Government of **Western Australia**
Department of **Water**

Looking after all our water needs

Southern Perth Basin groundwater-resource assessment

Application of SWAMS and ESCP Models

Hydrogeological record series

Report no. HG26
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Water Resource Management Division

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Summary

The Department of Water is developing the *South West groundwater areas water management plan* as part of its strategy for managing Western Australia's water resources. During this process the department will determine an allocation limit for the South West groundwater areas (including the Blackwood, Bunbury and Busselton-Capel groundwater areas) with the aid of numerical groundwater models to quantify the resource and the potential impacts of abstraction.

Between 2003–06, the Department of Water and the Water Corporation conducted joint hydrogeological investigations to assess the feasibility of abstracting an additional 45 gigalitres per year (GL/yr) of groundwater from the South West Yarragadee. These investigations resulted in a significantly improved understanding of the hydrogeology of the southern Perth Basin, and the development of two computerised numerical groundwater-flow models of the area: the regional-scale South West Aquifer Modelling System version 2 (SWAMS v2) model and the local-scale Eastern Scott Coastal Plain (ESCP) model. The SWAMS v2 and ESCP models have been used to simulate changes in groundwater abstraction and climate, as well as the resulting impacts on groundwater levels at several sites of identified ecological and social value (including other users of the groundwater resource).

Several abstraction scenarios for predictive modelling have been tested – based on a range of possible future abstraction options in the South West. One of the key approaches was to compare the model outputs from the different abstraction scenarios to those of a base case. A current-use scenario, representing 30 years' abstraction at the rate of the actual groundwater use of 64 GL/yr (as in 2004), was adopted as the base case. The effect of reduced recharge due to the possibility of a drier climate was also simulated. All scenarios have been modelled for a 30-year forecast period (from 2004–33), representing the usual planning timeframe.

Depending on the abstraction levels in each scenario, the modelling results show a range of potential watertable drawdowns along the coastal plains and the Blackwood valley, including large sections along St Johns Brook. For the highest-level abstraction scenario – the projected regional growth together with the proposed Water Corporation abstraction – drawdown of up to 0.5–2 metres (m) is predicted in areas where the Yarragadee Formation occurs at shallow depths. However, along the coastal plains where surface-water inundation occurs, the drawdowns may be lower than predicted by SWAMS (because the model underestimates recharge in these areas). Recent recharge estimates for the Swan Coastal Plain have shown that recharge could be 60 per cent higher than what is applied in the SWAMS model. This issue has been resolved in the ESCP model, which is a fully integrated surface-water and groundwater model.

The SWAMS model has also been used to estimate optimum volumes of groundwater abstraction whereby the resulting watertable drawdown would not exceed the preliminary ecological water requirements (EWR) criteria set for key groundwater-dependent ecosystems (GDEs). It is estimated that approximately 40 GL/yr of groundwater could be abstracted from the Yarragadee aquifer while meeting the criteria; however, the actual sustainable abstraction could be as much as 70 GL/yr (because the SWAMS model overestimates drawdowns in the coastal areas). In addition, approximately 50 GL/yr can be abstracted from the Leederville and Superficial aquifers. This model output indicates that, in total, approximately 90–120 GL/yr of groundwater could be abstracted from the southern Perth Basin aquifers on an ecologically sustainable basis if the environmental water provisions

(EWP) were set at the preliminary EWR levels. However, to achieve sustainable abstraction levels, some redistribution would be required to shift major abstractions away from key GDEs. The abstraction values would require further confirmation through development and application of local-scale models for the coastal plains.

Predicted watertable drawdowns from the proposed Water Corporation abstraction of 45 GL/yr from the Yarragadee aquifer are concentrated near the Yarragadee subcrop area – beneath the Superficial aquifer to the south of Bunbury and in the area to the south-east of Busselton. Drawdowns are also predicted along the valleys of the rivers and tributaries either where the Yarragadee Formation is exposed or the Leederville Formation is thin. Such drawdowns are generally less than 1 m, except near the Blackwood River and its tributaries, where predicted drawdowns are as much as 2–3 m. Predicted drawdown in the Yarragadee aquifer near other users' bores is less than 3 m and is unlikely to have a significant effect on well production, provided the water levels have not declined to near the base of the screened intervals.

The modelled groundwater decline for a hypothetical case of reduced rainfall recharge by 5 per cent throughout the next 30 years (as a result of climate change) showed a regional water-level decline of 0.25–0.5 m in most areas. In areas of higher recharge, such as to the north of the Blackwood River and in the northern part of the Scott Coastal Plain, watertable decline is as much as 2 m. On the coastal plains, the effect of recharge reduction is offset by a corresponding reduction in evapotranspiration; hence a lesser impact is predicted in these areas.

The predicted reduction in groundwater discharge to the Blackwood River for each abstraction scenario using the SWAMS model has been provided in Table S1. Results show that in the Blackwood River the annualised average groundwater discharge reduces by between 8 and 23 per cent based on the different scenarios of abstraction and climate change. It is predicted that the Water Corporation proposal by itself would reduce the groundwater discharge to the Blackwood River by 9 per cent. The effect of reduced groundwater discharge on the river flow is more prominent in the summer months when the river baseflow is mainly comprised of the groundwater contribution (Figure S1).

Table S1: Reduction in annual groundwater discharge to the Blackwood River

Scenario/abstraction	Reduction in discharge to Blackwood River (%)	Estimated annual reduction in discharge (GL)#
Current use (64 GL/yr)#	8%	2.0
Current entitlement (112 GL/yr)#	11%	2.8
Optimisation (~90 GL/yr)	(6% increase)	(1.5 increase)
Current use plus regional growth (64–159 GL/yr over 30 years)	14%	3.5
Current use plus regional growth plus Water Corporation (109–204 GL/yr over 30 years)	23%	5.8
Water Corporation (45 GL/yr)	9%	2.3
Current entitlements plus Water Corporation (157 GL/yr)	20%	5.0
Current use plus reduced regional growth plus reduced Water Corporation (89–147 GL/yr over 30 years)	17%	4.3
Current use (64 GL/yr) with 5% reduction in rainfall recharge	13%	3.2

#As in 2004; #Relative to estimated groundwater discharge of 25 GL/yr

During winter the river flow is significantly higher as a result of runoff, hence any impact of reduced groundwater discharge on the river flow will be negligible.

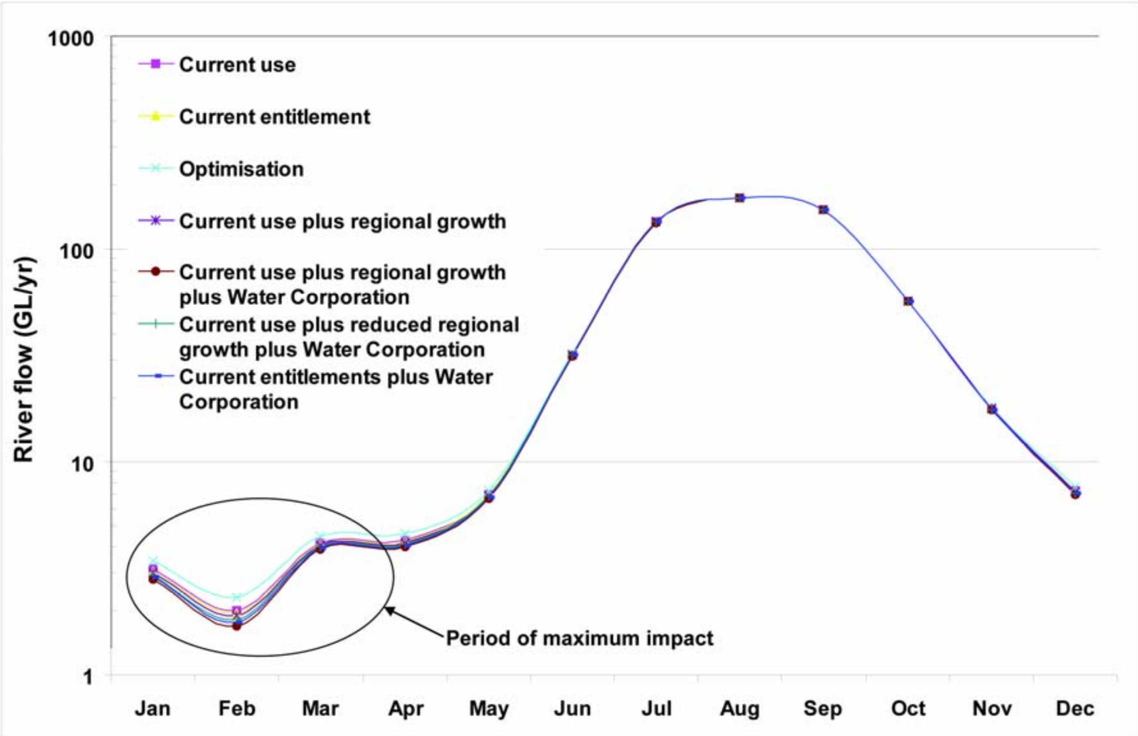

Figure S1: Predicted monthly flow in the Blackwood River for model scenarios

The reduced fresh-groundwater discharge to the Blackwood River is likely to result in a 6–21 per cent increase in the average salinity of the river in the driest month of February (Figure S2). In the winter months, the river salinity mostly depends on runoff and is not affected by reductions in groundwater discharge. The ESCP modelling shows negligible watertable decline near the Donnelly River for each of the scenarios, implying that groundwater discharge to this river will not significantly reduce. However, the model's calibration in this area is poor and hence the estimated decline should be interpreted with some caution.

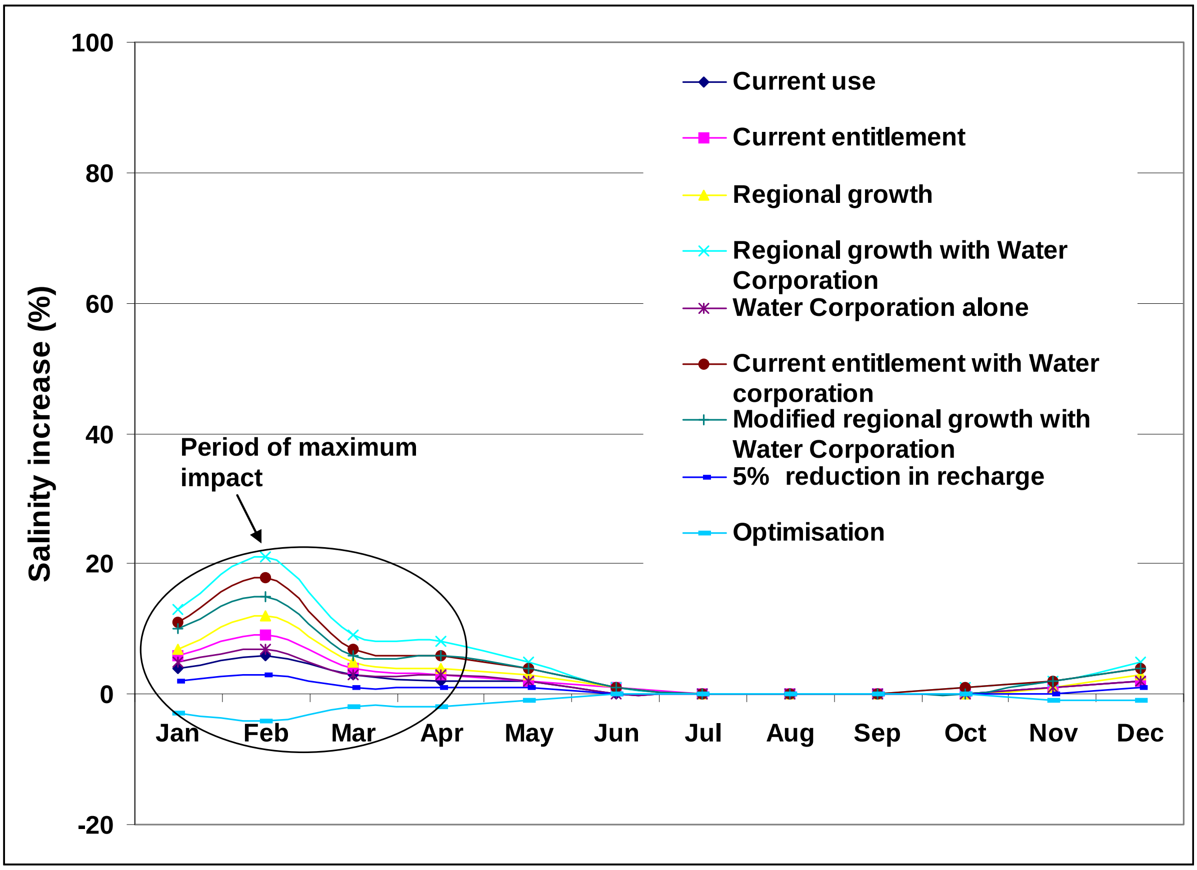

Figure S2: Predicted salinity change in the Blackwood River

Modelling shows that abstraction will cause watertable decline at potential acid sulfate soil (PASS) sites on both the Swan and Scott coastal plains. The sites on the Swan Coastal Plain are more at risk from localised abstraction. On the Scott Coastal Plain the predicted declines appear to be mostly within the preliminary EWR levels. The Water Corporation's abstraction is predicted to have a low-level impact on the Scott Coastal Plain, whereas on the Swan Coastal Plain, the drawdown from the Water Corporation's proposed abstraction is more significant (although this could be partly because the SWAMS model is overestimating drawdown).

The SWAMS model has been used to derive the water balances of the southern Perth Basin and the Yarragadee aquifer in particular. Figure S3 illustrates the relative changes in the aquifer water-balance components in response to different abstraction scenarios. Increases in abstraction cause changes to the ocean outflow and discharge to rivers, as well as depletion in storage. The increase in abstraction induces additional leakage from the overlying aquifers.

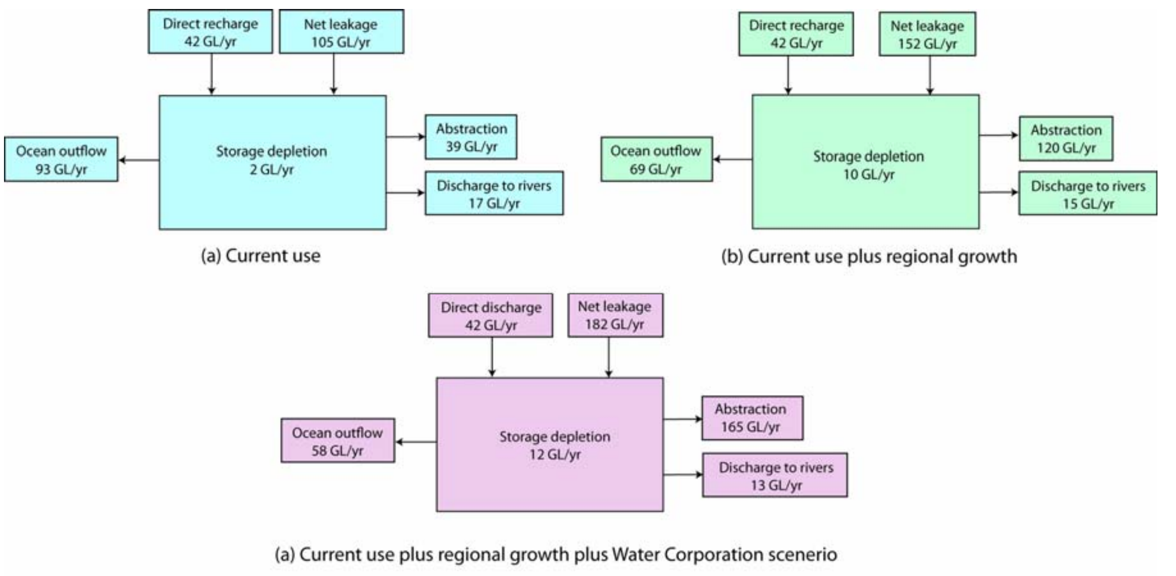

Figure S3: Yarragadee aquifer water balances for selected scenarios

The ESCP and SWAMS modelling results will help the Department of Water to balance the environmental, social and economic values of the resource and set the allocation limit for the southern Perth Basin's groundwater system. The allocation limit will be defined in the *South West groundwater areas water management plan.*

1 Introduction

1.1 Background

As part of its strategy for managing Western Australia's water resources, the Department of Water is developing the *South West groundwater areas water management plan* to enable equitable allocation of the region's groundwater. The South West groundwater areas include the Blackwood, Bunbury and Busselton-Capel groundwater areas (see figures 1 and 2).

The state's South West region contains large resources of fresh groundwater that are being tapped for domestic, irrigation, industrial and public water-supply use in the region. The groundwater is contained mainly within the Superficial, Leederville and Yarragadee aquifers of the southern Perth Basin. The surface geology and a representative geological cross-section are shown in figures 3 and 4 respectively. The geology and hydrogeology of the southern Perth Basin have been discussed in detail in Baddock (2005) and will not be repeated in this report.

Between 2003–06, the Department of Water and the Water Corporation conducted joint hydrogeological investigations to assess the feasibility of abstracting an additional 45 GL/yr of groundwater from the South West Yarragadee aquifer for public water supply. The investigations comprised large-scale drilling, geophysical and hydrogeochemical explorations and resulted in a significantly improved understanding of the hydrogeology of the southern Perth Basin. As a result, two numerical groundwater-flow models were developed, incorporating all significant aquifers of the southern Perth Basin, including the South West Yarragadee.

The South West Aquifer Modelling System (SWAMS) is a regional groundwater model consisting of a database with abstraction, monitoring and environmental data, a MODFLOW 2000 saturated-flow model, pre- and post-processors, and a GIS database. The construction and validation of the SWAMS database required considerable time and resources. There have been two major versions of the SWAMS model: SWAMS v1.2.1 and SWAMS v2. SWAMS v1.2.1 was completed in January 2004 (CyMod 2004) as a calibrated transient model and was reviewed by an independent panel of peer reviewers. The peer review concluded that although the model adequately represented groundwater flows in the Yarragadee aquifer, additional refinement of the model and further model calibration was warranted: firstly, to better define the impacts of abstraction, and secondly, to be a more effective management tool for the allocation of groundwater. The review panel considered that the model was not suitable for simulating flow within and between the Leederville and Superficial formations, and might not accurately represent groundwater flows in the Yarragadee Formation. As a result, it was considered that uncertainties would be associated with the model's predictions (ERM 2004).

Accordingly, additional hydrogeological investigations were carried out and corresponding modifications to the model were made, resulting in an enhanced model version (SWAMS v2) that was completed in July 2005 (Sun 2005). A subsequent peer review (by the same panel) concluded that SWAMS v2 was a considerable improvement on SWAMS v1.2.1, and had been developed to a stage where it could be used with some degree of confidence to evaluate the risks associated with growth in regional groundwater demand and alternative Water Corporation borefield scenarios. The panel recommended the model be used as a risk management tool whereby potential impacts were predicted, the consequent risks evaluated and, where risks were considered untenable, either alternative scenarios were developed or risk monitoring and management procedures were put in place (ERM 2005).

In 2005–06, a local-scale groundwater-flow model was developed specifically for the area of the eastern Scott Coastal Plain that has unique hydrodynamics with respect to surface water and groundwater interactions, as well as a number of groundwater-dependent ecosystems (GDEs) including Lake Jasper. The Eastern Scott Coastal Plain (ESCP) model can simulate both surface water and groundwater flow (and exchange) and was developed using the MODHMS package (HydroGeoLogic Inc.) by Aquaterra as consultants to the Department of Water (Aquaterra 2006). The Swan Coastal Plain in the north of the study area is believed to have similar hydrodynamics and thus the development of a model similar to ESCP is warranted.

An independent review of the ESCP model (CyMod 2006) concluded that it was a ‘significant advance’ with respect to the modelling of some aspects of the eastern Scott Coastal Plain. However, the reviewer commented that the model had not been validated or evaluated for uncertainty. MDBC (2000) noted that for complex models, uncertainty analysis was difficult due to ‘excessive computational demands and scarcity of specialist knowledge and software’. When used in a relative manner, model scenarios can reduce the uncertainties in aquifer properties on simulated groundwater decline over the long term.

Both the SWAMS v2 and the ESCP models have been used to simulate water-level changes in the study area resulting from different abstraction and climate scenarios, as well as the impacts on several identified sites of ecological and social value. The results are presented in this report and will form an integral part of the planning process to support the development of *South West groundwater areas water management plan*. Providing information to assess the Water Corporation’s proposed abstraction of 45 GL/yr was a significant consideration when developing the abstraction scenarios to be tested with the SWAMS v2 and the ESCP models. Consequently the results will be presented in this report.

1.2 SWAMS v2 model overview

The SWAMS model was developed to:

- provide a management tool for the ongoing assessment of licences and water use in the South West groundwater areas
- simulate groundwater flow within and between all hydrogeological units in the southern Perth Basin within the active groundwater-flow system
- establish a water budget for the Yarragadee aquifer
- provide first estimates of water budgets for other aquifers
- predict the scale of changes in groundwater potentiometric heads/water levels within the hydrogeologic units under a range of scenarios, including the proposed Water Corporation abstraction of 45 GL/yr
- evaluate likely changes in groundwater discharge to rivers (including the Blackwood River), streams, wetlands and the ocean.
- predict the general decline in water levels near other groundwater users, wetlands, rivers and streams in the project area, and provide seasonal variations in such reductions
- provide results that will support the determination of allocation limits based on impacts on identified groundwater-dependent ecosystems (GDEs).
- estimate the likely range and uncertainty of water-level changes in areas affected by large-scale abstraction to enable assessment of the risk of water-level changes that may impact on GDEs.
- identify the groundwater capture area for the previously proposed Water Corporation scheme that will enable the determination of public drinking water source protection areas
- allow an evaluation of the increased risk of seawater intrusion resulting from the previously proposed 45 GL/yr of groundwater abstraction.

The location of the SWAMS model area is shown in Figure 5 The active model domain extends approximately 190 km in the north-south direction and 70 km in the east-west direction, covering an active area of about 8500 km^2, of which 6000 km^2 is onshore. The finite-difference grid consists of 363 rows and 193 columns. The grid is variable, ranging in size from 250 m x 250 m to 1000 m x 1000 m. This provides sufficient resolution for a broad representation of the rivers, lakes and wetlands.

Vertically, the model has eight layers, which typically represent the major geological formations or aquifers making up the southern Perth Basin. Figure 6 shows the schematic numerical model representation of the conceptual hydrogeology of the southern Perth Basin.

A generalised description of the hydrogeology of the SWAMS model layers is given in Table 1 (Sun 2005).

Table 1: Generalised description of the hydrogeology of the SWAMS model layers (Sun 2005)

Layer	Hydrogeological unit	Description
1	Coastal plain superficial sediments Blackwood Plateau surface sediments	Coastal plain: minor aquifer associated with Bassendean Sand, Tamala Limestone and Safety Bay Sand, with aquitard units within the Guildford Formation. Blackwood Plateau: sediments to 30 m depth below surface, decreasing to 10 m in main streams and rivers, and comprising aquifer and aquitard units of Leederville Formation members, and the Yarragadee Formation in outcrop areas.
2	Mowen aquitard	Aquitard with minor aquifer units within the Quindalup and Mowen members of the Leederville Formation.
3	Leederville aquifer	Minor to major aquifer with some aquitard units in the Vasse Member of the Leederville Formation.
4	Parmelia aquitard	Aquitards of the Bunbury Basalt and Parmelia Formation shale member.
5	Yarragadee unit 1 aquifer	Minor to major aquifer with aquitard units within the Yarragadee Formation unit 1.
6	Yarragadee unit 2 aquifer	Major aquifer within the Yarragadee Formation unit 2
7	Yarragadee unit 3 aquifer	Major aquifer within the Yarragadee Formation unit 3 – regionally dominant aquifer.
8	Cockleshell Gully/Lesueur Sandstone aquifer	Major aquifer within the Cockleshell Gully Formation and Lesueur Sandstone containing fresh groundwater; CGF has some aquitard units.

Boundary conditions

The southern Perth Basin is bounded on the east and west by major faults. These faults do not permit groundwater flow into or out of the model area from the east or west. No-flow boundary conditions are assigned in all layers on the western and eastern model boundaries. The vertical extent of the model is defined as the depth at which groundwater salinity exceeds 1000 mg/L TDS (not including the localised areas of higher salinity in the Superficial aquifer). The model surface at this depth is assigned as a no-flow surface.

In the Superficial aquifer, occurring only on the Swan Coastal Plain and the Scott Coastal Plain, the northern and southern boundaries are the ocean, which is modelled as a constant head coincident with the shoreline. Aquifers below the Superficial aquifer extend offshore and discharge upwards into the ocean. The boundary conditions offshore consist of constant heads covering the submerged areas of layer 2, and the aquifer limits offshore for layers 3 to 8. Environmental heads (those greater than 0 m AHD) were specified in all the offshore parts of the model domain using the Ghyben-Herzberg principle, whereby a 2.5 m constant head value is defined for every 100 m depth of sea water. Environmental heads in the north and south of the model domain are generally within 0.8 and 1.8 m of sea level respectively.

Drainage

All major drainage features (rivers) within the model domain were modelled in SWAMS v2 to incorporate any groundwater discharge to the river systems. These include the Margaret, Blackwood, Scott and Donnelly rivers, St Johns and Barlee brooks on the Blackwood Plateau and the Scott Coastal Plain. All the rivers on the Swan Coastal Plain in the northern part of the region were included in the model.

Recharge and evapotranspiration

The recharge distribution over the model domain was determined using two independent processes, WEC-C and WAVES, based on land use as characterised by leaf-area index. The basic inputs to the two processes were land-use distribution and surface geology (used to infer soil type). Land use includes natural vegetation, farming, pine plantations and urbanisation, and was determined from remote sensing data. The WEC-C used a vegetation model that estimated the excess water requirements from which net recharge was inferred. The second process used the WAVES unsaturated/saturated flow model to also estimate excess water requirements from which net recharge was inferred for various land use and soil types (Baddock 2005). These results formed the basis for generating an initial rainfall recharge distribution, which was subsequently refined during model calibration.

In some areas of the Swan and Scott coastal plains, groundwater discharges through evapotranspiration (EVT). Therefore, on the coastal plains an EVT function was applied to allow for groundwater discharge from roots and direct evaporation in areas of shallow watertable. EVT depends on the watertable's depth from the surface and is applied in the model using the EVT package in MODFLOW.

Faults

Based on a review of piezometric heads, geology and carbon-14 data, a number of major faults were identified as being hydrogeologically significant and therefore included in the model. Figure 5 shows the location of the faults modelled. The Darling fault forms the eastern boundary of the model domain and is impermeable. The Dunsborough fault forms part of the western boundary of the model and is also impermeable. Generally, the conceptual hydrogeological understanding suggests that the faults are relatively impermeable and are groundwater-flow barriers. The faults within the model domain – the Busselton, Darradup and some other minor faults – are thus modelled as horizontal flow barriers (HFB) for the affected layers of the model (those below the Leederville aquifer). This was done using the HFB package in MODFLOW. The upper layers post-date the faulting and hence are unaffected by the faults.

Abstraction

Groundwater in the SWAMS model area is abstracted from both the Superficial and confined aquifers (the Leederville, Yarragadee and Lesueur). Groundwater abstraction in the region falls into two major categories:

1. Measured abstraction, which includes Water Corporation and Busselton/Bunbury water-board abstractions (public licensed abstraction) and other large users such as mining companies.
2. Abstraction by private users, which is not generally metered or measured.

During the model calibration period these abstractions were quantified both spatially and temporally on a monthly basis. The Water Corporation, private utilities and mining companies typically measure and report abstraction on a monthly basis (as volumes) for their operating bores.

A survey of historical abstraction by unmetered users has been useful to approximate actual use. In general, it is estimated that 80 per cent of the annual licensed allocation is actually abstracted by the users in this category. This estimate is based on regional knowledge and past compliance reporting of actual use. After seasonality factors are estimated for each user group, the annual abstraction is scaled on a monthly basis to account for seasonal water use (Figure 7).

Unlicensed abstraction, which is permitted from bores that abstract groundwater of less than 1500 kilolitres per year (kL/yr), is mainly from the Superficial aquifer. Because this usage is considered to have negligible effects in the model area, it is ignored.

Calibration

Models are calibrated to minimise error. Calibration involves comparing modelled and measured data over a selected period to allow aquifer parameters to be adjusted. The residual error between measured and simulated heads indicates the accuracy of calibration. The SWAMS v2 model was calibrated in steady state and under transient conditions. The transient model was calibrated from 1990 to 2003 using historical groundwater data. The average absolute errors in the Superficial, Leederville and Yarragadee aquifers and the Mowen aquitard on the Blackwood Plateau are 0.8, 3.6, 3.2 and 5.6 metres respectively.

Overall, the calibration error is believed to be close to what can be achieved under existing hydrogeological interpretation and boundary conditions for a regional-scale model. Confidence in the model calibration is enhanced by comparing the modelled ages of flow paths and patterns (isochrones) with the observed groundwater ages from the carbon-14 data. The calibration statistics show that the current model is a reasonable and valid representation of the southern Perth Basin aquifer system.

Calibrated model parameters

The horizontal hydraulic conductivity (k_h), vertical hydraulic conductivity (k_v) and storage coefficients for each model layer, recharge, and drain conductance were adjusted as part of the model calibrations. A summary of the calibrated aquifer parameters is given in Table 2.

Table 2: Calibrated aquifer parameters (Sun 2005)

Superficial aquifer (layer 1)		
Parameter	**Calibration**	**Comments**
Hydraulic conductivity (m/d)	0.001 – 20	
Specific yield (-)	0.1 – 0.2	
Specific storage (1/m)	0.005	
Vertical hydraulic conductivity (m/d)	1 x 10-5 – 0.5	Includes Bunbury Basalt
Leederville aquifer (layers 2–4)		
Parameter	**Calibration**	**Comments**
Hydraulic conductivity (m/d)	0.0001 – 23	
Specific yield (-)	0.05 – 0.2	Not including Bunbury Basalt
Specific storage (1/m)	1 x 10-7– 1 x 10-5	
Vertical hydraulic conductivity (m/d)	1 x 10-5 – 0.2	Includes Bunbury Basalt
Yarragadee aquifer (layers 5–8)		
Parameter	**Calibration**	**Comments**
Hydraulic conductivity (m/d)	0.1 – 30	
Specific yield (-)	0.05 – 0.2	
Specific storage (1/m)	1 x 10-7– 5 x 10-6	
Vertical hydraulic conductivity (m/d)	10-5 – 0.07	

1.3 Eastern Scott Coastal Plain model

Aquaterra (2006) developed the Eastern Scott Coastal Plain (ESCP) model using a 'cut-out' portion of the SWAMS v2 regional groundwater model. The ESCP model was then refined to achieve a more detailed and accurate simulation of local-scale groundwater flow and integrated surface-water flow. The purpose of the ESCP local-scale modelling is to provide an advanced tool to predict water-level changes due to abstraction and rainfall variability. However, the emphasis of the model is to simulate water levels in Lake Jasper and groundwater interactions with Lake Jasper. The primary objectives of the modelling are:

- under a range of abstraction and climate scenarios, predict the changes in groundwater potentiometric heads/water levels within the hydrogeological units and corresponding changes in the lake levels
- evaluate likely changes in groundwater discharge to rivers, streams and wetlands, as well as ocean environments
- predict the general decline in water levels near other groundwater users, wetlands, rivers and streams in the project area, and provide seasonal variations in such reductions
- use these results to support the determination of sustainable yields based on impacts on identified groundwater-dependent ecosystems (GDEs)
- estimate the likely range and uncertainty of water-level changes in areas affected by large-scale abstraction to enable assessment of the risk of water-level changes that may impact on GDEs.

Accordingly, the model has been constructed so that groundwater flow, overland flow, and wetland and lake water-levels can be simulated. The level of model complexity is 'complex' as defined by the *Groundwater flow modelling guideline* (MDBC 2000), notably because it is able to predict the response of the integrated surface-water and groundwater systems.

The ESCP model incorporates the following hydrological processes:

- rainfall recharge including irrigation recharge
- induced recharge and evapotranspiration
- groundwater exchange with rivers and ocean
- groundwater abstraction
- groundwater and surface-water interactions at Lake Jasper and other significant lakes, creeks and wetlands.

The MODHMS package was selected for the ESCP model because it can be used to simulate the groundwater and surface-water interactions. MODHMS (HydroGeoLogic Inc.) is a MODFLOW-based code for fully integrated groundwater/surface-water modelling (Aquaterra 2006).

Model domain and grid

The model domain includes an area of the eastern Scott Coastal Plain between the Scott River (about 30 km north-west of Lake Jasper) and the Donnelly River (about 7 km south and east of Lake Jasper). The model domain is 46 km west-to-east and 42 km north-to-south (Figure 8). The model grid has 94 rows and 158 columns. The grid shape is the same as the original SWAMS v2 model from which it was excised, and cell sides are 250 to 1000 m in length. The finer cells are located over the wetland areas.

Layering and parameterisation

The model has eight layers similar to SWAMS v2; however, the ground elevations were refined, the hydraulic conductivity zones were altered and other changes were made to improve the model's calibration. The significance of each model layer is provided, as follows:

- OLF layer: a topographic layer for simulating overland flow over the sandy plain and true-to-surface elevations.
- Layer 1: an unconfined surficial/superficial layer, including Lake Jasper, with zonation based on shallow hydrogeology and an upper elevation coincident with the OLF layer.
- Layer 2: Mowen aquitard or a 20 m thick slice of the surface geology or sub-crop geology.
- Layer 3: Leederville aquifer with 20 m minimum thickness or a 20 m thick slice of the underlying formation where the Leederville is absent.
- Layer 4: Parmelia aquitard with a 20 m minimum thickness or 20 m thick slice of the underlying formation and Bunbury Basalt.
- Layer 5: Yarragadee aquifer 'Unit 1' with a 30 m minimum thickness.
- Layer 6: Yarragadee aquifer 'Unit 2' with a 30 m minimum thickness or 30 m thick slice of the underlying formation.
- Layer 7: Yarragadee aquifer 'Units 3 & 4' with a basal elevation coincident with the actual base of the Yarragadee or 100 m thick slice of the underlying formation.
- Layer 8: The lowest active portion of the Yarragadee aquifer and Cockleshell Gully Formation within the Bunbury Trough.

Hydraulic properties

The hydraulic conductivity (K_h and K_v) values in the ESCP model were refined and new zones were introduced to improve model calibration and to simulate the open water within Lake Jasper. The specific yield (Sy) in layer 1 of the new model has been increased to 0.3 in the sandy areas. Outside this area, the Sy is the same as in SWAMS v2. The Sy of deeper layers are identical to that of SWAMS. The storage coefficients (SC) in the local model are of a similar order of magnitude to those in SWAMS v2.

Overland flow domain

Runoff from the Blackwood Plateau was estimated and applied as a boundary condition in the OLF (overland flow) package. Other surface-flow boundaries, called 'critical depth boundaries', were assigned to the major streams at low elevations (near the Donnelly and Scott rivers) to capture and remove surface runoff. The unsaturated zone was modelled using the pseudo soil option to simulate the seasonal wetting and drying of cells near the watertable.

Lake Jasper and other wetlands

Lake Jasper was simulated in two zones: a zone of permanent deep water using the MODFLOW basic package, and a zone of possible shallow water using the OLF package. The wetlands were simulated as areas of shallow and exposed watertable consistent with vegetation zonation and topography. Where/when the (simulated) watertable rises above the ground surface, then the (simulated) overland flow moves downhill (via the OLF package) and towards surface-drainage features (towards drain cells and into critical depth cells), and vertically into the aquifer (if unsaturated) or may be lost as evapotranspiration (via the EVT package). If the topography prevents runoff, then the MODHMS represents the area as a wetland or lake.

Drains

Drain cells are applied where there are rivers and visible gullies. The drainage network around the Scott River is modelled with drain elevations incised 4 m below the ground. It is conceptually understood that the gullies play a role in draining the watertable.

Boundaries

Lateral flow boundaries were placed in the model along fault lines, as was done in SWAMS v2. Constant head cells were placed at the sea floor with a head of 0 m or mean sea level. Constant heads are identical to those of SWAMS v2. Abstraction wells were placed at various locations in the model aquifer, just as they were for SWAMS v2.

Model calibration

The ESCP model was calibrated using a quasi-steady state and transient conditions against the average-recorded water levels observed in bores and in Lake Jasper. Calibration emphasis was on Lake Jasper’s water levels and the surrounding shallow groundwater levels, and the deeper groundwater levels of the Yarragadee aquifer near/under the wetlands. A root mean square (RMS) error of 2.75 m was achieved from the quasi-steady state calibration. The model calibration was subsequently refined under transient conditions. An RMS error of 2.43 m was achieved as a result. Close to Lake Jasper an RMS error of 0.25 m was achieved. The similarity of the simulated and measured watertable contours provides evidence of the model’s calibration. The extent of surface water simulated in the model corresponds well with that shown in the aerial photographs for Lake Quitjup and Lake Jasper.

1.4 Assumptions and limitations in the models

- SWAMS v2 has been developed using the MODFLOW package (which is a simplified representation of the complex geology) and hydrodynamics that focus on groundwater-flow processes. Its use is highly restricted in areas where groundwater and surface-water interactions are significant. This is especially the case on the coastal plains. This problem has been rectified for the Scott Coastal Plain by developing the ESCP local-scale model. The ESCP model has shown that surface runoff plays an important role in the water balance of the Superficial aquifer. Similarly, on the Swan coastal plain, the surface water will have an influence on the groundwater regime; however, this has not been modelled. Recent recharge estimates on the Swan Coastal Plain by Mauger (2007) have shown that recharge in this area in SWAMS could be significantly underestimated. The results of simulation by SWAMS v2 in this area will therefore need to be interpreted in this context.
- SWAMS v2 can only model saturated continuous flow. In areas of perched watertable, the model results are less representative.
- SWAMS-model uncertainties may also come from the complexity of the hydrogeology, the boundary conditions and the large spatial scale for a regional model.
- The domain of the ESCP model was cropped from SWAMS v2 and consequently the time-variant specified heads at the northern and eastern boundaries of the model are wholly dependent on SWAMS v2 and the inaccuracies therein.

