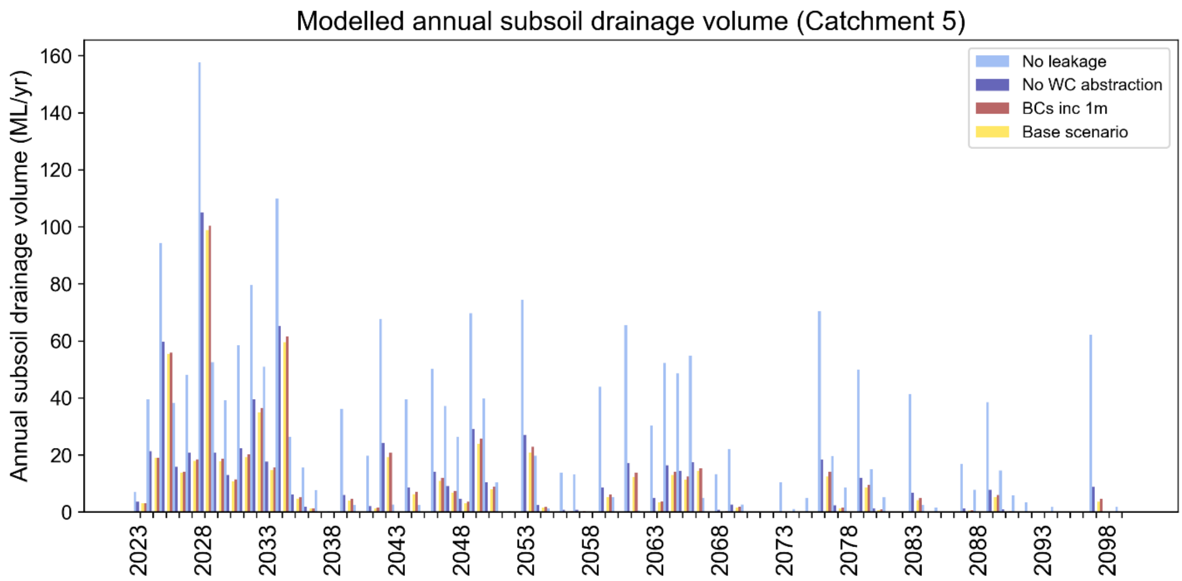
Catchment Number	Minimum L/s	Median L/s	Mean L/s	90th Percentile L/s	95th Percentile L/s	Maximum L/s
180	0.0	0.0	1.8	7.1	9.8	36.1
182	0.0	0.0	1.8	7.2	11.0	47.0
183	0.0	0.0	0.0	0.0	0.0	2.6
184	0.0	0.0	0.0	0.0	0.0	5.6
185	0.0	0.0	0.0	0.0	0.0	3.7
187	0.0	0.0	0.9	3.8	6.6	33.0
188	0.0	0.0	0.0	0.0	0.0	1.6
201	0.0	0.0	6.7	22.1	36.8	270.0
202	0.0	3.5	27.1	85.9	132.4	756.2
203	0.0	0.0	0.0	0.0	0.0	1.0
205	0.0	0.0	0.3	1.4	2.0	7.6
206	0.0	2.8	4.1	10.9	13.1	36.7

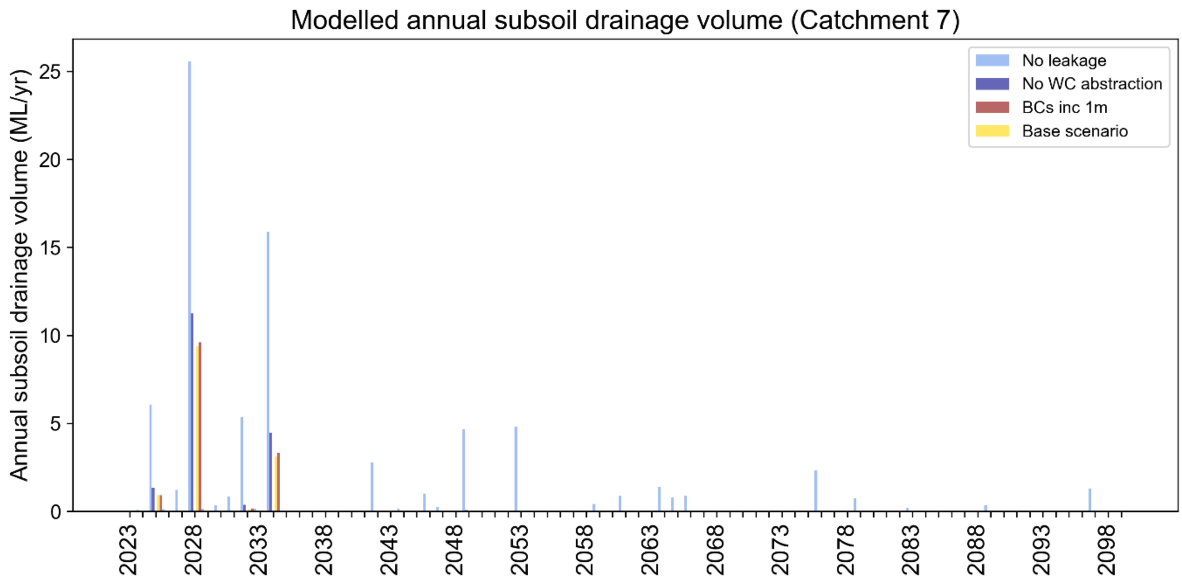
Appendix G: Catchment annual subsoil drainage volumes for the three sensitivity simulations

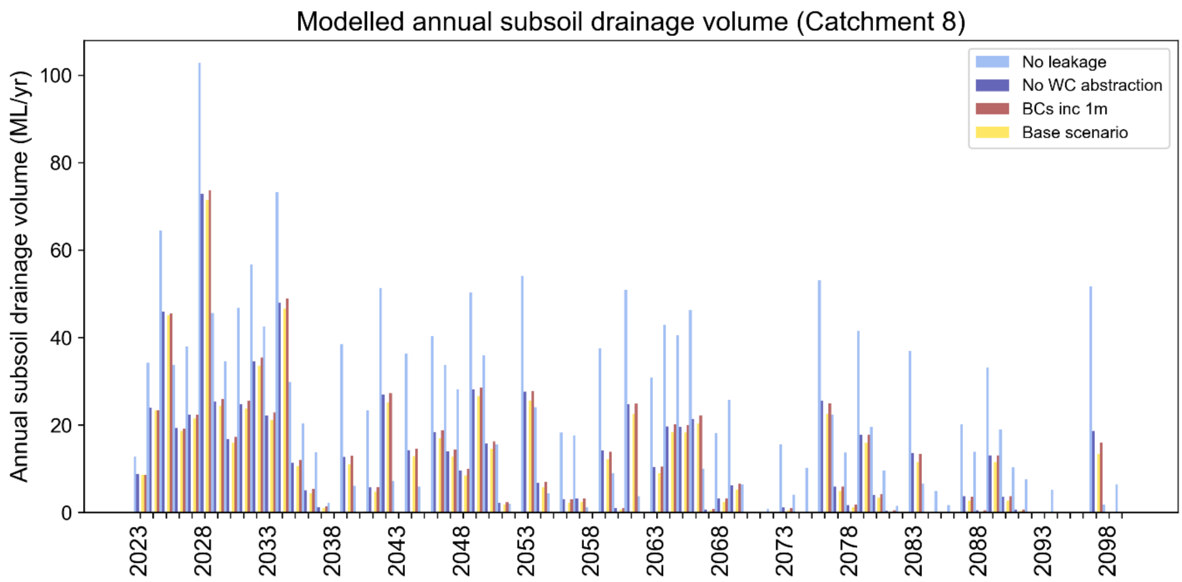
Appendix G: Annual subsoil drainage flow volumes for the sensitivity simulations

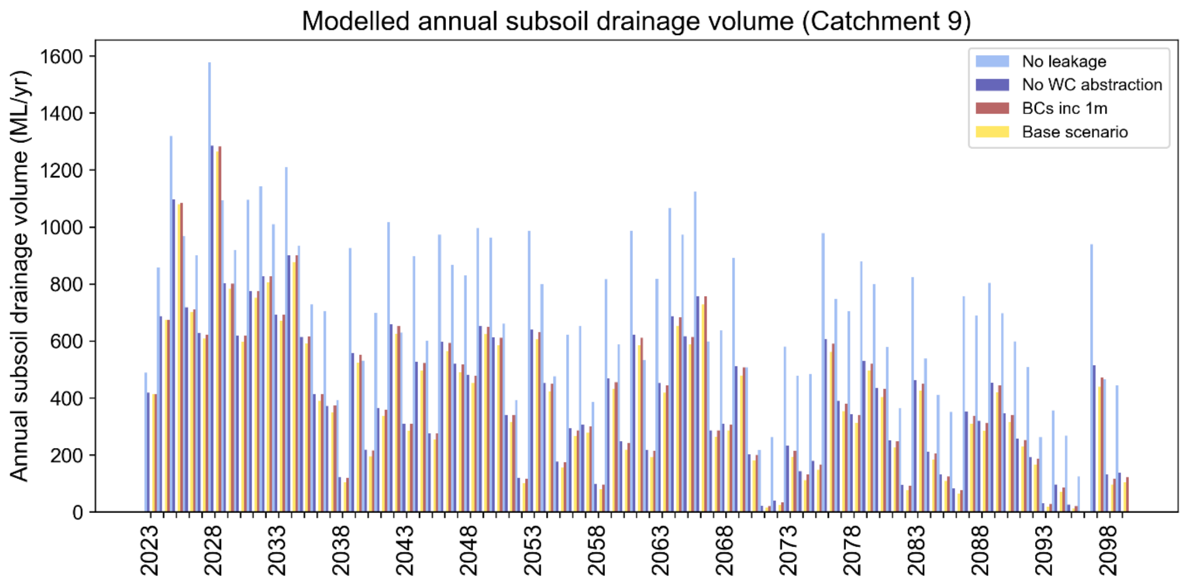


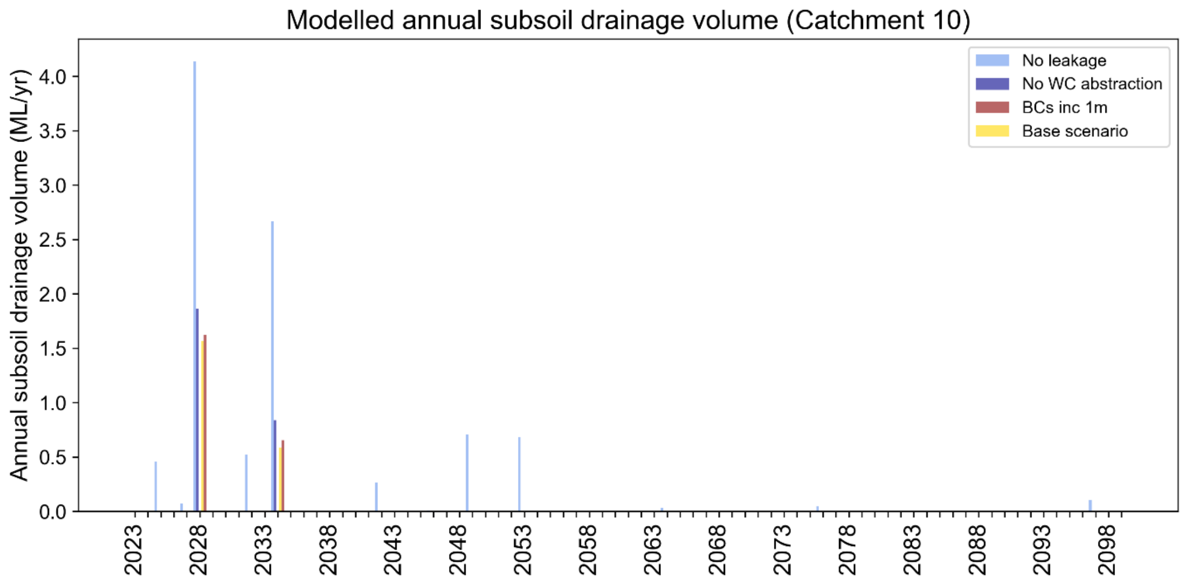


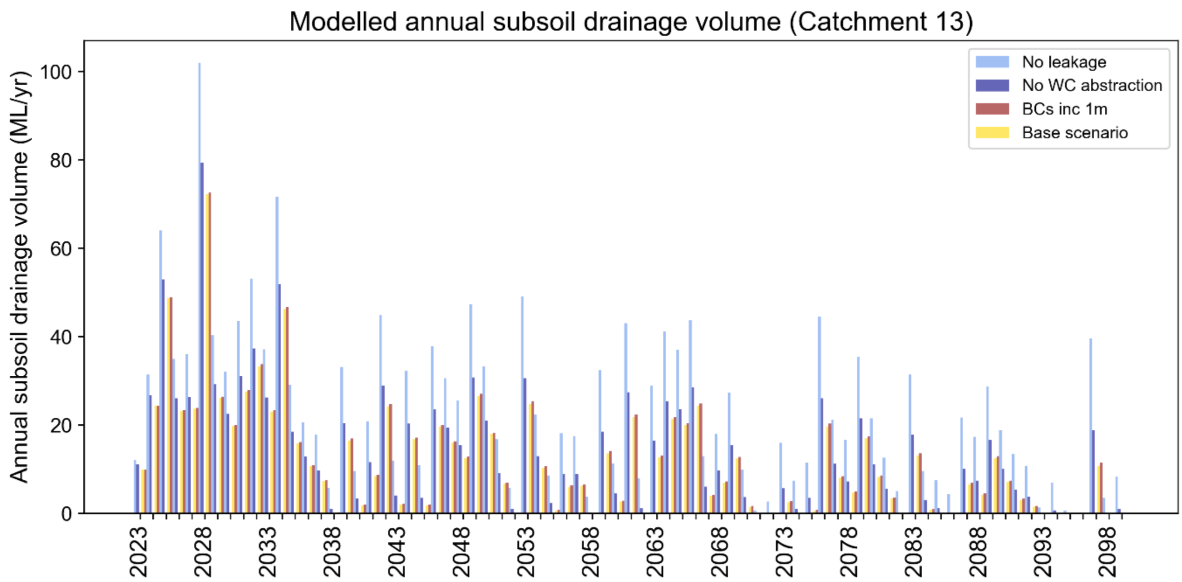

Modelled annual subsoil drainage volume (Catchment 5)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario

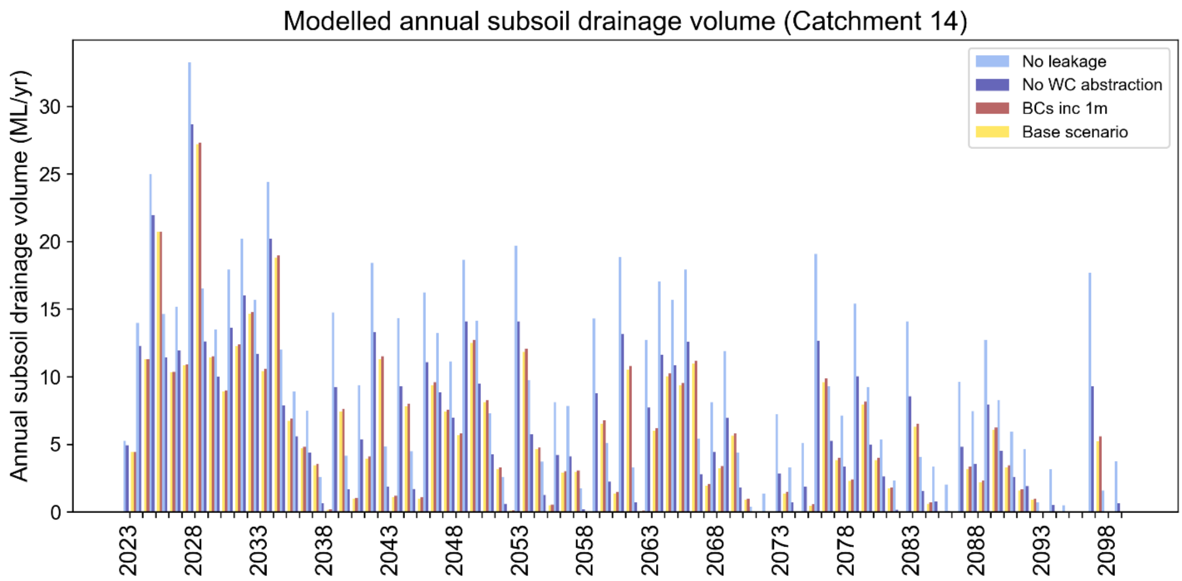

Modelled annual subsoil drainage volume (Catchment 7)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario

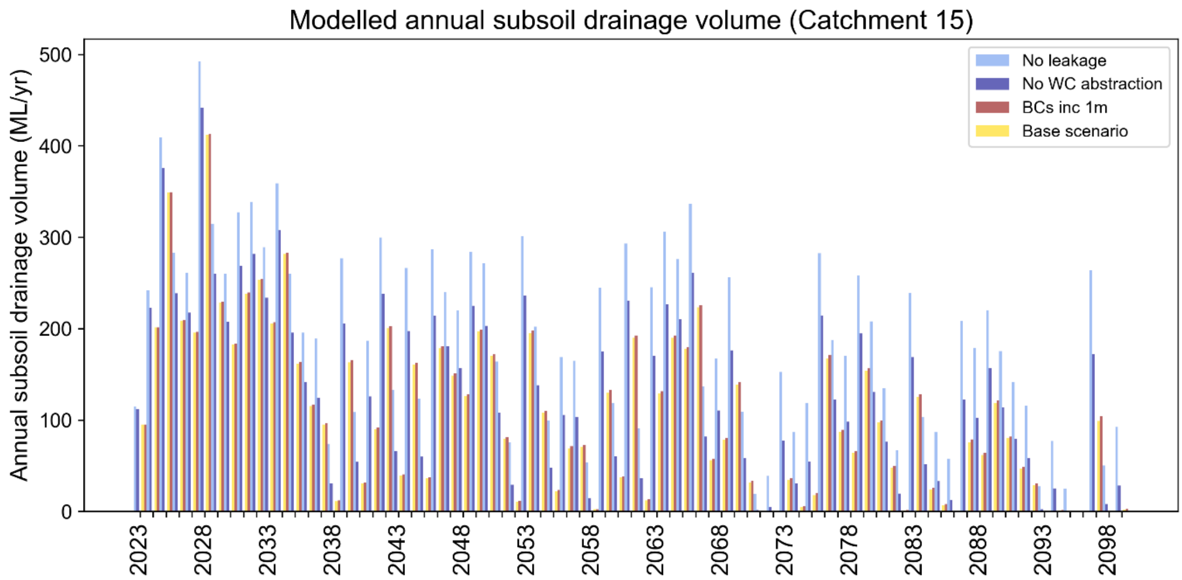

Modelled annual subsoil drainage volume (Catchment 8)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario

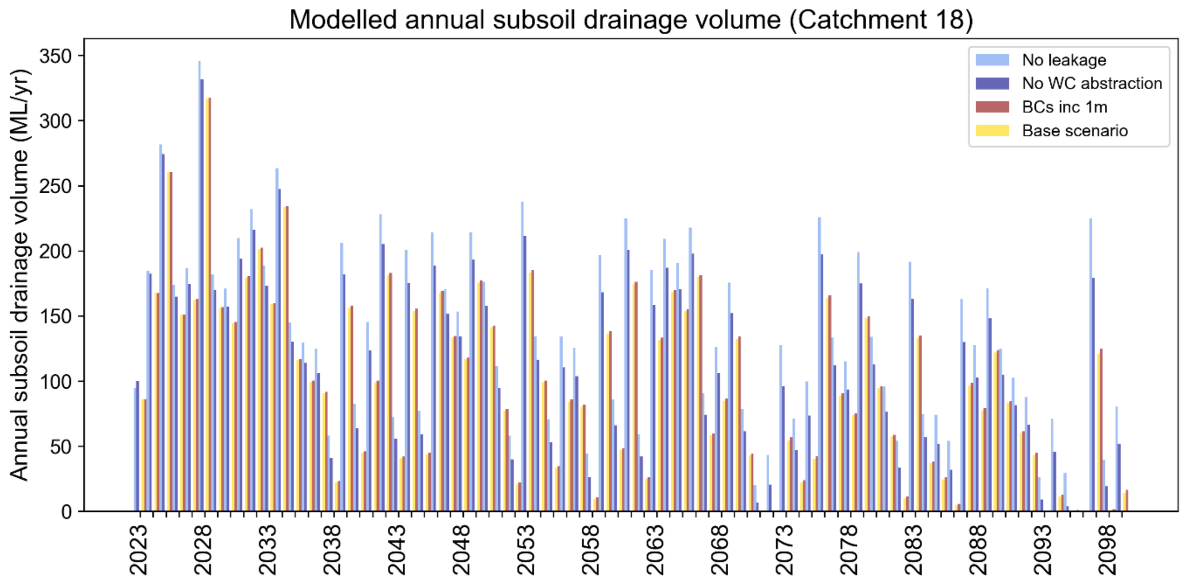

Modelled annual subsoil drainage volume (Catchment 9)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario

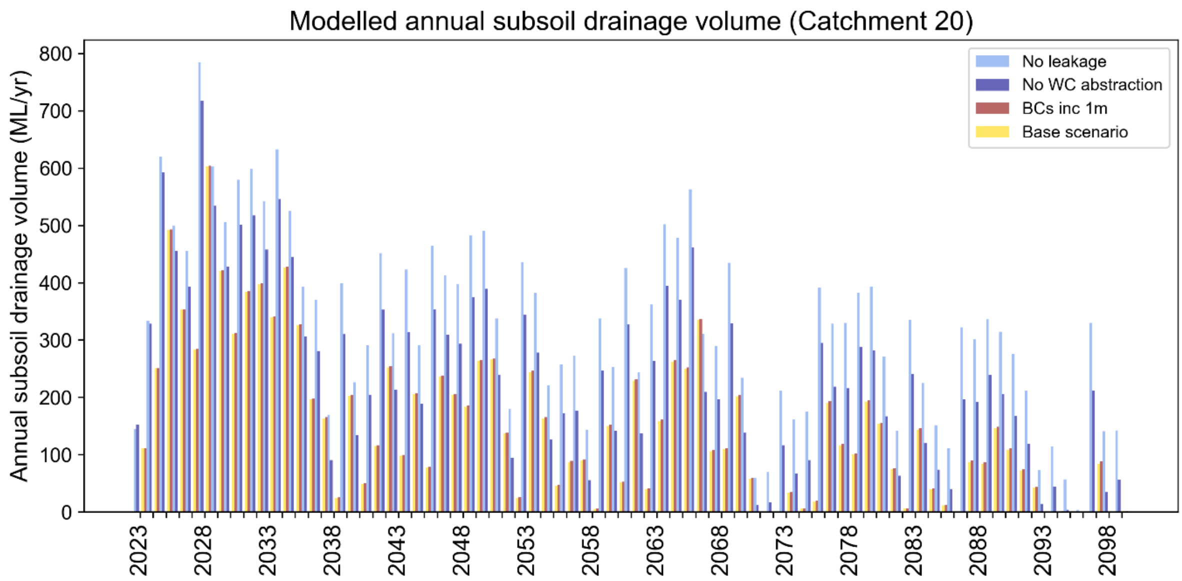

Modelled annual subsoil drainage volume (Catchment 10)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario

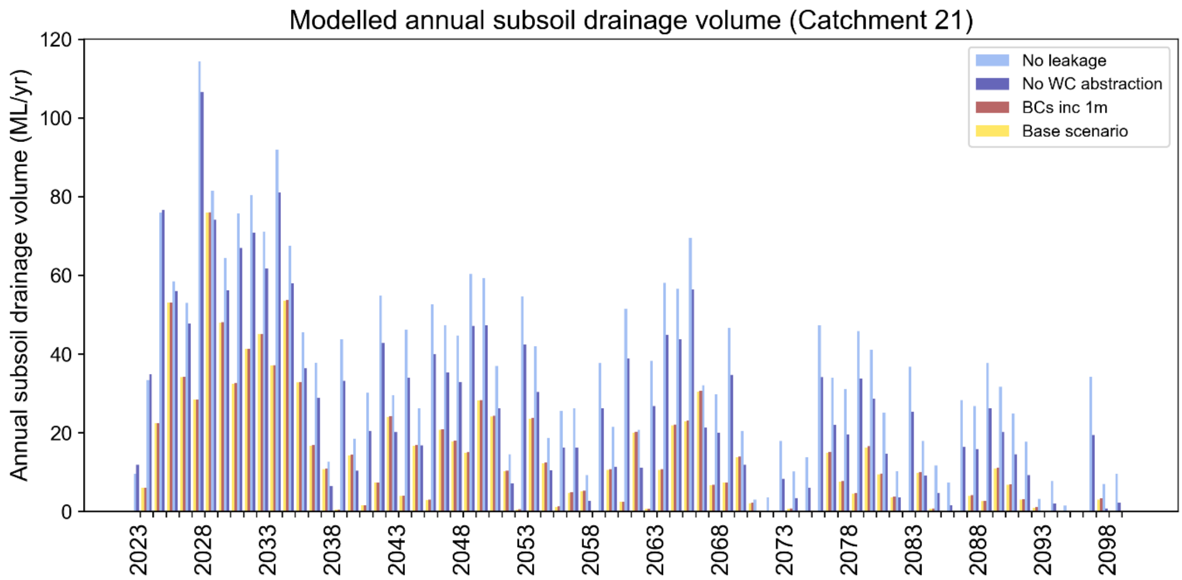

Modelled annual subsoil drainage volume (Catchment 13)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario

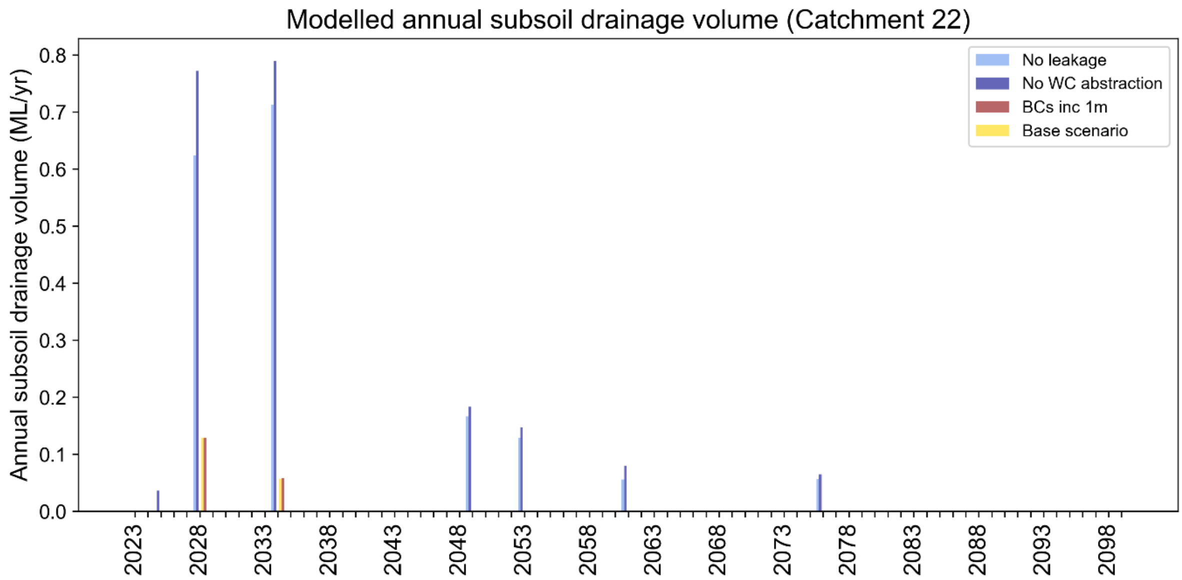

Modelled annual subsoil drainage volume (Catchment 14)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
5
10
15
20
25
30
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

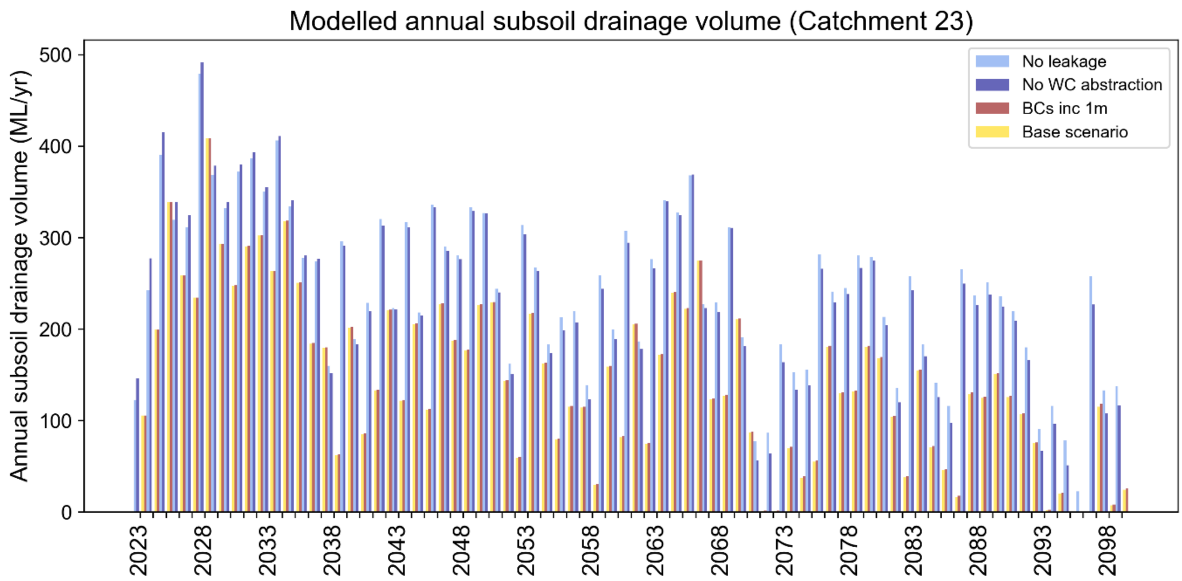

Modelled annual subsoil drainage volume (Catchment 15)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
100
200
300
400
500
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

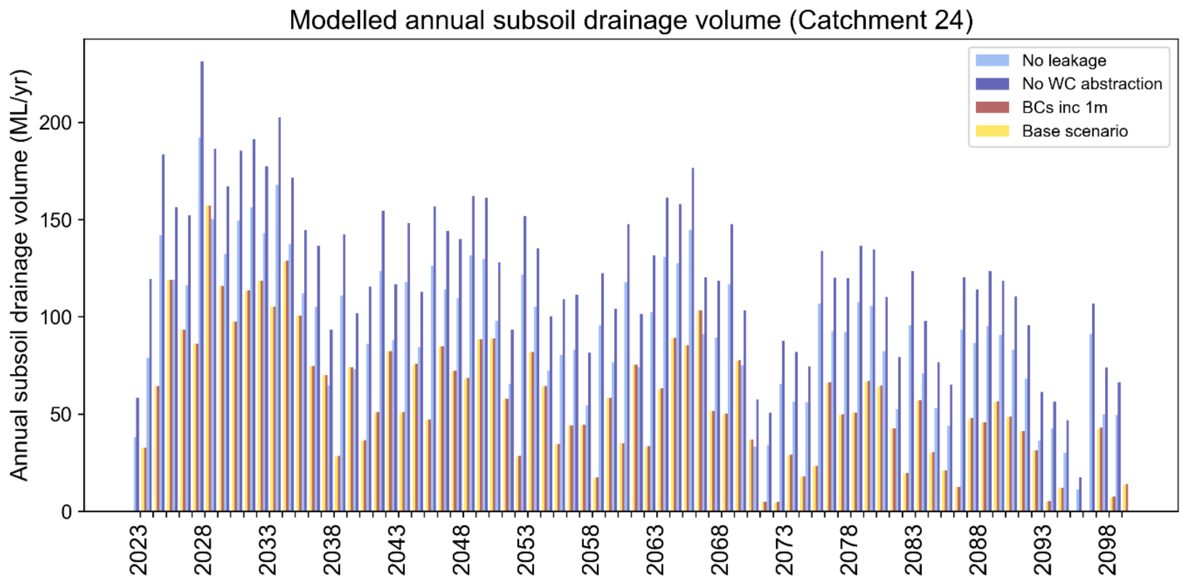

Modelled annual subsoil drainage volume (Catchment 18)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
50
100
150
200
250
300
350
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

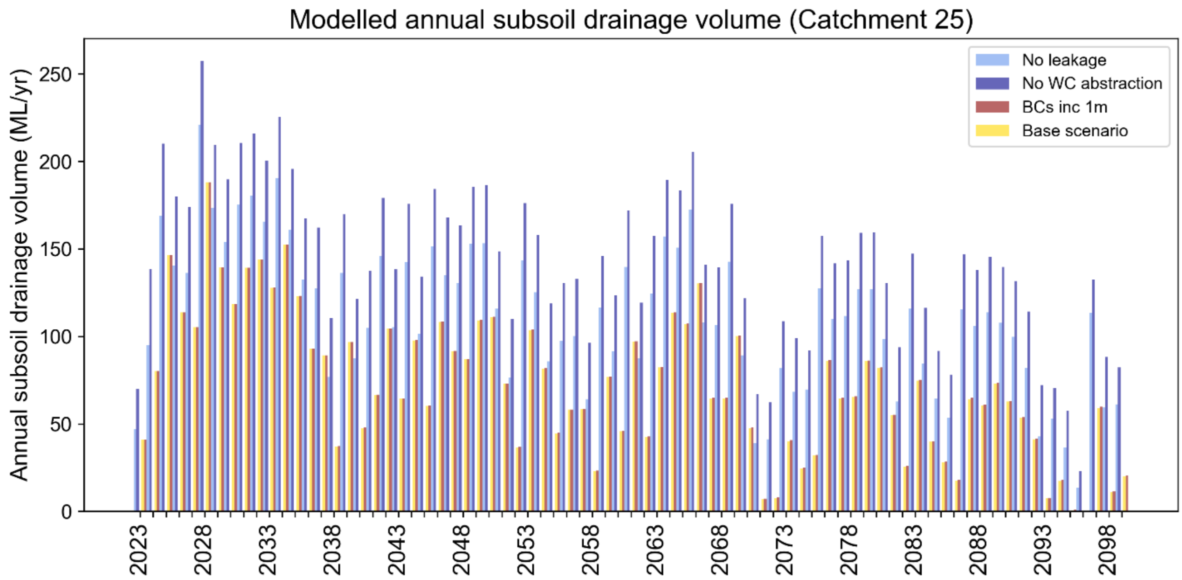

Modelled annual subsoil drainage volume (Catchment 20)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
100
200
300
400
500
600
700
800
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

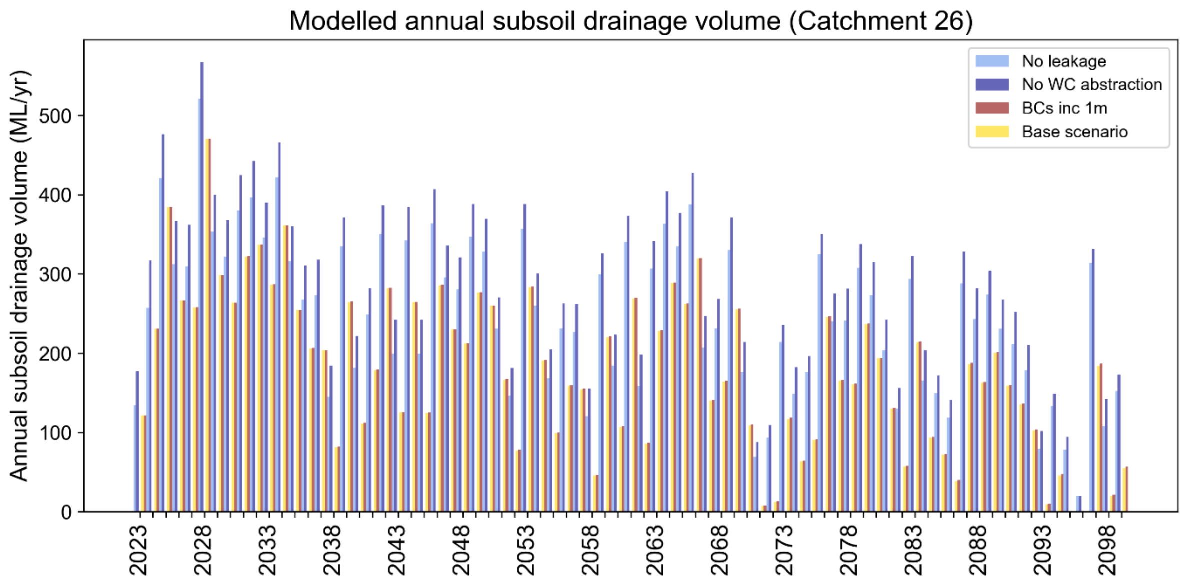

Modelled annual subsoil drainage volume (Catchment 21)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
20
40
60
80
100
120
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

