Department of **Water and Environmental Regulation**

Department of **Primary Industries and Regional Development**

GOVERNMENT OF WESTERN AUSTRALIA

Reconnecting rivers flowing to the Vasse Estuary

Hydrological and water quality modelling

Revitalising Geographe Waterways

VASSE taskFORCE

Water Science technical series

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Cover photograph: Flow through Vasse Diversion Drain – Lower Vasse River culvert, Ben Marillier, Department of Water and Environmental Regulation

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Summary

This Reconnecting Rivers project is part of the Revitalising Geographe Waterways program, which aims to improve the ecological health and amenity of waterways in the Geographe region.

The Reconnecting Rivers project was developed in response to the community's desire to investigate how modifications to the current drainage network might benefit water quality in the Lower Vasse River and Vasse Estuary. There is a strong community belief that increasing flows would improve water quality by 'flushing' nutrient-enriched water and sediments from these waterways. High nutrient concentrations in the waterways at the end of spring contribute to algal blooms during summer. In addition, a large build-up of nutrient-rich sediments occurs in the Lower Vasse River and Vasse Estuary, which contributes to algal growth during the warmer months (when inflows cease). This study investigated whether re-directing flows from the upper Sabina and Vasse rivers – which have slightly better water quality than the lower rivers – or utilising alternative water sources from the catchment might be able to lower nutrient concentrations and mobilise sediment away from the problem areas. The study also investigated whether decreasing water residence times in the Lower Vasse River would be beneficial, given blue green algal (Cyanobacteria) growth is impeded by flowing water.

The community's proposals (scenarios) considered in this study included:

1 Reconnecting flows from the upper catchment of the Vasse and Sabina rivers

- Reconnection of the Vasse Diversion Drain to the Lower Vasse River
- Reconnection of the Sabina Diversion Drain to the Lower Sabina River

2 Using alternative water sources from the catchment

- Summer discharge of treated recycled water into the Lower Vasse River
- Storage of water in the catchment for discharge into the Lower Vasse River in summer

3 Removing barriers to flow in the Lower Vasse River and Vasse Estuary

- Removal of the Butter Factory weir and modifications to the Lower Vasse River channel to remove pools
- Removal of the Vasse surge barrier.

Also examined were two modifications to drainage infrastructure planned for the near future:

- Upgrades to the bridge at Causeway Road
- Adding a formalised spillway to the Vasse Diversion Drain to direct water to the Lower Vasse River in large floods to safeguard the drain's banks

Another proposal was:

- Storing more water in the Vasse Estuary at the end of the flow season

Methodology

This study assessed the feasibility of the proposed scenarios in terms of flood risk, and changes to long-term hydrology and water quality. Scenarios considered were identified by Vasse Taskforce partners and through public meetings

To do this, the Department of Water and Environmental Regulation (DWER) developed a one-dimensional (1D) dynamic flood model using the software package MIKE11. The model was calibrated to observed flood events and long-term monitoring of water levels in the Vasse and Wonnerup estuaries. The model domain included the Vasse-Wonnerup wetlands, Lower Vasse River and Lower Sabina River. The model was used to quantify the change in flood regime for the 1% annual exceedence probability (AEP)[1] event for each option and this was compared with flood development strategies and building floor level in affected areas. The flood modelling was supported by a comprehensive analysis of flood hydrology for the catchment.

The MIKE 11 model also used meteorological and flow inputs from 2001–14 to examine overall changes to hydrology that would eventuate for the different scenarios. Change in water levels, river discharge, residence time, scouring potential and nutrient mass balance were examined. These indicate how the estuary and rivers are likely to function under different management regimes and with varying degrees of 'reconnection'.

Results

Reconnecting the Vasse Diversion Drain to the Lower Vasse River

This option becomes feasible by increasing capacity at the Vasse Diversion Drain offtake structure using two 900 mm culverts to restrict the maximum allowable discharge to the Lower Vasse River. It does not represent an unacceptable risk to the flood regime with restricting culverts. This would increase average annual flow volume by around 54% with all of the flow delivered in winter and spring but with no increase to summer flows or flushing. Consequently, more water would be diverted to the Vasse Estuary with an increase in average water levels. This scenario is unlikely to scour sediment from the river, and would increase nutrient loads to the estuary, but with a slight decrease in total phosphorus concentration in the river in winter and spring.

Complete reconnection of the Vasse Diversion Drain is not feasible as it would result in a dramatic and unacceptable increase in flooding in Busselton.

Reconnecting the Sabina Diversion Drain to the Lower Sabina River

This option becomes feasible by introducing one or two 900 mm culverts to the Sabina Diversion weir, and would not unacceptably increase flooding downstream. It would increase flow in the river by around 20–25%, delivering more water to the estuary in winter, but with no change in summer flow. Total nitrogen and phosphorus loads from the river would increase by 40% and 6% respectively. Nitrogen concentrations would remain similar, with a moderate decrease in phosphorus concentrations in winter and spring.

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[1] 1% AEP flood event is a flow event that has a 1% probability of occurring in any given year.

Summer release of treated recycled water into the Lower Vasse River

This scenario had no impact on the river's flood regime, and was the only scenario shown to be effective in increasing flow during summer, and reducing nutrient concentrations. However, many considerations for the overall feasibility of this option were not considered in this study including:

- availability of water
- ability to adequately treat wastewater to the required nutrient concentrations
- presence of non-nutrient contaminants
- community acceptance
- requirements of the *Environment Protection and Biodiversity Conservation Act 1999* (Cth).

Storing of more water in the Vasse Estuary

It is possible to store more water in the Vasse Estuary at the end of spring by increasing the check board height. This would increase the risk of flooding in the estuary by reducing the available storage capacity should a large rainfall event occur. There is ample flow at the end of winter and early spring to fill the estuary to a higher level, even in dry years. The desirability of this option should be considered in the context of the ecological and social objectives for the estuary.

Removal of the surge barrier

There is a flood risk associated with removal of the surge barrier which provides protection from extreme water levels in Geographe Bay. The risk of storm surge will increase as sea levels rise in the coming decades. This option would completely change the estuary's ecological character with substantial inundation of saline to hypersaline water occurring during summer and autumn.

Removal of the Butter Factory weir and filling of river pools

This scenario involves conversion of the Lower Vasse River to an ephemeral stream by removing the weir and filling the river pools to minimise standing water during summer. In the context of flooding the scenario is possible – assuming the final form of the river is appropriately designed.

This option would require a more detailed investigation and community acceptance if it were to be pursued further.

Bridge upgrades at Causeway Road

Main Roads WA is upgrading the bridge at Causeway Road and this presents an opportunity to minimise afflux at the new bridge and reduce the risk of flooding upstream. The current bridge restricts flow during periods of high water levels.

Adding a formalised spillway to the Vasse Diversion Drain

To avoid the risk of levee failure on the Vasse Diversion Drain near the offtake structure to the Lower Vasse River, the Water Corporation is proposing to upgrade the drain to include a formalised spillway to divert water up to a maximum rate of 7 m^3/s to the Lower Vasse River. This scenario was assessed in combination with increased culvert capacity at the offtake structure and was found to be feasible in combination with two 900 mm culverts. The time-to-peak on the Vasse Diversion Drain is six hours compared with 24 hours in the estuary and Lower Vasse River, which means that water flowing over the spillway does not impact the flood peak in the river.

Storage of water for summer release

This option was not modelled because of the expense and water quality issues associated with storing water in the upper catchment during summer.

Recommendations

- All of the management options considered in this study are revisited once specific ecological and social objectives have been defined for the Lower Vasse River and the Vasse Estuary.
- DWER works with the Water Corporation to incorporate appropriate spillway infrastructure near the Vasse Diversion Drain offtake structure.
- DWER works with the Water Corporation to increase diversion capacity at the Vasse Diversion Drain offtake structure to the Lower Vasse River.
- DWER works with Main Roads WA to minimise afflux for the 1% AEP flood event at the upgraded Causeway Road bridge.
- The City of Busselton considers raising road levels on Causeway Road and Southern Drive to provide improved flood protection for established homes in the area.
- The sandbar at Wonnerup Inlet needs to be managed to the highest-possible standard to prevent flooding.
- Any new surge barrier or diversion infrastructure is designed with manual and/or automatic controls to allow flexibility in operation and the option to reverse changes; for example, valved culverts or adjustable check board height.
- If drainage infrastructure is modified, measurement of water quality and quantity should be continued to enable assessment of the intervention.
- If reconnection options that increase flows to either the Vasse or Sabina rivers are pursued, culverts should be closed for the first-flush event in the drains, and left open for the remainder of the flow season.
- In the event of flooding in the Vasse Estuary or Lower Vasse River, culverts should be closed for the duration of the event.
- An operational strategy for culverts should be developed with clearly defined roles and responsibilities.
- If specific interventions are deemed desirable by the relevant stakeholders (e.g. the Vasse Estuary Technical Working Group), then it would be appropriate to progress this work to design and implementation phases.

1 Introduction

The Ramsar-listed Vasse and Wonnerup estuaries are located close to Busselton in the south-west of Western Australia. The estuaries are of ecological and social importance, providing habitat for migratory birds and a recreational area for residents and tourists. The estuary catchments include the Lower Vasse, Lower Sabina and Abba rivers flowing to the Vasse Estuary and the Ludlow River flowing to the Wonnerup Estuary, as well as the estuary foreshores and parts of Busselton.

The region has a long history of clearing and drainage modification to allow productive farming and provide flood protection for Busselton. As a result, flows and water quality have been altered from their natural state with consequences for the ecological health of the estuaries and the lower reaches of the Vasse River. Although both estuaries suffer from poor water quality, the symptoms are more prevalent in the Vasse than the Wonnerup. Algal blooms, de-oxygenation and/or fish kills are a regular occurrence during summer in the Vasse Estuary and the Lower Vasse River.

This study is one component of the Revitalising Geographe Waterways program, which aims to improve the ecological health and amenity of waterways in the Geographe region.

Artificial drainage diverts water from the upper Sabina and Vasse rivers to the ocean, which under the natural drainage configuration would have flowed to the Vasse Estuary. This study examines potential strategies for redirecting some of this water into the Vasse Estuary via the Lower Vasse or Lower Sabina rivers, as well as other potential changes to drainage infrastructure or management.

The following drainage modification options were examined:

- Redirecting flow from the Vasse Diversion Drain into the Lower Vasse River
- Redirecting flow from the Upper Sabina River to the Lower Sabina River
- Summer discharge of treated recycled water into the Lower Vasse River
- Retaining more water in the Vasse Estuary at the end of the flow season
- Removal of the Vasse surge barrier
- Removal of the Butter Factory weir
- Bridge upgrades at Causeway Road
- Adding a concrete spillway to the Vasse Diversion Drain
- Storage of water in the catchment for discharge into the Lower Vasse River in summer.

This study evaluates the different drainage and infrastructure options with regard to flooding and hydrology. Drainage and reconnecting rivers scenarios were identified by the members of the Vasse Taskforce, through the Vasse partnership and through public meetings facilitated by the City of Busselton. Ecological, economic or social considerations are not addressed. However, the changes to water quality by way of nitrogen and phosphorus concentrations and loads are quantified and discussed, as these may affect estuarine ecology.

Floodplain management

Busselton is positioned low in the landscape and is surrounded by water, thus altering drainage has the potential to change the area's flooding regime.

DWER is the state government's lead agency for floodplain mapping and providing advice on floodplain development. In accordance with the *Water Agencies (Powers) Act 1984*, its function is to 'develop plans for and provide advice on flood management'. Floodplains should be managed for the benefit of the whole community so that the risk and damages are minimised and environmental values are protected (Department of Water 2014).

The 1 in 100 annual exceedence probability flood event (1% AEP) has generally been adopted in Australia and overseas as the basis for floodplain management. DWER uses the following guiding principles when assessing development proposals in flood-prone areas:

- proposed development has adequate flood protection from a 1% AEP flood
- proposed development does not detrimentally impact on the existing 1% AEP flooding regime of the general area.

When assessing development proposals for floodplains, some of the factors considered include depth of flooding, velocity of flow, obstructive effects on flow, possible structural damage, difficulty in evacuation during major floods and potential regional economic or social benefit.

This report considers the flood behaviour and potential increase in flood levels associated with the proposed drainage modifications in the context of these guiding principles.

Improving ecology – what difference can be made by altering flow?

The concept of using water releases to improve river condition is not new: environmental water releases are used throughout Western Australia. In 2009, the National Water Commission published the report *Pulsed flows: a review of environmental costs and benefits and best practice* (Watts et al. 2009), in which the use of water releases in waterway management was discussed. Water releases can contribute to improved sediment condition, dilution, flushing or floodplain connection.

The introduction of increased flow in the Lower Vasse River is aimed at scouring sediment, lowering nutrient concentrations and reducing algal blooms. Whereas in the Sabina River, the aim is to improve water quality through dilution. The following types of flow are relevant:

- ***Flushing flows*:** flows that mobilise sediments
- ***Dilution flows*:** flows that reduce the concentrations of salinity, contaminants or algae.

Pulsed flows have been used extensively in Australia and overseas to achieve ecological outcomes. They are most commonly used in regulated waterways with upstream storages that allow control of the magnitude and timing of water released. For example, in the Lower Darling River, Mitrovic et al. (2011) demonstrated that a single large flow of 3000 ML/day released from the upstream Menindee Lakes system could remove an established algal bloom, while a discharge of 300 ML/day (velocity 0.03 m/s) was sufficient to prevent thermal stratification and supress bloom development.

In contrast to this example where an upstream reservoir is used for flow control, flows in the Lower Vasse and Lower Sabina rivers following reconnection would depend on catchment rainfall and the diversion structures. The use of pulsed flows is not an option.

Modelling objectives

The modelling objectives varied slightly depending on the option. For proposed drainage modifications, the following were examined (where applicable):

A. Flow regime, water levels and residence times

B. The 1% AEP flood regime

C. Nutrient loads.

For the redirection of flow into the lower Vasse and Sabina rivers, additional outputs included:

D. Peak flow rate that could be redirected into the Lower Vasse River and/or Lower Sabina River without detrimental changes to the 1% AEP flood regime, and determination of appropriate culvert sizes for offtake structures

E. Seasonal flows, and nitrogen and phosphorus loads in the rivers and estuary

F. Calculation of bed shear stress in the Lower Vasse River

G. Residence times (flushing) of water in the Lower Vasse River.

Modelling methodology

To meet the objectives outlined above, DWER constructed and calibrated a 1D hydraulic model for the Lower Vasse River, Lower Sabina River and Vasse-Wonnerup estuary to simulate typical seasonal variations in hydrology and event-based flood hydraulics. The MIKE11 2014 package was selected for model implementation.

A 1% AEP design flood was simulated for the rivers and estuary to quantify the base-case scenario against which the different flood scenarios for the proposed drainage modifications could be compared. By examining expected changes to the 1% AEP flood event, it was possible to assess the feasibility of the proposed modifications against the floodplain development strategy for the affected areas. A time period of a few days was modelled in the flood scenarios.

To calculate changes to the system’s overall hydrology, bed shear stress, residence time and nutrient mass balance, the same hydraulic model was used but with a simulation period of multiple years to capture varying seasonal conditions.

This report is targeted at practitioners with an interest in the management of the Lower Vasse River, the Vasse-Wonnerup wetlands and their catchments. It is structured as follows:

- Section 2 describes the hydrology, catchments and drainage associated with Vasse-Wonnerup wetlands, and discusses ocean and estuary water levels, climate, river flows and water quality.
- Section 3 reviews flood history and previous flood studies. The RORB (Runoff Routing B) modelling used to derive design flood flows (i.e. the flows that would eventuate with rainfall with 1%, 5% etc. exceedence probabilities) is discussed.
- Section 4 discusses the construction and calibration of the MIKE11 hydraulic model covering the Vasse-Wonnerup wetlands and the lower Vasse and Sabina rivers.
- Section 5 presents the scenario modelling and describes how different management options will affect flooding and hydrology in the rivers and estuary.
- Section 6 discusses selected scenarios to highlight the likely changes arising from the different scenarios and makes recommendations.

2 Catchment and estuary description

This section describes the climate affecting the Vasse-Wonnerup estuary catchment, as well as its drainage patterns. Average flows to the estuaries and in the diversion drains that flow to the ocean are presented. Ocean water levels, the Wonnerup Inlet sand bar and surge barrier management – each of which affect drainage from the estuaries – are described in Section 2.3. Land uses and water quality are discussed at the end of the section.

2.1 Climate

Busselton has a Mediterranean climate with winter-dominant rainfall and hot, dry summers. Average annual rainfall for 1975–2014 was 743 mm with pan evaporation of 1399 mm. Figure 2-1 shows the monthly average rainfall and evaporation for sites closest to the estuaries.

Rainfall sites and flow gauges used in the modelling are shown in

Figure 2-2. Pluviometers that record sub-daily rainfall are located at Happy Valley (9988; 509182), Busselton Aero (9603), Ludlow (9877) and Aston Downs (9909).

Since the 1970s south-west Western Australia has experienced declining rainfall and increasing temperatures, and climate modelling predicts that this trend will continue through the 21st century (Hope et al. 2015). Thus, the Vasse-Wonnerup wetlands will be influenced by reducing rainfall and streamflow, accompanied by increasing temperatures and evaporation in the coming decades.

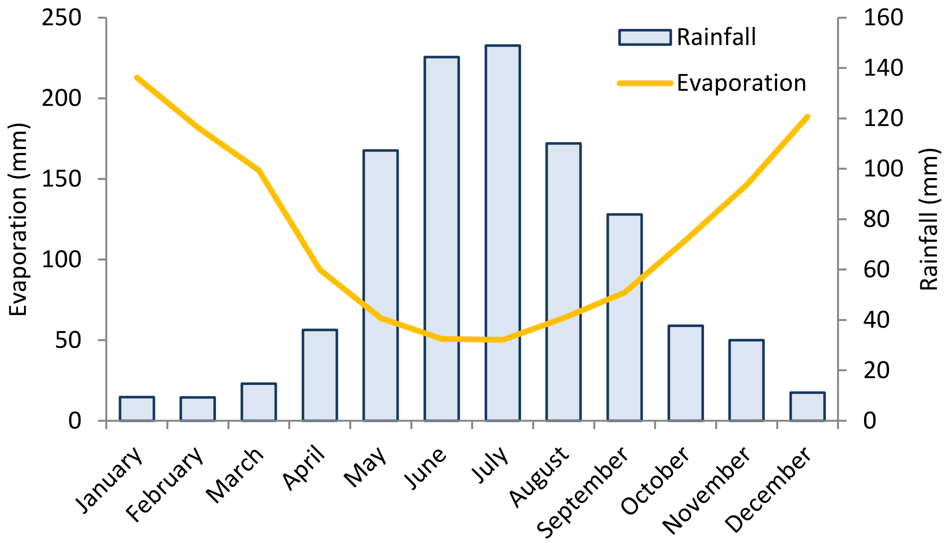


Figure 2-1: Average monthly rainfall and evaporation in Busselton 1975–2014 (source: Scientific Information for Land Owners data drill)

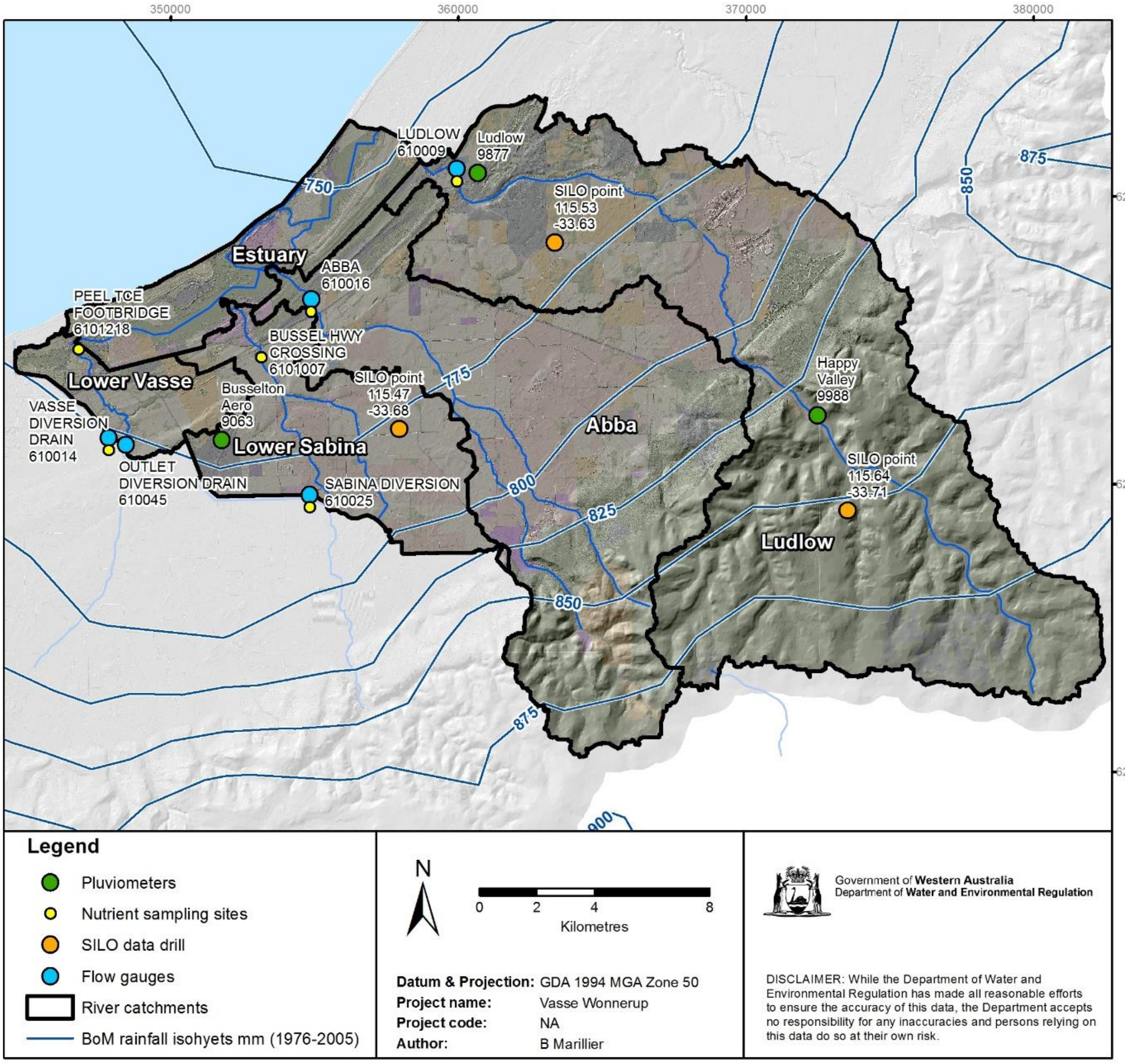


Figure 2-2: Rainfall sites and flow gauges used in modelling

2.2 Drainage history

The catchment of the Vasse-Wonnerup wetland system has been extensively modified to allow for agricultural development and provide flood protection for Busselton. Table 2-1 lists the major drainage modifications and catchment changes since European settlement in 1830.

In the 1880s, a diversion channel redirected the Capel River, which naturally flowed to the Wonnerup Estuary, to the ocean. This reduced the Wonnerup Estuary catchment area from 679 km^2 (previously included the Capel River and Gynudup Brook catchments) to its current size of about 230 km^2. Since then, the only major river flowing to the Wonnerup Estuary has been the Ludlow River (catchment area 216 km^2). In 1927, a major drain was constructed to divert the headwaters of the Sabina and most of the Vasse River to the ocean. This reduced the Vasse Estuary catchment from area of about 480 km^2 to an area of about 221 km^2. The rivers flowing to the Vasse Estuary are the Lower Vasse, Lower Sabina and Abba rivers (Figure 2-3).

In 1908 floodgates were installed on the exit channel of both estuaries to prevent inflow of sea water. These were replaced in 1929 and again in 2004 (GHD 2003). Figure 2-4 shows the major rivers and control structures of the Vasse-Wonnerup system.

Most of the main drains and sub-drains have been in place since the 1930s. Recent works have focused on upgrading or replacing infrastructure, as opposed to major realignments or new drains. However, compensation basins on the Vasse and Sabina diversion drains were constructed between 2001 and 2009 (GHD 2013) to reduce flooding in the Vasse Diversion Drain.