- The ESCP model is not capable of simulating water levels and flows in the Donnelly and Scott rivers. This would require a catchment-runoff and river-flow simulator, which is beyond the scope of the current project.
- The ESCP model can simulate and predict seasonal water levels in the wetlands and in Lake Jasper; however, predictive certainty will tend to decrease with distances away from observation bores.
- In relation to groundwater decline in Lake Jasper and nearby wetlands, the predictive uncertainty of the ESCP model has not been assessed. A reliable assessment may require abstraction test data (or other analogue data) collected over a suitable timeframe.
- The actual rooting depths of various vegetation species under various climatic conditions have not been recorded, although they are based on research findings of Banksia woodland on the Swan Coastal Plain. The evapotranspiration is based on approximate rooting depths and climate data; hence the evapotranspiration submodel used for the ESCP model may be less reliable under climatic conditions significantly wetter or drier than previously experienced.
- Neither the SWAMS nor ESCP models can simulate saltwater interface and its onshore movement due to abstraction. Separate model(s) capable of simulating density coupled with groundwater flow should be developed to study the effects on the saltwater interface.

Calibration, sensitivity, uncertainty analyses and prediction are always imperfect in groundwater-modelling studies. As a result, engineering and environmental assessments should give a ‘balanced’ weighting to quantitative and qualitative sources of information and should not rely exclusively on the results of a single groundwater model (Aquaterra 2006).

2 Groundwater-use constraints

2.1 Ecological water requirements

Part of the allocation planning process is to identify the groundwater-dependent ecosystems (GDEs) in the study area. The water requirements to maintain those ecosystems at a low level of risk are then determined. The water requirements for wetlands and terrestrial vegetation are described in terms of the maximum watertable decline (metres) and the maximum rate of groundwater decline. This represents the ecological water requirement (EWR) for the most sensitive species at the site. If the water depth meets this requirement, all the vegetation species at the location will be maintained.

The identified potential GDEs within the study area are the:

- flora and vegetation of the Blackwood River, Barlee Brook and Donnelly River
- riverine pools of the Blackwood River, Barlee Brook and Donnelly River
- flora and vegetation of tributaries of the Blackwood River; for example, Reedia wetlands
- Swan and Scott coastal plain wetlands
- flora and vegetation in depressions on the Blackwood Plateau (including the Margaret River wetlands)
- flora and vegetation at the interface between the Blackwood Plateau and the Scott Coastal Plain.

A map of potential GDEs (Figure 9) was compiled using existing wetland mapping and river mapping (incorporating a 300 m buffer to account for riparian or floodplain areas). Areas of coastal limestone that could potentially contain cave-water ecosystems were mapped; however, these were outside the model domain area (Hyde 2006).

The Department of Water then reviewed aerial photography, reports on ecological values and maps with the aim of selecting representative sites where environmental water provisions (EWPs) might eventually be set. The objective was to select sites that:

- had high ecological value
- were representative of wetland groups or suites (if applicable) or of local/regional vegetation communities
- gave adequate geographical coverage of the study area and ecosystem types
- represented areas that were likely to be at risk of impacts due to groundwater abstraction, but also included areas that were less likely to be influenced by absraction and might be considered as future ‘reference’ or ‘control’ sites.

Selection of reference GDE sites was focused on areas within the model domain where the potential impact of future allocation scenarios could be tested. The selection process identified 86 preliminary representative sites for wetland and terrestrial vegetation. Figure 10 shows the location of these sites. Summary information about each of the sites is given in Appendix I.

2.2 Social water requirements

Social water requirements (SWRs) are identified to meet social and cultural values. In the study area, the social values include recreation and tourism pursuits, Aboriginal culture and heritage, Australian heritage, landscape and aesthetic values, as well as educational and scientific opportunities (Goodreid 2007).

Unlike EWRs, SWRs were not specified quantitatively or empirically in terms of specific water levels or flows. Instead, for the purpose of this study, SWRs were set using the corresponding EWR criteria at the same site. This process has been adopted to determine SWRs for many of the social values identified at key recreational sites in the area. For example, the SWR to support the social value of swimming and wading at Sues Bridge in summer would be supported by the EWRs related to summer water quality and flow in the Blackwood River. Hence, the ecological and the social water requirements are the same. This is not surprising given the affinity that visitors and residents have for the ecology, nature/wilderness and scenic views in the area (CALM 2005).

2.3 Acid sulfate soils

Acid sulfate soils (ASS) are naturally occurring soils and sediments containing sulfide minerals, predominantly pyrite (an iron sulfide). In an undisturbed state below the watertable, these soils are benign and are known as potential acid sulfate soils (PASS). However, when these soils are drained, excavated, or the watertable is lowered, the sulfides may react with oxygen to form sulfuric acid. Other complex secondary reactions can also occur, including mobilisation of heavy metals. When PASS have been disturbed and there is evidence of oxidation, the soils are referred to as actual acid sulfate soils (AASS) (Degens & Wallace-Bell 2009). On the Scott and Swan coastal plains, a survey of ASS materials in the shallow formations was undertaken to broadly identify the likely spatial extent of this geochemical hazard, as well as the characteristics of the materials that define the nature of the hazard.

On the Swan and Scott coastal plains a respective total of 52 and 56 sites were sampled as a series of broad transects across the plains (figures 11 and 12). This work contributed to the development of ASS risk maps in these areas. Summary information about each of the sites is given in Appendices II and III (unpublished Department of Water data).

At sites where PASS materials were found, the depth was recorded along with the watertable depth during the summer minimum. This data was used to calculate the resulting watertable in relation to the PASS-material depth from the modelling of the various groundwater-allocation scenarios. Where the modelled watertable dropped to 25 cm or greater below the PASS material, a ‘severe’ risk was assigned. Risk in this instance refers to the risk of sulfide oxidation and the subsequent generation of sulfuric acid. Where the watertable dropped to between the uppermost level of the PASS material and 25 cm below this level, a ‘high’ risk was assigned. Where the watertable occurred near the top of the PASS or up to 50 cm above the layer, a ‘moderate’ risk was assigned; and finally, where the watertable was greater than 50 cm above the PASS layer, a ‘low’ risk was assigned.

2.4 Impact on other bore users

Abstracting groundwater involves abstraction from bores, which leads to a lowering of the potentiometric heads around the bore. The cone of depression of an individual bore can interfere with neighbouring bores, causing a cumulative drawdown effect. The effect decreases with distance between the bores. In an unconfined aquifer, a drawdown cone may not be sufficiently large to have any detrimental impact on other bores; while in a confined aquifer, measurable drawdown may be propagated to large distances. The modelling results were used to assess the potential drawdown from the Water Corporation’s proposed abstraction on other users’ bores completed in the Yarragadee aquifer.

3 Modelling scenarios

3.1 Description of scenarios

The scenarios for predictive modelling are based on a range of possible future abstraction options in the South West. The simulated groundwater declines are presented as relative changes in groundwater levels between each scenario and the base-case scenario. This enables the relative comparison of the model outputs from the different abstraction rates to that of the adopted base-case abstraction. Using both the SWAMS and ESCP models, five main allocation scenarios (A–E) have been modelled for comparison with the base case.

All scenarios have been modelled for a 30-year period representing the normal planning timeframe. As both the SWAMS and ESCP models have been calibrated to 2003, the year 2004 has been used a starting year for all forward-predictive simulations.

Current-use (base-case) scenario

The current-use scenario representing 30 years' abstraction (from 2004 to 2033) at 64 GL/yr – based on actual abstraction from all aquifers in 2004 – was adopted as the base case. The modelling results are more accurate when used in relative terms with the base case instead of an absolute value of the water level. This is due to filtering of errors in calibration and uncertainty in model starting heads (initial conditions). This comparative approach reduces the uncertainties in modelling, particularly relating to the aquifers' hydraulic properties. It makes the simulated watertable decline more sensitive to water-balance components such as recharge and abstraction. Such an approach allows prediction of a net effect of abstraction, provided recharge is the same in the two scenarios or allows the effect of reduced recharge due to climate change to be predicted (by keeping the same abstraction).

Adoption of the current-use scenario as the base case is justified because this scenario predicts very low values of drawdown in the Yarragadee aquifer over 30 years and the resulting impacts on the watertable are negligible. Also, as most ecological water requirements (EWRs) for the groundwater-dependent ecosystems (GDEs) are being met in the region currently, it may be appropriate to consider the current-use-scenario water levels as a base case to assess drawdown from any increased abstraction, so that impacts on GDEs may be assessed in turn. A recent study by Commander and Palandri (2007, in draft) found that the water levels in the Superficial aquifer on both the Scott and Swan coastal plains were stable or slightly declining in spite of localised water-level declines in the underlying Yarragadee aquifer, reflecting little impact at the watertable and thus justifying the current-use scenario's suitability as a base case for predicting watertable declines in other scenarios. However, there are some areas such as Quindalup (near bore BN14) where large-scale abstraction from the Leederville aquifer has caused localised drawdown of up to 2 m at the watertable. While there are a few areas such as these where the summer watertable has been declining, the water levels would be expected to stabilise if the water use remained at the current level. Such declines in groundwater levels from current-use abstraction, however, will need to be factored into the predicted drawdown for other scenarios. Figure 13 from Commander and Palandri (2007, in draft) provides a spatial distribution of the trends in watertable declines from past use.

Current entitlements — scenario A

For scenario A, existing entitlements totalling 112 GL/yr from all aquifers (as at October 2004) are assumed to be fully used each year for the entire 30-year period. For some users, current levels of use are well below their entitlements. This scenario does not include any projected regional demand that is not currently part of an existing entitlement. In this scenario, it is assumed that Perth's additional water needs (45 GL/yr) are met through another source such as desalination of sea water. Figures 14 to 16 show the location of the bores operating under current entitlements.

Meeting the ecological water requirements (optimisation) — scenario B

In scenario B, meeting the EWRs for GDEs is given the highest priority in water allocation planning. It is assumed that all entitlements and projected regional need would not be met while achieving all EWRs. In order to meet EWRs, the modelling optimises groundwater abstraction regionally such that the EWRs are met. To achieve this, abstraction has been redistributed over several groundwater subareas (see Figure 17 for their locations). The abstraction was optimised in each subarea iteratively using a MODFLOW parameter estimation code (PEST) until a maximum value of groundwater abstraction for a given water-level-decline criteria at each GDE site was obtained.

Regional growth — scenario C

Securing our water future – A state water strategy for Western Australia (Government of Western Australia 2003) states that for new water-source-development projects involving inter-regional transfers, 'all reasonable regional needs including social, recreational and projected future development will be satisfied before transfers can take place'. The regional growth in demand is based on a study by Economic Consulting Services (ECS 2003). In this scenario, highest priority is given to meeting the future water needs of the region that is expected to rise by 95 GL/yr in 30 years' time. The total maximum abstraction in this scenario is 159 GL/yr including the current use of 64 GL/yr. The spatial distribution of abstraction points for this scenario is based on land use and accessibility of suitable aquifers. Figure 18 shows the location of selected sites for regional-growth bores. For the purpose of modelling, the growth was assumed to increase linearly over 30 years. This scenario assumes that Perth's water needs (an additional 45 GL/yr) are met through another source such as desalination.

Regional growth and Water Corporation proposal — scenario D

This scenario is based on the Water Corporation's South West Yarragadee proposal to obtain an additional 45 GL/yr for the integrated water supply scheme, in addition to the total projected future regional need of 159 GL/yr by 2033. The total abstraction thus modelled in this scenario is 109 GL/yr, increasing to 204 GL/yr by the end of the 30-year period. The Water Corporation's proposed borefield is located in the Jarrahwood groundwater area, as shown in Figure 19. The proposal comprises eight production bores at four sites. It is proposed to split the abstraction such that 22.5 GL/yr is from Yarragadee Unit 1 and the rest is from the Yarragadee Unit 3. The Water Corporation has selected this configuration to minimise the impacts of abstraction.

Reduced regional growth and Water Corporation proposal — scenario E

It is possible that environmental impacts from scenarios C and D may be unacceptable; hence, under Scenario E, the Water Corporation's abstraction is reduced from 45 GL/yr to 25 GL/yr and the future regional growth is likewise capped at 58 GL/yr (approximately equal to the total groundwater entitlements as at July 2005). Under this scenario, regional demand would be met as it grows from the current use of 64 GL/yr to 122 GL/yr. The total abstraction simulated in the model increases from 89 GL/yr to 147 GL/yr in 30 years. Table 3 shows a summary of the scenarios and the corresponding abstraction volumes.

Other inferred modelling results

Results from the main scenarios have been used to infer impacts of the Water Corporation proposal alone, and then the Water Corporation proposal together with the current entitlements – without running the model separately.

Water Corporation proposal (45 GL/yr)

The difference in groundwater levels and flows between the scenarios C and D has been calculated to assess the relative effect of the proposed Water Corporation abstraction at 45 GL/yr only.

Current entitlements plus Water Corporation proposal (157 GL/yr)

Water-level response to an abstraction scenario at current entitlements (112 GL/yr as at October 2004) and the Water Corporation's proposed abstraction (45 GL/yr) was assessed using results from scenario A, with the additional drawdown from the Water Corporation's proposal derived from the difference between scenarios C and D. This scenario assumes that abstraction will take place at the current rate of entitlement together with the Water Corporation's 45 GL/yr for the entire 30 years; while in reality the abstraction will progressively increase from the current use of approximately 64 GL/yr to 112 GL/yr over 10–15 years (as per growth in regional needs).

Table 3: Summary of abstraction for each scenario

Abstraction Scenario	Total abstraction (GL/yr)	Groundwater area	Predicted maximum abstraction rates				% of total
			Superficial (GL/yr)	Leederville (GL/yr)	Yarragadee (GL/yr)	GWA Totals (GL/yr)	
Base case: current use (Oct 2004)	64	Blackwood	0.3	0.2	7.1	7.6	12%
		Bunbury	2.0	5.8	14.9	22.7	36%
		Buss-Capel	5.0	11.1	17.4	33.5	53%
Scenario A: current entitlement (Oct 2004)	112	Blackwood	0.5	0.5	10.0	11.0	10%
		Bunbury	2.9	8.6	21.5	33.0	29%
		Buss-Capel	6.1	15.7	46.3	68.1	61%
Scenario B: optimisation	90 (optimised)	Blackwood	0.5	2.3	7.0	9.8	11%
		Bunbury	2.6	12.0	9.2	23.8	26%
		Buss-Capel	8.2	22.3	26.0	56.5	63%
Scenario C: current use + regional growth	64 to 159 (increasing over 30 years)	Blackwood	0.3	0.7	30.0	31.0	20%
		Bunbury	2.0	6.8	22.9	31.7	20%
		Buss-Capel	5.0	21.7	69.2	95.9	60%
Scenario D: current use + regional growth + WC	109 to 204 (increasing over 30 years)	Blackwood	0.3	0.7	30.0	31.0	15%
		Bunbury	2.0	6.8	22.9	31.7	16%
		Buss-Capel	5.0	21.7	114.2	140.9	69%
Scenario E: current use + reduced regional growth + WC	89 to 147 (increasing over 30 years)	Blackwood	0.3	0.7	21.6	22.6	15%
		Bunbury	2.0	6.8	21.9	30.7	21%
		Buss-Capel	5.0	19.2	69.3	93.5	64%

3.2 Groundwater recharge and effect of drier climate

While there is scientific consensus that climate change is occurring, predicting how a particular region (e.g. the South West) will be affected is a difficult task. The CSIRO has developed a number of climate change scenarios for the South West. The worst-case climate change scenario to 2030 is a 20 per cent decrease in average annual rainfall. The best-case scenario is a 5 per cent increase in average annual rainfall over the same period (Whetton 2001; IOCI 2002). A case of 5 per cent gradual reduction in rainfall was adopted for simulating a drier climate in SWAMS.

Changes in climate include alterations to rainfall (quantity, intensity and duration), temperature, evapotranspiration and soil-moisture retention. SWAMS predictive runs have been made with two scenarios of recharge: one representing a long-term average annual recharge and another where the long-term average annual recharge has been reduced by 5 per cent for each year. On average, a 5 per cent flat reduction is similar to modelling recharge gradually decreasing to 10 per cent over the same time period. While there is an uncertainty about the relationship between reductions in rainfall to that of recharge, the present modelling has shown that in the past, a 10 per cent reduction in recharge has been a result of approximately 5 per cent reduction in rainfall.

The average runoff (instead of average rainfall) in the South West region for the 33-year period of 1971–2003 was used to develop a scaling factor for estimating the long-term average recharge. This was because the changes in runoff have a better relationship with the changes in recharge (Sun 2005). To obtain recharge that represents the long-term average, the model-calibrated recharge was changed from an average of 655 GL/yr for the 1990–2003 calibration period to 620 GL/yr as the average for 1971–2003 – using the scaling factor derived from stream runoffs for these two periods.

To simulate the effect of a drier climate on the groundwater levels, the long-term average recharge of 620 GL/yr was reduced by 5 per cent to 590 GL/yr. The difference in the modelled water levels from a scenario run with the long-term recharge of 620 GL/yr and those run with a reduced recharge of 590 GL/yr provides the net effect of a drier climate on the groundwater levels.

The climate scenario has been run on the SWAMS model only. It is considered that the evapotranspiration submodel used for the ESCP model may be less reliable under climatic conditions that are significantly wetter or drier than previously experienced (Aquaterra 2006).

4 Modelling results

4.1 Predicted water-level decline

Results of the SWAMS model predictive runs for each scenario are presented as watertable-decline maps using the difference between the watertable from each scenario and the base-case watertable. The effect of a drier climate on groundwater levels for each of the scenarios through reduced rainfall (recharge) is estimated from the difference between the watertable elevations in two scenarios that have the same abstraction but different recharge rates: one with the long-term average recharge and the other with 5 per cent reduced recharge. The area covered by the ESCP model has been marked on the groundwater-decline maps derived from the SWAMS model and simulated declines in this area are considered to have an unacceptable level of uncertainty. For the ESCP area (i.e. the eastern Scott coastal plain), more accurate drawdown has been derived because the model better represents the effect of the induced recharge from the post-winter surface-water ponding in this predominantly internally drained area. Declines in the watertable at the representative groundwater-dependent ecosystem (GDE) sites have been graphed (refer to Figure 10 for their locations), while declines at the PASS sites have been presented separately for the Swan and Scott coastal plains (refer to figures 11 and 12 for the locations of these sites).

Current entitlements (scenario A)

The large-scale abstraction for the current entitlements scenario is mainly concentrated in the Swan Coastal Plain area. The majority of Yarragadee abstraction takes place in the area south of Bunbury. The modelled watertable drawdown is greatest where up to 2 m drawdown takes place on the Swan Coastal Plain in areas where the Yarragadee aquifer directly subcrops beneath the superficial formations and where the overlying Leederville aquifer is thin (Figure 20). On the Vasse shelf (west of Busselton fault), the Yarragadee aquifer does not exist and large-scale abstraction from the Leederville aquifer in the irrigation areas causes drawdown of up to 2 m locally.

Drawdowns of up to 0.5–1 m are predicted on the Blackwood Plateau near areas of Yarragadee outcrop, such as near the Blackwood River and along Poison Gully and Milyeannup Brook. There is about 0.05–0.25 m of drawdown along the St Johns Brook. Drawdowns on the Scott Coastal Plain are better simulated by the ESCP local-scale model, which show a maximum of 0.25 m drawdown for the current entitlements scenario in this area. A graph of drawdowns at the key GDEs (Figure 21) shows that most are within the criteria limits, except on the Swan Coastal Plain to the south of Bunbury where drawdowns at some GDEs exceed the criteria levels. Because the SWAMS model does not take into account the induced recharge from surface water in this area, the drawdowns are likely to be overestimated. In general, modelling shows that the current entitlements' abstraction is within the acceptable limits of the preliminary EWR criteria.

Optimisation (scenario B)

This scenario was modelled using the SWAMS model only. Running of this scenario has been an iterative and time-consuming process. The SWAMS model has been optimised to yield approximately 90 GL/yr from the major aquifers of the southern Perth Basin while meeting the EWR criteria: 40 GL/yr of this is from the Yarragadee aquifer. In addition, approximately 50 GL/yr is abstracted from other aquifers in the model area. From model test runs it was found, in general, that the EWR criteria were not sensitive to abstraction from the Leederville aquifer in the Bunbury Trough and there was a limit to volumes that could be abstracted from the Superficial aquifer. Increased decline compared with scenario A at GDE sites 5, 76, 61, 55 and 3 is due to localised groundwater abstraction in the Yarragadee aquifer. Increased decline at 36, 37, 38 and 7 on the Vasse shelf where the Yarragadee aquifer is not present is due to pumping from the Leederville aquifer. Hence, the optimisation was performed on the Yarragadee aquifer only. Some spatial redistribution of abstraction will be required to mitigate localised impacts. This scenario is likely to produce significant water and land-use planning implications and choices.

Recent recharge estimates for the Swan Coastal Plain by Mauger (2007) have shown that recharge for this area could be about 60 per cent greater than that applied in SWAMS v2. The local-scale modelling on the eastern Scott Coastal Plain has shown that surface-water-induced recharge in areas of poor drainage can attenuate watertable decline by as much as 80 per cent. Applying this factor broadly to the SWAMS model optimisation results from the coastal plains, it is likely that if the SWAMS regional model was modified to take into account the extra recharge on both the Swan and Scott coastal plains, an additional 30 GL/yr could be abstracted from the Yarragadee aquifer while meeting the EWR criteria in these areas. The optimised groundwater abstraction obtained from the SWAMS model for each management subarea is provided in Table 4 and the corresponding drawdown at each GDE site is shown in Figure 22.

Regional growth (scenario C)

In this scenario, abstraction increases from 64 GL/yr (current use) to 159 GL/yr over 30 years. Most abstraction in the Bunbury Trough is from the Yarragadee aquifer, while on the Vasse Shelf the abstraction is from the Leederville aquifer. Drawdown patterns are similar to those of the current entitlements scenario (Figure 23), with increased drawdown (particularly on the Scott Coastal Plain) as a result of projected growth in local groundwater use for the dairy and horticulture industry. A graph of water-level drawdown at the key GDEs (Figure *24*) shows the drawdown is either breaching or just within the EWR criteria at these sites. This abstraction results in a significant increase in drawdown near most environmentally important areas along the Blackwood River. A low-level (<0.25 m) impact on Lake Jasper is seen as a result of abstraction from this scenario.

Table 4: Optimised abstraction volumes from the Yarragadee aquifer

Groundwater area	Subarea	Optimised abstraction volume (GL/yr)
Blackwood	Beenup*	0.20
Blackwood	Rosa*	0.13
Blackwood	Scott 1*	1.40
Blackwood	Scott 2*	0.52
Blackwood	State Forest 1*	0.38
Blackwood	State Forest 2*	0.00
Blackwood	State Forest 3*	1.80
Blackwood	State Forest 4*	2.52
Bunbury	Australind	0.40
Bunbury	Boyanup	0.23
Bunbury	Dardanup	3.63
Bunbury	East Bunbury	1.44
Bunbury	Eaton	2.89
Bunbury	South Bunbury	0.15
Bunbury	Stratham-Gelorup	0.42
Busselton-Capel	Busselton-Chapman Hill	1.80
Busselton-Capel	Capel-Ludlow	1.16
Busselton-Capel	Donnybrook	6.43
Busselton-Capel	Elgin-Capel River	4.64
Busselton-Capel	Jarrahwood	7.34
Busselton-Capel	Kingswood	0.20

**Proposed subareas (see Figure 17 for location)*

Regional growth plus Water Corporation (scenario D)

For this scenario, the proposed Water Corporation abstraction of 45 GL/yr is added to scenario C (regional growth). The effects of this abstraction on the watertable over 30 years are significant in terms of drawdown along the coastal plains and the Blackwood valley, including large areas along St Johns Brook (Figure 25). Watertable drawdowns of 3–5 m are common in areas where the Yarragadee Formation subcrops or underlies an area where the Leederville Formation is thin. There are a large number of GDE sites on the Swan Coastal Plain and the Blackwood Plateau where the EWR criteria would be breached (Figure 26). On the Swan Coastal Plain, attenuation of drawdown is expected if recharge from surface water is taken into account.

Water Corporation abstraction

Drawdown from the proposed Water Corporation abstraction of 45 GL/yr from the Yarragadee aquifer has been estimated by taking the difference in water levels of scenarios C and D above. Drawdown is concentrated near the area where the Yarragadee is subcropping beneath the Superficial aquifer to the south of Bunbury, in the area to the south-east of Busselton, and along the valleys of the rivers and tributaries where the Yarragadee Formation is either exposed or where the overlying Leederville Formation is thin (Figure 27). Figure 28 shows that EWR criteria at some GDEs would be breached, particularly those along the Blackwood River. It is unlikely that drawdown shown for the Swan coastal plain will be observed (because of extra recharge from the surface water). Drawdown at most GDEs are well within the EWR criteria.

The predicted drawdowns at other users' bores in the Yarragadee aquifer as a result of the Water Corporation's proposed abstraction are shown in figures 29 and 30 for Yarragadee units 1 and 3 respectively. The drawdown is about 8–20 m near the borefield and generally less than 3 m near the existing users' bores and is unlikely to have a significant impact on well production. However, if the abstraction water levels in other users' bores are close to the bottom of the screened interval, some deepening of the bores may be required to maintain abstraction rates.

Current entitlements and the Water Corporation proposal

Predicted water-level drawdown as a result of abstraction at current entitlements (112 GL/yr in October 2004), together with Water Corporation's proposed abstraction of 45 GL/yr, was assessed using results from scenario A with the additional drawdown from the Water Corporation's proposal derived from scenarios C and D. This scenario assumes that abstraction will take place at the current entitlements rate together with the Water Corporation's 45 GL/yr for the entire 30 years, while in reality the abstraction will increase progressively from the current use of approximately 64 GL/yr to 112 GL/yr over 10–15 years (as per growth in regional needs). The estimated drawdown is therefore conservative, as shown in figures 31 and 32.

Reduced regional growth and Water Corporation (Scenario E)

This scenario tested the effect of reduced regional growth and a reduced allocation to the Water Corporation. Compared with scenario D, this scenario showed significantly less drawdown (Figure 33). However, criteria at several key GDEs were still breached: most of them along the Blackwood River (Figure *34*). The maximum drawdown is 1–2 m in the vulnerable areas such as the Yarragadee subcrop and outcrop.

Effect of reduced rainfall recharge

The effect of a drier climate has been simulated by taking the difference in the modelled water levels from the current-use scenario run with a 'normal' recharge and the same scenario run with a recharge reduced by a constant 5 per cent for the 30-year simulation period. This provides the net effect of a drier climate on the water levels (figures 35 and 36). In general, the water levels are predicted to decline by 0.25–0.5 m in most areas. Areas of higher recharge to the north and south of the Blackwood River are most affected (water levels can decline by as much as 1 m). On the Scott Coastal Plain, water-level declines reach as much as 5 m in areas of topographical highs. Watertable decline at GDEs will generally be well within the criteria; however, at some sites, they may breach the criteria by up to 0.25 m. These declines will be in addition to those resulting from any increases in drawdown abstraction modelled in the other scenarios.

Summary of groundwater level decline at GDE reference sites

Table 5 provides a summary of modelling results at the GDE reference sites for the Blackwood Plateau and the Swan and Scott coastal plains in terms of whether water levels are within or exceed the preliminary EWR criteria set for each site. These results are illustrated graphically in figures 37–39. Modelling results show that the watertable declines will exceed the preliminary EWR criteria at 16 out of 27 sites (60 per cent) on the Swan Coastal Plain, 13 out of 24 sites (54 per cent) on the Blackwood Plateau, and 8 out of 35 sites (23 per cent) on the Scott Coastal Plain for the regional growth and Water Corporation scenario (which has the highest level of abstraction). For the Water Corporation scenario alone, the EWR criteria would be exceeded at 22, 42 and 6 per cent of all sites on the Swan Coastal Plain, Blackwood Plateau and Scott Coastal Plain respectively. As stated previously, the modelled declines on the Swan Coastal Plain are likely to be overestimates. A large proportion of the predicted impacts on the GDEs of the Blackwood Plateau are due to the proximity of the proposed Water Corporation abstraction. Potential climate change alone, simulated by a 5 per cent reduction in recharge, results in EWR criteria being exceeded in 10 out of 35 (28 per cent) of sites on the Scott Coastal Plain. The numbers of sites where EWR criteria is exceeded for current entitlements are low on the Blackwood Plateau (4 per cent) and the Scott Coastal Plain (6 per cent), but high on the Swan Coastal Plain (33 per cent) because of some large groundwater licences in this area.

Table 5: Summary of modelling results at GDE reference sites

Scenario	Swan Coastal Plain		Blackwood Plateau		Scott Coastal Plain	
	Number of sites within criteria	**Number of sites exceeding criteria**	**Number of sites within criteria**	**Number of sites exceeding criteria**	**Number of sites within criteria**	**Number of sites exceeding criteria**
Current entitlements	18	9	23	1	33	2
Regional growth	13	14	16	8	28	7
Regional growth plus Water Corporation	11	16	11	13	27	8
Reduced regional growth plus reduced Water Corporation	15	12	13	11	28	7
Current entitlement plus Water Corporation	8	19	10	14	23	12
Water Corporation alone	21	6	14	10	33	2
Climate change (5% recharge reduction) alone	26	1	20	4	25	10

4.2 Reduction in groundwater discharge to rivers

Groundwater discharge to the Blackwood River including tributaries (St Johns Brook, Poison Gully and Milyeannup Brook) takes place downstream of Nannup. The estimated groundwater contribution to the river flow between Nannup and Hut Pool is estimated from water-flow snapshot measurements and salt-mass balance and is about 20–30 GL/yr (Mauger 2003). This includes contributions to the Blackwood River from its tributaries. It is estimated that about 50 per cent of this discharge occurs from the Yarragadee Formation and the remainder occurs from the Leederville Formation.

The simulated groundwater discharge to the Blackwood River in the SWAMS model is about 61 GL/yr, based on the average annual water balance for the model calibration period, which is higher than the analytically determined volumes. Part of this overestimate is possibly due to errors in the estimation of groundwater discharge from the Leederville aquifer in the model. In view of this discrepancy, this model has been used to assess the relative decrease in groundwater discharge between scenarios, instead of the absolute decrease in the discharge volumes. The fractional reduction from the base case has been applied to the analytically estimated volume to obtain reductions in discharge volumes for each scenario. The average simulated groundwater discharge for the calibration run has been adopted as the base case for comparison. Groundwater discharge to the Blackwood River has been obtained from the modelled water balances for each scenario (Table 6).

Results show that in the Blackwood River the annualised average groundwater discharge reduces by 8–23 per cent based on the different scenarios of abstraction and climate change. These equate to a 2.4–6.9 GL/yr reduction from an estimated present groundwater discharge of 25 GL/yr depending on the abstraction scenario. A redistribution of abstraction (away from environmentally sensitive areas) by optimisation increases the groundwater discharge by 6 per cent. The Water Corporation proposal by itself is expected to reduce the groundwater discharge by 9 per cent. These estimated reductions in groundwater discharge to the Blackwood River from SWAMS v2 are similar to those obtained from a local-scale model of the Blackwood River valley (URS 2006). The effect of reduced groundwater discharge on the river flow is more prominent in the summer months when the river flow is mainly comprised of groundwater contribution as baseflow. During winter the river flow is significantly higher as a result of runoff, hence any impact of reduced groundwater discharge on the river flow will be negligible (Figure 40).

It is likely that groundwater also discharges into the Donnelly River. However, the ESCP modelling results show that negligible groundwater decline occurs near the Donnelly River for the different scenarios; so it is unlikely that groundwater discharge to the river will be significantly reduced. However, the model's calibration in this area is poor and therefore the estimated declines may not be accurate. The model has not been calibrated to the groundwater discharge to the rivers on the Swan Coastal Plain. Therefore, at this stage it is not possible to assess the impacts of abstraction on these rivers using the SWAMS model.

Table 6: Reduction in groundwater discharge to the Blackwood River

Abstraction	Scenario/run	Modelled groundwater discharge (GL/yr)	Reduction in discharge to Blackwood River (%)	Estimated annual reduction in discharge (GL)*
Average annual discharge for 1990–2003	Calibration	61.4	Reference volume	–
Current use (64 GL/yr)	Actual abstraction for 2004	56.6	8%	2.0
Current entitlement (112 GL/yr)	Scenario A	54.9	11%	2.8
Optimisation (~90 GL/yr)	Scenario B	64.9	6 % increase	1.5 (increase)
Current use plus regional Growth (64–159 GL/yr)	Scenario C	52.6	14%	3.5
Current use plus regional growth plus Water Corporation (109–204 GL/yr)	Scenario D	47.4	23%	5.8
Water Corporation (45 GL/yr)	Inferred from scenarios C and D	–	9%	2.3
Current entitlements plus Water Corporation (157 GL/yr)	Inferred from scenarios A, C and D	–	20%	5.0
Current use plus reduced regional growth plus reduced Water Corporation (89–147 GL/yr)	Scenario E	50.8	17%	4.2
Current use (64 GL/yr) with 5% reduction in rainfall recharge	Recharge reduced from 620 to 590 GL/yr for the entire period in current-use scenario	53.4	13%	3.2

**Based on estimated 25 GL/yr groundwater discharge to the Blackwood River from summer-flow observations.*

4.3 Impact on Blackwood River salinity

The effect of reduced groundwater discharge to the Blackwood River from the different abstraction scenarios has been assessed using a simple salt-mass balance method. The average salinity of the groundwater discharging to the river has been adopted as 350 mg/L. Table 7 and

Figure 41 show the river salinity as a result of reduction in groundwater discharge from the different abstraction scenarios.

The maximum increase in river salinity is in the driest month of February, when the salinity is predicted to increase between 6–21 per cent depending on the level of abstraction. For the other months, the salinity increase is generally less than 15 per cent. There is very little difference in salinity in the winter months when the river flow is dominated by the runoff (Figure *42*). The effect of the Water Corporation's proposed abstraction alone would result in a maximum increase in salinity of 7 per cent in the driest month.

Table 7: Predicted increase in Blackwood River salinity

Month	Percent increase in salinity for each scenario								
	Current use	**Current entitlement**	**Regional growth**	**Regional growth with Water Corporation**	**Water Corporation alone**	**Current entitlement with Water corporation**	**Modified regional growth with Water Corporation**	**5% reduction in recharge**	**Optimisation**
Jan	4	6	7	13	5	11	10	2	-3
Feb	6	9	12	21	7	18	15	3	-4
Mar	3	4	5	9	3	7	6	1	-2
Apr	2	3	4	8	3	6	6	1	-2
May	2	2	3	5	2	4	4	1	-1
Jun	0	1	1	1	0	1	1	0	0
Jul	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0
Sep	0	0	0	0	0	0	0	0	0
Oct	0	0	0	1	0	1	0	0	0
Nov	1	1	1	2	1	2	2	0	-1
Dec	2	2	3	5	2	4	4	1	-1

4.4 Groundwater-level declines at PASS sites

Figures 43 to 56 graphically illustrate the groundwater-level decline at the PASS sites compared with the maximum decline criteria set for each site based on a ‘moderate level of risk’ as defined in Section 2.3. There are numerous sites where the decline criteria have been set at nearly ‘zero’. These sites are vulnerable to relatively small increases in abstraction. For example, the current entitlements scenario (scenario A) would breach the criteria at many locations on the Swan Coastal Plain. However, on the Scott Coastal Plain, the predicted groundwater-level decline for this scenario would be mostly within the criteria. The groundwater-level decline on the Swan Coastal Plain may be overestimated by SWAMS v2; therefore, the predicted decline may be less. Scenarios C, D and E all show significant impacts on the Swan Coastal Plain, whereas on the Scott Coastal Plain the impacts are generally subdued. The Water Corporation’s abstraction has low-level drawdown on the Scott Coastal Plain; however, on the Swan Coastal Plain the drawdown is more significant, but this may partly be due to overestimation of drawdown by SWAMS in this area.

4.5 Water-balance assessment

Global water balance

The average water balances of each aquifer have been derived from the SWAMS model for each modelled scenario, along with the annual averages for the model calibration period (1990–2003) (Table 8). A water balance based on current water use for the onshore part of each aquifer is presented in Figure 57.

The water balances include total recharge as input to the model, net leakage from overlying and underlying aquifers, flux at constant heads, storage change, groundwater discharge to rivers, discharge by evapotranspiration (EVT) – in areas of shallow watertable – and abstraction. The net recharge is estimated by addition of the gross recharge and the losses by EVT.

Water balances from each scenario (Table 8) show that the net leakage to the Yarragadee aquifer from the overlying Superficial and Leederville aquifers increases from about 100–180 GL/yr as abstraction increases, while the discharge to the ocean from the Yarragadee aquifer decreases from 103–57 GL/yr. In Table 8, the water-balance components have been calculated as an average of the last five years of the simulation period.

The storage depletion is larger during periods when abstraction is increasing (such as the regional growth scenario), while the storage depletion is less for the current-use scenario with constant abstraction because a near steady-state is reached by the end of the simulation period.