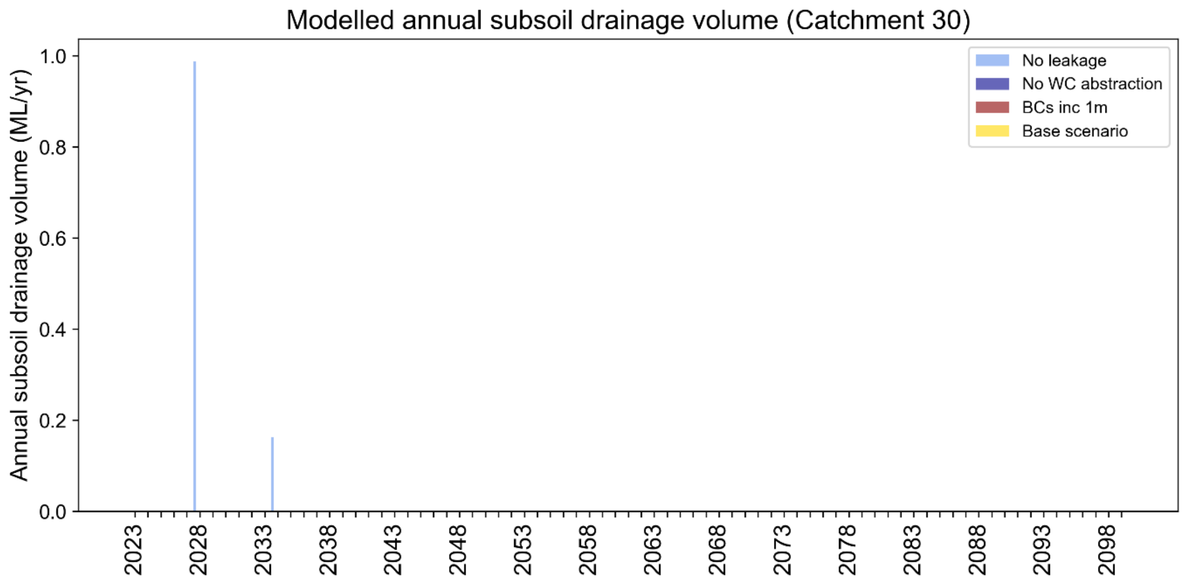

Modelled annual subsoil drainage volume (Catchment 22)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

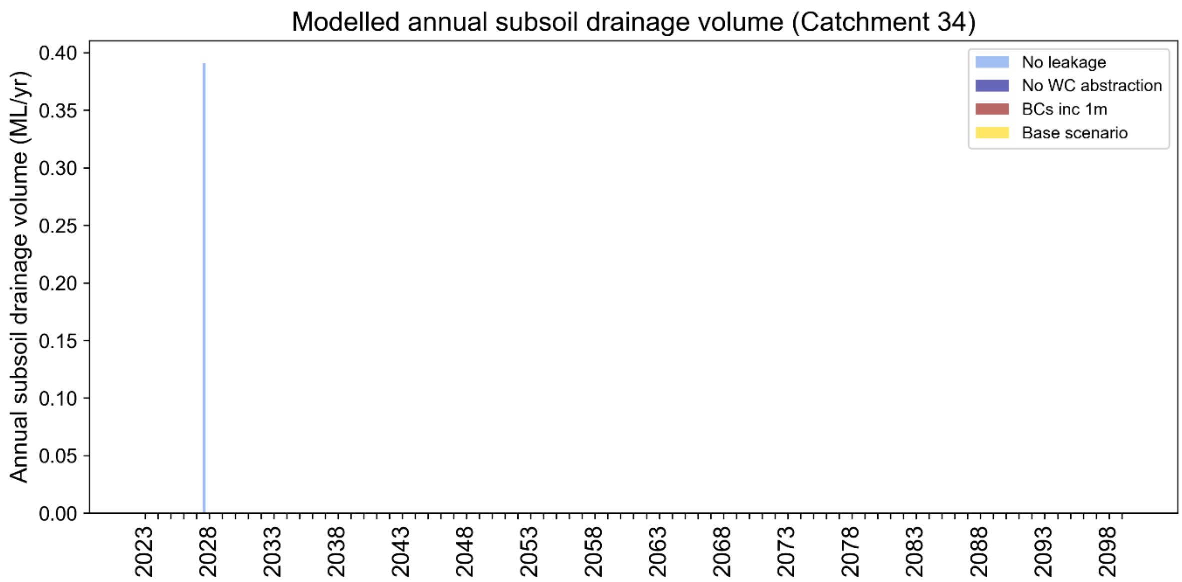

Modelled annual subsoil drainage volume (Catchment 23)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
100
200
300
400
500
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

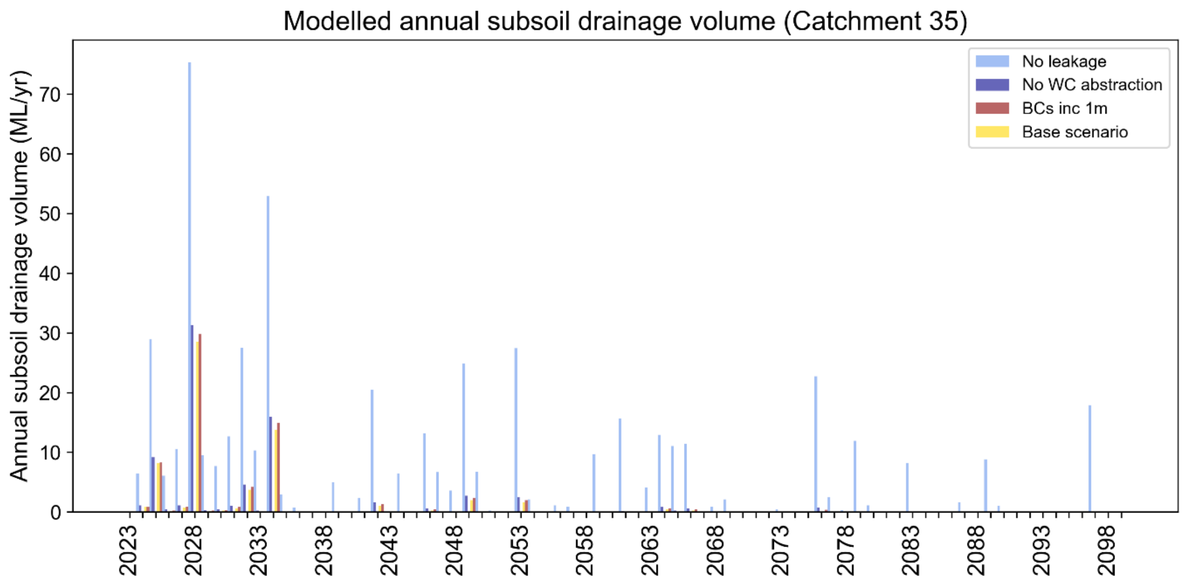

Modelled annual subsoil drainage volume (Catchment 24)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
50
100
150
200
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

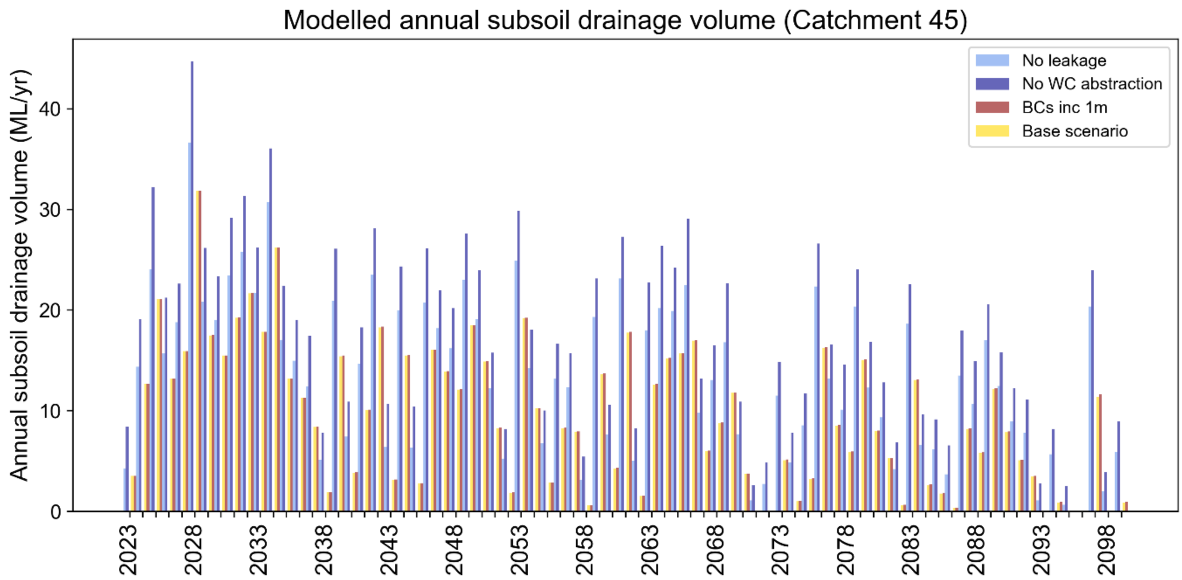

Modelled annual subsoil drainage volume (Catchment 25)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
50
100
150
200
250
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

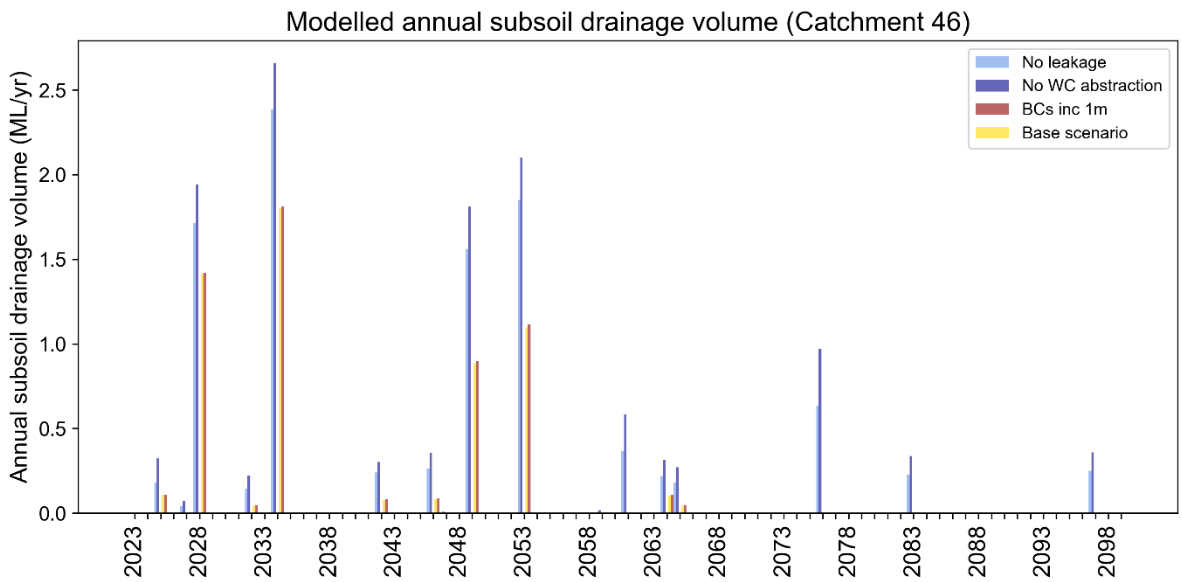

Modelled annual subsoil drainage volume (Catchment 26)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
100
200
300
400
500
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

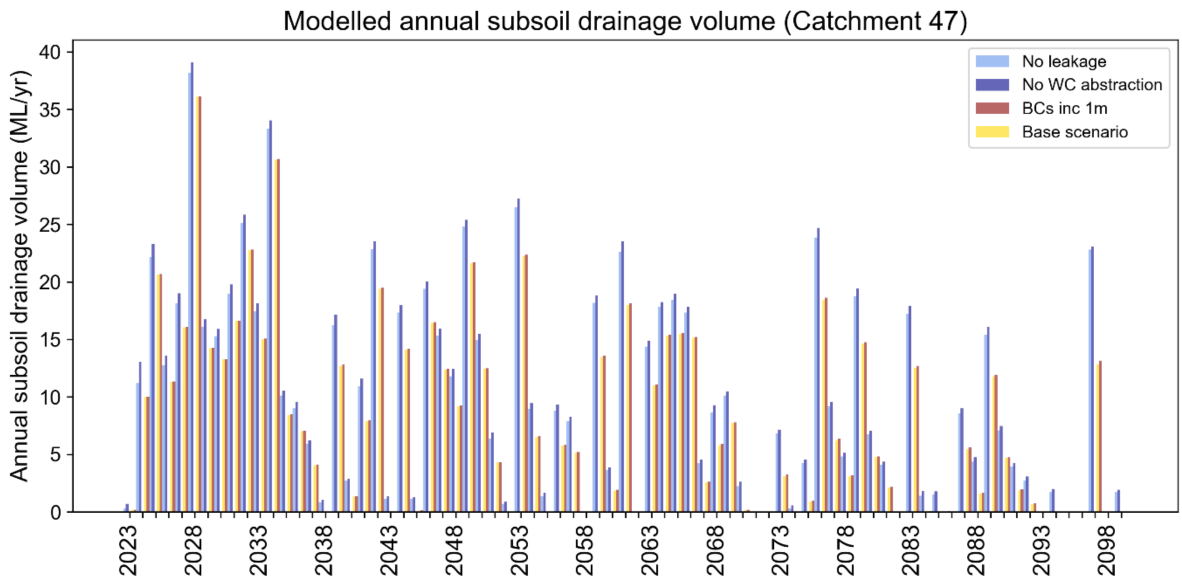

Modelled annual subsoil drainage volume (Catchment 30)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0.0
0.2
0.4
0.6
0.8
1.0
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

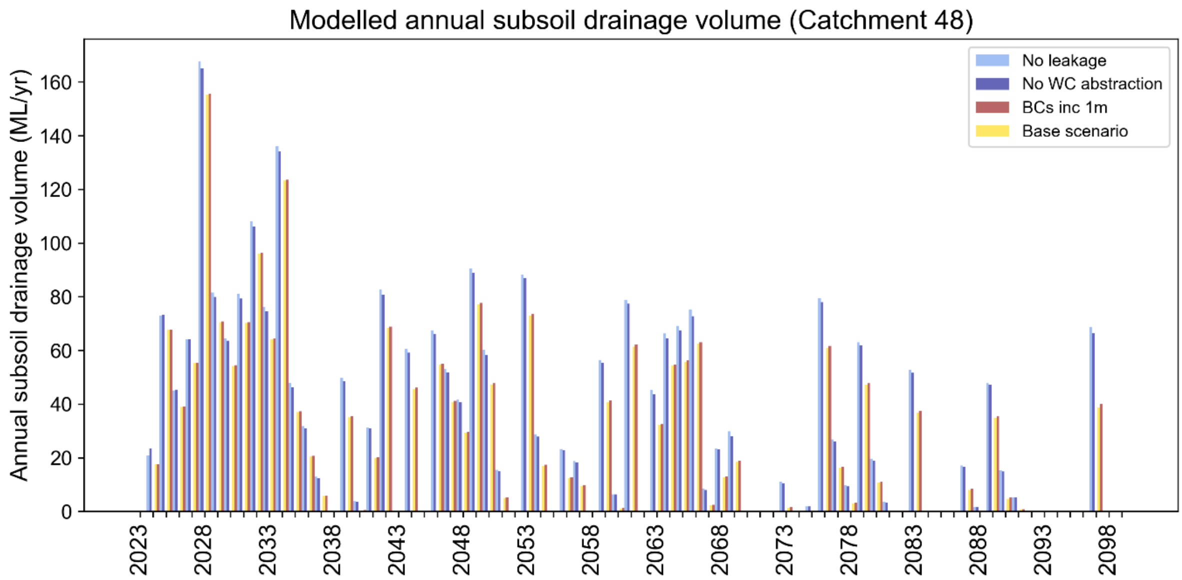

Modelled annual subsoil drainage volume (Catchment 34)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

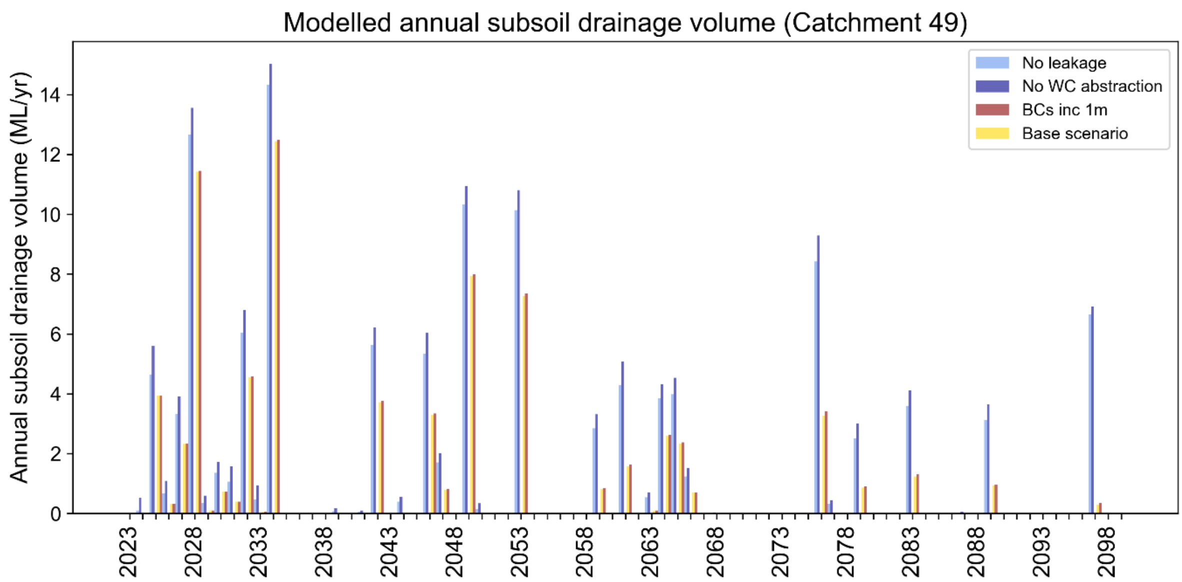

Modelled annual subsoil drainage volume (Catchment 35)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario

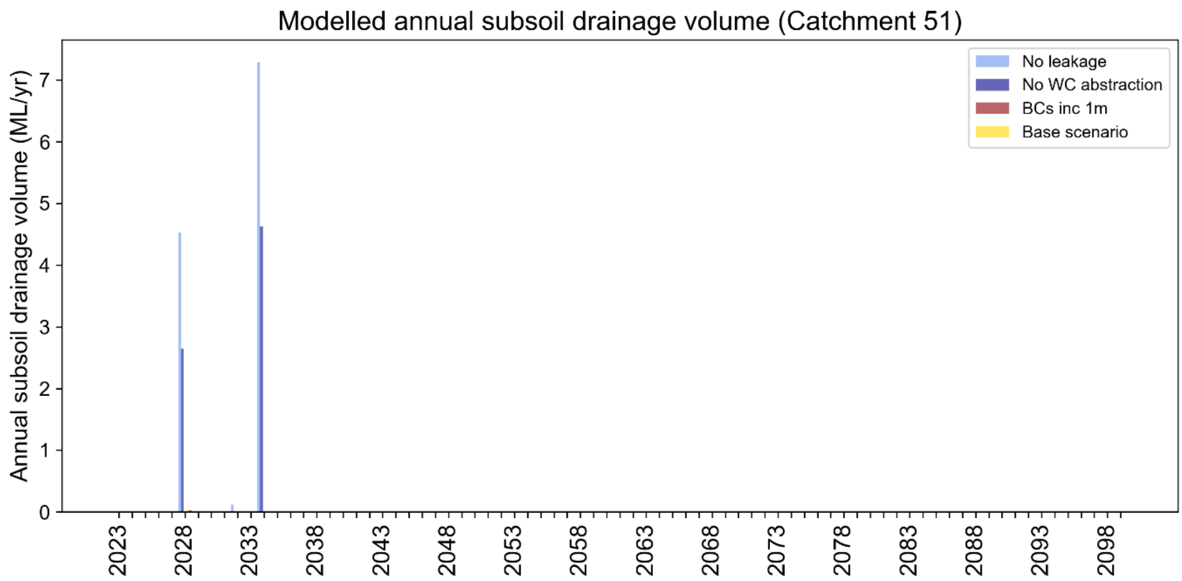

Modelled annual subsoil drainage volume (Catchment 45)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario

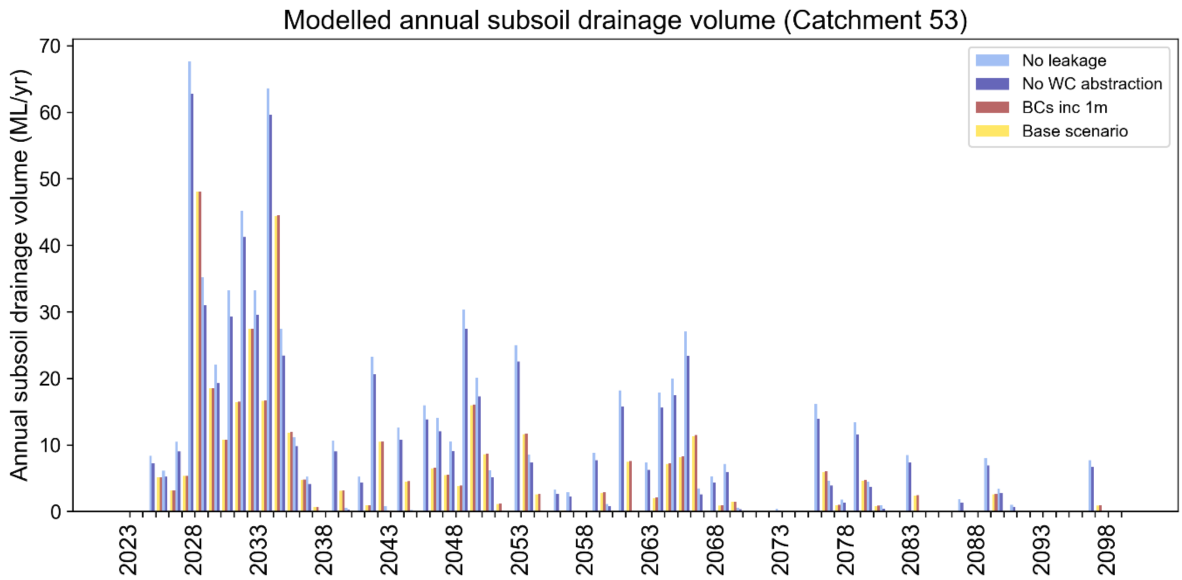

Modelled annual subsoil drainage volume (Catchment 46)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario

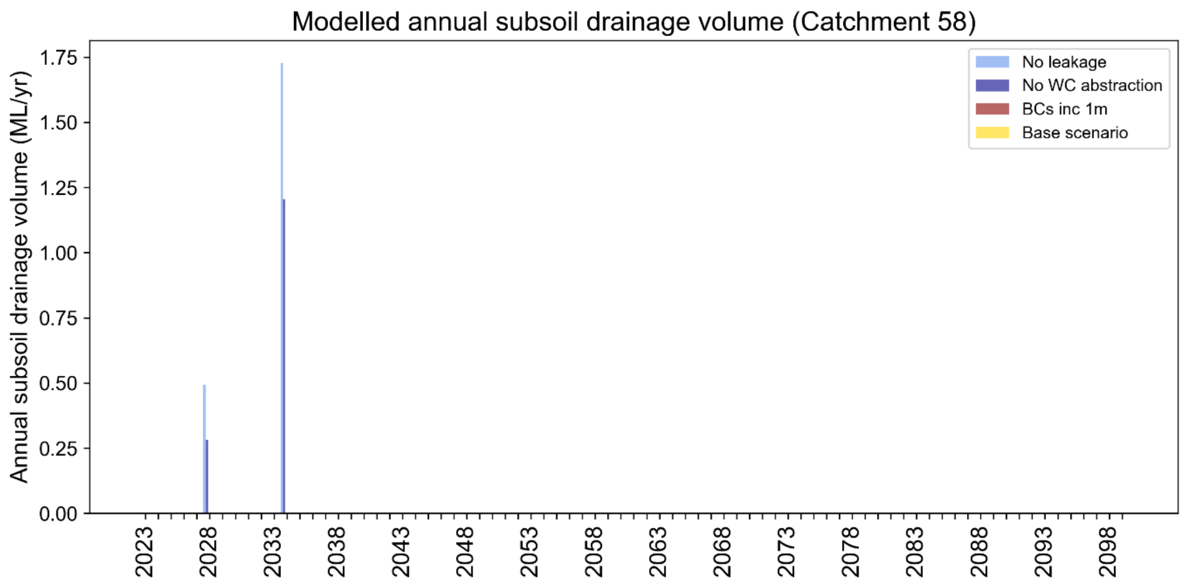

Modelled annual subsoil drainage volume (Catchment 47)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
5
10
15
20
25
30
35
40
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

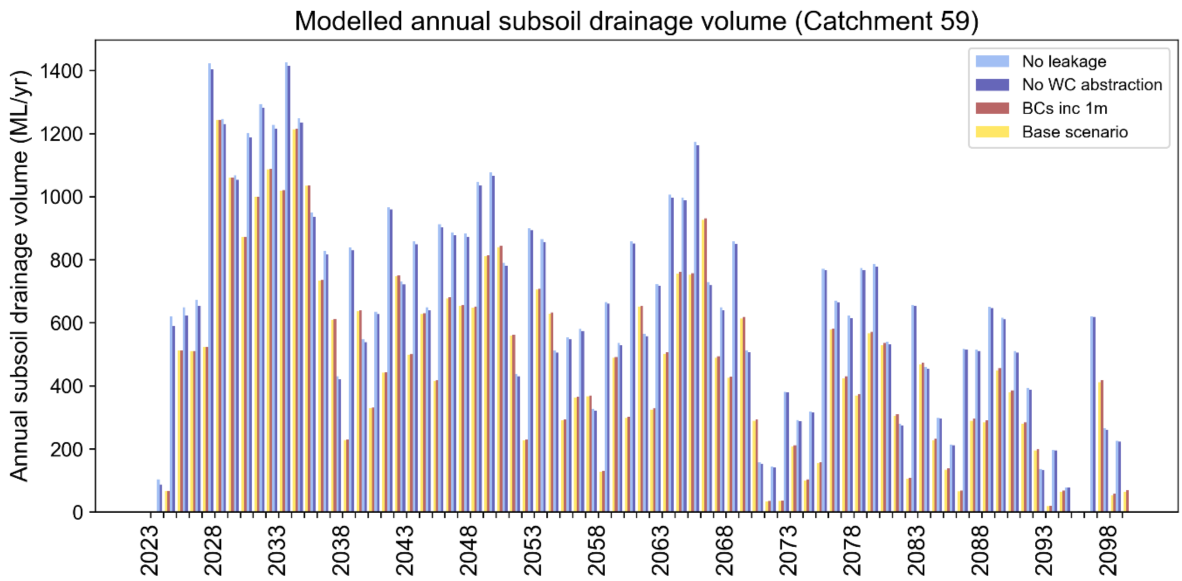

Modelled annual subsoil drainage volume (Catchment 48)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
20
40
60
80
100
120
140
160
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

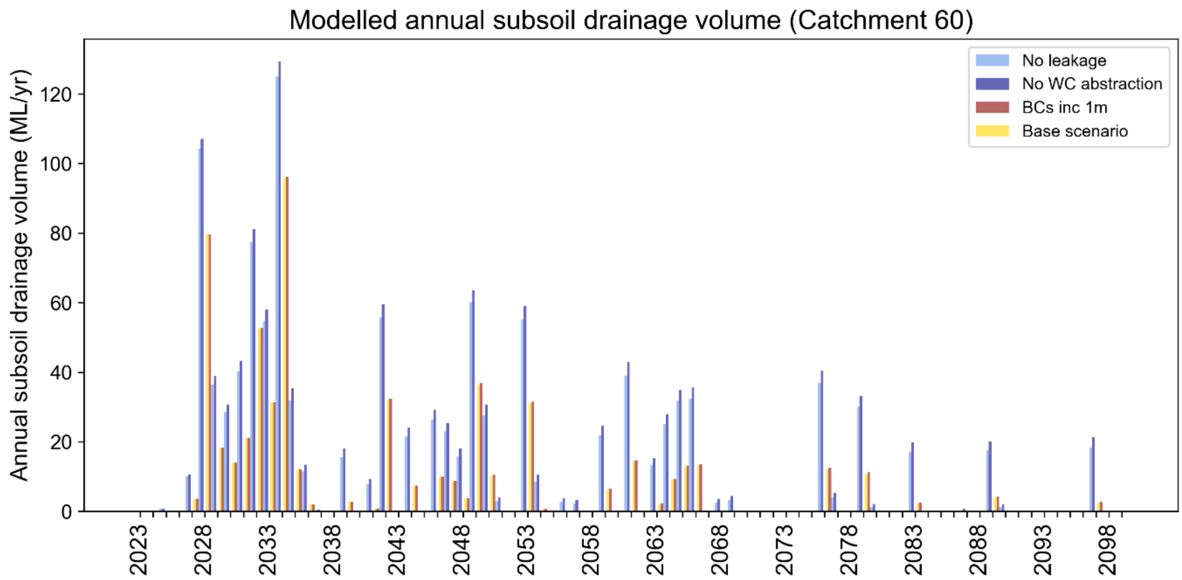

Modelled annual subsoil drainage volume (Catchment 49)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
2
4
6
8
10
12
14
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

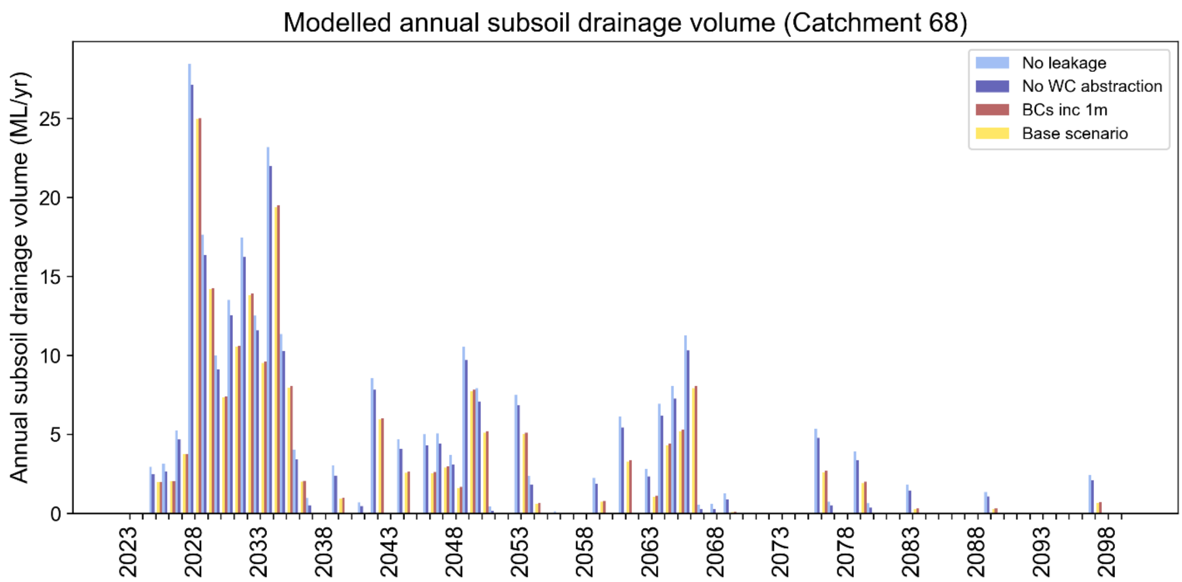

Modelled annual subsoil drainage volume (Catchment 51)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
1
2
3
4
5
6
7
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

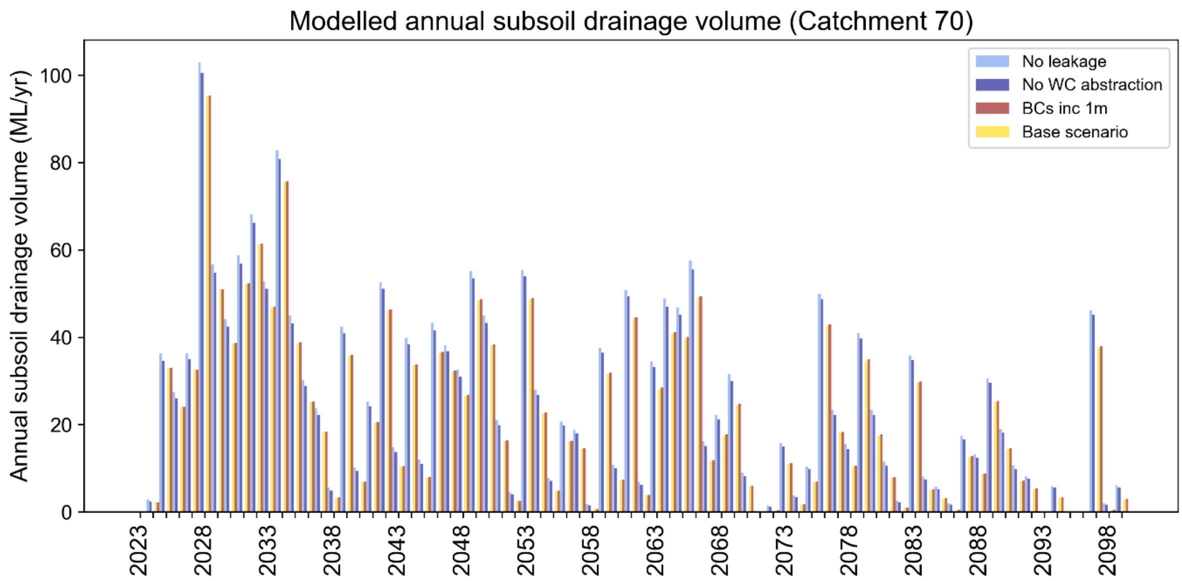

Modelled annual subsoil drainage volume (Catchment 53)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
10
20
30
40
50
60
70
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