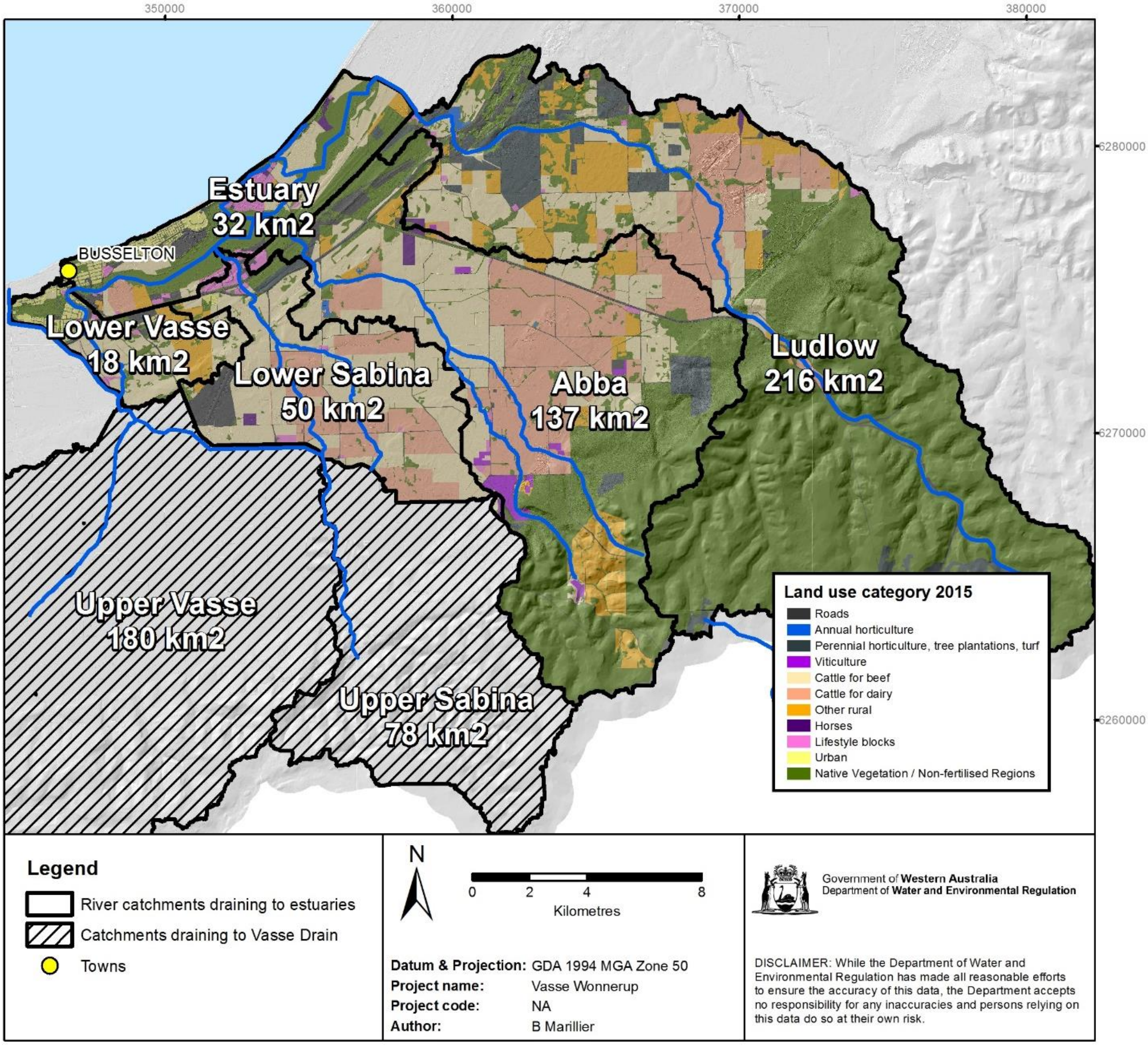


Figure 2-3: Land uses in the catchments of the Vasse and Wonnerup estuaries

Table 2-1: Summary of drainage history in the Vasse-Wonnerup catchment

Year	Location	Details	Source
1830	Busselton district	European settlement began.	City of Busselton (2013)
1840	Busselton district	European settlement continued. Crops included rye, barley, oats, dairy cattle, potatoes. Timber cutting and milling began.	City of Busselton (2013)
1880s	Capel River	Diversion channel directing the Capel River to Geographe Bay was constructed.	GHD (2013)
1840–1900	Busselton district	Demand for drainage works steadily increased.	Water Authority (1994)
1900		The first Land Drainage Act was enacted by Parliament. This allowed funding for farmers to complete their own drainage works under supervision of the Public Works Department.	Water Authority (1994)
1904	Capel River	The first major work began on the Stirling Estate west of Capel near the Capel River. Main and tributary channels were excavated and a floodgate was erected.	Water Authority (1994)
1904	Wonnerup Estuary South Drain	Extension of the south drain to discharge into the Wonnerup Estuary.	Water Authority (1994)
1907–1908	Vasse-Wonnerup estuary	A scheme was commenced to alleviate flooding in Busselton and Wonnerup. Floodgates were constructed at the mouths of the Vasse-Wonnerup estuaries to prevent salt water ingress.	Water Authority (1994)
1915	Vasse Estuary	A cut was made to drain water from New River to the ocean.	Brearley (2005)
1925	Busselton district	Busselton Drainage District proclaimed under the Land Drainage Act, and the government was given more control over drainage works.	Water Authority (1994)
1927 (after a large flood in 1926)	Vasse Estuary	A major drain was constructed to divert the headwaters of the Sabina, and virtually all of the Vasse River's flow direct to the ocean.	Brearley (2005)
1928–1929	Vasse-Wonnerup estuary	New tidal gates were constructed at the mouth of the Vasse Wonnerup Estuaries.	Water Authority (1994)
1930s onwards	Busselton district	Continued agricultural growth and clearing result in increased runoff volume, higher flood levels, and quicker time to flow peak.	GHD (2013)
1942	Vasse-Wonnerup estuary	Removable stop-gates were added to the floodgates	Brearley (2005)
1954–1986	Busselton district	Major capital works including enlargement of main drains.	Water Authority (1994)
1964–1965	Vasse Diversion Drain	The Vasse Diversion Drain is redesigned to reduce flood flows.	(PWDWA drawing set 41338) in GHD (2013)
1983	Vasse Diversion Drain	Entry to Vasse Diversion Drain was redesigned.	(PWD53848-04-02) in GHD (2013)
1993	Vasse Diversion Drain	Vasse Diversion Drain is upgraded to increase peak flow capacity to 143 m^3/s.	GHD (2013)
2001	Vasse Diversion Drain	Compensation basin #2 built on VDD	GHD (2013)
2003	Vasse Diversion Drain	Compensation basin #1 built on VDD	GHD (2013)
2004	Vasse-Wonnerup estuary	New surge barrier (cement) was installed. Wonnerup floodgates: new site was 20m upstream from the original gates. The Ballarat Bridge was removed.	Brearley (2005)
2008	Sabina Diversion weir	Weir upgraded	
2009	Sabina Diversion Drain	Compensation basin #3 built on Sabina Diversion Drain.	GHD (2013)

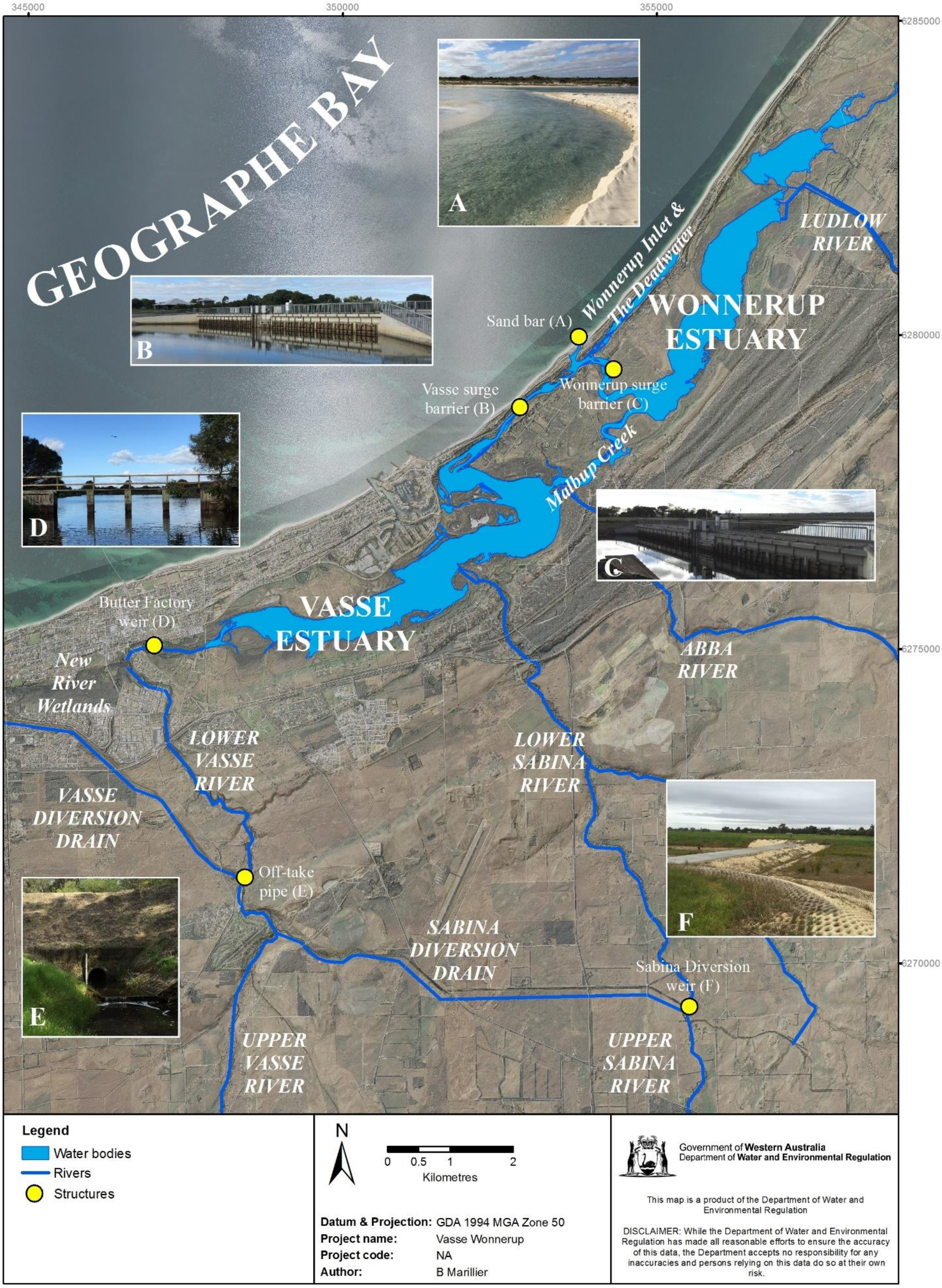


Figure 2-4: Hydrological features of the Vasse-Wonnerup system

2.3 Estuaries, rivers and drains

2.3.1 Vasse-Wonnerup wetland system

The **Vasse-Wonnerup wetland system** consists of the Vasse and Wonnerup estuaries which are periodically connected in winter via the Malbup Creek (Figure 2-4). The estuaries receive inflows from the catchment during winter and spring, and discharge to Geographe Bay through the Wonnerup Inlet.

The **Vasse Estuary** has a regularly inundated area of about 350 ha. It receives inflows from the Abba, Lower Sabina and Lower Vasse rivers and is connected to the **New River Wetlands** to the west. The Vasse surge barrier allows water to discharge from the estuary through 13 flap-gates, preventing inflow and thus providing storm surge protection. A reverse flap-gate (called the propped gate) allows flow between the inlet and the estuary if required, although it is usually closed. A smaller fish gate can be used for fish passage. The surge barrier has slots to allow temporary installation of check boards to increase the barrier's effective sill height and retain more water in the estuary during summer. Further upstream the **Butter Factory weir** is located on the Lower Vasse River where it meets the estuary. The weir is used to retain water in the river (in the centre of Busselton) during summer.

The **Wonnerup Estuary** has a regularly inundated area of about 300 ha and receives inflow from the Ludlow River at its northern end. The design of the Wonnerup surge barrier is similar to that of the Vasse surge barrier, and includes 11 flap-gates, as well as propped and fish gates. Check boards can be put in place to retain water in the estuary during summer.

The **Wonnerup Inlet** is located on the seaward side of the surge barriers and is tidally influenced when the sand bar is open. It connects both the Wonnerup and Vasse estuaries to the ocean and water levels within the inlet influence water levels in the two estuaries by limiting outflows through the surge barriers when the inlet water levels are higher than the estuary water levels. The inlet is also connected to a narrow lagoon, **the Deadwater**, which runs parallel to the coast.

The **sand bar** at the outlet of the system plays an important role in controlling water levels in the estuaries. When the bar is closed, water can collect in the inlet and limit the outflow through the surge barriers. When the bar is open, the water level in the inlet is controlled by sea level and the height of the sand bar sill. The sand bar is opened artificially using an excavator, but can also open naturally due to outflows from the estuaries, and will close naturally due to sand movement in Geographe Bay.

2.3.2 Surge barrier management

The Water Corporation manages the surge barriers, check boards and sand bar, following guidelines established in 1990 (Appendix A; Lane et al. 1997). Fresh water is retained in the estuaries in summer to maintain the surrounding pastures. Other objectives related to surge barrier management include flood protection for Busselton, provision of habitat for waterbirds, and prevention of algal blooms and fish deaths.

The Water Corporation inserts the check boards into the Vasse and Wonnerup surge barriers in late August or early September each year to maintain water in the estuaries at the end of the flow season. The boards are kept in place until the start of the flow season in the following year. During winter the surge barriers operate without the boards to allow for maximum conveyance of flood water while still preventing storm surge flowing into the estuary.

When the check boards are in place the effective sill heights of the surge barriers are 0.4 mAHD. Water will be retained up to this height, but when water exceeds 0.4 mAHD it will overtop and discharge to the inlet. When the boards are removed the sill heights are -0.4 mAHD and water can discharge from the estuary if downstream water levels are lower than upstream levels.

Since 1988, summer water levels have been maintained at -0.1 mAHD by allowing sea water through the barrier (via the fish gate). Before 1988 sea water was not let into the estuaries, and most of the Vasse Estuary dried out (down to where the Abba River flows in).

Both the Wonnerup and Vasse surge barriers have a fish gate which can be opened to allow passage of fish or water exchange. These gates can allow water to exchange in both directions or be configured to allow inflow to the estuaries only. The fluxes are small relative to other fluxes, but can result in a significant increase in salinity upstream of the surge barriers. During times of extremely poor water quality, water has also been pumped from the inlet to the estuary.

2.3.3 Lower Vasse River

The Lower Vasse River flows through Busselton and discharges to the eastern edge of the Vasse Estuary at the Butter Factory weir. With the Upper Vasse catchment (180 km^2) now diverted, the river has a small catchment area of 18 km^2. Land use in the catchment is mostly rural (horticulture and pasture for beef cattle), with some urban areas close to Busselton.

The river extends downstream for 5 km from the Vasse Diversion Drain to the Butter Factory weir, its bed elevation dropping from 4.5 mAHD to -1.0 mAHD. At the upstream end, a 900 mm offtake pipe diverts a small portion of the flow in the Vasse Diversion Drain to the Lower Vasse River. The 900 mm offtake pipe has a penstock gate valve that can be used to control the amount of flow. The penstock can be opened up to 90 to 95% and closed so that only a trickle of water flows through the pipe. The river is connected to the New River Wetlands via a small culvert running under West Street.

The lower sections of the river in town have almost no grade, with the whole reach acting as a river pool. Regular algal blooms occur in this part of the river during summer, which is of major concern to local residents. Nutrient pollution, in combination with stagnant fresh water and high summer temperatures, creates the environmental conditions that encourage algal growth dominated by toxic blue greens (Cyanobacteria)

The **Butter Factory weir** is operated to retain water in the Lower Vasse River during summer, as the main body of the estuary downstream dries. The weir boards are inserted to a height of 0.4 mAHD late in the flow season and then removed at the start of the flow season the following year.

2.3.4 Lower Sabina River

The Lower Sabina River has a catchment of 50 km^2. The Upper Sabina catchment (78 km^2) no longer contributes any flow directly to the lower river, although some minor sub-drains in the upper catchment may spill in large events. The Lower Sabina catchment is located entirely on the Swan Coastal Plain and land use is predominantly dairy and beef grazing.

The river extends 8 km, from the Sabina Diversion weir to the centre of the Vasse Estuary near Barracks Drive, and falls in elevation from 25 mAHD to 0 mAHD. Although some sections of the river are incised into the coastal plain, the channel is small in most places. In the upper reaches the channel is only 5 m wide and 1 m deep with regular breaks along the river banks.

2.3.5 Abba River

The Abba River has a 137 km^2 catchment area, making it the largest river catchment of the Vasse Estuary. The headwaters of the Abba are located in the forest on the Whicher Scarp and Blackwood Plateau.

The river extends about 20 km from the plateau to the eastern end of the Vasse Estuary, falling from more than 100 mAHD to sea level – most of this drop occurring where the scarp meets the coastal plain.

The Abba River has better water quality than the Vasse and Sabina rivers, although nitrogen concentrations are still high.

2.3.6 Ludlow River

The Ludlow River discharges to the northern end of the Wonnerup Estuary and has a catchment area of 216 km^2. Much of the catchment is located in forested parts of the Whicher Scarp and Blackwood Plateau, but the river’s water quality is still poor.

2.3.7 Vasse Diversion Drain

The Vasse Diversion Drain has a catchment area of 303 km^2 and receives inflows from the upper Sabina (catchment 78 km^2) and upper Vasse (catchment 180 km^2) rivers and discharges to Geographe Bay. The drain was constructed in the 1920s and diverts much of the upper catchment which previously drained into the Vasse Estuary. This has reduced the risk of flooding in the estuary, however levee bank failures in the late 1990s illustrate that the drain still poses a potential hazard for Busselton, although construction of the compensation basins has reduced the risk of levee failure.

2.4 River flows

Of the rivers that contribute flow to the Vasse and Wonnerup estuaries, gauged data are available for the Ludlow (610009) and Abba (610016 and 610062). Flow is also recorded in the Vasse Diversion Drain downstream of Hill Road (610014), at the Vasse Diversion Drain offtake structure (610045) and in the Sabina Diversion Drain (610025). The gauging stations are shown in Figure 2-2.

The flow data used in this study were derived from a Source catchment model calibrated with the available data (Hall in prep.). Simulated daily flows were extracted from the catchment model at the locations shown in Figure 2-5. The daily flows are suitable for use in simulations of multiple years, but not for flood simulations that require a shorter timestep. Derivation of design flows for flood simulation is discussed in Section 3.

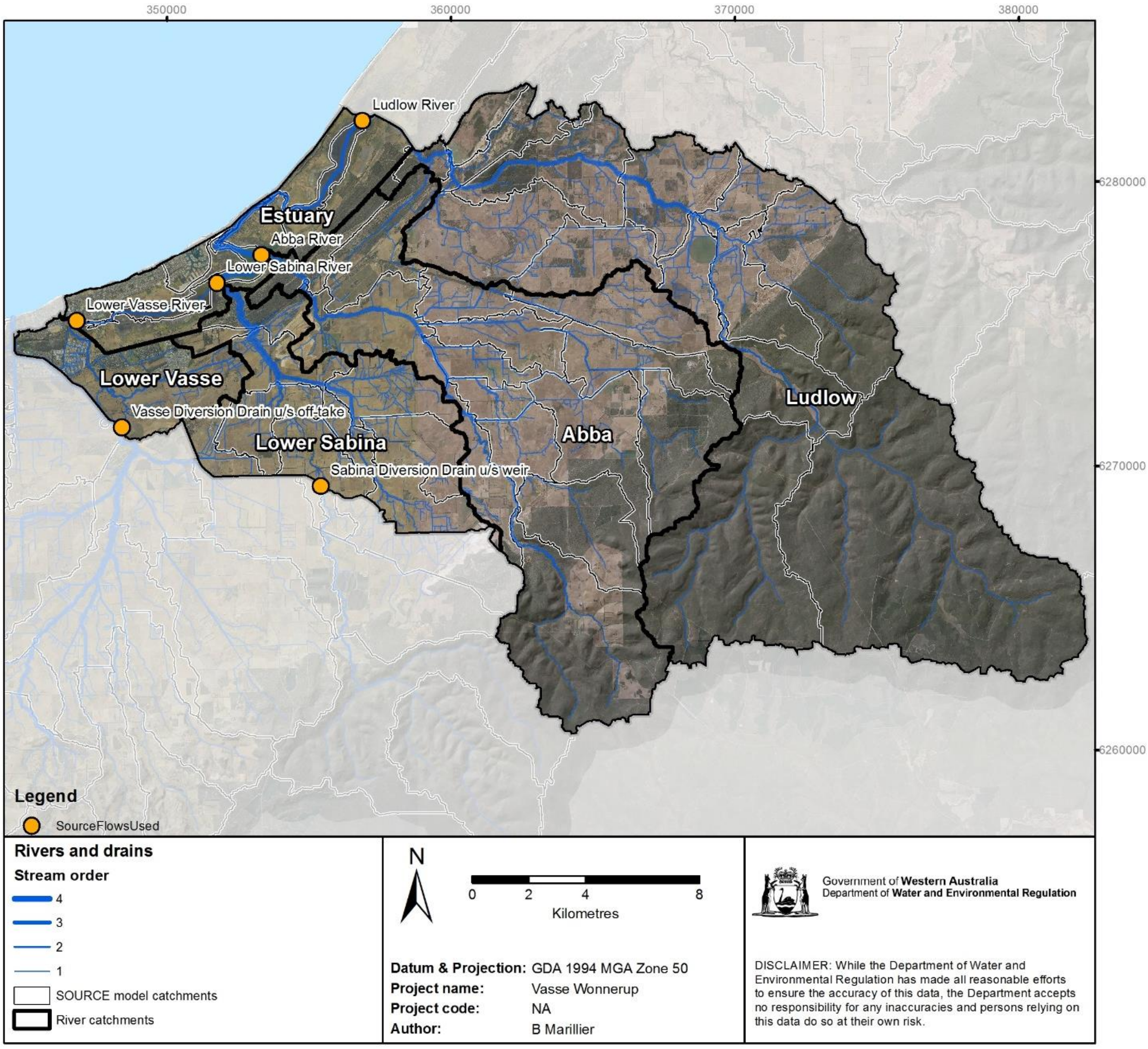


Figure 2-5: Source model catchments of the Vasse-Wonnerup estuary

2.4.1 Flows to the Vasse Estuary

The average annual water fluxes to and from the Vasse Estuary from the inflowing rivers, rainfall and evaporation are shown in Figure 2-6, based on modelled flows and estimated rainfall onto and evaporation from the estuary for the years 2001–14. Flows in the Vasse and Sabina diversion drains are also shown.

On average, most of the flow to the Vasse Estuary comes from the Abba River. In drier years the proportion of flow from the Vasse Diversion Drain offtake pipe increases relative to other sources. The offtake pipe is only 900 mm in diameter, but because the Vasse Diversion

Drain has a longer flow season (Figure 2-7) and a relatively large annual flow volume, the pipe contributes a substantial amount of water to the estuary.

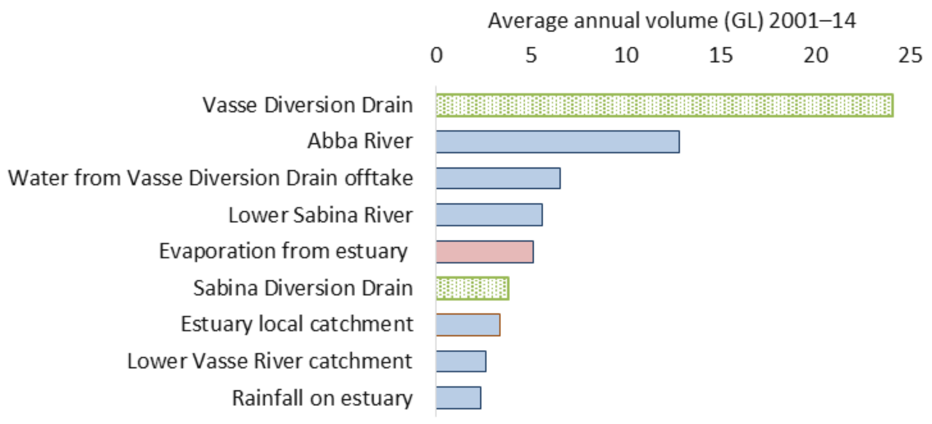


Figure 2-6: Average annual flows (2001–14) in the major rivers flowing to the Vasse Estuary and in the Vasse and Sabina diversion drains

2.4.2 Flow in the Vasse and Sabina diversion drains

The drainage options considered in this study included redirection of water from the Upper Sabina River into the Lower Sabina River and from the Vasse Diversion Drain into the Lower Vasse River. Normally these flows would discharge to the ocean through the Sabina and Vasse diversion drains. The annual average flow volumes in these drains are shown in Figure 2-6. As the Sabina Diversion Drain flows into the Vasse Diversion Drain, the total amount of water available for redirection is the volume shown for the Vasse Diversion Drain. If water were diverted from the Upper Sabina River to the Lower Sabina River, then less water would be available for redirection at the Vasse Diversion Drain offtake structure. It is also important to note that the flow volumes in the Vasse and Sabina diversion drains are far greater than the natural flows would have been, due to the cleared catchment and artificial drainage.

Figure 2-7 shows the average monthly flows (2001–14) available for redirection at the Sabina Diversion weir and the Vasse Diversion Drain offtake pipe, and the flows in the Lower Sabina and Lower Vasse rivers. On average, water is only available for redirection from May to November. There is close to zero flow during summer (December–April). The Vasse Diversion Drain has substantially more flow than the other locations and a longer flow season.

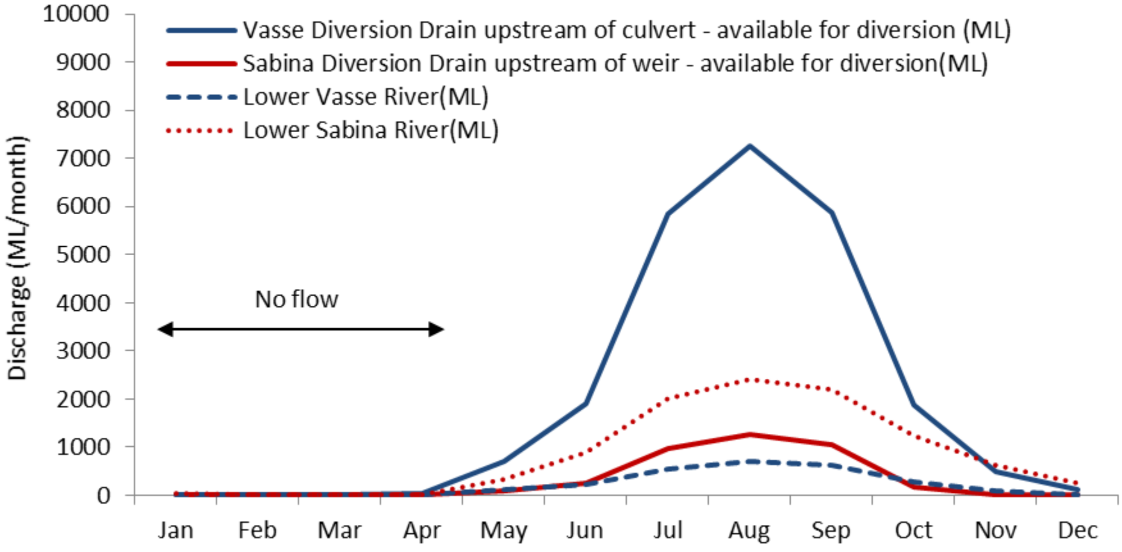


Figure 2-7: Modelled average monthly flows on the Vasse and Sabina diversion drains upstream of diversion structures and downstream Lower Vasse and Lower Sabina river flows (2001–14)

2.5 Water levels in the ocean and estuaries

2.5.1 Geographe Bay

Geographe Bay is micro-tidal with a range of less than 2 m. During winter, low barometric pressure results in higher water levels that exceed 1 mAHD several times a year. Winter sea levels are important as they control outflow through the surge barriers and are coincident with the inflows from the catchment. Sea levels are lowest during summer and drop to below -0.2 mAHD regularly.

Sea-level data for 1975–2015 were generated for Geographe Bay by combining adjusted Busselton Jetty and Bunbury data for the period before 2002 with the Port Geographe gauge data from 2002 onwards. For 1975–2015, an increasing linear trend of 1.9 mm/year in sea level was observed (Figure 2-8), which is similar to the estimated global average sea-level rise of 2.0 mm/year for 1971–2010 (IPCC 2013). Sea levels will continue to rise this century and the Intergovernmental Panel on Climate Change (IPCC 2013) predicts that the rate of rise will increase, with average global increases being between 170 and 380 mm by around 2050.

The highest sea level ever recorded in Geographe Bay is 1.79 mAHD, associated with the passing of Cyclone Alby in 1978 (Worley Parsons 2013). The event caused widespread coastal flooding and erosion but did not cause flooding in the Vasse Estuary because of protection from the surge barrier, the short duration of the storm surge and the absence of river flow. Figure 2-8 shows the measured sea level for 4 and 5 April 1978 during Cyclone Alby.