Table 8: Annual water balance derived from the SWAMS model

Aquifer	Storage depletion (GL)	Ocean discharge (GL)	Wells (GL)	Rivers (GL)	EVT (GL)	Recharge (GL)	Net leakage (GL)
Calibration period 1990–2003							
Superficial (Swan)	9	-15	-2	-5	-167	206	-27
Superficial (Scott)	12	-75	0	-2	-107	199	-26
Leederville	16	-45	-15	-108	-4	206	-50
Yarragadee	4	-103	-28	-18	0	44	101
Total	**40**	**-238**	**-45**	**-133**	**-278**	**655**	
Current use: base case							
Superficial (Swan)	7	-13	-3	-5	-150	195	-30
Superficial (Scott)	6	-70	0	-1	-95	188	-27
Leederville	14	-41	-20	-95	-4	194	-49
Yarragadee	2	-93	-39	-17	0	42	105
Total	**29**	**-217**	**-62**	**-119**	**-249**	**618**	
Current entitlement: scenario A							
Superficial (Swan)	7	-12	-4	-4	-137	194	-44
Superficial (Scott)	6	-69	0	-1	-94	188	-28
Leederville	17	-35	-26	-92	-4	194	-55
Yarragadee	3	-78	-77	-16	0	42	126
Total	**33**	**-194**	**-107**	**-114**	**-235**	**618**	
Regional growth: scenario C							
Superficial (Swan)	10	-12	-3	-4	-135	194	-49
Superficial (Scott)	8	-69	0	-1	-89	188	-36
Leederville	29	-31	-32	-90	-3	194	-67
Yarragadee	10	-69	-120	-15	0	42	152
Total	**56**	**-180**	**-155**	**-111**	**-228**	**618**	
Regional growth plus Water Corporation: scenario D							
Superficial (Swan)	10	-12	-3	-4	-128	194	-57
Superficial (Scott)	8	-68	0	-1	-87	188	-39
Leederville	39	-28	-32	-83	-3	194	-87
Yarragadee	12	-58	-165	-13	0	42	182
Total	**69**	**-165**	**-200**	**-102**	**-219**	**618**	
Reduced regional growth and Water Corporation: scenario E							
Superficial (Swan)	7	-12	-3	-4	-136	194	-46
Superficial (Scott)	7	-69	0	-1	-89	188	-35
Leederville	26	-32	-29	-89	-3	194	-67
Yarragadee	5	-68	-113	-14	0	42	147
Total	**46**	**-181**	**-145**	**-108**	**-229**	**618**	

Note: Water balances are average per year for the last five years of the simulation period except for the calibration period where these are annual average per year for the specified period.

Groundwater management unit (GMU) water balances

Water balances for each GMU (each aquifer within a subarea) in the Blackwood, Busselton-Capel and Bunbury groundwater areas (GWAs) have been estimated using the SWAMS model for all significant aquifers in the study area. The water balances have been estimated for three scenarios of abstraction: current use, current entitlement and the optimisation case. For these scenarios all components of inflow (recharge and throughflow) and outflow (abstraction, flow to ocean and streams, evapotranspiration and throughflow) have been estimated.

The water-balance data have been analysed by taking into account the ratio of abstraction to combined outflow, which indicates the level of use of the groundwater resource in each GMU. The Department of Water will use these results to assess an optimum level of abstraction for the relevant aquifer in each subarea and to estimate allocation limits. The graph of abstraction to outflow ratio for the Yarragadee aquifer for each of the scenarios is presented in Figure 58. From the graph it is seen that this ratio is significantly higher for the current use and entitlements in the Busselton, Australind and East Bunbury subareas (30–60 per cent) and is low for the Jarrahwood, Kingswood and several subareas in the Blackwood GWA, indicating under-use in these areas (<10 per cent) and scope for redistribution of entitlements.

4.6 Sustainable yield and allocation limit

In the previous sections of this report, the models were used to run several scenarios of abstraction (from 64 GL/yr to 204 GL/yr) and their corresponding impacts on the groundwater levels at GDE locations. It was shown, for higher abstraction levels, that higher drawdown was expected. When the model was optimised such that abstraction at each subarea level met the environmental criteria, it was seen that the southern Perth basin aquifers were able to yield a maximum of 90 GL/yr, of which about 40 GL/yr could be drawn from the Yarragadee aquifer. Recent recharge estimates for the Swan Coastal Plain by Mauger (2007) have shown that recharge for this area could be about 60 per cent greater than that applied in SWAMS v2. Applying this factor broadly to the SWAMS model optimisation results from the coastal plains, it is likely that if the SWAMS regional model was modified to take into account the extra recharge on both Swan and Scott coastal plains, an additional 30 GL/yr could be abstracted from the Yarragadee aquifer while meeting the EWR criteria in those areas. If abstractions were to exceed a volume of 120 GL/yr, the corresponding drawdown would be expected to exceed the preliminary criteria for groundwater level decline at the GDEs.

Average annual water balance for the Yarragadee aquifer shows that the total inflow to the aquifer is about 150 GL/yr, which includes leakage of about 100 GL/yr from the overlying Leederville Formation. The outflow from the Yarragadee aquifer comprises 100 GL/yr of ocean discharge and about 20 GL/yr of discharge to the rivers as baseflow, and 30 GL/yr as the average abstraction.

A comparison of the ratio of abstraction to total flow (Figure 58) showed there was significant scope for the redistribution of abstraction in the Yarragadee aquifer so that impacts would be minimised (i.e. to bring the groundwater-level decline within the criteria levels).

The term ‘sustainable yield’ can have slightly different definitions depending on the decision-making process. When the sustainable yield is defined from a purely ecological perspective, it can be defined simply as ‘the level of water abstraction from a particular system that, if exceeded, would compromise key environmental assets, or ecosystem functions and productive base of the resource' (Australian Government National Water Commission 2007). Derivation of the sustainable yield can also consider other values in addition to the environment. The Australian Government's Department of Environment and Heritage (2004) defined sustainable yield as: 'the groundwater abstraction regime, measured over a specified planning timeframe that allows acceptable levels of stress and protects dependent economic, social, and environmental values'*.* Therefore, the main requirement for assessing the sustainable yield in this context is the level of acceptable stress and identification of trade-offs – and balancing these with the economic value of the water.

This report will define the sustainable yield as the amount of water from a water resource that can be abstracted over time while maintaining the ecological values (including assets, functions and processes), and not involving a triple-bottom-line assessment. For the Yarragadee aquifer the sustainable yield is thus the optimised volume as provided in Table 4.

The Department of Water has undertaken a multi-criteria assessment (MCA) of the groundwater resources of the southern Perth basin in consultation with a wide cross-section of the community. Deriving the environmental water provisions (EWPs) from the MCA will be a complex exercise, including community consultations, mitigation of impacts and trade-offs. The outcomes of this assessment will help to balance the environmental, social and economic values of the resource. The model will need to be optimised again by changing the previous constraints from the EWRs to EWPs. The optimised groundwater abstraction would thus provide the allocation limit.

5 Conclusions

The South West Aquifer Modelling System version 2 (SWAMS v2) regional-scale model and the Eastern Scott Coastal Plain (ESCP) local-scale model have been used to simulate changes in groundwater abstraction and climate, as well as the resulting impacts on groundwater levels at several sites of identified ecological and social value (including other users of the groundwater resource).

Several scenarios for predictive modelling have been run using the two models and changes in water levels have been estimated relative to a base-case scenario, which is current-use abstraction at 64 GL/yr (as in 2004) for the 30-year simulation period to 2033. A scenario with a 5 per cent reduction in rainfall recharge throughout the 30-year period has also been run to represent the effects of climate change.

The spatial distribution of the relative modelled groundwater-level declines for each scenario have been estimated and presented as contour maps. The modelled groundwater-level declines at key groundwater-dependent ecosystems (GDEs) have been graphed to show the degree of impacts from each scenario. As expected, the groundwater-level decline is seen to increase with increasing abstraction, with some of the largest groundwater-level declines occurring near areas where the Yarragadee aquifer outcrops.

For the current entitlements scenario, groundwater-level declines of up to 2 m take place on the Swan Coastal Plain in areas where the Yarragadee aquifer directly subcrops beneath the superficial formations and where the overlying Leederville aquifer is thin in the area south-east of Busselton. Groundwater-level declines of up to 0.5–1 m take place on the Blackwood Plateau near areas of Yarragadee outcrop such as near the Blackwood River and along Poison Gully and Milyeannup Brook. There are about 0.05–0.25 m of groundwater-level declines along St Johns Brook. Maximum groundwater-level decline of 0.25 m takes place on the Scott Coastal Plain. The local-scale modelling on the eastern Scott Coastal Plain has shown that surface-water-induced recharge in areas of poor drainage can attenuate the groundwater-level decline estimated by SWAMS by as much as 80 per cent. Furthermore, recent studies have shown the recharge on the Swan Coastal Plain may be more than what is applied in the SWAMS v2 model.

The SWAMS model has been optimised to yield about 90 GL/yr from the major aquifers of the southern Perth Basin while meeting the EWR criteria; however, if additional recharge potentially available from surface water in the coastal plains is taken into account, it is possible that up to 120 GL/yr could be abstracted from the major aquifers while meeting the EWR criteria (up to 70 GL/yr of this from the Yarragadee aquifer). Yet this scenario would require some spatial redistribution of abstraction to mitigate localised impacts.

For scenario D – regional growth plus the Water Corporation abstraction of 45 GL/yr – there is significant drawdown along the coastal plains and the Blackwood valley, including large areas along St Johns Brook. Drawdowns of up to 3–5 m are common in areas where the Yarragadee Formation subcrops or underlies an area where the Leederville Formation is thin.

Scenario E – reduced regional growth and a smaller Water Corporation allocation – showed significantly less drawdown. However, EWR criteria at several key GDEs were still breached: most of them along the Blackwood River.

The modelled groundwater-level declines for a hypothetical case of rainfall recharge being reduced by 5 per cent for the next 30 years showed a general water-level decline by 0.25–

0.5 m in most areas. Areas of higher recharge to the north and south of the Blackwood River would be most affected (water levels could decline by as much as 1 m). On the Scott coastal plain, water-level declines could be as much as 5 m in areas of topographical highs. Watertable decline at GDEs would generally be well within the criteria; however, at some isolated sites they might breach the criteria by up to 0.25 m.

The ESCP modelling results show that negligible groundwater-level decline occurs near the Donnelly River for the different scenarios; so it is unlikely that groundwater discharge to the river will be significantly reduced. However, the model's calibration in this area is poor and therefore the estimated groundwater-level decline may not be accurate. For the Blackwood River, modelling results show that the annualised average groundwater discharge reduces by 8–23 per cent based on the different scenarios of abstraction and climate change. This is likely to result in a 6–21 per cent increase in the average salinity of the river in the driest month of February.

The Water Corporation has recently developed a local-scale model of the area of the Blackwood River and its tributaries. This model has improved calibration to the observed values of groundwater discharge to the river. However, the model results are similar to those of SWAMS v2 in terms of groundwater-level decline and reductions in groundwater discharge to the Blackwood River.

6 Recommendations

Recent recharge estimates for the Swan Coastal Plain have shown that SWAMS could be underestimating recharge in this area, hence the groundwater-level decline on Swan Coastal Plain derived from SWAMS (as shown in this report) may be overestimated. Similar to the ESCP model, a local-scale model of the Swan Coastal Plain is warranted in view of the similar hydrodynamic conditions (with respect to the groundwater and surface-water interactions) and a consequent scope for attenuation of watertable decline.

All local models should be integrated into the SWAMS regional model. This process will require modifications to the SWAMS model based on the parameters of the local-scale models. This will improve the efficiency and accuracy of the modelling system.

The Department of Water has undertaken a multi-criteria assessment (MCA) analysis of the groundwater resources of the southern Perth Basin in consultation with a wide cross-section of the community. The outcomes of this assessment will help to balance the environmental, social and economic values of the resource and to estimate the environmental water provisions (EWP).

When the EWPs or the acceptable level of changes to the groundwater regime at the groundwater-dependent ecosystems (GDEs) are developed, the models' groundwater abstractions should again be optimised to reflect these changes and the allocation limit derived from this process.

This report's results should be used to show which areas may be affected by various abstraction scenarios, and thus to identify areas where groundwater monitoring is important. Absolute values of drawdown will only be apparent after abstraction at a greater rate than present is carried out and water levels are monitored. This will allow better calibration of the models.

Groundwater models are generally a simple representation of a complex hydrogeological system, and are subject to inaccuracies in calibration arising from inadequate knowledge of spatial variations in hydraulic properties and groundwater recharge. Environmental impact assessments should not solely rely on the results of modelling. Information from groundwater models should be used together with other hydrogeological information.

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Glossary

Abstraction	The withdrawal of water from any water resource.
AHD	Australian Height Datum, which is equivalent to: Mean Sea Level (MSL) + 0.026 m; Low Water Mark Fremantle (LWMF) + 0.756 m.
Allocation limit	The volume of water set aside for annual licensed use.
Alluvium	Unconsolidated sediments transported by streams and rivers and deposited.
AMG	Australian Map Grid
Anticline	Sedimentary strata folded in the usually of inverted U-shape.
Aquifer	A geological formation or group of formations able to receive, store and transmit significant quantities of water.
Unconfined	A permeable bed only partially filled with water and overlying a relatively impermeable layer. Its upper boundary is formed by a free watertable or phreatic level under atmospheric pressure.
Confined	A permeable bed saturated with water and lying between an upper and a lower confining layer of low permeability, the hydraulic head being higher than the upper surface of the aquifer.
Semi-confined	A semi-confined or a leaky aquifer that is saturated and bounded above by a semi-permeable layer and below by a layer that is either impermeable or semi-permeable.
Semi-unconfined	Intermediate between semi-confined and unconfined, when the upper semi-permeable layer easily transmits water.
Archaean	Period containing the oldest rocks of the Earth’s crust – older than 2.4 billion years.
Baseflow	Portion of river and stream flow coming from groundwater discharge.
Basement	Competent rock formations beneath which sedimentary rocks are not found.
Bore	A narrow, normally vertical hole drilled into a geological formation to monitor or withdraw groundwater from an aquifer (see also Well).
Colluvium	Material transported by gravity downhill of slopes.
Confining bed	Sedimentary bed of very low hydraulic conductivity.
Conformably	Sediments deposited in a continuous sequence without a break.
Cretaceous	Final period of Mesozoic era; 65–144 million years ago.
Decline	The difference between the elevation of the initial watertable and its position after a decrease in recharge (i.e. rainfall).
Dewatering	Short-term abstraction of groundwater to lower the watertable and permit the excavation of 'dry' sediment.
Drawdown	The difference between the elevation of the initial piezometric surface and its position after pumping or gravitational drainage.

Ecologically sustainable yield	The amount of water that can be abstracted over time from a water resource while maintaining the ecological values (including assets, functions and processes).
Ecological water requirement	The water regime needed to maintain the ecological values (including assets, functions and processes) of water-dependent ecosystems at a low level of risk.
Environmental water provisions	The water regimes that are provided as a result of the water allocation decision-making process taking into account ecological, social, cultural and economic impacts. They may meet in part or in full the ecological water requirements.
Evapotranspiration	A collective term for evaporation and transpiration. It includes water evaporated from the soil surface and water transpired by plants.
Fault	A fracture in rocks or sediments along which there has been an observable displacement.
Flux	Flow
Formation	A group of rocks or sediments that have certain characteristics in common, were deposited about the same geological period, and that constitute a convenient unit for description.
Groundwater-dependent ecosystem	An ecosystem that is dependent on groundwater for its existence and health.
Hydraulic	Pertaining to water motion.
Conductivity	The flow through a unit cross-sectional area of an aquifer under a unit hydraulic gradient.
Gradient	The rate of change of total head per unit distance of flow at a given point and in a given direction.
Head	The height of the free surface of a body of water above a given subsurface point.
Lacustrine	Pertaining to, produced by, or formed in a lake.
Leach	Remove soluble matter by percolation of water.
Permian	An era of geological time; 225–280 years ago.
Porosity	The ratio of the volume of void spaces, to the total volume of a rock matrix.
Potentiometric surface	An imaginary surface representing the total head of groundwater and defined by the level to which water will rise in a bore.
Quaternary	Relating to the most recent period in the Cainozoic era, from 2 million years to present.

Salinity	A measure of the concentration of total dissolved solids in water. 0–500 mg/L; fresh 500–1500 mg/L; fresh to marginal 1500–3000 mg/L; brackish >3000 mg/L; saline
Scarp	A line of cliffs (steep slopes) produced by faulting or by erosion
Specific yield	The volume of water that an unconfined aquifer releases from storage, per unit surface area of the aquifer, per unit decline in the watertable.
Storage coefficient	The volume of water that a confined aquifer releases from storage, per unit surface area of the aquifer, per unit decline in the component of hydraulic head normal to that surface.
Sustainable yield	The level of water abstraction from a particular system that, if exceeded, would compromise key environmental assets, or ecosystem functions, and the productive base of resource.
Syncline	A U-shaped fold in sedimentary strata.
Tectonic	Pertaining to forces that produce structures or features in rocks.
Tertiary	The first period of the Cainozoic era; 2–65 million years ago.
Transmissivity	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.
Transpiration	The loss of water vapour from a plant, mainly through the leaves.
Watertable	The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.
Well	An opening in the ground made or used to obtain access to underground water. This includes soaks, wells, bores and excavations.

Contributors

This report was prepared by S Varma with modelling support from NH Milligan (CyMod Systems) and A Druzynski. DP Commander, CA O'Boy and P Wallace-Bell provided technical and editorial support.

Figures

Figure 1: Location of the study area

Figure 2: Groundwater areas of the South West

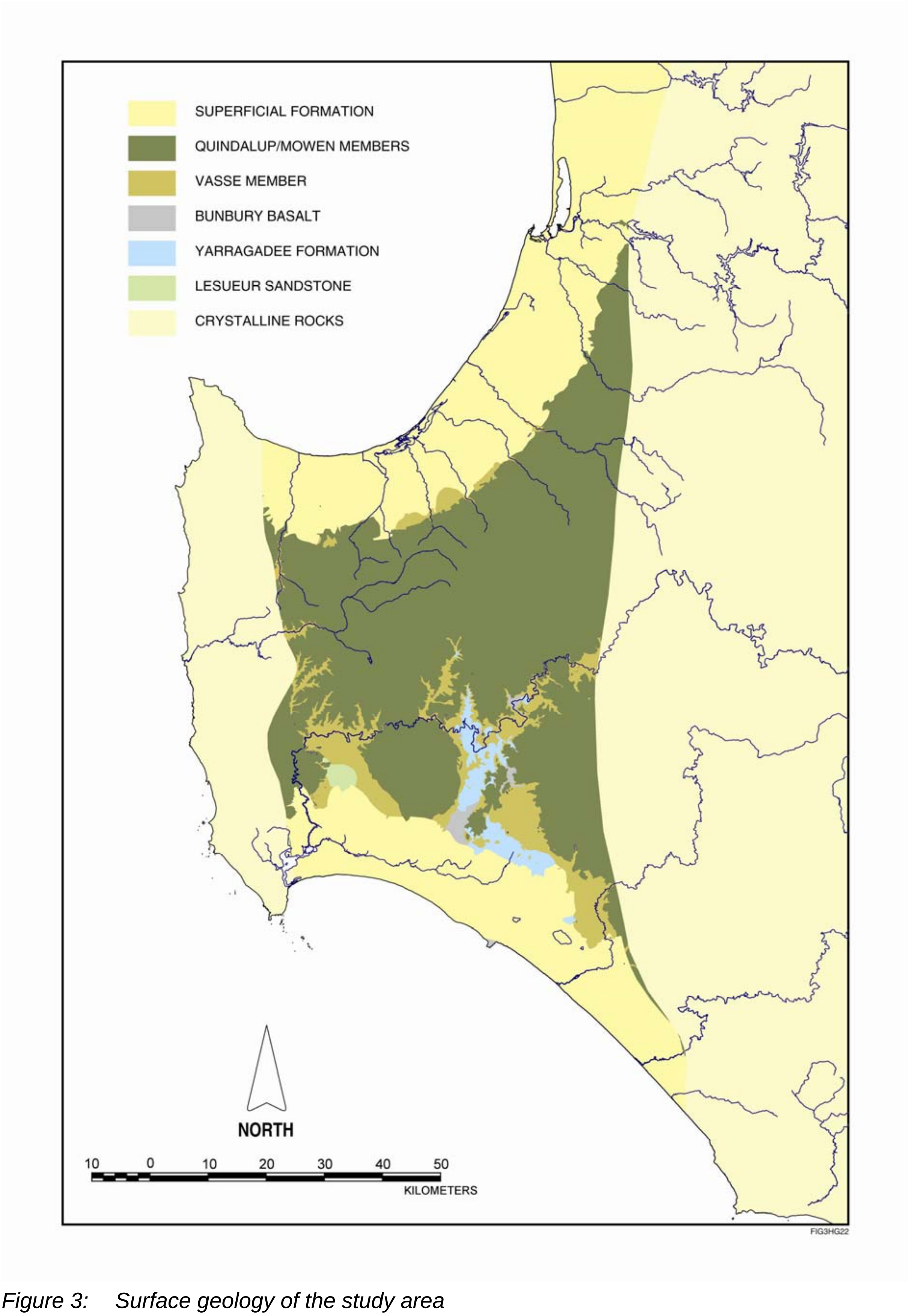


Figure 3: Surface geology of the study area

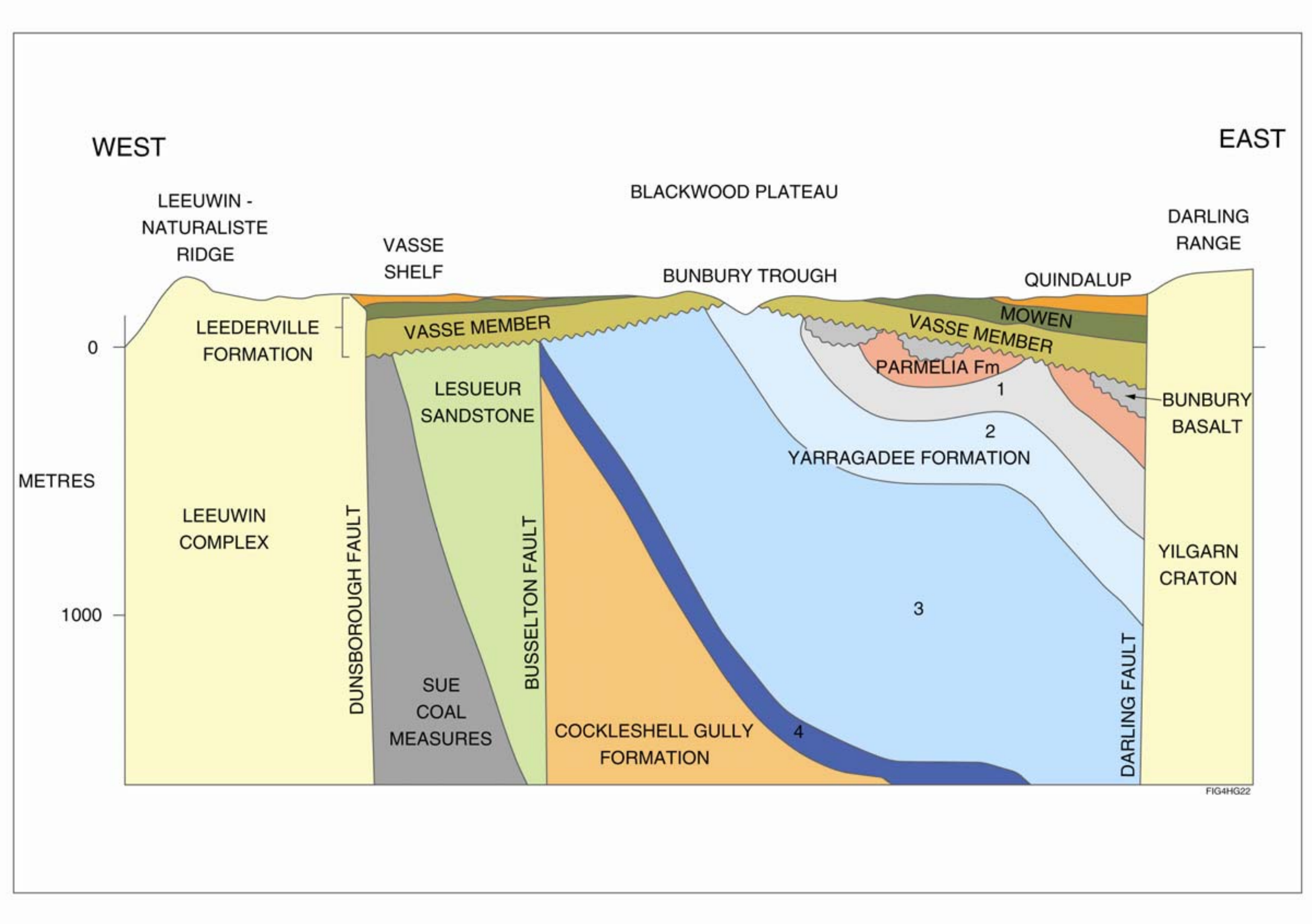


Figure 4: Geological structure

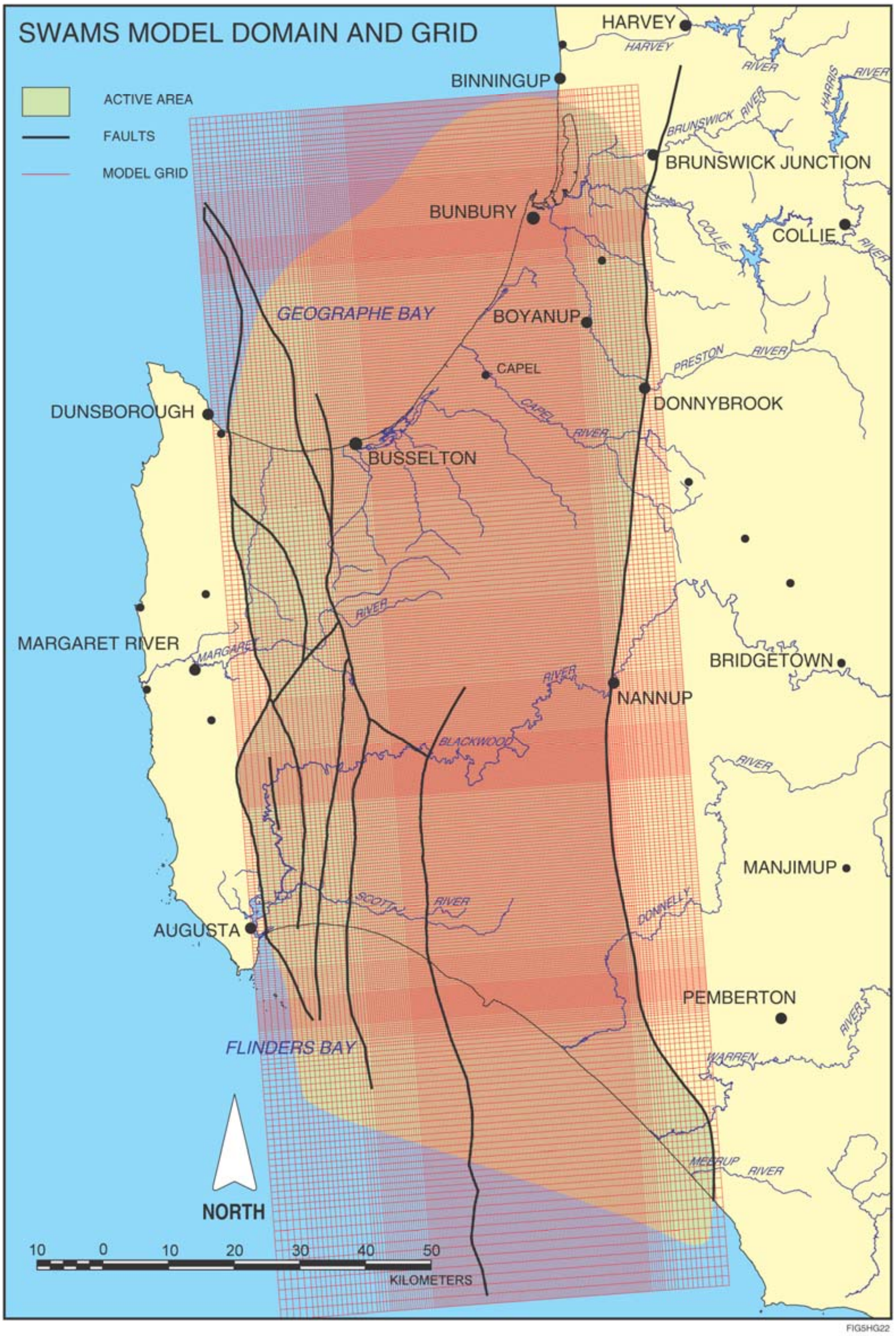


Figure 5: SWAMS model domain

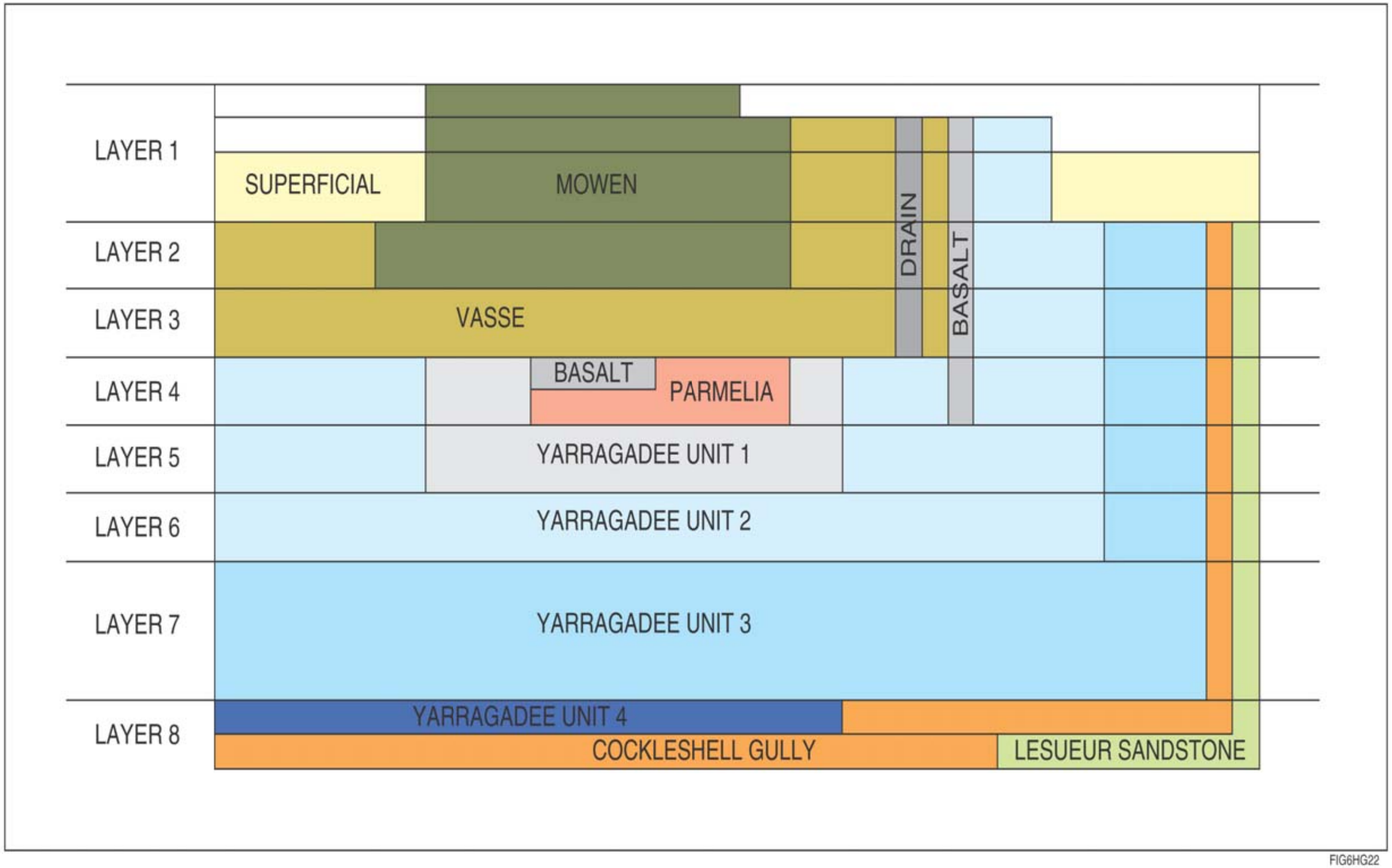
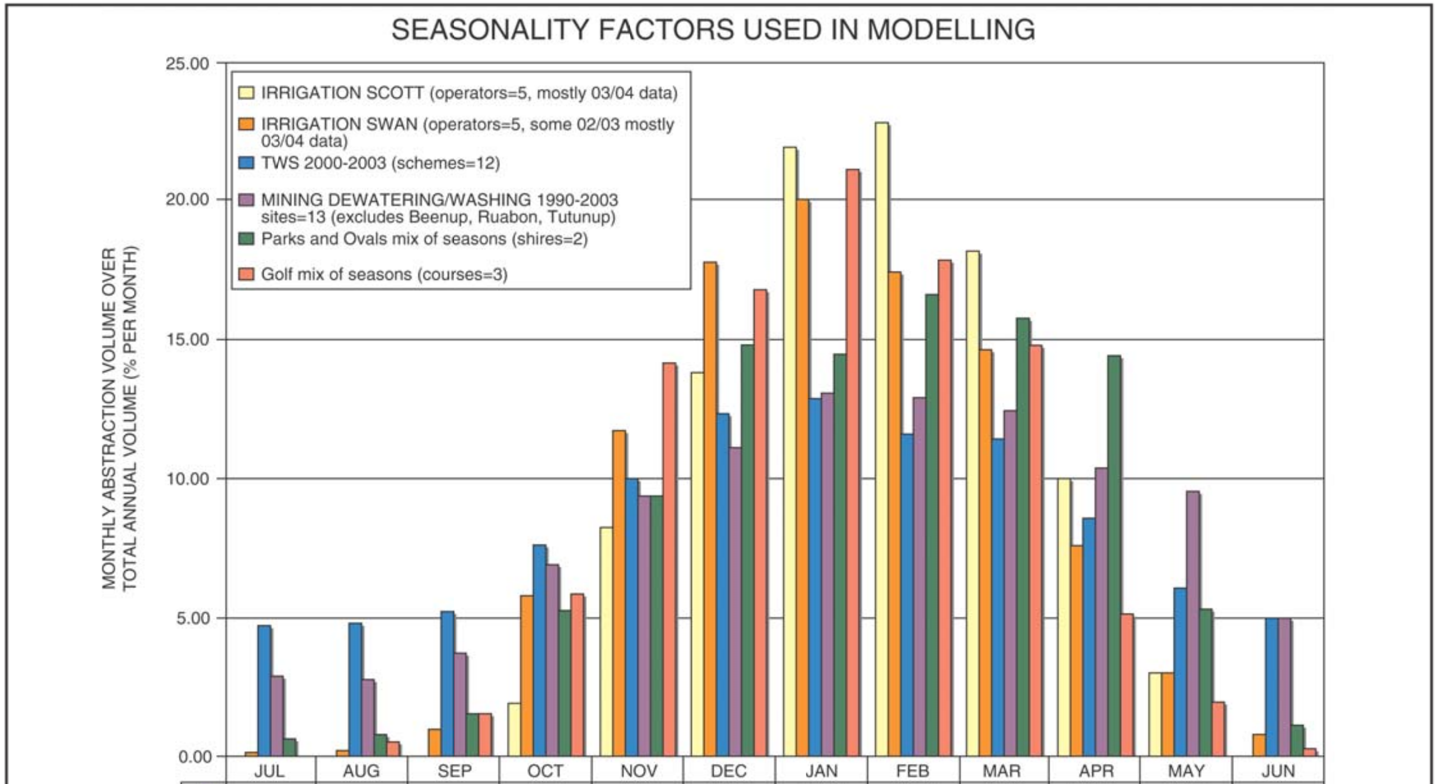


Figure 6: Conceptual layering in the groundwater models (Sun 2005)



	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
IRRIGATION SCOTT	-	-	-	1.92	8.30	13.80	21.90	22.77	18.20	10.03	3.07	-
IRRIGATION SWAN	0.11	0.17	0.91	5.79	11.68	17.79	20.03	17.46	14.64	7.62	3.02	0.78
TWS	4.67	4.75	5.23	7.61	10.02	12.26	12.91	11.63	11.42	8.52	6.05	4.94
MINING DEWATERING/WASHING	2.87	2.78	3.69	6.95	9.37	11.11	13.03	12.90	12.47	10.36	9.51	4.97
Parks and Ovals	0.59	0.75	1.53	5.26	9.37	14.81	14.50	16.66	15.75	14.37	5.33	1.11
Golf	0.04	0.49	1.55	5.89	14.14	16.82	21.14	17.88	14.78	5.07	1.94	0.26

FIG7HG22

Figure 7: Seasonal variation in abstraction (Sun 2005)