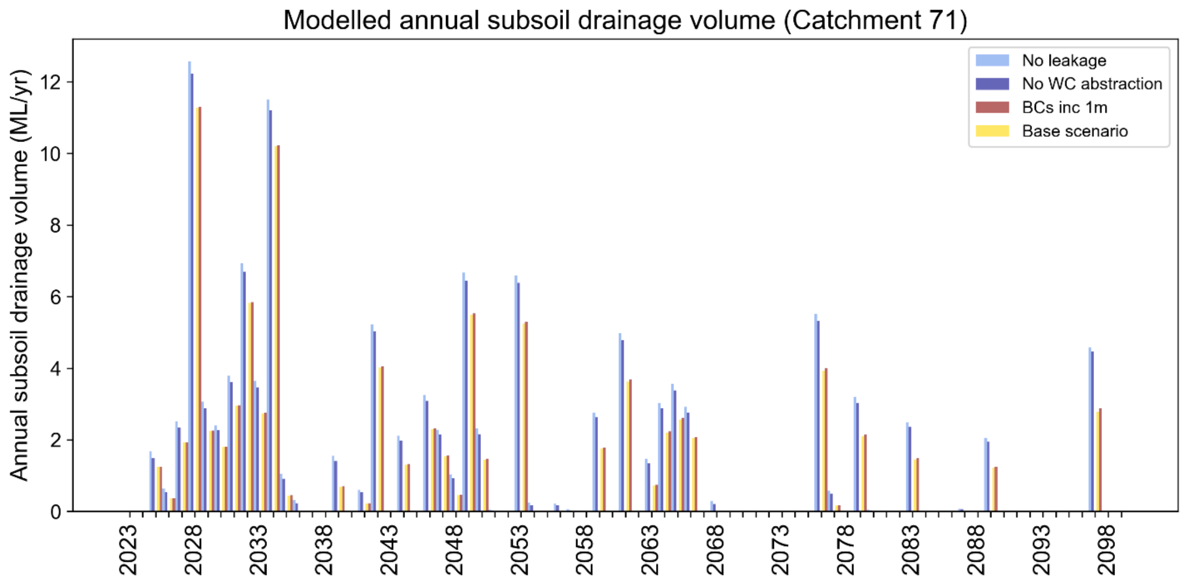

Modelled annual subsoil drainage volume (Catchment 58)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

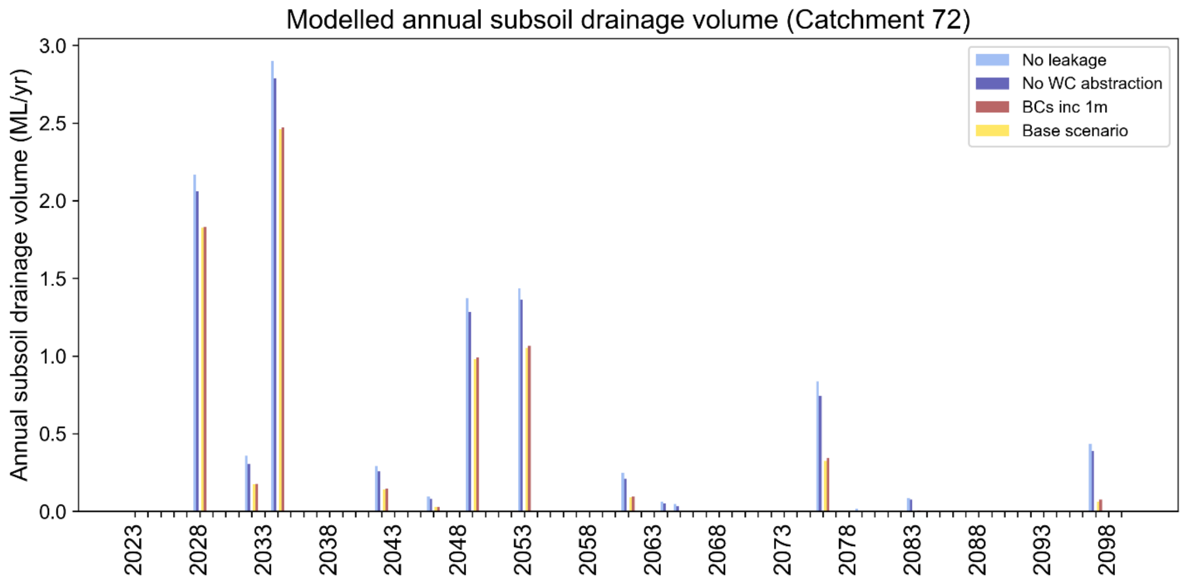

Modelled annual subsoil drainage volume (Catchment 59)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario


Modelled annual subsoil drainage volume (Catchment 60)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario


Modelled annual subsoil drainage volume (Catchment 68)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario


Modelled annual subsoil drainage volume (Catchment 70)
Annual subsoil drainage volume (ML/yr)
0
20
40
60
80
100
No leakage
No WC abstraction
BCs inc 1m
Base scenario
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098


Modelled annual subsoil drainage volume (Catchment 71)
Annual subsoil drainage volume (ML/yr)
0
2
4
6
8
10
12
No leakage
No WC abstraction
BCs inc 1m
Base scenario
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098


Modelled annual subsoil drainage volume (Catchment 72)
Annual subsoil drainage volume (ML/yr)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
No leakage
No WC abstraction
BCs inc 1m
Base scenario
2023
2028
2033
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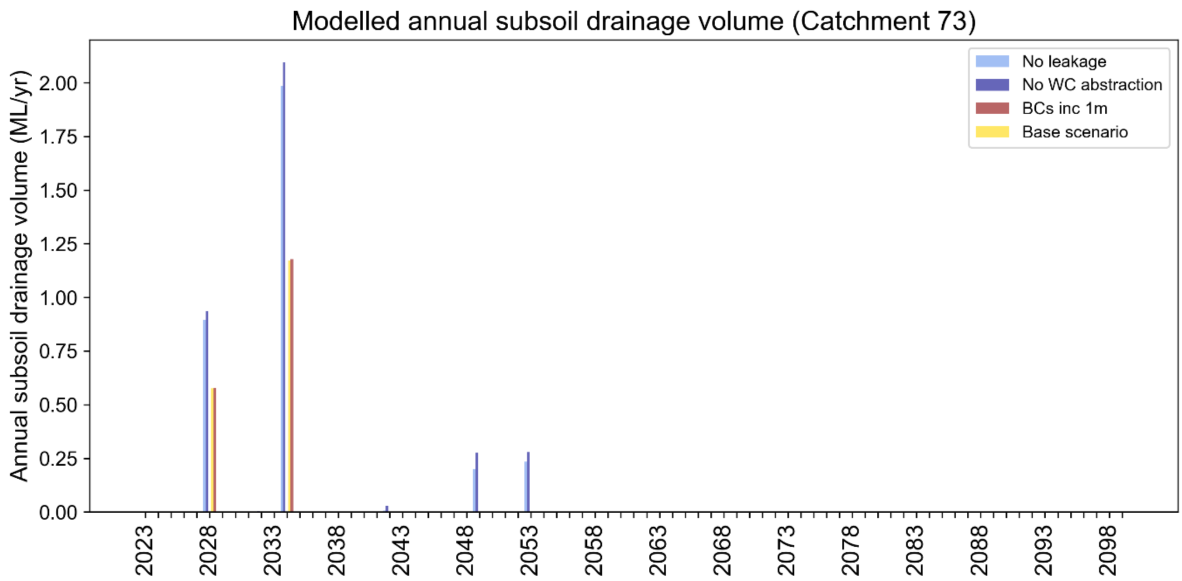
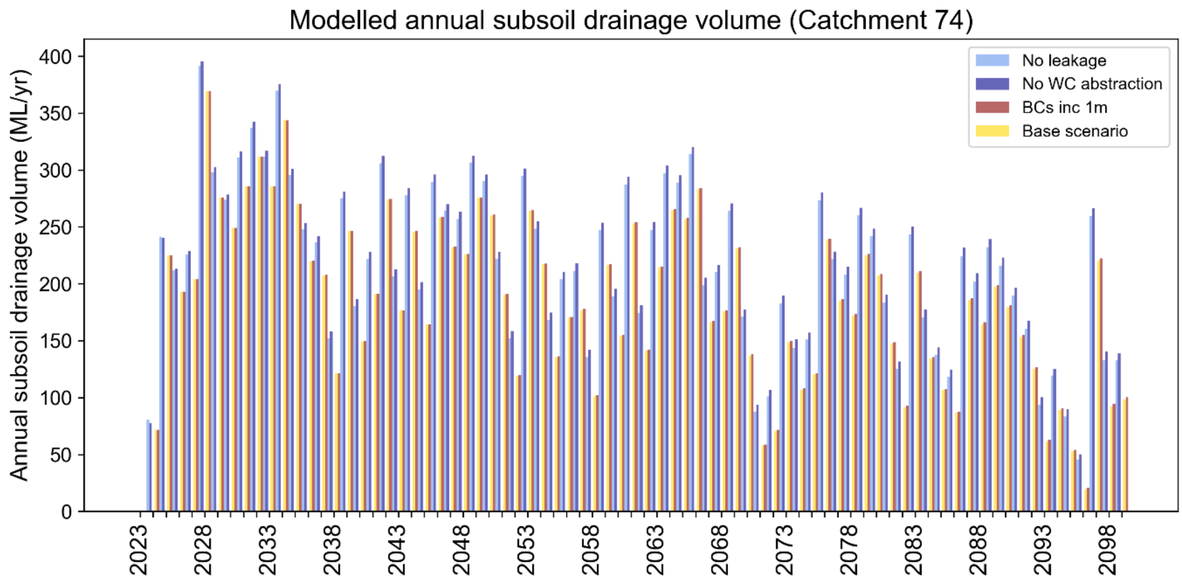
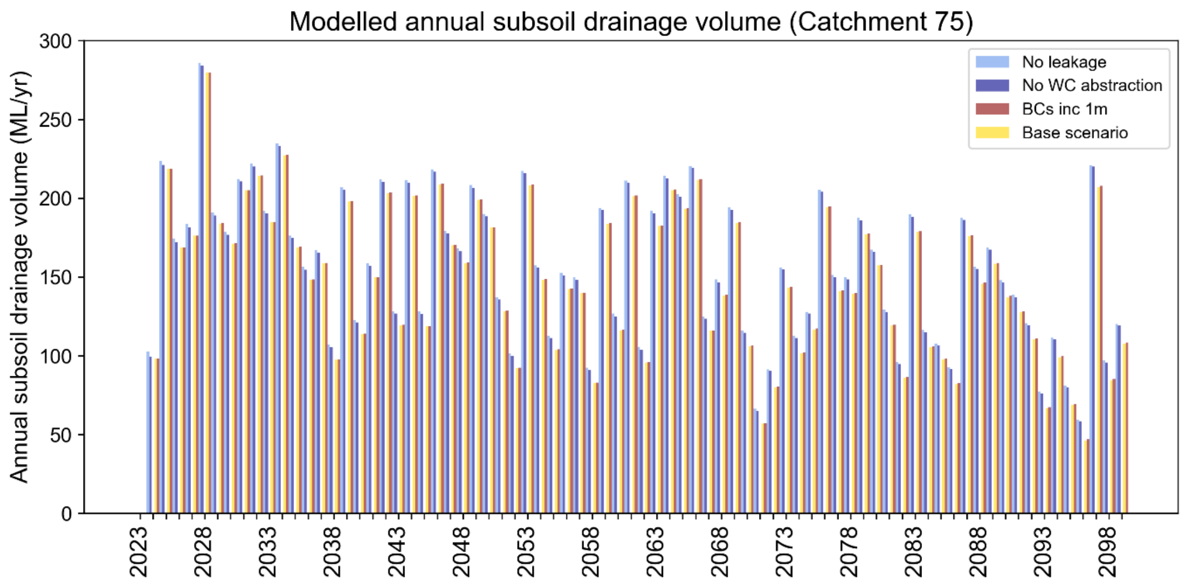
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098



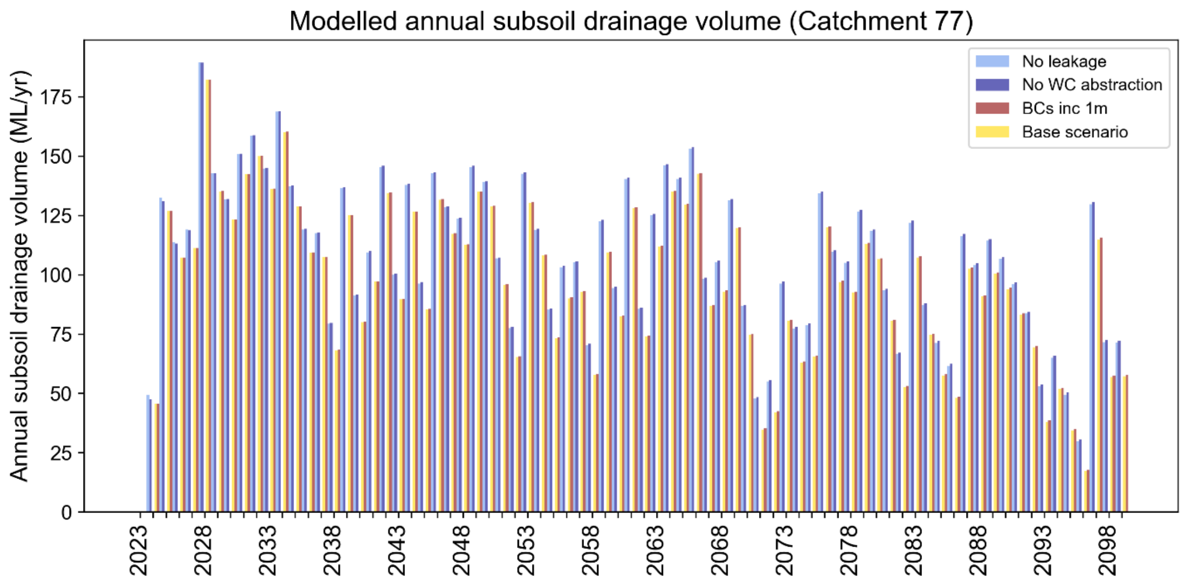
Modelled annual subsoil drainage volume (Catchment 73)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

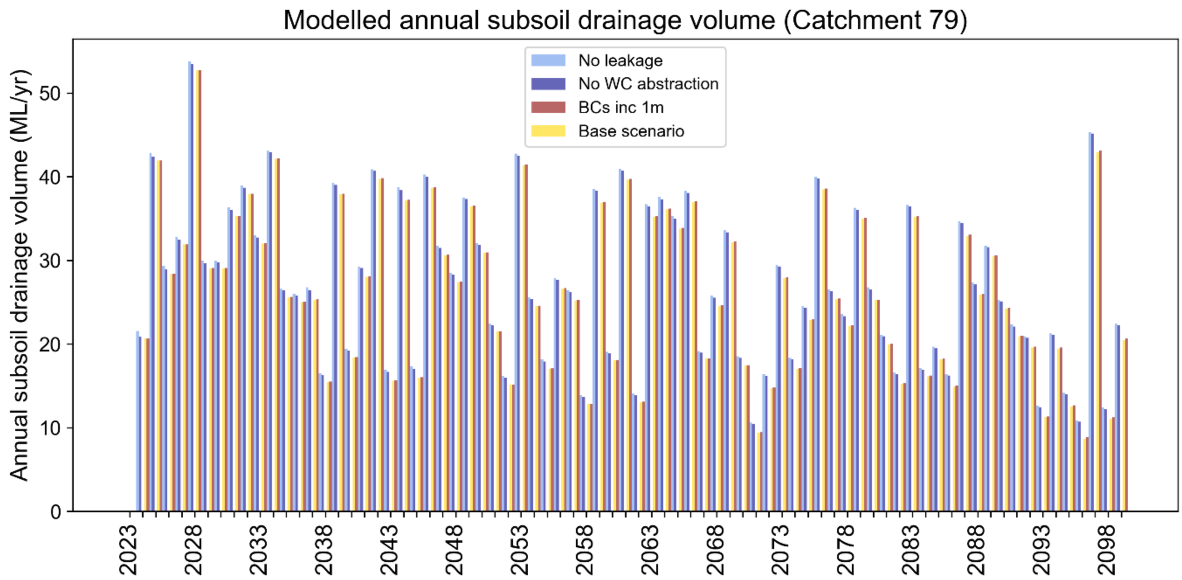


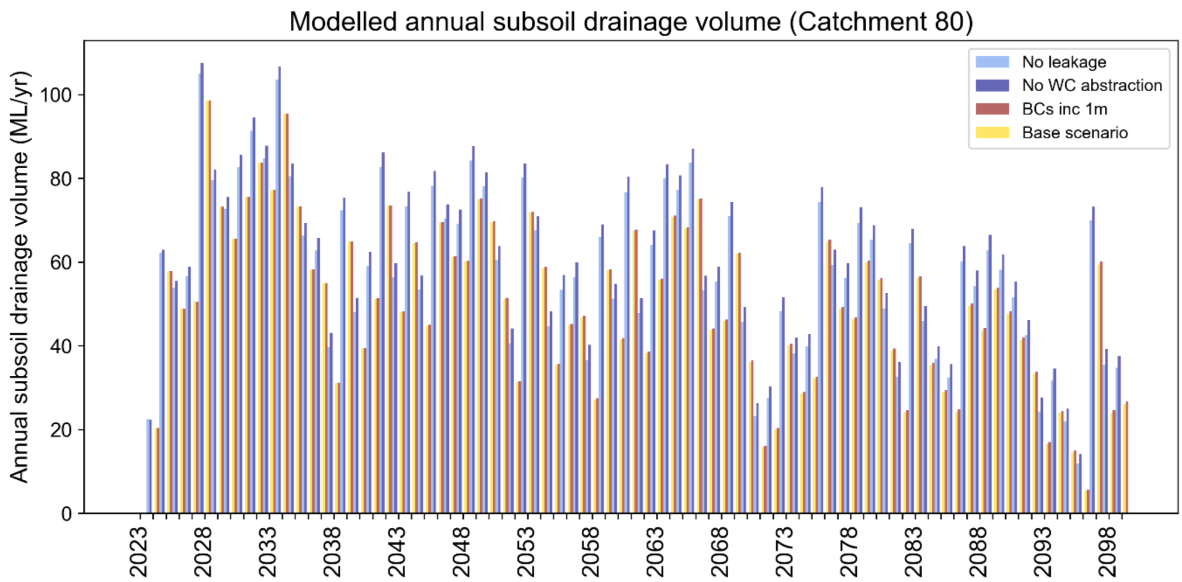
Modelled annual subsoil drainage volume (Catchment 74)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
50
100
150
200
250
300
350
400
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

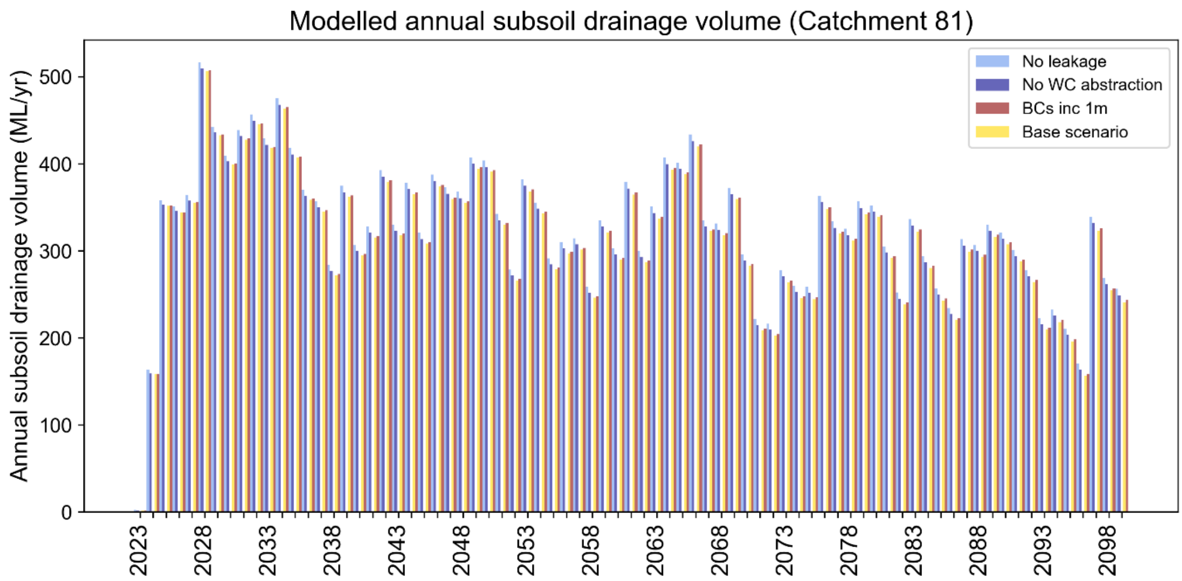


Modelled annual subsoil drainage volume (Catchment 75)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
50
100
150
200
250
300
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

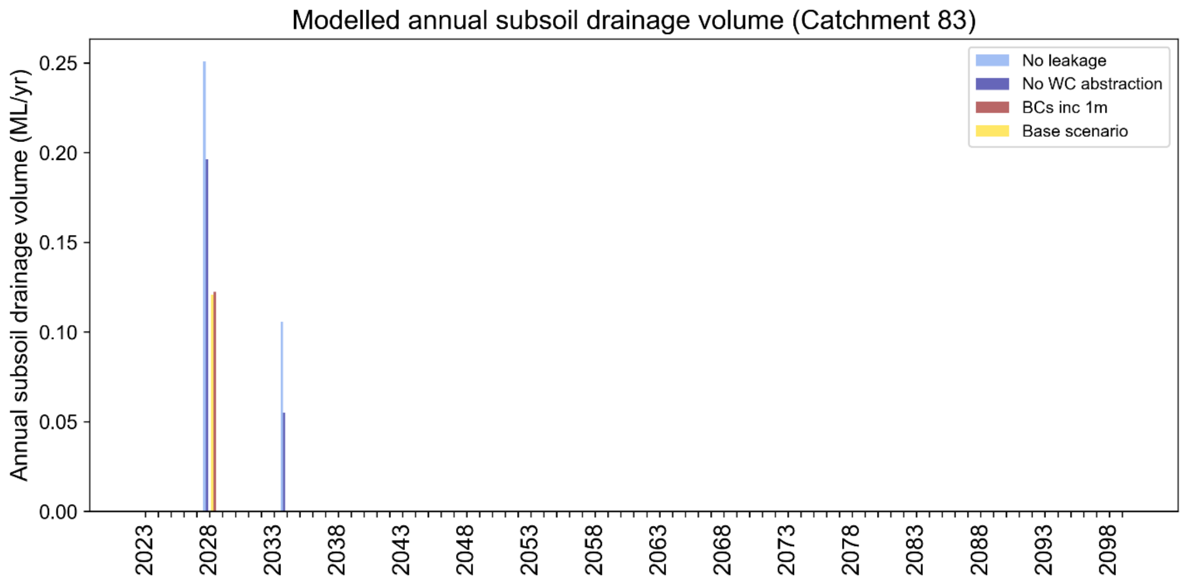

Modelled annual subsoil drainage volume (Catchment 77)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
25
50
75
100
125
150
175
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098


Modelled annual subsoil drainage volume (Catchment 79)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
10
20
30
40
50
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

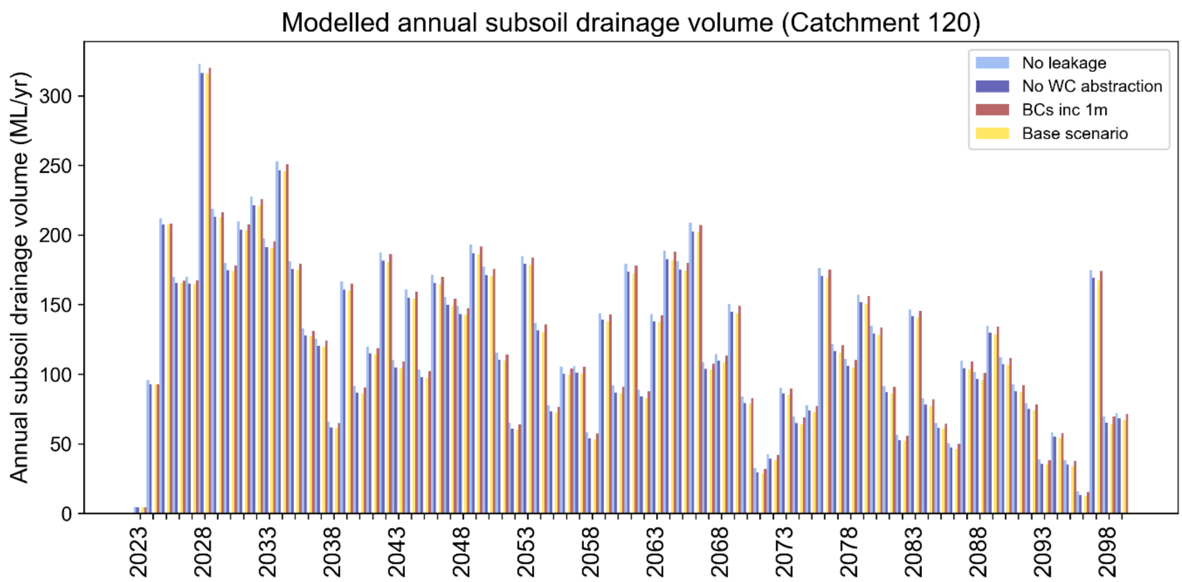

Modelled annual subsoil drainage volume (Catchment 80)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
20
40
60
80
100
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098



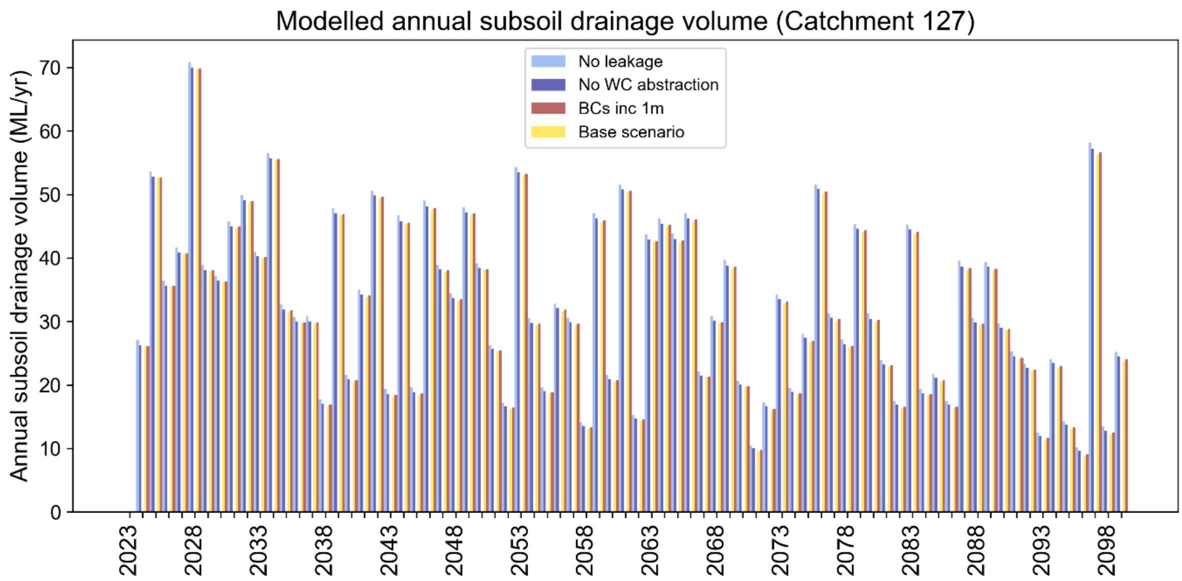
Modelled annual subsoil drainage volume (Catchment 81)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario

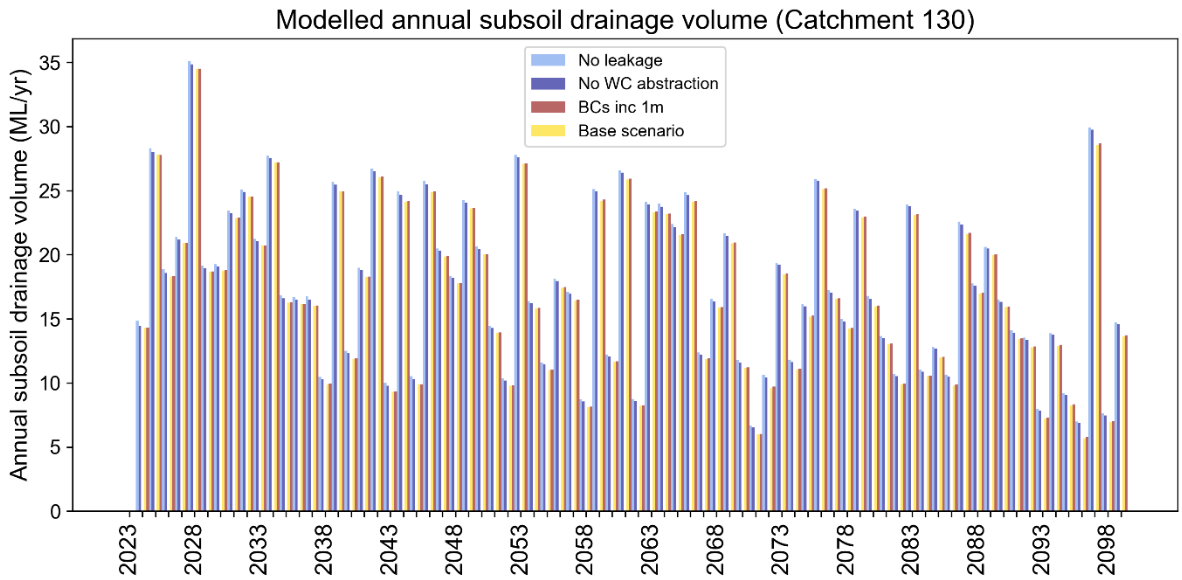


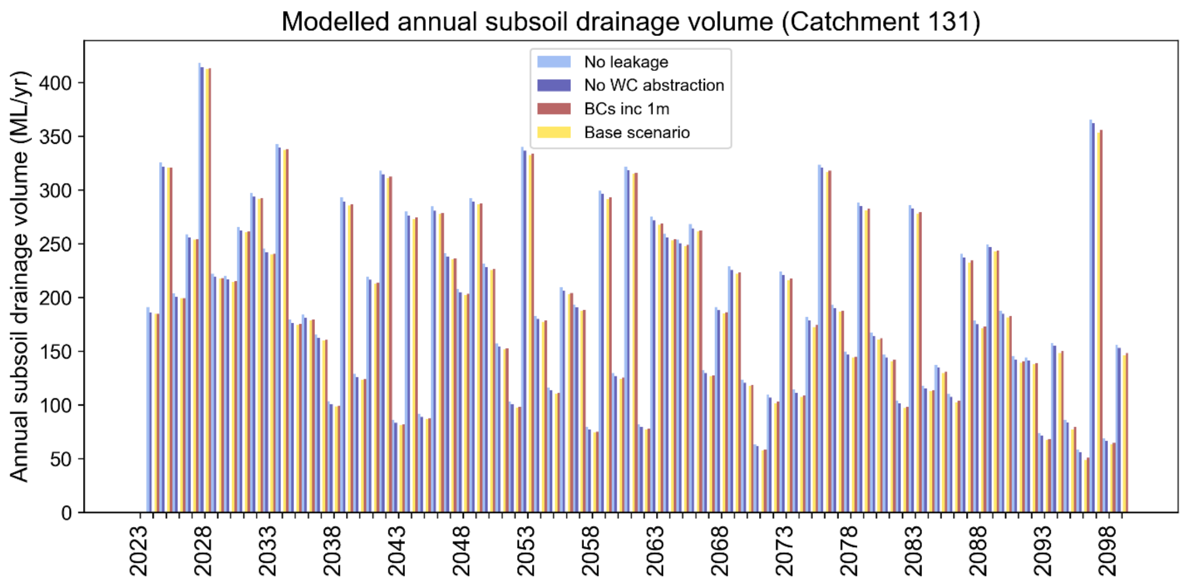
Modelled annual subsoil drainage volume (Catchment 83)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario

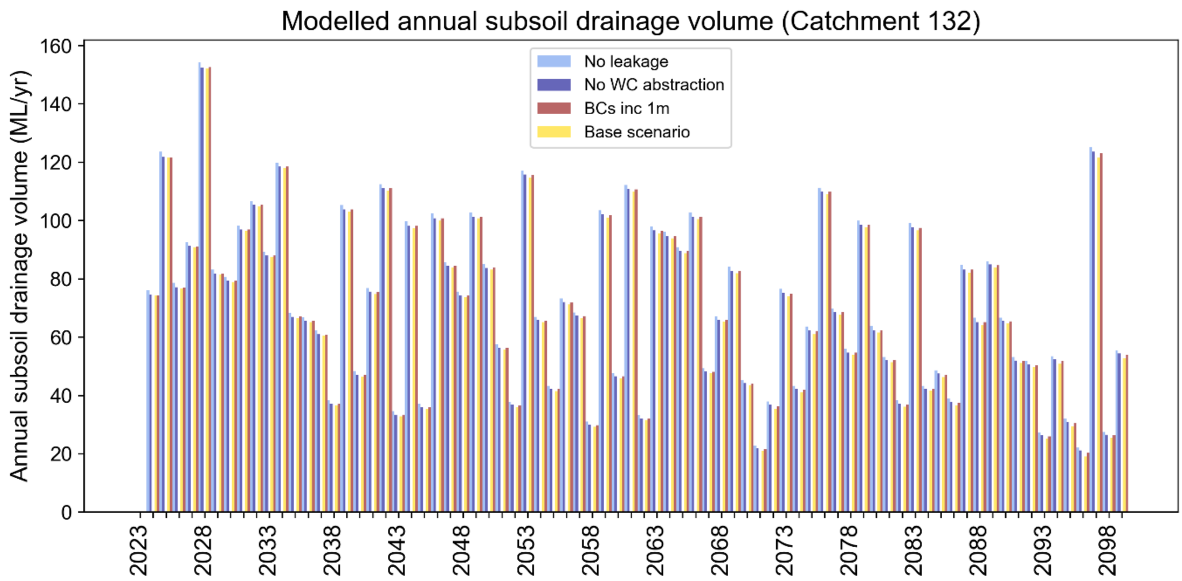


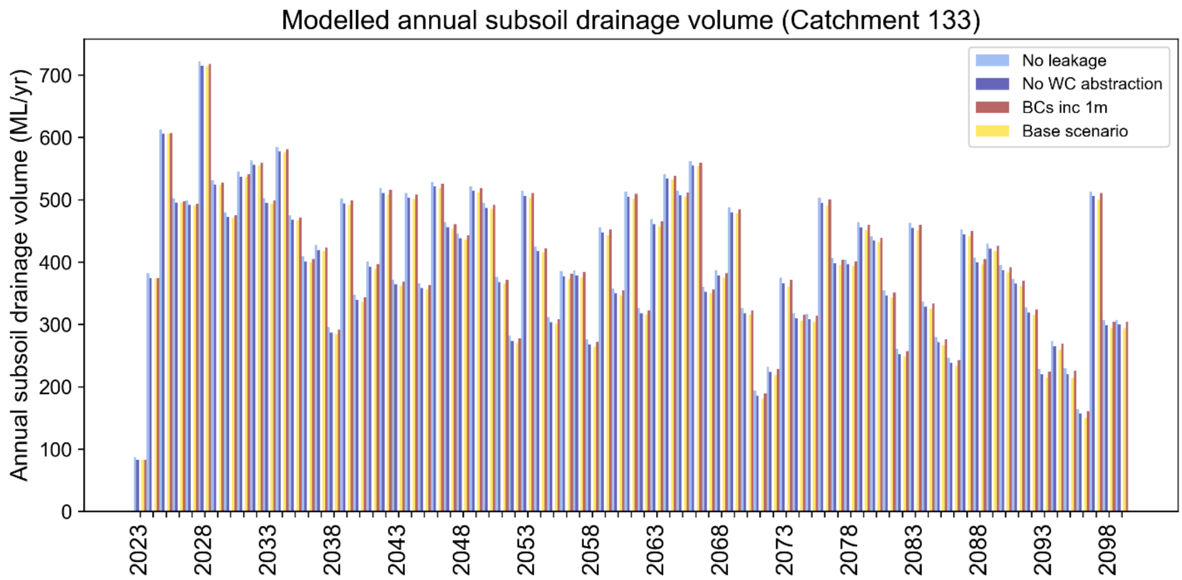
Modelled annual subsoil drainage volume (Catchment 120)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario