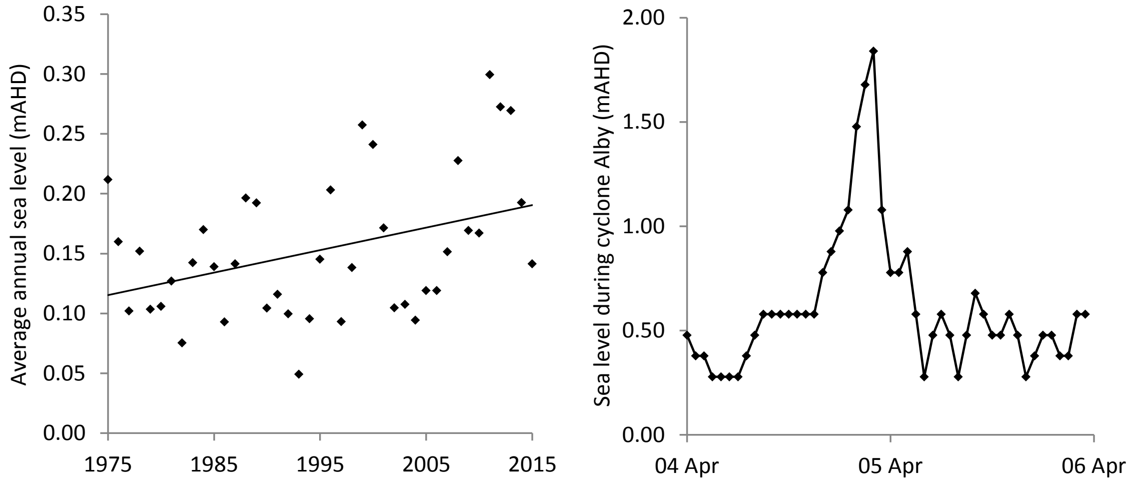


Figure 2-8: Average annual sea level for Geographe Bay from 1975–2015 (left) and sea level near Bunbury during the passage of Cyclone Alby in 1978 (right)

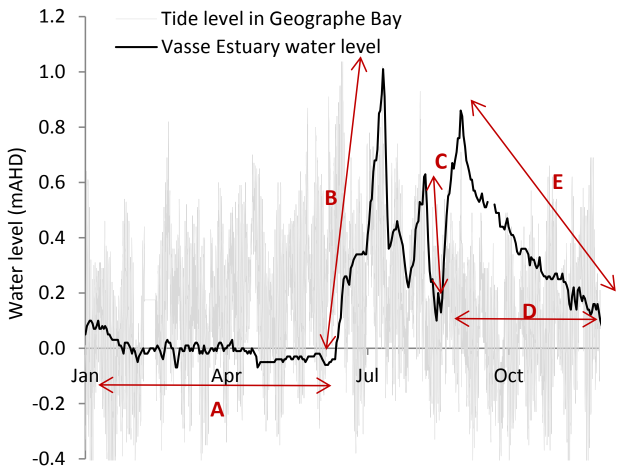
2.5.2 Vasse Estuary

Water levels in the Vasse Estuary generally vary from about -0.1 mAHD in summer to 1.1 mAHD in winter. Higher water levels can occur under flood conditions, and before 1988, sea water was not let into the estuary and the level generally dropped to about -0.4 mAHD. During winter, water levels rise rapidly as a result of direct rainfall on the estuary and river inflows. Multiple other factors also influence the water levels including evaporation and sea level, as well as sand bar and surge barrier management. Before construction of the Vasse Diversion Drain, the estuary and Busselton experienced regular winter flooding.

Reliable continuous water-level data for the Vasse Estuary are available from the sources listed in Table 2-2. These datasets can be used to understand estuarine hydrology and for model calibration. For example, Figure 2-9 shows typical water levels recorded during 2007 for the Vasse Estuary and Geographe Bay. The annotation describes the factors influencing the water levels at different times of the year.

Table 2-2: Water-level data for the Vasse Estuary

Source	Monitoring location	Begin	End
DoW	Upstream and downstream of Vasse surge barrier	18/01/2001	12/02/2004
DPAW	Upstream of Vasse surge barrier	1/01/2004	20/11/2014
Water Corporation	Upstream and downstream of Vasse and Wonnerup surge barriers	27/01/2015	Ongoing



A. During summer water levels are maintained at -0.1 mAHD by allowing sea water through the Vasse surge barrier.

B. The estuary is filling due to winter rainfall. The highest water levels are recorded during periods of higher tide or when closure or partial closure of the sand bar is restricting outflow.

C. When the sand bar is open and the tide is low water can flow out through the surge barriers and water levels decline.

D. The sand bar is closed and check boards are installed to a height of 0.4mAHD and restrict outflow through the surge barriers.

E. Water levels decline due to direct evaporation and leakage in late spring and summer.

Figure 2-9: Recorded daily mean water levels in the Vasse Estuary for 2007 shown in black, and Geographe Bay shown in grey

For major flooding (very high water levels) in the Vasse Estuary, two conditions must prevail: first, restriction of outflow at the surge barrier due to the sand bar being closed or sustained high sea levels and second, significant catchment inflow.

2.6 Catchment land uses and water quality

Figure 2-3 shows the Vasse and Wonnerup estuary catchments and land uses.

Only 22% of the Vasse Estuary catchment is uncleared native vegetation, with most of the cleared land used for grazing by beef and dairy cattle. The cleared land has greater water yield than the uncleared land, and also much higher nutrient concentrations due to fertiliser use and animal production.

Water quality is sampled as part of ongoing monitoring associated with the water quality improvement plan (DoW 2010). Seasonal median total nitrogen (TN) and phosphorus (TP) concentrations for all rivers in the Vasse-Wonnerup catchment are shown in Appendix B.

This section discusses data from the Lower Vasse River (6101218), Vasse Diversion Drain (610014), Lower Sabina River (6101007) and Sabina Diversion Drain (610025), which are upstream and downstream of the proposed redirection points.

The water quality data recorded for these rivers between 2001 and 2015 are displayed using box and whisker plots (Figure 2-10 and Figure 2-11). Flow season data (May–July and August–October) are presented with the Australian and New Zealand Environment and Conservation Council (ANZECC) nutrient concentration guideline values for lowland rivers (TN: 1.2 mg/L; TP: 0.065 mg/L). Grouping the data in this way shows the first-flush signal – the first flows of the season have higher nutrient concentrations than subsequent flows. Summer data (November–April) are rarely collected due to lack of flow.

Median concentrations are above ANZECC guideline values except for TP concentrations in the Sabina Diversion Drain.

The relative concentrations of the rivers and drains, above and below possible redirection locations are as follows:

- TP concentrations are lower in the Vasse Diversion Drain than in the Lower Vasse River, but TN concentrations are similar.
- TP concentrations are lower in the Sabina Diversion Drain than in the Lower Sabina River, but TN concentrations are higher in the Sabina Diversion Drain.

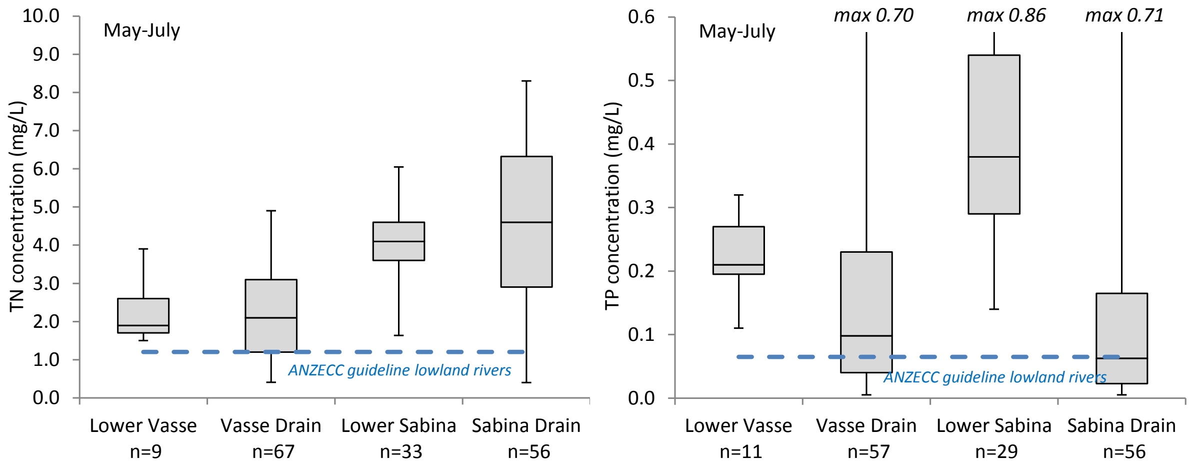


Figure 2-10: Total nitrogen and total phosphorus concentrations May to July

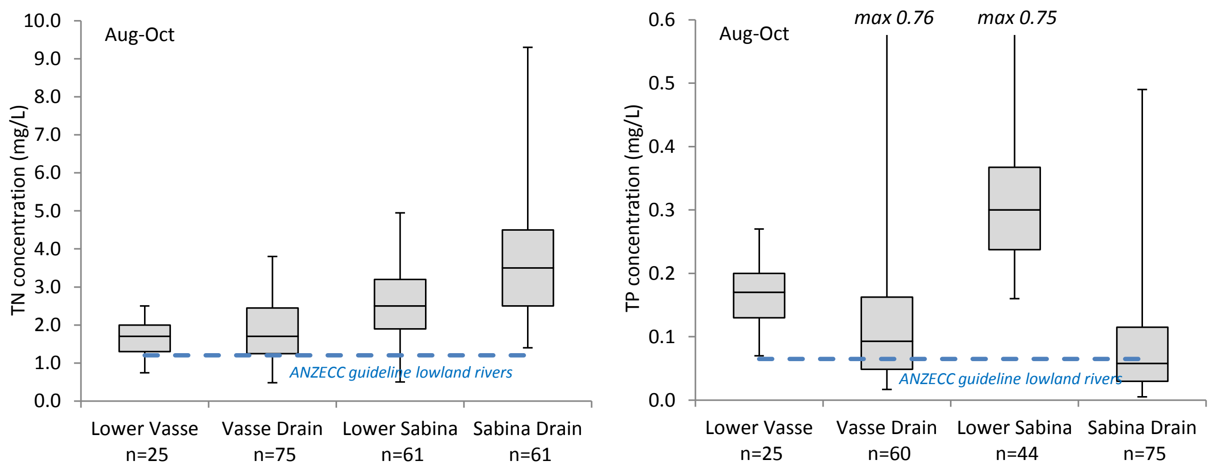


Figure 2-11: Total nitrogen and total phosphorus concentrations August to October

3 Design flows for flood modelling

Flood history and flood studies are discussed in sections 3.1 and 3.2 below, and reviewed in Appendix C. The remainder of this chapter describes the process of generating flood flows for input to the MIKE11 hydraulic model to create the flood simulations. Design rainfall (Section 3.4) were input to a RORB rainfall-runoff model (Section 3.5) to generate design flood flows for different AEP events. Final refinement of the RORB model parameters was achieved by comparing RORB modelled flow with flood flows derived in the flood-frequency analysis (FFA) (Section 3.3).

3.1 Flood history

Floods have occurred regularly since the early years of European settlement in Busselton. Flooding and inundation caused problems for agriculture and was the main reason for construction of the large artificial drainage network within the catchment. Significant flood events are listed below.

Table 3-1: Historical flooding in the Geographe catchment

Year	Details	Source
1843	Cyclone affects Perth Colony. At Bunbury the tide increased by 4 feet.	BoM website
1872	Cyclone – Bunbury was affected.	BoM website
1909	Flood – Rainfall estimated at 107 mm in 12 hours, with a further 23 mm the following day.	West Australian (1909) in GHD (2013)
1937	Cyclonic storm passes Busselton resulting in a storm surge into the estuary and damage to the floodgates.	The Mercury, Hobart TAS (1937) in GHD (2013)
1963	Flood – Heavy rainfall in July causes extensive flooding. The banks of the Vasse Diversion Drain were breached.	WAWA (1987) in GHD (2013)
1963	Flood – Riverine flooding in August on the Capel and Ludlow rivers.	WAWA (1987) in GHD (2013)
1964	Flood – Vasse Diversion Drain embankment overtopped. The catchment was already saturated from winter rainfall.	WAWA (1987) in GHD (2013)
1965	Flood – 97 mm of rainfall falls on the 20 July, but the Vasse Diversion Drain does not fail.	WAWA (1987) in GHD (2013)
1967	Flood – 19 and 20 June, high rainfall resulted in flooding, and the Vasse Diversion Drain was overtopped briefly.	WAWA (1987) in GHD (2013)
1978	Cyclone Alby.	Public Works Department (1978)
1986	Flood – Highest levels seen in the Vasse Diversion Drain since 1965 upgrade.	GHD (2013)
1988	Flood – June.	GHD (2013)
1990	Flood – Peak flows estimated at 130–140 m^3/s after rainfall of 81–103 mm across the catchment.	GHD (2013)
1997	Flood – Between 69 and 107 mm of rain fell in 19 hours. Peak flows of 128 m3/s in the Vasse Diversion Drain, which overtopped/failed in a number of locations. After this event a commitment was made to improve the drainage infrastructure.	GHD (2013)
1999	Flood – Similar to 1997.	GHD (2013)

3.2 Previous flood studies

Several flood studies have been completed in the catchment during the past 30 years:

- *Busselton regional flood study* (WAWA 1987)
- *Vasse River Diversion Drain flood hydrology study* (WAWA 1997)
- *Busselton regional flood study review* (JDA 1998)
- *Hydrologic review of Busselton flood protection* (GHD 2013)
- *Coastal inundation modelling for Busselton, Western Australia, under current and future climate* (Martin et al. 2014)

Most of this work focused on flood protection for Busselton and the Vasse Diversion Drain in particular, given it was not originally constructed with capacity for the 1% AEP flood event. The *Busselton regional flood study* was completed in 1987 and estimated design flows for the area's major rivers and design water levels for the Vasse and Wonnerup estuaries.

Flooding resulting from a breach in the Vasse Diversion Drain in 1997 triggered a response from the Water Authority (WAWA 1997) and the regional flood study completed the following year made several recommendations related to drain's capacity (JDA 1998). One of these was to construct compensation basins in the catchment to restrict peak flow in the drain, which was partially implemented by the Water Corporation. GHD (2013) was commissioned to assess the impact of the compensation basins on flows in the Vasse Diversion Drain. This study found that the drain was at capacity for the peak flow in a 1% AEP flood event, and therefore still presented a flood risk, prompting the Water Corporation to consider further upgrades.

The previous studies did not focus on estuarine flooding or flooding in the lower reaches of the Vasse and Sabina rivers. However, the rainfall and hydrological analyses are still relevant and have been incorporated or considered in the present study where appropriate.

3.2.1 Floodplain development strategies

DWER uses floodplain development strategies to ensure an adequate level of flood protection for development on floodplains. The existing strategies for the lower Vasse and Sabina rivers are based on 1% AEP flood levels from the older WAWA 1987 study. Floodplain development strategies for these rivers are included in Appendix D. The strategy for the Lower Vasse River shows extensive flooding of urban areas between the Strelly Street and Causeway Road bridges for the 1% AEP event. On the Lower Sabina River, the 1% AEP flood is contained within the river banks, however mapping is not provided upstream of the old Bussell Highway bridge (now Tuart Drive).

3.3 Flood-frequency analysis

Flood-frequency analysis (FFA) is a statistical method that uses gauged flows to calculate flood flows (m^3/s) for different AEP rainfall events. FFA was completed for flow gauges on the Ludlow River (610009) and the Abba River (Wonnerup Siding 610016).

3.3.1 Methodology

Peak annual flow series were used for FFA of the Abba and Ludlow gauges. The flow series for each gauge was assessed for completeness and accuracy, and the quality of the gauging station and flow record was discussed with the regional hydrographer before analysis.

The Ludlow River annual series consists of 22 years of data from 1991–2012; the Abba River annual series is only eight years long (1995–2002). Given the short record for these two gauges the annual series was extended using nearby flow gauges and a simple weighting based on catchment area (Appendix E). The following flow gauges were used to create or extend the annual series to 54 years (1959–2012):

- Abba River, Wonnerup Siding (610016), 1995–2002, catchment area 128 km^2
- Ludlow River, Ludlow River (610009), 1992–2012, catchment area 208 km^2
- Ludlow River, Happy Valley (610005), 1974–98, catchment area 109 km^2
- Capel River, Scott (610129), 1959–67, catchment area 336 km^2
- Capel River, Yates (610219), 1967–75, catchment area 315 km^2

The program Flike V4.50 (Kuczera 2001) was used to fit a Log Pearson type III (LPIII) distribution to the annual data series for the rivers. For the Ludlow River (610009), the 22-year gauged record was used to fit the distribution, with censored flows for the infilled flows from the ungauged record (one censored flow above 70 m^3/s, 32 below). For the Abba River, an uncensored annual flow series for the full (infilled) 54-year record was used, as the eight-year gauged record was insufficient to fit a distribution. This means that the confidence limits for the Abba River FFA overestimate the certainty of the LPIII distribution.

3.3.2 Results

The FFA results for the two gauges are summarised in Table 3-2 and plots of the fitted LPIII distributions are shown in Appendix E. For the AEPs of less than 1%, the FFA is unreliable and therefore not included in the table below.

Table 3-2: Estimated peak flow using flood-frequency analysis – Ludlow and Abba rivers

Annual Exceedence Probability	Ludlow River (610009) (m^3/s)	Abba River (610016) (m^3/s)
20%	20	20
10%	36	33
5%	60	50
2%	108	76
1%	161	99

3.4 Design rainfall

3.4.1 Rainfall intensity frequency duration (IFD)

Design rainfall gives expected rainfall intensity and duration for events of different magnitude and is used as input for flood models. GHD completed design rainfall analysis in its 2013 study and the composite IFD table is appropriate for use in the current study (Table 3-3 and Figure 3-1).

GHD (2013) analysed rainfall IFD for the Chapman Hill (509063) and Yoongorillup (9771) stations using three methods:

- Australian Rainfall and Runoff (AR&R 1987 – Pilgrim 2001)
- CRC-FORGE (Durrant & Bowman 2004)
- Rainfall frequency analysis based on observed data at each station

The rainfall frequency analysis was 20–30% higher than those calculated using AR&R 1987. The difference was attributed to the several large rainfall events that have occurred since the AR&R rainfall data were created.

The IFD table (Table 3-3) was compared with the 2013 interim design rainfalls released by the Bureau of Meteorology (BoM) as part of the revision of Australian Rainfall and Runoff (Appendix E). Although GHD's design rainfalls were greater than those provided by BoM for all durations and event magnitudes, this study used the GHD data because they were based on analysis of local data.

Table 3-3: Adopted rainfall intensity frequency duration table based on work by GHD (2013)

	Event rainfall (mm) Annual Exceedence Probability					
Event duration	**10%**	**5%**	**2%**	**1%**	**1 in 200**	**1 in 500**
6hr	60	67	78	86	94	111
12hr	75	84	97	107	122	141
24hr	95	105	120	131	152	175
36hr	105	115	130	146	164	193
48hr	115	125	140	156	176	207
72hr	125	135	148	168	189	221

3.4.2 Temporal patterns

Temporal patterns were extracted from the AusIFD software for Bunbury (zone 8) and applied to the rainfall data. The methodology used to calculate design temporal patterns is described in Book II Section 2 of AR&R 1987. The method provides a separate temporal pattern for events with ARI < 30 years (3% AEP) and events with ARI > 30 years, as shown in Appendix E.

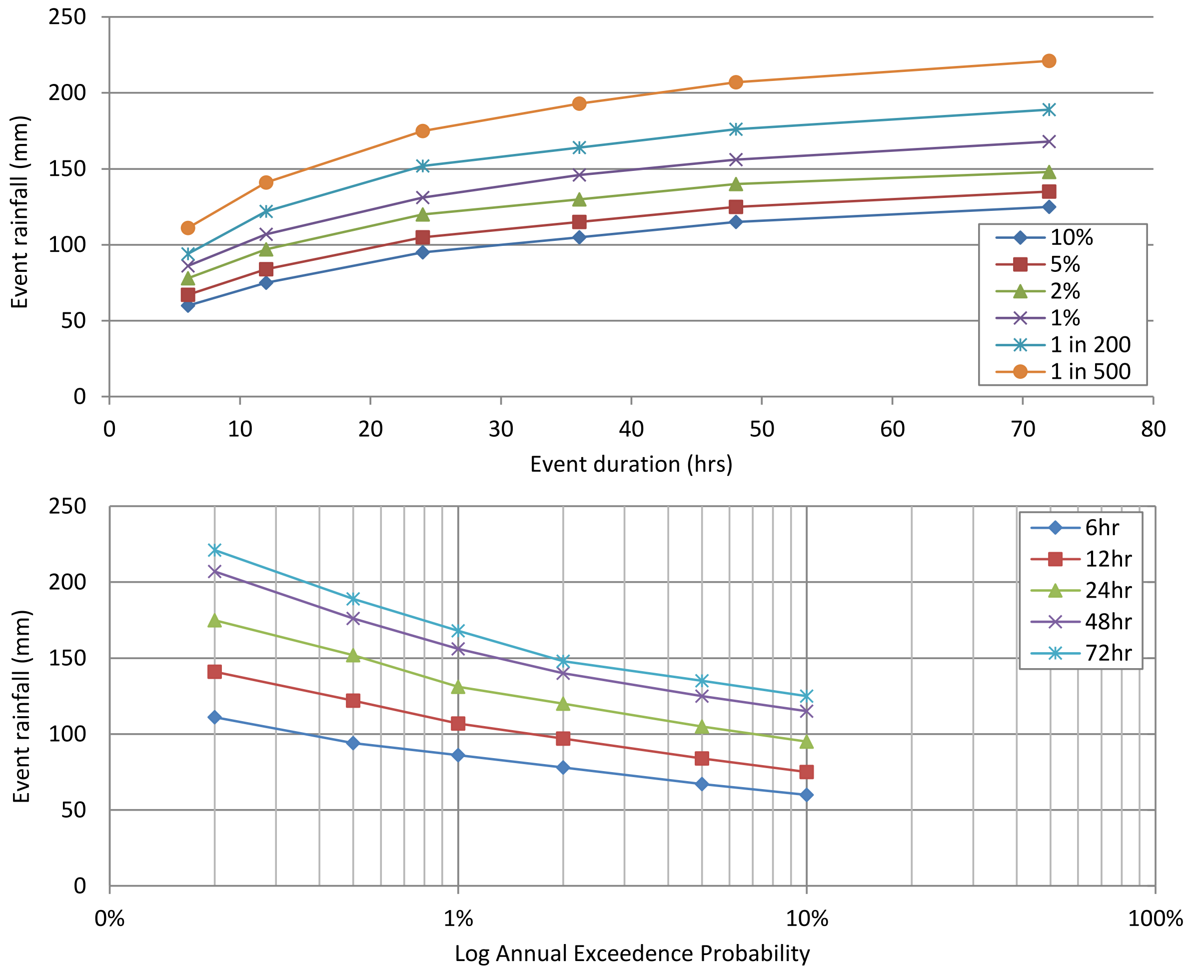


Figure 3-1: Rainfall intensity frequency duration (IFD) data plotted with event duration versus event rainfall for different AEPs (top); and rainfall IFD probabilistic plot for log AEP versus event rainfall for different event durations (bottom)

3.4.3 Areal reduction factor

The design rainfall (discussed above) was derived from analysis of rainfall at single sites. The design rainfall across an entire catchment is related to design rainfall at points using areal reduction factors (ARF).

For parts of Western Australia, the CRC-FORGE technical manual (Durrant & Bowman 2004) provides methods to estimate ARFs for catchments between 1 and 10 000 km^2. Chapter 6 of the manual describes the appropriate method for calculating ARFs for south-west catchments. This method was used to calculate the ARF for the catchments of the Vasse and Wonnerup estuaries (433 km^2). For annual series in the state's south-west, the equation provided in CRC-FORGE does not vary the ARF with event magnitude (Table 3-4).

Table 3-4: Areal reduction factor

Catchment area (km^2)	Duration (hrs) 6	12	24	36	48	72
433.8	0.82	0.87	0.91	0.93	0.94	0.95

Based on Chapter 6 of CRC FORGE manual (Durrant & Bowman 2004)

3.5 RORB modelling

RORB is a runoff and streamflow routing program, described in Laurenson et al. (2010). The model divides a catchment into subareas and routing reaches, which generate and route flow through the catchment based on an input rainfall time-series.

The purpose of the RORB modelling was to establish the inflow hydrographs at the boundary of the hydraulic model for the 10%, 5%, 2% and 1% AEP flood events. RORB models were constructed for the Ludlow, Abba and Lower Sabina rivers, as well as the combined Lower Vasse River and Vasse Estuary local catchment. The Wonnerup Estuary catchment was included as part of the Ludlow River RORB model.

3.5.1 Catchment delineation

Catchment delineation was completed using ArcGIS based on terrain data and the existing drainage network. The combined catchment area for the RORB models is 433 km^2. This excludes the catchment of the Vasse Diversion Drain and Upper Sabina River, in which flood flows are directed to the ocean via the Sabina and Vasse diversion drains. Figure 3-2 shows the extent of the four RORB models, catchment areas, and the node-link routing network.

3.5.2 Rainfall intensity data used in RORB modelling

When modelling design flows, RORB requires rainfall intensity data in units of millimetres per hour (mm/hr). The rainfall intensity data is then distributed in time, based on the temporal patterns described previously. Rainfall intensity data from Table 3-3 with areal reduction factors applied, shown in Table 3-5, were used in RORB.

Table 3-5: Rainfall intensity data used in Runoff Routing B modelling with areal reduction factors applied

Rainfall intensity (mm/hr) selected events for RORB with ARF applied						
	Annual Exceedence Probability					
Hours	**10%**	**5%**	**2%**	**1%**	**1 in 200**	**1 in 500**
6hr	8.18	9.13	10.63	11.72	12.81	15.12
12hr	5.46	6.12	7.06	7.79	8.88	10.26
24hr	3.61	3.99	4.56	4.98	5.78	6.66
36hr	2.71	2.97	3.36	3.77	4.24	4.98
48hr	2.25	2.45	2.74	3.05	3.45	4.05
72hr	1.65	1.78	1.96	2.22	2.50	2.92

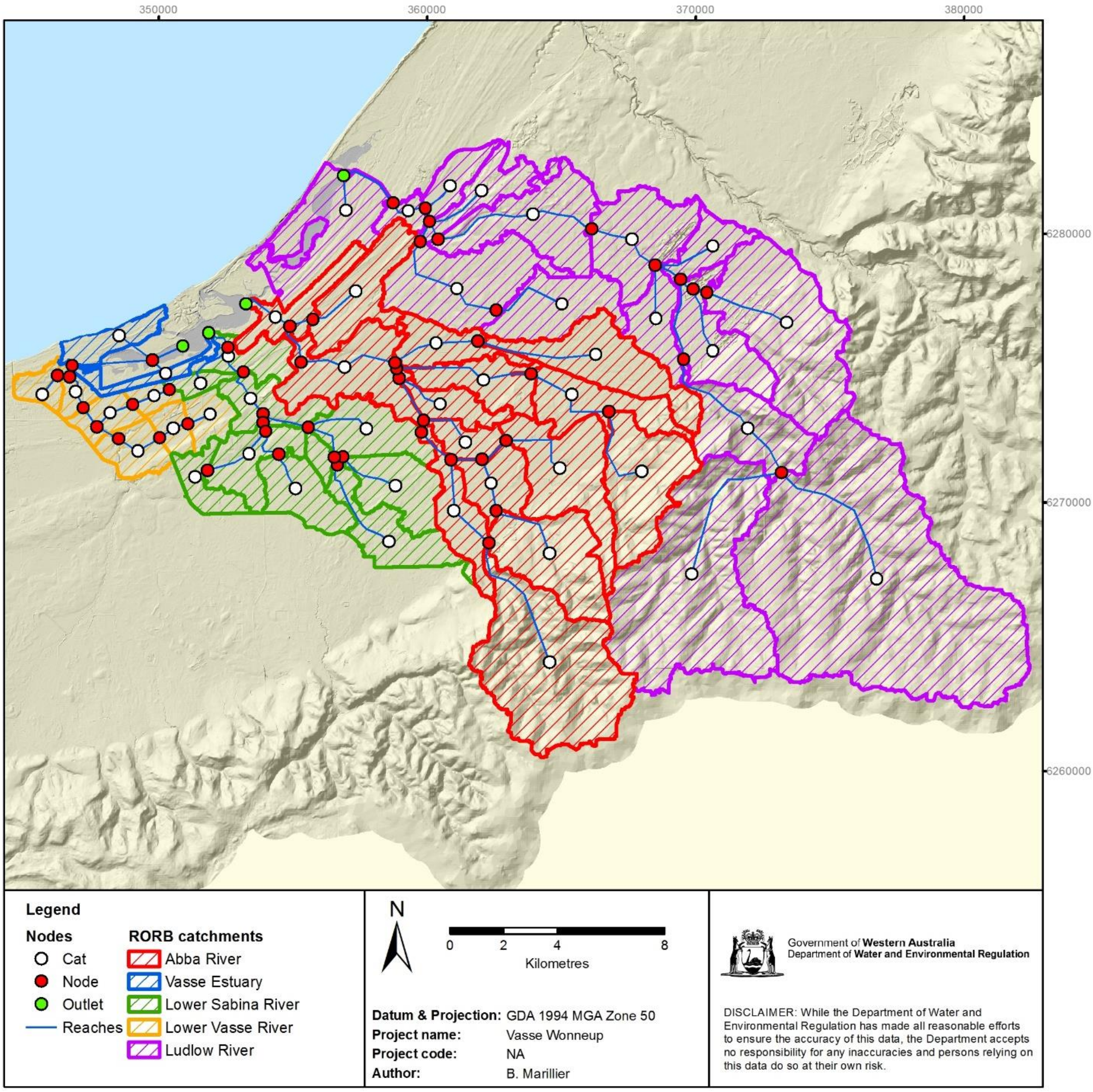


Figure 3-2: Runoff Routing B models in the Vasse-Wonnerup estuary catchment

3.5.3 Baseflow separation

RORB does not model the baseflow component of streamflow, so baseflow must be removed from the hydrograph before model calibration, and then added to the output design hydrographs. Before calibration of the RORB models, baseflow was removed from gauged data using the Eckhardt two parameter digital filter (Eckhardt 2005) shown below.

$$B_{k+1} = \frac{(1 - BFI_{max}).\alpha.B_k + (1 - \alpha).BFI_{max}.Q_{k+1}}{1 - \alpha.BFI_{max}}$$

where:

α = baseflow filter parameter
BFI_{max} = maximum value of ratio between baseflow and total flow
B_k = baseflow at timestep k
Q_k = total flow at timestep k

The parameters of α and BFI_{max} were adjusted to remove baseflow from each hydrograph and match the recession curve at the tail of the event. The parameter α was set to 0.98, and BFI_{max} to 0.4. These parameters were determined for use on a discharge series at a one-hour timestep. An example of the baseflow separation is shown in Figure 3-3.