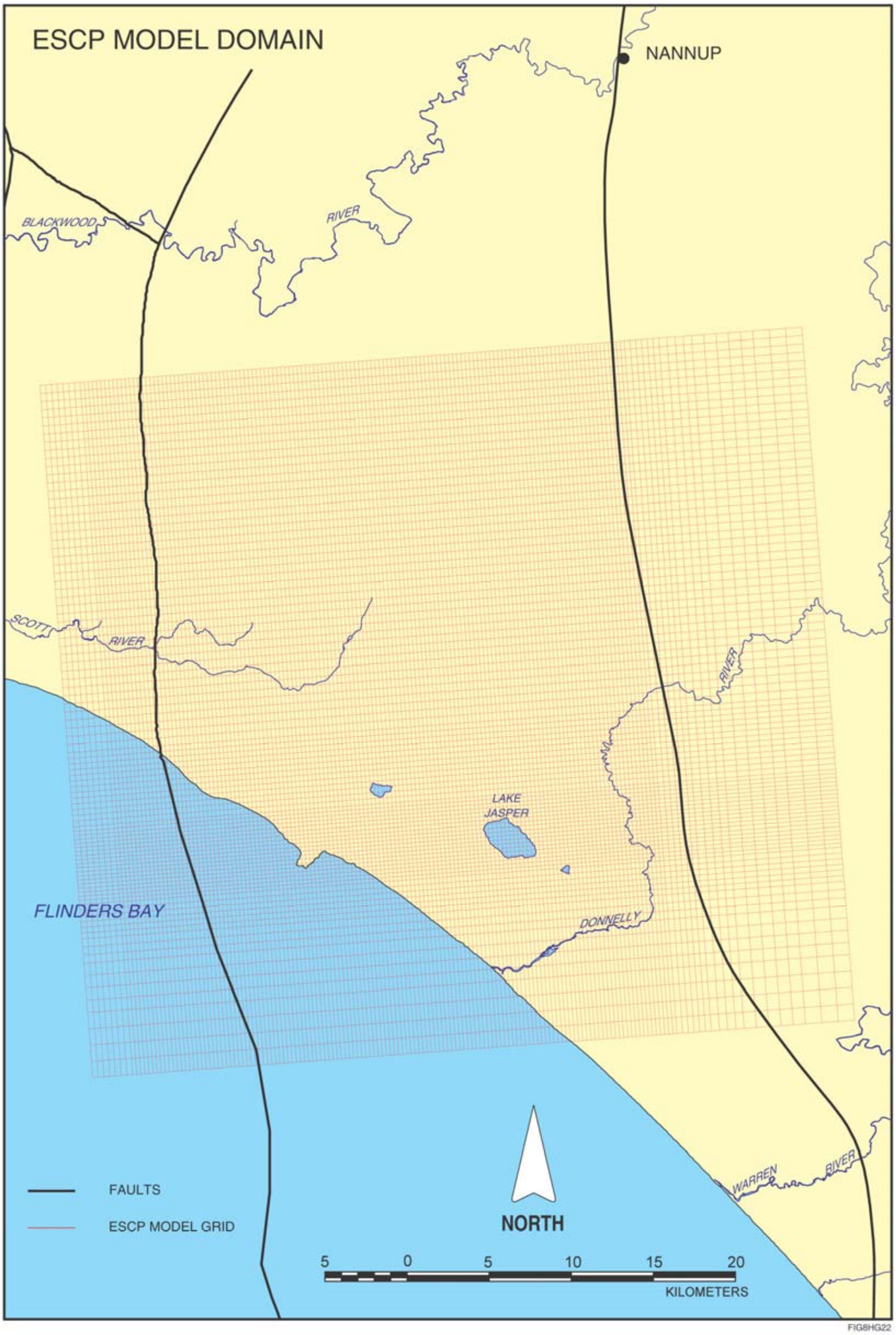


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Figure 9: Groundwater-dependent ecosystems of the South West region

Figure 10: Location of preliminary GDE reference sites

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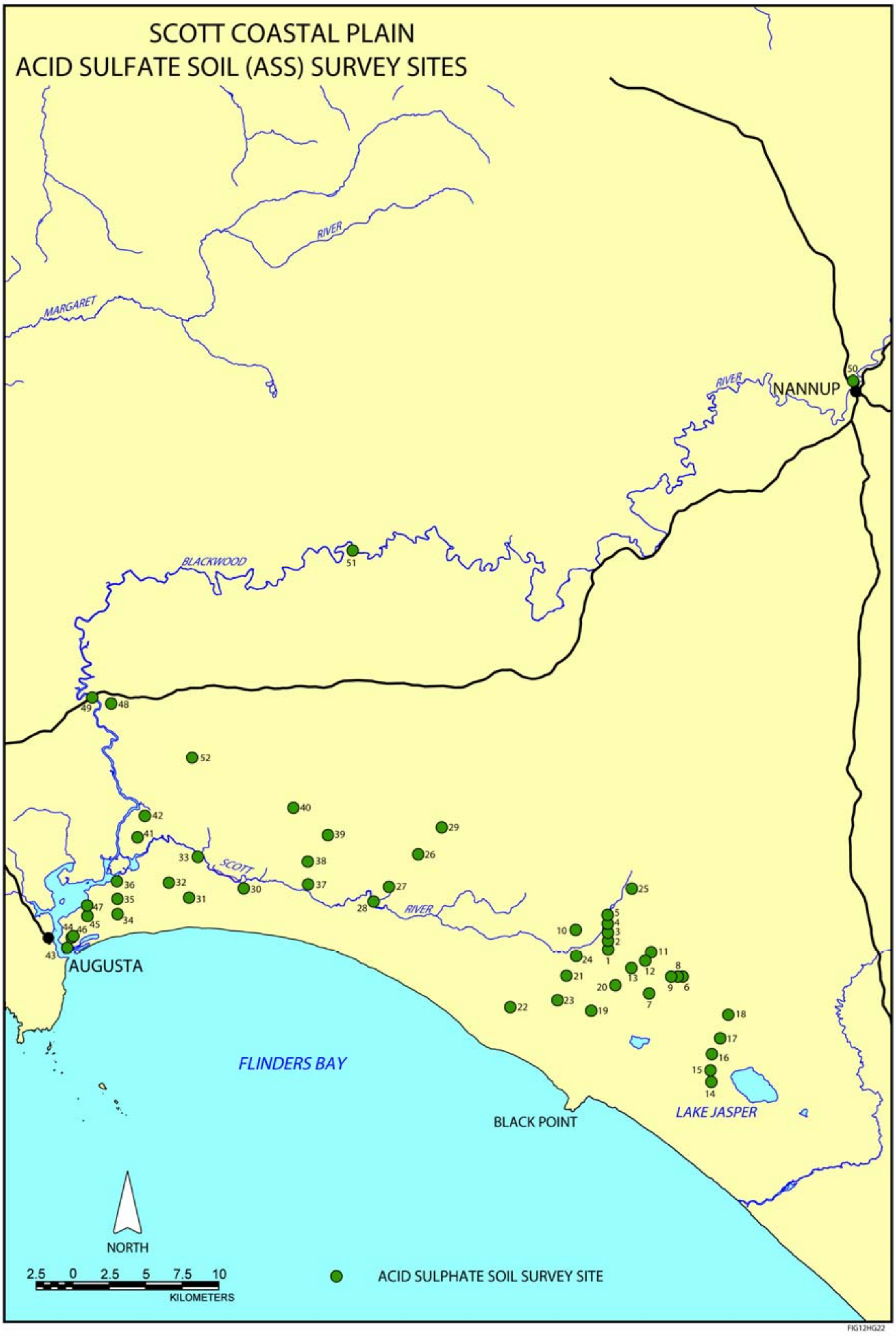

Figure 12: Location of PASS criteria sites on the Scott Coastal Plain

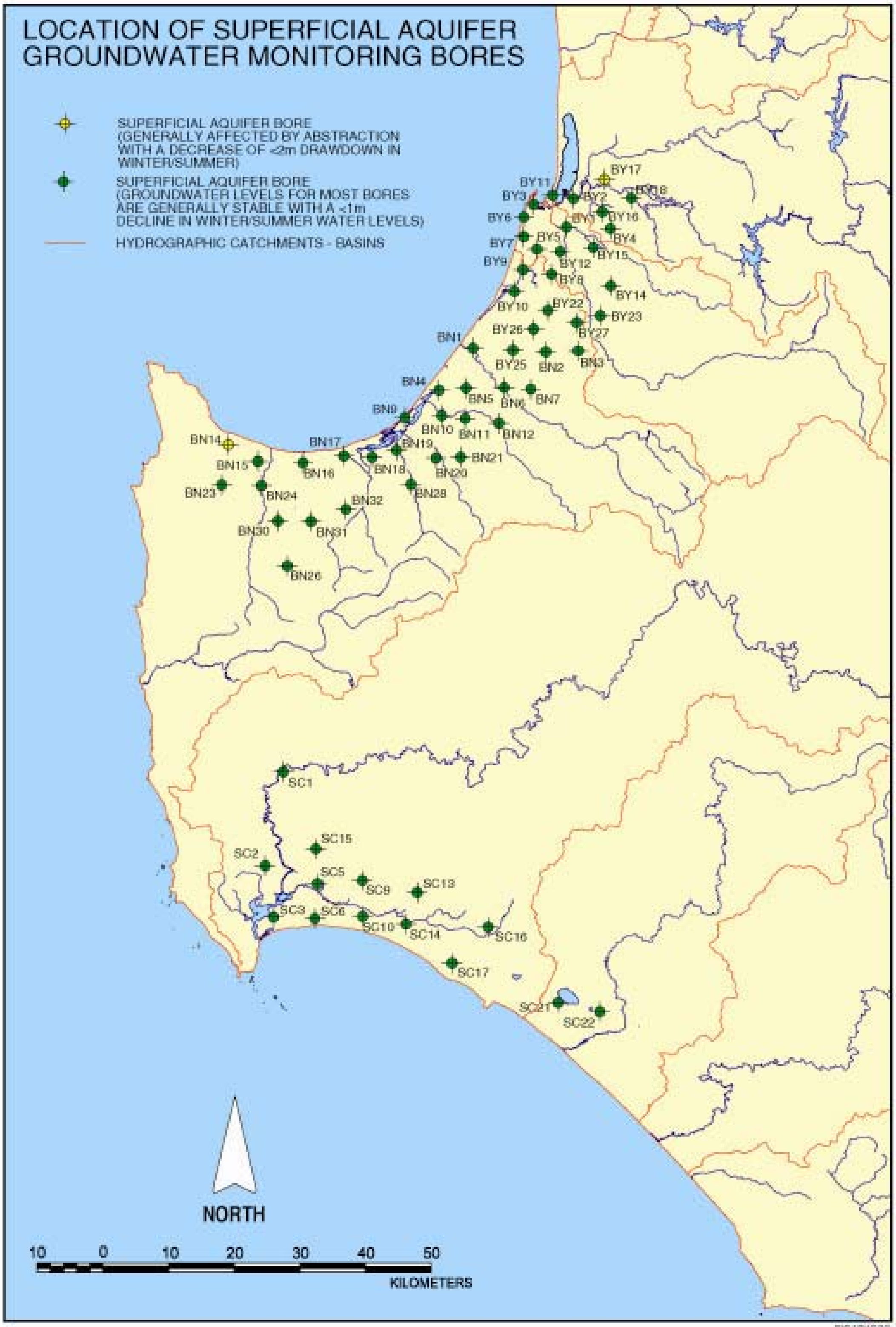

Figure 13: Summary map of water level trends in the Superficial Formation

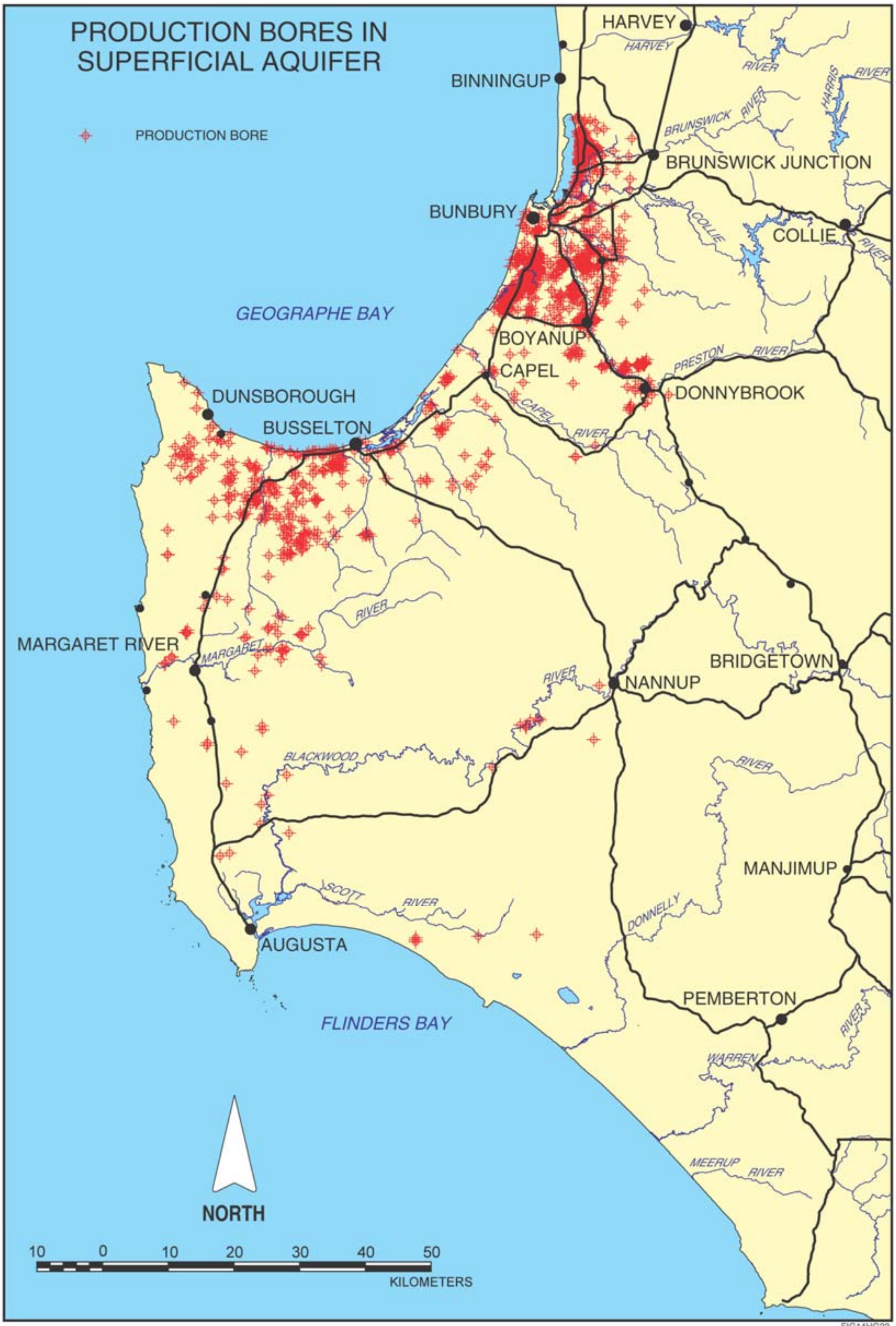

Figure 14: Currently licensed bores in the Superficial aquifer

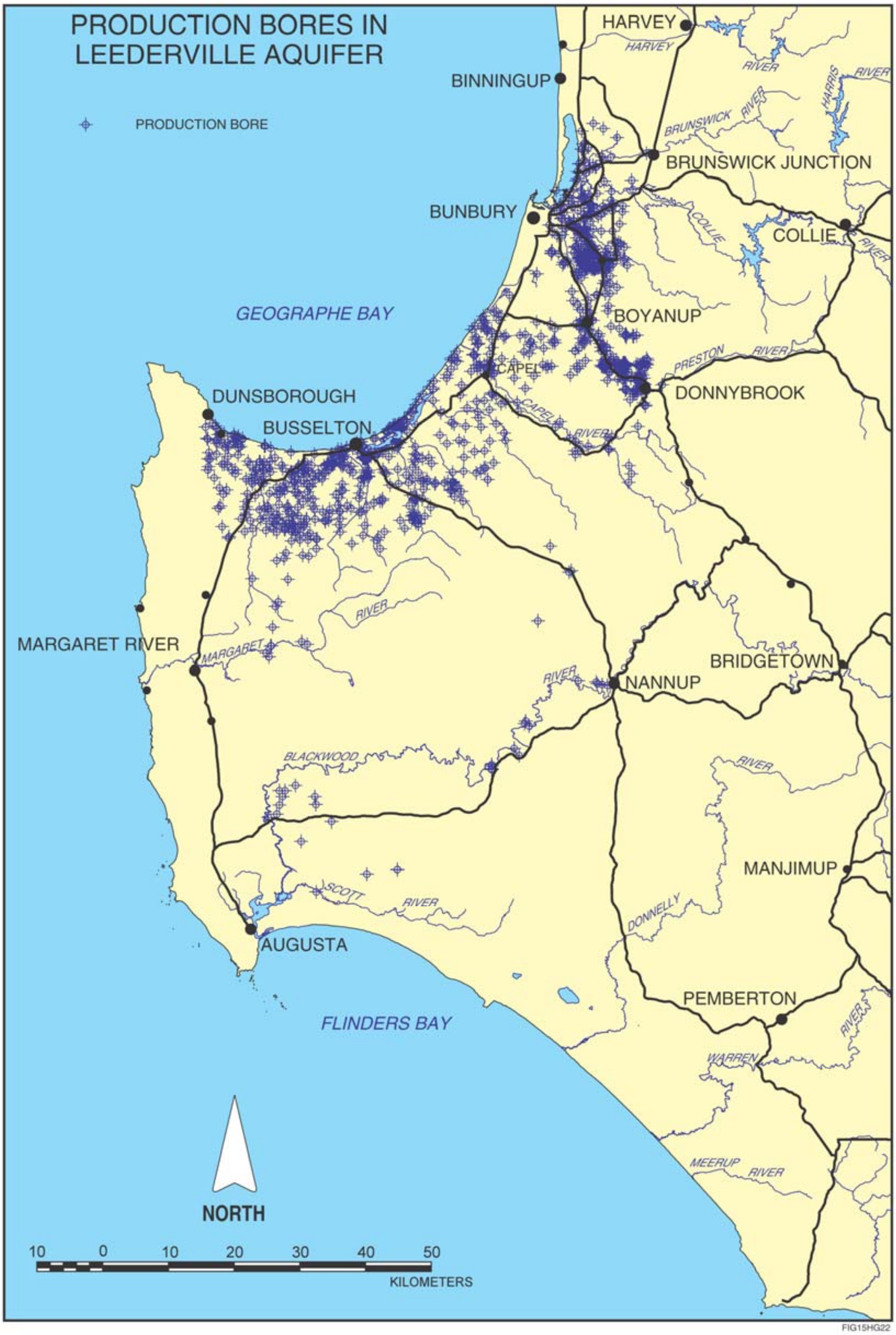

Figure 15: Currently licensed bores in the Leederville aquifer

Figure 16: Currently licensed bores in the Yarragadee aquifer

Figure 17: Proposed groundwater subareas

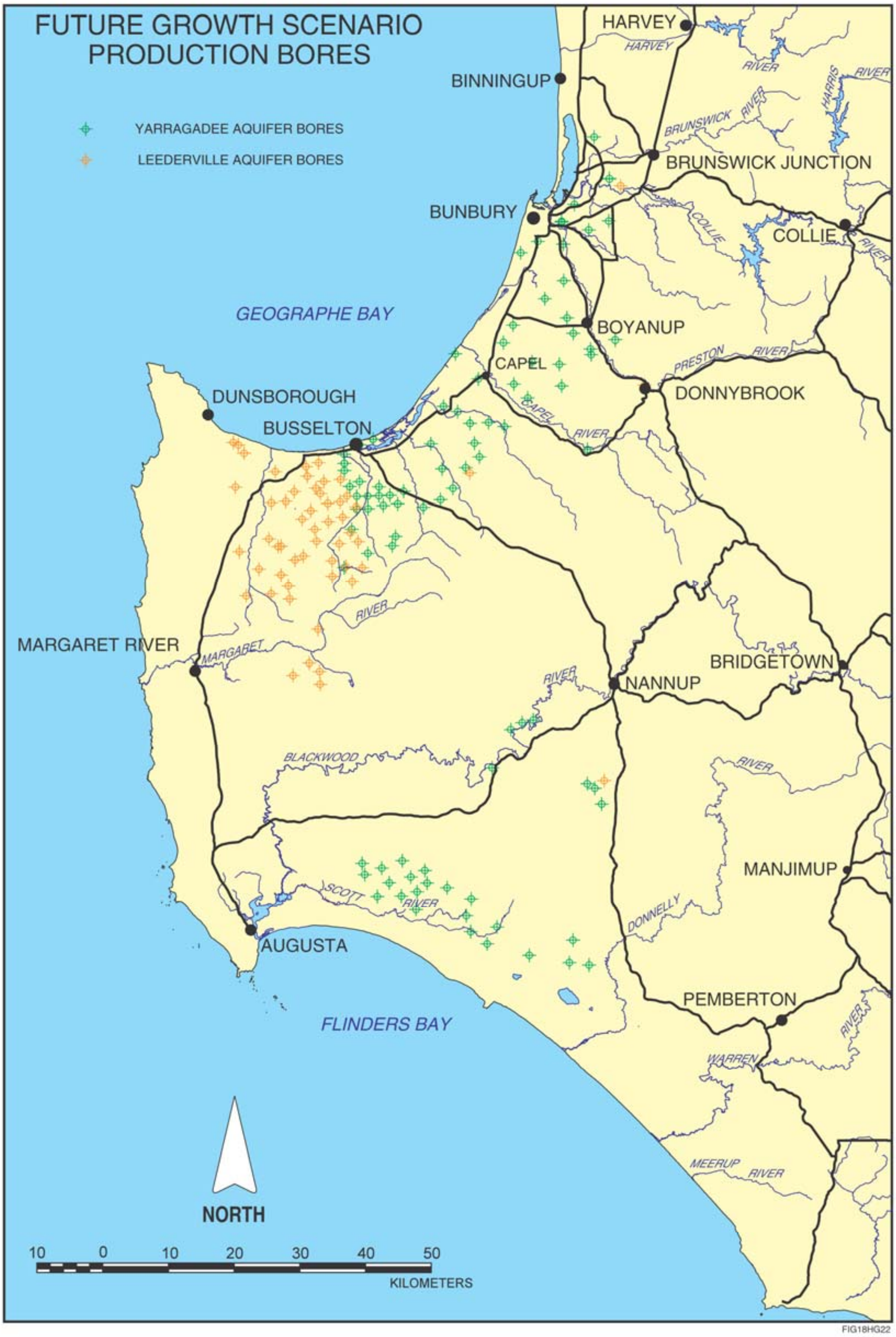

Figure 18: Regional growth bore locations

Figure 19: Proposed Water Corporation bore locations

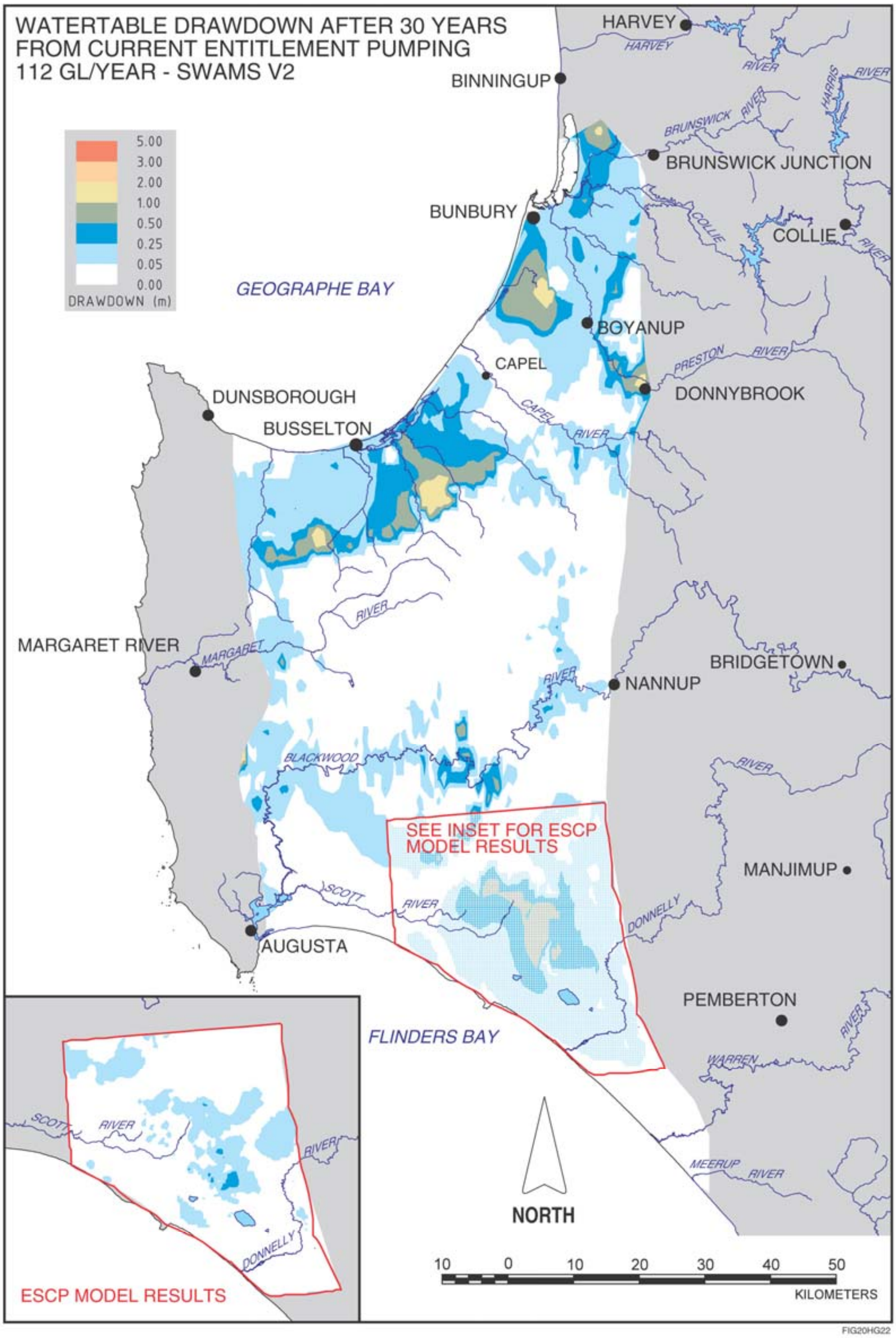

Figure 20: Predicted drawdown at the watertable from current entitlements abstraction (scenario A)

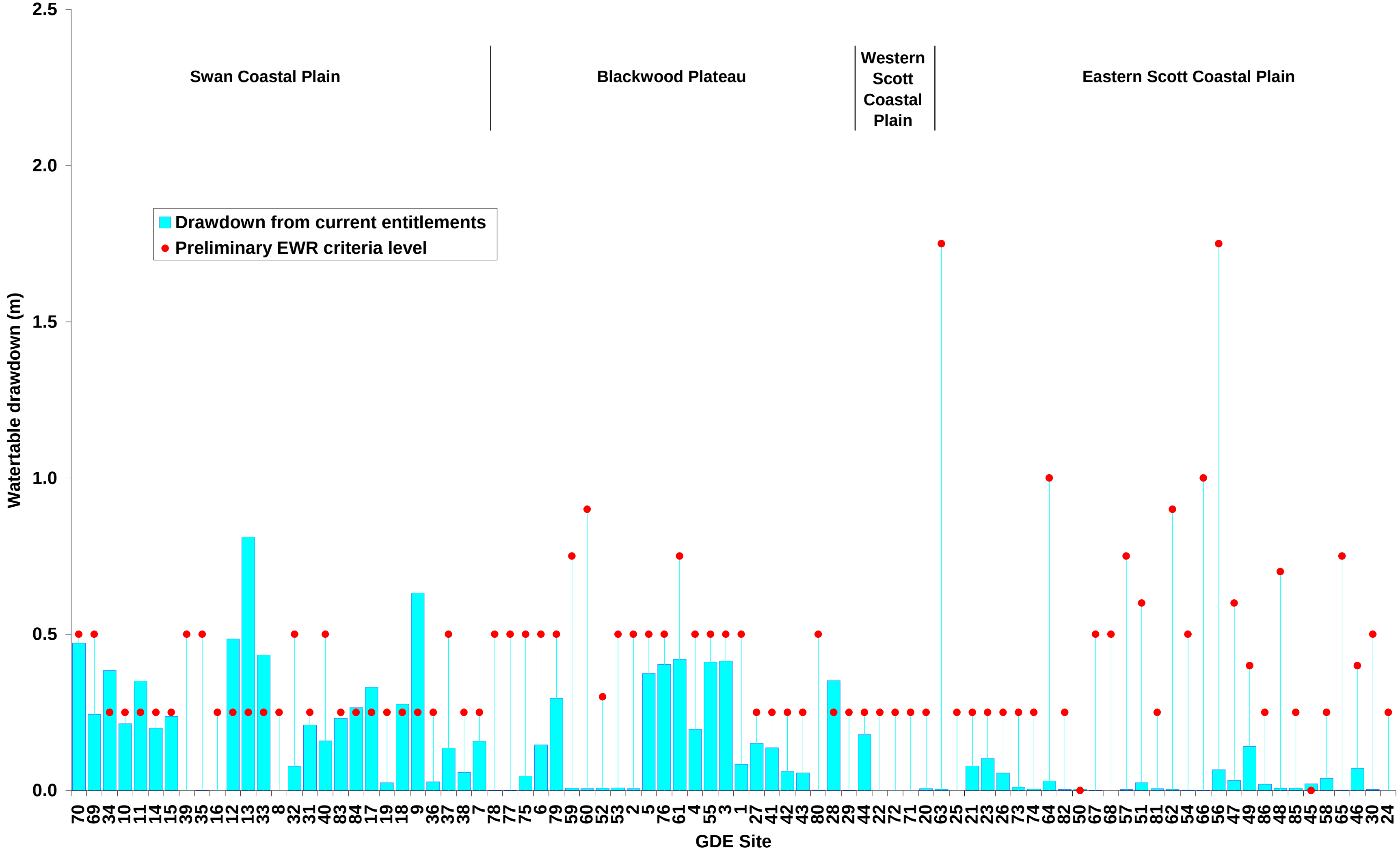

Figure 21: Predicted watertable drawdown at GDE reference sites from the current entitlements abstraction (scenario A)

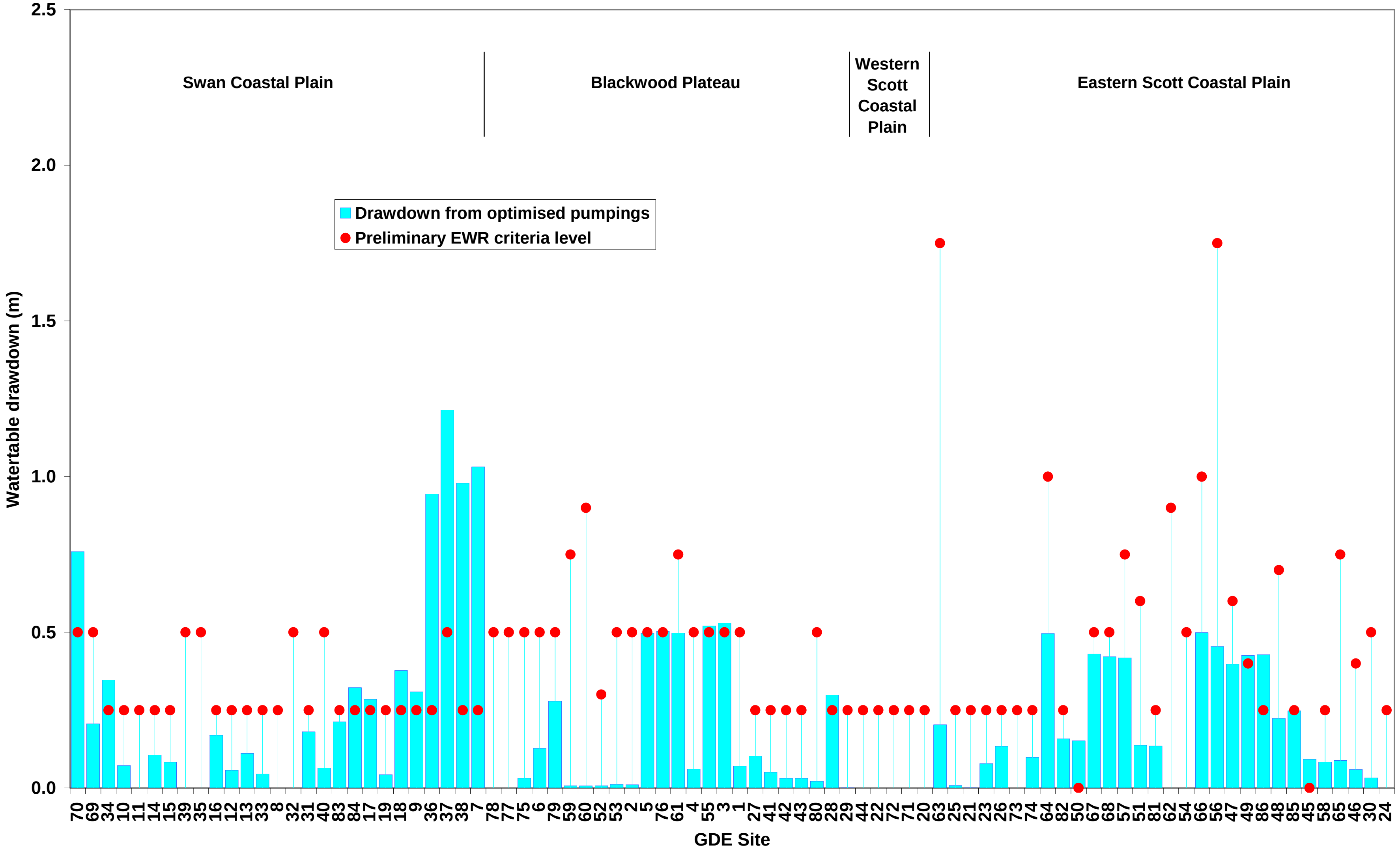

Figure 22: Optimised watertable drawdown at GDE reference sites (scenario B)

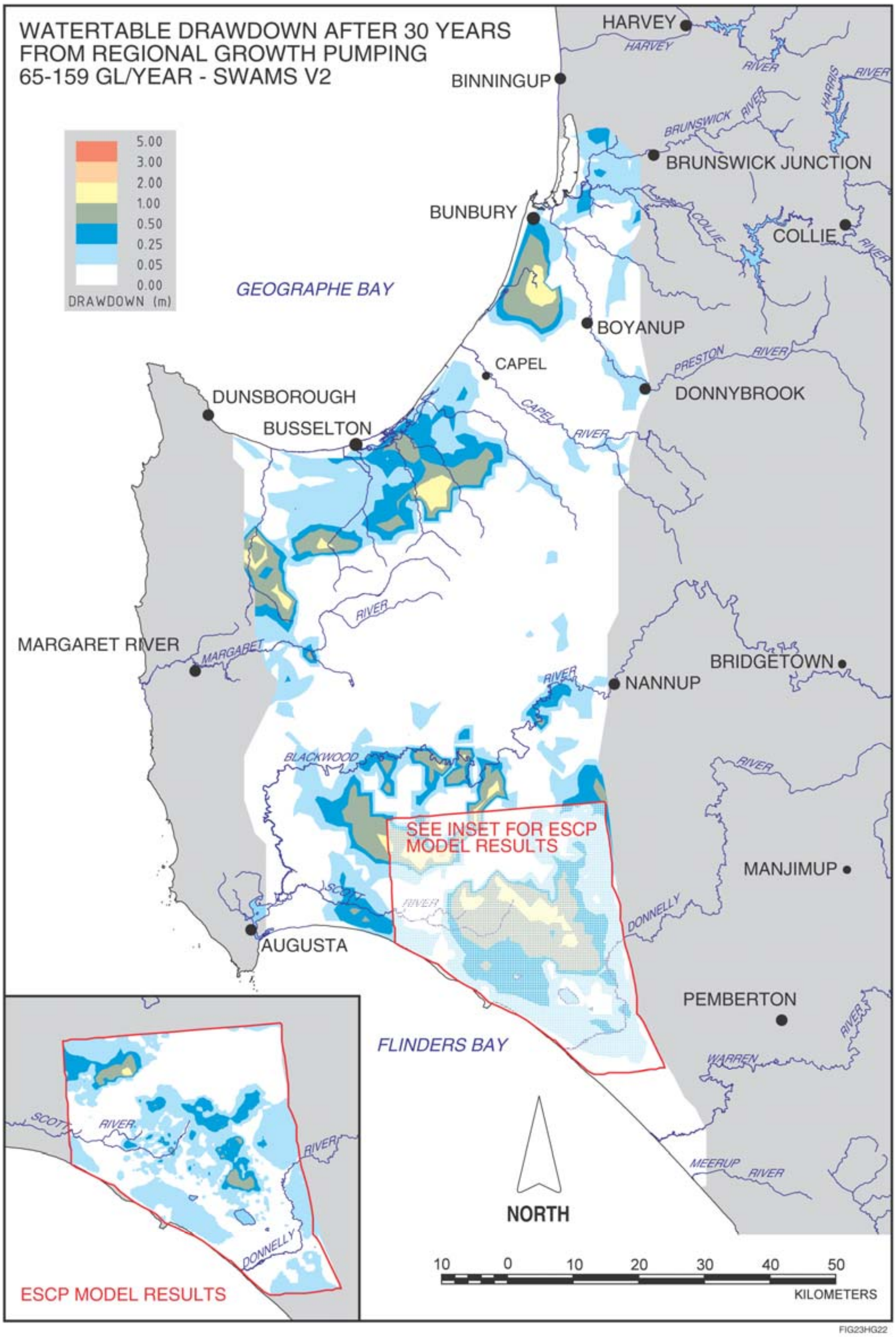

Figure 23: Predicted drawdown at the watertable from regional growth abstraction (scenario C)