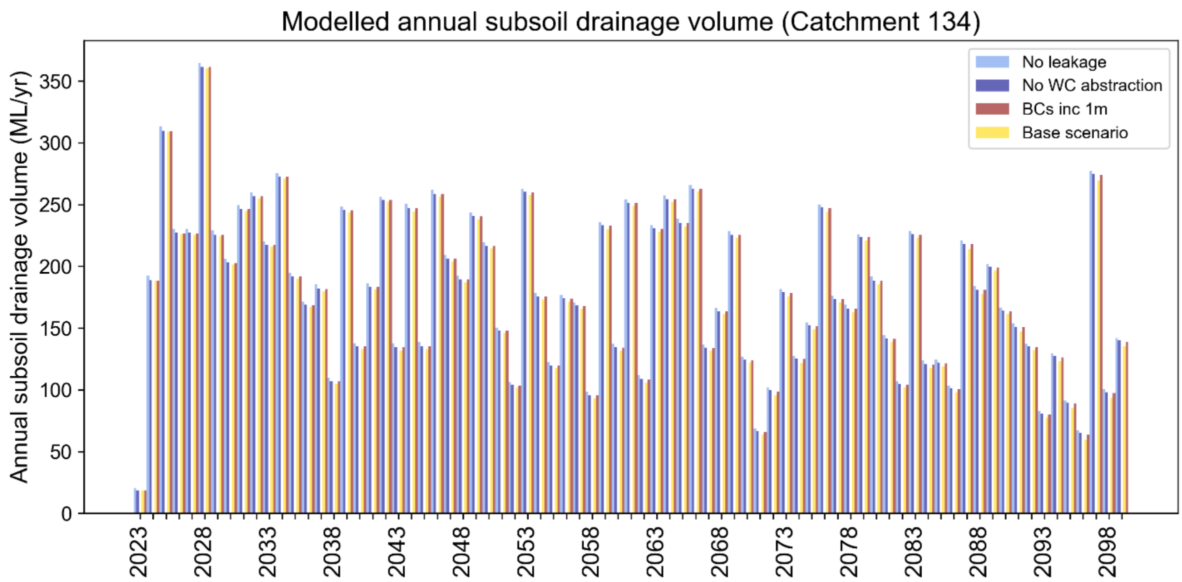

Modelled annual subsoil drainage volume (Catchment 127)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
Annual subsoil drainage volume (ML/yr)
0
10
20
30
40
50
60
70
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

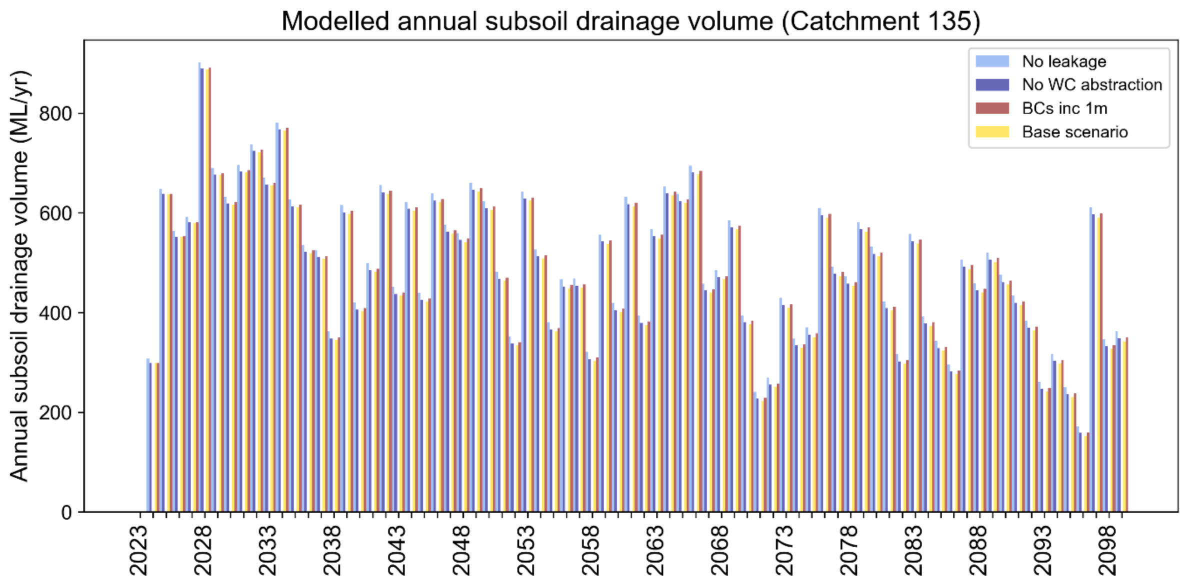

Modelled annual subsoil drainage volume (Catchment 130)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
Annual subsoil drainage volume (ML/yr)
0
5
10
15
20
25
30
35
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098


Modelled annual subsoil drainage volume (Catchment 131)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
Annual subsoil drainage volume (ML/yr)
0
50
100
150
200
250
300
350
400
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

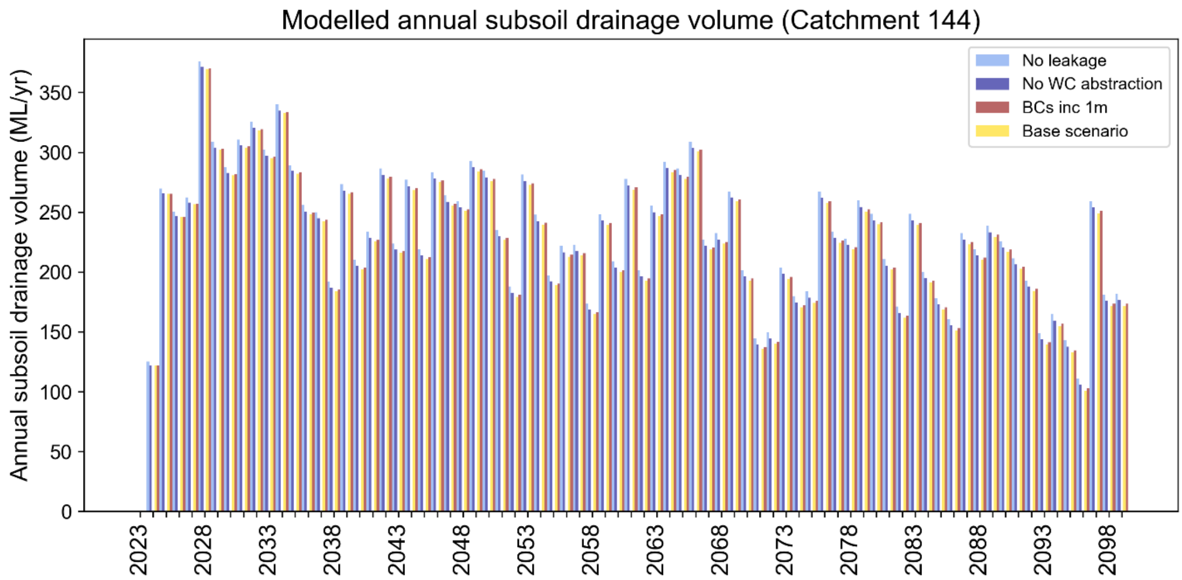

Modelled annual subsoil drainage volume (Catchment 132)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
20
40
60
80
100
120
140
160
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098


Modelled annual subsoil drainage volume (Catchment 133)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
100
200
300
400
500
600
700
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

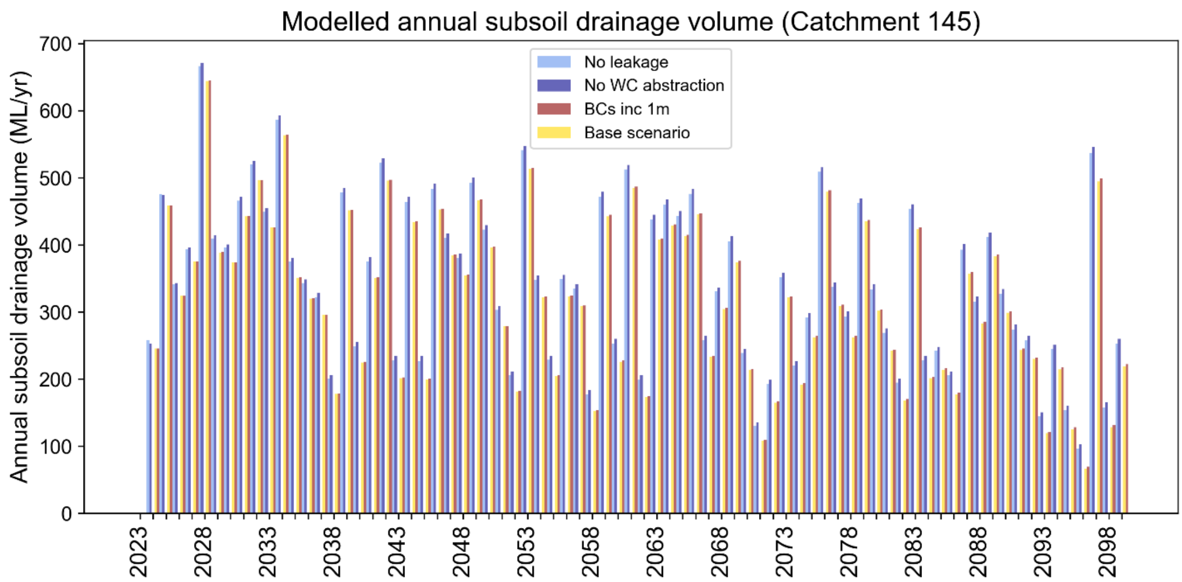

Modelled annual subsoil drainage volume (Catchment 134)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
50
100
150
200
250
300
350
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098



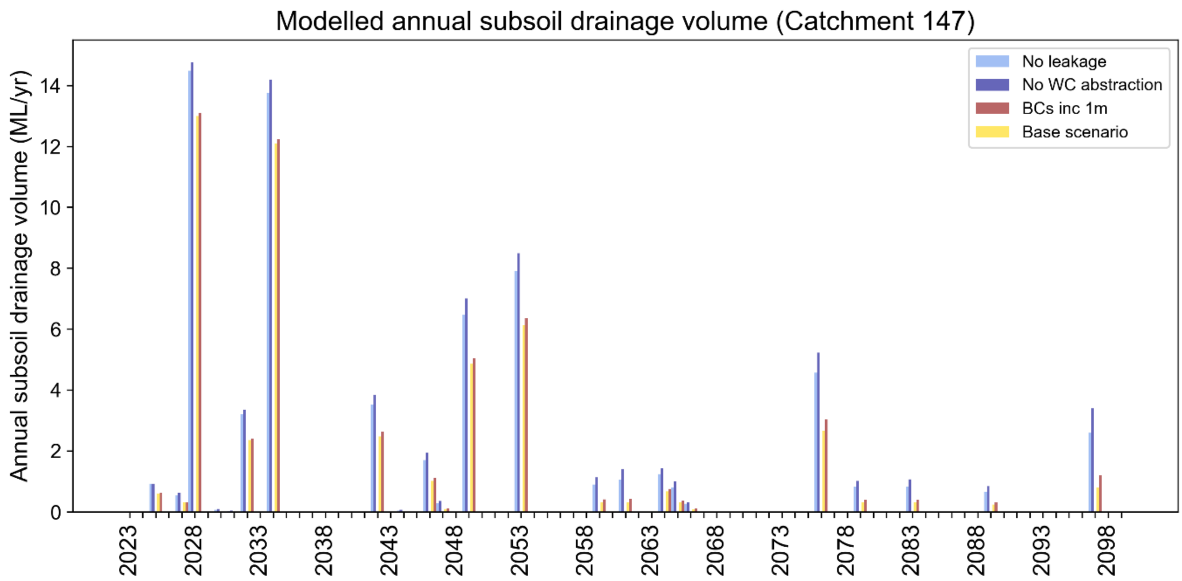
Modelled annual subsoil drainage volume (Catchment 135)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
200
400
600
800
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

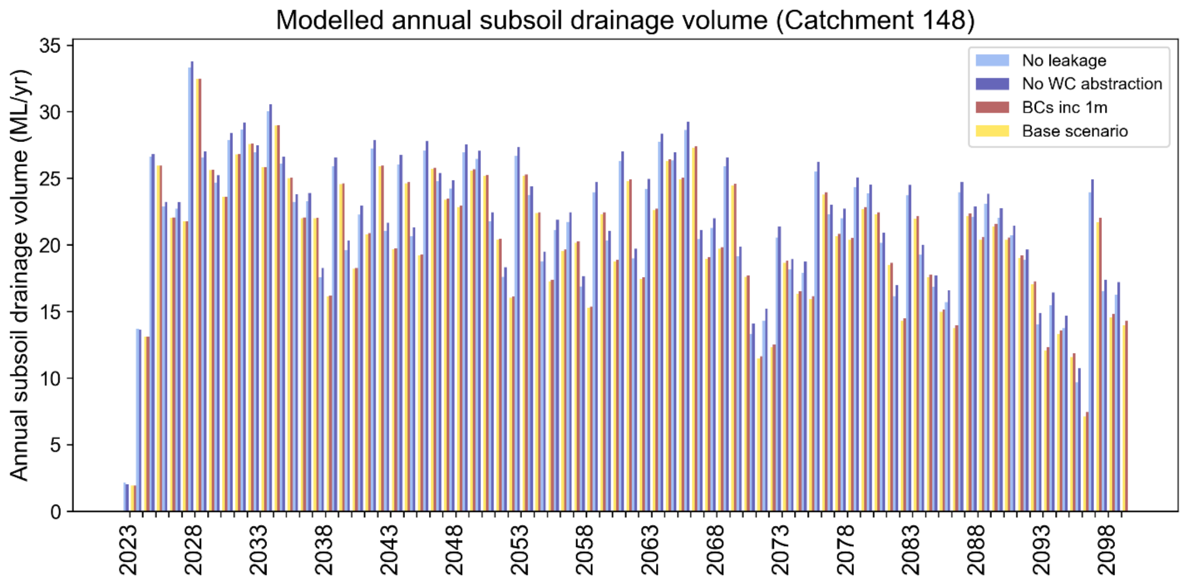


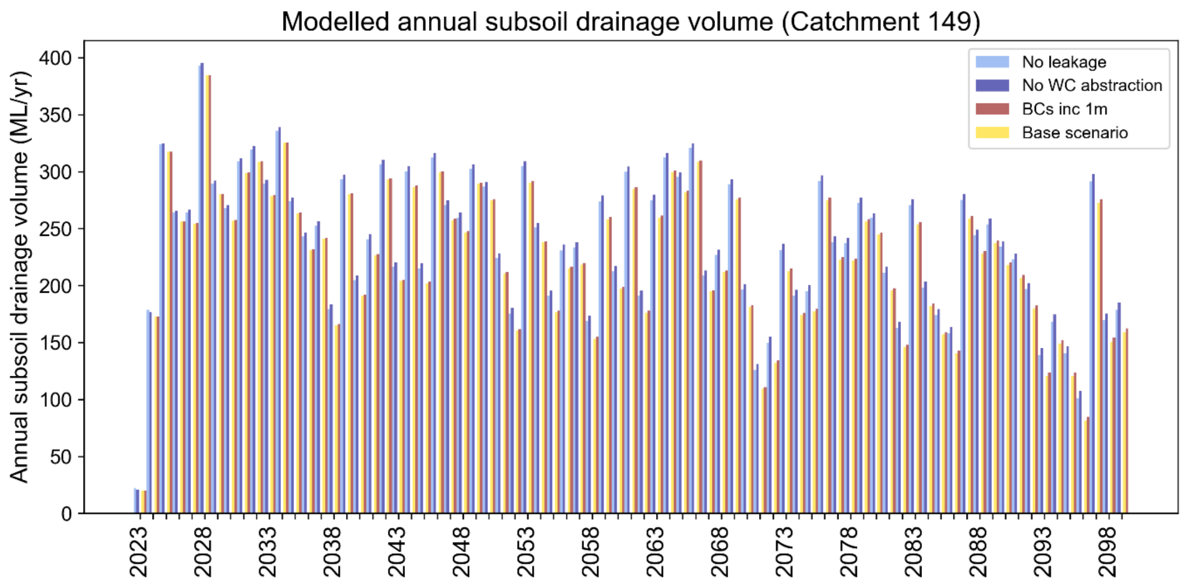
Modelled annual subsoil drainage volume (Catchment 144)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
50
100
150
200
250
300
350
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

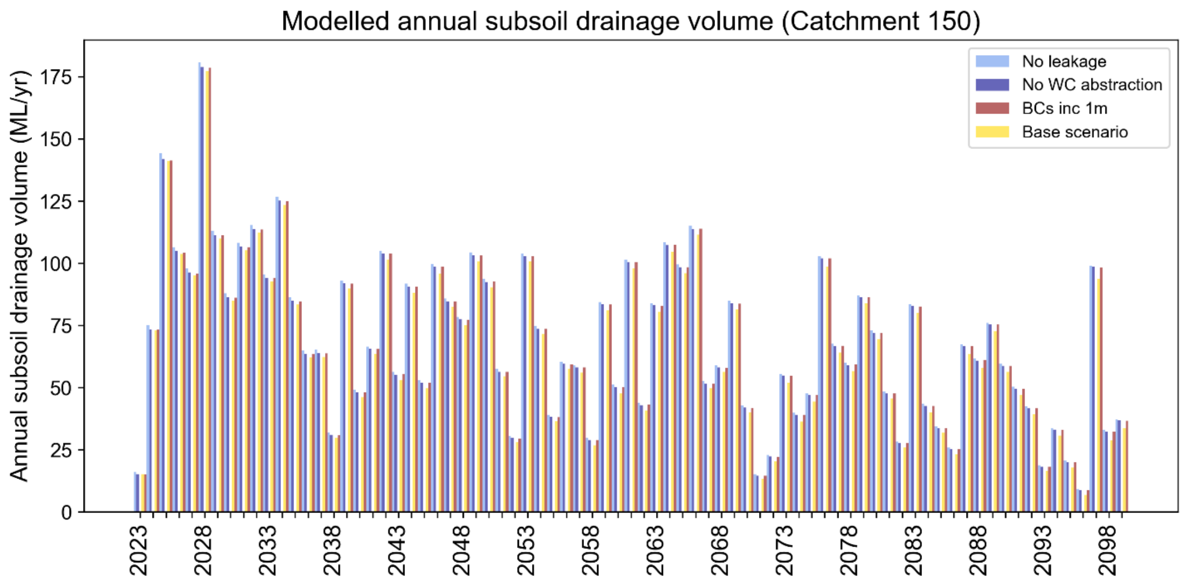


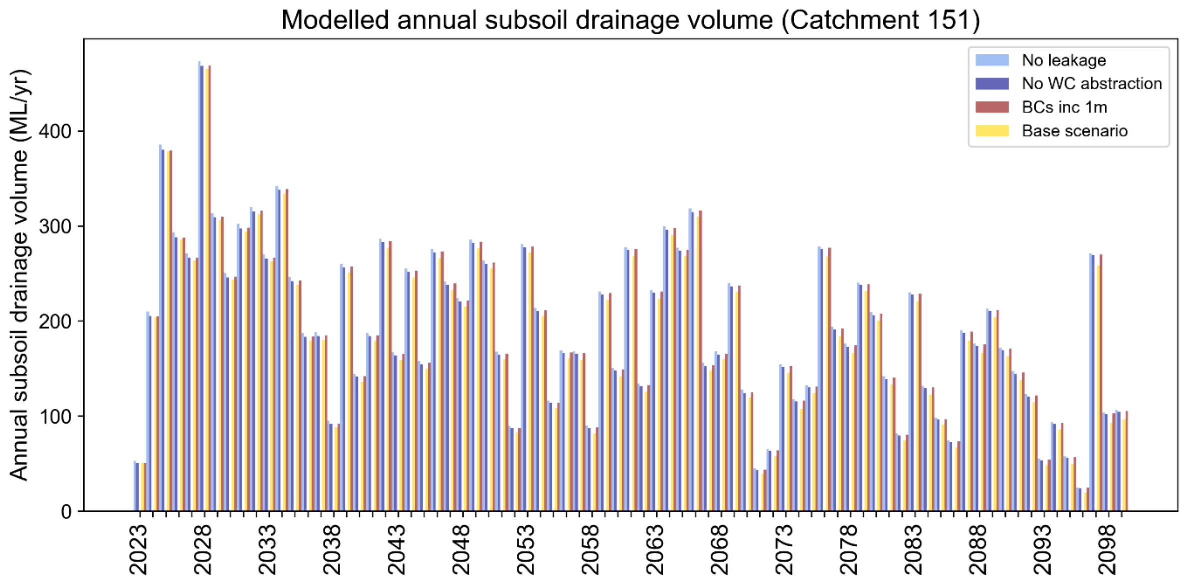
Modelled annual subsoil drainage volume (Catchment 145)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
100
200
300
400
500
600
700
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

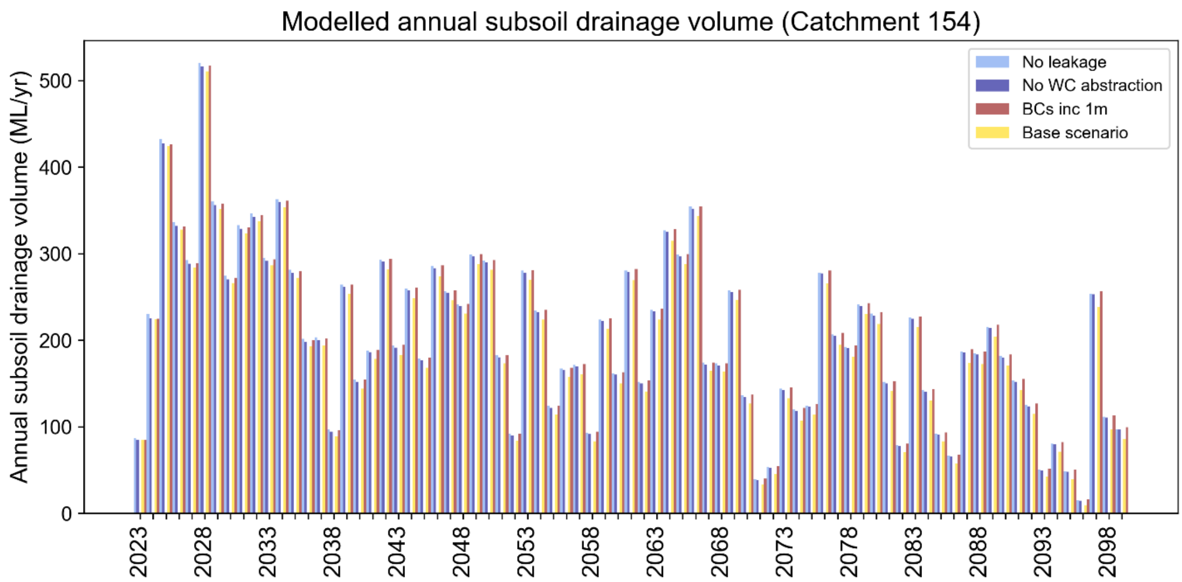

Modelled annual subsoil drainage volume (Catchment 147)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
2
4
6
8
10
12
14
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

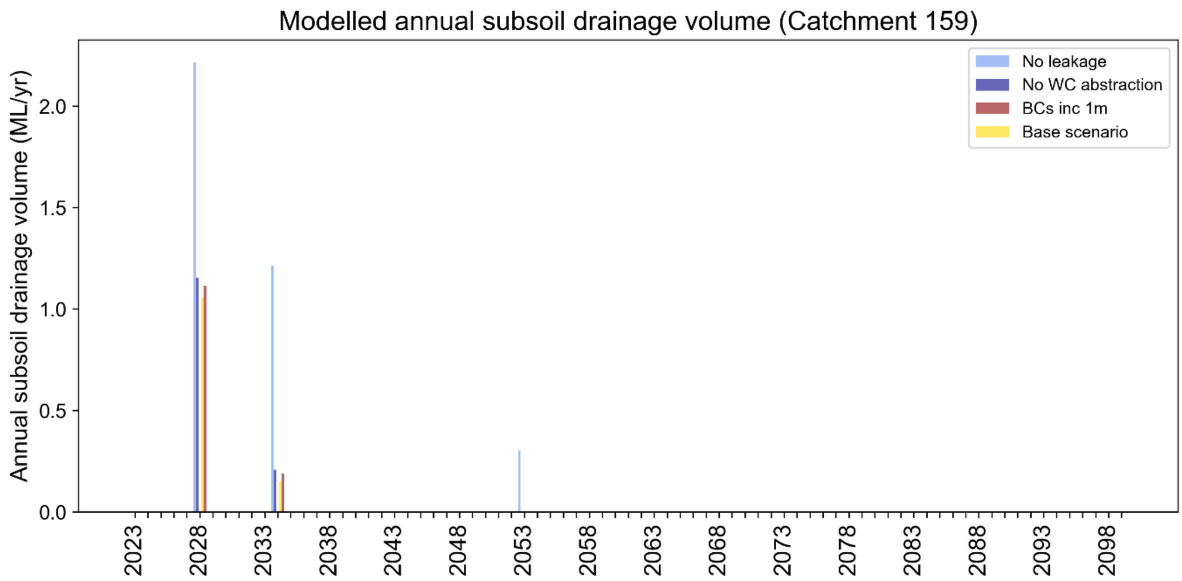

Modelled annual subsoil drainage volume (Catchment 148)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
5
10
15
20
25
30
35
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

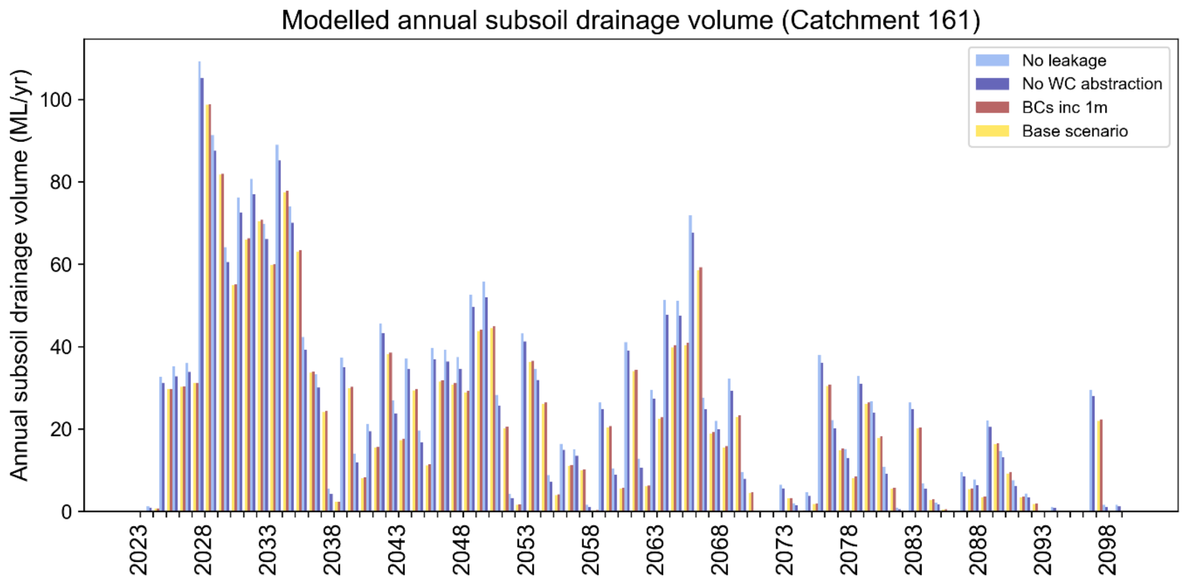

Modelled annual subsoil drainage volume (Catchment 149)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
50
100
150
200
250
300
350
400
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

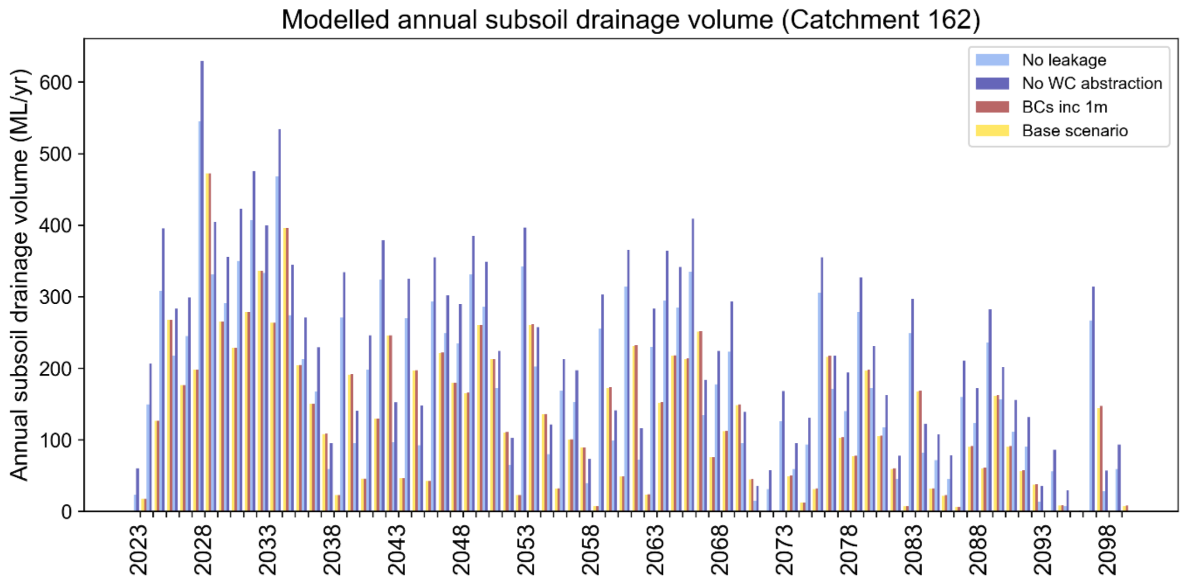

Modelled annual subsoil drainage volume (Catchment 150)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
25
50
75
100
125
150
175
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

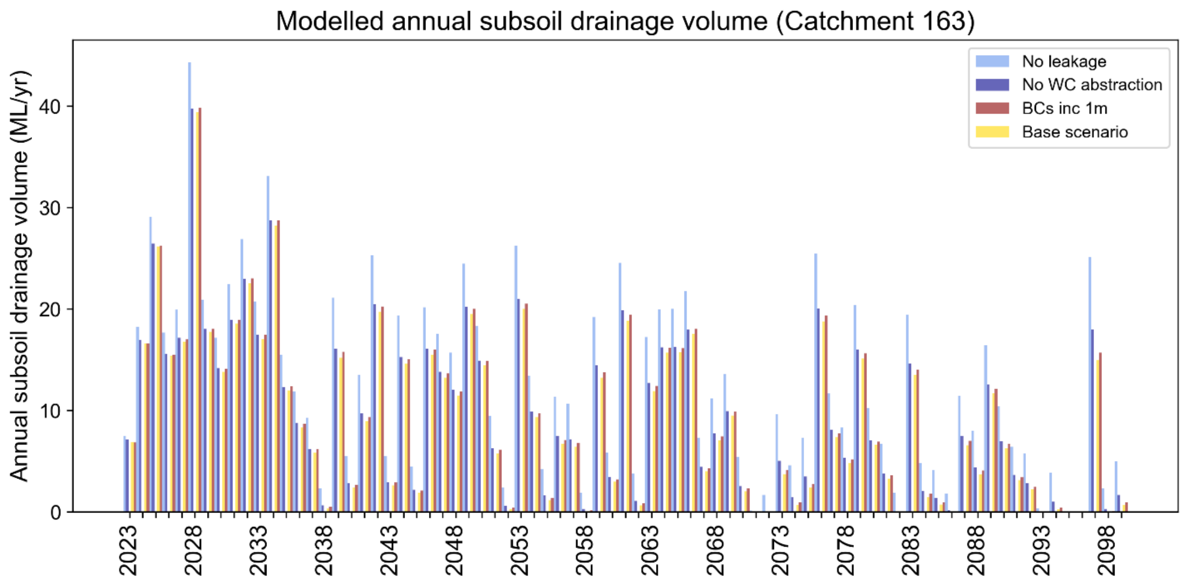

Modelled annual subsoil drainage volume (Catchment 151)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
100
200
300
400
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

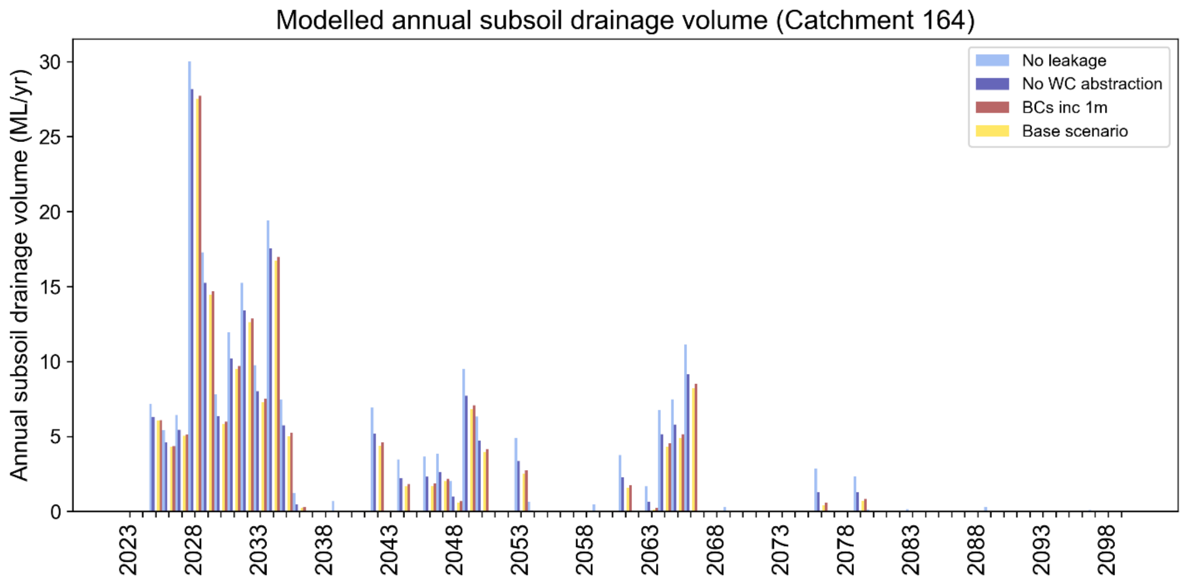

Modelled annual subsoil drainage volume (Catchment 154)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
100
200
300
400
500
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

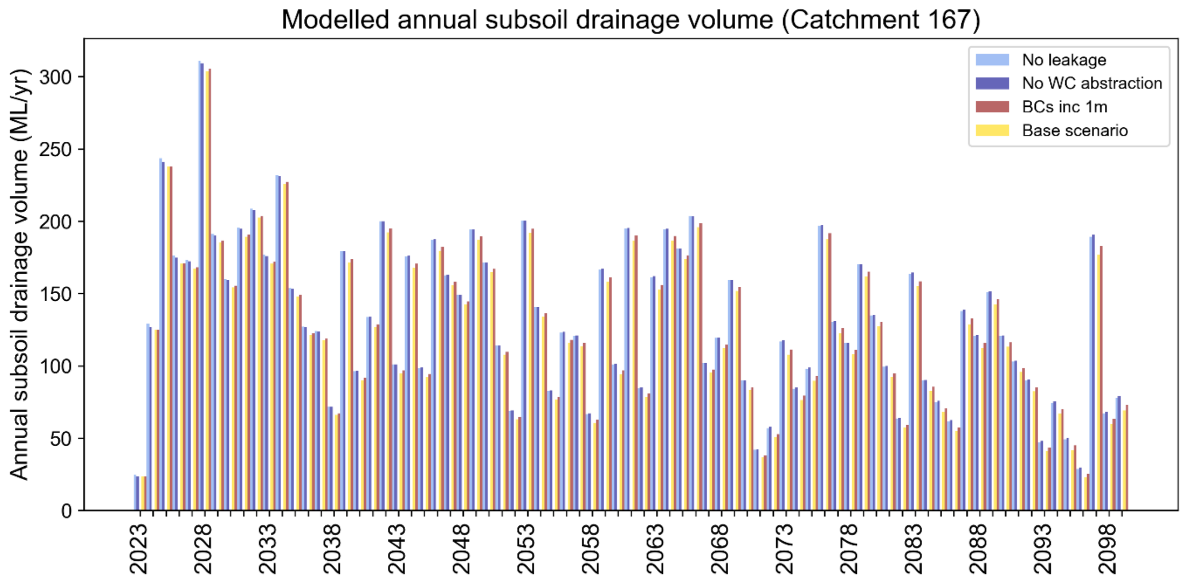

Modelled annual subsoil drainage volume (Catchment 159)
Annual subsoil drainage volume (ML/yr)
0.0
0.5
1.0
1.5
2.0
No leakage
No WC abstraction
BCs inc 1m
Base scenario
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