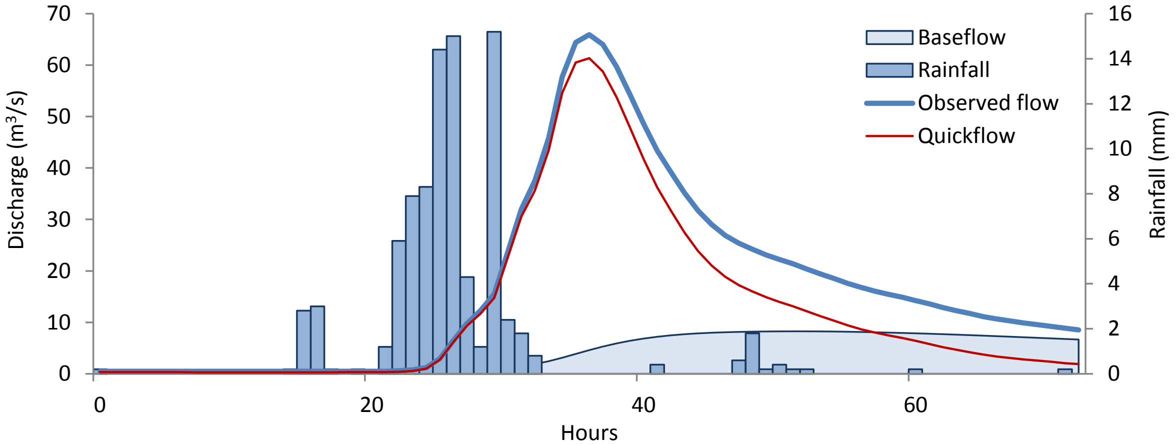


Figure 3-3: Example of baseflow separation for the 1997 event on the Ludlow River

3.5.4 Baseflow addition for design events

Baseflow was added to design events using the baseflow addition method reported by GHD (2010) as part of the Murray floodplain development strategy. The following equation shows how baseflow is derived from direct runoff based on a RORB modelled hydrograph.

$$B_k = (Br.B_{k-1}) + (Bc.Qr_k)^{Bm}$$

where:

B_k = baseflow at timestep k
B_k = baseflow at timestep k-1
Qr_k = direct runoff at timestep k
Br, Bc, Bm = calibrated parameters

The calibrated parameters were determined by first performing a baseflow separation on an observed hydrograph, calculating the direct runoff component (quickflow), and then deriving the appropriated parameter values to reconstitute the hydrograph using baseflow. Using the baseflow separation parameters defined in the previous section, the calibrated baseflow addition parameters were *Br* = 0.97, *Bc* = 0.014 and *Bm* = 0.98. These parameters were used to calculate design baseflow for all events.

Initial baseflow was assigned for each of the catchments as follows:

- Ludlow River: 2 m^3/s
- Abba River: 1.5 m^3/s
- Lower Sabina River: 0.5 m^3/s
- Lower Vasse River: 0.2 m^3/s

Using this method, baseflow was added to the RORB design flows with about 10% additional under-peak flow rate and 30% total event volume for the 1% AEP 24-hour event.

3.5.5 Rainfall and flow data

Flow data is available on the Ludlow River at the Ludlow gauge (610009) and on the Abba River at Wonnerup Siding (610016). Both of these gauges have a record covering the late 1990s when large flow events occurred in the catchment.

Rainfall pluviometers at Happy Valley (509182) and Aston Downs (9909) were used in RORB model development. These stations have a period of operation that coincides with the flow record and are suitable for calibration of the RORB models.

3.5.6 Calibration of RORB models and validation against regional parameters

The RORB models were calibrated and validated using a two-step process.

Firstly, each model was calibrated to the gauged flow to optimise Kc, runoff coefficient and initial loss to match the recorded hydrograph.

Secondly, the Kc and initial loss from the calibration run were combined with regional runoff coefficient parameters developed by the Water Corporation and GHD (2013) as a validation of the calibrated parameters. The regional parameters assume that the runoff coefficient of the catchment varies with cleared area and event size (total rainfall depth), with a different runoff coefficient used for 'lower catchments'; that is, catchments on the coastal plain. The regional parameter set is shown in Table 3-6 below.

Areally reduced rainfall (mm)	RoC (foothills)	RoC (60–85% cleared)	RoC (40–60% cleared)	RoC (25–40 % cleared)	RoC (10–25% cleared)	RoC (0–10% cleared)
50	0.40	0.35	0.30	0.24	0.18	0.12
60	0.41	0.36	0.30	0.24	0.18	0.12
70	0.42	0.36	0.31	0.25	0.19	0.13
80	0.42	0.37	0.31	0.25	0.19	0.13
90	0.43	0.37	0.32	0.26	0.20	0.14
100	0.43	0.38	0.33	0.27	0.21	0.15
110	0.44	0.39	0.33	0.27	0.21	0.15
120	0.45	0.39	0.34	0.28	0.22	0.16
130	0.45	0.40	0.34	0.28	0.22	0.16
140	0.46	0.40	0.35	0.29	0.23	0.17
150	0.46	0.41	0.36	0.30	0.24	0.17
160	0.47	0.42	0.36	0.30	0.24	0.18
170	0.47	0.42	0.37	0.31	0.25	0.19
180	0.48	0.43	0.37	0.31	0.25	0.19
190	0.49	0.43	0.38	0.32	0.26	0.20
200	0.49	0.44	0.38	0.32	0.26	0.20
210	0.50	0.44	0.39	0.33	0.27	0.21
220	0.50	0.45	0.39	0.33	0.27	0.21

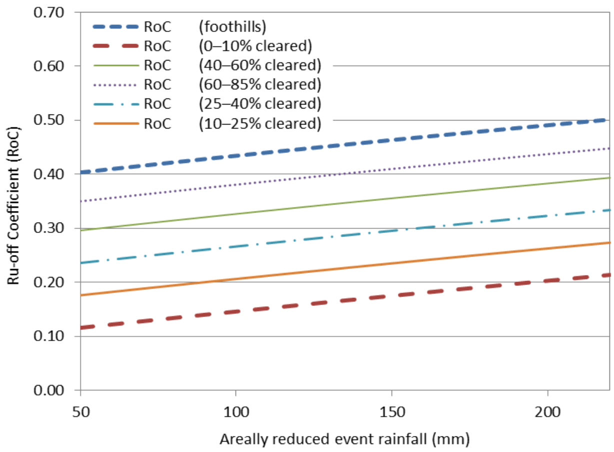


Table 3-6: Regional Runoff Routing B coefficients developed by the Water Corporation and GHD (2013) for different proportions of land clearing. Additional categories of 40–60% cleared and 10–25% cleared were interpolated

The calibrated parameters for the events in 1997, 1999 and 2016 for the Abba and Ludlow rivers were found to be broadly consistent with the Water Corporation parameters, as shown in the calibration plots in Appendix E.

3.6 Design hydrology

3.6.1 Design parameters for RORB

The adopted design parameters for the RORB models were based on calibration, validation against regional parameters, and comparison with flood-frequency analysis (FFA) and previous studies.

Comparison with FFA illustrated that for larger events, the RORB models were underestimating peak discharge relative to FFA; and for smaller events, peak flows were overestimated. Runoff coefficients were adjusted in the RORB models to better match the FFA.

Table 3-7 shows the runoff coefficients from the regional parameter set and the coefficients adopted to fit the FFA for the 1% AEP event – parameter sets for other event probabilities are shown in Appendix E.

Initial loss was set to 20 mm for the Ludlow River and 10 mm for the other catchments. The parameter *m* was set to 0.85 for all models. Kc was varied between catchments based on model calibration, as shown in Table 3-8.

Table 3-7: Initial and adopted runoff coefficients (RoC) for modelling of 1% AEP design flows

		Adopted parameters				Regional parameters			
Event duration	1% AEP rainfall	Ludlow River	Abba River	Sabina River	Vasse River	Ludlow River	Abba River	Sabina River	Vasse River
Hours	(mm)	RoC	RoC	RoC	RoC	RoC	RoC	RoC	RoC
6	70	0.36	0.38	0.38	0.38	0.31	0.36	0.28	0.28
12	93	0.37	0.39	0.39	0.39	0.32	0.37	0.29	0.29
24	120	0.39	0.40	0.40	0.40	0.34	0.39	0.31	0.31
36	136	0.40	0.41	0.41	0.41	0.35	0.40	0.32	0.32
48	147	0.41	0.42	0.42	0.42	0.36	0.41	0.32	0.32
72	160	0.42	0.43	0.43	0.43	0.36	0.42	0.33	0.33

Table 3-8: Initial loss, m and Kc for modelling of design flows

Catchment	Inital loss (mm)	m	Kc
Ludlow River and Wonnerup Estuary foreshore	20	0.85	14
Abba River	10	0.85	15
Lower Sabina River	10	0.85	15
Lower Vasse River and Vasse Estuary foreshore	10	0.85	12

3.6.2 Design flows used in hydraulic modelling

RORB modelled flows for the Vasse, Sabina, Abba and Ludlow rivers

The final design hydrographs for the 10%, 5%, 2% and 1% AEP events with durations of six, 12, 24, 36, 48 and 72 hours were extracted from the RORB models. Baseflow was added to the hydrographs, as described in the previous section. The hydrographs shown in Appendix E show the discharge from the rivers to the Vasse-Wonnerup estuary.

For all rivers the 24-hour duration event was critical for the 1% AEP event, and this duration was adopted for use in the hydraulic model.

Flows on the Vasse Diversion Drain upstream of the offtake structure

The Water Corporation provided design hydrographs for the 5% and 1% AEP events in the Vasse Diversion Drain based on the RORB modelling completed by GHD (2013). The compensation basins on the Vasse Diversions Drain have resulted in the six-hour event being critical (Water Corporation pers. comm.).

Flows to the Lower Vasse River from the offtake structure through one 900 mm culvert

Because of the possibility that the penstock gate valve (located at the offtake structure from the Vasse Diversion Drain to the Lower Vasse River) may be open during a flood event, the 1% AEP design flood flow assumes that the penstock is three-quarters open. The Water Corporation hydrographs in the Vasse Diversion Drain were combined with a rating curve developed for the 900 mm pipe to produce a flood hydrograph for discharge through the pipe to the Lower Vasse River (shown in Appendix F).

All durations modelled showed a peak flow through the culvert of around 2.8 m^3/s and a steady baseflow of between 2.0 and 2.5 m^3/s for the tail of the event. In the Lower Vasse River, this means that for the 1% AEP event the culvert will add flow for the full duration of the event. The 1% AEP combined peak flow for the Lower Vasse River and culvert is 16.8 m^3/s.

The hydraulic model simulates flow in the culvert dynamically based on flood levels in the Vasse Diversion Drain.

Design flows upstream of the Sabina Diversion weir

Design flows were made available by the Water Corporation upstream of the Sabina Diversion weir. As noted by GHD (2013), the weir is not expected to overtop in events up to and including the 1% AEP event and has been overdesigned. However, if this structure is modified to allow diversion in low-flow conditions then these design hydrographs can be used to estimate design flooding in larger events.

3.6.3 Comparison of design flows with FFA and previous other studies

The design flows adopted for this study are compared with the flood-frequency analysis (FFA) and the results of previous studies in Table 3-9.

The RORB flows were adjusted to meet the FFA for the Ludlow and Abba rivers and are therefore very similar, although they are slightly higher than those estimated in the previous studies for the 1% AEP event. The magnitude of peak flows for the Lower Sabina and Lower Vasse rivers are comparable with the previous studies.

The runoff coefficients adopted for this study varied with event magnitude so that the RORB modelled flows better matched the FFA, resulting in a non-linear response with increasing event size. For this reason, peak discharge for the 5% event is lower than that estimated in previous studies which used fixed runoff coefficients for all events.

Table 3-9: Comparison of Runoff Routing B design peak flows with flood-frequency analysis and previous studies for the Ludlow, Abba, Lower Sabina and Lower Vasse rivers

	Ludlow River peak flow (m^3/s)			
AEP	FFA this study	RORB this study	WAWA[1] (1987)	JDA[2] (1998)
10%	36	43		
5%	60	65	89	90
2%	108	113	102	
1%	161	156	115	141

	Abba River peak flow (m^3/s)			
AEP	FFA this study	RORB this study	WAWA[1] (1987)	JDA[2] (1998)
10%	33	38		
5%	50	50	69	67
2%	76	79	79	
1%	99	100	87	86

	Lower Sabina River peak flow (m^3/s)			
AEP	FFA this study	RORB this study	WAWA[1] (1987)	JDA[2] (1998)
10%		14		
5%		19	27	29
2%		31	31	
1%		39	34	35

	Lower Vasse River peak flow (m^3/s)			
AEP	FFA this study	RORB this study	WAWA[1] (1987)	JDA[2] (1998)
10%		8		
5%		10	12	13
2%		14		
1%		17	15	16

[1] *WAWA results for 4%, 2% and 1% events*

[2] *JDA results for 4% and 1% events*

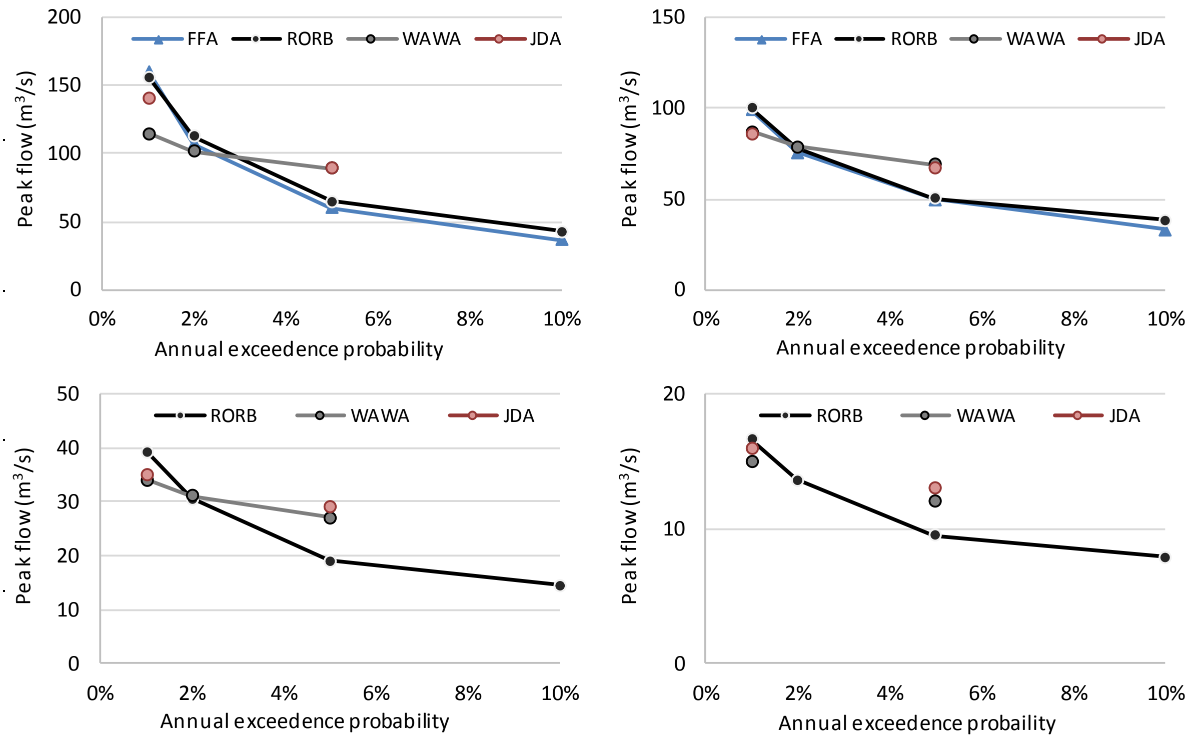


Figure 3-4: Comparison of design peak flows

4 Hydraulic (MIKE11) modelling

A hydraulic model was constructed using the MIKE11 2014 release <www.mikepoweredbydhi.com/>. The model can simulate to event-based flood hydrodynamics (multiple days) and seasonal variations in estuary hydrology (multiple years) and was used to assess the different drainage modifications.

The model development entailed two steps, which are presented in this section.

1. **Model design and construction –** consisted of extracting drainage cross-sections from terrain data, definition of boundary conditions, insertion of structures, and numerical stabilisation.
2. **Model calibration –** used observed water-level data from the Vasse and Wonnerup estuaries upstream of the respective surge barriers for the period 2001–14, and a flood event in winter 2016. Model calibration also involved comparison of water levels with photography of flood events and previous estimates of design flood levels for the estuaries.

The model was then used to examine the changes to hydrology that would result from the proposed drainage modifications discussed in Section 1. The short-term model runs (multiple days) used to assess flood risk are referred to as the *flood simulations*. The longer model runs (multiple years) are referred to as the *hydrological simulations*. The same model was used for both simulations with differing boundary conditions. The scenario modelling of the drainage modifications is presented in Section 5.

4.1 Model construction

4.1.1 Model domain

The model domain includes the full extent of the Lower Vasse and Lower Sabina rivers, the New River Wetlands, the Vasse and Wonnerup estuaries, Malbup Creek, the Wonnerup Inlet and the Deadwater. Such a large domain is necessary because of the interconnectedness of the waterbodies. Small sections of each of the Vasse and Sabina diversion drains were included so that structures located at the junction of the drains with the lower river reaches could be modelled dynamically within MIKE11. The MIKE11 model domain is defined by the linear channel network and drainage cross-sections as shown in Figure 4-1. Cross-sections were defined to ensure that storage within the estuary could be accounted for. The stage-volume relationship from the cross-sections was validated against the LiDAR terrain data for the estuaries.

4.1.2 Topography

Terrain data was used to define the channel slope and cross-section geometry for the rivers and estuaries. The terrain data was sourced from four separate datasets:

- A 2008 LiDAR digital elevation model (DEM) (Department of Water) which provided accurate elevation data for dry areas of land. Inundated sections of the estuaries, inlet and Lower Vasse River were not captured by the LiDAR.

- A 2008 DEM based on a real-time kinematic (RTK) survey (Department of Parks and Wildlife) which included elevation data for the inundated areas, but excluded the Lower Vasse River upstream of the Butter Factory weir.
- A 2009 marine LiDAR survey of the offshore bathymetry from Two Rocks to Cape Naturalist.
- A 2014 bathymetric survey (Department of Water) of the inundated parts of the Lower Vasse River and a section of the channel upstream of the Vasse surge barrier.

These datasets were combined to produce a single 1 m horizontal resolution integrated DEM with an estimated vertical accuracy of ±15 cm. The DEM covers the extent of the study area and was used to extract river channels and cross-sections for the model.

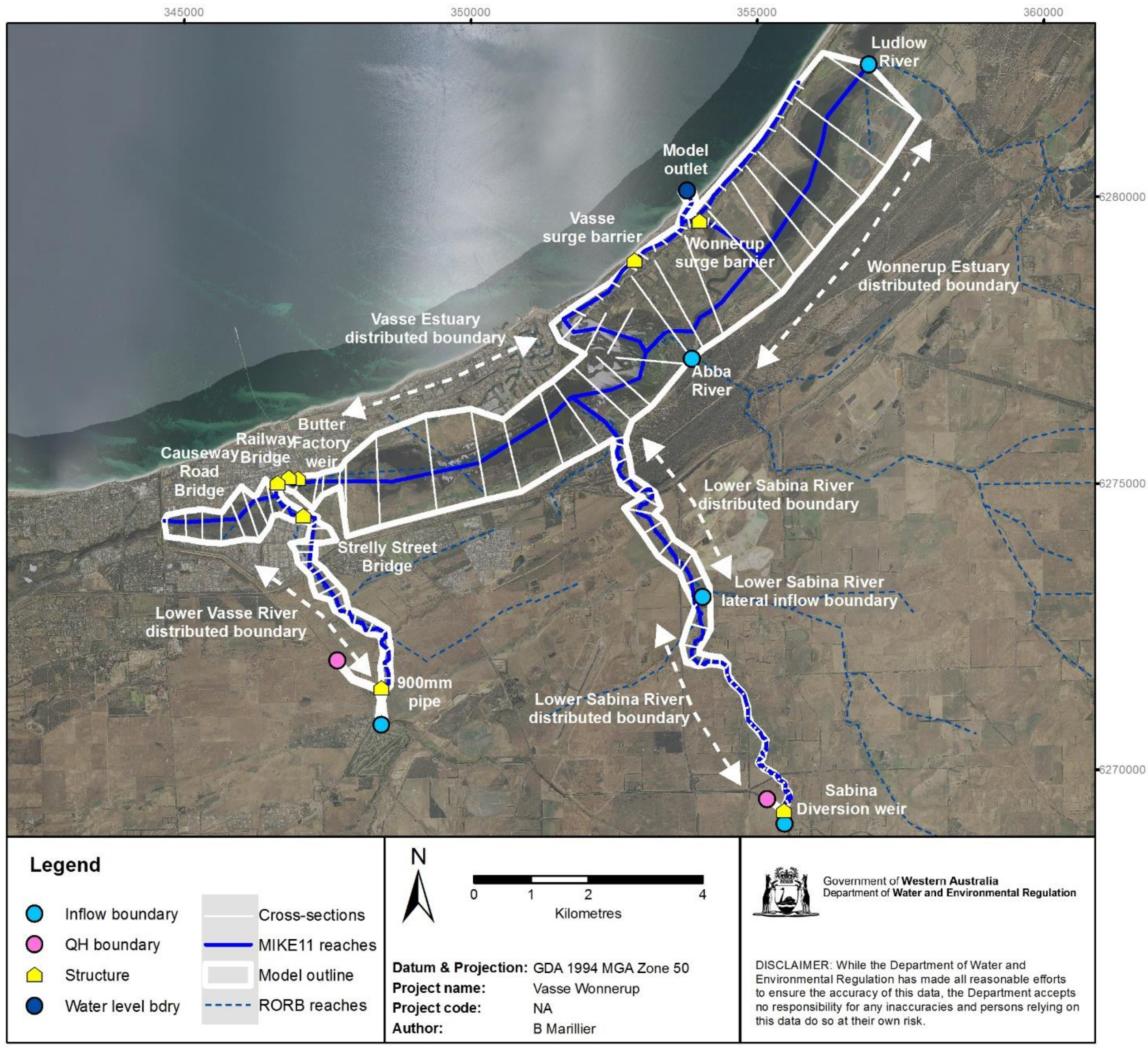


Figure 4-1: MIKE11 model extent for the Lower Vasse River and estuary

4.1.3 Rainfall and evaporation boundaries

Rainfall and evaporation can be included in MIKE11 as global (same input over the whole model domain) or distributed (different inputs in different areas) boundary conditions. The global option was used for the estuary model, which applies rainfall and evaporation to the wetted area of the model, calculated from the flow width at each cross-section, the spacing between the cross-sections, and rainfall and evaporation depth data.

Flood simulations

The design rainfall (Section 3.4) was used as a global boundary condition. Evaporation was not included as it is an insignificant flux during a flood event.

Hydrological simulations

Daily rainfall and pan evaporation data were sourced from the Scientific Information for Land Owners (SILO) data drill service of the Queensland Department of Environment and Resource Management. Rainfall and evaporation were both applied as global boundaries. Typically, a pan reduction factor would be applied to the evaporation dataset to account for the lower evaporation rates occurring in large waterbodies. In this case, however, no reduction factor was applied given the shallow depth of the Vasse and Wonnerup estuaries, and summer water temperatures regularly exceeding 30°C.

During summer, the fish gates of the surge barriers are periodically opened to maintain minimum water levels in the estuaries and/or to allow fish passage. Once the water level in the Vasse Estuary reaches -0.1 mAHD, the fish gate is opened up enough to maintain this water level. That is, the evaporation from the estuary surface is balanced by the inflow through the fish gate. Fish gate flow was incorporated into the model by reducing the evaporation rate from the estuaries to 1 mm/day between March and June.

4.1.4 Inflow boundaries

Rivers

River inflow boundaries were configured in MIKE11 for the Abba and Ludlow rivers, and the Vasse and Sabina diversion drains. Distributed inflow boundaries were used for the catchments of the Lower Vasse and Lower Sabina rivers and the local catchments of the Vasse and Wonnerup estuaries.

Flood simulations

The design flows developed using RORB were used as inflow boundaries for the Lower Vasse, Lower Sabina, Abba and Ludlow rivers, and the local catchment of the Vasse Estuary. The Water Corporation provided inflow hydrographs for the Vasse and Sabina diversion drains for design flood events based on work completed by GHD (2013). Flows through the offtake pipe from Vasse Diversion Drain to the Lower Vasse River, and at the Sabina Diversion weir, were modelled dynamically within MIKE11 using structures. The resulting hydrographs were validated against rating curves.

Hydrological simulations

Flows from a Source rainfall-runoff model were used for all river inflow boundaries. The daily flows were converted to hourly flow rates based on the observed hydrograph shape from the Vasse Diversion Drain over the simulation period (see example in Appendix G). Hourly flows are required to ensure that peak water levels and bed shear stress can be calculated based on the higher flow rates associated with the peak of the hydrograph.

Water-level boundary conditions at the model outlet (Wonnerup Inlet sand bar)

Different methods were used to define the flood and hydrological simulation boundaries.