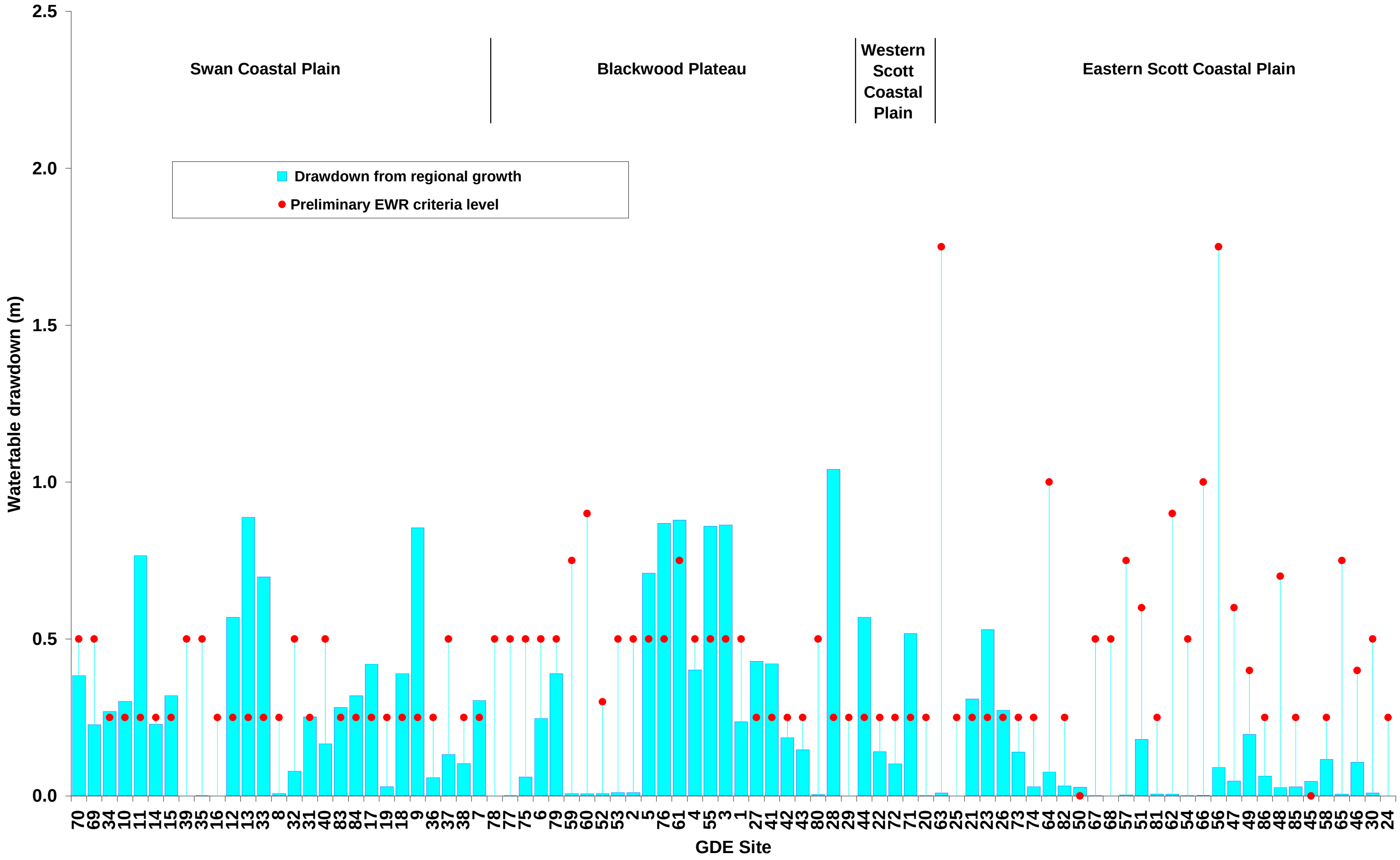

Figure 24: Predicted watertable drawdown at GDE reference sites from the regional growth abstraction (scenario C)

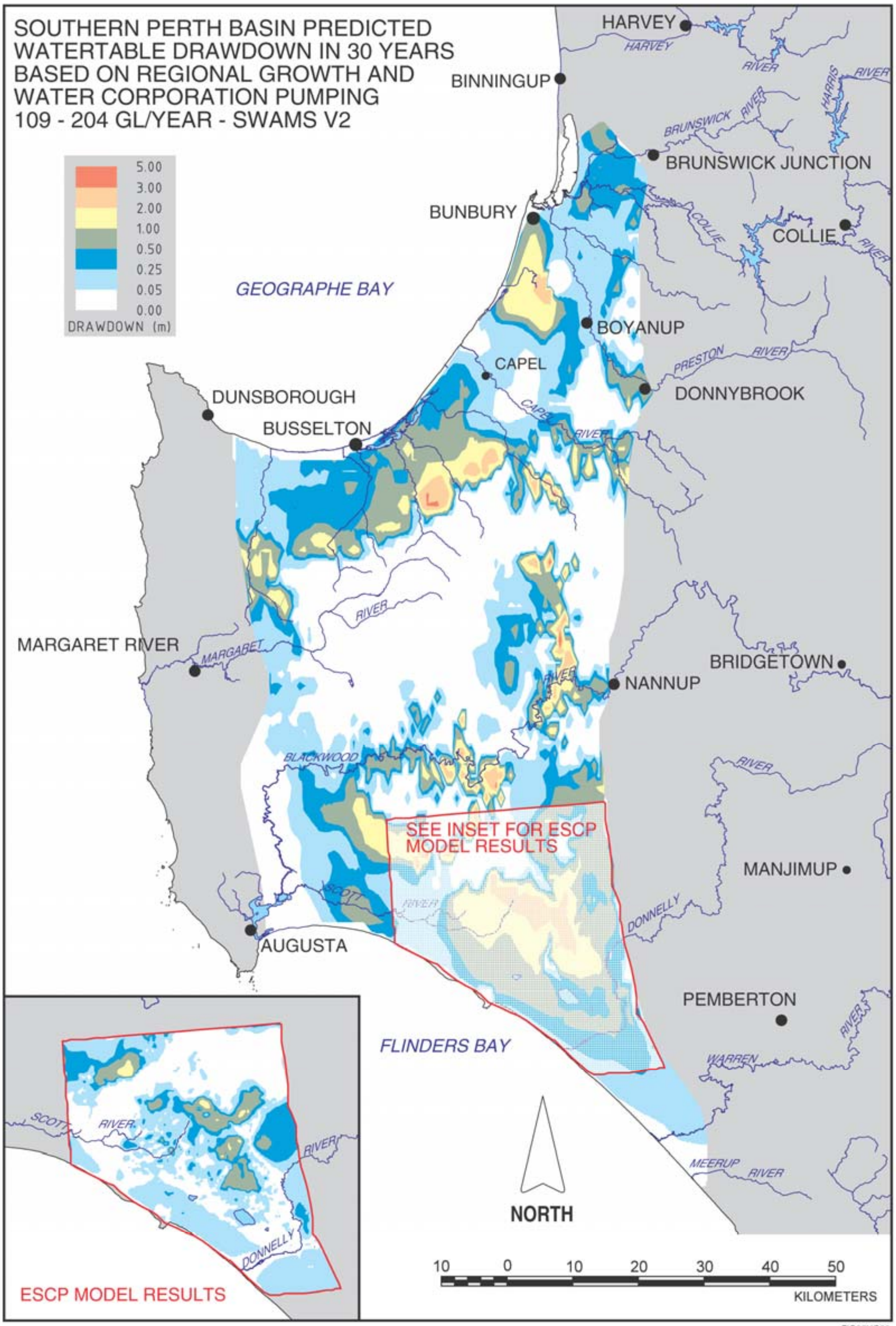

Figure 25: Predicted drawdown at the watertable from regional growth and Water Corporation abstraction (scenario D)

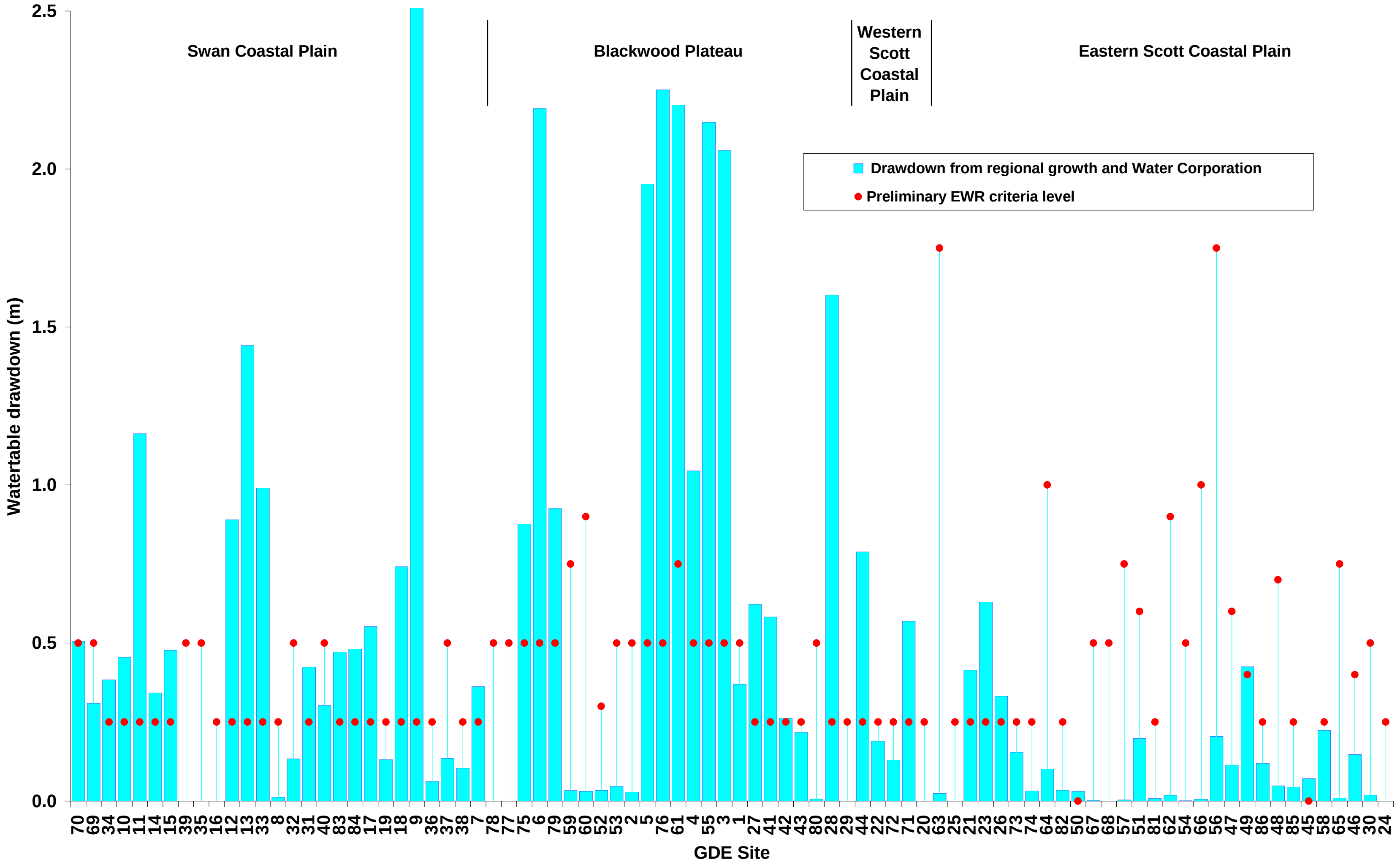

Figure 26: Predicted watertable drawdown at GDE reference sites from the regional growth and Water Corporation abstraction (scenario D)

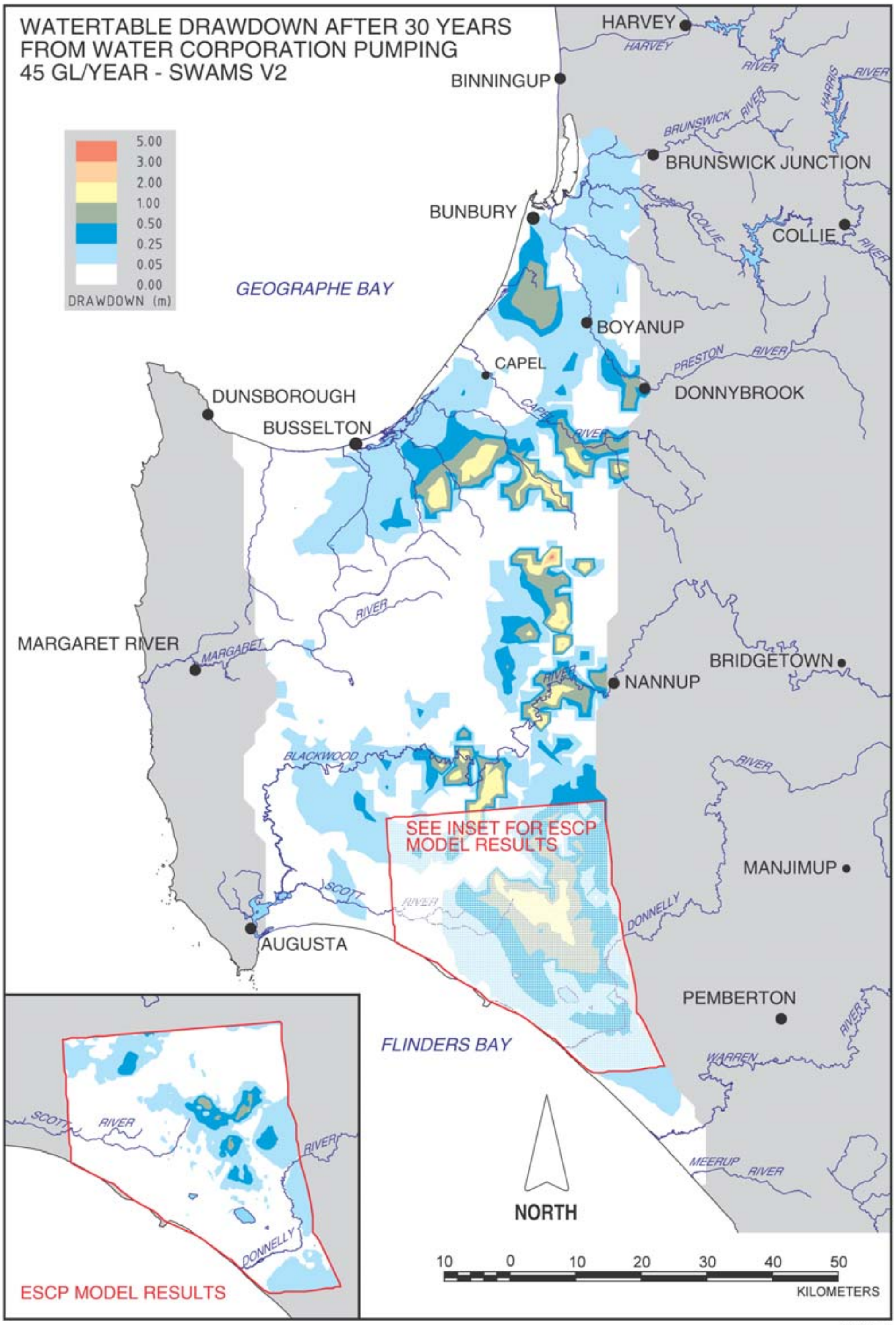

Figure 27: Predicted drawdown at the watertable from Water Corporation abstraction alone

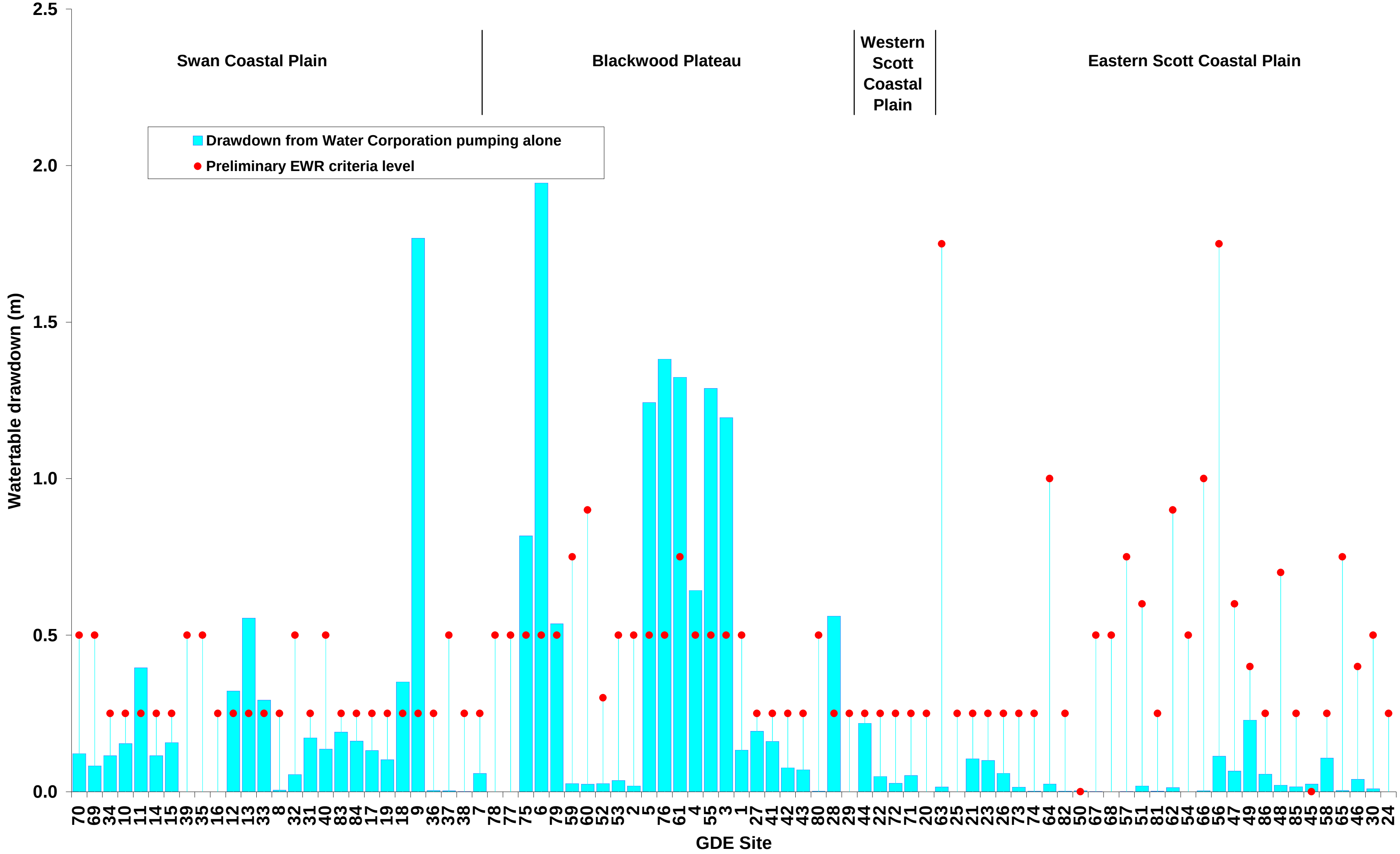

Figure 28: Predicted watertable drawdown at GDE reference sites from Water Corporation abstraction alone

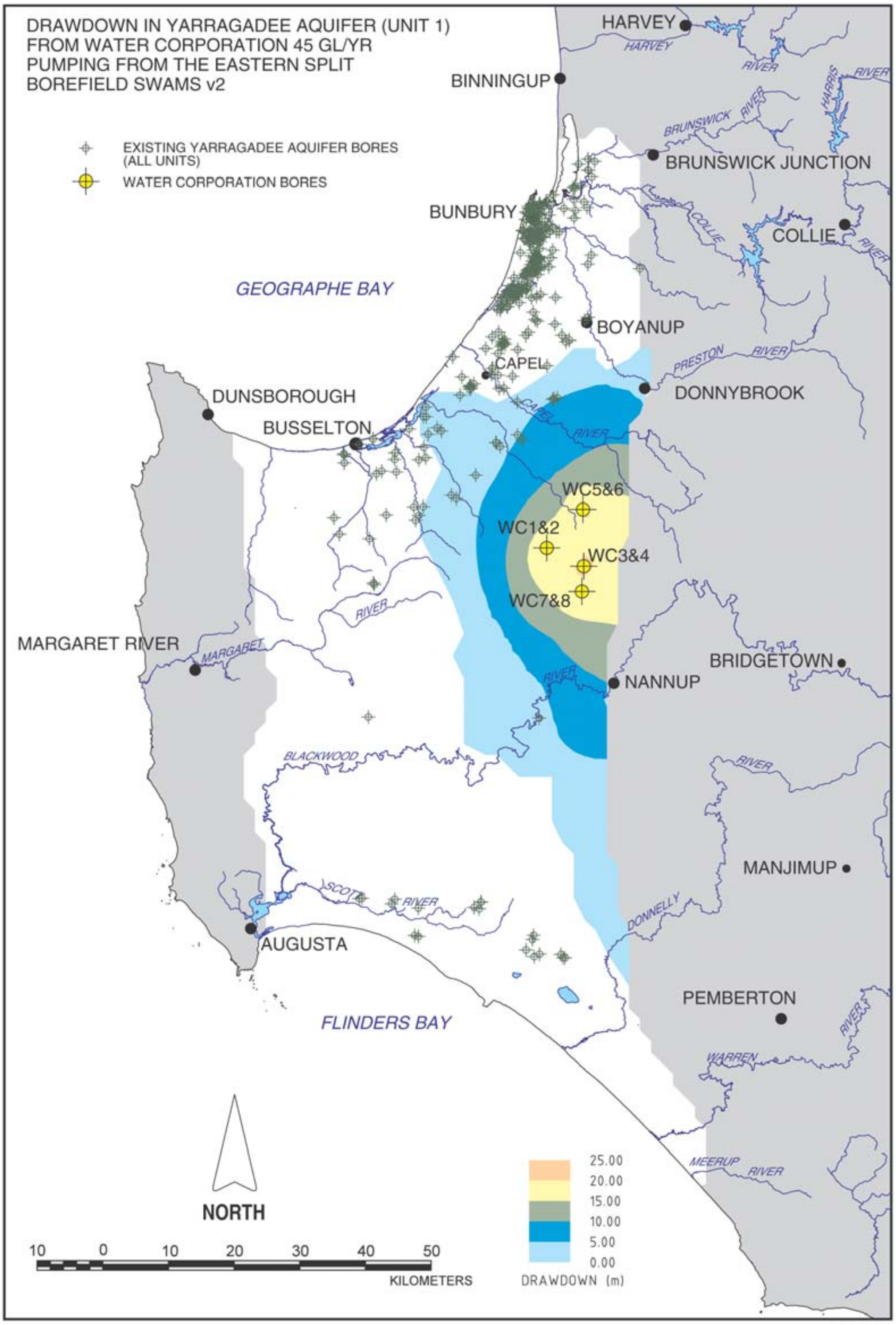

Figure 29: Predicted drawdown from Water Corporation abstraction in Yarragadee aquifer (Unit 1)

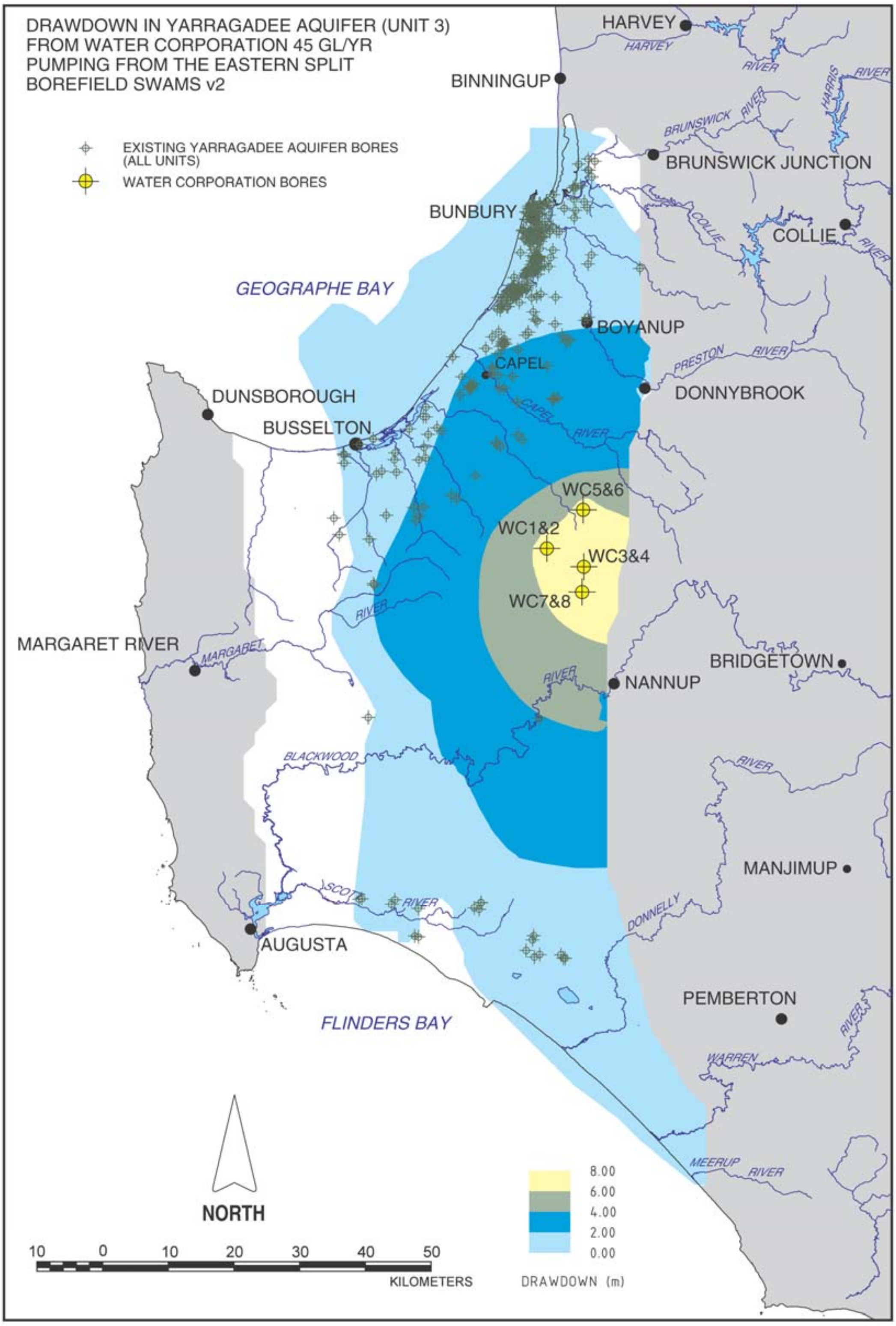

Figure 30: Predicted drawdown from Water Corporation abstraction in Yarragadee aquifer (Unit 3)

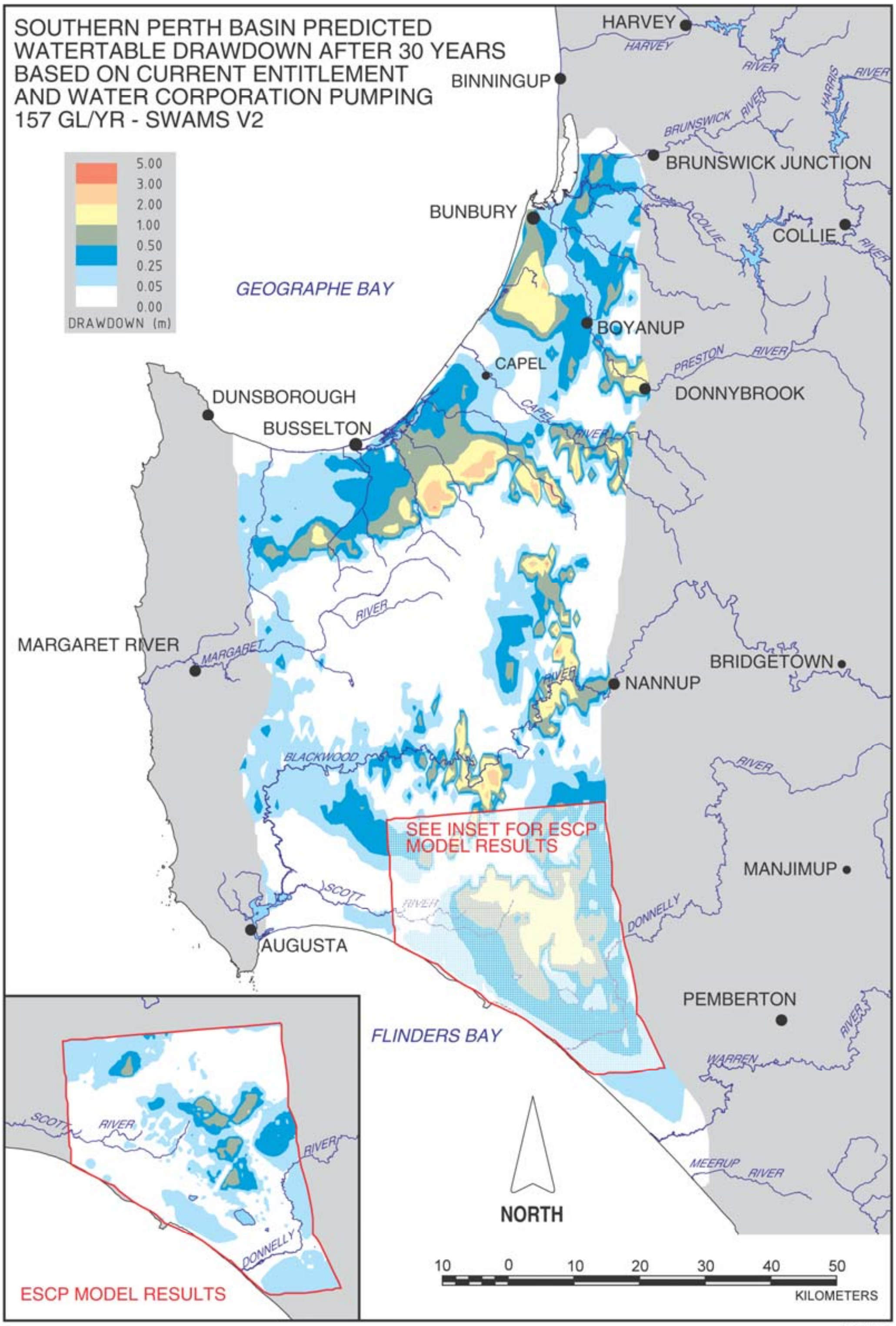

Figure 31: Predicted drawdown at the watertable from the current entitlements and Water Corporation abstraction

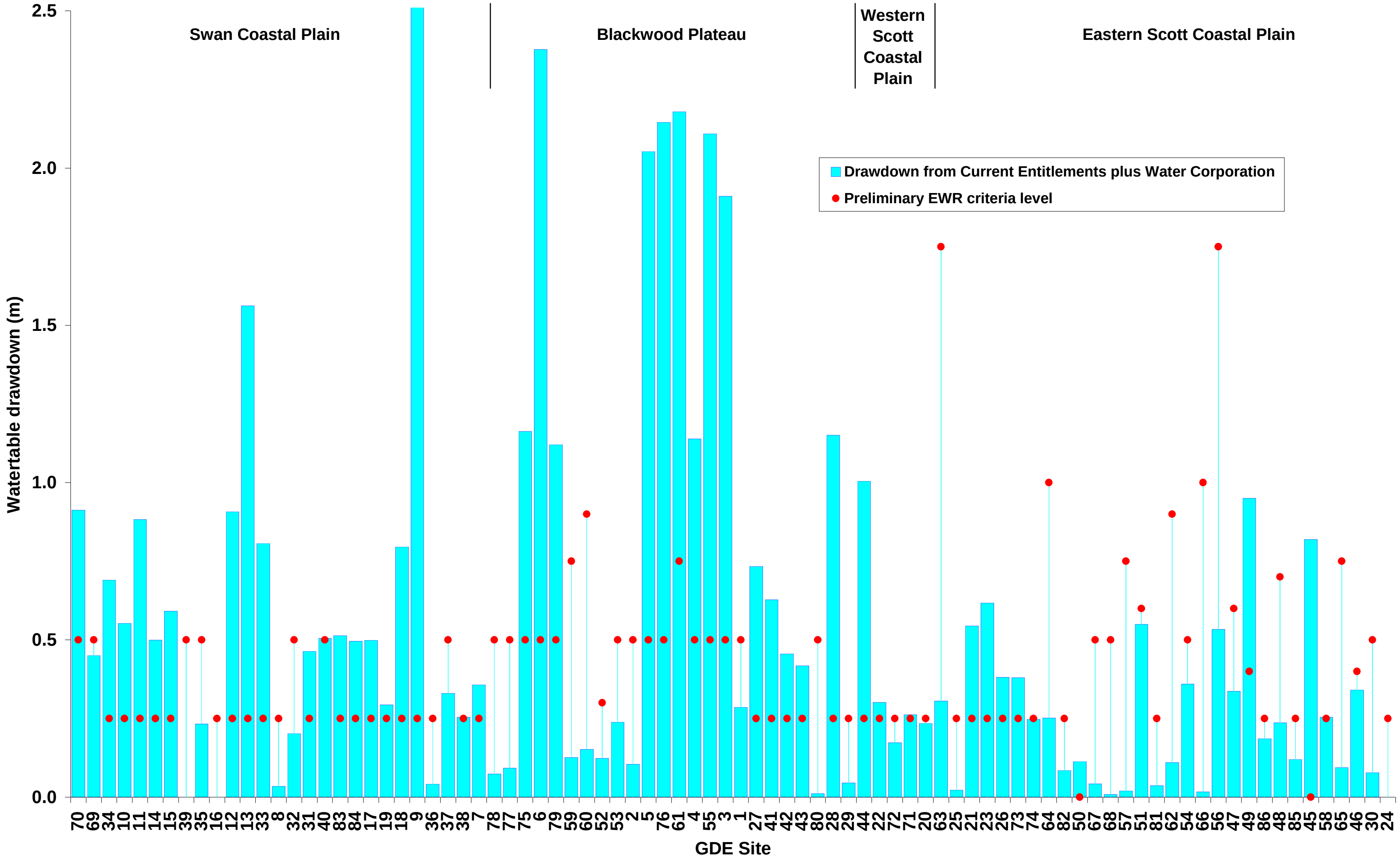

Figure 32: Predicted watertable drawdown at GDE reference sites from the current entitlements plus Water Corporation abstraction

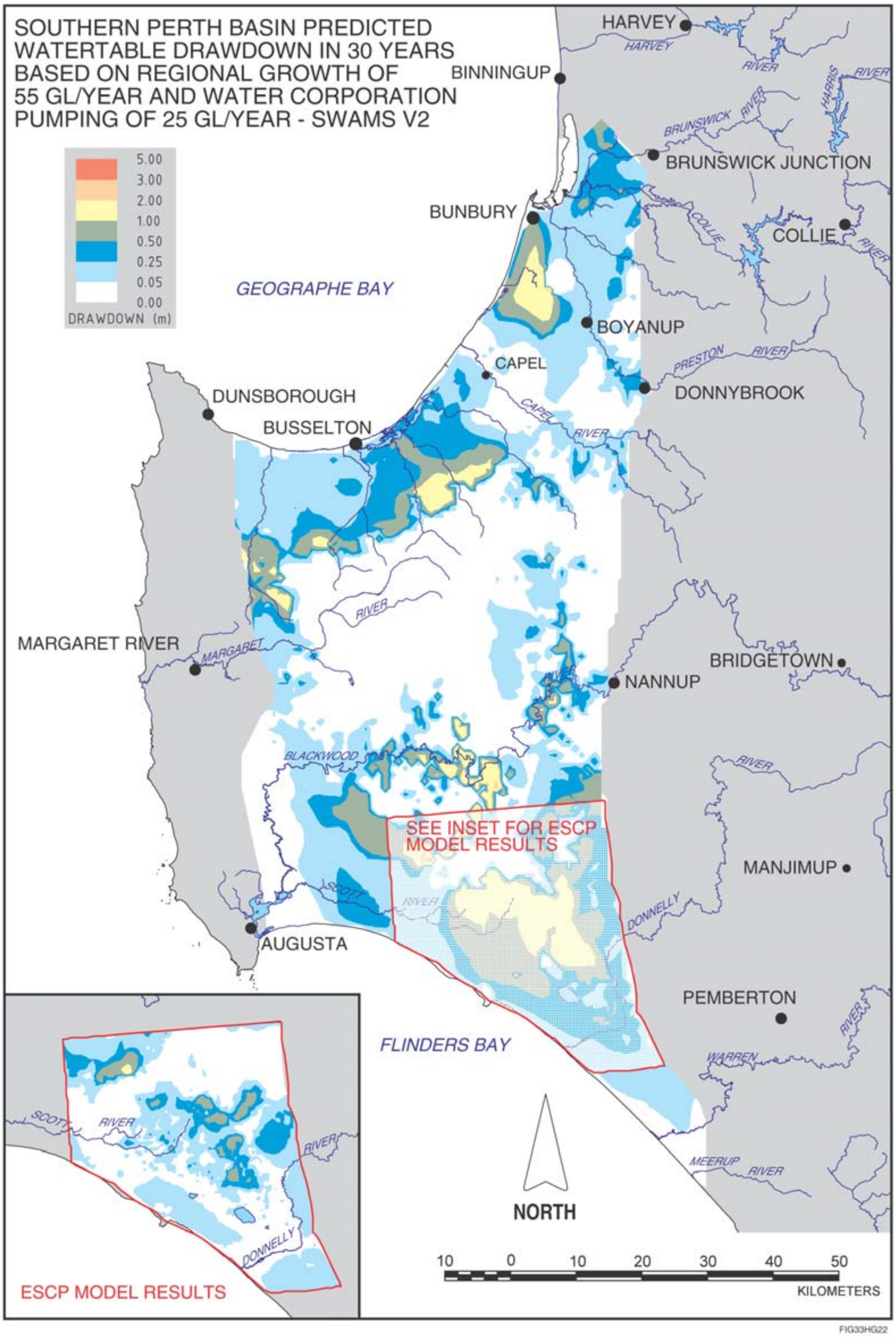

Figure 33: Predicted drawdown at the watertable from a reduced regional growth and reduced Water Corporation abstraction (scenario E)