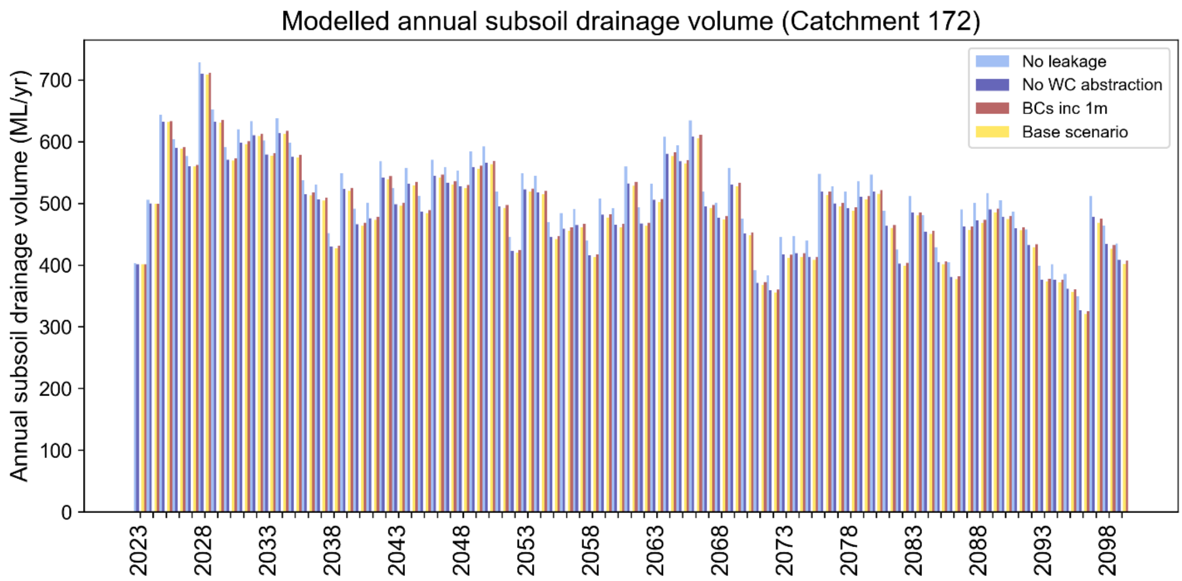

Modelled annual subsoil drainage volume (Catchment 161)
Annual subsoil drainage volume (ML/yr)
0
20
40
60
80
100
No leakage
No WC abstraction
BCs inc 1m
Base scenario
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

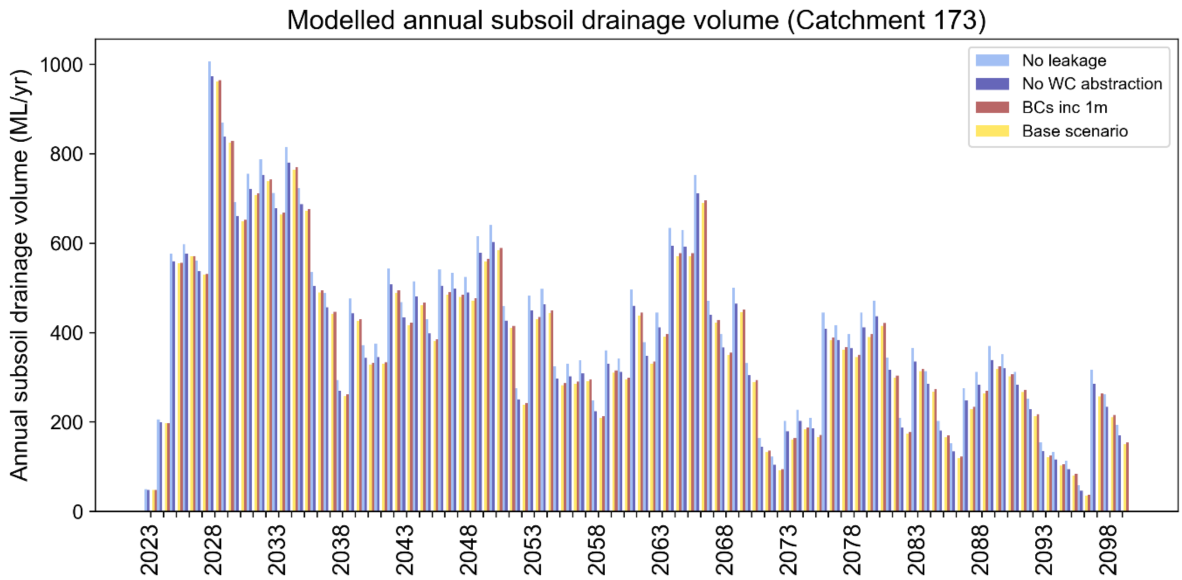

Modelled annual subsoil drainage volume (Catchment 162)
Annual subsoil drainage volume (ML/yr)
0
100
200
300
400
500
600
No leakage
No WC abstraction
BCs inc 1m
Base scenario
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

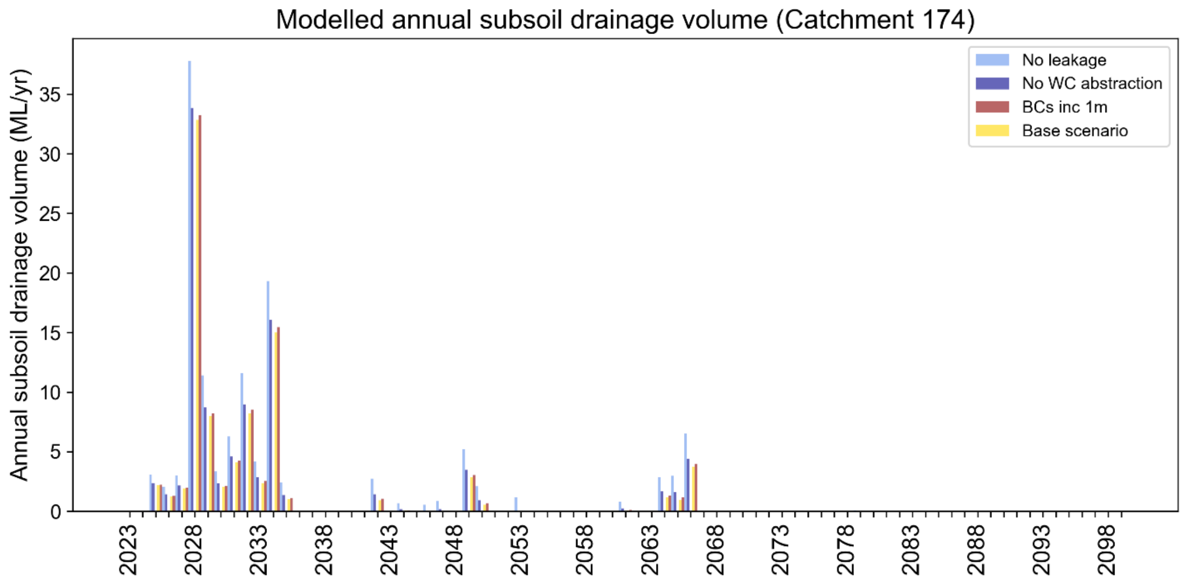

Modelled annual subsoil drainage volume (Catchment 163)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
10
20
30
40
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

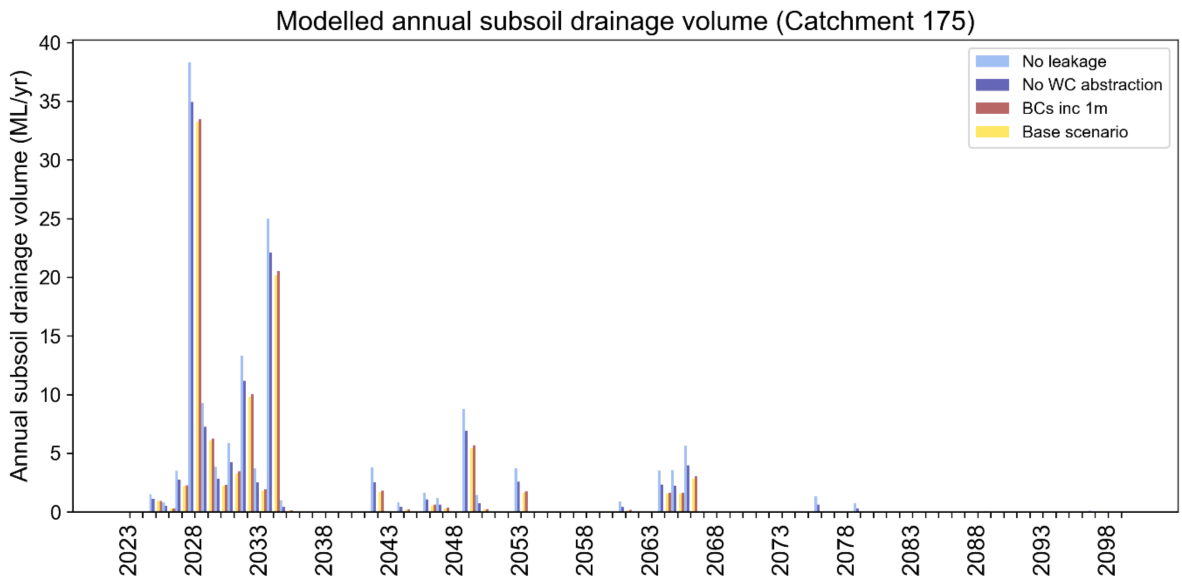

Modelled annual subsoil drainage volume (Catchment 164)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
5
10
15
20
25
30
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098

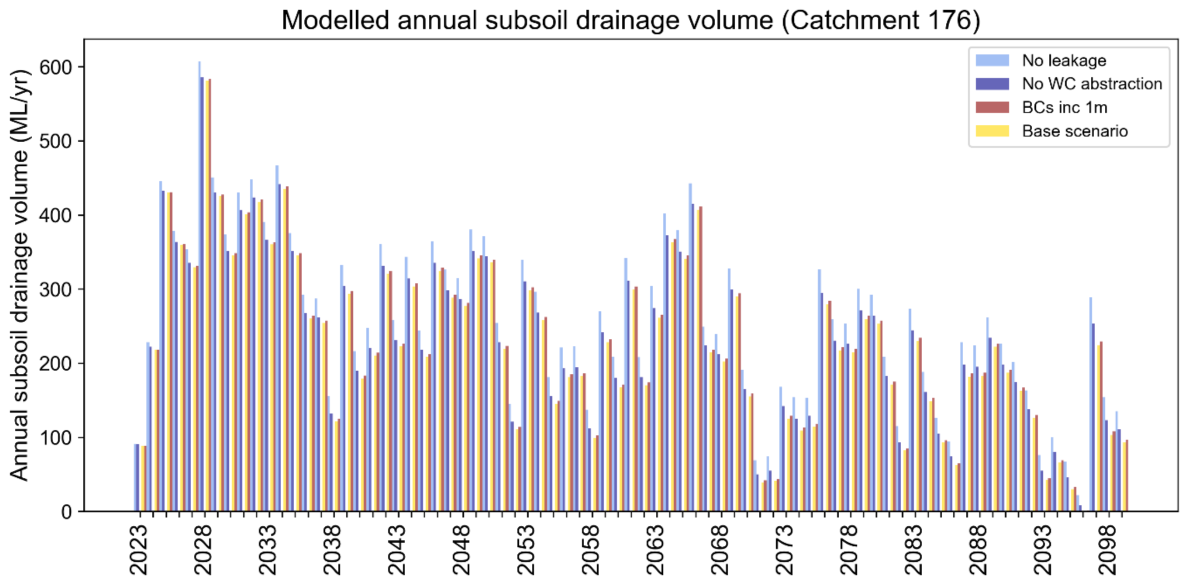

Modelled annual subsoil drainage volume (Catchment 167)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
50
100
150
200
250
300
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098


Modelled annual subsoil drainage volume (Catchment 172)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
100
200
300
400
500
600
700
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098


Modelled annual subsoil drainage volume (Catchment 173)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
200
400
600
800
1000
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098


Modelled annual subsoil drainage volume (Catchment 174)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
5
10
15
20
25
30
35
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098


Modelled annual subsoil drainage volume (Catchment 175)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
5
10
15
20
25
30
35
40
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098


Modelled annual subsoil drainage volume (Catchment 176)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
100
200
300
400
500
600
2023
2028
2033
2038
2043
2048
2053
2058
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2068
2073
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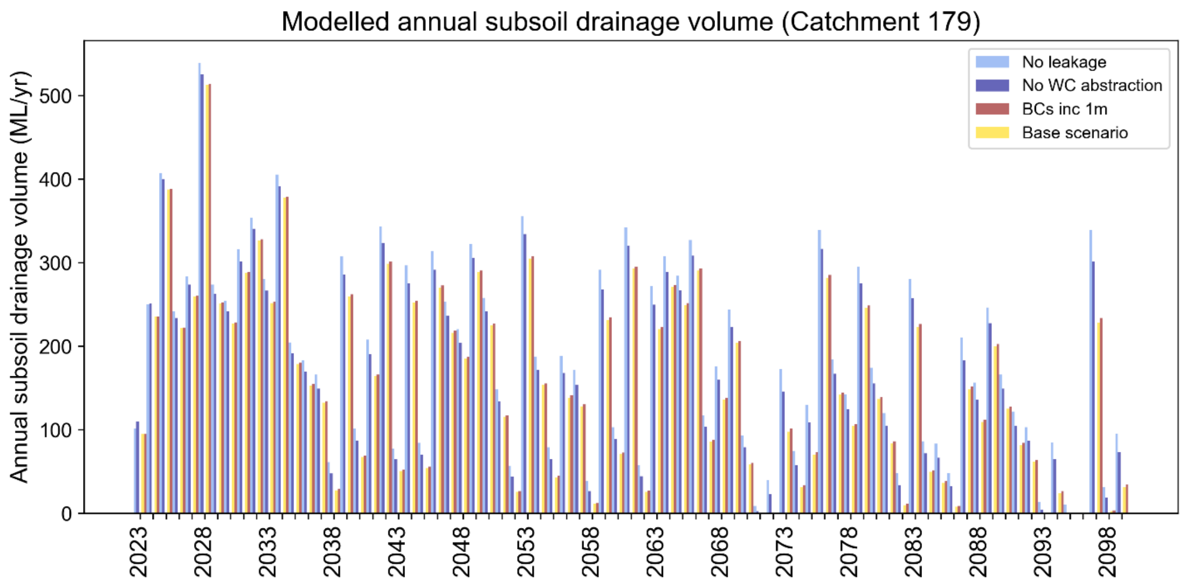
Modelled annual subsoil drainage volume (Catchment 179)
Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
100
200
300
400
500
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
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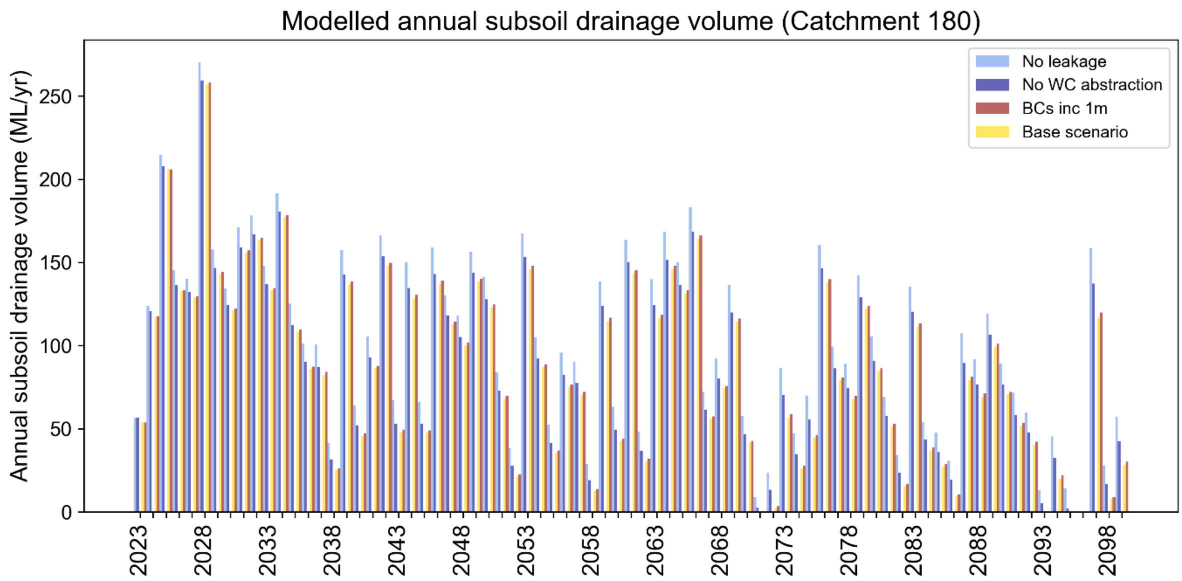
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Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
50
100
150
200
250
2023
2028
2033
2038
2043
2048
2053
2058
2063
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2073
2078
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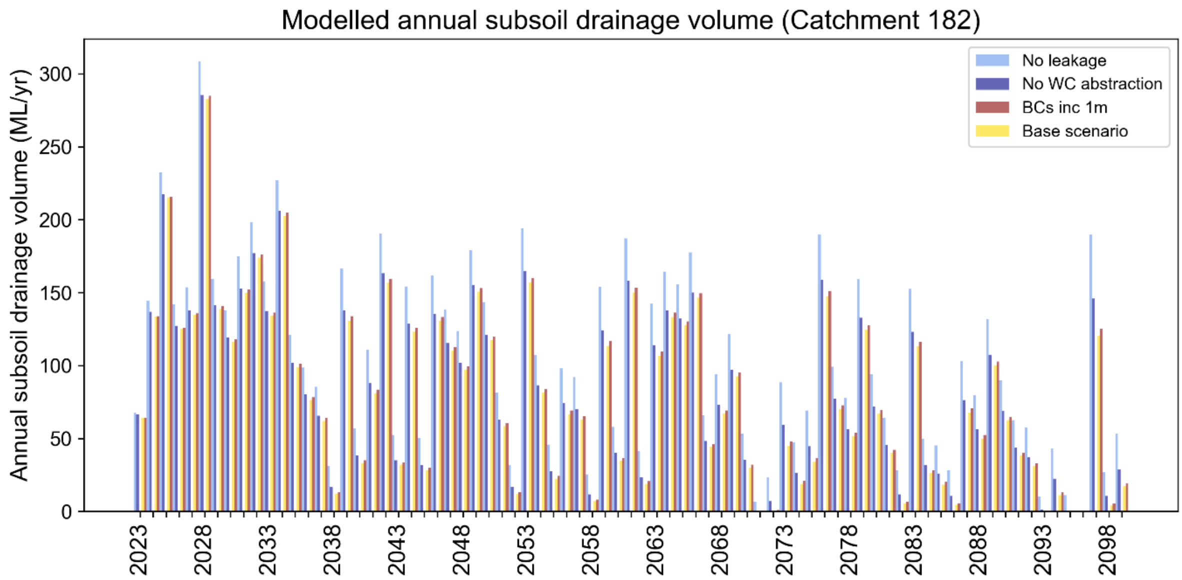
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Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
50
100
150
200
250
300
2023
2028
2033
2038
2043
2048
2053
2058
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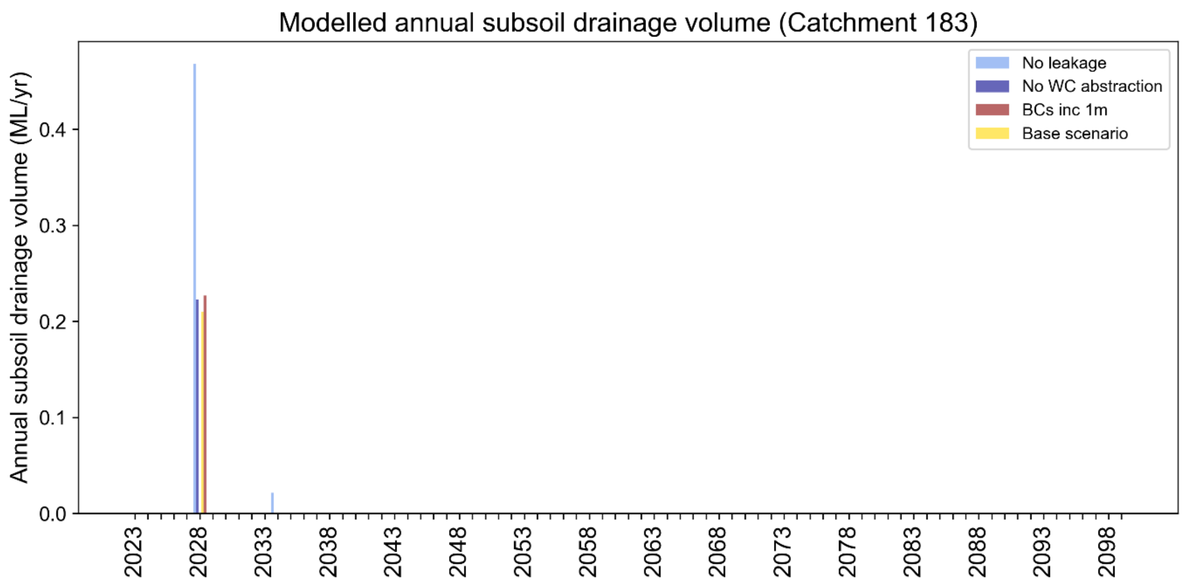
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BCs inc 1m
Base scenario
0.0
0.1
0.2
0.3
0.4
2023
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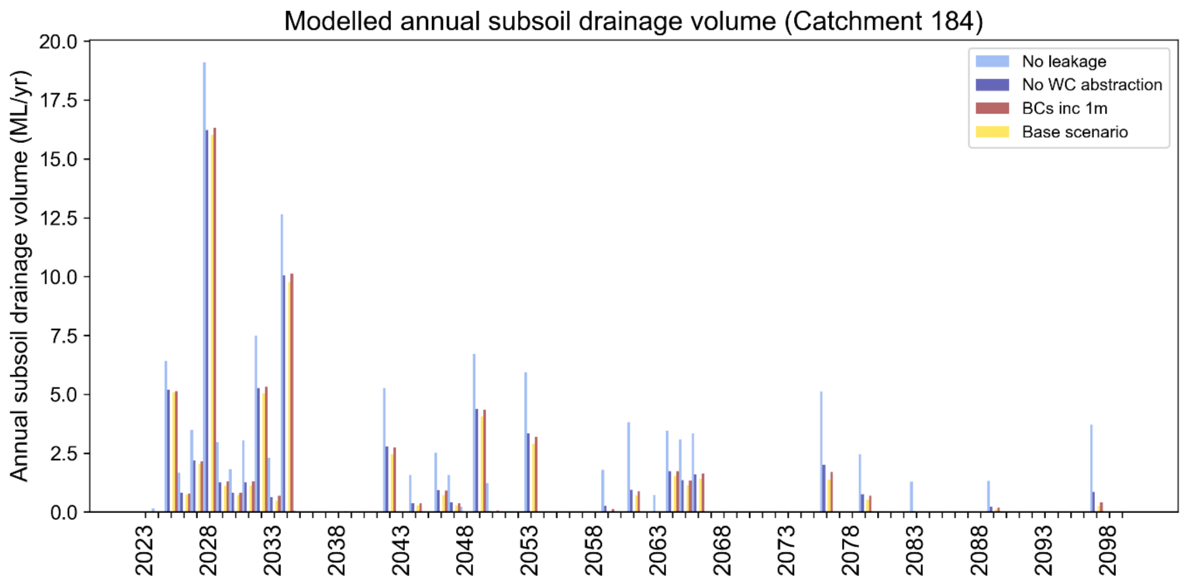
2093
2098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Annual subsoil drainage volume (ML/yr)
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
2023
2028
2033
2038
2043
2048
2053
2058
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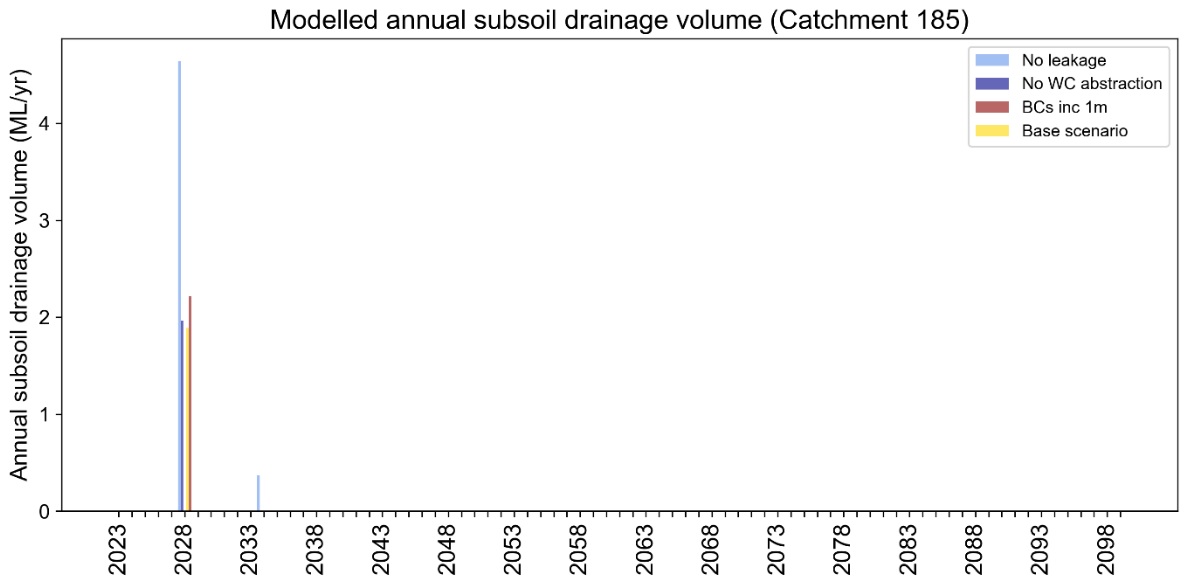
2068
2073
2078
2083
2088
2093
2098
No leakage
No WC abstraction
BCs inc 1m
Base scenario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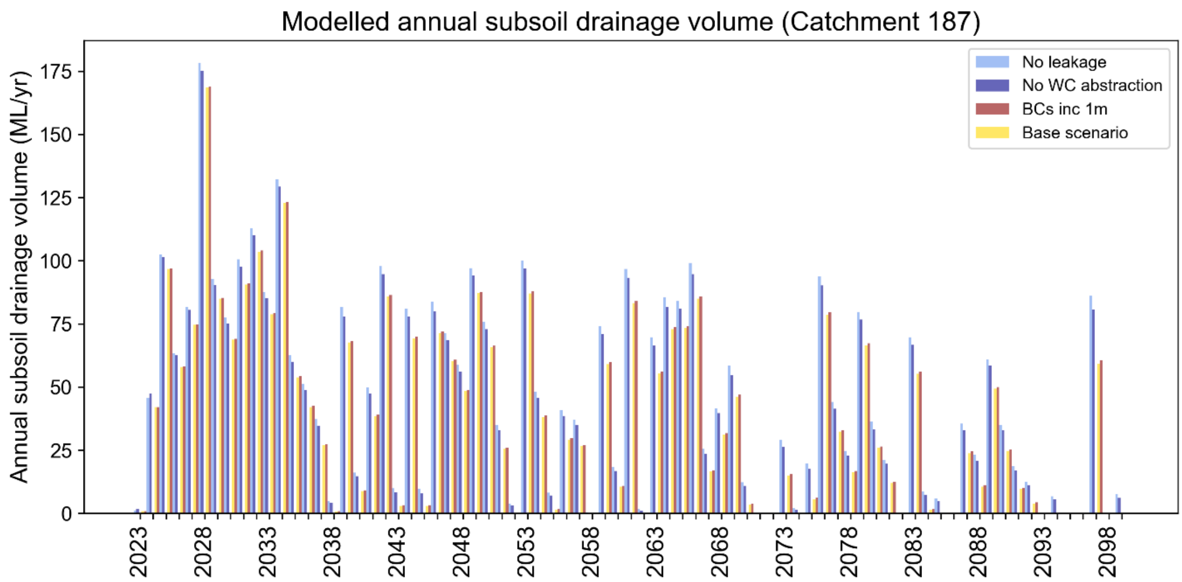
Annual subsoil drainage volume (ML/yr)
0
1
2
3
4
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098
No leakage
No WC abstraction
BCs inc 1m
Base scenario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Annual subsoil drainage volume (ML/yr)
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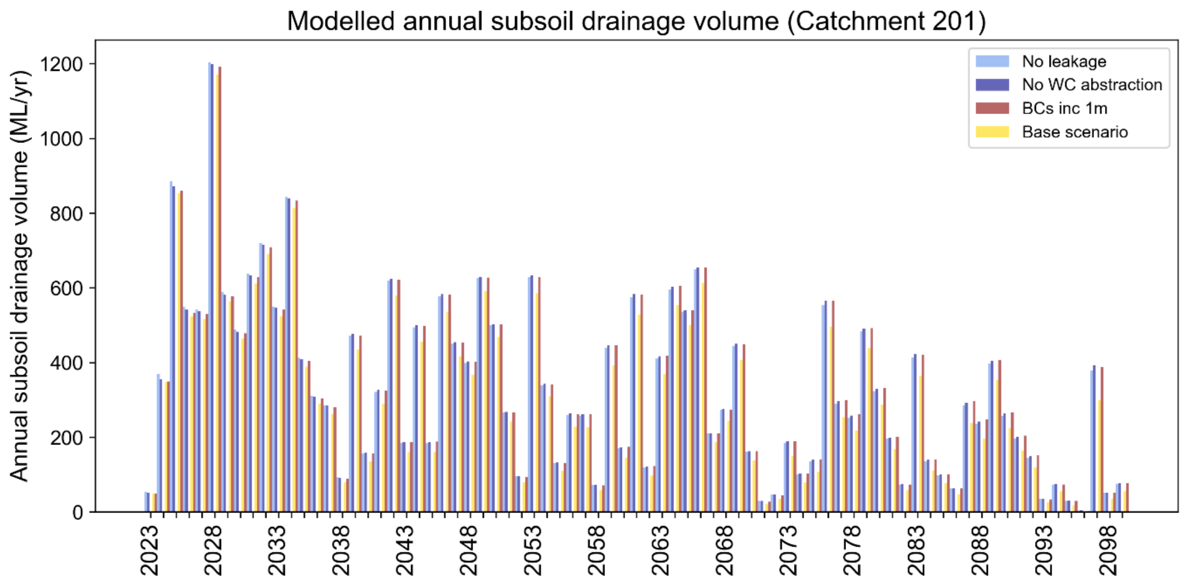
50
75
100
125
150
175
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
2073
2078
2083
2088
2093
2098
No leakage
No WC abstraction
BCs inc 1m
Base scenario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Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
200
400
600
800
1000
1200
2023
2028
2033
2038
2043
2048
2053
2058
2063
2068
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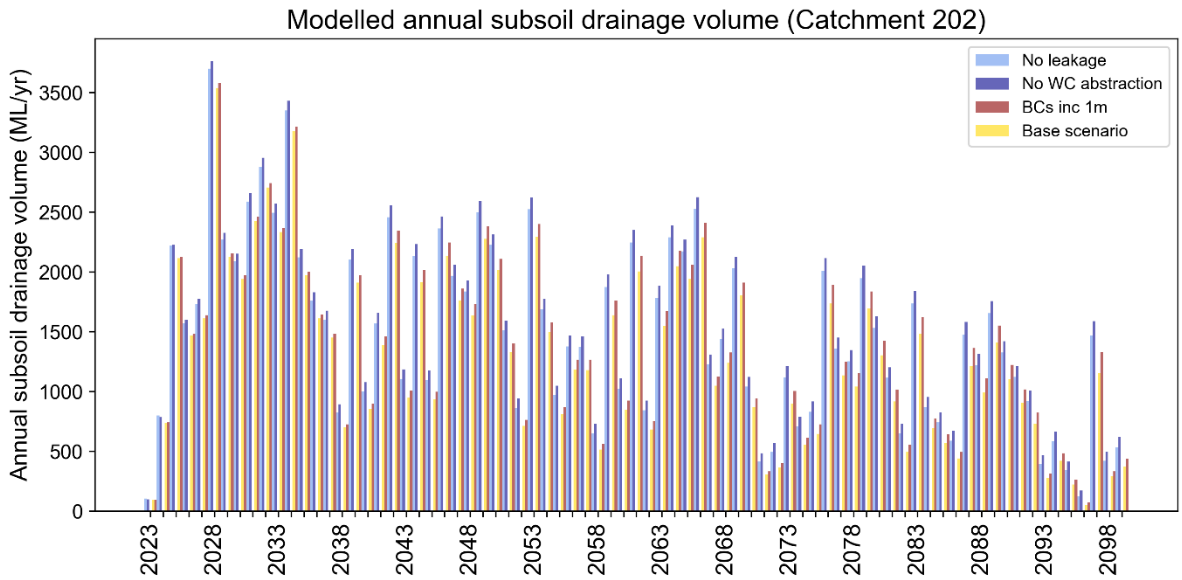
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Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
500
1000
1500
2000
2500
3000
3500
2023
2028
2033
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2043
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2058
2063
2068
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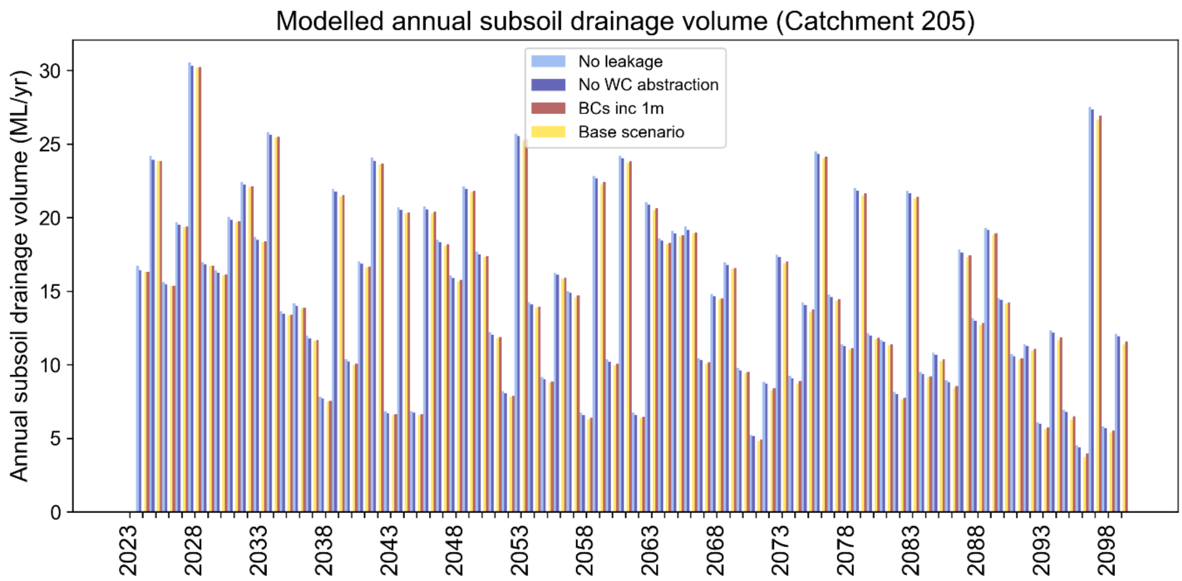
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Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
5
10
15
20
25
30
2023
2028
2033
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2043
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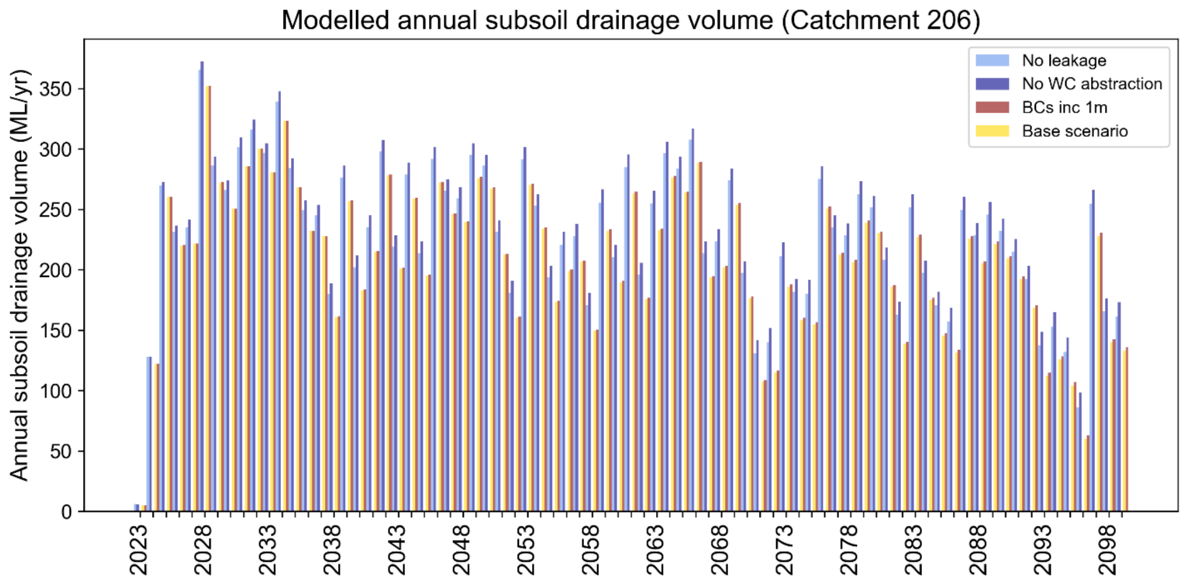
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Annual subsoil drainage volume (ML/yr)
No leakage
No WC abstraction
BCs inc 1m
Base scenario
0
50
100
150
200
250
300
350
2023
2028
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Appendix 2 District groundwater management scheme concept engineering report

PENTIUM
WATER

EAST WANNEROO GROUNDWATER MANAGEMENT SCHEME

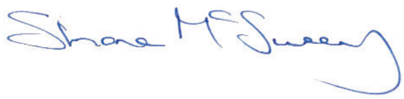
Concept Engineering Design Report

Rev 0
04/04/2025

Document Status

Version	Purpose of document	Authorised by	Reviewed by	Review Date
Rev A	Draft for Review	R Pilson	S Katebizaki	10/03/2025
Rev B	Draft for Review	R Pilson	S McSweeney	19/03/2025
Rev 0	Issued for Review	R Pilson	S McSweeney	04/04/2025

Approval for Issue

Name	Signature	Date
S McSweeney		04/04/2025

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Version: Rev 0

Date: 4 April 2025

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1. Introduction

The East Wanneroo Groundwater Management Scheme (EWGWMS) is a critical water infrastructure and management proposal central to facilitating the implementation of the Department of Planning, Lands and Heritage (DPLH) East Wanneroo District Structure Plan (EWDSP).