Flood simulations

For flood simulations, it was assumed the Wonnerup Inlet sand bar was open and outflow from the estuary would be affected by Geographe Bay sea levels. The sea-level boundary condition was based on measured water levels at Port Geographe and Bunbury Outer Harbour, and extreme sea-level analysis completed by Worley Parsons (2013). The extreme sea-level analysis used water-level datasets from Bunbury Harbour, Busselton Jetty and Port Geographe to calculate water-level extreme values for different AEPs (Table 4-1).

Table 4-1: Recommended sea-level extreme values (source: Worley Parsons 2013)

AEP	Total WL Port Geographe (mAHD)
20%	1.52
10%	1.62
2%	1.82
1%	1.92

The three highest sea levels on record since 1975 were as follows:

- 1978 – Cyclone Alby 1.84 mAHD (Bunbury)
- 2007 – storm surge and high tide 1.56 mAHD with second peak at 1.26 mAHD
- 2003 – storm surge and high tide 1.36m AHD

In addition, a sustained storm surge in 1996 was applied as a boundary condition because water levels reached a peak of 1.13 mAHD and remained above 0.7 mAHD for 38 hours.

These four boundary conditions, shown in Figure 4-2, were used in a sensitivity analysis of the hydraulic model. Figure 4-3 shows simulated water levels in the Vasse Estuary for the 1% AEP flow event using the different boundary conditions. The peak water levels were similar and varied between 1.42 and 1.44 mAHD. Based on this analysis, the 2007 event was adopted for design simulations since it corresponded to a 20% to 10% AEP extreme sea level (Table 4-1) and resulted in a slightly higher estuary peak water level of 1.44 mAHD than the other sea-level boundary conditions.

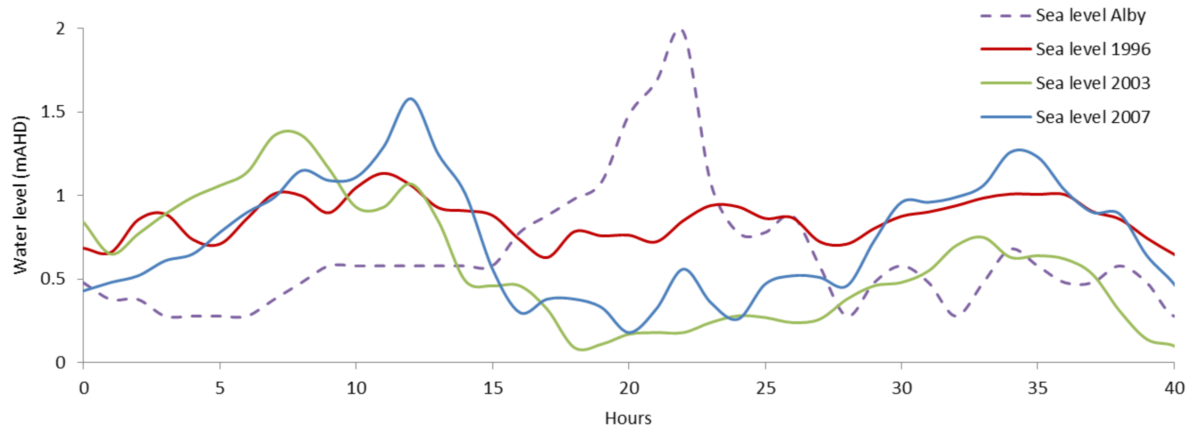


Figure 4-2: Extreme high water-level events considered as boundary conditions

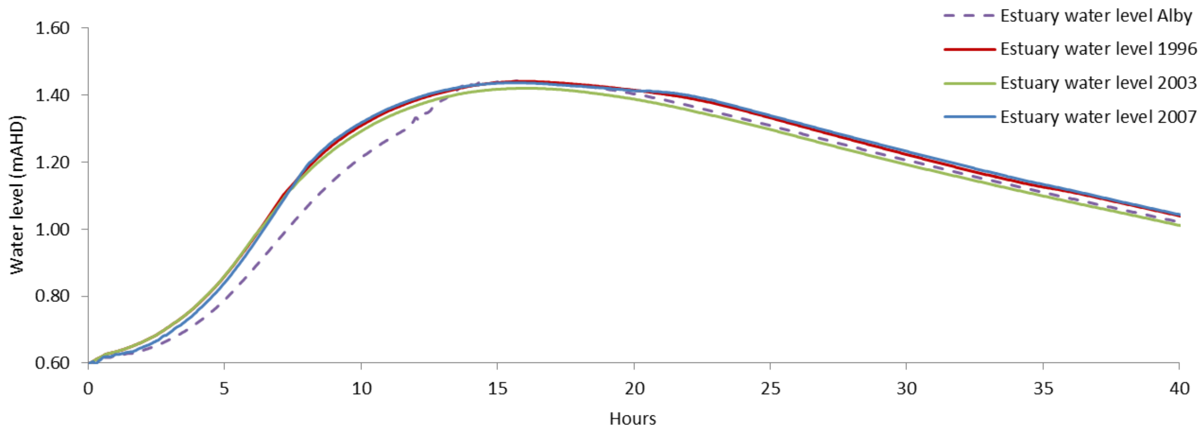


Figure 4-3: Simulated Vasse Estuary water levels for ocean boundary conditions from Figure 4-2 for the 1% AEP flow event

Hydrological simulations

The boundary condition over longer simulations is complicated by the dynamics of the sandbar and the intermittent insertion of the check boards in the surge barriers. To include the sandbar and check board dynamics, a water-level boundary that included these components was used.

The hourly water-level boundary was developed using the following assumptions:

- The water-level boundary is the greater of the water level in Wonnerup Inlet and the effective surge barrier sill height.
- The water level in Wonnerup Inlet is assumed to be the sea level in Geographe Bay when the sand bar is open or maximum sand bar elevation when the sand bar is closed. The estuary will only fill during extended periods of sand bar closure, so the measured water levels in the estuary can be used to infer the timing of sand bar closure.
- Check boards are temporarily installed in the Vasse and Wonnerup surge barriers on 1 September and removed on 1 May the following year. During this period, the

effective sill height is 0.4 mAHD (the height of the check boards). For the rest of the year, when the check boards are not in place, the sill height is -0.4 mAHD.

Water can flow from the estuary when the estuary water level is greater than the water-level boundary condition.

Figure 4-4 shows an example of the water-level boundary condition for 2013 and 2014. The sand bar closure was validated against Landsat 8 imagery to confirm that the sand bar state used in the boundary condition was correct for the corresponding image date (imagery is shown in Appendix H).

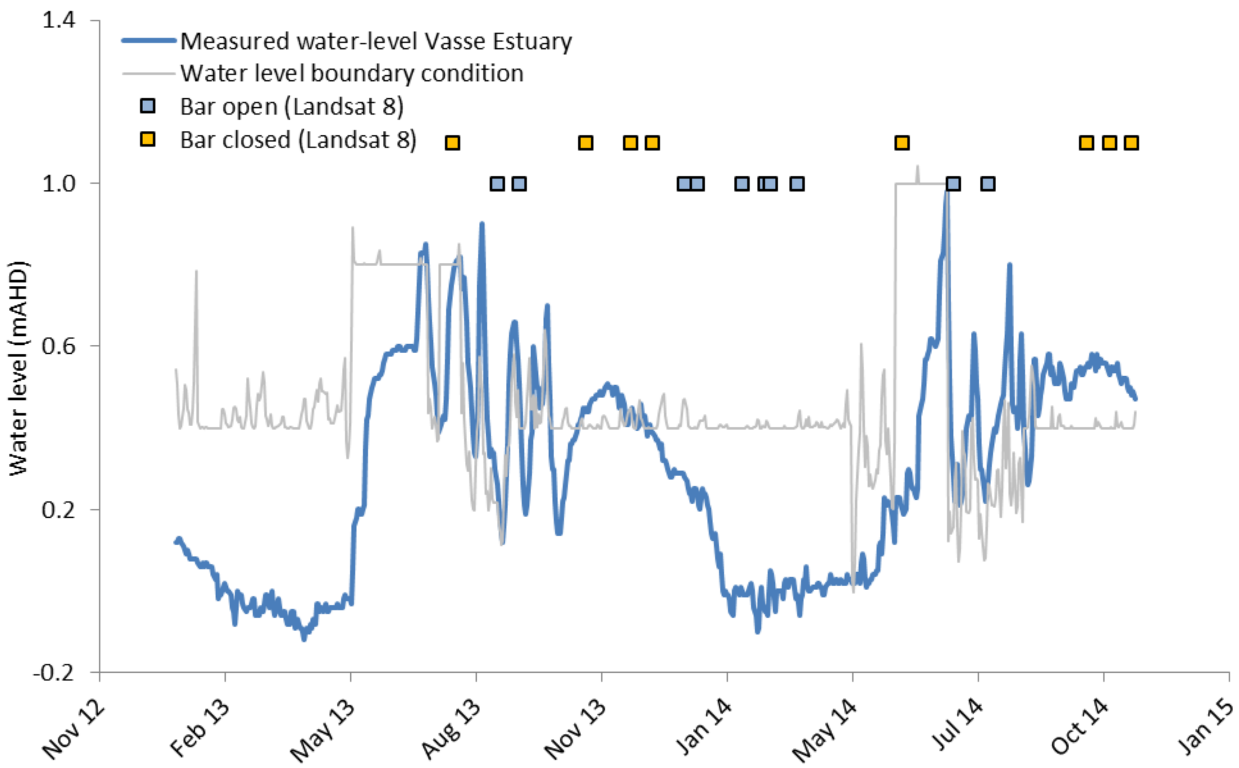


Figure 4-4: Artificial water-level boundary condition including the effects of check boards and sand bar closure

4.1.5 Discharge-stage (QH) boundary conditions for the Vasse and Sabina diversion drains

QH boundaries were used to control outflow in the Vasse and Sabina diversion drains. This relationship was calculated in MIKE11 using channel dimensions.

4.1.6 Structures

Multiple structures were included within the model. Structure diagrams with key dimensions are included in Appendix I. Structures were not included on the Lower Sabina River, although channel cross-sections that account for constriction at the Tuart Drive and Bussell Highway bridges were included.

All structures were modelled explicitly with the energy equation within MIKE11 using culverts, weirs, or a combination of both unless otherwise specified. These are listed below:

- **Vasse floodgates**: 13 culverts, 2 m wide by 1.5 m high, sill height -0.4 mAHD, positive flow only.
- **Wonnerup floodgates**: 11 culverts, 2.8 m wide by 1.55 m high, sill height -0.4 mAHD, positive flow only.
- **Offtake structure 900 mm pipe on Vasse Diversion Drain**: single circular culvert closed above 600 mm height, Manning's n of 0.16, sill height 4.98 m, which is the bed level of the Vasse Diversion Drain.
- **Butter Factory weir**: weir at 0.4 mAHD (boards assumed permanently in place), 8 m wide. Additional width at 0.8 mAHD which is the approximate spill height of the right-hand bank.
- **Strelly Street bridge**: one culvert 12.3 m wide by 2.1 m high, sill height -0.5 mAHD, weir spill (bridge) height at 2 mAHD.
- **Causeway Road bridge**: one culvert 5.4 m wide by 2.25 m high, sill height -1 mAHD, weir spill (bridge) height at 2.1 mAHD.
- **Railway footbridge**: one culvert 9.8 m wide by 2.6 m high, sill height -0.8 mAHD, weir spill (bridge) height at 1.8 mAHD.
- **West Street and culvert linking river wetlands and Lower Vasse River**: modelled as a cross-section within MIKE11 with a 1 m wide slot to -0.50 mAHD.
- **Layman Road and culvert on Malbup Creek:** Modelled as a cross-section within MIKE11 based on road elevation with a culvert invert level of 0.44 mAHD.
- **Sabina Diversion weir:** weir at 25.67 mAHD with a 20 m culvert width at this level.

A Manning's n of 0.013 was used for all structures unless specified.

4.1.7 Simulation parameters

All models used the one-dimensional fully-dynamic Saint-Venant equation. A 10-second timestep was used for the flood simulations which ran for a model period of four days. A 30-second timestep was used for the hydrological simulations which ran from 2001 to 2014 inclusive.

The MIKE11 hydrodynamic parameter *delta* was set to 0.9 to improve model stability.

Bed resistance

Manning's n was set to 0.025 for the main bodies of the estuaries and their outlet channels. A higher resistance of 0.05 was used in the Lower Vasse River to account for thick weeds and vegetation, and the small section of Vasse Diversion Drain was assigned an n of 0.04 to account for rock riffles in the main channel. The heavily vegetated lower reaches of the Sabina River between Sues Road and the Vasse Estuary were assigned a Manning's n of 0.07, and the remainder of the river was set to 0.05.

Initial conditions

For the design flood simulations, initial water level was set to 0.6 mAHD in the estuary, which is a typical winter high-water level. For the multi-year simulation the initial water level was set to 0.2 mAHD, but this had little impact on the overall simulation as the model stabilised by the start of the first flow season.

4.2 Model stabilisation and mass-balance verification

The MIKE11 model was assessed for instabilities in discharge and water level and was found to be stable for the design flood simulations.

For the multi-year simulations some minor oscillations occurred at some structure locations for low flows, but these did not substantially influence peak flows or the overall water balance.

The MIKE11 water balance tool was used to identify discrepancies in the mass balance of the model. For both the base case 1% AEP design flood and the hydrological simulation, the mass balance error was less than 0.1% of total flows.

4.3 Model calibration

4.3.1 Long-term calibration to water levels

Water-level data upstream of the Vasse and Wonnerup surge barriers were collected by the Department of Parks and Wildlife from 2004–14 and this was used for model calibration. Figure 4-5 shows modelled and observed water levels for the two estuaries from 2004–14, and summary statistics are included below in Table 4-2.

Table 4-2: Calibration statistics for estuary water levels 2004–14

Statistic	Observed	Modelled
Vasse maximum level (m)	1.08	1.03
Vasse minimum level (m)	-0.18	-0.28
Vasse NSE[1]	0.77	
Wonnerup maximum level (m)	0.93	0.99
Wonnerup minimum level (m)	-0.49	-0.47
Wonnerup NSE	0.61	

NSE Nash-Suttcliffe Efficiency

The calibration indicates that the model adequately replicates the wetting and drying of the estuary. Peak water levels were modelled to within 6 cm of the peak recorded water levels for the two estuaries.

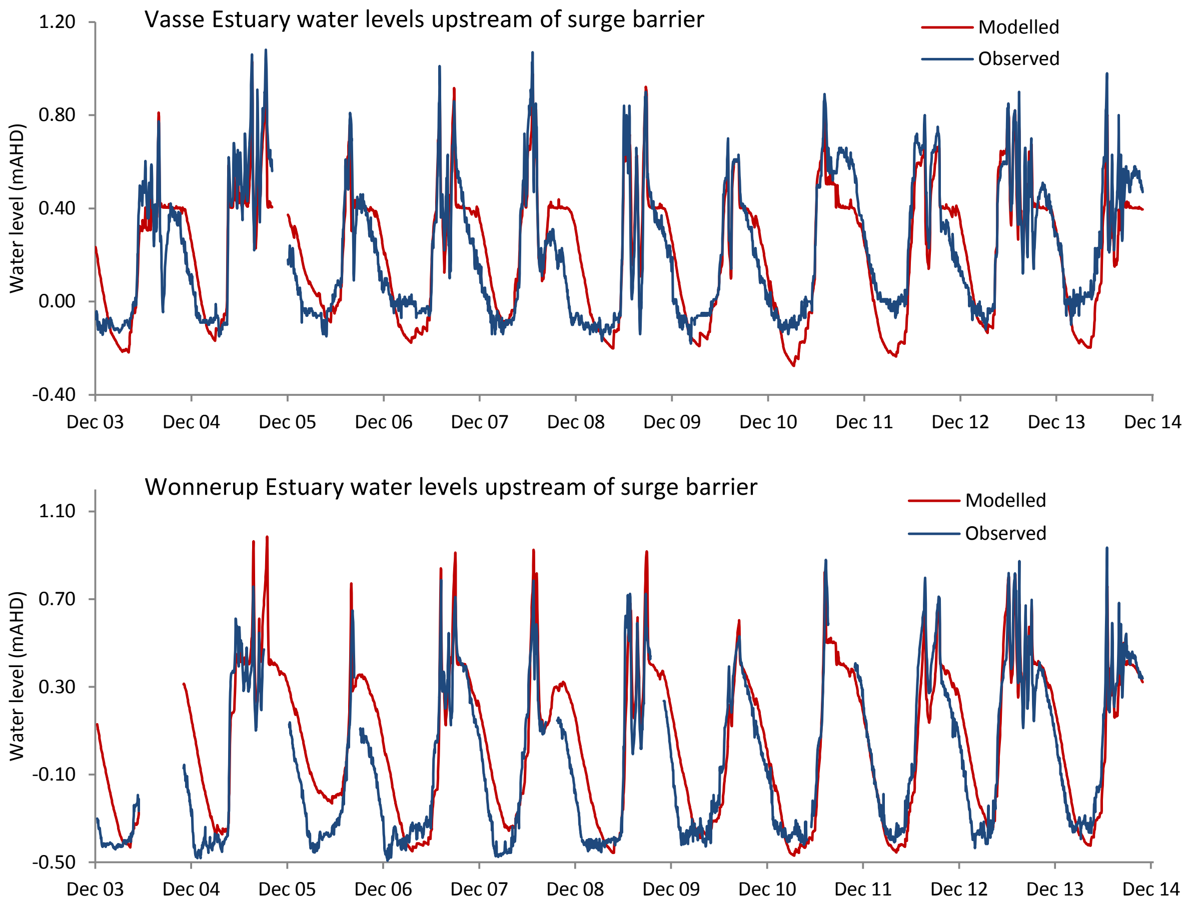


Figure 4-5: Modelled and observed water levels for the Vasse and Wonnerup estuaries

4.3.2 Hydraulic validation July 2016 rainfall event

In July 2016, a significant rainfall event occurred in the Vasse-Wonnerup catchment concurrently with a storm surge in Geographe Bay. A total of 143 mm of rainfall fell in Busselton over three days (approximately a 10% AEP event) and the Water Corporation recorded peak water levels of nearly 0.96 mAHD upstream of the Vasse surge barriers with water exceeding bank capacity in parts of the Lower Vasse River.

The hydraulic model was validated for this event, as shown in Figure 4-6. The modelled peak water level upstream of the surge barrier was 0.95 mAHD, with a similar rising limb and time to peak compared with measured water levels. The model overestimated water levels at the tail of the event.

The model was also validated against a photograph taken on the Lower Vasse River, as shown in Figure 4-7. Modelled water levels were similar to those observed near the Causeway Road bridge.

4.3.3 Calibration to discharge

DWER records discharge at the 900 mm offtake pipe connecting the Vasse Diversion Drain to the Lower Vasse River, and these data were used for calibration of inflows through the pipe in the MIKE11 model. Given it is this structure that would be modified to divert flows from the Vasse Diversion Drain to the Lower Vasse River, it is important that the base-case hydraulic behaviour is reproduced.

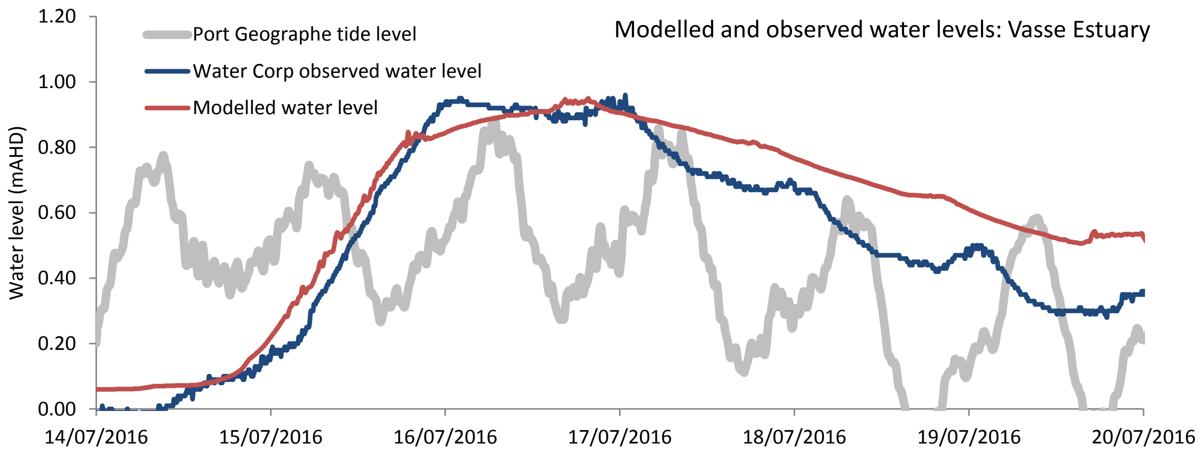


Figure 4-6: Hydraulic model calibration for July 2016 event in the Vasse Estuary

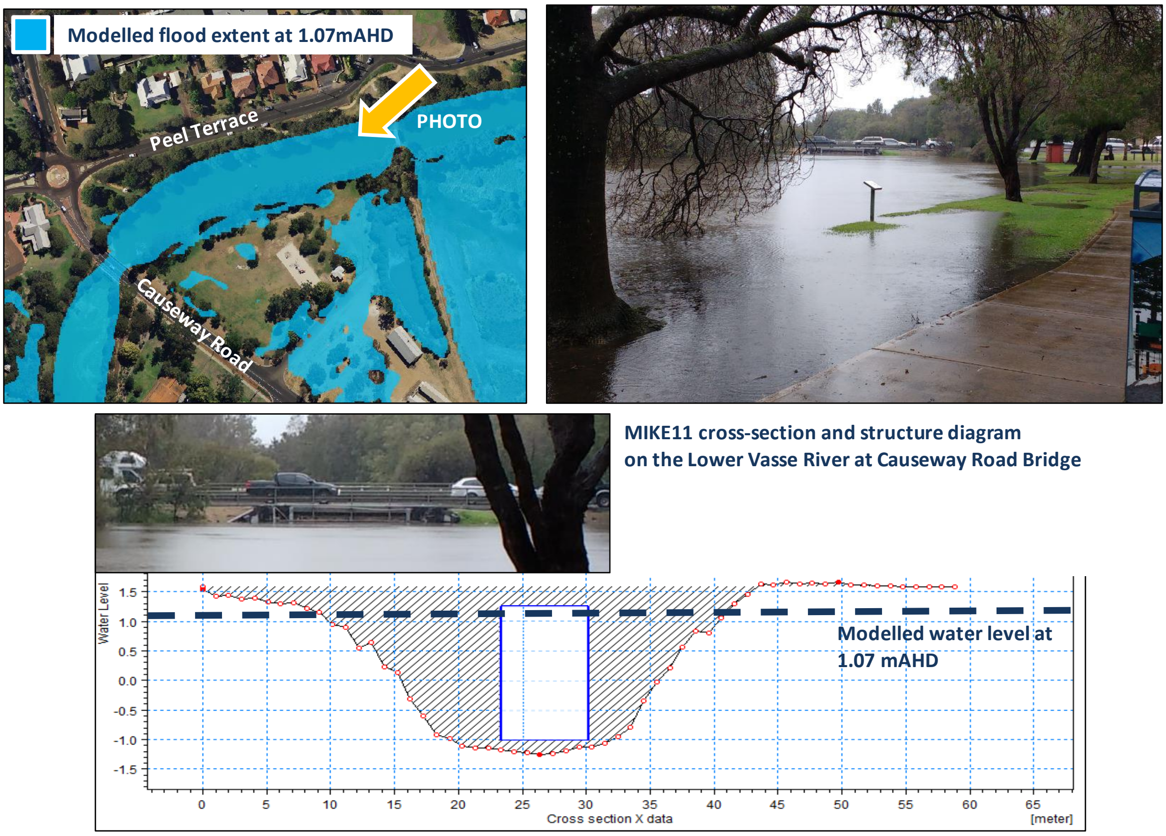


Figure 4-7: Photo showing flooding in the Lower Vasse River and modelled peak water levels July 2016

There is a close match between the observed and modelled flows through the Vasse offtake pipe (Figure 4-8). Several features were necessary in the model to replicate the observed flow behaviour, including:

- A small ridge in the Vasse Diversion Drain downstream of the offtake structure that dams low flows, diverting water into the Lower Vasse River.
- The valve within the pipe is approximately three-quarters open, as shown in the structure diagram in Appendix I.
- Manning's n was set to 0.04 for the Vasse Diversion Drain to account for channel roughness.

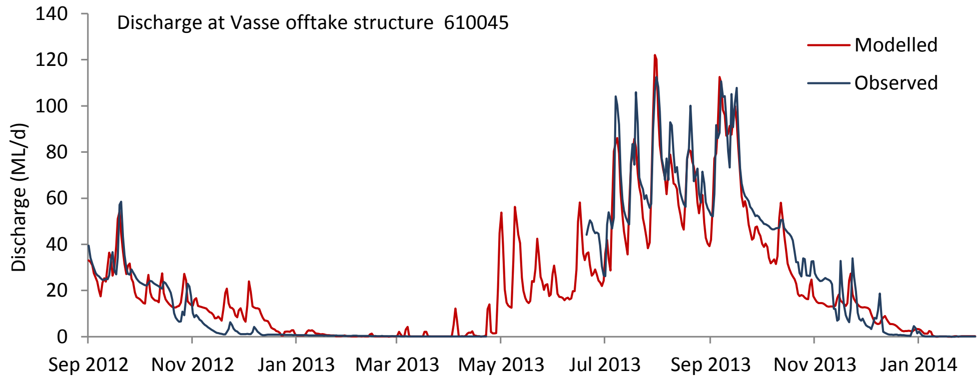


Figure 4-8: Modelled and observed discharge at the Vasse offtake for 2012 and 2013

A Nash-Sutcliffe coefficient of efficiency of 0.85 was achieved between modelled and observed daily discharge. The calibration illustrates that the flow hydraulics are realistic for this section of the model.

4.4 Comparison of design flooding with previous studies

The design flood levels simulated by MIKE11 for the 1% AEP event in the Vasse and Wonnerup estuaries are compared with the previous studies in Table 4-3.

Table 4-3: Comparison of design flood levels with previous studies

1% AEP design flood level	WAWA (1987) mAHD	JDA (1998) mAHD	Current mAHD
Vasse Estuary	1.35	1.46	1.45
Wonnerup Estuary	1.35	1.46	1.45
Lower Sabina River DS Tuart Drive bridge	4.22	4.25	4.24
Lower Vasse River US Causeway Road bridge	1.58	1.52	1.50

The peak water levels are comparable to the most recent study (JDA 1998) at all locations.

It is important to note that the design water level is sensitive to the boundary conditions used at the ocean outlet. The previous studies assumed an initial estuary water level of 0.8 mAHD and the current study assumes 0.6 mAHD with an open sand bar, high tide and storm surge. However, severe flooding could also result from sandbar closure during a flood event which would result in higher levels than those tabulated here. Management of the sandbar is imperative for flood prevention.