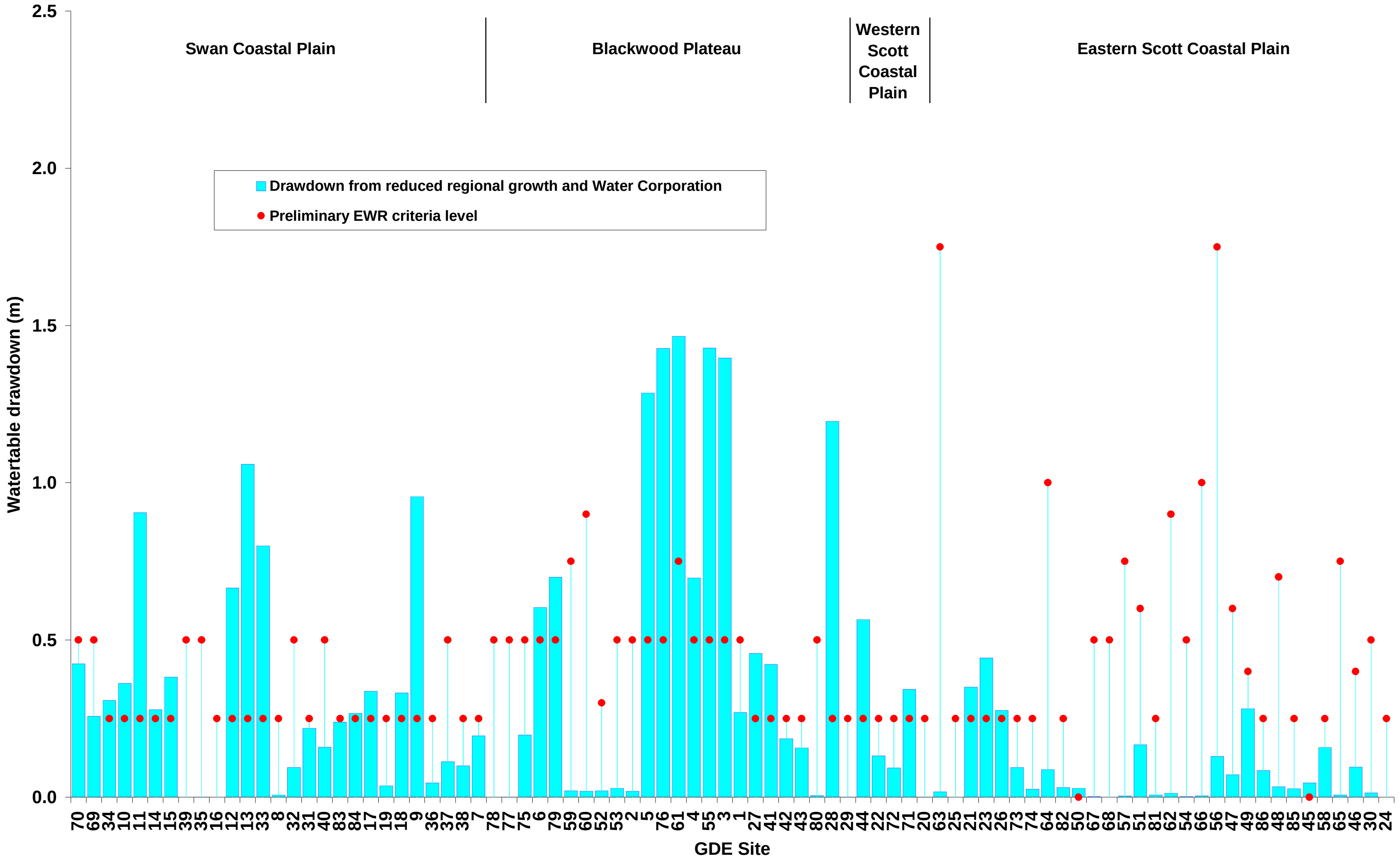

Figure 34: Predicted watertable drawdown at GDE reference sites from a reduced regional growth and reduced Water Corporation abstraction (Scenario E)

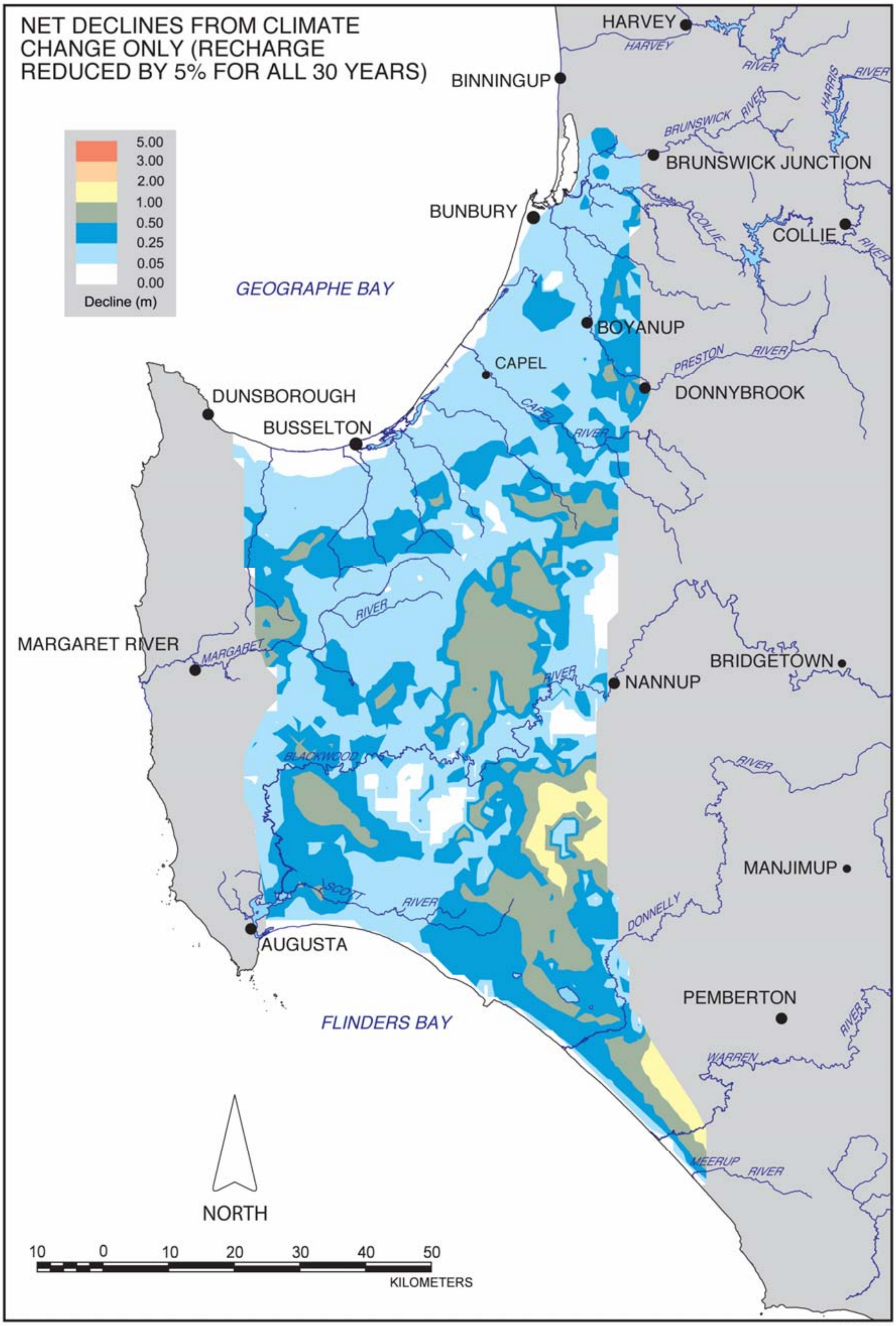

Figure 35*: Predicted decline from the effect of reduced rainfall*

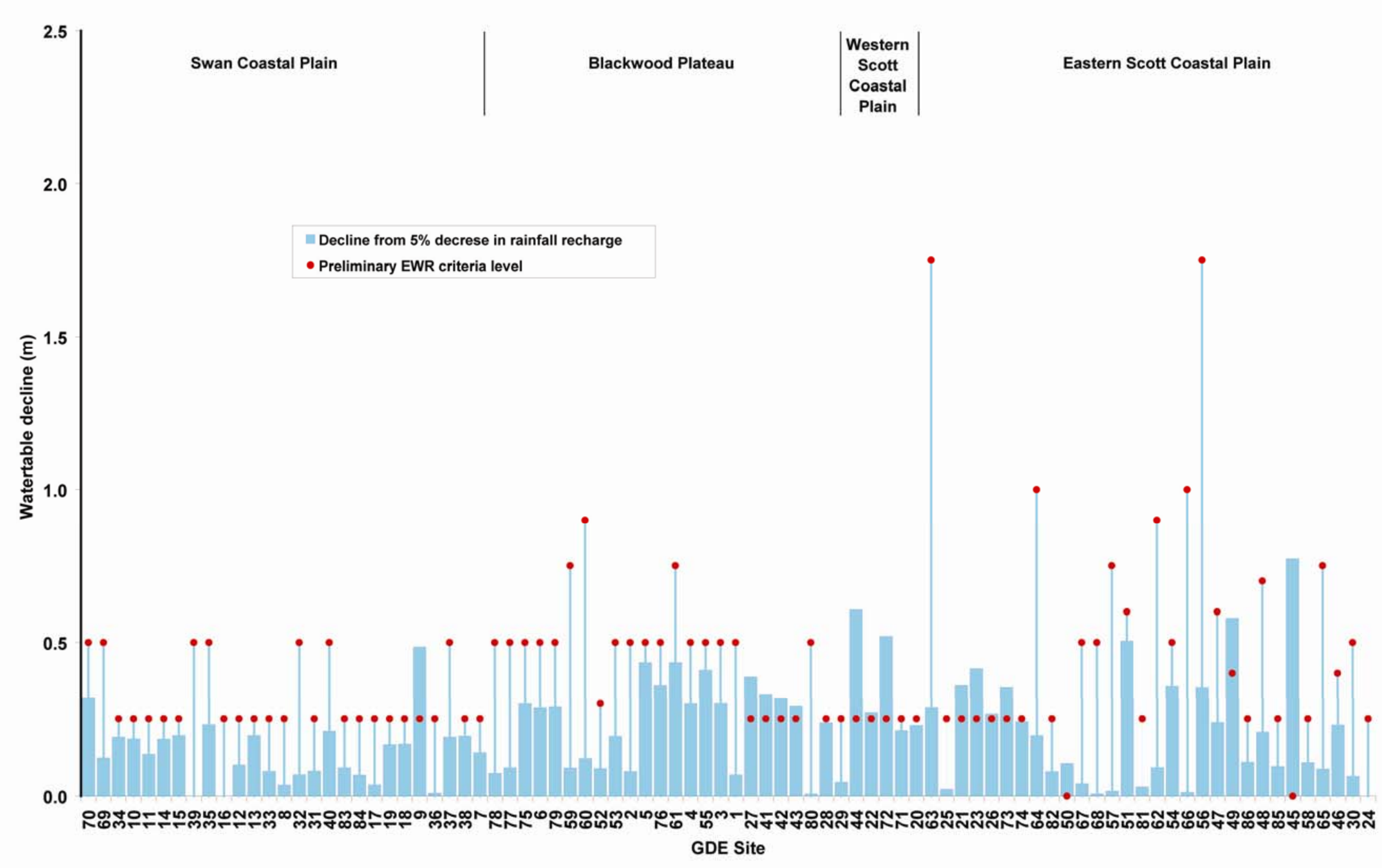

Figure 36: Predicted watertable decline at the GDE reference sites from the effects of reduced rainfall recharge

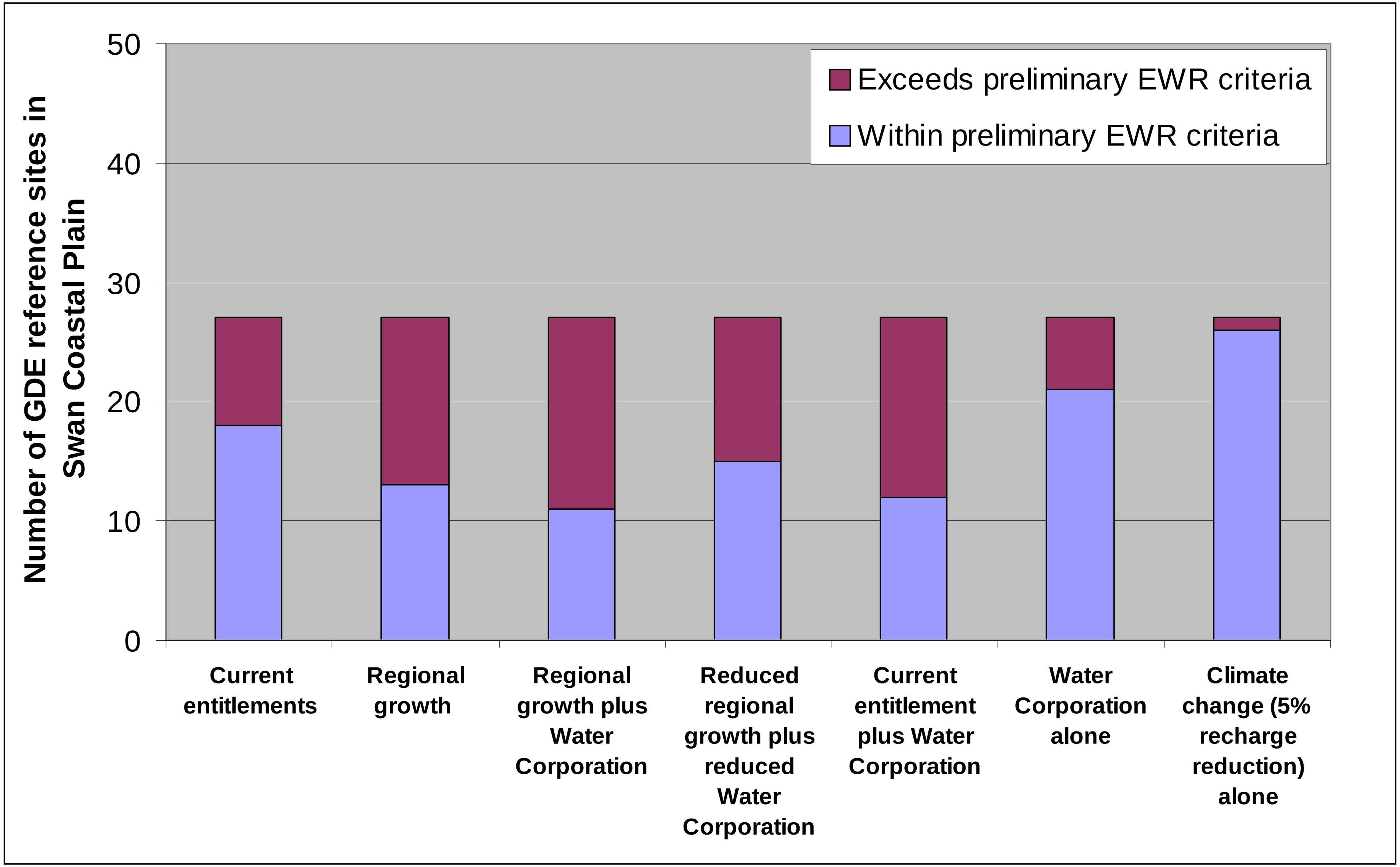

Figure 37: Summary of where EWR criteria is within or exceeds set levels at GDE reference sites on Swan Coastal Plain

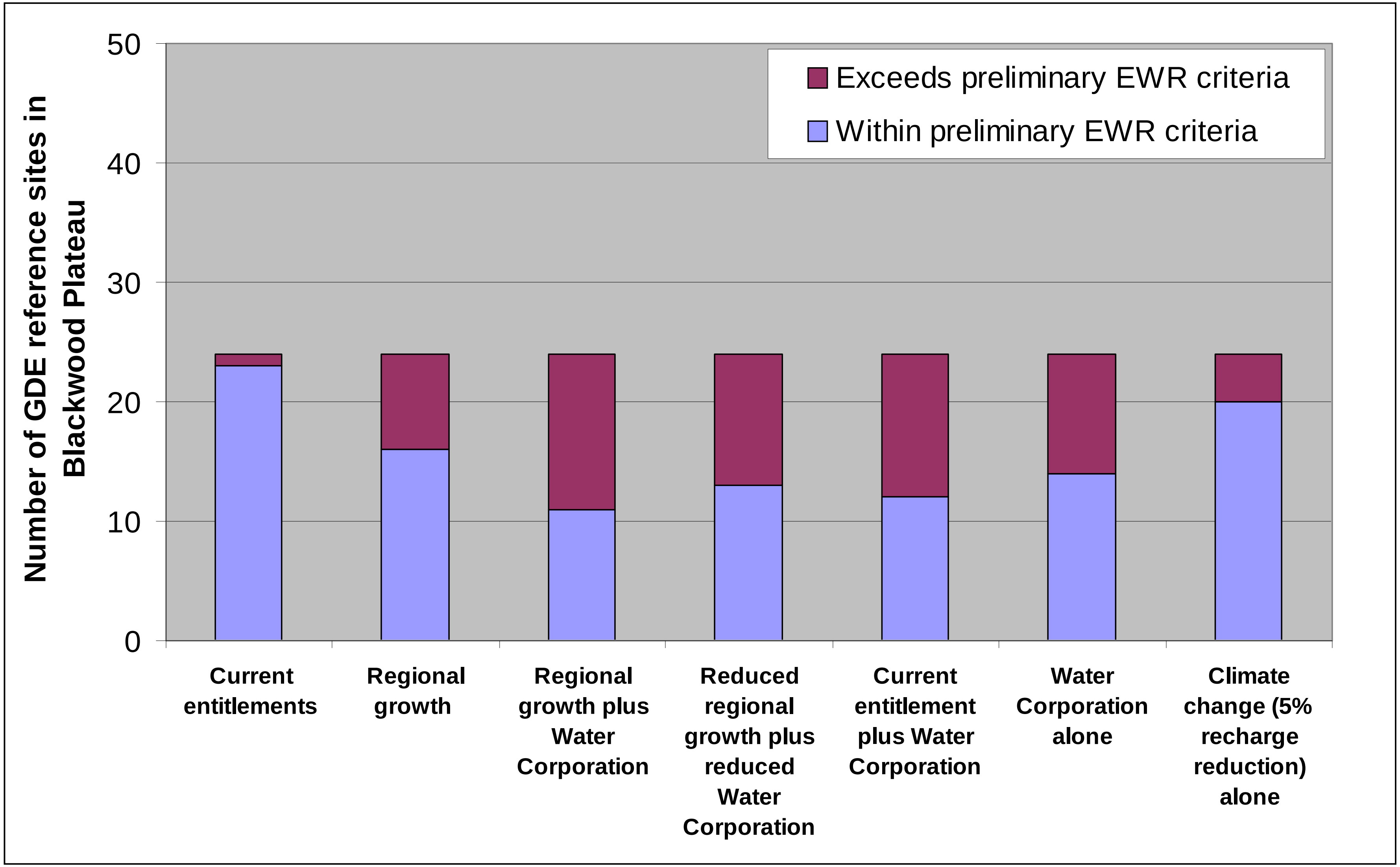

Figure 38: Summary of where EWR criteria is within or exceeds set levels at GDE reference sites on Blackwood Plateau

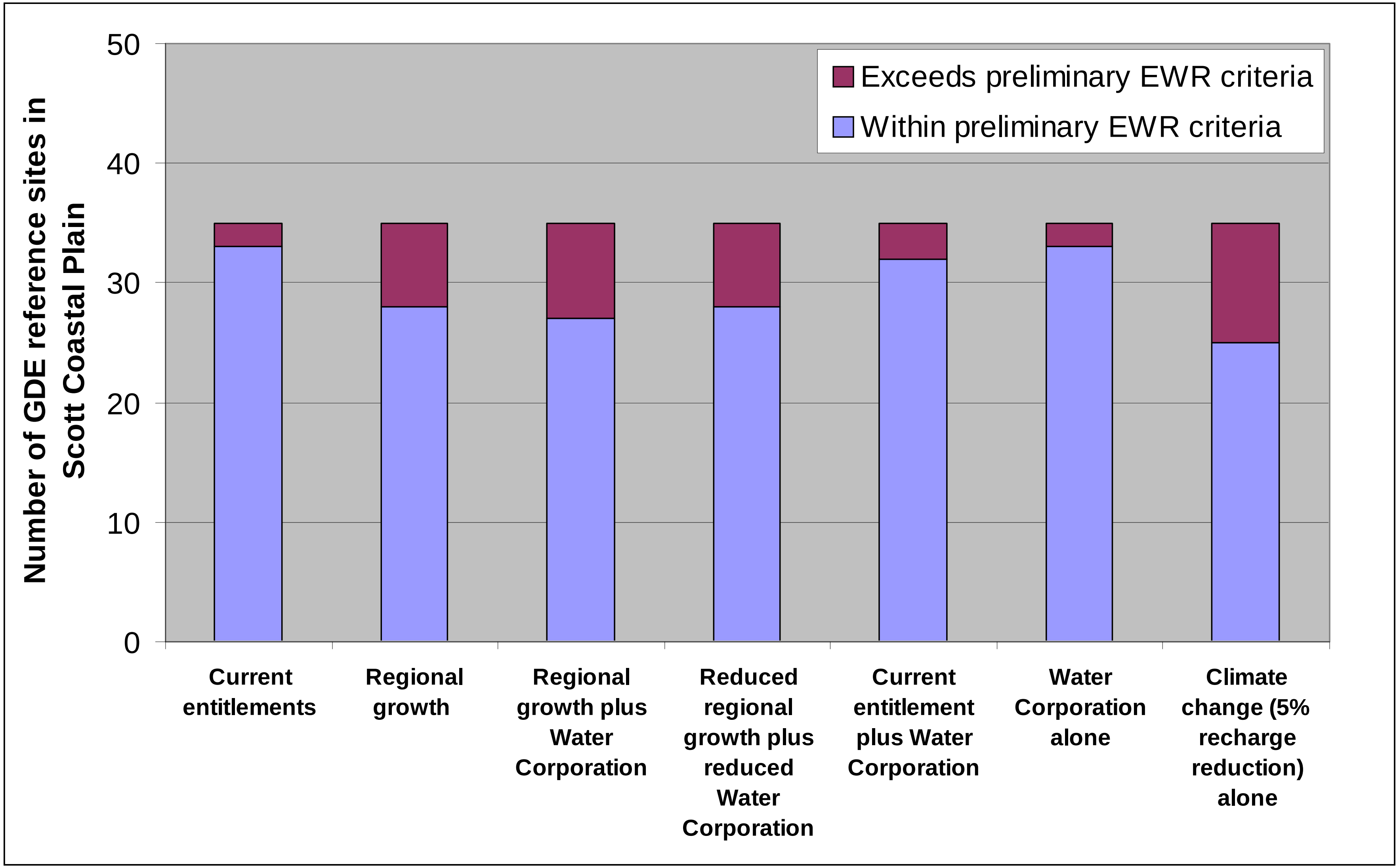

Figure 39: Summary of where EWR criteria is within or exceeds set levels at GDE reference sites on Scott Coastal Plain

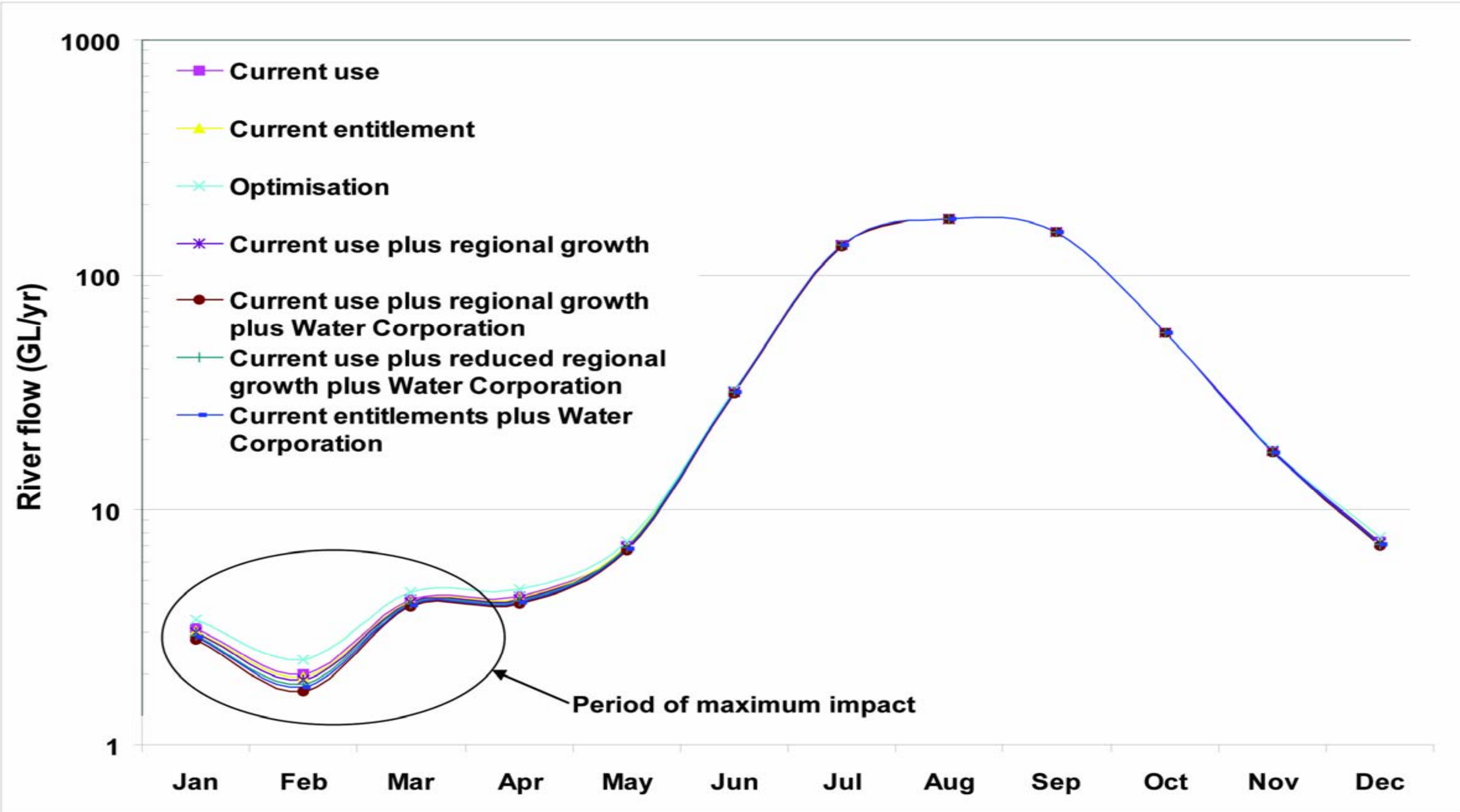

Figure 40: Predicted monthly flow in Blackwood River at Hut Pool

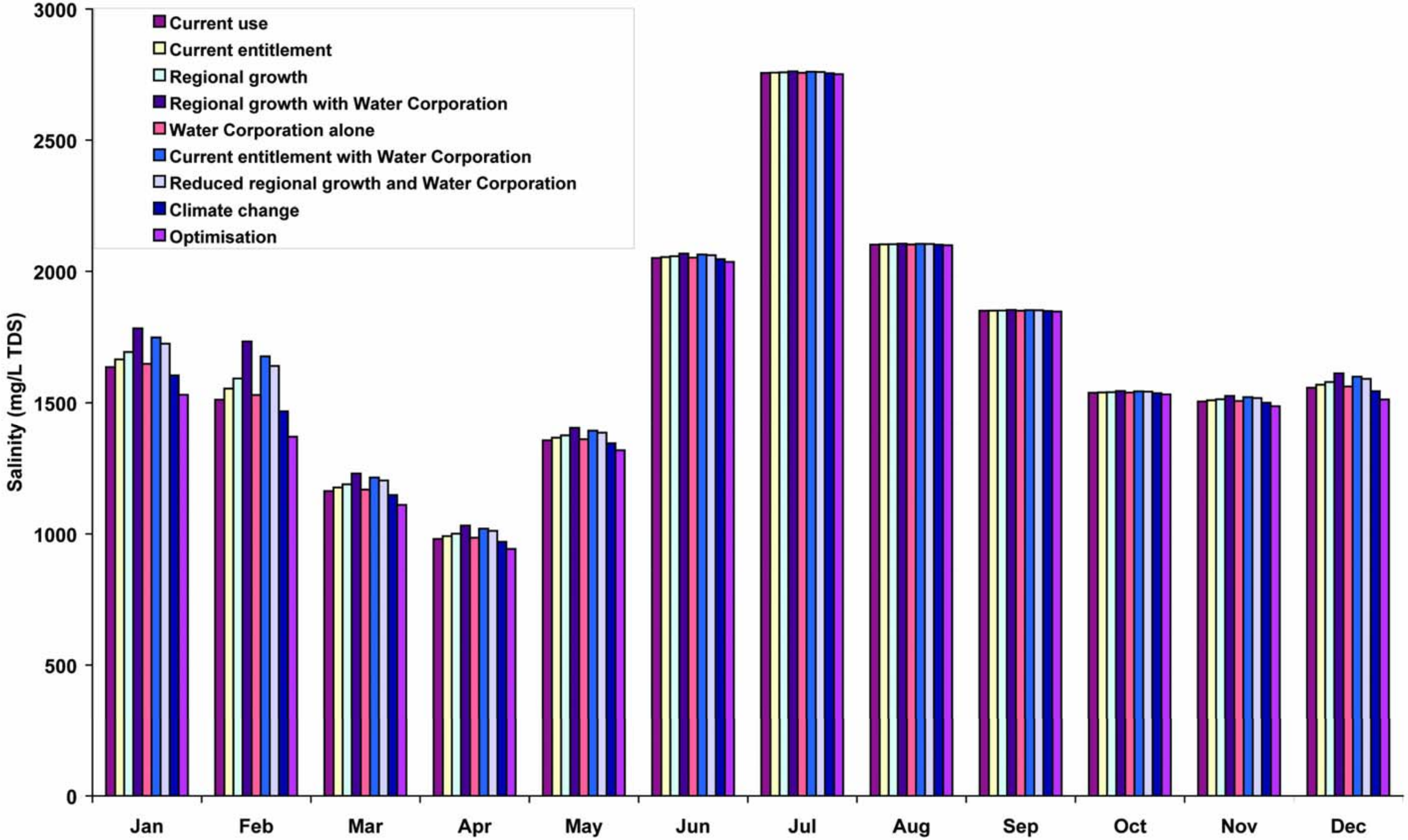

Figure 41: Predicted river salinity as a result of reduction in groundwater discharge for the different scenarios

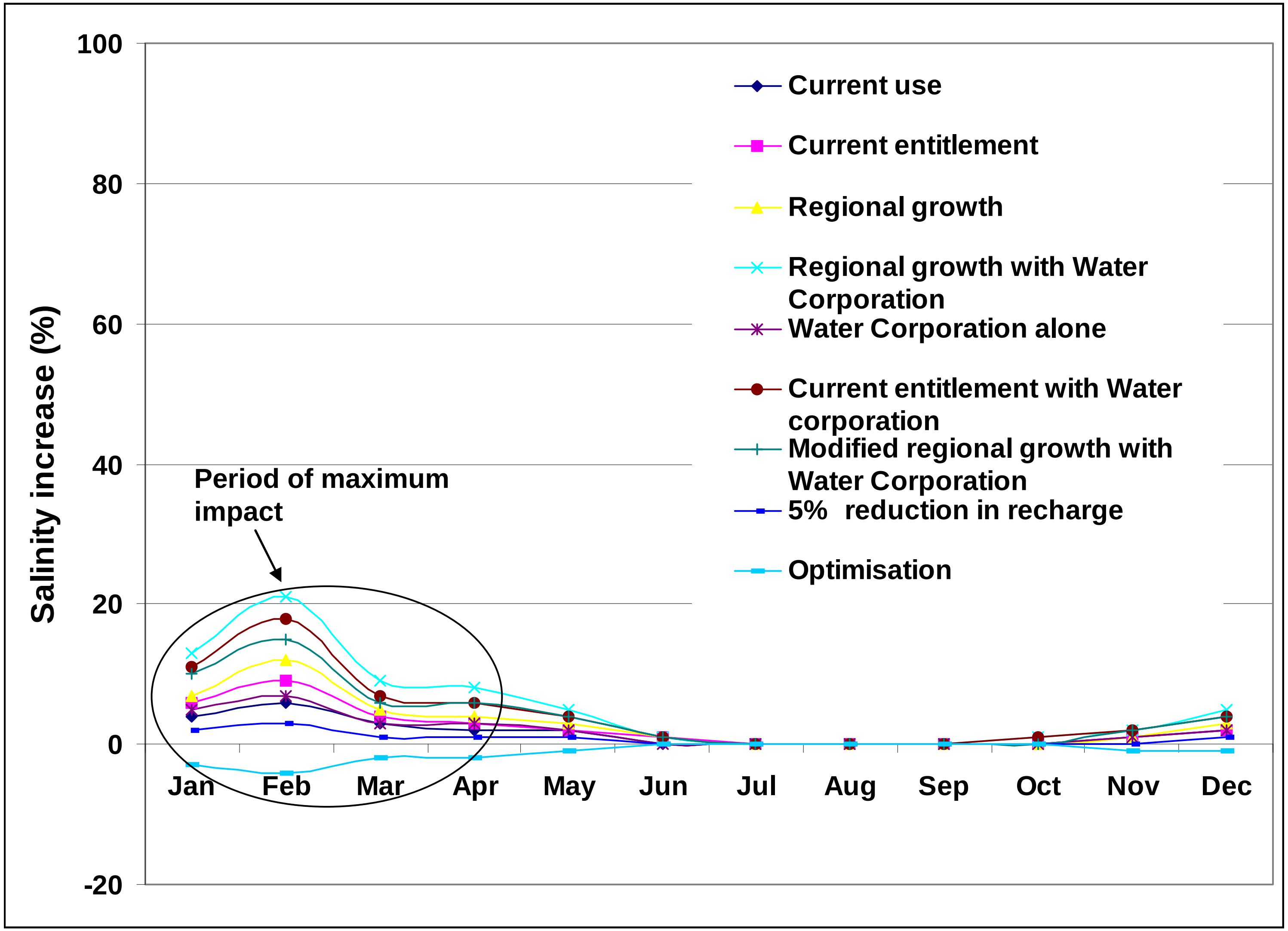

Figure 42: Predicted salinity change in the Blackwood River at Hut Pool

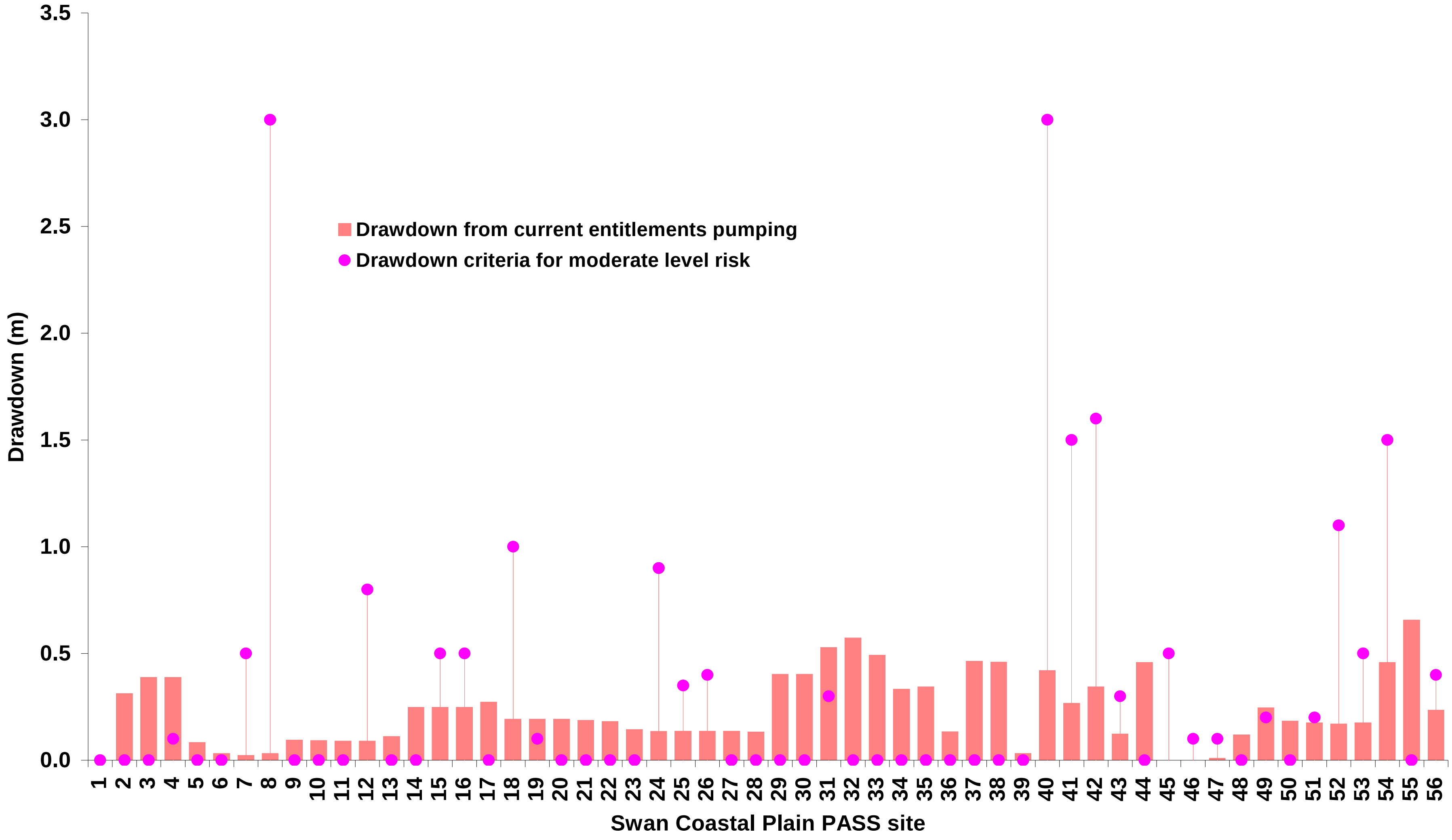

Figure 43: Predicted watertable drawdown at PASS sites on Swan Coastal Plain for current entitlements (scenario A)