The EWDSP is approximately 25 kilometres (km) north of the Perth Central Business District (CBD). The EWDSP (and the EWGWMS) cover an area of 8,300 hectares (ha)

1.1. Purpose of this Report

The purpose of this report is to:

- Define the East Wanneroo Groundwater Management Scheme (EWGWMS) proposal and its purpose.
- Identify the key legislative environmental and planning approval requirements relevant to the implementation of the EWGWMS.
- Provide a concept design and quantify the infrastructure required to implement the EWGWMS and to estimate the capital costs (CAPEX) of this infrastructure to a Class 4 level of accuracy.

Present a concept level staged implementation pathway for the two defined development areas subject to the EWGWMS

2. EWGWMS - Requirement Overview

The East Wanneroo Groundwater Management Scheme (EWGWMS) proposal is the critical water infrastructure and water management framework underpinning the EWDSP. The EWGWMS was defined in the East Wanneroo District Water Management Strategy (EWDWMS) (Urbaqua, 2021) to specifically respond to the following competing issues:

1. **Post development groundwater level rise**. Groundwater levels will increase within the superficial aquifer across the EWDSP area as a direct result of:
    a. The recent harvesting of pine plantation areas within adjoining State Forest areas. The Gnangara pine plantation was a significant source of groundwater drawdown.
    b. Increases in groundwater recharge into the superficial aquifer compared to the existing EWDSP landscapes due primarily to the increase in impervious surface areas (i.e., roads, houses, car parks, schools) and direct infiltration via soakwells and stormwater drainage infrastructure (i.e., bioretention swales). The transition of land use from horticulture and market gardening will result in reduced groundwater abstraction from those land uses that will result in a change to the water balance.
2. **Minimise engineering fill material**. Engineering fill is a significant development cost driver influencing the delivery of affordable residential lots. Reducing the import of sand fill within the EWDSP area is in alignment with the State Planning Policy 2.4 Planning for Basic Raw Materials (WAPC 2021) objective on the sustainable use of basic raw materials including minimising sand fill in new urban areas.

In summary, the EWDWMS predicted a 3 to 4 metres (m) increase in groundwater levels across the EWDSP area. The rise in groundwater levels across the EWDSP will have a corresponding rise in lake and wetland water levels as they are expressions of local groundwater.

The predicted higher groundwater levels across the EWDSP present a significant risk to:

- The ecological health of the significant wetlands / lakes within the EWDSP which would potentially experience a significant increase in water levels subject to the future climates.
- The viability of 'urban' land use areas proposed in the approved EWDSP particularly within the topographical low-lying areas adjacent to the mapped wetland/lakes. Essentially, without a groundwater management system, a significant portion of the EWDSP area, including 'Urban Deferred' zoned areas, could not be developed.
- Damage or undermine the structural integrity of key infrastructure, including roads, schools and parks existing and proposed within the approved EWDSP.
- Potential environmental impact to lakes and wetlands due to the mobilisation of acidic groundwater following contact with acid sulphate soils.

Compromise the performance of constructed urban drainage systems, potentially leading to flooding of developed residences

3. District Scale Groundwater and Lake Water Level Modelling

The East Wanneroo Groundwater Flow Model Report (Pentium Water, 2025) presents the construction and calibration of a detailed district scale groundwater flow model. The report also presents the groundwater and lake water level outcomes of future development scenario simulations undertaken to inform the concept engineering design of the EWGWMS. The groundwater flow modelling exercise also including simulations of development scenarios using four of the 32 proposed climate scenarios. The four climate scenarios simulated were as follows:

- Dry_1 (Drying climatic trend)
- Int_1 (Intermediate climatic trend)
- Wet_1 (Wet climatic trend)
- Wet_2 (Very wet climatic trend)

These climate scenarios were applied to a “no development” land use outcome (to obtain a baseline) and then subsequently to a “development” situation to assess likely impacts of various climate scenarios on proposed future developments.

The results of these simulations broadly indicated the following, with respect to groundwater and local lake water levels:

- Dry climate scenarios typically lead to low groundwater levels and lake levels falling from one annual winter peak to the next, as more water leaves the system than entered it
- Wet climate scenarios typically lead to elevated groundwater level and lake levels being maintained from one annual winter peak to the next, or in some cases, increasing slightly.

In very wet years with the compounding effect of very high rainfall events, regardless of the lake level at the start of winter, lake levels rise rapidly in response to a significant rain event and could lead to allowable peak levels in lakes being exceeded leading to localised flooding.

4. Local Environmental Context

4.1. Desktop review

Table 1 outlines the key technical hydrological (groundwater and surface water), geological and geotechnical studies, water balance/modelling assessment, wetland assessment and the water management framework (embedded in DWMS) which underpin the EWGWMS proposal.

Table 1 - Key Technical Investigations, Surveys and Reports

Document	Details	Spatial Coverage
Groundwater		
• East Wanneroo integrated groundwater-lake flow modelling: Predictive scenario modelling to support the Gnangara Sustainability Strategy (DoW 2009).	• The modelling concluded: o The existing regime of water augmentation within Lake Jandabup increases the lake's seasonal minimum water level by 0.5 m. o Urbanisation of the EWDSP area could increase seasonal maximum water levels in Lake Mariginiup by 0.4 m and Lake Jandabup by 0.7 m. o Pine clearing has the potential to increase seasonal maximum water levels in Lake Mariginiup by 0.2 m and Lake Jandabup by 0.7 m. o Re-establishment of banksia woodlands in the cleared pine plantation areas (within the State Forest) reduces these gains by 0.1 m in Lake Mariginiup and 0.3 m in Lake Jandabup. • Water levels in the Superficial Aquifer in the East Wanneroo region are predicted to increase by up to 4 m if the full range of land-use changes including urbanisation and pine clearing are implemented.	• Portion of the Gnangara State Forest & the DSP area.
• Perth Shallow Groundwater Systems Investigation - Lake Mariginiup (DoW 2010).	• Assessed the hydrogeochemical changes within Lake Mariginiup. • Key recommendations: o Endorse the Forest Products Commission pine harvesting schedule, but with the inclusion of water chemistry monitoring of the water table. o Support the development of water sensitive urban design in the East Wanneroo area.	• Perth Shallow Groundwater Systems Investigation - Lake Mariginiup (DoW 2010).
• Environmental management of groundwater abstraction from the Gnangara Mound (DoW 2013 & DWER 2020).	• Describes the DWER's compliance with Ministerial conditions set in MS No. 819 – Gnangara Mound groundwater resources. This includes: o Monitoring (long term) water levels and the ecological condition (riparian vegetation, frogs, and macroinvertebrates) of Lake Jandabup and Lake Mariginiup. • The compliance report concluded water levels within Lake Mariginiup had declined since 1997 which has contributed to the poor health of wetland vegetation. The health of *Eucalyptus rudis* adjacent to the wetland has been in decline for much of the long-term monitoring period.	• Lake Jandabup • Lake Mariginiup.
• East Wanneroo Groundwater Model (EWGWM) (Pentium Water 2023).	• The EWGWM outputs include: o Spatial extent of subsoil drainage in the EWDSP. o Subsoil drainage flow rates.	• EWDSP

<table>
<tr><td></td><td>Subsoil drainage volumes requiring management through the groundwater control system.
Climate variability and potential impacts on groundwater levels.
Changes in lake Mariginiup, Lake Jandabup, Lake Gnangara water levels.</td><td></td></tr>
<tr><td colspan="3">Wetland & Eco-Hydrological Assessment</td></tr>
<tr><td>Study of Ecological Water Requirements on the Gnangara and Jandakot Mounds under Section 46 of the Environmental Protection Act 1986 (Froend et al 2004)</td><td>Provides a summary of existing information on groundwater dependent ecosystems (GDEs) within the Gnangara region and the EWDSP area.
Reviews the environmental water requirements for the wetlands across a range of hydro-ecological parameters (vegetation, waterbirds, macroinvertebrates, and ASS risks).
Assessment of the susceptibility of the wetlands from water level change and depth to groundwater.
This report was used to review risks to the ecological risks to wetlands within the EWDSP area (Lake Mariginiup, Lake Jandabup, and Gnangara Lake) from the predicted groundwater levels</td><td>Gnangara and Jandakot Mounds.</td></tr>
<tr><td>Review of 2030 Proposed Revised Water Thresholds - Gnangara groundwater system (Kavazos et al 2020)</td><td>Detailed analysis of the likely ecological effects of proposed revisions of water level criteria set under Ministerial Statement No. 819.
The assessment includes:
potential impacts from a reduction of groundwater abstraction of up to 44 GL/year by 2030 within the Gnangara groundwater resource.
Describes the likelihood of the proposed DWER groundwater thresholds will maintain the ecological values and managerial objectives in the context of Ministerial Statement No. 819 of twelve wetland sites and five terrestrial sites within the Gnangara groundwater system.</td><td>Gnangara State Forest
EWDSP
Lake Gwelup.</td></tr>
<tr><td colspan="3">East Wanneroo</td></tr>
<tr><td>EWDWMS (Urbaqua 2021).</td><td>The EWDWMS has been prepared for the EWDSP which responds to:
Better Urban Water Management (WAPC, 2008).
The EWDWMS establishes the management framework for:
Future LWMS.
The scope of works for the EWGWM.
The EWDDC addresses:
Wetlands subject to Ministerial Statement No. 819 and commitments associated with the allocation of groundwater.
Surface water catchments and water protection areas.
Predevelopment 1-dimensional surface water model of the EWDSP area has been constructed to provide an estimate of the likely volumes and top water levels in key wetlands during minor and major flood events.
Nutrients export for each major wetland catchment using DWER’s Urban Nutrient Decision Outcomes (UNDO) tool.
Annual maximum and minimum water levels.
Controlled Groundwater Level for the EWDSP area (represented by the 1986-95 AAMGL).
Wetland assessment:</td><td>EWDSP</td></tr>
</table>

	o Review of historical water quality data for Lake Gnangara, Lake Jandabup, and Mariginiup Lake. o Review of the. o Review of risks to the wetlands (water quality and quantity). o Wetland DWER UNDO assessment and water quality objectives.	
• Environmental Assessment Study East Wanneroo District Structure Plan (Emerge 2021).	• Review of DBCA's Geomorphic Wetlands of Swan Coastal Plain database. • Wetland vegetation community mapping. • Wetland buffer review and management framework.	EWDSP.
• EWDSP (DPLH 2021).	• The EWDSP defines the following elements: o EWDDCP wetland and the district groundwater infrastructure requirements. o District wetland management framework. o Future sequential planning process and technical assessment(s) requirements.	•

4.2. Hydrological and Environmental Context

Table 2 summarises the EWDSP environmental setting.

Table 2 - EWDSP environmental summary

Factor	Key environmental values
Climate	• Temperate climate, with dry hot summers and cold wet winters. • Annual average rainfall between 2010 and 2021 is 702 mm.
Existing land uses	• Urban, commercial, industrial along some western and southern parts. • Market gardens, pastoral, and rural residential in the centre of the study area. • Areas of native vegetation predominantly Banksia woodland with some Tuart woodland and riparian vegetation (Pinjar and Herdsman complexes) associated with the wetlands and lakes. • State Forest area which incorporates a pine plantation and sand extraction land use.
Geology	• Quaternary Superficial formations consisting of Tamala Sand, Bassendean Sand.
Hydrogeology	• Shallow superficial aquifer overlying the Leederville Aquifer. • Vertical connectivity between the aquifers is limited.
Wetlands	• North-south chain of wetlands, including major lakes, formed in the interdunal depressions between Bassendean and Spearwood Dune Systems. • The 24 Conservation Category Wetland (CCWs) within the EWDSP, several of which are known to be groundwater dependent ecosystems and contain high environmental values including Melaleuca woodlands, Banksia woodland and Tuarts. • The lakes are throughflow lakes with groundwater flowing from east to west towards the coast. Water levels in the lakes are largely controlled by groundwater inflow with seasonal storm event flows. • The wetlands within the EWDSP have been subject to reductions in water level due to o long-term decrease in average annual rainfall climate change). o Increased groundwater abstraction across the Gnangara Mound and groundwater demand from pine plantations. • The reduction in water levels has resulted in Lake Jandabup being artificially maintained to meet the minimum water level criteria set in MS 819. • The progressively drying of the wetland, including Lake Mariginiup, has resulted in increased ASS exposure.

Groundwater flow system	• Inflow from the northeast, near the top of the Gnangara groundwater mound. • Outflow to the west / southwest, with an overall gradient towards the coast. • Recharge into the Superficial Aquifer varies depending on land use, vegetation type and depth to groundwater. • Bore abstraction by Water Corporation and various private licensed and unlicensed water users.
Vegetation & flora	• The regional vegetation complexes within the EWDSP area are: o Karrakatta Complex – Central and South (23% remaining). o Bassendean Complex – Central and South (26.1% remaining). o Pinjar Complex (30% remaining). o Herdsman Complex (33.9% remaining). • The regional vegetation complexes within the wetlands consist of: o Pinjar Complex (Lake Adams, Mariginiup Lake, Jandabup Lake). o Herdsman Complex (Lake Badgerup). o Bassendean Complex – Central and South (Lake Gnangara). • Identified SCP 20a Banksia Woodland Threatened Ecological Communities (TEC) patches and Tuart Woodland TEC patches. • The EWDSP contains approximately 40% of all remaining Pinjar complex vegetation across the Swan Coastal Plain, indicating the DSP's significance for this vegetation complex. Lake Adams, Mariginiup Lake, Jandabup Lake support Pinjar complex vegetation within their foreshore areas, which collectively have an extensive interface with proposed future development areas (Emerge 2018). • Priority flora species occur at locations within the Lake Jandabup wetland buffer.
Terrestrial fauna	• Native vegetation (Banksia woodland) adjacent to the wetland areas provides habitat for the threatened Carnaby's cockatoo species. • Wetlands also support a diverse range of fauna including invertebrates, fish, and birds. • Waterbirds rely on the wetland and adjacent buffer area for breeding habitat, foraging/feeding and drought refuge areas.

5. East Wanneroo Groundwater Management Scheme (EWGWMS)

5.1. EWGWMS Proposal Summary

The East Wanneroo DWMS identified the central hydrological risks resulting from the implementation of the EWDSP. In summary the key hydrological risks, which the EWDWMS and the subsequent EWGWMS mitigate include:

- Short term: Flooding and inundation from small, minor and major flood events and impacts of rising groundwater. Specifically, the EWDWMS identified an increase in peak water levels in wetlands adjacent to development area(s).
- Long term: A fully developed EWDSP is projected to result in significant groundwater level rise. This is caused by a combination of increased local runoff and recharge from urban land uses and reduced local abstraction for irrigation as horticulture ceases.

The EWDWMS proposes to actively manage groundwater and lake water levels to mitigate the risk associated with groundwater level rise. The EWDWMS identified the East Wanneroo Groundwater Management Scheme (EWGWMS) as a required district scale groundwater management scheme. The objectives of this scheme are:

- Control groundwater levels in topographical low-lying areas through subsoil drains. Then capture the additional groundwater volume in local stormwater basins or local constructed capture and pumping infrastructure.
- Transfer the excess groundwater from local drainage basins or hubs via piped infrastructure into selected wetlands / lakes within the EWDSP.
- Establish a district scale pumping and pipeline network which would transfer excess water volumes from the selected wetlands / lakes within the EWDSP to an off-site vegetated stormwater basin which recharges the superficial aquifer outside of the EWDSP and the Gnangara priority public drinking water area.

The short and long-term hydrological risks (defined in the EWDWMS) will be managed through controlling groundwater levels, transferring and then storing water into selected storage hubs and then EWDSP wetlands/lakes. The EWDSP wetlands/lakes subject to the EWGWMS (underpinning the water storage areas and linked to local subsoil pumping network and the district scale water transfer system) were affirmed through technical assessments including groundwater flow modelling, surface water catchment modelling, and lake water balance analysis. The wetlands/lakes subject to management include:

- District level wetlands / lakes including:
  - Coogee Swamp
  - Little Coogee Flat
  - Lake Adams
  - Mariginiup Lake
  - Little Mariginiup
  - Jandabup Lake
  - Badgerup Lake
  - Little Badgerup Lake
  - Gnangara Lake
- Local wetland areas including:
  - CCW UFI 8154
  - REW UFI 8163 – Boundary Road.
  - REW UFI 8121 – Damian Road.
  - REW UFI 8108 - Jambanis Road.

The concept design also considers the influence of both surface and groundwater following a 1 % AEP rainfall event coinciding with high groundwater levels associated with a Wet_2 climate scenario. This is a conservative design consideration but the most appropriate design consideration as it would require the biggest water transfer infrastructure and would constitute a “worse case” scenario from a cost perspective.

The total flow to each lake was assumed to be comprised of a combination of four separate flow sources, each being calculated/modelled individually and then combined to obtain the total flow as shown below:

- Groundwater flows intercepted by subsoil drainage system
    - Flows which gravitate to the nearby lake (wetland catchments)
    - Flows which are collected in an infiltration basin and collection sump and need to be pumped to a nearby lake (storage catchments)
- Surface water flows from 1 % AEP storm event:
    - Storm flows which gravitate to the nearby lake (wetland catchments)
    - Storm flows which are collected in an infiltration basin and collection sump and need to be pumped to a nearby lake (storage catchments)

The key design features of the EWGWMS are defined in Table 3 and illustrated in Figure 1 and Figure 2.

Table 3 - EWGWMS key design features

Groundwater Management Scheme - Key Design Features	
Proposal title	**East Wanneroo Groundwater Management Scheme (EWGWMS)**
Proponent	Department of Planning, Lands, and Heritage
Short Description	The EWGWMS proposal seeks to construct and operate an integrated groundwater management scheme and associated lake level management infrastructure. The proposal includes: • Controlling groundwater levels at the Controlled Groundwater Level (CGl) as set out in the approved EWDWMS (2021). • Control lake levels in accordance with simulated pre-development conditions in the lakes and wetlands and with reference to the water level criteria set out in Ministerial Statement no. 819 for Lake Mariginiup and Lake Jandabup. • Collection system: Subsoil drainage infrastructure will function as a groundwater level control and collection system across large parts of the EWDSP area. The objective of the subsoil drains is to control the predicted peak of the groundwater level within the topographical lower areas of the EWDSP to facilitate development and protect the wetlands. • Transfer system: Groundwater collected by the subsoil drains would discharge into ‘local drainage hubs’ (which may be a combination of local stormwater basins, local wetlands, or construction collection points). The groundwater stored within these ‘local drainage hubs’ is pumped via a local piped network, into selected wetlands/lakes within the EWDSP for storage. District scale pump and pipe infrastructure will then manage lake water levels and convey excess water to a disposal location. The lakes/wetlands which form the focus of the water storage areas and the land subsoil pumping network, and the district scale water transfer system include: o District level wetlands / lakes including: § Coogee Swamp (district scale lake water level management) § Little Coogee Flat (local subsoil pumping network) § Lake Adams (local subsoil pumping network) § Mariginiup Lake (district scale lake water level management) § Little Mariginiup

	§ Jandabup Lake (district scale lake water level management) § Badgerup Lake (district scale lake water level management) § Little Badgerup Lake (local subsoil pumping network) § Gnangara Lake (district scale lake water level management) o Local wetland incorporated within the local subsoil pumping network include: § Conservation Category Wetland (CCW) UFI 8154 § Resource Enhancement Wetland (REW) UFI 8163 – Boundary Road § REW UFI 8121 – Damian Road § REW UFI 8108 - Jambanis Road • Lake water level control system: A core component of the district scale groundwater management scheme is the transfer and storage of harvested groundwater/stormwater in specified lakes and wetlands. The wetlands / lakes at established peak water and/or ecological threshold (or triggers) water will be transferred via district pump and pipeline(s) to a stormwater bioretention basin / managed aquifer recharge (MAR) area located outside of the EWDSP and the Gnangara priority public drinking water area. Wetland/lake water maximum water levels triggers will be subject to: o Wetland/lake specific water level and ecological criteria established in collaboration with DWER and DBCA. o Adaptive management framework which responds to: § The long term East Wanneroo groundwater and surface water monitoring program. § Climate change. o The staging of the EWDSP development and the installation of the district scale drainage and pump infrastructure.

Figure 1 and Figure 2 illustrate the EWGWMS proposal inclusive of:

- The estimated subsoil drainage areas. The East Wanneroo groundwater model (Pentium Water 2025) builds on the EWDWMS predicted groundwater assessment and underpins the predicted subsoil drainage area across the EWDSP area.
- Local drainage hubs and associated pump stations
- Local subsoil pumping network
- District scale lake water level management network.

Buffer storage lakes and wetland (i.e., Lake Jandabup) within the EWDSP.

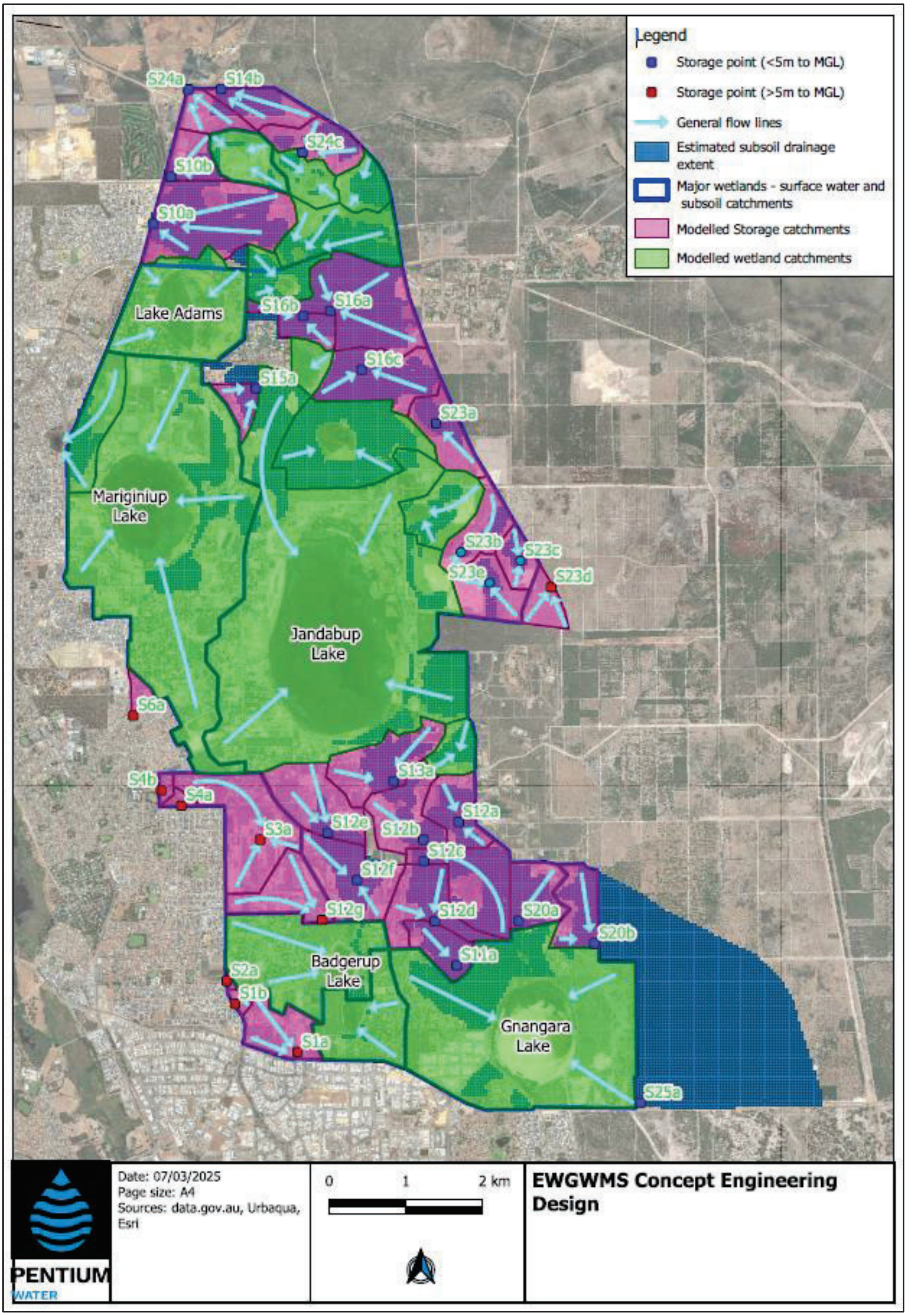

Figure 1 - Catchments with indicative flow directions

6. EWGWMS - Scheme Components

6.1. Basis of Design

DPLH commissioned Pentium Water to develop a groundwater flow model for the EWDSP area to inform the concept engineering design for the EWGWMS. The groundwater flow model (Pentium Water 2025) is a numerical groundwater flow model and associated lake water level model that has been developed to facilitate predictive modelling of the proposed development under various development outcomes and under four climate scenarios.

The groundwater model has been developed as a design tool and will be available for future studies to further inform decision making processes associated with the development of the EWDSP area including the conceptual and preliminary design of a district scale groundwater and lake water management scheme (i.e. the EWGWMS).

The East Wanneroo Groundwater Flow Model Report (Pentium Water 2025) is available as Appendix 1 to the East Wanneroo District Water Management Strategy Addendum 1 (Urbaqua, 2025).

Subsequent lake water balance modelling has been undertaken to optimise the concept design and inform this concept engineering design exercise.

6.2. Infrastructure Overview

To determine the size and extent of the pumping and piping infrastructure which would be required at full build out for the entire East Wanneroo development (up to 55 000 lots), the combined effects of a 1 % AEP and a “Wet_2” climate scenario were assessed.

The infrastructure required to manage runoff from intense rainfall events combined with rising groundwater levels consists of the following:

- subsoil drainage
- infiltration basins
- sumps containing pumps
- pump stations located at lakes to transfer water to Lake Jandabup
- transfer piping associated with all pumping systems

a pump station located at Lake Jandabup to transfer water 23 km to an infiltration system to the north of the East Wanneroo development area.

6.3. Subsoil Drains

The spatial extent of the EWDSP area likely to require subsoil drainage system is shown in Figure 1 and illustrates the areas of the EWDSP where the groundwater is predicted to rise to within 2m of the surface.

The drainage from the subsoil system is managed in different ways depending on fall to the local lake. If there is sufficient fall, subsoil drains are simply allowed to drain under gravity to the nearest lake. If there is insufficient fall (shown as “storage catchments” in Figure 1), subsoil drainage is directed to an adjacent infiltration basin which contains a sump/pump arrangement.

6.4. Flood Storage Basins

Each flood storage basin or infiltration basin has a subsoil drainage system installed below its base if required and the area and depth of the basin is sized according to the required storage volume coupled with a nominated infiltration rate. If the infiltration rate is high, the basin volume can be reduced but the flow rate from the basin will be higher. In the case of gravity flow, pipes will need to be larger and in the case of pumped flows, the capacity of the discharge pipework will need to be increased. This will route infiltrated stormwater to the nearest lake or wetland more quickly and will increase peak flow rates leading to a rapid increase in lake level. Conversely, if infiltration basins are larger and have slower infiltration rates, flood peaks can be attenuated and managed effectively with smaller downstream infrastructure.

It is recommended that an optimisation study be performed to establish the most cost-effective sizes of flood storage basins and associated sump pumps and discharge pipes. For the purposes of this concept study, an infiltration rate of 1m/d was used for the infiltration basins (with the exception of Lake Adams and Lake Coogee which had infiltration rates of 0.6 and 0.15 m/d respectively) and their depth was assumed to be 1.2m (refer to Table 4 and Table 5 for additional model parameters). It is recommended that Local Water Management Strategies (LWMS') conservatively adopt the lower infiltration rates for "trapped" catchments (i.e. flood storage basins that will be reliant on the EWGWMS to support infiltration through harvesting of under drainage or subsoil drainage). These trapped catchments are located within Stage 2 and 3 of the EWDSP.

6.5. Sumps Containing Pumps

The sumps adjacent to the lower lying infiltration basins are assumed to contain duty/standby pumps, capable of transferring the water to the nearby lakes at a flow rate matching the peak flow rate estimated to enter the sump. The proposed locations of the sumps are given in Figure 2, Figure 3 and Figure 4.

6.6. Pump stations at Lakes

Each of the lakes (Badgerup Lake, Gnangara Lake, Lake Adams, Little Badgerup Lake, Little Coogee Swamp and Mariginiup Lake) were assumed to have pumping infrastructure to enable water to be transferer to Jandabup Lake. Similarly, Jandabup Lake was also assumed to contain a permanently installed pump station complete with a suitably sized power supply from the grid and level instrumentation, to enable the level of the lake to be continuously monitored and pumped out when required

6.7. Transfer Piping

Transfer piping was assumed to be installed to enable water to be pumped from each of the lakes to Lake Jandabup. The piping from the sumps to the lakes and the piping from the lakes to Lake Jandabup Lake, was assumed to follow existing or proposed roads or service corridors to minimise disruption to the overall services layout. An overall layout of the proposed piping infrastructure is given in Figure 2. Greater detail of the piping north of Lake Jandabup is shown in Figure 3 and to the south of Lake Jandabup is shown in Figure 4.