5 Scenario modelling

5.1 Drainage modifications included in scenario modelling

The drainage modifications proposed in Section 1 were:

- Redirecting flow from the Vasse Diversion Drain into the Lower Vasse River
- Redirecting flow from the Upper Sabina River to the Lower Sabina River
- Summer release of treated recycled water into the Lower Vasse River
- Retaining more water in the Vasse Estuary at the end of the flow season
- Removal of the Vasse surge barrier
- Removal of the Butter Factory weir
- Bridge upgrades at Causeway Road
- Adding a concrete spillway to the Vasse Diversion Drain
- Storage of water for summer release

These were represented in the model by adding culverts to divert more flow from the Vasse and Sabina diversion drains to the Vasse Estuary, upgrading the Causeway Road bridge, constructing a concrete spillway on Vasse Diversion Drain, increasing surge barrier check board height, introducing recycled water to the Lower Vasse River, and surge barrier and Butter Factory weir removal. The drainage modification scenarios are summarised in Table 5-1. They are 'numbered' for ease of reference. The base-case scenario (S00) defines the system's current status.

Model simulations demonstrate the likely changes to flooding and long-term hydrology arising from the drainage modifications, and thus the potential benefit or harm can be assessed. Not all scenarios were simulated for both changes to flooding and long-term hydrology.

All the scenarios listed above were modelled, with the exception of 'Storage of water for summer release' for the reasons given below:

- **Storage of water in compensation basins for release in summer.** The basins provide flood protection for Busselton by storing flood waters and slowly releasing them downstream. The basin storage capacity has been calculated to provide 1% AEP flood protection (with the basin being empty before the flood). The basins could not be used to store water or for treatment of water without compromising their flood protection function.
- **Introduction of dedicated reservoirs for summer water releases.** This is a very expensive option and has limitations in terms of water quality. It is probable that water stored in the reservoirs would be prone to algal growth in exactly the same way as the Lower Vasse River, since the waterbody would contain nutrient-rich, still and warm water during summer. This means that any water stored in the reservoirs would be unsuitable for release to the Lower Vasse River or other downstream waterbodies.

Table 5-1: List of scenarios

Scenario ID	Description	Flood simulation	Hydrology simulation
S00	Base case VDD offtake one 900 mm culvert assumed three-quarters open	Yes	Yes
S00s	Base case with spillway at VDD offtake	Yes	No
S00sb	Base case with spillway at VDD offtake and Causeway Rd bridge upgrade	Yes	No
S01	VDD offtake one 900 mm culvert fully open	Yes	Yes
S02	VDD offtake one 900 mm and one 450 mm culvert	Yes	Yes
S03	VDD offtake two 900 mm culverts	Yes	Yes
S03s	As S03 with spillway at VDD offtake	Yes	No
S03sb	As S03 with spillway at VDD offtake and Causeway Rd bridge upgrade	Yes	No
S04	VDD offtake three 900 mm culverts	Yes	Yes
S04s	As S04 with spillway at VDD offtake	Yes	No
S04sb	As S04 with spillway at VDD offtake and Causeway Rd bridge upgrade	Yes	No
S05	VDD fully connected to the LVR	Yes	Yes
S06	VDD offtake two 900mm culverts open only Aug–Oct	No	Yes
S07	Recycled water discharged to LVR year-round	No	Yes
S08	Vasse and Wonnerup barriers check boards set at 0.6mAHD	No	Yes
S09	SDD weir with one 450 mm culvert	Yes	Yes
S10	SDD weir with one 900 mm culvert	Yes	Yes
S10a	SDD weir with two 900 mm culverts	Yes	Yes
S11	SDD fully connected to the LSR	Yes	Yes
S12	Surge barriers removed	Yes	Yes
S13	Two 900mm culverts on VDD offtake, one 900 mm culvert on SDD weir	No	Yes
S14	No Butter Factory Weir, partially fill LVR, VDD offtake two 900 mm culverts	Yes	Yes

Culverts assumed fully open for all scenarios unless specified

SDD: Sabina Diversion Drain

VDD: Vasse Diversion Drain

5.2 Scenario implementation

This section describes how each scenario was implemented in the model simulation. This involves changes to boundary conditions, structures and the river network.

5.2.1 Inclusion of spillway on the Vasse Diversion Drain (S00s, S00sb, S03s, S03sb, S04s, S04sb)

The Water Corporation indicated that in a 1% AEP flood event, the Vasse Diversion Drain would likely overtop near the Lower Vasse River. The peak overbank flow rate was estimated at 7 m^3/s. To avoid the risk of levee failure the Water Corporation is proposing to upgrade this section of the drain to include a concrete spillway (Water Corporation pers. comm.) to divert this water to the Lower Vasse River.

The spillway was implemented in MIKE11 by adding an additional channel on the right levee bank of the Vasse Diversion Drain with a 20 m broad-crested weir structure set at 8.85 mAHD (Figure 5-1) (about 0.5 m below bank height). The additional channel discharges to the Lower Vasse River below the existing 900 mm culvert. This structure was implemented in the model to meet the required 7 m^3/s discharge for the 1% AEP six-hour critical duration event for the Vasse Diversion Drain (see Appendix J).

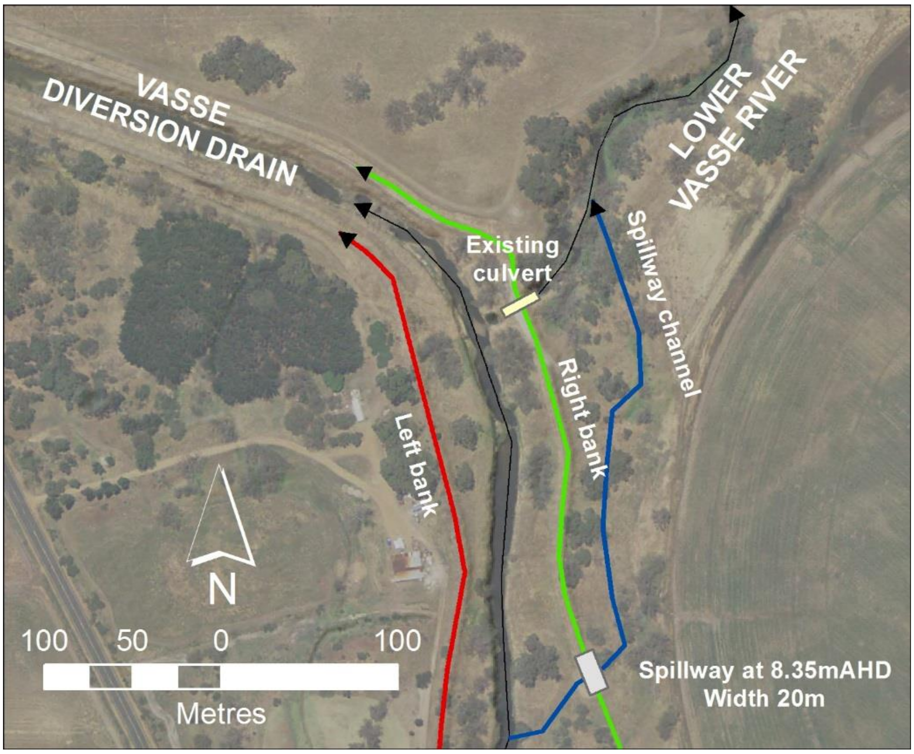


Figure 5-1: Spillway diagram

5.2.2 Bridge upgrade at Causeway Road (S00sb, S03sb, S04sb)

Main Roads WA plans to upgrade the Causeway Road bridge in 2017–18, which should reduce afflux[2] at the bridge during flood events. A bridge upgrade was included as a scenario in combination with the spillway and culvert upgrades.

In the base-case scenario, the Causeway Road bridge was modelled as a culvert 5.4 m wide, with a lower level of -1.0 mAHD and an upper level of 1.3 mAHD. The bridge deck was modelled as a broad-crested weir with an elevation of 2.1 mAHD and width of 40 m. For the bridge upgrade scenario, it was assumed that the culvert was widened to 18 m (which is closer to the full channel width) and the upper level of the culvert increased to 2 mAHD (Figure 5-2).

[2] Afflux is the rise in water level upstream of an obstruction.

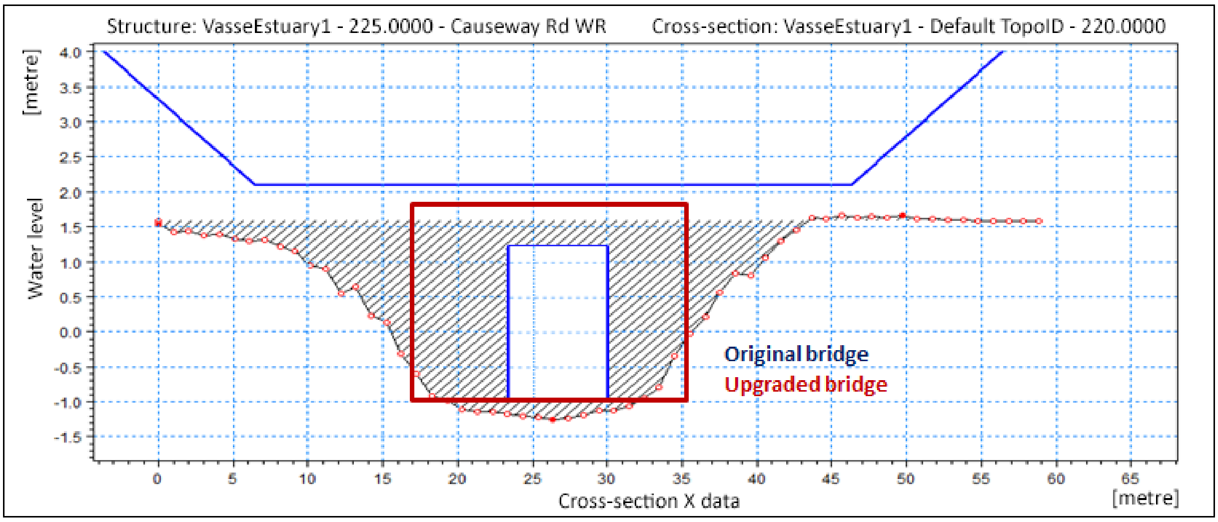


Figure 5-2: Causeway Road bridge upgrade in MIKE11

5.2.3 Culvert upgrades at the Vasse Diversion Drain offtake (S01, S02, S03, S04)

The culvert upgrade scenarios were modelled by adding culverts (Figure 5-3) at the junction of the Vasse Diversion Drain and Lower Vasse River and recalculating the rating curves in MIKE11. The culverts were assumed to be circular, straight and 10 m long with a drop of 0.13 m, and were assigned a Manning's n of 0.016.

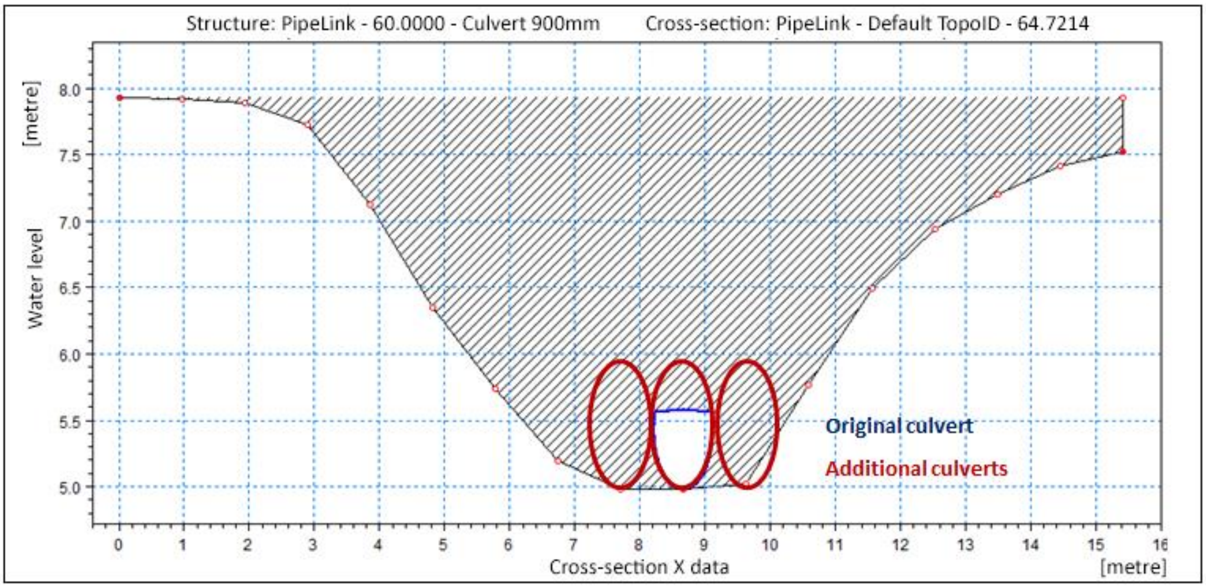


Figure 5-3: Culvert upgrades in MIKE11

5.2.4 Full diversion of the Vasse Diversion Drain to the Lower Vasse River (S05)

For this scenario the Vasse Diversion Drain was blocked downstream of the junction with the Lower Vasse River (Figure 5-4). The drain was assumed to be fully connected to the river with an open channel. All flow from the drain was diverted into the Lower Vasse River.

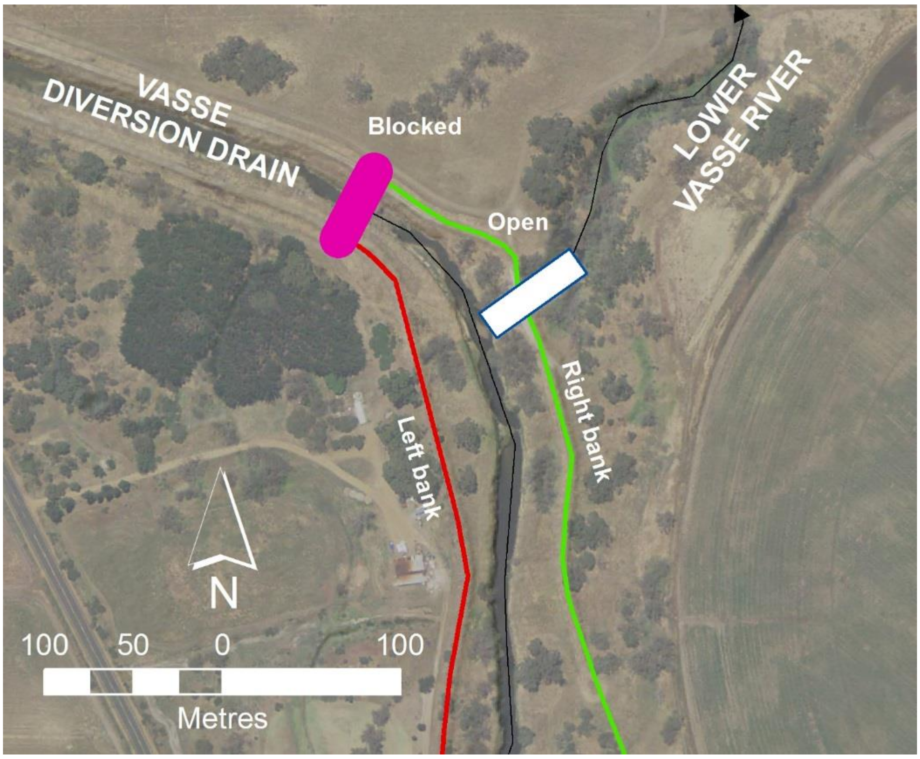


Figure 5-4: Full reconnection of Vasse Diversion Drain

5.2.5 Opening of two 900 mm culverts August to October only (S06)

Flow is only allowed from the Vasse Diversion Drain through two 900 mm culverts to the Lower Vasse River for the second half of the flow season. This was implemented in MIKE11 by applying the discharge results from scenario S03 as a boundary condition to the Lower Vasse River during the months of August, September and October.

5.2.6 Discharge of recycled wastewater to the Lower Vasse River (S07)

For this scenario water from the Busselton wastewater treatment plant was discharged to the Lower Vasse River at a rate of 4.5 ML/day (consistent with recent discharge rates supplied by the Water Corporation). At present, the golf course uses about one third of this discharge but for the purposes of scenario modelling, it was assumed that the entire volume was discharged to the river year-round. This was implemented using a boundary condition in MIKE11.

5.2.7 Vasse and Wonnerup surge barriers check boards raised to 0.6 mAHD (S08)

This scenario assumes the check board heights of the Vasse and Wonnerup surge barriers are 0.6 mAHD from 1 September to 1 May (instead of base-case height of 0.4 mAHD). The boundary condition in MIKE11 was modified to account for the change in weir height.

5.2.8 Addition of culvert on the Upper Sabina River (S09, S10, S10a)

To reconnect the Upper Sabina and Lower Sabina rivers, additional culverts and channel excavation would be required at the current diversion weir structure. This was implemented in MIKE11 by modifying the cross-sections downstream of the diversion weir to ensure bed level was at or below the bed level of the Sabina Diversion Drain upstream. For scenario S09, a 450 mm culvert was added below the diversion weir; for scenario S10 a 900 mm culvert was added; and for scenario S10a two 900 mm culverts were added (Figure 5-5). The culverts were inserted at bed level to allow all low flows to be diverted to the Lower Sabina River.

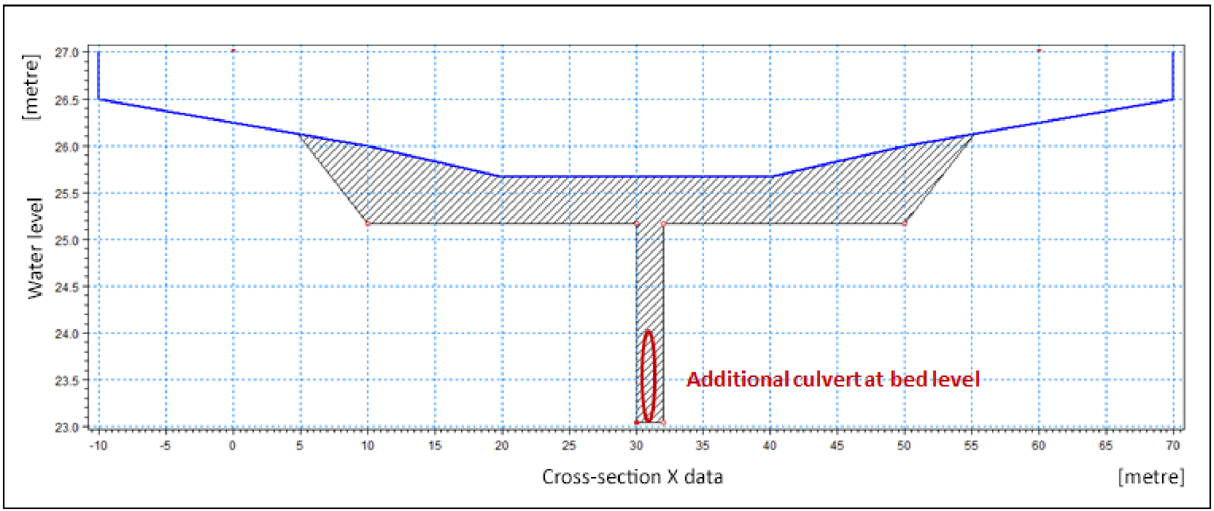


Figure 5-5: Addition of culverts at Sabina Diversion weir

5.2.9 Upper Sabina River fully diverted (S11)

To fully divert the Upper Sabina River to the Lower Sabina River, the diversion weir was removed, and the Sabina Diversion Drain was blocked downstream of the junction (Figure 5-6). This was implemented in MIKE11 by raising the cross-section height downstream on the Sabina Diversion Drain and removing the weir structure separating the upper and lower reaches of the river. The channel opening was assumed to be 6 m wide and at the bed level of the upstream reach.

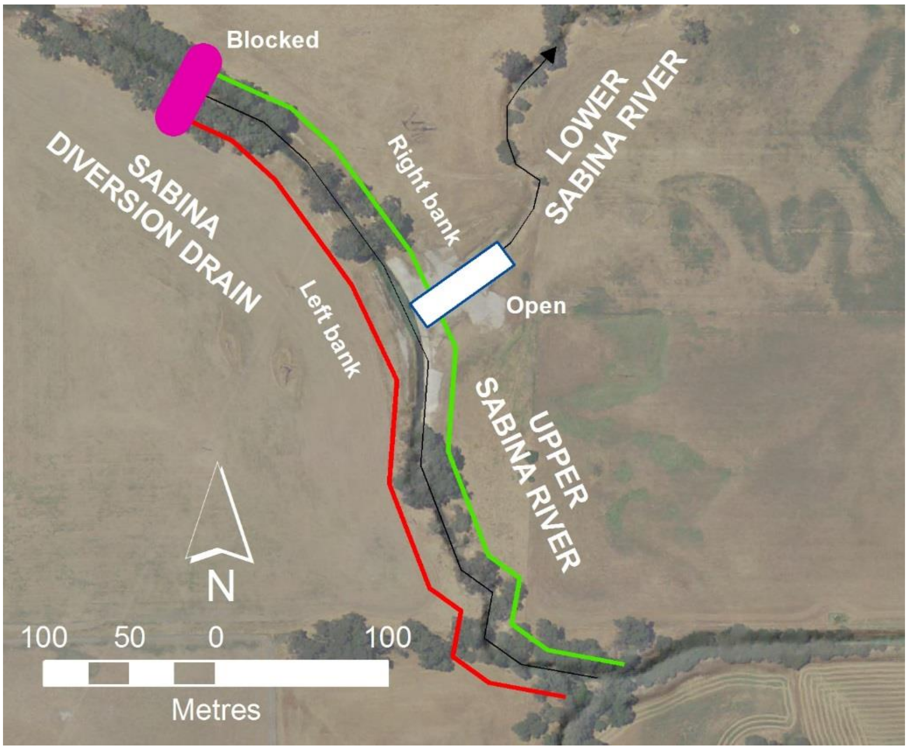


Figure 5-6: Full reconnection of Upper Sabina River

5.2.10 Removal of Vasse and Wonnerup surge barriers (S12)

This scenario was implemented by removing the surge barriers from the MIKE11 model and applying a sea-level boundary with no sand bar for the full duration of the simulation.

5.2.11 Combined scenario – two 900 mm culverts connecting Vasse Diversion Drain to the Lower Vasse River, one 900 mm pipe connecting Upper Sabina River to the Lower Sabina River (S13)

This scenario was implemented as a combination of S03 and S09. Inflow to the Vasse Diversion Drain was reduced by the volume of flow diverted to the Lower Sabina River, thus reducing the amount of water available for diversion to the Lower Vasse River (see Figure 5-7).

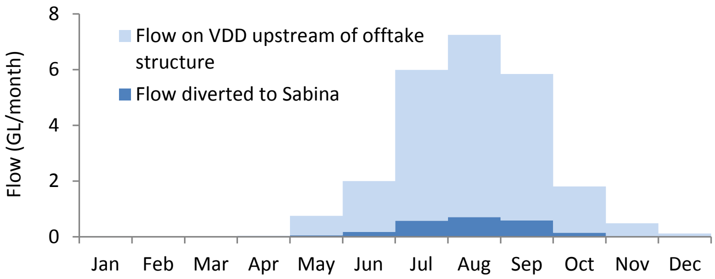


Figure 5-7: Average monthly reduction of flow at the Vasse Diversion Drain offtake structure with flow diversion upstream at Sabina Diversion weir

5.2.12 Combined scenario – pools on the Lower Vasse River filled, Butter Factory weir removed, with bridge upgrades, spillway and two 900 mm culverts at Vasse Diversion Drain/Lower Vasse River offtake (S14)

This scenario was implemented by modifying the cross-sections of the Lower Vasse River to a minimum elevation of -0.2 mAHD and completely removing the Butter Factory weir. This removes all pools from the Lower Vasse River and places the bed level at about the same minimum level as Ford Road in the estuary. The spillway and bridge upgrades were implemented in the same way as for previous scenarios.

5.3 Flood simulation results and discussion

5.3.1 Feasibility criteria for flooding

The 1% AEP 24-hour duration storm was used to model the flood level in the Lower Vasse River, Lower Sabina River and Vasse Estuary for the different flood scenarios. The 24-hour duration event was selected as it results in the highest peak water level in the estuary and rivers.

For the **Lower Vasse River** the changes in the peak flood level were compared with the floodplain development strategy (1.58 mAHD) and minimum building floor levels (1.60 mAHD) for the low-lying area near Causeway Road and Southern Drive. If the existing strategy provides adequate flood protection, the scenario is considered acceptable from a flood perspective.

For the **Lower Sabina River** the change in the peak flood level was compared with building floor levels for houses near Tuart Drive (5.5 mAHD). If peak flood levels for a particular scenario are not likely to exceed the minimum floor level in this low-lying area, then the flood risk is deemed acceptable.

Results and key findings are reported for each of the scenarios in the following section.

5.3.2 Summary of peak flood water level and discharge

Table 5-2 and Table 5-3 summarise peak flood level and discharge for all scenarios at the locations shown in Figure 5-8. Smaller flood events were not considered as part of the feasibility assessment for the scenarios. However, Appendix K includes detailed long-sections for peak discharge and stage on the Lower Vasse River for the base-case scenario and S03s for event magnitudes of 5%, 2% and 1% AEP.