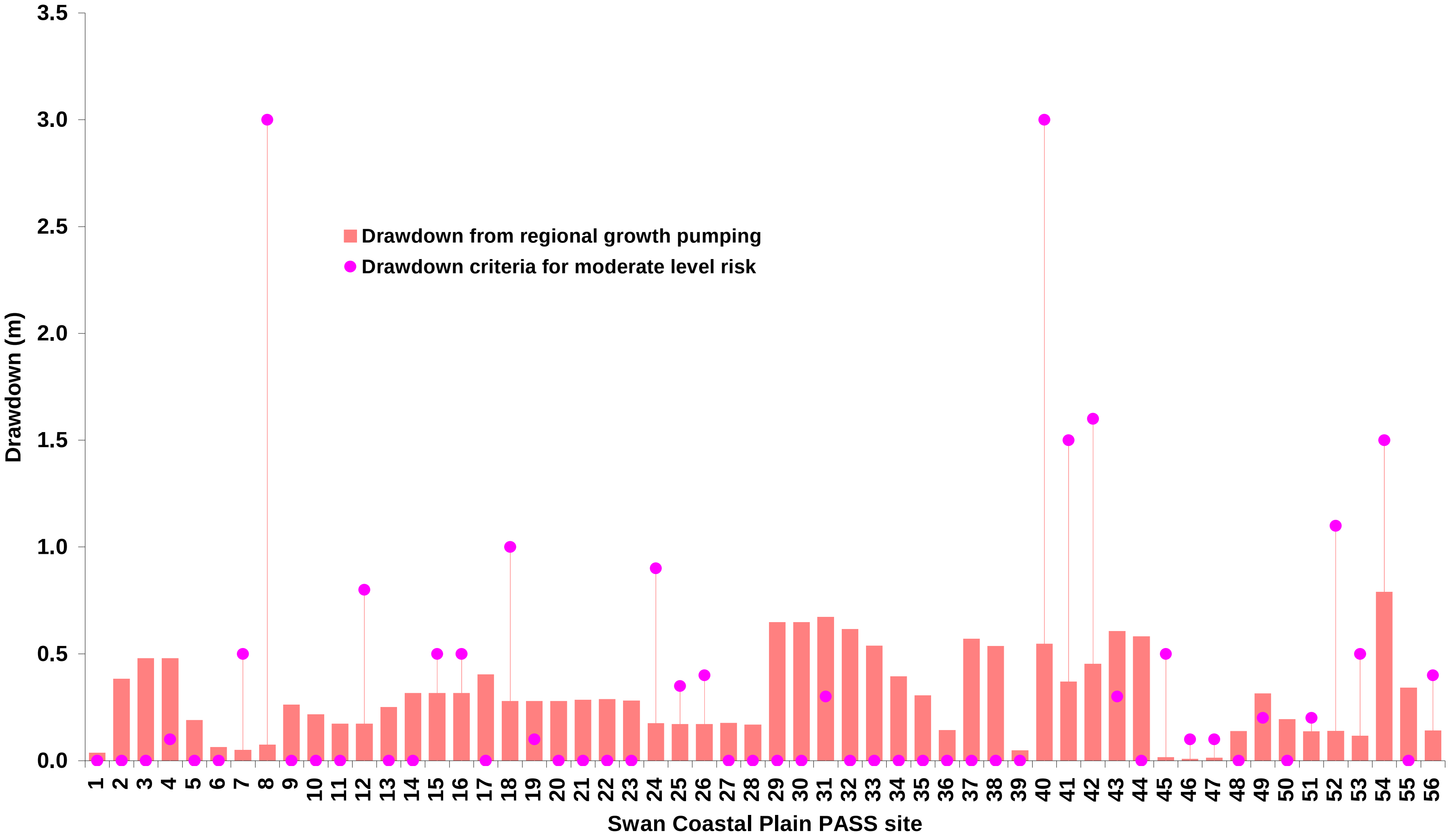

Figure 44: Predicted watertable drawdown at PASS sites on Swan Coastal Plain for regional growth (scenario C)

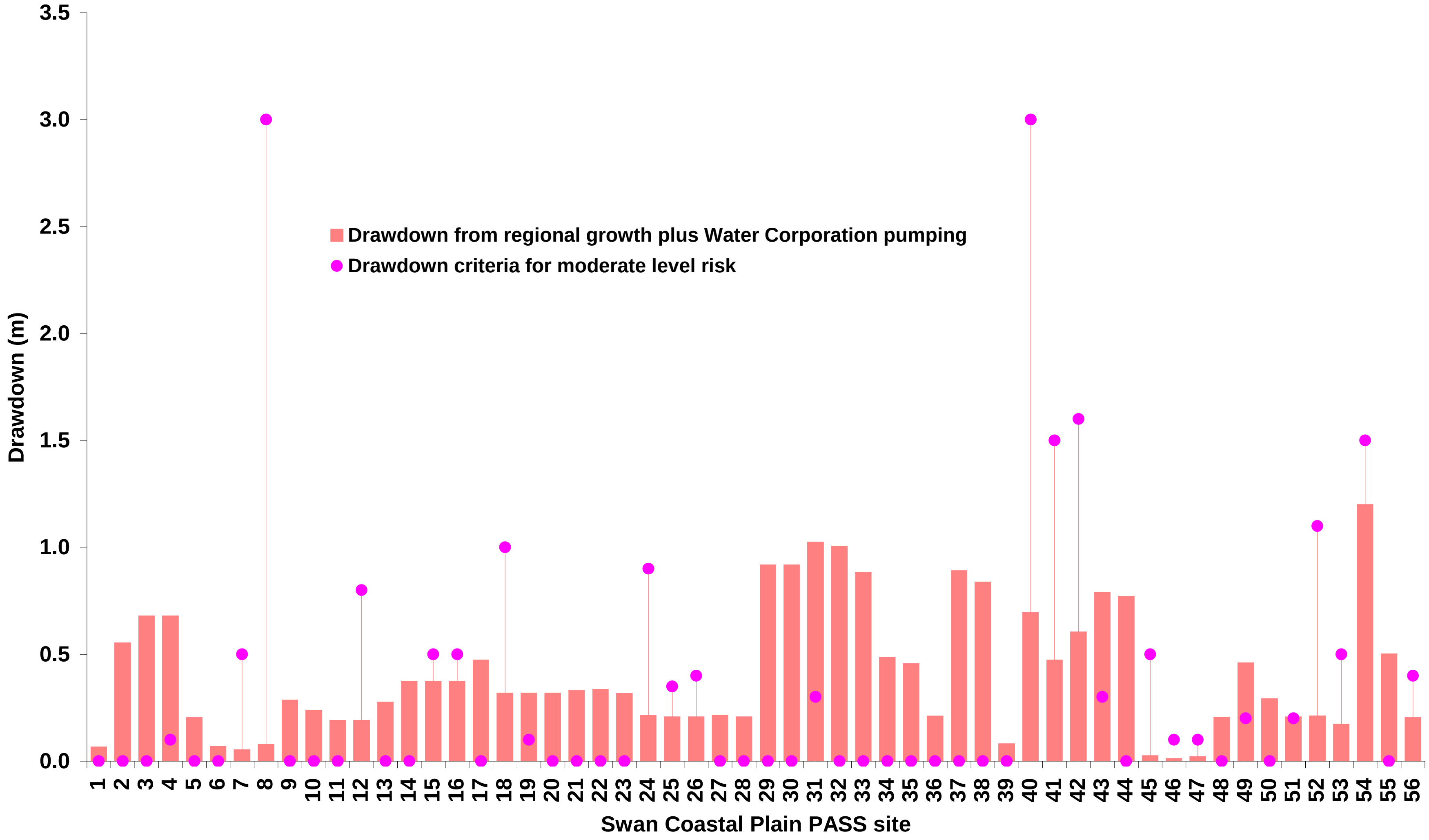

Figure 45: Predicted watertable drawdown at PASS sites on Swan Coastal Plain for regional growth plus Water Corporation (scenario D)

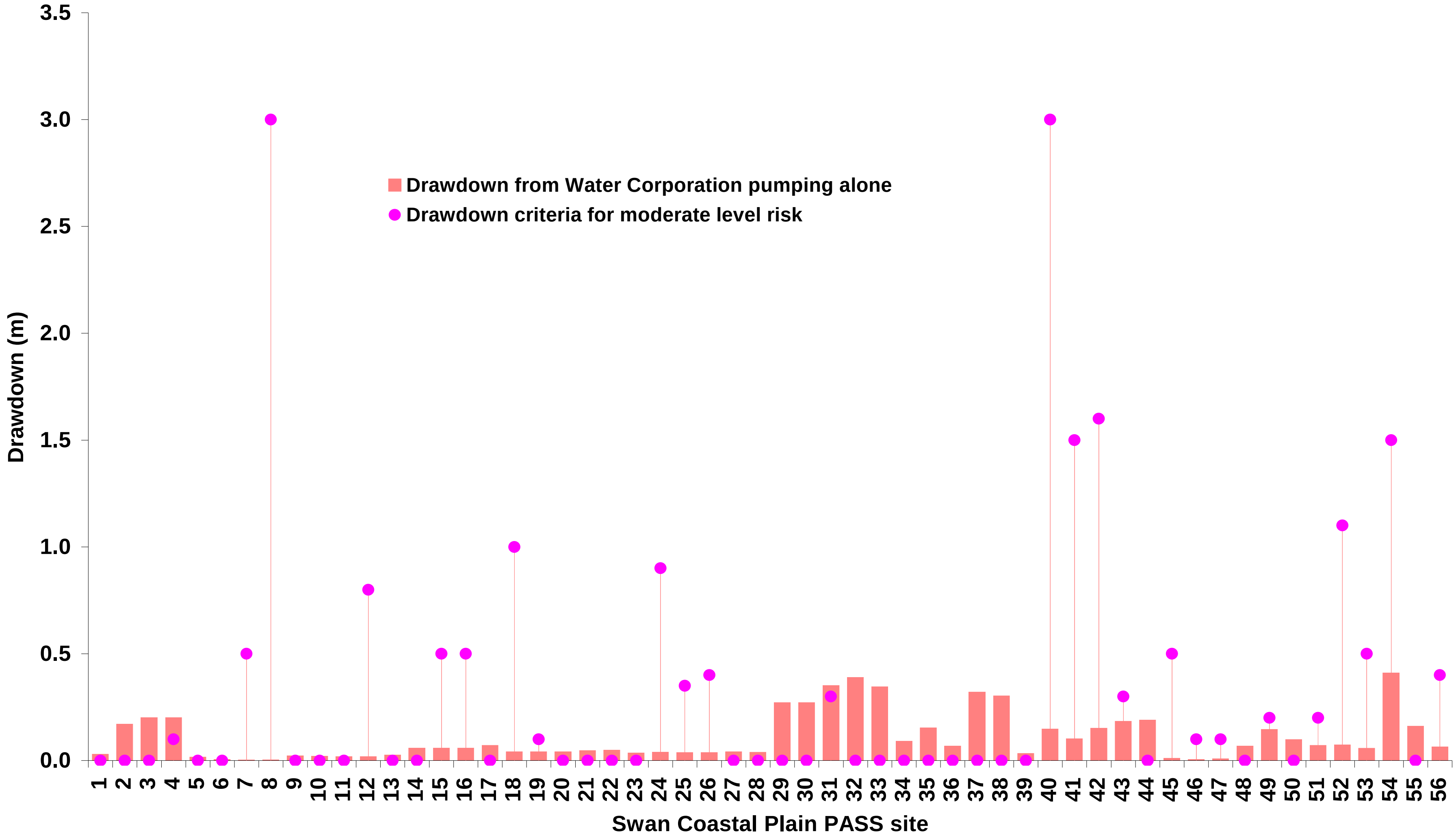

Figure 46: Predicted watertable drawdown at PASS sites on Swan Coastal Plain for Water Corporation abstraction alone

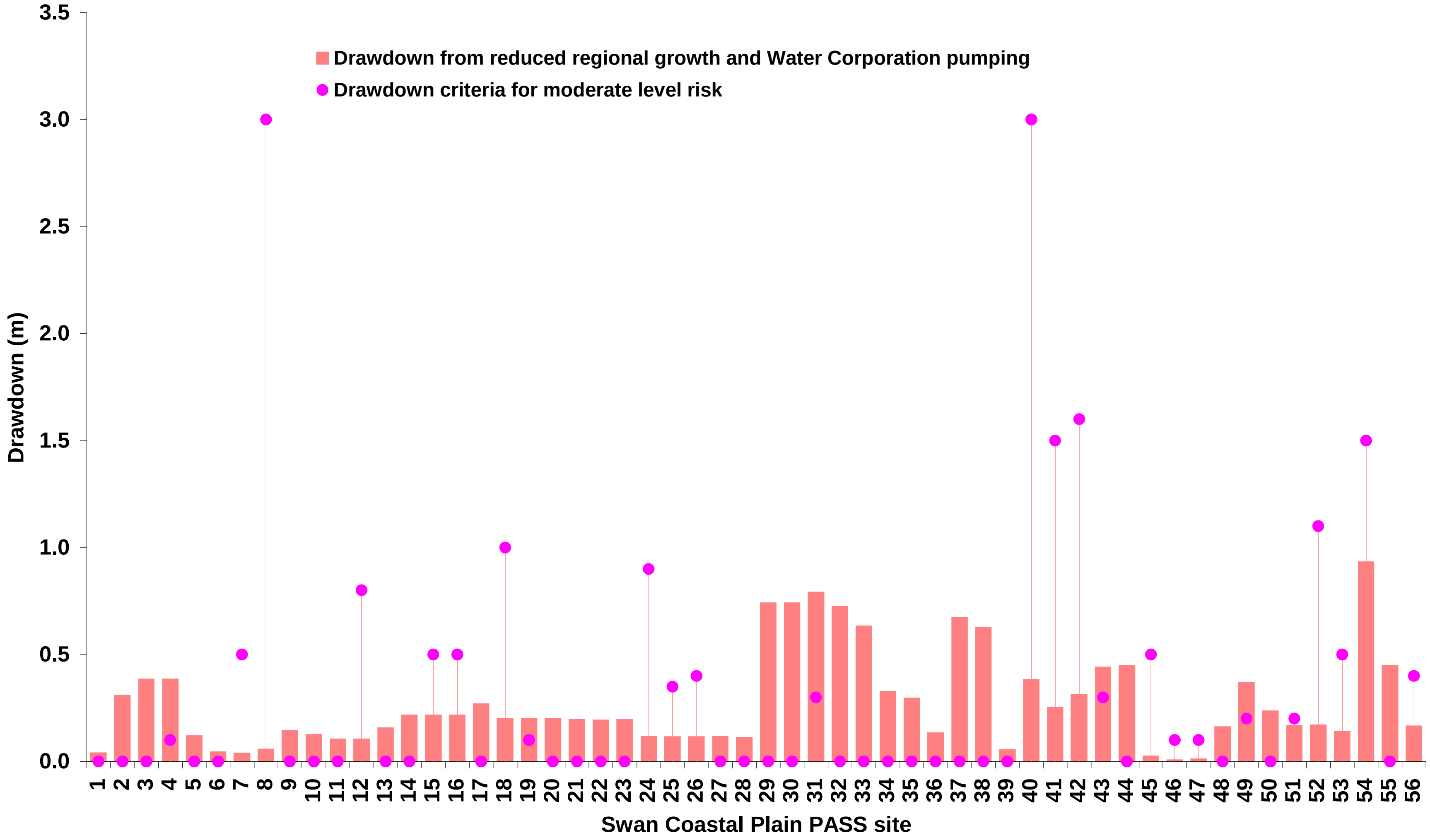

Figure 47: Predicted watertable drawdown at PASS sites on Swan Coastal Plain for reduced regional growth and Water Corporation (scenario E)

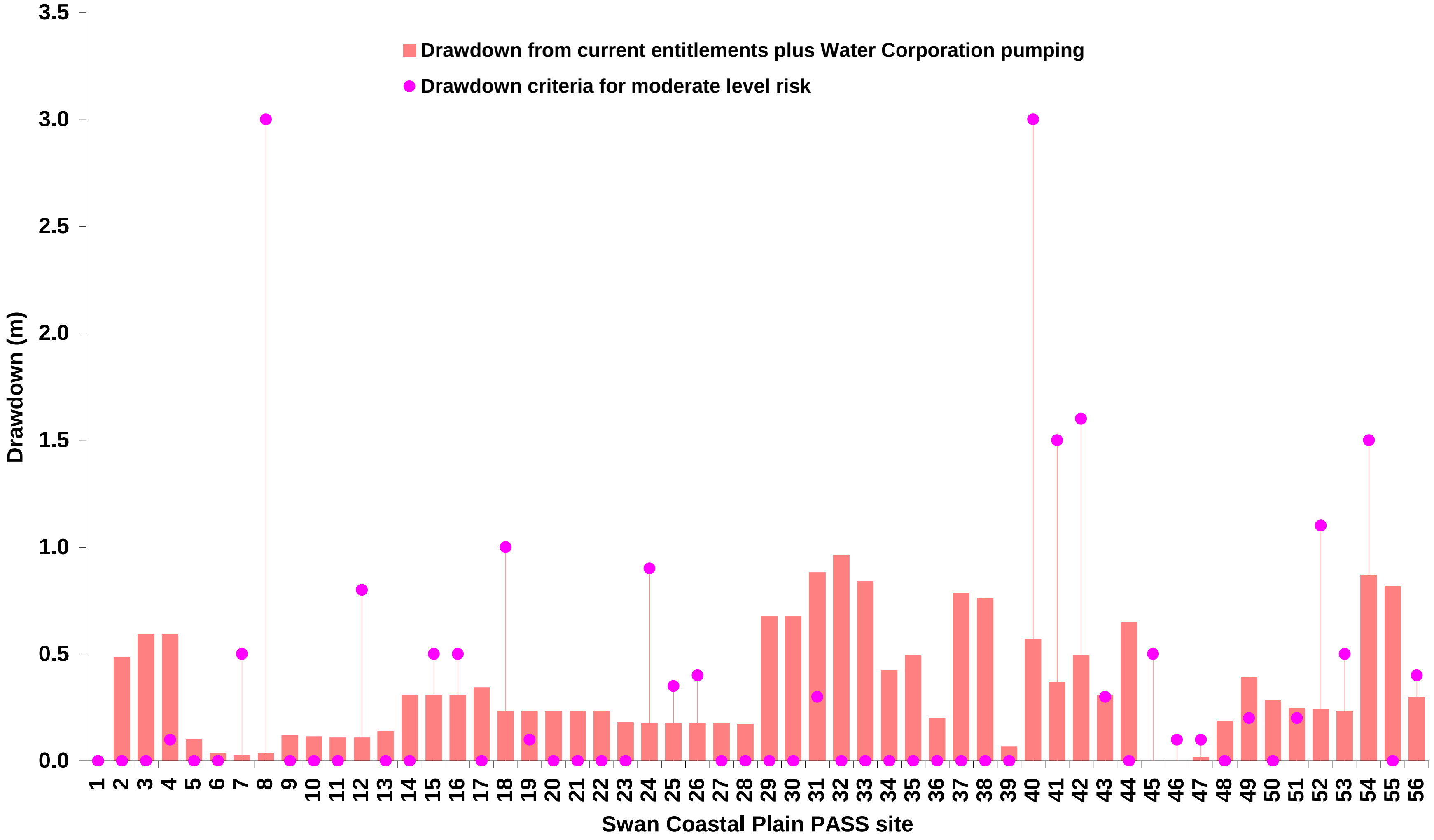

Figure 48: Predicted watertable drawdown at PASS sites on Swan Coastal Plain for current entitlements plus Water Corporation scenario

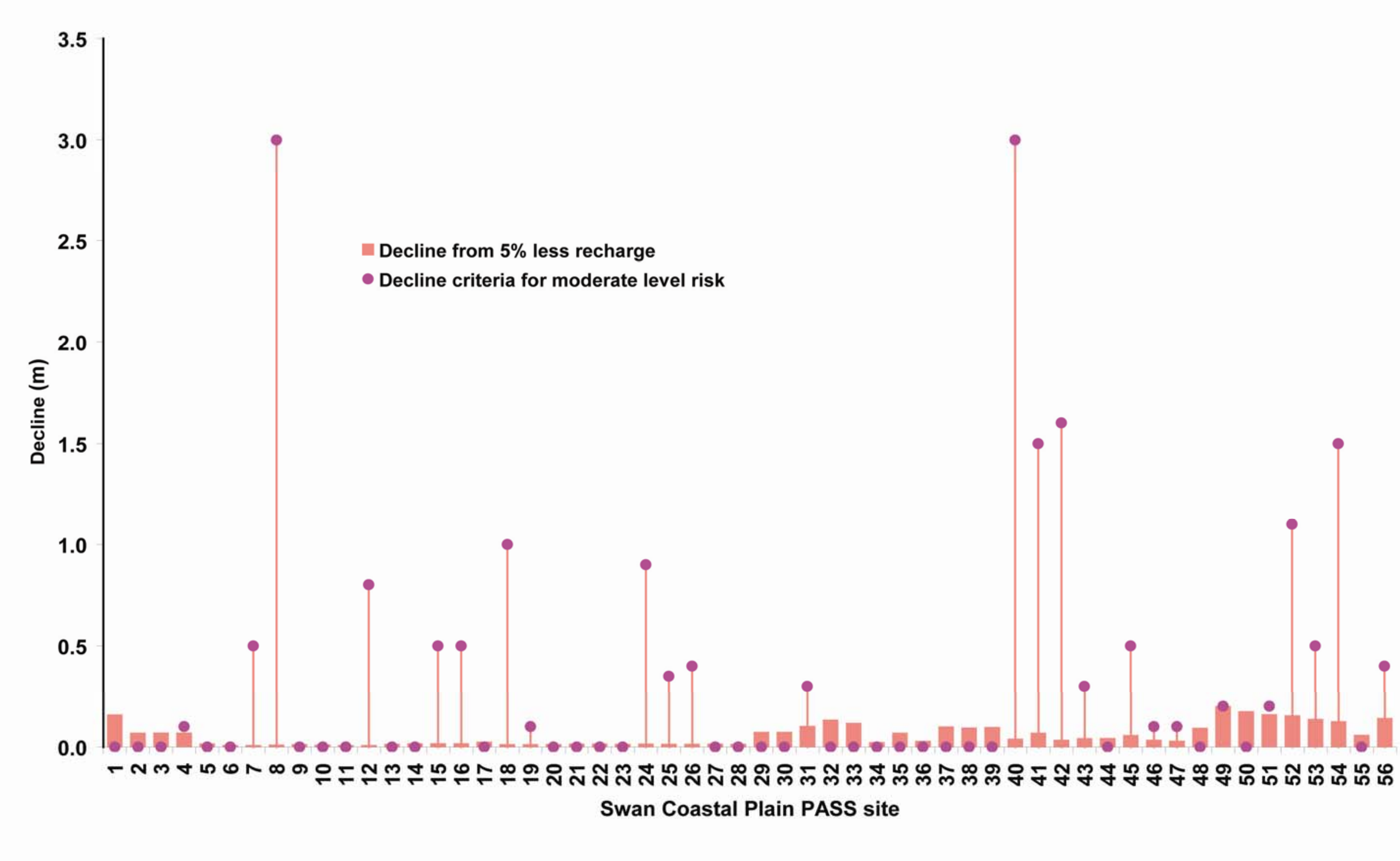

Figure 49: Predicted watertable decline at PASS sites on Swan Coastal Plain for 5 per cent less rainfall recharge

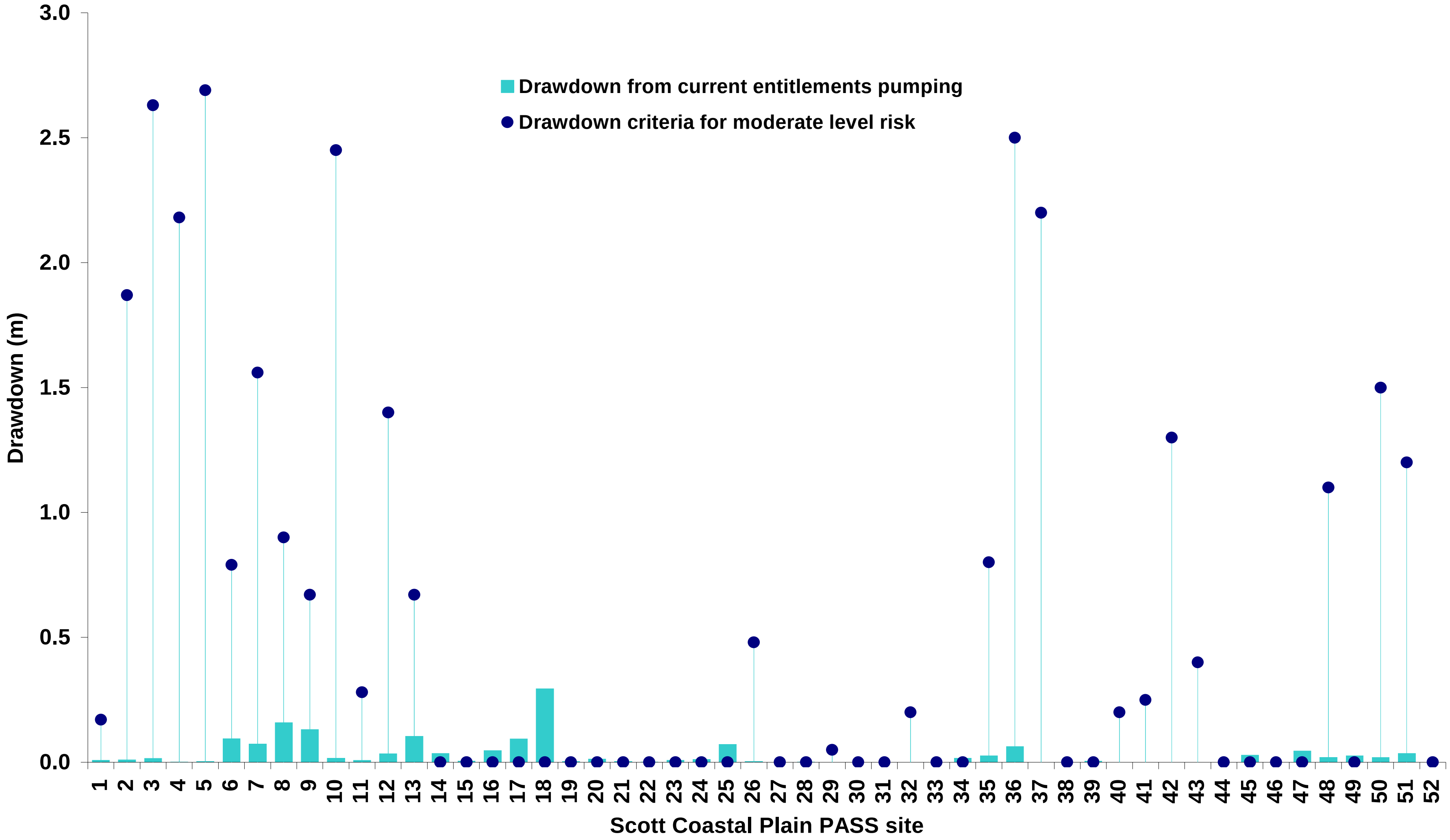

Figure 50: Predicted watertable drawdown at PASS sites on Scott Coastal Plain for current entitlements (scenario A)

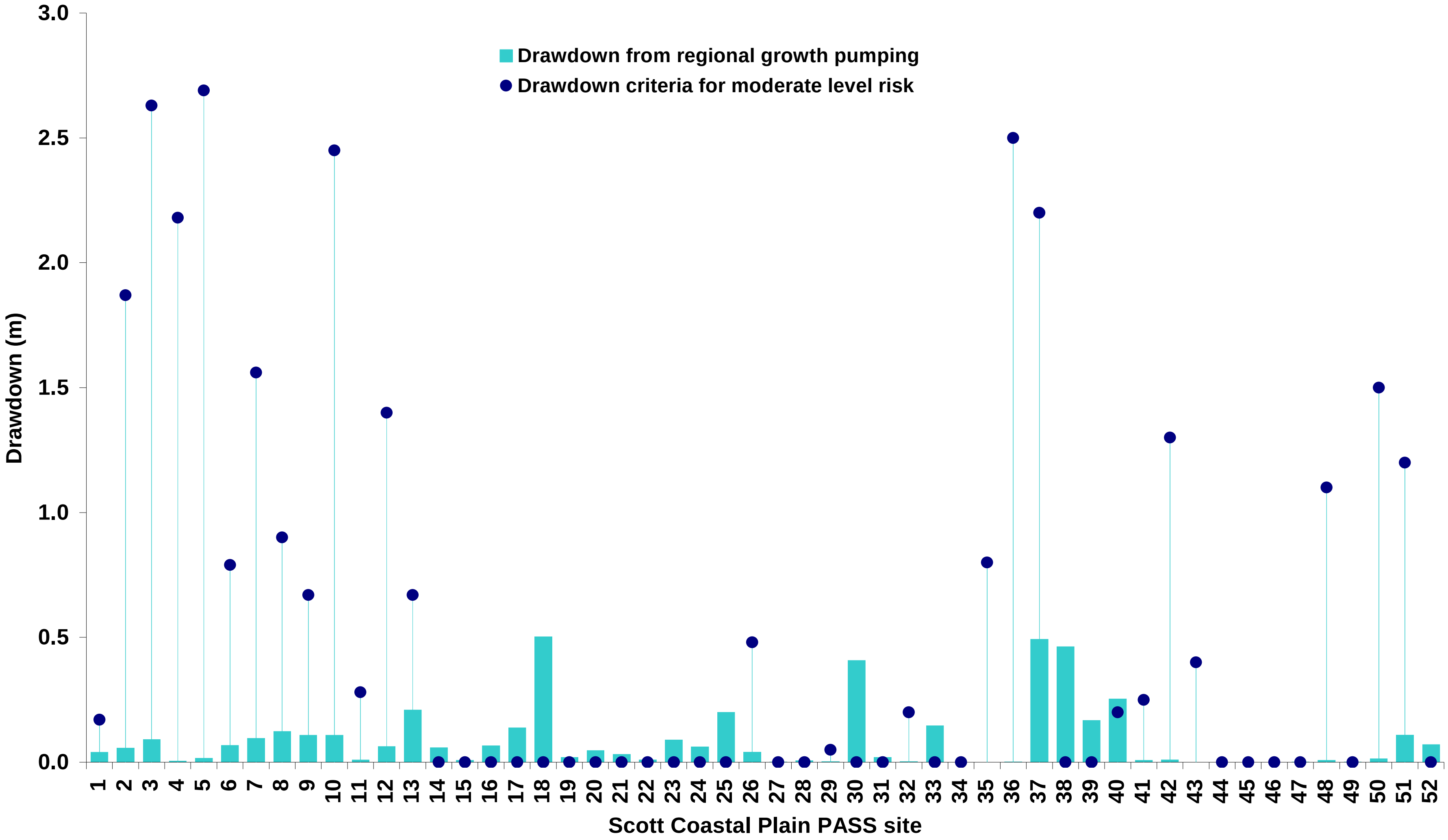

Figure 51: Predicted watertable drawdown at PASS sites on Scott Coastal Plain for regional growth (scenario C)

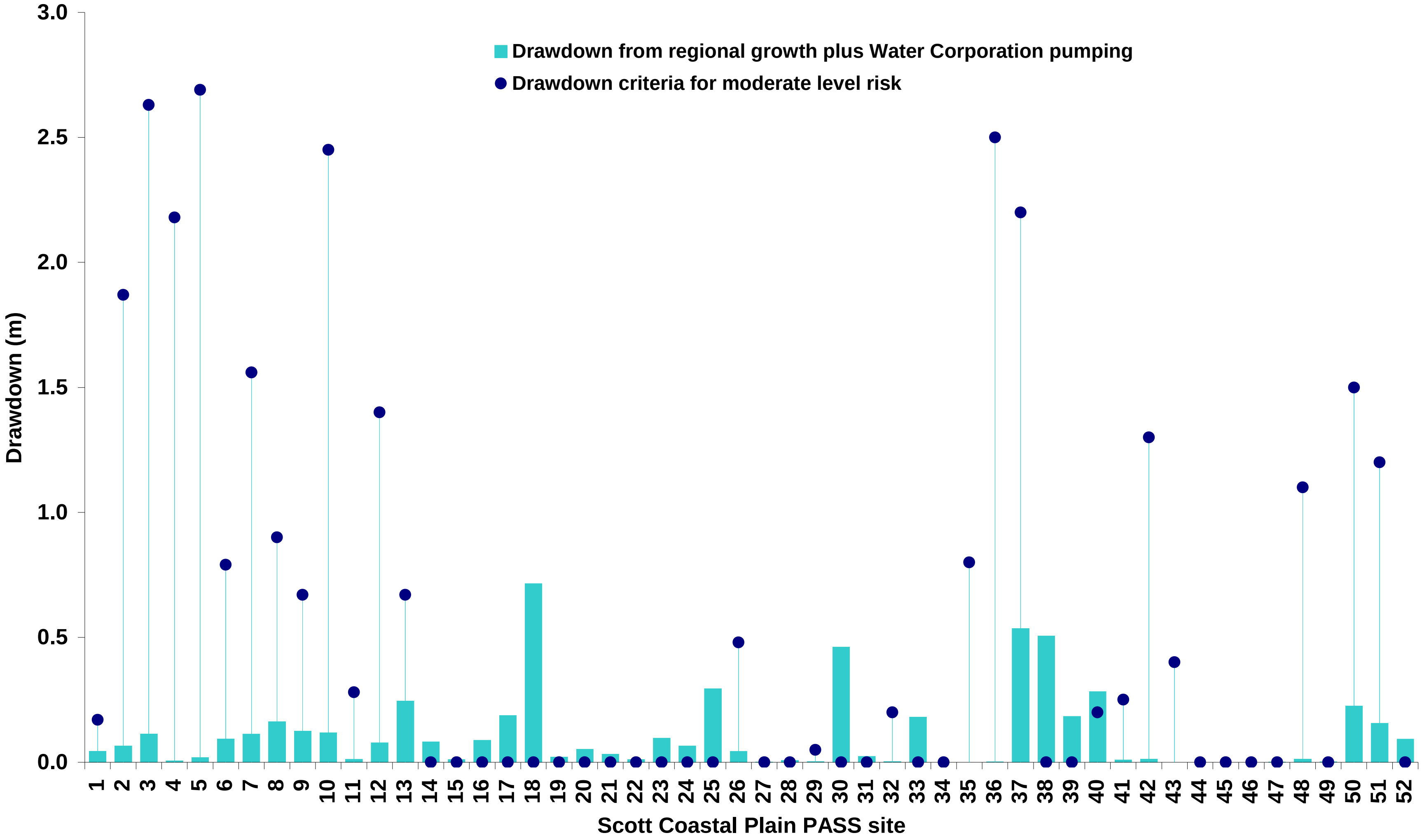

Figure 52: Predicted watertable drawdown at PASS sites on Scott Coastal Plain for regional growth plus Water Corporation scenario

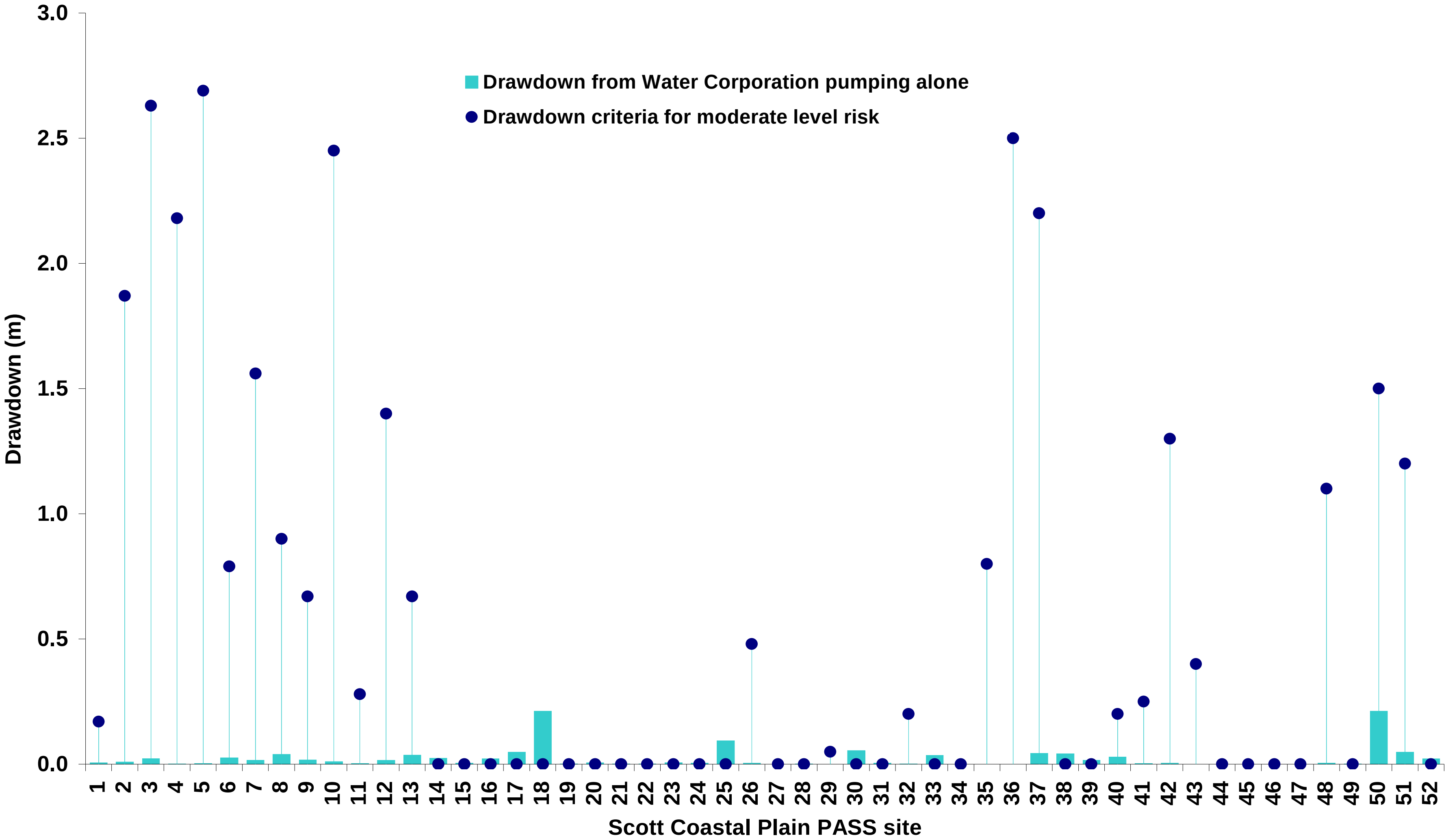

Figure 53: Predicted watertable drawdown at PASS sites on Scott Coastal Plain for Water Corporation abstraction alone