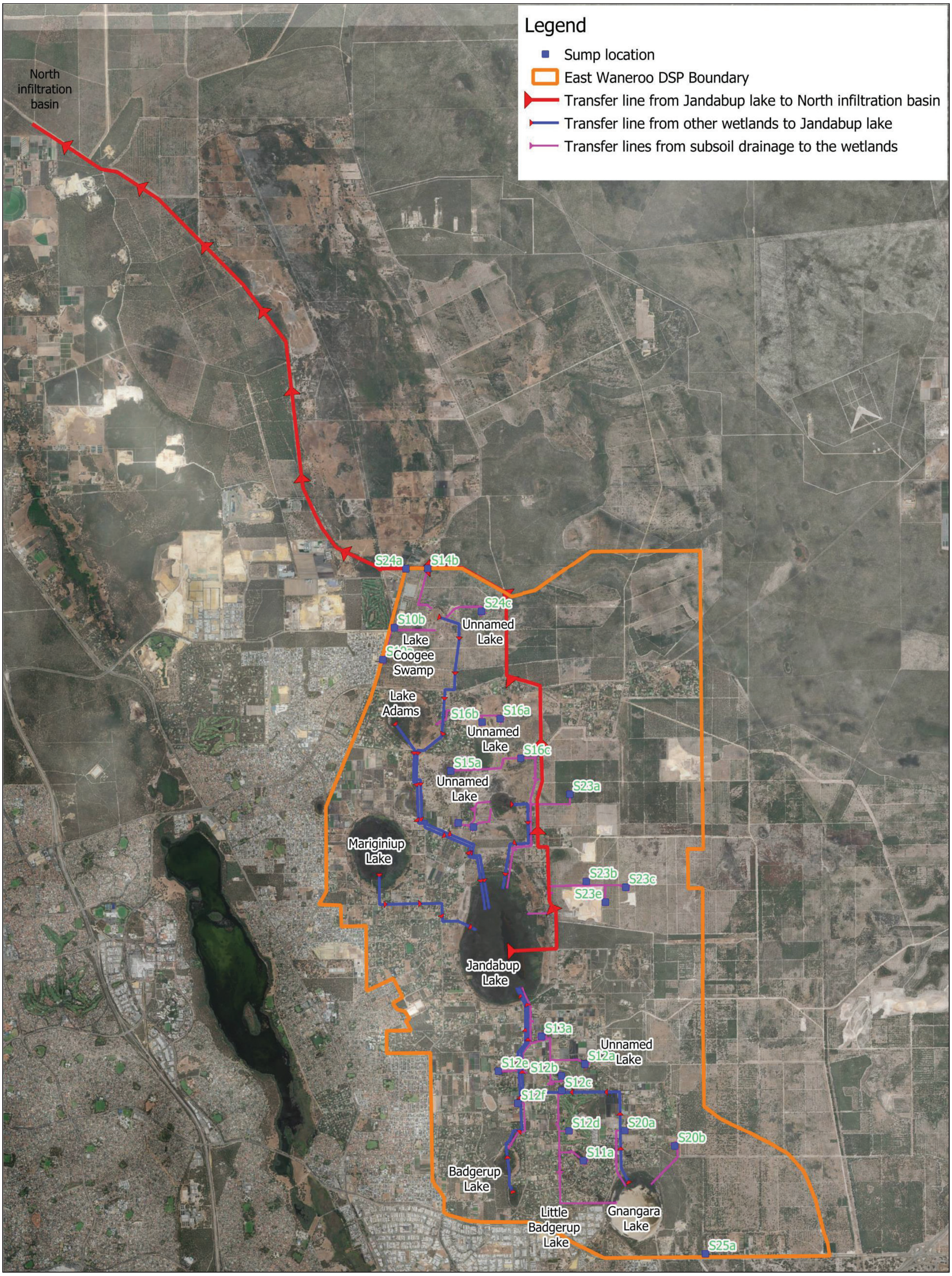

Figure 2 - Proposed Major Pipe Routes

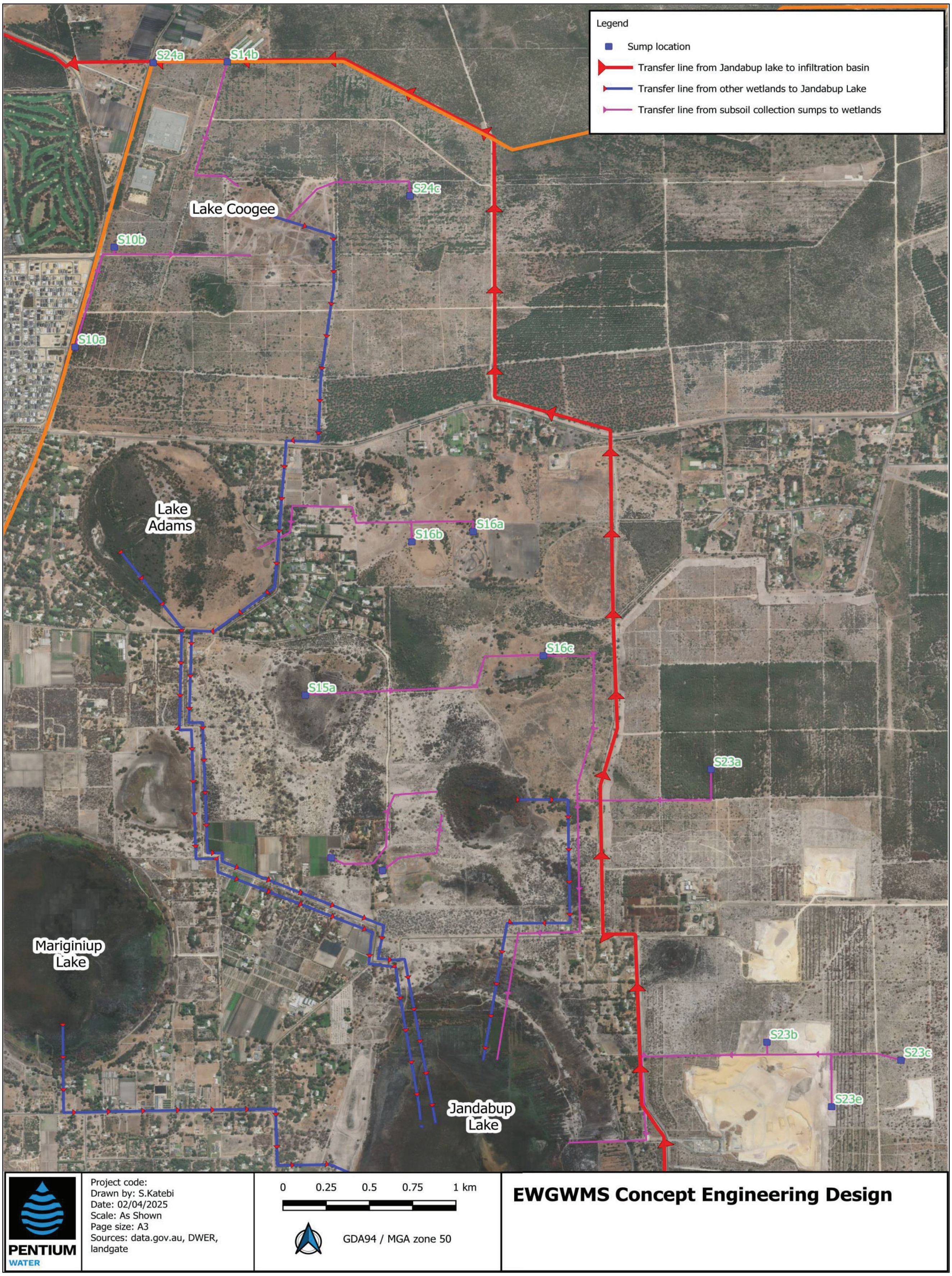

Figure 3 - Northern Pipe routes into Jandabup Lake

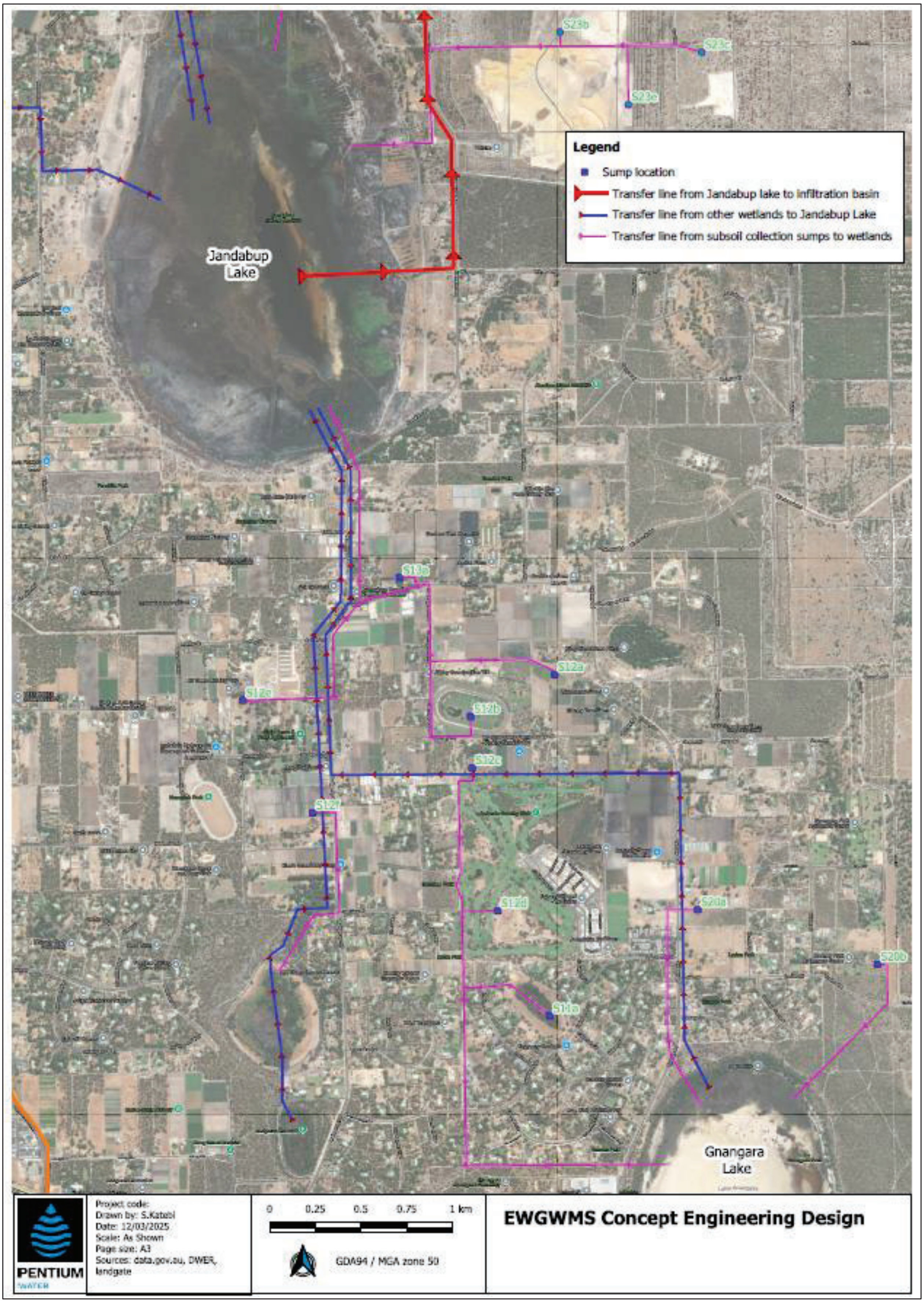

Figure 4 - Southern Pipe Rotes to Jandabup Lake

6.8. Lake Jandabup Pump Station and Transfer main to the Northern Infiltration Basin

Lake Jandabup is assumed to receive water from all the other lakes in the development area because it has the greatest volume/storage capacity. Although large, the storage capacity is not sufficient to cope with large rain events, even with the attenuation afforded by the infiltration basins, and hence a large permanent pump station was assumed to be installed adjacent to Lake Jandabup.

This pump station was required to convey all the surplus water to an alternative location and was conservatively sized to cope with a required peak flow of 1500 L/s.

The pipe route is approximately 22.7 km in length and hydraulic modelling determined that the most practical and cost effective pipe configuration was 4 no. DN 710 PN 8 buried HDPE pipes running in parallel. The advantage of having 4 no. pipes is that they are easier to weld and install and provide the option of only using 1 no. pipe if flows are low, but this can be increased to using all 4 no. pipes, if flows are high.

Clearly an easement will be required for the proposed pump station and pipework, but if this is allocated adjacent to main arterial roads early in the planning stage, then a staged approach to their construction could be adopted. For example, two pipes could be installed initially, and this could be followed by installation of the remaining two pipes at a later stage in the development sequence.

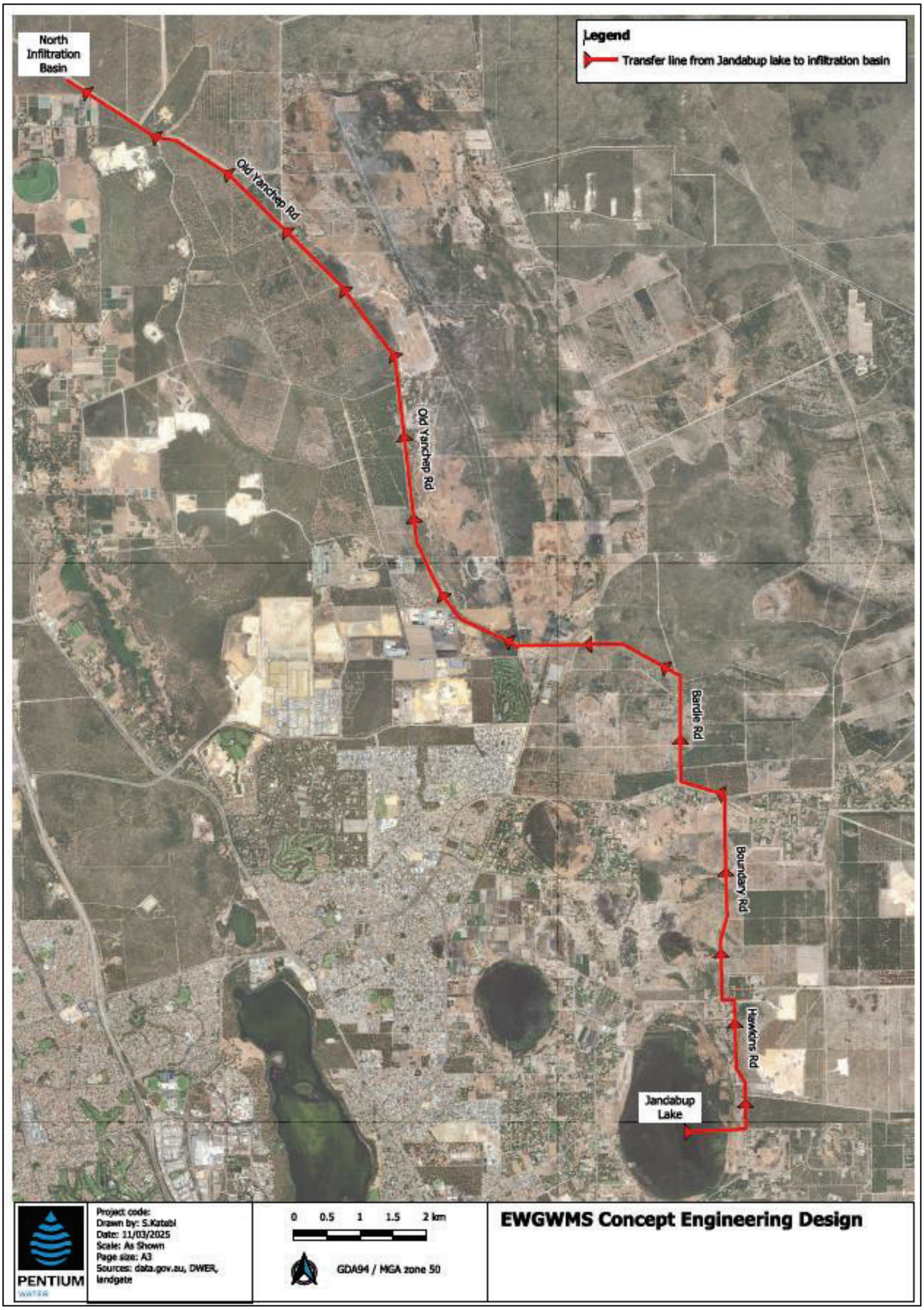

Figure 5 - Transfer Pipeline from Lake Jandabup to Northern Infiltration Basin

6.9. Northern Infiltration Basin

The location chosen for disposal of the surplus water from the EWGWMS is Lot 2798, 600 Old Yanchep Rd, Carabooda in the City of Wanneroo. This location is approximately 23 km to the north of Lake Jandabup (Figure 6).

The location is outside of the designated P1 and P2 zones of the PDWSA and has an area of 74.8 ha. The ground levels at the site are between 39 mAHD and 57 mAHD (refer to Figure 7). The Perth Groundwater Map (refer to Figure 8) indicates that the depth to groundwater in this location is between 25 and 35 m.

Infiltration rates in the area have been conservatively estimated at this site to be approximately 3 m/d.

To accommodate the required peak flow rate of 1500 L/s, approximately 6% of the site will be required for infiltration purposes.

6.9.1. Land Tenure and access

Access and use of the 74.8 ha site for a regional-scaled infiltration basin will require the approval of the following key stakeholders, who have existing approved land tenure and management arrangements across the site:

1. The Department of Biodiversity, Conservation and Attraction (DBCA): The site is wholly within the Gnangara-Moore River State Forest - State Forest 65. The DBCA manages State Forest No. 65 on behalf of the Conservation Commission of Western Australia. The regional-scaled drainage basin land use (including replanting the basin areas) will require approval from the department.
2. Hanson: Tenement M70/1316 overlaps the site. Hanson has existing approval under the *Mining Act 1978* and the EP Act to clear the regrowth vegetation and extract the sand resource. Hanson would need to approve access to their tenement and the land use.

There is the potential for a sequential land use agreement with Hanson. In this scenario, Hanson would clear the site (or regrowth vegetation) and extract the sand material within the site at agreed locations and depth(s) for the purpose of resource abstraction. Hanson could then relinquish control of the site and leave the landform in the quarrying or basin format to allow the establishment of the disposal infiltration basin.

6.9.2. Alternate locations

Alternate infiltration basin locations were considered closer to the EWDSP area but the location of a disposal location was heavily restricted by the PDWSA areas gazetted over the State Forest 65 / Gnangara Mound, which otherwise would be ideal, proximal disposal location.

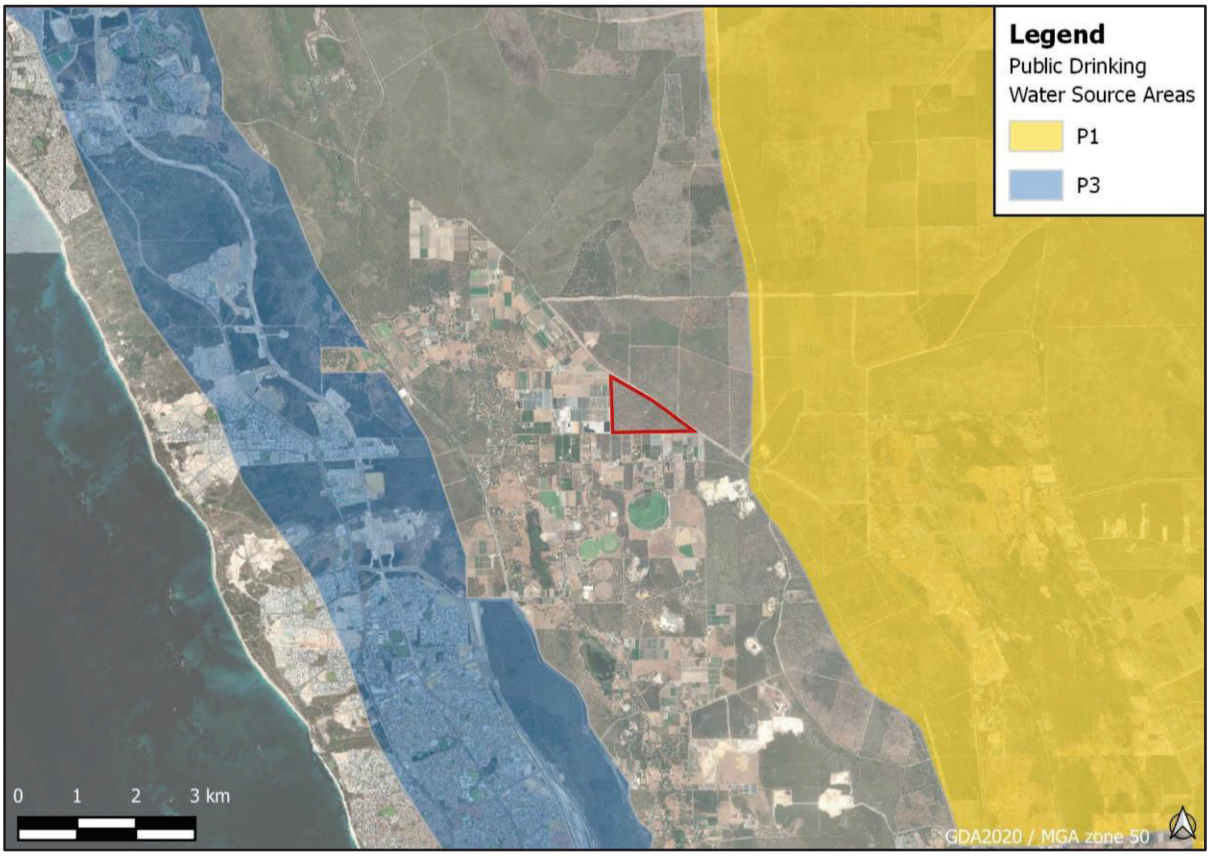

Figure 6 - Proposed infiltration location relative to public drinking water sources

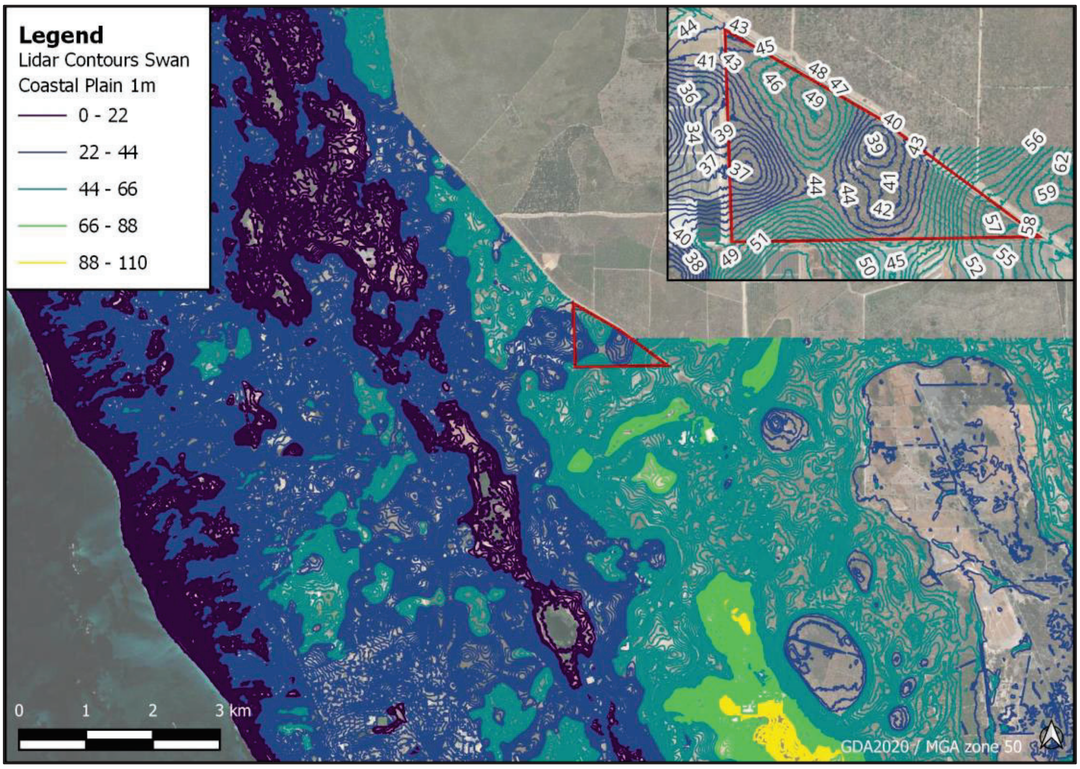

Figure 7 - Topography of the site and surrounds

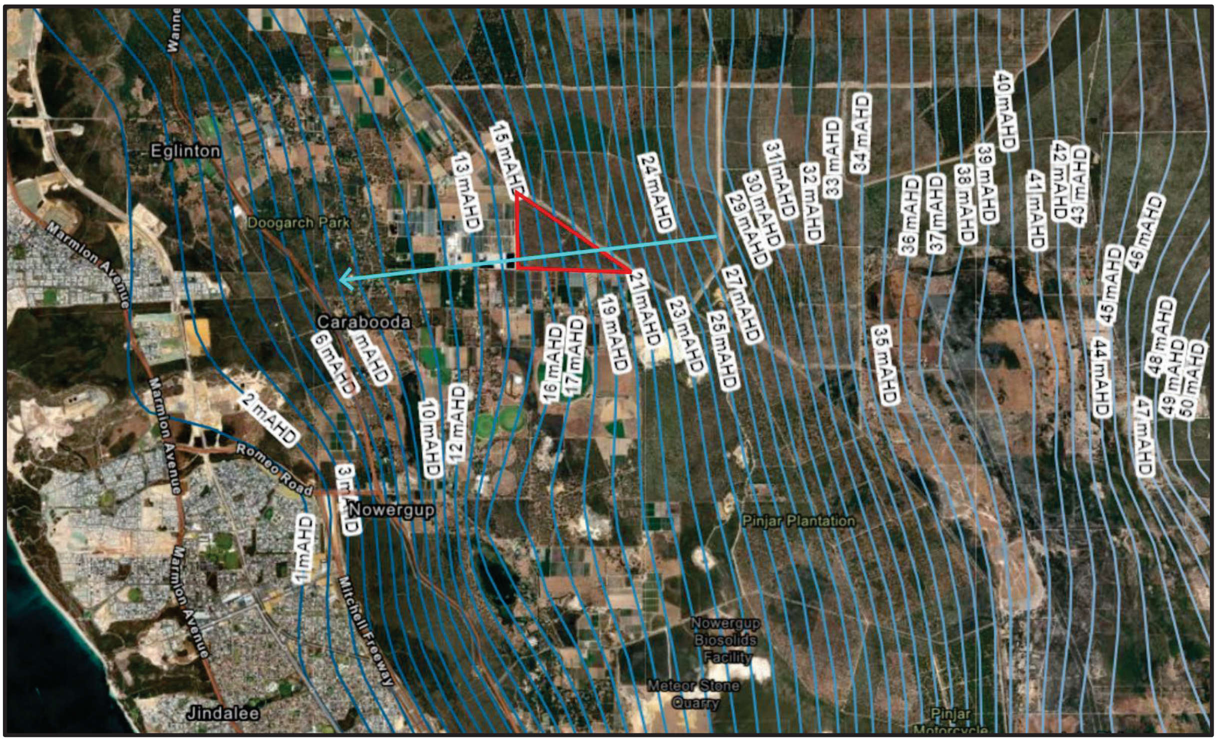

Figure 8 - Groundwater levels around the site (maximum levels 2019). From the Perth Groundwater Map. Interpreted groundwater flow direction indicated with blue arrow

7. EWGWMS – Concept Design of infrastructure connectivity

7.1. Introduction to future scenario considerations

As groundwater level management is critical for the sustainable development of the EWDSP area, future scenario groundwater and lake water level modelling was carried out to inform the conceptual design of the groundwater management system. The future scenario models were selected to indicate:

- The groundwater rise that could occur post-development.
- The required extent of subsoil drainage infrastructure.
- The areas unlikely to be impacted by rising groundwater.
- Indicative subsoil drainage flow rates and annual subsoil drainage volumes to inform the concept design of the groundwater management scheme.
- Indicative post-development lake levels, to further understand potential infrastructure requirements of the water management scheme.

Several variables become a consideration when looking at potential future scenarios, including:

- Future climate
- Changes in land use
- Changes in public and private abstraction
- Lake augmentation
- Staging of the land use changes
- The extent and elevation of subsoil drainage
- The return of any subsoil drainage water at surface water bodies
- Leakage from the Superficial Aquifer into the underlying Leederville Aquifer.

Furthermore, there is significant inherent uncertainty with each of these variables.

The East Wanneroo Groundwater Flow Modelling report (Pentium Water, 2025) discusses the numerous potential permutations of the future scenario variables, however, it is impractical to simulate all possible permutations. A selection of scenarios was identified to inform the concept engineering design of the EWGWMS which provides an indicative range of subsoil drainage flow rates, annual subsoil drainage volumes, and lake and groundwater levels.

The following climate and development scenarios were assessed through the groundwater flow modelling exercise:

- Four different climate scenarios, referred to as Wet 1, Wet 2, Dry 1 and Int 1 scenarios.
- Four development options, including 'no development', 'full-build out', 'staged development' and 'short term staged development to the end of 2039'.

Section 7 of the Groundwater Flow Model Report (Pentium Water, 2025) describes the future scenario modelling undertaken to inform the concept design of the EWGWMS. Section 9 of the same report presents results of concept engineering design simulations model via the groundwater flow model.

The future scenario model outputs used in the concept engineering design is the "worst case" scenario from a groundwater and lake water level perspective, which occurs during a Wet_2 climate scenario (when groundwater and lake water levels are at their highest during that synthetic climate simulation) and when a 1 % AEP rainfall event are experienced simultaneously.

7.2. Water Management Scheme - Collection and Transfer Design

7.2.1. Concept introduction

Groundwater flows are intercepted by the subsoil drainage system and either flow under gravity to the nearby lake (wetland catchments) or are pumped there (storage catchments).

Additionally, surface water flows from the 1% AEP rainfall event either flow directly into the nearby wetland/lake under gravity (wetland catchments) or are pumped to the nearby lake or wetlands (storage catchments) following infiltration within the flood storage basins where they contribute to the subsoil flows under draining these basins.

The pumped flows are restricted by the size of the pump which is correlated to an appropriate infiltration rate from each flood storage basin or infiltration basin to the collection sump.

For consistency, the storage catchments used have the same basin ID's as those identified in the EWDWMS (S12f, S10a etc.).

7.2.2. Wetland Catchment Parameters (refer to Figure 1 for location of wetland catchments)

The catchment parameters for the wetland catchments are given in Table 4 below.

Table 4 – Wetland Catchment Parameters

Wetland/Lake ID	Total wetland draining catch-ment and wetland area (ha)	Wetland/Lake reserves (ha)	Resi-dential area (ha)	Add-itional Open Space areas (ha)	Rural land (Assu-med no runoff) (ha)	Industrial (Ass-umed same as urban land-use) (ha)	Total volume (m3) - First 15 mm rainfall event	Total 1% AEP volume to wetland - runoff only (m3)
Badgerup	207.26	31.73	48	30	97.53	0	14324	165,577
Gnangara	604.49	309.27	196.9	0	20	78	47891	634,122
Jandabup	1419.24	511.00	727.00	0	0	181.24	76650	1,344,583
Lake Coogee	54.37	31.24	0.00	0	0	23.10	4686	59,374
Little Badgerup	115.39	53.50	61.89	0	0	0	8025	117,404
Mariginup	867.76	235.00	632.76	0	0	0	35250	769,762
Adams	198.85	32.42	0.00	0.00	166.43	0.00	17345.13	159,575

Table 5 – Additional Wetland catchment parameters

Wetland/Lake ID	Bioretention Basin Top Area (ha)	Bioretention volume (m3)	Total subsoil discharge to wetland 1% AEP event (m3)	Total 1% AEP volume to wetland - runoff and subsoils (m3)
Badgerup	0.40	1,059	0	165,577
Gnangara	2.31	6,063	53,420	687,543
Jandabup	7.63	20,031	1,181,311	2,525,895
Lake Coogee	0.19	509	326,880	386,253
Little Badgerup	0.52	1,365	0	117,404
Mariginup	5.31	13,956	0	769,762
Adams	0.00	0	0	159,575

7.2.3. Storage Catchment Parameters (refer to Figure 1 for location of storage catchments)

The "storage" catchments require collection points or sumps as they are internally draining, and excess groundwater and rainfall generated water cannot leave these catchments without being pumped from the relevant collection point or sump adjoining an infiltration basin.

The key parameters for these catchments are shown below in Table 6.

Table 6 - Storage catchment parameters

Catchment ID	Catchment Area (ha)	Bush Reserve Area (ha)	Total 1% AEP Volume (m3) (excluding losses)	Infiltration Basin Area (ha) based on 1.2m depth	Assumed Infiltration rate (m/d)
S12f	96.90	7.65	87853.17	7.32	1
S10a	163.62	13.54	147741.80	12.31	0.15
S10b	37.16	0.57	36016.14	3.00	0.15
S12e	61.15	21.50	39027.82	3.25	1
S12a	56.19	0.00	55313.24	4.61	1
S12b	75.82	0.00	74633.96	6.22	1
S12c	97.39	0.00	95868.45	7.99	1
S11a	42.15	0.00	41489.41	3.46	1
S12d	74.63	0.00	73463.41	6.12	1
S13a	85.80	0.00	84465.56	7.04	1
S14b	47.40	0.00	46663.61	3.89	0.15
S15a	24.73	0.00	24341.55	2.03	1
S16a	146.91	0.00	144619.29	12.05	0.6
S16b	33.87	0.00	33343.79	2.78	0.6
S16c	99.17	0.00	97624.33	8.14	1
S20a	54.95	0.00	54090.71	4.51	1

S20b	54.27	0.00	53420.34	4.45	1
S23a	54.72	0.00	53863.32	4.49	1
S23b	53.21	0.00	52379.04	4.36	1
S23c	30.07	0.00	29601.50	2.47	1
S23e	59.24	0.00	58311.13	4.86	1
S24a	35.33	0.00	34781.31	2.90	1
S24c	55.39	0.00	54527.59	4.54	0.15
PS (179)	24.72	0.00	24344.70	2.03	1
PS (203)	8.80	0.00	8662.89	0.72	1

The runoff volumes generated are from the 1 % AEP of 147 mm over 36 hours but have been adjusted for losses – first 15 mm deducted.

7.2.4. Collection and transfer system parameters

The key parameters used in the water balance model are given in Table 7.

Table 7 - Key Routing Model Parameters

Description	Parameter	Notes
Infiltration rate of infiltration basins	0.15 to 1 m/d	Could be varied from 0.1 m/d to 5 m/d to assess the potential size of pumping infrastructure
Infiltration basin depth	1.2 m	Based on IPWEA subdivisional guidelines. Could be varied from 1m to 2.5 m to identify an optimal depth if required.
1 % AEP 36 hour rainfall depth	147 mm	This event was assumed to be superimposed on the relatively high groundwater and lake water levels which would be experienced in the modelled “Wet_2” climate scenario.
Runoff coefficient	Varies between 0.55 and 0.7 , based on proposed infrastructure in each catchment	Different areas in each catchment were assigned suitable runoff coefficients to provide realistic flow volumes
Lake levels	CGL, empty, overflow	Refer to Table 8 below

7.2.5. Groundwater flows

Groundwater flows were adopted from the output of the groundwater model (East Wanneroo Groundwater Flow Model, Pentium Water 2025). These flows were intercepted via subsoil drains installed 2m below the ground surface in the areas identified as requiring subsoil drainage (refer to Figure 60 of the Groundwater Flow Model Report and Figure 1 in this report). The peak monthly flows were converted to peak instantaneous flows (in L/s) for the gravity and pumped flows. Gravity flows were assumed to be constant and to flow directly to the nearby lake. Pumped flows were assumed to enter an infiltration basin and then drain to an adjacent collection point or sump at a constant rate set by the infiltration rate of the infiltration basin.

7.2.6. Surface water flows

The surface water flows were generated by using the 1 % AEP storm event (147 mm over 36 hours). To develop a hydrograph for each catchment, a surrogate hydrograph was modelled for a 22.14 ha catchment which was deemed to be representative of the other catchments in the area. This yielded a peak flow of 0.10143 m^3/s after a duration of approximately 24 hours. From this, a unit hydrograph (1 ha) was calculated to have a peak flow of 0.004581 m^3/s and this in turn, was used to generate peak flows for all the remaining catchments based on their respective areas. The first 15 mm of rainfall in the 1% AEP event was assumed not to report to runoff but to be lost. The runoff coefficients used varied depending on the catchment type but ranged from approximately 0.55 to 0.7.

For the "wetland" catchments (gravity flow directly to lakes), the appropriate hydrograph was used with hourly time steps over the 36 hour duration of the storm, to calculate flow rates.

For the "storage" catchments, the runoff volume was calculated using the storm depth spread over the catchment area and this was assumed to be temporarily stored in an infiltration basin. The infiltration rate of the infiltration basin set the discharge rate to the adjacent sump and pump.

7.2.7. Combined Flows

The gravity flows from the groundwater and surface water models remained separate with the groundwater flow remaining constant and the surface water flow changing throughout the 36 hours duration of the storm event based on the representative hydrograph.

The pumped flows from the infiltration basins also remain constant throughout the 36-hour storm duration with their respective rates set by the infiltration rate of the infiltration basin.

7.2.8. Lake levels

A storage volume vs depth curve was estimated for each lake from SRTM data. This allowed a lake volume/level model to be developed which uses an hourly time step and calculates the depth of water in the lake based on the inflow and outflow occurring every hour. The rise and fall of the lake level allowed the pumping rate out of the lake to be adjusted to prevent it from overflowing.

The groundwater model identified key high and low levels for each lake and the same key levels were used in each lake volume/level model (refer to Table 27 of the Groundwater Flow Model Report). These levels are summarised in Table 8 below.

The starting lake water level in each water balance models (i.e. prior to the 1 % AEP) was set as the midpoint between the minimum desired annual peak (spring) and the absolute maximum peak as is described in Kavavos et al. (2020). Following this, the flow rate of the pump in each lake was adjusted to determine the flow required to prevent the lake from exceeding the critical freeboard level at defined in Table 27 of the Groundwater Flow Model report and the column highlighted in red in Table 6 below.

In addition to pumped and gravity flows from its own catchment, the model for Lake Jandabup also has flows from the other lakes entering each hour and this allowed the size of the required pump to convey the water to the Northern Infiltration Basin to be determined.

Table 8 - Lake Level Parameters

Lake	Level invert (mAHD)	Min Desired Annual Peak (Spring) (mAHD)	Absolute Max Peak (Short Term) (mAHD)	Assumed Lake start level – Average of Short Term and Critical Freeboard Level (mAHD)	Critical Freeboard Level (mAHD)	Critical Spill Level (mAHD)
Badgerup	40.3	41.5	42	41.75	42.5#	43
Gnangara	41.05	42	43	42.5	44.5	45
Lake Adams	43	44	45	44.5	45.4	46
Little Badgerup	40.3	41.5	42	41.75	42.5#	43
Little Coogee	46.1	47.5	49	48.25	49.0#	49.5
Mariginiup	40.3	42.1	42.6	42.35	45.1	45.5
Jandabup	43.8	44.7	46.2	45.45	47.0	47.5

Critical Freeboard Level assumed to be 0.5m below Critical Spill Level

The lake water balance models were combined and run simultaneously allowing Infiltration rates, infiltration basin depths, and pumping rates to be adjusted to determine the flow rates of the pumps. Pipelines were then sized based on the relevant flows, heads and applicable pipe lengths.