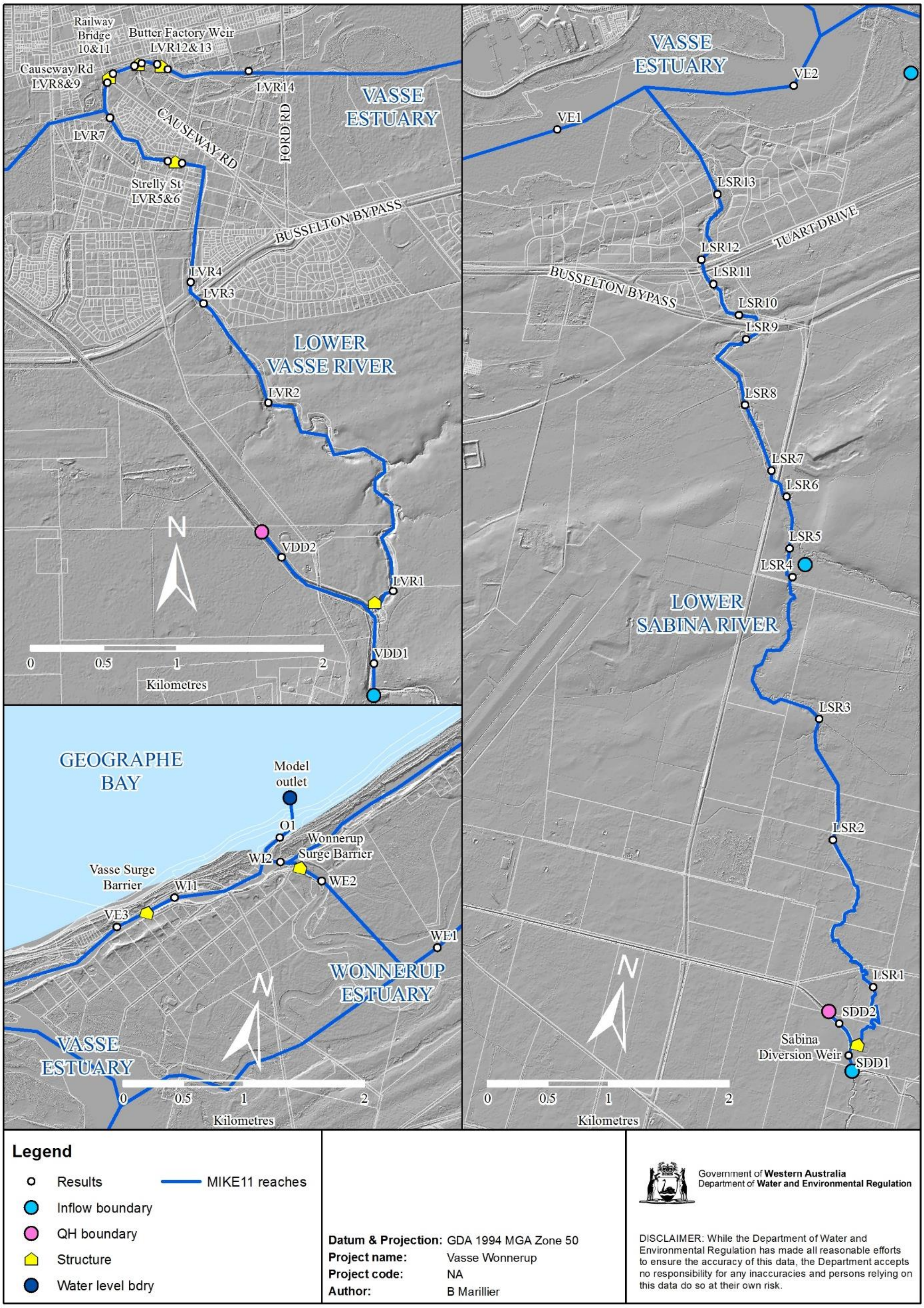


Figure 5-8: Reporting locations for peak stage and discharge

Table 5-2: 1% AEP peak water level (mAHD) for flood simulations at reporting locations

Peak flood level (mAHD) 1 % AEP 24 hr duration event

ID	Description	M11 chainage	S00	S00s	S00sb	S01	S02	S03	S03s	S03sb	S04	S04s	S04sb	S05	S09	S10	S10a	S11	S12	S14
VDD1	VDD US	195	9.32	9.26	9.26	9.31	9.30	9.26	9.22	9.22	9.22	9.19	9.19	8.41	9.32	9.32	9.32	9.32	9.32	9.22
VDD2	VDD DS	1300	7.88	7.81	7.81	7.86	7.85	7.81	7.76	7.76	7.76	8.26	8.26	4.10	7.88	7.88	7.88	7.88	7.88	7.76
LVR1	LVR DS junction	276	4.36	4.56	4.56	4.42	4.46	4.56	4.66	4.66	4.66	4.73	4.73	6.15	4.36	4.36	4.36	4.36	4.36	4.66
LVR2		2279	1.64	1.65	1.65	1.68	1.72	1.81	1.81	1.81	1.92	1.92	1.92	3.31	1.64	1.64	1.64	1.65	1.66	1.83
LVR3	US Busselton Bypass	3028	1.58	1.58	1.58	1.61	1.64	1.73	1.74	1.73	1.83	1.84	1.83	3.23	1.58	1.58	1.58	1.63	1.62	1.75
LVR4	DS Busselton Bypass	3272	1.55	1.55	1.54	1.57	1.59	1.65	1.65	1.64	1.75	1.75	1.74	3.16	1.55	1.56	1.56	1.61	1.60	1.67
LVR5	US Strelly St	4230	1.52	1.52	1.50	1.53	1.54	1.58	1.59	1.54	1.66	1.66	1.60	3.09	1.52	1.52	1.52	1.58	1.56	1.54
LVR6	DS Strelly St	4250	1.51	1.51	1.49	1.52	1.53	1.57	1.57	1.53	1.64	1.64	1.57	3.08	1.51	1.51	1.52	1.57	1.55	1.53
LVR7	River wetlands	4819	1.50	1.50	1.49	1.51	1.52	1.56	1.56	1.52	1.62	1.63	1.55	3.06	1.50	1.51	1.51	1.57	1.54	1.51
LVR8	US Causeway Rd	220	1.50	1.50	1.48	1.51	1.52	1.56	1.56	1.51	1.62	1.62	1.55	3.03	1.50	1.51	1.51	1.57	1.54	1.50
LVR9	DS Causeway Rd	240	1.47	1.48	1.48	1.48	1.48	1.50	1.50	1.51	1.53	1.53	1.54	2.59	1.48	1.48	1.48	1.54	1.51	1.49
LVR10	US Railway Bridge	432	1.47	1.48	1.48	1.48	1.48	1.50	1.50	1.51	1.53	1.53	1.54	2.59	1.48	1.48	1.48	1.54	1.51	1.49
LVR11	DS Railway Bridge	468	1.46	1.47	1.47	1.47	1.47	1.48	1.48	1.49	1.50	1.50	1.51	2.39	1.47	1.47	1.47	1.54	1.50	1.47
LVR12	US Butter Factory	622	1.46	1.47	1.47	1.47	1.47	1.48	1.48	1.48	1.50	1.50	1.50	2.35	1.47	1.47	1.47	1.54	1.50	1.47
LVR13	DS Butter Factory	664	1.46	1.46	1.46	1.46	1.46	1.47	1.47	1.47	1.48	1.48	1.48	1.68	1.46	1.46	1.46	1.53	1.49	1.47
LVR14	US Ford Rd	1368	1.46	1.46	1.46	1.46	1.46	1.47	1.47	1.47	1.48	1.48	1.48	1.67	1.46	1.46	1.46	1.53	1.49	1.47
SDD1	SDD US	140	25.57	25.57	25.57	25.57	25.57	25.57	25.57	25.57	25.57	25.69	25.69	25.57	25.54	25.49	25.45	26.84	25.57	25.57
SDD2	SDD DS	415	25.31	25.31	25.31	25.31	25.31	25.31	25.31	25.31	25.31	25.31	25.31	25.31	25.28	25.21	25.18	23.32	25.31	25.31
LSR1		793	23.61	23.61	23.61	23.61	23.61	23.61	23.61	23.61	23.61	23.61	23.61	23.61	23.76	23.99	24.15	25.62	23.61	23.61
LSR2		2375	20.08	20.08	20.08	20.08	20.08	20.08	20.08	20.08	20.08	20.08	20.08	20.08	20.11	20.19	20.25	21.14	20.08	20.08
LSR3		3521	16.27	16.27	16.27	16.27	16.27	16.27	16.27	16.27	16.27	16.27	16.27	16.27	16.30	16.34	16.38	16.89	16.27	16.27
LSR4	US lateral inflow	5340	10.98	10.98	10.98	10.98	10.98	10.98	10.98	10.98	10.98	10.98	10.98	10.98	10.99	11.00	11.02	11.24	10.98	10.98
LSR5	DS lateral inflow	5762	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.20	10.23	10.25	10.59	10.19	10.19
LSR6	US Sues Rd	6063	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.95	9.98	10.01	10.43	9.94	9.94
LSR7	DS Sues Rd	6177	9.85	9.85	9.85	9.85	9.85	9.85	9.85	9.85	9.85	9.85	9.85	9.85	9.87	9.90	9.92	10.35	9.85	9.85
LSR8		6965	7.96	7.96	7.96	7.96	7.96	7.96	7.96	7.96	7.96	7.96	7.96	7.96	7.97	7.99	8.01	8.28	7.96	7.96
LSR9	US Bussell Hwy	7850	6.59	6.59	6.59	6.59	6.59	6.59	6.59	6.59	6.59	6.59	6.59	6.59	6.61	6.64	6.66	7.08	6.59	6.59
LSR10	DS Bussell Hwy	7860	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.58	6.60	6.62	7.03	6.56	6.56
LSR11	US Tuart Dr	8425	5.39	5.39	5.39	5.39	5.39	5.39	5.39	5.39	5.39	5.39	5.39	5.39	5.40	5.42	5.44	5.78	5.39	5.39
LSR12	DS Tuart Dr	8780	4.24	4.24	4.24	4.24	4.24	4.24	4.24	4.24	4.24	4.24	4.24	4.24	4.25	4.27	4.28	4.56	4.24	4.24
LSR13		9313	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.35	2.36	2.53	2.34	2.34
VE1	Vasse Estuary	5271	1.46	1.46	1.46	1.46	1.46	1.47	1.47	1.47	1.48	1.48	1.48	1.67	1.46	1.46	1.46	1.53	1.49	1.47
VE2	Vasse Estuary	993	1.45	1.46	1.46	1.46	1.46	1.47	1.47	1.47	1.48	1.48	1.48	1.67	1.46	1.46	1.46	1.53	1.49	1.47
VE3	Vasse Estuary	3206	1.40	1.40	1.40	1.40	1.40	1.41	1.41	1.41	1.42	1.42	1.42	1.61	1.40	1.40	1.41	1.46	1.38	1.41
WI1	Wonnerup Inlet	3505	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.36	1.59
WI2	Wonnerup Inlet	3943	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.38	1.58
WE1	Wonnerup Estuary	3590	1.45	1.46	1.46	1.46	1.46	1.47	1.47	1.47	1.48	1.48	1.48	1.66	1.46	1.46	1.46	1.53	1.49	1.47
WE2	Wonnerup Estuary	270	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.34	1.58
O1	Ocean outlet	306	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.54	1.58

Table 5-3: 1% AEP peak discharge (m^3/sec) for flood simulations at reporting locations

Peak discharge (m^3/s) 1% AEP 24 hr duration event																				
ID	**Description**	**M11 chainage**	**S00**	**S00s**	**S00sb**	**S01**	**S02**	**S03**	**S03s**	**S03sb**	**S04**	**S04s**	**S04sb**	**S05**	**S09**	**S10**	**S10a**	**S11**	**S12**	**S14**
VDD1	VDD US	97	128.1	128.2	128.2	128.1	128.1	128.1	128.2	128.2	128.1	128.2	128.2	128.5	128.1	128.1	128.1	128.1	128.1	128.2
VDD2	VDD DS	1235	125.3	120.4	120.4	124.1	123.3	120.4	116.7	116.7	116.7	113.8	113.8	0.1	125.3	125.3	125.3	125.3	125.3	116.7
LVR1	LVR DS junction	151	2.6	7.7	7.7	3.8	4.7	7.5	11.4	11.4	11.2	14.3	14.3	128.5	2.6	2.6	2.6	2.6	2.6	11.4
LVR2		2190	10.7	11.8	11.8	11.8	12.6	15.2	15.5	15.5	18.6	18.6	18.6	131.5	10.7	10.7	10.7	10.7	10.7	15.5
LVR3	US Busselton Bypass	3083	16.1	16.3	16.3	17.2	18.0	20.7	20.7	20.7	24.1	24.1	24.1	131.3	16.1	16.1	16.1	16.1	16.1	20.7
LVR4	DS Busselton Bypass	3205	16.1	16.3	16.3	17.2	18.0	20.7	20.7	20.7	24.0	24.1	24.1	131.2	16.1	16.1	16.1	16.1	16.1	20.7
LVR5	US Strelly St	4191	15.9	16.1	16.1	17.0	17.8	20.3	20.3	20.3	23.3	23.3	23.3	127.7	15.9	15.9	15.9	15.8	15.7	20.3
LVR6	DS Strelly St	4302	15.9	16.1	16.1	17.0	17.8	20.2	20.2	20.3	23.3	23.2	23.3	127.4	15.9	15.9	15.9	15.8	15.7	20.3
LVR7	River wetlands	4864	15.6	15.8	15.8	16.7	17.4	19.7	19.6	19.6	22.3	22.3	22.4	122.0	15.6	15.5	15.5	15.3	15.1	19.7
LVR8	US Causeway Rd	214	7.8	7.8	8.1	8.6	9.2	11.2	11.3	11.8	14.2	14.2	16.7	87.8	7.8	7.8	7.8	8.2	9.0	12.0
LVR9	DS Causeway Rd	246	7.8	7.8	8.1	8.6	9.2	11.2	11.3	11.8	14.2	14.2	16.7	87.8	7.8	7.8	7.8	8.2	9.0	12.0
LVR10	US Railway Bridge	400	7.8	7.8	8.1	8.6	9.4	11.3	11.3	11.7	14.2	14.3	16.6	87.9	7.8	7.8	8.0	8.3	9.1	11.9
LVR11	DS Railway Bridge	545	7.9	7.9	8.1	8.6	9.4	11.3	11.3	11.7	14.2	14.3	16.6	87.9	7.9	7.9	8.0	8.3	9.1	11.9
LVR12	US Butter Factory	626	7.9	7.9	8.2	8.6	9.4	11.3	11.3	11.7	14.2	14.3	16.6	87.9	7.9	7.9	8.0	8.3	9.1	11.9
LVR13	DS Butter Factory	649	7.9	7.9	8.2	8.6	9.4	11.3	11.3	11.7	14.2	14.3	16.6	87.8	7.9	7.9	8.0	8.3	9.1	11.9
LVR14	US Ford Rd	1423	9.1	9.1	9.4	9.9	10.3	12.2	12.2	12.3	14.7	14.8	15.6	84.9	9.1	9.1	9.1	9.5	9.8	12.7
SDD1	SDD US	113	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9
SDD2	SDD DS	437	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.2	29.7	28.4	0.1	31.9	31.9
LSR1		731	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0.9	1.9	3.4	4.7	33.1	1.2	1.2
LSR2		2322	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.7	5.6	7.0	8.3	36.7	4.9	4.9
LSR3		3592	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.5	8.5	9.9	11.2	39.5	7.8	7.8
LSR4	US lateral inflow	5097	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	10.3	12.1	13.5	14.8	43.1	11.4	11.4
LSR5	DS lateral inflow	5551	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	11.4	28.1	29.6	31.0	59.4	27.4	27.4
LSR6	US Sues Rd	6120	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	28.8	30.6	32.0	33.4	61.6	29.9	29.9
LSR7	DS Sues Rd	6368	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	29.9	31.9	33.4	34.7	62.8	31.2	31.2
LSR8		6761	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4	31.2	34.1	35.6	36.9	64.7	33.4	33.4
LSR9	US Bussell Hwy	7855	40.2	40.2	40.2	40.2	40.2	40.2	40.2	40.2	40.2	40.2	40.2	39.7	40.9	42.4	43.6	70.7	40.2	40.2
LSR10	DS Bussell Hwy	7976	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	40.2	41.7	43.2	44.4	71.4	41.0	41.0
LSR11	US Tuart Dr	8588	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.9	43.4	44.6	71.6	41.2	41.2
LSR12	DS Tuart Dr	8765	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.9	43.4	44.6	71.6	41.2	41.2
LSR13		9407	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.2	41.9	43.4	44.6	71.6	41.2	41.2
VE1	Vasse Estuary	5488	31.5	31.6	31.8	32.1	32.7	34.4	34.5	34.6	36.8	36.8	36.8	74.3	31.5	31.6	31.6	32.5	35.2	34.9
VE2	Vasse Estuary	1282	48.9	49.0	49.2	49.5	50.1	51.8	51.8	52.0	54.1	54.1	54.2	93.5	49.4	50.0	50.4	58.6	53.5	52.2
VE3	Vasse Estuary	3005	62.8	62.9	63.0	63.0	63.2	63.6	63.7	63.8	64.2	64.2	64.5	75.2	62.9	63.2	63.4	67.4	79.4	63.8
WI1	Wonnerup Inlet	3638	62.8	62.9	63.0	63.0	63.2	63.6	63.7	63.8	64.2	64.2	64.5	75.2	62.9	63.2	63.4	67.4	79.3	63.8
WI2	Wonnerup Inlet	3904	81.0	81.2	81.3	81.3	81.6	82.3	82.4	82.6	83.1	83.1	83.5	105.6	81.2	81.6	81.9	88.1	88.4	82.5
WE1	Wonnerup Estuary	3727	110.2	109.4	109.4	109.4	109.0	107.9	107.8	107.6	107.2	107.1	106.8	86.3	110.0	109.4	109.0	100.3	124.2	109.1
WE2	Wonnerup Estuary	239	81.0	81.2	81.3	81.3	81.5	82.3	82.4	82.6	83.1	83.2	83.6	105.7	81.2	81.6	81.9	88.1	88.2	82.5
O1	Ocean outlet	515	145.5	145.8	145.9	146.0	146.3	147.3	147.5	147.8	148.4	148.5	149.1	181.4	145.8	146.4	146.9	156.6	171.4	147.8

5.3.3 Lower Vasse River reconnection scenarios S01 to S05 and S14

Results – flooding

These scenarios assessed the impact of diverting additional water into the Lower Vasse River using culvert upgrades (S01, S02, S03, S04) and a new spillway (S03s, S04s), as well as a bridge upgrade at Causeway Road (S03sb, S04sb). These scenarios can be compared with the base-case scenario with the same spillway and bridge upgrade (S00, S00s, S00sb). S14 assessed the flood implications of two 900 mm culverts at the Vasse Diversion Drain offtake combined with filling/modifying the drainage channel of the Lower Vasse River to allow complete draining during summer. This scenario required the Butter Factory weir to be removed and the river pools to be filled. Scenario S05 is the full reconnection of the Vasse Diversion Drain to the Lower Vasse River.

The land adjacent to the Lower Vasse River between the Busselton Bypass and Butter Factory weir is at most risk of flooding, as demonstrated in the long-section (Figure 5-10). The lowest-lying section of land between Causeway Road and Southern Drive would be the first location to flood. The left bank overtops to the river wetland, which acts as a natural compensation basin during periods of high river flow.

Scenarios S01 to S04 incrementally increased the volume of water diverted to the Lower Vasse River. Even with three 900 mm culverts (S04), the impact on flood levels in the main body of the Vasse Estuary was minimal, with an increase of 2 cm relative to the base case (S00). However, on the Lower Vasse River upstream of Causeway Road, flood levels were increased from 1.50 mAHD to 1.62 mAHD (+12 cm) for S04, which would be above building floor level for houses between Southern Drive and Causeway Road. In this same area S03 resulted in a flood-level increase to 1.56 mAHD (+6 cm).

The long-section of peak flood level shown in Figure 5-11 shows the Causeway Road bridge is the main restriction to flow on the Lower Vasse River, however some afflux is also evident at the other bridges and structures. The upgrade of Causeway Road bridge reduces afflux for scenarios S03sb and S04sb, and this offsets the increase in flood level associated with additional culverts at the Vasse Diversion Drain offtake. For S03sb, flood levels upstream of Causeway Road increase to 1.51mAHD (+1.3cm) and for S04sb to 1.55mAHD (+4.5cm).

For scenario S14 (Figure 5-12), filling of pools to a level of -0.2 mAHD resulted in a 1 cm increase in flood levels on the Lower Vasse River upstream of Causeway Road compared with the base case. The deepest sections of the river did not add to conveyance during the flood event because they were lower than the downstream bed-level of the estuary. Depending on bed and bank vegetation in the 'filled' sections of the river, flood levels could potentially increase as a result of higher roughness and therefore a detailed design and risk assessment (including modelling) would be necessary before river training was undertaken.

Inclusion of the spillway (from Vasse Diversion Drain to the Lower Vasse River) did not significantly impact flood levels on the Lower Vasse River given it would contribute flow only during peak stage on the Vasse Diversion Drain (which occurs well before maximum flood level in the estuary). This is demonstrated in Figure 5-9 which compares S00 and S00s. For the same reason S03s and S04s show no increase in flood levels relative to S03 and S04 respectively.

Peak flood stage for the Lower Vasse River between the Busselton Bypass and Butter Factory weir were mapped to a 2008 LiDAR elevation dataset to estimate the extent of inundation for the scenarios (Figure 5-13 and Figure 5-14). Floodwaters were contained within the riverbanks upstream of the Busselton Bypass, hence this area was not mapped.

The culvert upgrade scenarios S03 and S04 resulted in a small increase in the extent of inundation – the low-lying area near Southern Drive being the most affected. With the Causeway Road bridge upgrade, the area of inundation for S03sb and S04sb was only slightly greater than for the base-case flood extent S00.

Results for S05 (Vasse Diversion Drain fully connected) indicated a dramatic increase in flood extent, yet this may be overestimated as results from a 1D model were extrapolated to a 2D domain. In the case of S05 where flood levels were well above bank level, overbank storage was not adequately considered (this was not the case for S03 and S04 which were contained within the MIKE11 channel). Despite this caveat, it is clear that increasing the peak discharge on the Lower Vasse River from 16 m^3/s to 122 m^3/s would substantially increase flood levels in the estuary's main body from 1.46 mAHD (base case) to 1.67 mAHD (+21 cm).

Feasibility – flooding

The existing floodplain development strategy for the Lower Vasse River provides adequate flood protection for the following scenarios:

- All scenarios S00s through to S03sb are unlikely to result in detrimental flooding in the Busselton area, and thus are feasible options.
- Scenario S14 may also be feasible, but the river's final form would need to be appropriately designed to allow conveyance of flood flows.
- If the Causeway Road bridge is upgraded then S04sb is feasible – as long as the final design of the bridge is appropriate.

The following scenarios are not feasible:

- Scenario S04 and S04s are not feasible as there is a risk of flooding above building floor level with the current Causeway Road bridge.
- S05 would result in severe flooding of Busselton.

Figure 5-17 compares the 1% AEP flood level upstream of Causeway Road bridge for each scenario relative to the floodplain development strategy and building floor level. The strategy recommends a 0.7 m freeboard above the 1% AEP peak flood level.

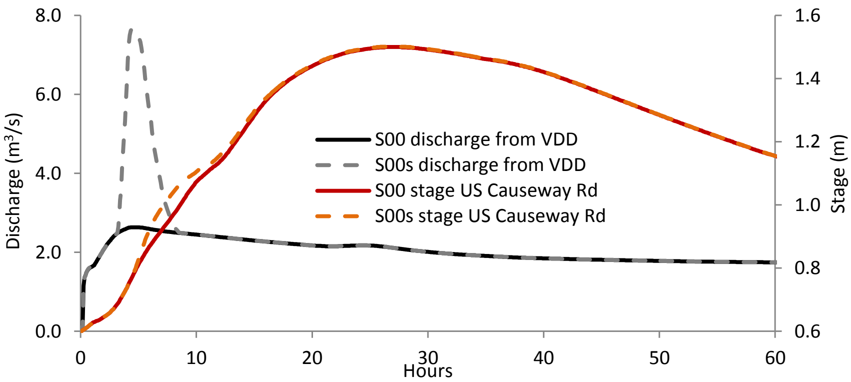


Figure 5-9: Comparison of base case and spillway scenario flows for the 1% AEP event. Increased discharge from the spillway does not increase peak flood level on the Lower Vasse River

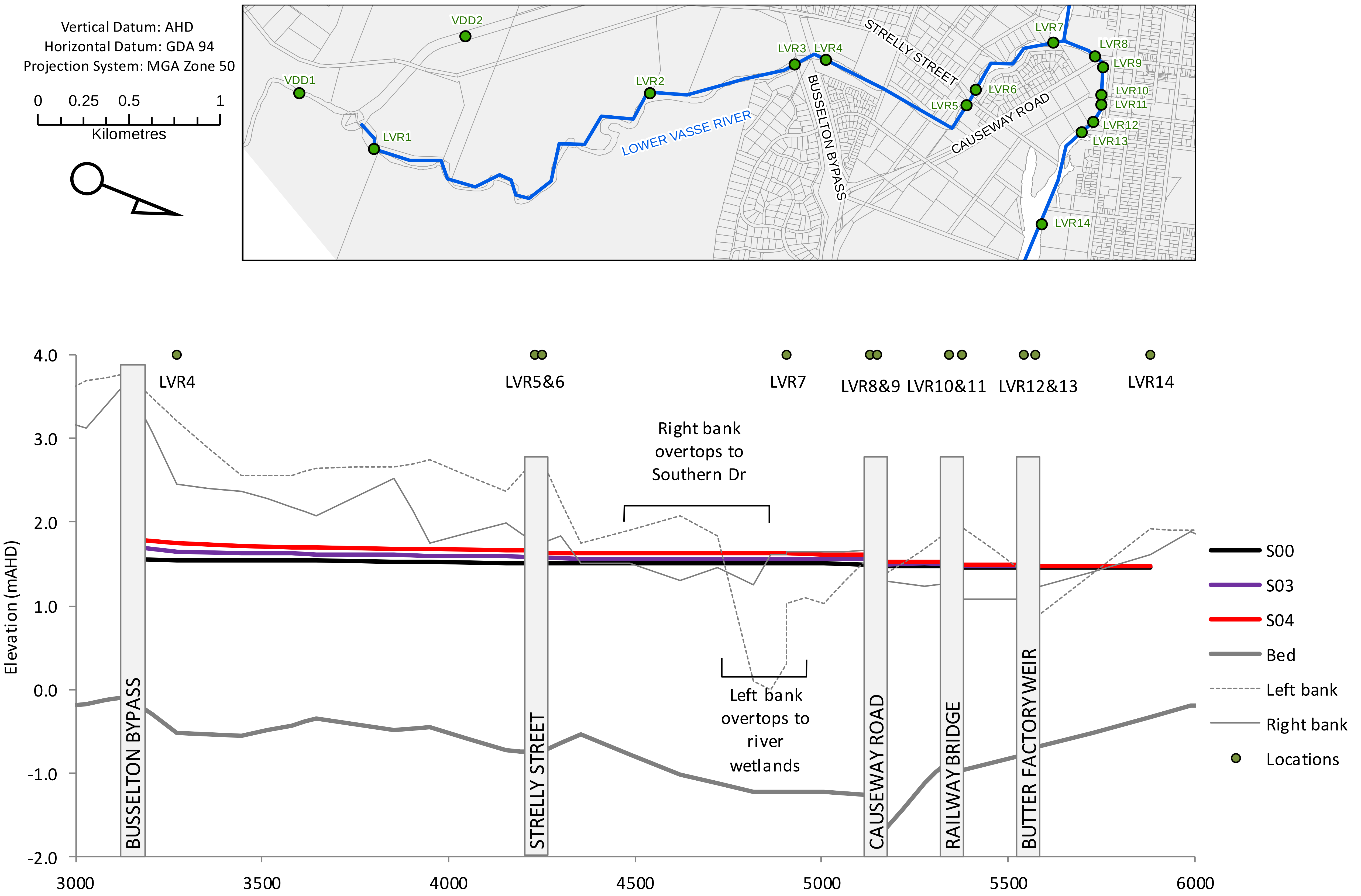


Figure 5-10: Long-section showing 1% AEP peak flood level for S00, S03 and S04 on the Lower Vasse River, Busselton Bypass to Butter Factory weir