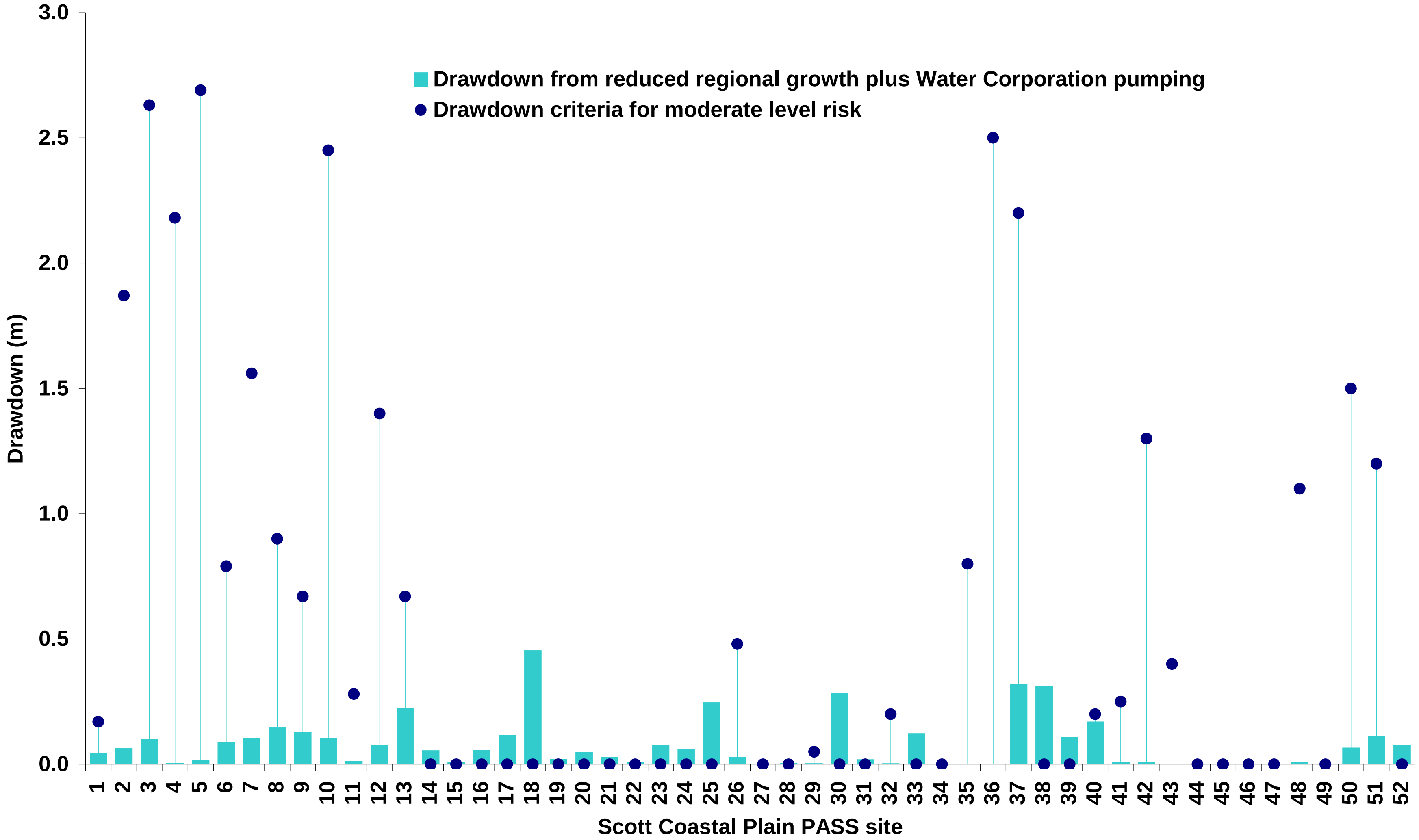

Figure 54: Predicted watertable drawdown at PASS sites on Scott Coastal Plain for reduced regional growth and Water Corporation scenario

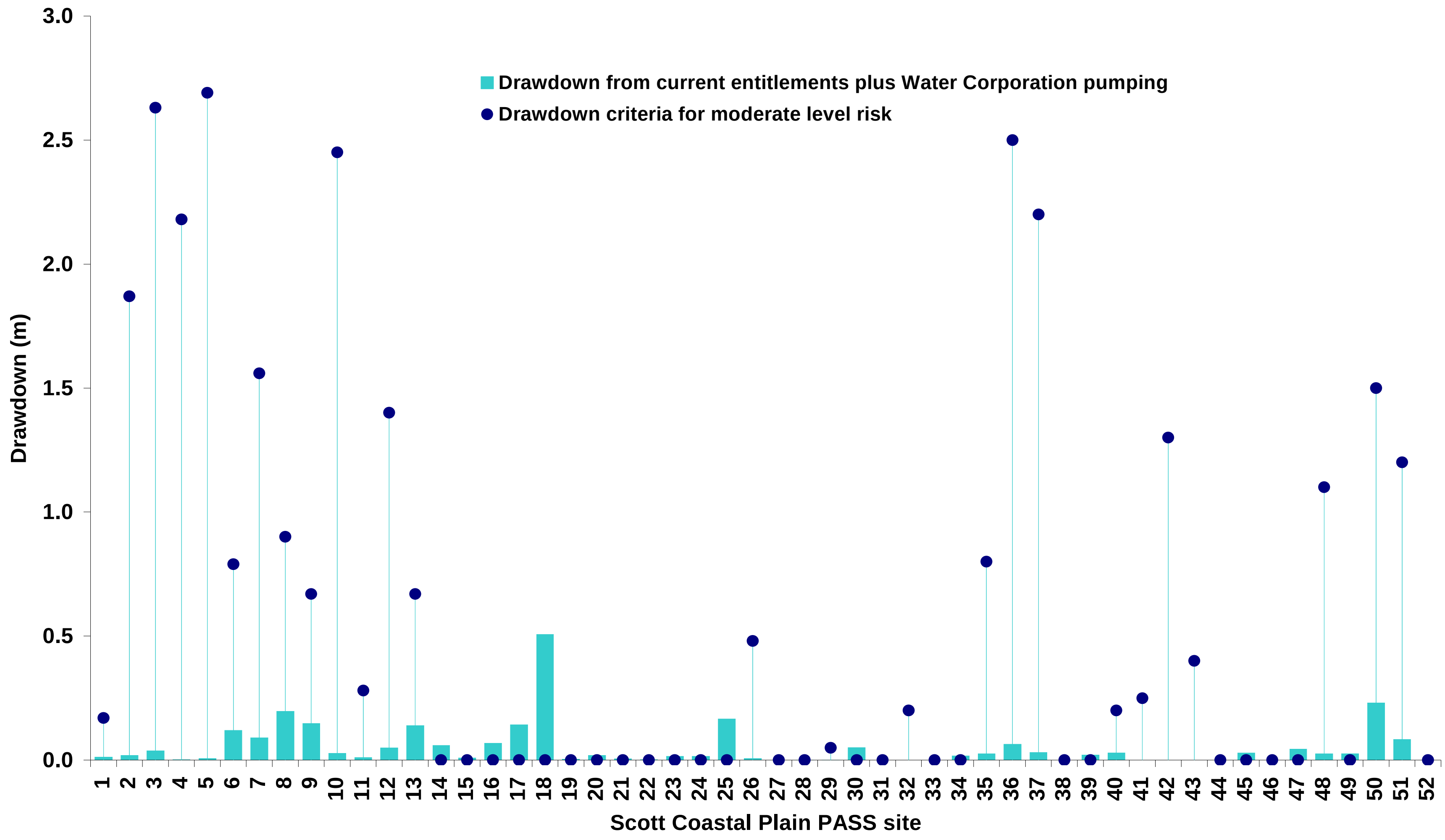

Figure 55: Predicted watertable drawdown at PASS sites on Scott Coastal Plain for current entitlements plus Water Corporation scenario

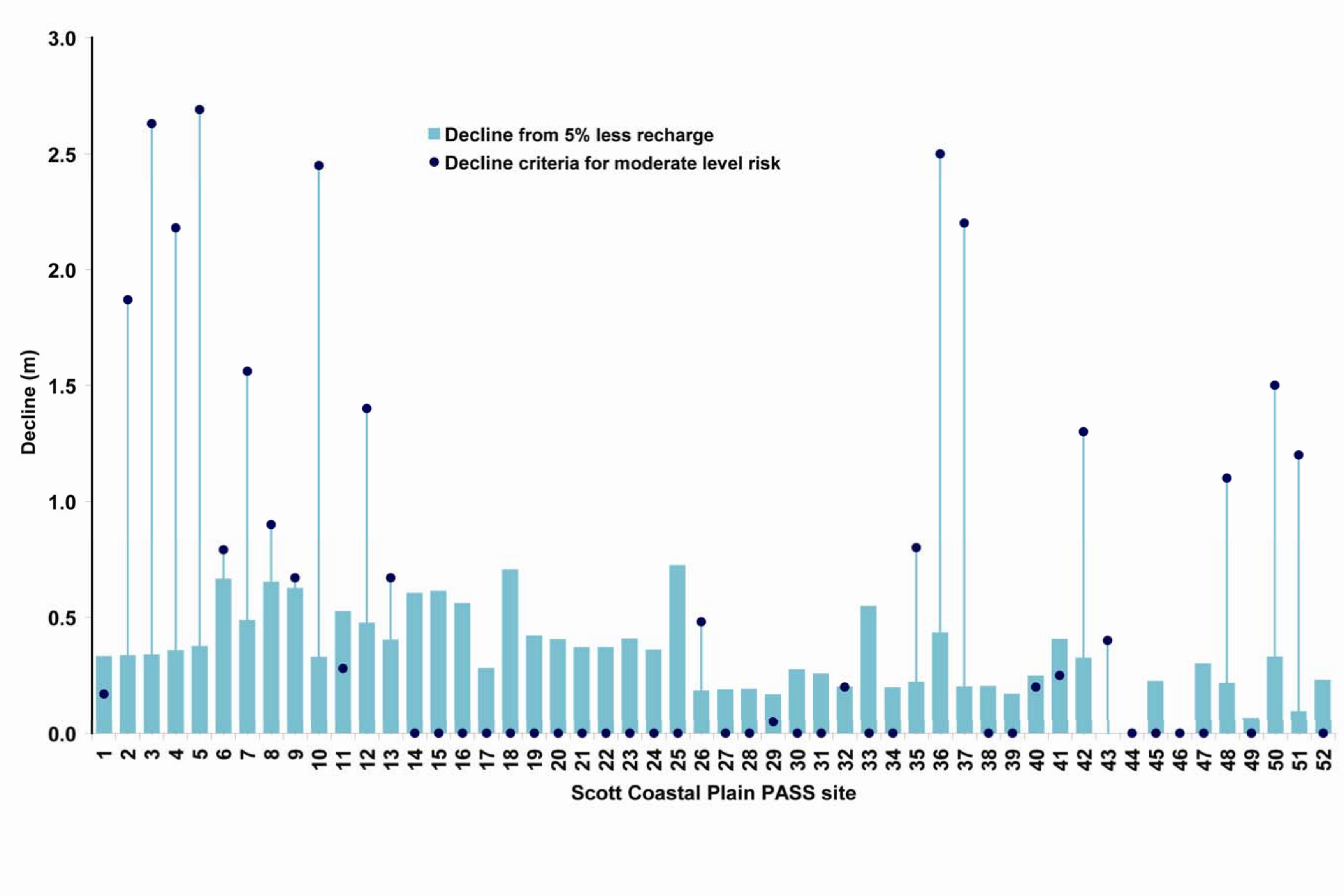

Figure 56: Predicted watertable decline at PASS sites on Scott Coastal Plain for 5 per cent less recharge

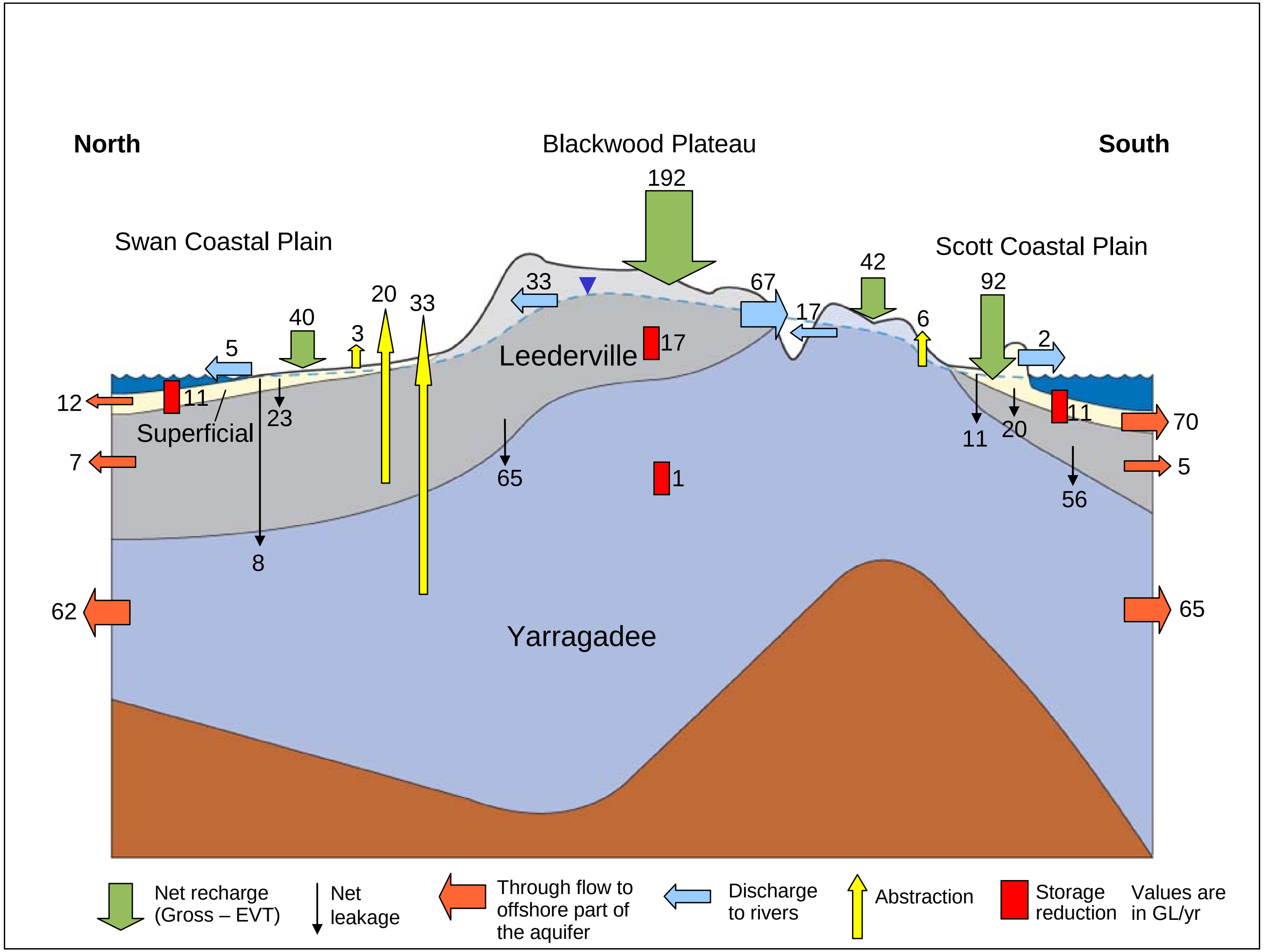

Figure 57: Water balance of onshore part of southern Perth Basin

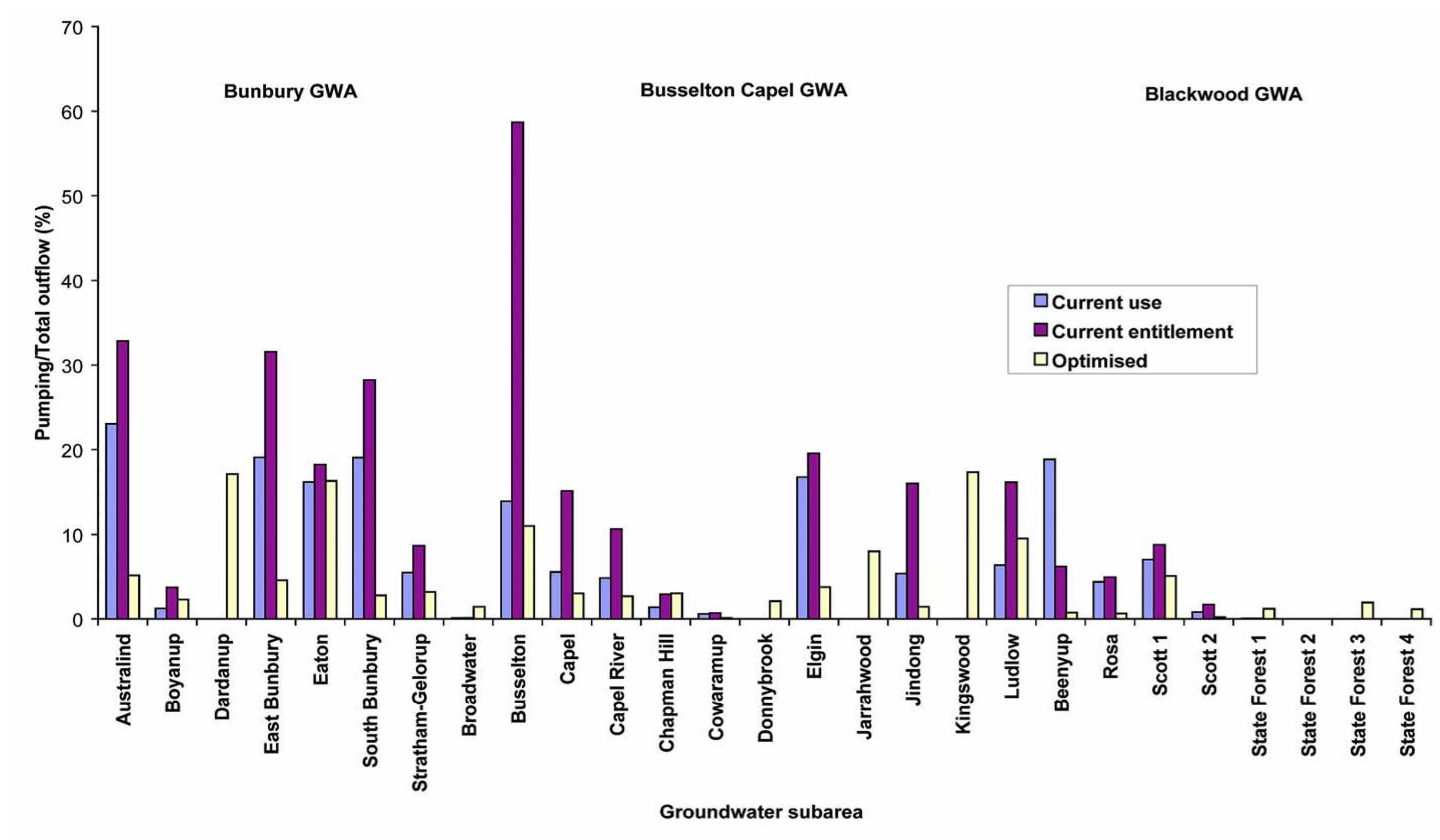

Figure 58: Yarragadee aquifer use indicator

Appendix I: EWR criteria sites

EWR site No.	Description	Name/location	Preliminary EWR criteria level (m)
1	GDE rivers within the Leederville (Mowen Member)	Blackwood River main stem	0.50
2	GDE mInor gully within Leederville (Vasse Member)	Blackwood River main stem	0.50
3	GDE rivers within the Yarragadee Formation	Blackwood River main stem	0.50
4	GDE rivers within the Parmelia Formation	Blackwood River main stem	0.50
5	GDE rivers within the Parmelia Formation	Blackwood River main stem	0.50
6	GDE rivers within the Leederville (Mowen Member)	St Johns Brook Lower	0.50
7	Palusplain (TEC) (Threatened Plant Community)	Busselton	0.25
8	Estuary-Shoreline and Peripheral (Conservation)	Capel River	0.25
9	Sumpland (TEC)	Approx 12 km south of Capel town centre	0.25
10	Dampland (Threatened Plant Community)	3 km south-east of Bunbury town centre	0.25
11	Palusplain (TEC)	3 km south of Bunbury town centre	0.25
12	Sumpland	9 km south-west of Bunbury town centre	0.25
13	Sumpland (Conservation)	12.5 km south-southwest of Bunbury town centre	0.25
14	Creek (Threatened Plant Community)	3.5 km south-east of Bunbury town centre	0.25
15	Dampland (TEC)	4.5 km south-east of Bunbury town centre	0.25
16	Sumpland (Conservation)	10 km south-east of Bunbury town centre	0.25
17	Estuary-Waterbody (RAMSAR)	Vasse-Wonnerup	0.25
18	Palusplain (TEC) (Threatened Plant Community)	Approx 11 km south-west of Capel town centre	0.25
19	Floodplain (TEC)	Approx 9.5 km south-east of Capel town centre	0.25
20	Sumpland (seasonally inundated basin)	In National Park between Scott River Rd and the coast	0.25
21	Sumpland (seasonally inundated basin)	5 km east of Chester Rd/South Coast Rd	0.25
22	Sumpland (seasonally inundated basin)	Sumpland in Scott River wetland system	0.25
23	Sumpland (seasonally inundated basin)	Scott River wetland system, off Paget Rd	0.25
24	Dampland (seasonally waterlogged basin)	Fly Brook Wetlands	0.25
25	Dampland (seasonally waterlogged	North of Milyeannup Rd/South Coast Rd	0.25

EWR site No.	Description	Name/location	Preliminary EWR criteria level (m)
	basin)	intersection	
26	Dampland (seasonally waterlogged basin)	Scott River wetland system, Chester Rd/South Coast Rd	0.25
27	Dampland (seasonally waterlogged basin)	In National Park near Blackwood River approx 7 km downstream of Sues Bridge	0.25
28	Dampland (seasonally waterlogged basin)	In National Park near Kimba Road	0.25
29	Dampland (seasonally waterlogged basin)	Within National Park on Sues Rd between Sues Bridge and Brockman Hwy	0.25
30	Donnelly River and Floodplain	Donnelly River and Floodplain	0.50
31	Palusplain (Conservation)	DGBS ROS-41	0.25
32	Terrestrial Vegetation (Bunbury Proposed ROS 38)	Part of Tuart Forest National Park	0.50
33	Lake (Conservation) Muddy Lakes	12 km south-southwest of Bunbury town centre	0.25
34	Dampland (Conservation)	Bunbury	0.25
35	Terrestrial Vegetation (Bunbury Proposed ROS 33)	18km south-east of Bunbury town centre	0.50
36	Estuary-Shoreline and Peripheral (Conservation)	Within Locke Nature Reserve, 10 km west of Busselton	0.25
37	Terrestrial Vegetation (Threatened Plant Community)	6 km upstream from mouth of Carbanup River	0.50
38	Palusplain (TEC)	9 km south of Quindalup townsite	0.25
39	Terrestrial Vegetation (Bunbury Proposed ROS 32)	23 km east of Bunbury town centre	0.50
40	Terrestrial Vegetation (Threatened Plant Community)	Approx 2 km south-west of Capel town centre	0.50
41	GDE Wetlands (Reedia) within Leederville (Vasse Member)	2 km south of Blackwood River confluence with Spearwood Creek	0.25
42	Sumpland (seasonally inundated basin)	In National Park near confluence of Adelaide Bk and Blackwood River, Geocrinia habitat	0.25
43	Sumpland (seasonally inundated basin)	Adelaide Brook Swamps	0.25
44	Sumpland (seasonally inundated basin)	Near intersection of Brockman Hwy and Dennis Rd	0.25
45	Lake Jasper (ANCA)	Gingilup-Jasper Wetland System	0.00
46	Palusplain	Jangardup Road	0.40
47	Palusplain	Black Point Road	0.60
48	Basin and Palusplain	Pneumonia Road	0.70
49	Basin	Black Point Road/Fouracres Road	0.40
50	Palusplain	Black Point Road/Dunes	0.00
51	Basin	Black Point Road/Dunes B	0.60
52	Headwater Basin	Blackwood Crossing/Longbottom Road	0.30
53	Paluslope	Brockman Highway	0.50

EWR site No.	Description	Name/location	Preliminary EWR criteria level (m)
54	Floodplain	Stewart Road Causeway	0.50
55	Creek and Palusplain	Poison Gully	0.50
56	Terrestrial (6–10 m)	Blackpoint Road/Fouracres Road	1.75
57	Terrestrial (0–3 m)	Darradup Road East	0.75
58	Sumpland (seasonally inundated basin)	Donnelly River Floodplain	0.25
59	Terrestrial (0–3 m)	Blackwood Crossing/Longbottom Road	0.75
60	Terrestrial (0–3 m)	Brockman Highway	0.90
61	Terrestrial (0–3 m)	Poison Gully	0.75
62	Terrestrial (6–10 m)	Stewart Road Causeway	0.90
63	Terrestrial (6–10 m)	Darradup Road North – Milyeannup Brook Floodplain	1.75
64	Terrestrial (6–10 m)	Jack Track	1.00
65	Terrestrial (0–3 m)	Scott Road near Lake Smith	0.75
66	Terrestrial (3–6 m)	Black Point Road	1.00
67	Floodplain	Darradup Road East – Red Gully Floodplain	0.50
68	Floodplain	Darradup Road West – Red Gully Floodplain	0.50
69	Floodplain	Bunbury	0.50
70	Floodplain	Bunbury	0.50
71	Dampland (seasonally waterlogged basin)	Along Scott River approx 6km south-east of Brennans Ford	0.25
72	Wetland (TEC)	At Brennans Ford on Scott River	0.25
73	Sumpland (seasonally inundated basin)	Scott River wetland system, south of Governor Broome Rd	0.25
74	Sumpland (seasonally inundated basin)	Gingilup Swamps Nature Reserve, ANCA wetland	0.25
75	GDE rivers within the Leederville (Mowen Member)	St Johns Brook Upper	0.50
76	Milyeannup Riparian Vegetation	Milyeannup Brook	0.50
77	Minor Gully Riparian Vegetation	Margaret River Swamps	0.50
78	Minor Gully Riparian Vegetation	Margaret River Swamps	0.50
79	Rosa Brook Riparian Vegetation	Rosa Brook	0.50
80	Spearwood Creek Riparian Vegetation	Spearwood Creek Swampland	0.50
81	Lake Quitjup Wetland Vegetation (ANCA)	Lake Quitjup	0.25
82	Wetland (ANCA)	Gingilup-Jasper Wetland System	0.25
83	Ludlow Swamp (ANCA)	McCarley's Swamp	0.25
84	Palusplain (Conservation)	Approx 11 km east-northeast of Busselton town centre	0.25
85	Dampland (Conservation)	NW Lake Jasper, South of Fox Property	0.25
86	Sumpland (Conservation)	Near Black Point Road	0.25

Appendix II: ASS criteria sites – Swan Coastal Plain

Map reference	Location	Easting mN_z50	Northing mN_z50	DoW site ID	PASS depth (mbgl)	Watertable decline criteria for moderate level risk (m)
1	Guynudup Brook Bussell Highway	367529	6290424	ASS61003601	0.2	0
2	West Of Ruabon Road Near Railway Formation	356689	6277476	ASS61003503	2.0	0
3	West Of Ruabon Road	356267	6277452	ASS61003502	na	0
4	West Of Ruabon Road	356020	6277547	ASS61003501	4.4	0.1
5	Calm Reserve Off Caves Road Busselton	337497	6273447	ASS61003206	0.3	0
6	Calm Reserve Off Caves Road Busselton	336170	6274011	ASS61003205	0.3	0
7	Calm Reserve Off Caves Road Busselton	335604	6273590	ASS61003203	2.1	0.5
8	Calm Reserve Off Caves Road Busselton	335737	6272909	ASS61003201	5.3	3
9	Corner Of Glenview Dr & Pries Rd Abbey	338432	6272922	ASS61003104	na	0
10	Bussell Hwy Opposite Cooksworthy Rd Abbey	338526	6273466	ASS61003103	1.3	0
11	Yale Crt Abbey	339004	6273941	ASS61003102	2.9	0
12	Macintyre St Abbey	339050	6274157	ASS61003101	2.9	0.8
13	Busselton Bypass Calm Reserve	339521	6272304	ASS61003001	0.5	0
14	Broadwater Reserve Of Grey Teal Place Busselton	342636	6273682	ASS61002903	0.8	0
15	Broadwater Reserve Of Grey Teal Place Busselton	342620	6273817	ASS61002902	1.9	0.5
16	Breaden St Busselton	342706	6274039	ASS61002901	2.2	0.5
17	Calm Reserve Busselton Bypass	341929	6272919	ASS61002808	1.3	0
18	Cross Rd Busselton	341187	6273893	ASS61002807	2.9	1
19	Sth End Of Cross Rd Busselton	341187	6273674	ASS61002806	2.6	0.1

Map reference	Location	Easting mN_z50	Northing mN_z50	DoW site ID	PASS depth (mbgl)	Watertable decline criteria for moderate level risk (m)
20	Calm Reserve Sth End Cross Rd Busselton	341185	6273443	ASS61002805	1.0	0
21	Calm Reserve Nth Of Busselton Bypass	341738	6273282	ASS61002804	1.1	0
22	Busselton Bypass Opposite Redgum Way	341876	6272904	ASS61002803	1.7	0
23	Busselton Bypass Rd Parking Bay	340787	6272510	ASS61002802	2.2	0
24	Queen Elizabeth Drive Bussellton	346371	6274477	ASS61002506	4.0	0.9
25	Queen Elizabeth Drive Bussellton	344735	6274238	ASS61002504	1.7	0.35
26	Bussellton Hs East Boundary	344862	6274617	ASS61002503	2.5	0.4
27	Cnr Prince Regent Dr & Frankland Way Busselton	345601	6274616	ASS61002502	1.3	0
28	Bovell St Busselton	345001	6274509	ASS61002501	1.6	0
29	W Scott Minninup Rd Stratham	369253	6299519	ASS61002304	1.8	0
30	W Scott Minninup Rd Statham	369394	6299452	ASS61002303	5.0	0
31	W Scott Minninup Rd Statham	369787	6299277	ASS61002301	2.5	0.3
32	Minninup Rd Public Access North Of Rich Rd	368628	6297042	ASS61002105	3.0	0
33	Rich Rd Stratham	368411	6297028	ASS61002104	2.8	0
34	Floodgate Road Wonnerup	353440	6279192	ASS61001803	0.3	0
35	Mccourts Rd	358081	6282957	ASS61001507	0.3	0
36	Forrest Beach Road Wonnerup	357261	6284102	ASS61001506	na	0
37	Harewoods Rd	370831	6301871	ASS61001402	1.0	0
38	Harewoods Rd South	370735	6301583	ASS61001401	0.1	0
39	Mallokup Rd Upstream Floodgates	364660	6288717	ASS61001203	0.3	0
40	Klaehn Cr Busselton	349082	6274012	ASS61001107	5.5	3
41	Vase Hwy Busselton	349761	6272919	ASS61001106	2.0	1.5
42	Blum Blvd Busselton	349433	6273792	ASS61001105	3.2	1.6
43	Osprey Drive East Busselton	351122	6274919	ASS61001104	2.2	0.3
44	Abba River	353658	6277000	ASS61000903	1.3	0

Map reference	Location	Easting mN_z50	Northing mN_z50	DoW site ID	PASS depth (mbgl)	Watertable decline criteria for moderate level risk (m)
45	King Rd	366059	6291274	ASS61000309	3.8	0.5
46	Edwards Rd Off Mallolup Rd	364824	6291800	ASS61000303	1.5	0.1
47	Roberts Rd Doongup	365272	6293259	ASS61000105	1.8	0.1
48	Corner Sandridge St & Pennent St	375252	6310316	ASS61102001	0.5	0
49	Centenary Road Near Prison East Bunbury	375475	6305322	ASS61101202	0.9	0.2
50	Reserve Off Robertson Road Bunbury	376092	6307207	ASS61101201	1.8	0
51	Department Of Agriculture Bunbury	376856	6308340	ASS61101103	2.7	0.2
52	Craigie Street Lia Bunbury	376610	6308470	ASS61101102	2.5	1.1
53	Kaeshagen Street Picton	377186	6309207	ASS61101101	2.8	0.5
54	Off Centenary Road Bunbury	372894	6305116	ASS61100804	4.8	1.5
55	Bunbury Primary School Oval	373321	6310943	ASS61100403	1.8	0
56	Jeffery Road Picton	378524	6310243	ASS61100109	1.9	0.4

Appendix III: ASS criteria sites – Scott Coastal Plain

Map reference	Location	Easting mE_z50	Northing nM_z50	DoW site ID	PASS depth (mbgl)	Watertable decline criteria for moderate level risk
1	SE of Don Rd	368840	6200921	ASS60900101	2.4	0.17
2	SE of Don Rd	368831	6201530	ASS60900102	3.9	1.87
3	SE of Don Rd	368827	6202086	ASS60900103	4.4	2.63
4	SE of Don Rd	368813	6202696	ASS60900104	5.4	2.18
5	SE of Don Rd	368803	6203306	ASS60900107	5.6	2.69
6	Jangardup Mine Rd	373939	6199066	ASS60900201	2.5	0.79
7	Jangardup Mine Rd	371642	6197909	ASS60900202	1.7	1.56
8	Jangardup Mine Rd	373607	6199062	ASS60900203	2.5	0.9
9	Jangardup Mine Rd	373152	6199062	ASS60900204	3.2	0.67
10	Don Rd	366612	6202276	ASS60900301	4	2.45
11	Black Point Track	371784	6200740	ASS60900401	3.2	0.28
12	Black Point Track	371379	6200158	ASS60900402	3.2	1.4
13	Black Point Track	370432	6199653	ASS60900403	2.5	0.67
14	Lake Jasper	375906	6191862	ASS60900501	1.50	0
15	Lake Jasper	375848	6192652	ASS60900502	1.00	0
16	Lake Jasper	375941	6193765	ASS60900503	2	0
17	Lake Jasper	376513	6194843	ASS60900504	1.25	0
18	Lake Jasper	377064	6196451	ASS60900505	1.4	0
19	Black Point Track	367679	6196726	ASS60900601	1.25	0
20	Black Point Track	369336	6198470	ASS60900602	1.1	0
21	East Gingilup Swamps	365976	6199123	ASS60900701	0.90	0
22	Gingilup Swamps	362134	6196977	ASS60900702	2.4	0
23	East Gingilup Swamps	365368	6197448	ASS60900703	0.9	0
24	South Dons Rd	366648	6200478	ASS60900704	1.2	0
25	Jacks Track	370462	6205105	ASS60900801	1	0
26	Milyeannup Coast Rd	355826	6207457	ASS60900901	2.5	0.48
27	Milyeannup Coast Rd	353821	6205229	ASS60900902	0.75	0
28	Milyeannup Coast Rd	352774	6204218	ASS60900903	1.8	0
29	Milyeannup Coast Rd	357441	6209305	ASS60900904	2.25	0.05
30	Milyeannup Coast Rd	343872	6205121	ASS60901001	1	0
31	Scott River Rd	340130	6204484	ASS60901101	1.6	0
32	Scott National Park	338744	6205511	ASS60901102	2.3	0.2
33	Brennans Ford	340733	6207284	ASS60901103	1.3	0
34	Scott National Park	335231	6203363	ASS60901201	2	0
35	Scott National Park	335221	6204404	ASS60901202	2.2	0.8

Map reference	Location	Easting mE_z50	Northing nM_z50	DoW site ID	PASS depth (mbgl)	Watertable decline criteria for moderate level risk
36	Scott National Park	335185	6205611	ASS60901203	3	2.5
37	South of Dennis Rd	348281	6205399	ASS60901301	3.5	2.2
38	South of Dennis Rd	348262	6206956	ASS60901302	2	0
39	South of Dennis Rd	349641	6208773	ASS60901303	1.8	0
40	East of Dennis Rd	347277	6210646	ASS60901304	3.2	0.2
41	North Scott National Park	336598	6208622	ASS60901401	2.75	0.25
42	North Scott National Park	337102	6210094	ASS60901402	3.1	1.3
43	East Augusta	331786	6201041	ASS60901501	1.9	0.4
44	East Augusta	332090	6201751	ASS60901502	1.8	0
45	East Augusta	333169	6203227	ASS60901503	6	0
46	East Augusta	332197	6201858	ASS60901504	0.1	0
47	Scott National Park	333150	6203952	ASS60901506	1.2	0
48	Wall Rd, Alexander Bridge	334799	6217811	ASS60901701	3	1.1
49	Alexander Bridge, Blackwood R	333491	6218225	ASS60901801	1.3	0
50	Blackwood R, Nannup	385613	6239942	ASS60902801	2.4	1.5
51	Blackwood R, Sues Rd	351336	6228319	ASS60902802	3.3	1.2
52	Scott River Rd (nth Beenyup)	340338	6214100	ASS60902901	1.6	0

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