7.3. EWGWMS Water Balance Model Results

The water balance model is sensitive to infiltration rates in the flood storage basins in the storage or trapped catchments. Setting the infiltration rate at 1m/day is a reasonable assumption and is likely to be consistent with industry expectations and allow the EWDSP and subsequent LSP to be advanced as planned and without a significant departure for the current planning.

The effect of increasing the infiltration rate in the flood storage or infiltration basins to more than 1 m/d, leads to overflows in the catchment routing to Gnangara Lake and Little Coogee Lake/Flat. Given the very shallow bathymetry of Little Coogee Flat/Lake it is likely that this area will require a specific management of these storage catchments. The land draining to Little Coogee Flat/Lake is derived from run-off from government landholding and, therefore, the infiltration rate for these flood storage basins have been modelled as 0.15 m/day in the concept design.

The infiltration rate at flood storage basins in the storage catchment routing to Lake Gnangara and Lake Adams has been nominated as 0.6 m/d to ensure lake water pumping infrastructure as these lakes is not unreasonably large. However, the water balance model is a concept design and certainly future preliminary design can better manipulate the concept design over the coming years.

Pumping can obviously be increased from local lakes and wetlands to Lake Jandabup, but this will simply require larger (and more expensive) infrastructure along with the assumption that the final infiltration point, 22.7 km to the north, has sufficient area to be able to store this water prior to infiltration. Infiltration rates were, therefore, limited to the values given above to minimise the size of downstream infrastructure. The infiltration rate sensitivity versus net developable area (or dwelling yield) across the DSP is a key consideration. The preferred design outcome could be better justified with a rapid cost-benefit analysis which considers stage implementation timing.

It should be noted that the operating cost for the required infrastructure is likely to be relatively low as it will only be required following extreme rainfall years or following significant storm events. Most years would require minimal pumping and hence in these years, just the maintenance cost would be incurred to ensure pumps are kept in good operating condition.

Figure 9 below shows the water level in Lake Jandabup during the modelled worst-case scenario. Even with the attenuation provided by the flood storage or infiltration basins, the level of Lake Jandabup still rises rapidly for the first 36 hours in response to the 1 % AEP. Thereafter, the rate of rise decreases because of the attenuation provided by the flood storage or infiltration basins in the catchments. Collectively, this leads to a conservative required pumping rate to the Northern Infiltration Basin of 1,500 L/s.

The response in the other lakes is similar, and each has its own pumping requirement which needs to be maintained to prevent overflow. The pumping rates are given below in Table 9.

Note that these pumping rates are not the exactly the same as those modelled in the groundwater model. This is because the water balance model has an hourly time step to simulate the effect of the 1 % AEP over 36 hours and this time step resolution cannot be readily adopted in the groundwater model. However, the overall findings of the groundwater model and the flood routing model with respect to lake levels and their potential to overflow is consistent.

Table 9 - Flows to and from each lake

Wetland/Lake ID	Peak flows to lakes from district scale subsoil drainage (L/s)	Peak flows from 1% AEP Rainfall surface runoff (L/s)	Groundwater model simulated Pump out Rates (L/s)	Pump out Rate from Lakes – Concept Design (L/s)
Badgerup Lake	187.8	2,555	50	50
Gnangara Lake	682.6	9,786	150	600
Lake Adams	323.5	2,462	100	100
Little Badgerup Lake	0.0	1,811	50	50
Little Coogee Swamp	242.9	916	100	700
Mariginiup Lake	155.9	11,879	100	50
Lake Jandabup	867.0	20,750	1500	1500

As shown in Table 9 above, setting the infiltration rate in the infiltration basins to between 0.15 and 1 m/d (depending on the basin) will still require significant pumping rates out of Lake Gnangara, Lake Adams and Little Coogee Swamp and will require a pumping rate from Lake Jandabup to the Northern Infiltration Basin of 1500 L/s. Even though the model indicated that Badgerup Lake, Little Badgerup Lake and Mariginiup did not require pumping infrastructure, infrastructure was still designed and costed for these lakes to be conservative.

Figure 9 shows the lake level in Lake Jandabup in hourly time steps commencing at the start of the 1 % AEP storm event. Note that the flows which drain to the lake under gravity, occur in the first 36 hours and thereafter, the pumped flows continue entering the lake for a significant period. The rate at which the lake level continues to increase after 36 hours has elapsed, is set by the infiltration rate of the infiltration basins.

To illustrate the significance of the infiltration rate in the infiltration basins, Figure 10 shows what would happen if an infiltration rate of 4m/d was used instead of between 0.15 and 1m/d. In this case, the attenuation is not sufficient and hence, after about 26 hours, Lake Jandabup is predicted to overflow, whereas using the lower infiltration rates prevents Lake Jandabup from overflowing provided continuous pumping at 1500 L/s is maintained for up to 30 days and possibly beyond that.

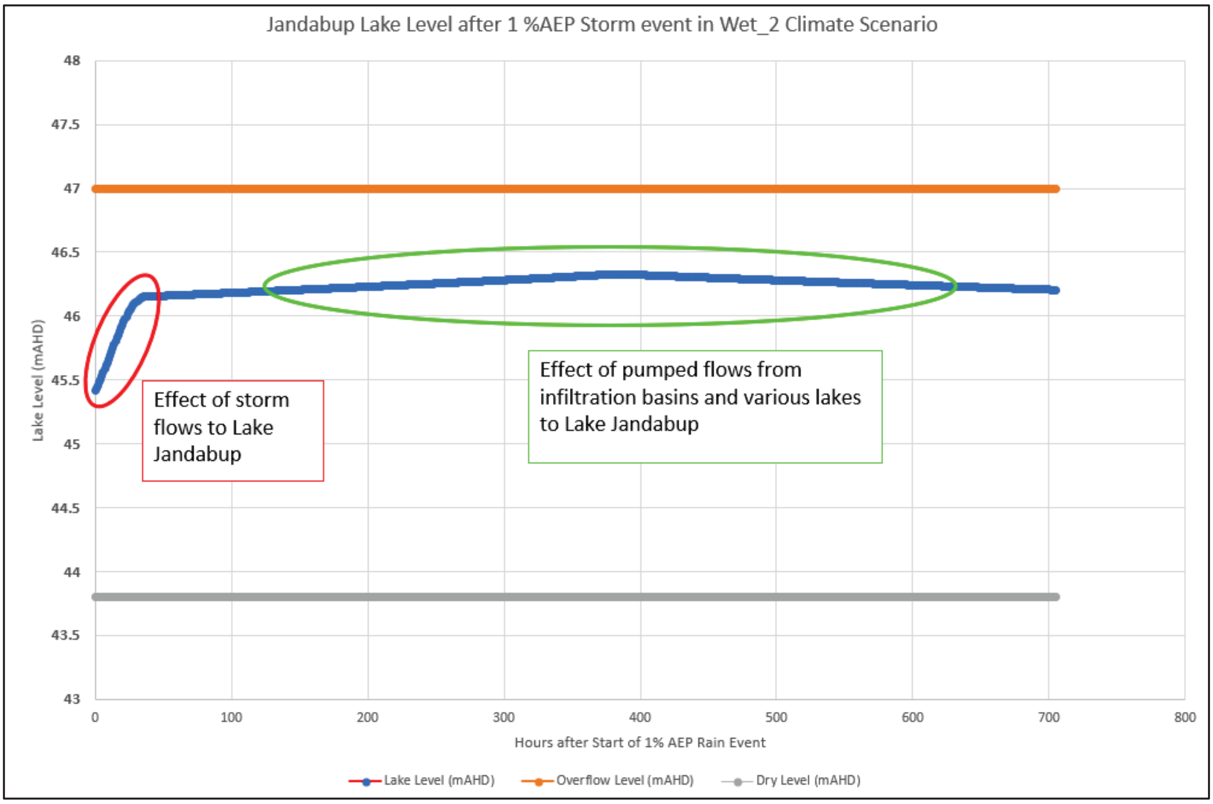

Figure 9 - Lake Jandabup Level after 1 % AEP Storm Event (1 m/d Infiltration Rate in most basins)

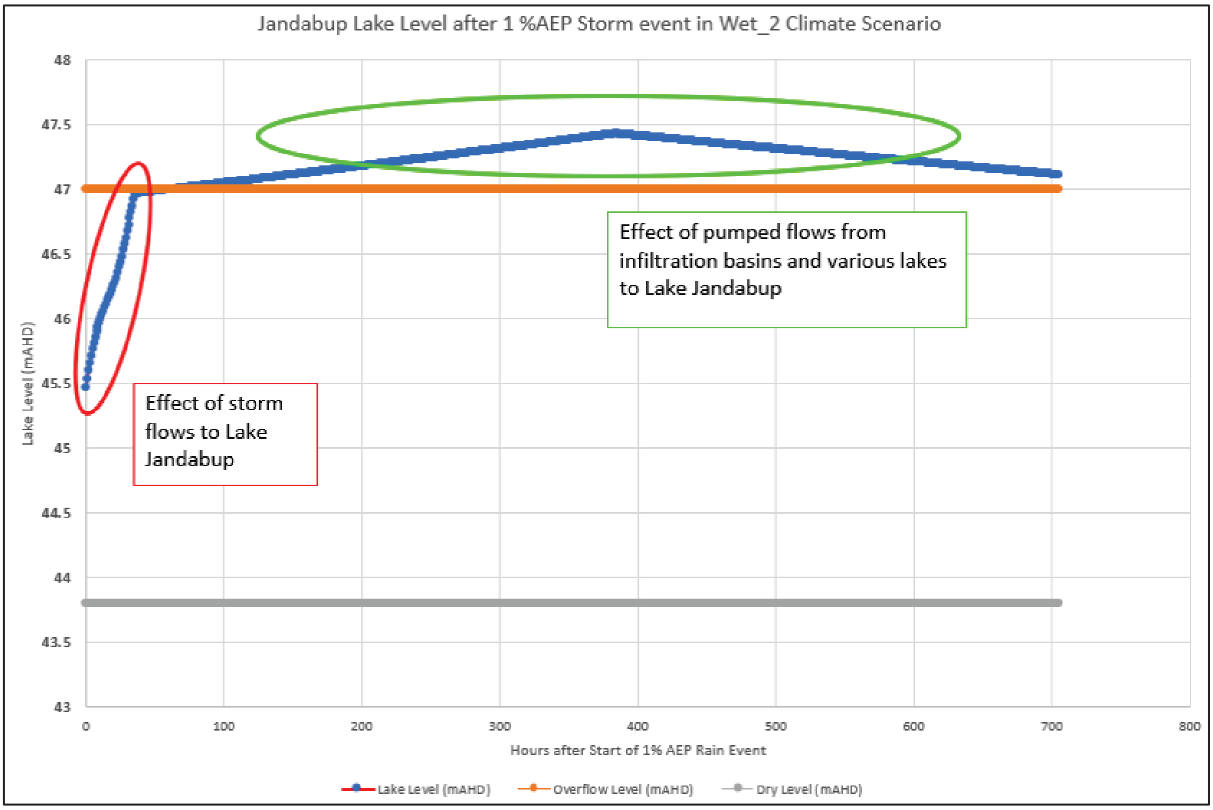

Figure 10 - Lake Jandabup Level after 1 % AEP Storm Event (4 m/d Infiltration Rate in most basins)

Once the water balance model had been used to determine the flow rates for the sump pumps, and lake pumps, a hydraulic spreadsheet was assembled to determine the sizes for the pumping infrastructure, and this allowed a cost estimate to be completed. Details of the cost estimate (CAPEX) are given in Section 8.

8. Cost Estimate for Proposed EWGWMS Concept Design

8.1. Introduction

The cost estimate is based on a Class 4 level of accuracy (-15% to +50%). It should be noted that more detailed work is required to integrate the proposed pumps and piping with proposed precinct layouts so that this infrastructure does not clash with other services which may be proposed for the development area.

A summary of the costs is given in Table 10, and more details are provided in Appendix A.

8.2. Costs Included

The following items are included in the costs presented below:

- 25 no. Collection sumps c/w duty/standby submersible pumps as illustrated in Figure 3 and Figure 4.
- Pipeline from collection sump to nearest lake along road reserves etc. (Figure 2)
- 6 no. suction pipes, pump stations and discharge pipes from the various Lakes to Lake Jandabup
- Suction pipe, pumps and discharge pipe from Lake Jandabup to the Northern Infiltration Basin (see Figure 5)
- Northern Infiltration Basin earthworks (see Figure 6)
- Earthworks to construct an embankment to protect Old Yanchep Road
- SCADA and telemetry system to coordinate active management of sump pumps and lake pumps
- Detailed engineering design
- Survey and services identification
- Construction Mob and Demob
- Construction Indirects including site management, traffic management
- Allowance for approvals (wetland evaluations, vegetation surveys, environmental approvals, heritage approvals etc.)
- Testing, commissioning and Completion Documentation

8.3. Costs Excluded

Certain items have been excluded from the costs. These are as follows:

- Subsoil drainage infrastructure throughout the urban development precincts (assumed to be install by proponents)
- Subsoil drainage pipework under infiltration basins. This cost was assumed to be included in the normal civil construction cost for land development proponents.
- Land tenure, property acquisition and associated approvals process
- Earthworks in and around lakes to enhance their storage capacity
- Lot bulk earthworks development costs

8.4. Cost Overview

The costs presented in Table 10 are an overview of the costs. The costs have been rounded given that this is a Class 4 estimate.

Indirect Costs have been based on the Direct Costs and an allowance has been built into the detailed design to allow for changes during design development.

Table 10 - Cost overview

Direct Costs	Supply (AUD rounded)	Installation (AUD rounded)	Total (AUD rounded)
Subsoil collector pipelines:	$10,683,100	$29,002,100	$39,685,200
Intra-Lake Transfer Pipelines:	$11,450,000	$31,084,000	$42,534,000
Main Transfer Pipeline:	$28,373,000	$77,025,000	$105,397,000
Subsoil collector pumps:	$7,334,000	$16,282,000	$23,616,000
Intra-Lake Transfer Pump Costs:	$12,498,000	$21,747,000	$34,246,000
Main Transfer Pump Station:	$7,480,000	$13,016,000	$20,496,000
		Total – Directs	**$265,974,200**
Indirect Costs	% of Direct Cost		Total (AUD rounded)
Detailed Design (Consultancy and Engineering)	3.5		$9,309,000
Survey and Services Search	3		$7,979,000
Mob and Demob	7		$18,618,000
Construction Indirects incl. Site Management, Traffic Management etc.	54		$143,626,000
Approvals Costs (enviro, heritage etc.)	9		$23,938,000
Testing, Commissioning & Completion Documents	3		$7,979,000
		Total - Indirects	**$211,449,000**
		Total	**$477,423,000**

Based on the above estimate, the cost per lot for 55,000 lots will be about $8680 /lot.

The detailed costs are given in Appendix A to provide further information on the items included in the costs.

9. EWGWMS – Phase 1

9.1. Introduction

The groundwater modelling and associated analysis of lake water level presented in the Groundwater Flow Model report (Pentium Water 2025) indicates that control of water levels in Lake Mariginiup may be required following development of the revised Stage 1 EWDSP area, to maintain a healthy lake ecosystem and manage flood risk.

Therefore, as a contingency planning measure, a concept design for a “Phase 1” of the EWGWMS has been identified, comprising a lake transfer pump station and pipeline to convey water from Lake Mariginiup to Lake Jandabup.

9.2. Concept Engineering Design

9.2.1. Conveyance route and land tenure

The proposed conveyance alignment from Lake Mariginiup to Lake Jandabup is illustrated in Figure 11. The land tenure of the alignment is all in control of the state via land ownership in the name of the State of Western Australia, State Planning Commission, or via Caporn Street or Franklin Road under the governance of the City of Wanneroo. The land tenure provides certainty to the ability for the concept to be implemented.

9.2.2. Proposed Pump Station

Pumping infrastructure was designed using the outputs from the groundwater model and associated lake water level analysis. The future scenario simulation based on a Wet_2 climate scenario resulted in a lake management peak outflow of 156 L/s, which will need to be transferred from Lake Mariginiup to Lake Jandabup. The static water level difference between the two lakes is approximately 2m and the distance between them is 2780m following a route which follows existing road reserves as described above.

This combination produces at Total Dynamic Head of 12m and will require a 30kW pump. A duty /standby pump station is proposed with power supplied from existing reticulated power that is assumed to be available by the time this pump station is required.

A suction pump will be constructed in Lake Mariginiup, which will consist of a tower intake structure raised above the base of the lake to prevent silt ingress. The tower will also contain debris screens to prevent reeds and fauna from entering the suction. Access to the tower will consist of a small walkway with handrails either side but access to the public will be prevented by a gate with appropriate security treatments. The pump station itself, although relatively small, will be housed in a small building designed to blend into the surrounding landscape. The building will protect the pumps and reduce noise while the pumps are in operation.

9.2.3. Proposed Pipeline

The proposed pipeline to transfer the peak flow from Lake Mariginiup to Lake Jandabup is a buried DN 450 HDPE PN 8 pipe. This pipe will initially run south from Lake Mariginiup to Caporn Street (along a existing easement) and then runs east for about 1.2 km along Caporn Street until it reaches Franklin Road. It then follows Franklin Road to the south for approximately 350m and turns east again to discharge into Lake Jandabup via WAPC owned land (refer to Figure 11).
The discharge structure at Lake Jandabup will be a head wall outlet with rock pitching to prevent scour and erosion.

Figure 11 - Mariginiup Transfer Pipeline to Lake Jandabup

9.3. EWGWMS Phase 1 – Implementation

Successful implementation of Phase 1 of the EWGWMS is reliant on development of engineering designs supported by a detailed project plan, environment and heritage approvals, with funding in place for construction when required.

Key elements of the project plan will include:

- Triggers for Phase 1 implementation (aligned with the district monitoring program)
- Likely timeline and costs for delivery (including environmental approvals)
- Interim governance arrangements (including transitionary arrangements for when the full scheme is implemented)

Engineering designs and a detailed project plan will be delivered with funding provided under the East Wanneroo district developer contributions plan (EWDDCP). A preliminary outline of the key project plan elements is provided below.

9.3.1. Triggers for Phase 1 implementation

Preliminary triggers for implementation of Phase 1 of the EWGWMS have been determined based on groundwater and lake water level modelling and previous assessments of ecological water requirements for Lake Mariginiup and Lake Jandabup by Kavavos et al., 2020 and Gnangara Mound Ministerial Statement criteria (DoW, 2004). These are summarised as:

- The implementation of the EWGWMS Phase 1 infrastructure will be triggered should annual rainfall totals in East Wanneroo exceed 800mm for two years in a row.
- The commencement of pumping from Lake Mariginiup via that Phase 1 infrastructure should be considered when water levels in Lake Mariginiup exceed 42.6 m AHD, which is the preferred maximum peak as described in Kavavos et al., 2020.

These triggers will be reviewed following completion of wetland evaluations funded by the district developer contributions plan.

9.3.2. Likely timeline and costs for delivery

Environmental approvals will be required for construction and management of Phase 1 of the EWGWMS including a referral of the proposal to the Environmental Protection Authority (EPA) under Section 38 of the Environmental Protection Act 1986. The EPA's assessment will be contingent on completion of baseline wetland condition assessments for both Lake Mariginiup as the source, and Lake Jandabup as the receptor. Therefore, the timeline and costs for delivery will need to include consideration of the necessary timeframes to complete wetland assessments and satisfy environmental approval requirements. It is likely that the overall timeframe for design development, completion of investigations and approvals processes, and construction will exceed two years.

9.3.3. Interim governance arrangements

As noted above, engineering designs and a detailed project plan for Phase 1 of the EWGWMS will be delivered with funding provided under the district developer contributions plan (DDCP).

Ultimately, as outlined in Section 2.6 of the DWMS Addendum 1, it is proposed that the Water Corporation will develop and manage the full EWGWMS. However, should implementation of Phase 1 of the EWGWMS be necessary prior to finalisation of this governance model, the City of Wanneroo will take interim responsibility for delivery and management of the Phase 1 infrastructure with handover to the Water Corporation to follow when possible.

9.4. Phase 1 - Cost Estimate

The cost to construct a pump station at Lake Mariginiup and a transfer pipeline from Lake Mariginiup to Lake Jandabup including an outlet structure to Lake Jandabup is estimated at approximately $4.5M. The cost estimate is a Class 4 estimate (-15% to + 50%) and has been completed on the assumption that the transfer pipeline installation will be done concurrent with the necessary upgrade of Caporn Road and, therefore, would not require the reinstatement of a future upgraded Caporn Road. The cost estimate details are shown in Table 11.

Table 11 - Cost Estimate for Mariginiup Transfer Pipeline

Direct Costs	Description	Qty/Unit	Size (mm)	Supply (AUD rounded)	Installation (AUD rounded)	Total (AUD rounded)
Intra-Lake Transfer Pipeline from Lake Mariginiup to Lake Jandabup	PE 100 PN8 buried pipe	2781 m	450	$291,246	$790,662	$1,081,908
Pump station located at Lake Mariginiup	Incl surface pumps, electrical and civil works	2	26.71	$160,283	$278,892	$439,175
SCADA System and Controls for complete system	Incl telemetry, level sensors, main monitoring and control PLC	Lot	Variable	$170,000	$295,800	$465,800
					Total – Directs	**$1,986,882**
Indirect Costs				% of Direct Cost		Total (AUD rounded)
Detailed Design (Consultancy and Engineering)				12		$238,426
Survey and Services Search				7		$139,082
Mob and Demob				15		$298,032
Construction Indirects incl. Site Management, Traffic Management etc.				56		$1,112,654
Approvals Costs (enviro, heritage etc.)				11		$218,557
Testing, Commissioning & Completion Documents				13		$258,295
					Total - Indirects	**$2,265,046**
					Total	**$4,251,928**

10. Key Considerations

The concept engineering design exercise required significant consideration of a lake water balance, which incorporated inflows from subsoil drainage discharge, groundwater level rise, direct rainfall inputs, direct stormwater run-off, and importantly infiltrated stormwater run-off in trapped catchments through-out the EWDSP area. Stormwater runoff, both direct and indirect, as well as the management of rising groundwater levels via subsoil drainage is a key consideration of the EWGWMS.

Infiltration Rates – Yield versus infrastructure costs

Based on the outcomes of the overall water balance model, it appears that provided a reasonable portion of the surface flow generated by a 1 % AEP can be attenuated using a combination of infiltration basins and wetlands, instantaneous flow rates to the lakes can be reduced, leading to a reduction in the size and cost of the associated pumping and transfer infrastructure. However, as the cost of the pumping infrastructure is reduced, the spatial extent of the infiltration basins will increase to compensate. The land take of these flood storage basins in the trapped catchments is considerable and may begin to compromise the dwellings yields and proposed outcomes of the EWDSP if the flood storage basins cannot be incorporated into public open spaces, district open space, co-located ovals, school playing fields etc.

Infiltration rates were, therefore, limited to between 0.15 and 1 m/d to ensure maximum retention (attenuation) and to minimise the size of downstream infrastructure. The infiltration rate sensitivity versus net developable area (or dwelling yield) across the EWDSP is a key consideration. The optimum design outcome or preferred design outcome could be better justified with a rapid cost-benefit analysis or economic evaluation to determine whether a bigger infrastructure spend, or lower yield is more beneficial.

The installation of a regional groundwater and lake water management scheme is required to control rising regional groundwater levels due to development and, as such, all lots developed in the EWDSP area should contribute to the development of this infrastructure. However, a portion of the EWGWMS also includes the managed of trapped catchments across the EWDSP area. The equitable distribution of the CAPEX cost via the DDCP or headworks charges should be considered as it relates to the management of these trapped catchments. As indicated previously, the size of infrastructure and associated costs of this infrastructure is largely dependent on the size and infiltration rate in the flood storage basin of the trapped catchments. Any decision to maximise yield in these trapped catchments would be a direct benefit to the landowners in those catchments/precincts but would require an increase in CAPEX and, therefore, contributions across the DSP area. Careful consideration of the additional distribution of capital costs across the DSP should those additional considerations be made.

Uncertainty and the requirement for adaptive management

There is significant uncertainty in the groundwater modelling and, therefore, the concept engineering design due to the climate scenarios used to inform the groundwater flow model's future simulations. Consequently, the concept engineering design has adopted a conservative approach and has design and sized infrastructure to be capable of managing very high groundwater levels regionally and manage wetland and lake water levels in this high-level plus with a 1% AEP rainfall event on top of that. The conservatism in the concept design is necessary to ensure the cost estimate is conservative and the funds secured via either the DDCP (as originally envisaged) or via another arrangement is sufficient. This potential cost can then be communicated to the land development industry and be considered by all proponent advancing feasibility assessment for the acquisition and development of land across the EWDSP.

However, it is important to consider that the conservative climate scenarios used to inform the concept engineering design may not eventuate and that the implementation of the full EWGWMS should be continually considered based on ongoing analysis of district scale groundwater and lake water level data and active management based on informed wetland health assessments. It is possible that only certain elements of the EWGWMS identified in this report will need to be constructed and operated.

Northern Disposal Area and associated discharge pipeline

The Northern Disposal Area in Carabooda should be continually considered as the preferred location. The existence and restrictions posed by the PWDSA did not allow for a more practical and closer disposal location. The distance to this location in Carabooda creates significant additional costs to construction and will require a significant operating cost if required. Consideration should be given to more suitable disposal location closer to Lake Jandabup and possibly within the PDWSA given the potential infrequent nature of the required disposal. A temporary disposal location closer to Lake Jandabup could be considered prior to committing the funds to construction the disposal pipeline and infiltration basin in Carabooda.

Water supply opportunity

The Groundwater Flow Modelling report identifies significant variability in the annual excess water produced from the EWGWMS. However, based on the four climate scenarios simulated, there is consistently over 10 GL/yr of excess water produced from the scheme (not including the Dry climate scenario). Consideration should be given the economic benefit or financial benefit of this produced water and how the benefit could be used to offset the operating cost or potential the capital costs of the scheme and its burden on the EWDSP lot owners.

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Appendix A: Detailed Cost Estimate (Class 4)

Appendix A

This appendix contains detailed line items which make up the Class 4 cost estimate.

Item		Description	QTY/Unit	Size (mm)	Supply	Install	Total
Direct Costs							
	Subsoil collector pipelines:						
1	S12f	PE100 PN8 buried pipe	1214 m	560	$197,692	$536,686	$734,378
2	S10a	PE100 PN8 buried pipe	1443 m	800	$478,764	$1,299,728	$1,778,492
3	S10b	PE100 PN8 buried pipe	827 m	280	$33,494	$90,927	$124,421
4	S12e	PE100 PN8 buried pipe	1967 m	400	$162,755	$441,841	$604,596
5	S12a	PE100 PN8 buried pipe	2480 m	450	$259,728	$705,098	$964,826
6	S12b	PE100 PN8 buried pipe	2531 m	450	$265,063	$719,583	$984,646
7	S12c	PE100 PN8 buried pipe	3362 m	630	$691,543	$1,877,373	$2,568,915
8	S11a	PE100 PN8 buried pipe	2593 m	630	$533,400	$1,448,053	$1,981,453
9	S12d	PE100 PN8 buried pipe	2675 m	450	$280,212	$760,709	$1,040,921
10	S13a	PE100 PN8 buried pipe	1447 m	450	$151,609	$411,582	$563,190
11	S14b	PE100 PN8 buried pipe	996 m	250	$32,281	$87,635	$119,916
12	S15a	PE100 PN8 buried pipe	4866 m	280	$197,047	$534,935	$731,982
13	S16a	PE100 PN8 buried pipe	1576 m	710	$411,846	$1,118,064	$1,529,910
14	S16b	PE100 PN8 buried pipe	1280 m	355	$83,616	$226,996	$310,612
15	S16c	PE100 PN8 buried pipe	3325 m	560	$541,310	$1,469,526	$2,010,836
16	S20a	PE100 PN8 buried pipe	1156 m	450	$121,069	$328,672	$449,741
17	S20b	PE100 PN8 buried pipe	990 m	1200	$738,557	$2,005,004	$2,743,560
18	S23a	PE100 PN8 buried pipe	2888 m	280	$116,945	$317,478	$434,424
19	S23b	PE100 PN8 buried pipe	1770 m	450	$185,444	$503,435	$688,879
20	S23c	PE100 PN8 buried pipe	2471 m	180	$41,758	$113,364	$155,122
21	S23e	PE100 PN8 buried pipe	2386 m	280	$96,604	$262,256	$358,860
22	S24a	PE100 PN8 buried pipe	1424 m	200	$29,374	$79,743	$109,117
23	S24c	PE100 PN8 buried pipe	890 m	250	$28,857	$78,339	$107,195
23*	PS (179)	PE100 PN8 buried pipe	946 m	280	$38,304	$103,987	$142,292
23#	PS (203)	PE100 PN8 buried pipe	571 m	180	$12,648	$34,336	$46,984
24	**Intra-Lake Transfer Pipelines:**						
25	Badgerup to Lake Jandabup	PE100 PN8 buried pipe	4231 m	800	$1,403,730	$3,810,789	$5,214,518
26	Lake Gnangara to Lake Jandabup	PE100 PN8 buried pipe	5751 m	1000	$2,981,163	$8,093,143	$11,074,306
27			5751 m	1000	$2,981,163	$8,093,143	$11,074,306
28	Lake Adams to Lake Jandabup	PE100 PN8 buried pipe	4618 m	630	$950,065	$2,579,199	$3,529,265
29			4618 m	630	$950,065	$2,579,199	$3,529,265
30	L.Badgerup to Badgerup Lake	PE100 PN8 buried pipe	Incl above.				

31	Little Coogee Swamp to Lake Jandabup	PE100 PN8 buried pipe	7305 m	500	$946,649	$2,569,926	$3,516,575
32			7305 m	500	$946,649	$2,569,926	$3,516,575
33	Mariginup Lake to Lake Jandabup	PE100 PN8 buried pipe	2781 m	315	$147,538	$400,530	$548,067
	Pre 15 Lake to Jandabup	PE100 PN8 buried pipe	2258 m	315	$143,054	$388,356	$531,410
34	**Main Transfer Pipeline:**						
35	Lake Jandabup to discharge point	PE100 PN8 buried pipe	22753 m	710	$5,945,275	$16,139,994	$22,085,268
36			22753 m	710	$5,945,275	$16,139,994	$22,085,268
37			22753 m	710	$5,945,275	$16,139,994	$22,085,268
38			22753 m	710	$5,945,275	$16,139,994	$22,085,268
39	Pipe Fittings	Including valves, bends, tees, etc	Lot	Various sizes	$4,591,428	$12,464,626	$17,056,055
40	**Subsoil collector pumps:**			kW			
41	S12f	Incl wet wells, pumps, electrical and civil works	2	49.16	$99,319	$220,489	$319,808
42	S10a	Incl wet wells, pumps, electrical and civil works	2	123.73	$246,351	$546,899	$793,250
43	S10b	Incl wet wells, pumps, electrical and civil works	2	10.67	$22,333	$49,579	$71,912
44	S12e	Incl wet wells, pumps, electrical and civil works	2	93.75	$186,654	$414,373	$601,027
45	S12a	Incl wet wells, pumps, electrical and civil works	2	223.50	$444,983	$987,861	$1,432,844
46	S12b	Incl wet wells, pumps, electrical and civil works	2	164.10	$326,719	$725,316	$1,052,035
47	S12c	Incl wet wells, pumps, electrical and civil works	2	227.92	$453,794	$1,007,422	$1,461,216
48	S11a	Incl wet wells, pumps, electrical and civil works	2	130.91	$260,639	$578,619	$839,257
49	S12d	Incl wet wells, pumps, electrical and civil works	2	45.95	$91,489	$203,105	$294,594
50	S13a	Incl wet wells, pumps, electrical and civil works	2	65.39	$131,772	$292,534	$424,307
51	S14b	Incl wet wells, pumps, electrical and civil works	2	35.87	$72,749	$161,502	$234,250
52	S15a	Incl wet wells, pumps, electrical and civil works	2	124.65	$248,173	$550,943	$799,116
53	S16a	Incl wet wells, pumps, electrical and civil works	2	277.02	$555,043	$1,232,196	$1,787,240
54	S16b	Incl wet wells, pumps, electrical and civil works	2	138.71	$278,430	$618,114	$896,543
55	S16c	Incl wet wells, pumps, electrical and civil works	2	373.81	$744,247	$1,652,228	$2,396,475
56	PS (179)	Incl wet wells, pumps, electrical and civil works	2	643.07	$1,280,362	$2,842,404	$4,122,766
57	PS (203)	Incl wet wells, pumps, electrical and civil works	2	122.04	$242,974	$539,402	$782,376
58	S20a	Incl wet wells, pumps, electrical and civil works	2	58.67	$118,341	$262,716	$381,057
59	S20b	Incl wet wells, pumps, electrical and civil works	2	78.07	$155,432	$345,060	$500,492
60	S23a	Incl wet wells, pumps, electrical and civil works	2	81.84	$164,688	$365,607	$530,294
61	S23b	Incl wet wells, pumps, electrical and civil works	2	454.55	$910,101	$2,020,424	$2,930,525

62	S23c	Incl wet wells, pumps, electrical and civil works	2	26.25	$53,505	$118,781	$172,286
63	S23e	Incl wet wells, pumps, electrical and civil works	2	86.16	$173,318	$384,767	$558,085
64	S24a	Incl wet wells, pumps, electrical and civil works	2	8.21	$17,430	$38,694	$56,124
65	S24c	Incl wet wells, pumps, electrical and civil works	2	27.22	$55,445	$123,088	$178,534
66	**Intra-Lake Transfer Pump Costs:**						
67	Badgerup to Lake Jandabup	Incl surface pumps, electrical and civil works	2	820.13	$1,632,877	$2,841,206	$4,474,083
68	Lake Gnangara to Lake Jandabup	Incl surface pumps, electrical and civil works	2	1736.11	$3,456,592	$6,014,471	$9,471,063
69			2	1736.11	$3,456,592	$6,014,471	$9,471,063
70	Lake Adams to Lake Jandabup	Incl surface pumps, electrical and civil works	2	521.89	$1,039,083	$1,808,004	$2,847,087
71			2	521.89	$1,039,083	$1,808,004	$2,847,087
72	L.Badgerup to Badgerup Lake			Incl above.			
73	Little Coogee Swamp to Lake Jandabup	Incl surface pumps, electrical and civil works	2	354.91	$706,627	$1,229,530	$1,936,157
74			2	354.91	$706,627	$1,229,530	$1,936,157
75	Mariginup Lake to Jandabup Lake	Incl surface pumps, electrical and civil works	2	45.41	$90,404	$157,302	$247,706
75*	Pre 15 Lake to Jandabup Pump Costs	Incl surface pumps, electrical and civil works	2	820.13	$1,632,877	$2,841,206	$4,474,083
76	**Main Transfer Pumps to Northern Infiltration Basin:**						
77	Jandabup Lake to discharge point	Incl surface pumps, electrical and civil works	3	324.82	$970,066	$1,687,915	$2,657,981
78		Incl surface pumps, electrical and civil works	3	324.82	$970,066	$1,687,915	$2,657,981
79		Incl surface pumps, electrical and civil works	3	324.82	$970,066	$1,687,915	$2,657,981
80		Incl surface pumps, electrical and civil works	3	324.82	$970,066	$1,687,915	$2,657,981
81	SCADA System and Controls for complete system	Incl telemetry, level sensors, main monitoring and control PLC	Lot	Variable	$600,000	$1,044,000	$1,644,000
82	Infiltration Basins at discharge Point	Embankment to protect Road (Use natural basin shape otherwise)	120000	m3	$3,000,000	$5,220,000	$8,220,000
83	**Total of direct costs**						**$265,974,200**
Indirect Costs							
84	Detailed Design (Consultancy and Engineering)	3.5 %					$9,309,107
85	Survey and Services Search	3 %					$7,979,235
85	Mob and Demob	7 %					$18,618,215
86	Construction Indirects incl. Site Management, Traffic Management etc.	54 %					$143,626,226
86	Approvals Costs (enviro, heritage etc.)	9 %					$23,937,704
87	Testing, Commissioning & Completion Documents	3 %					$7,979,235
88	**Total of indirect costs**						**$211,449,000**
89	**Total cost**						**$477,423,200**