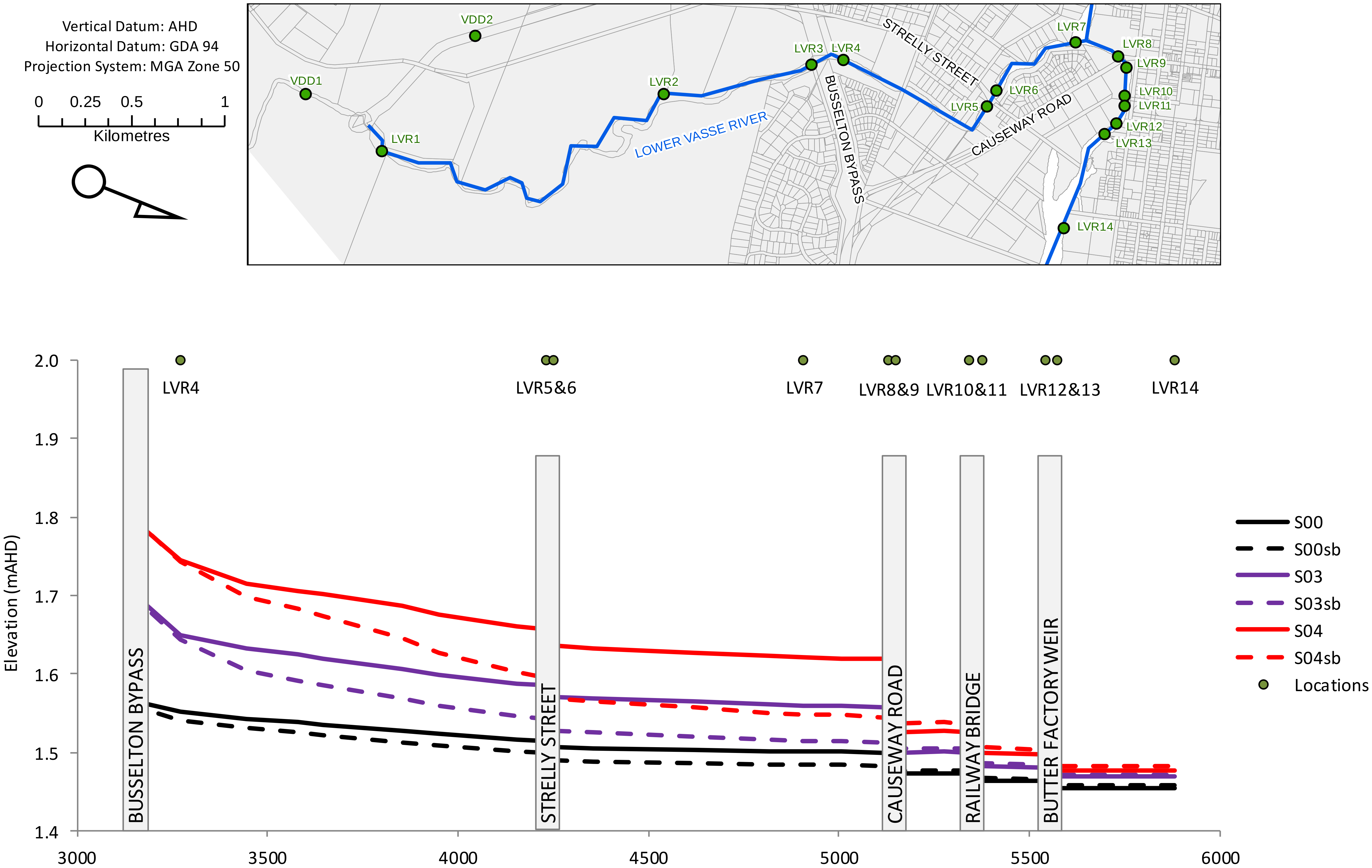


Figure 5-11: Long-section showing impact of Causeway Road bridge upgrade on 1% AEP flood levels for the Lower Vasse River (note vertical axis range 1.4 to 2 mAHD)

Figure 5-12: Long-section demonstrating the change in 1% AEP flood level for S14 – filling pools and removing weir on the Lower Vasse River

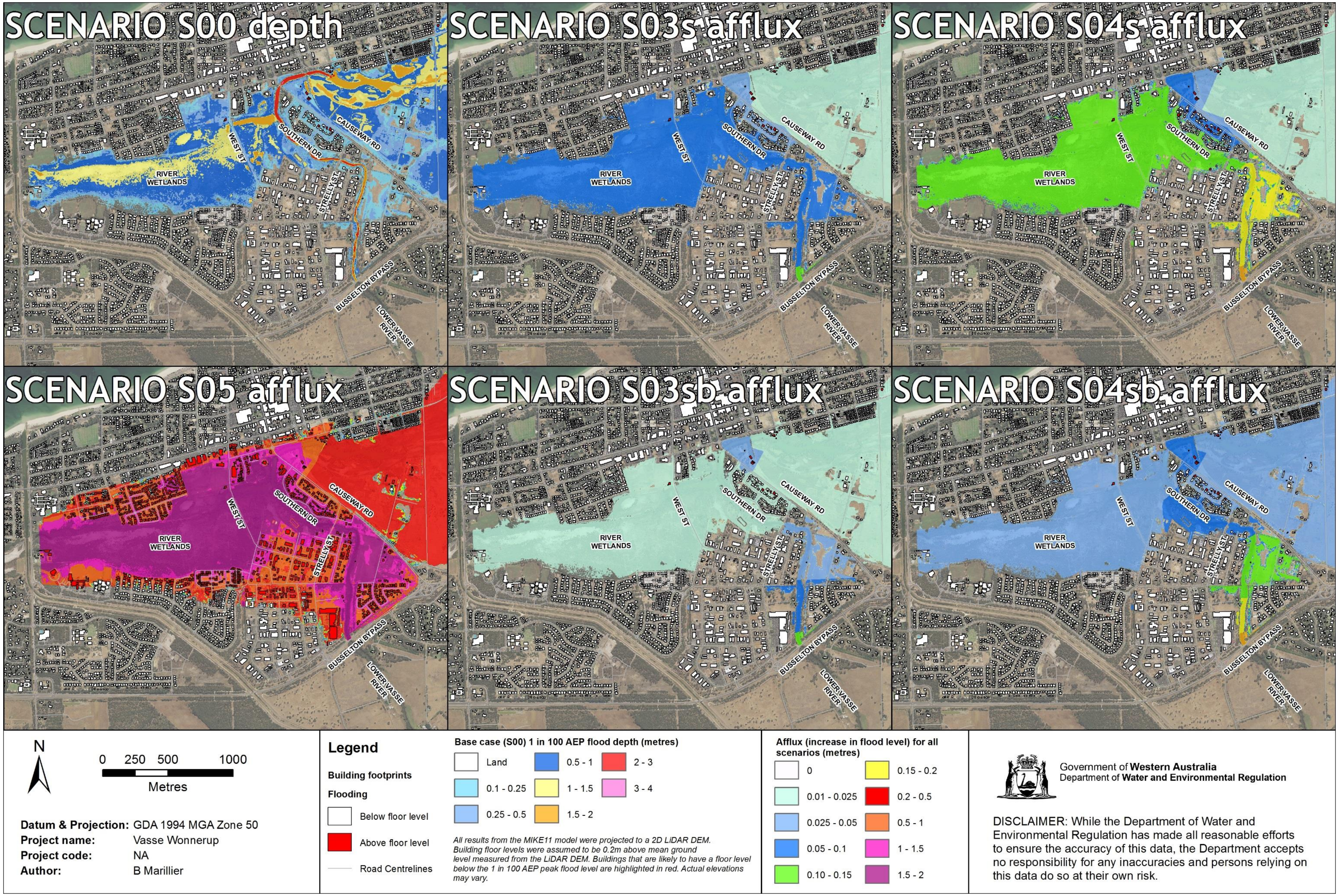


Figure 5-13: Extent of 1% AEP flooding on the Lower Vasse River between Busselton Bypass and the Butter Factory weir. Base case and reconnection scenarios

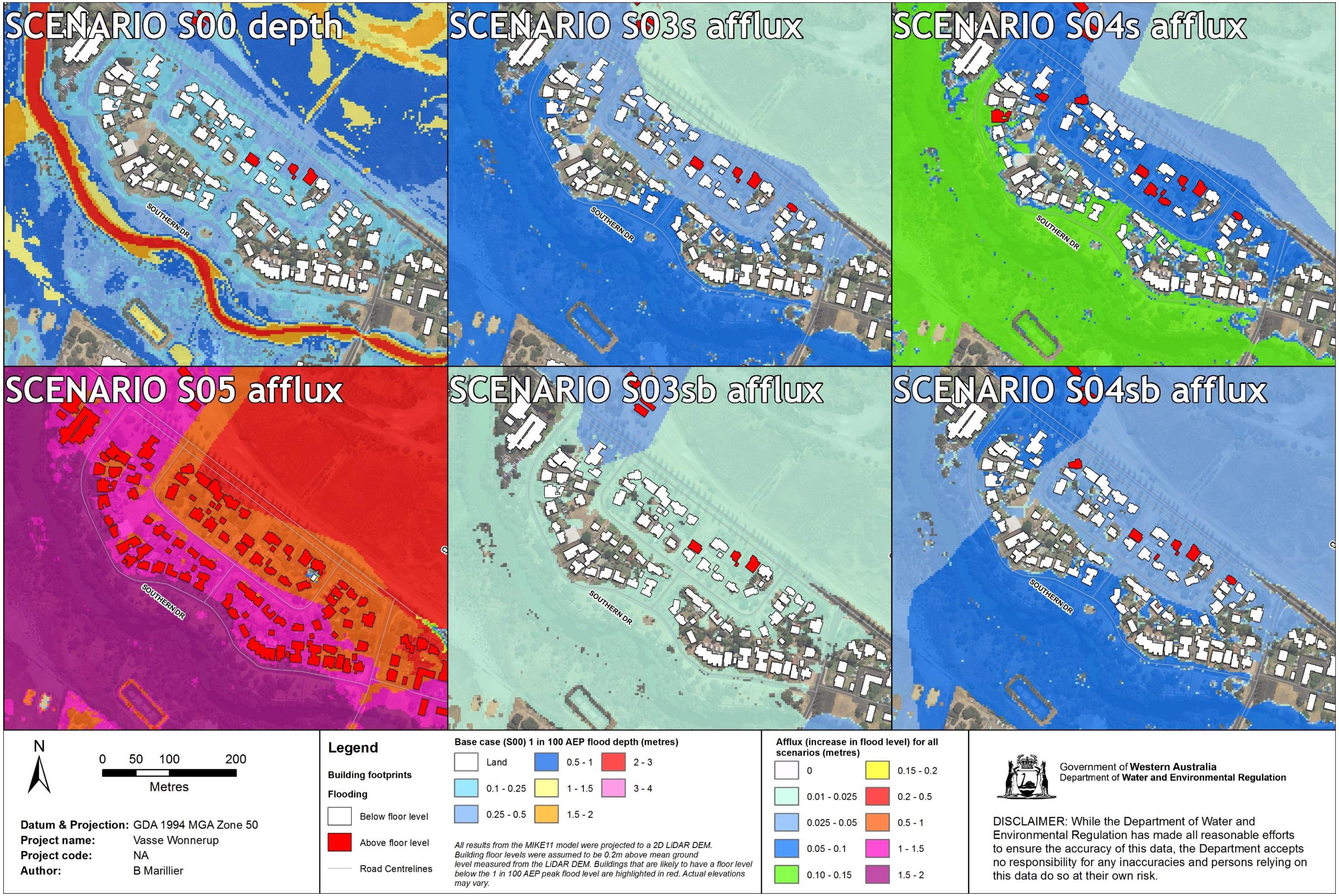


Figure 5-14: Extent of 1% AEP flooding on the Lower Vasse River between Southern Drive and Causeway Road. Base case and reconnection scenarios

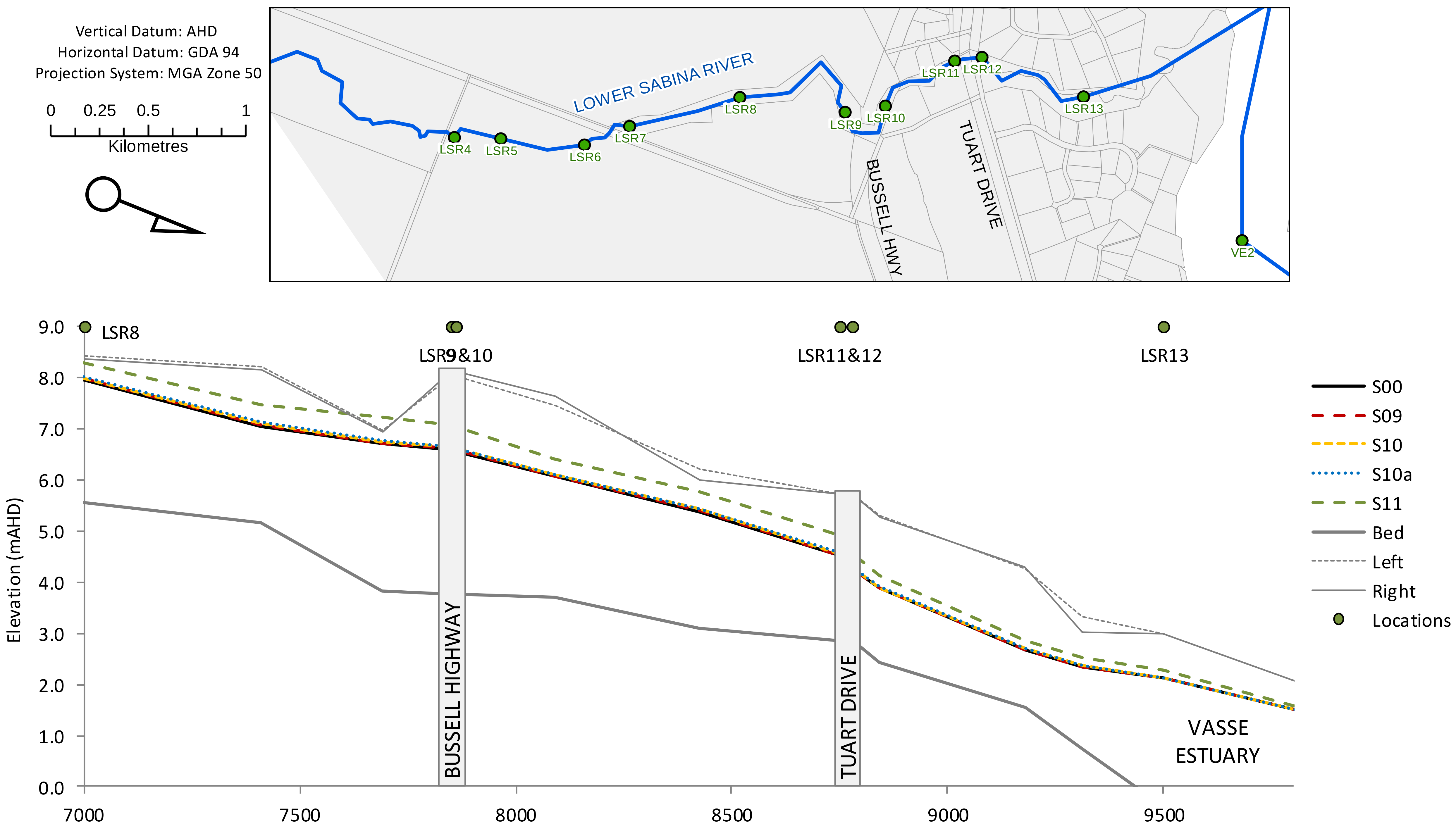


Figure 5-15: Long-section of peak flood levels for the 1% AEP event on the Lower Sabina River at Bussell Highway and Tuart Drive

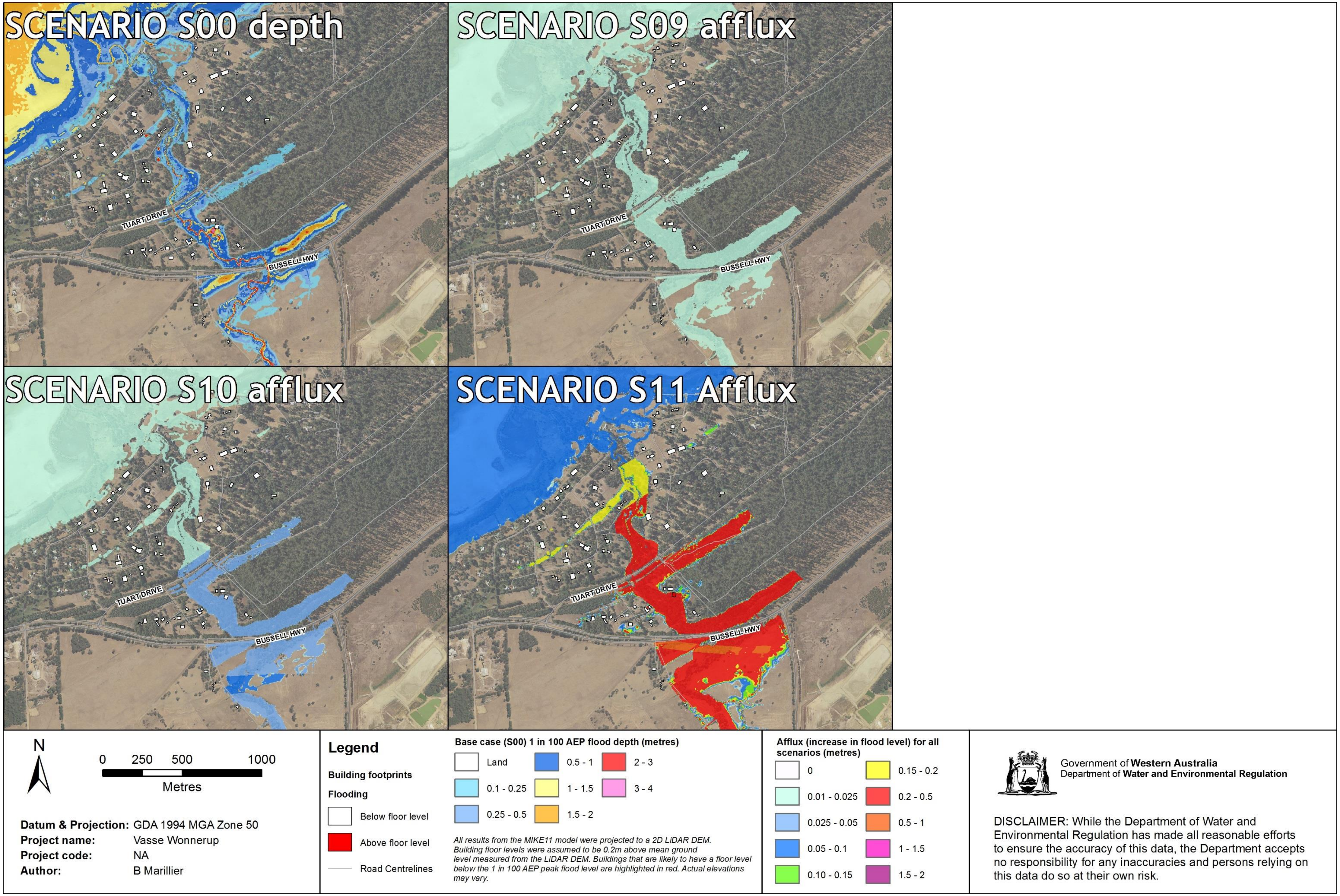


Figure 5-16: Extent of 1% AEP flooding on the Lower Sabina River for S00, S09, S10 and S11

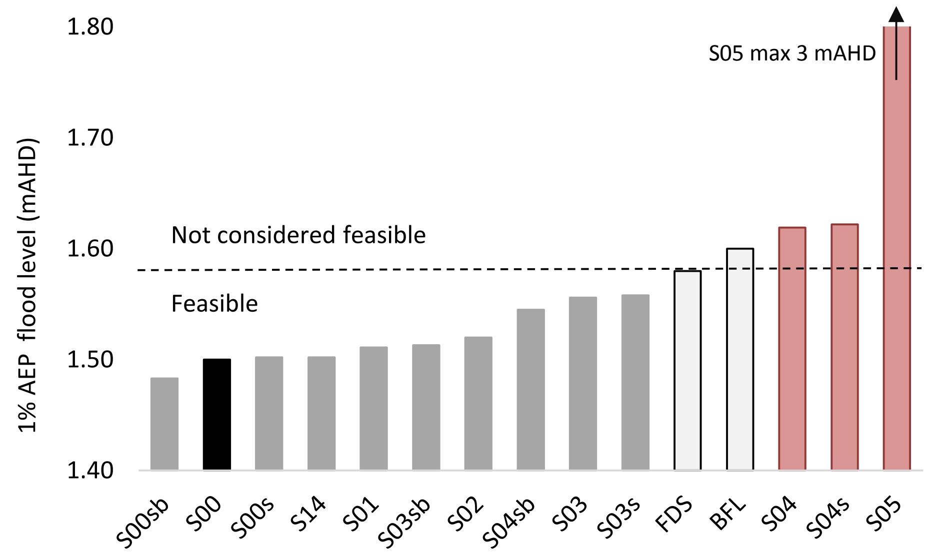


Figure 5-17: Feasibility of Lower Vasse River reconnection options relative to floodplain development strategy (FDS) and building floor level (BFL) upstream of Causeway Road bridge

5.3.4 Lower Sabina River reconnection scenarios S09 to S11

Results – flooding

Scenarios S09, S10 and S10a assess the potential for flooding on the Lower Sabina River by adding 450 mm and 900 mm culverts to the weir structure.

The land along the Lower Sabina River between the weir structure and Bussell Highway is predominantly used for grazing, with substantial storage areas available adjacent to the river. The channel's capacity is relatively small for the first several kilometres downstream, but the availability of floodplain storage and lack of infrastructure in this area limits the consequences of flooding. Between the Bussell Highway and Vasse Estuary the land is low-lying, with dwellings adjacent to the rivers that are at risk of riverine flooding. Hence the results of the reconnection scenarios are focused on the latter area.

The long-section in Figure 5-15 shows that S09, S10 and S10a do not have a substantial impact on flood levels on the lower reaches of the Sabina River, but S11 (full reconnection) does. The 1% AEP peak flood levels on the Lower Sabina River upstream of Tuart Drive are as follows:

- Base case S00 peak flood level 5.39mAHD
- S09 flood level increases to 5.40mAHD (+1cm)
- S10 flood level increase to 5.42mAHD (+3cm)
- S10a flood level increases to 5.44mAHD (+4cm)
- Full reconnection (S11) flood level increase to 5.78 mAHD (+38cm)

Scenario S11 also increases the flood level in the Vasse Estuary from 1.46 mAHD (base case) to 1.53 mAHD (+7cm).

Peak flood level for the Lower Sabina River between the Bussell Highway and the estuary were mapped to a 2008 LiDAR elevation dataset to estimate the flood extent (Figure 5-16). Several buildings would be affected by flood water for the base case (S00) and other scenarios. However, scenarios S09, S10 and S10a did not result in a significant increase in flood extent. For S11 the extent of flooding increased substantially upstream of Tuart Drive and the Bussell Highway.

Feasibility – flooding

The existing floodplain development strategy only extends to the downstream side of the Tuart Drive bridge over the Lower Sabina River and recommends a 0.5 m freeboard above the 1% AEP peak flood level. However, the upstream side of the bridge experiences the greatest water-level rise as flow increases in the river. Thus the overall feasibility for the Sabina River is based on the building floor levels for the area between Tuart Drive and the Bussell Highway and not on the floodplain development strategy.

Based on these criteria, the following scenarios are considered feasible:

- S09, S10 and S10a – given they are unlikely to result in detrimental flooding near Tuart Drive.

Scenario S11 is not feasible because it would result in an unacceptable increase to flood level in the Lower Sabina River and Vasse Estuary.

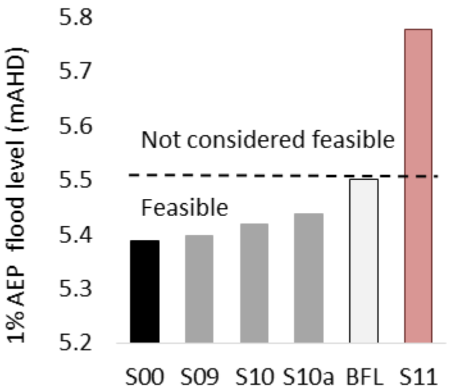


Figure 5-18: Feasibility of Lower Sabina River reconnection options relative to building floor level (BFL) for residential properties upstream of Tuart Drive

5.3.5 Removal of surge barriers S12

Results – flooding

This scenario resulted in flood level increasing in the Vasse Estuary from 1.46 mAHD to 1.49 mAHD (+3 cm) and in the Wonnerup Estuary from 1.45 mAHD to 1.49 mAHD (+4 cm). Water levels also increased 4 cm in the Lower Vasse River. Although the removal of surge barriers did not result in a substantial increase in flood levels, it would allow a large volume of sea water to enter the estuaries – as shown by the discharge results at the surge barrier location for the two estuaries (Figure 5-19). For scenario S12, removal of the surge barriers results in 1.1 GL of sea water entering the Vasse Estuary, and 0.8 GL entering the Wonnerup Estuary.

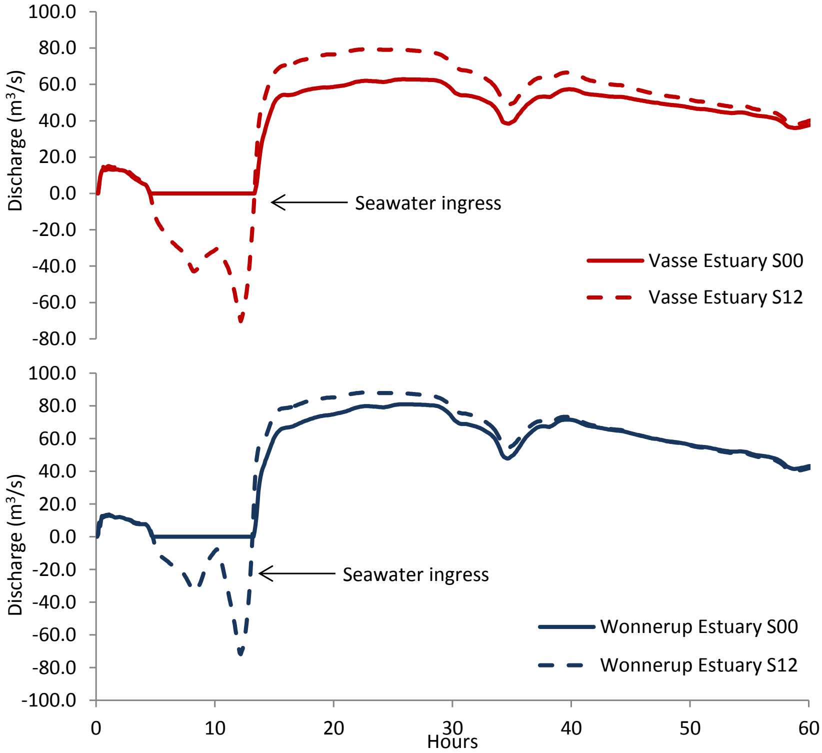


Figure 5-19: Discharge from the Vasse and Wonnerup estuaries for S00 and S12. Negative discharge values indicate inflow from Geographe Bay to the estuaries 'seawater ingress'

Feasibility – flooding

Sea-level rise is an important consideration for this scenario in the long-term. Sea level has risen at a rate of 2 mm/year for the past several decades; the IPCC (2013) estimates that globally-averaged sea levels will increase by 170–380 mm by around 2050. The surge barriers will become increasingly important for flood protection as ocean water levels rise.

Given the potential for storm surges and sea-level rise, removal of the surge barrier would present a significant increase in flood risk to Busselton.

5.3.6 Summary of flood simulation results

Flood simulations were done for the scenarios listed in Table 5-1, except for scenarios S06, S07, S08 and S13. For S06, S07 and S13, the changes to flood risk from the proposed drainage modifications could be deduced from other modelled scenarios. S08, which increases the height of the check boards at the end of summer from 0.4 mAHD to 0.6 mAHD, would only pose an increased flood risk if the check boards were left in place during the 1% AEP flood event. This is unlikely because flood events generally occur in winter when the check boards are not in place. Table 5-4 indicates the feasibility of the scenarios in terms of acceptable flood risk.

Table 5-4: Feasibility in terms of flood risk

Scenario ID	Description	Acceptable flood risk
S00	Base case VDD offtake one 900 mm culvert three-quarters open	
S00s	Base case with spillway at VDD offtake	✓
S00s	Base case with spillway at VDD offtake and Causeway Rd bridge upgrade	✓
S01	VDD offtake one 900 mm culvert fully open	✓
S02	VDD offtake one 900 mm and one 450 mm culvert	✓
S03	VDD offtake two 900 mm culverts	✓
S03s	As S03 with spillway at VDD offtake	✓
S03s	As S03 with spillway at VDD offtake and Causeway Rd bridge upgrade	✓
S04	VDD offtake three 900 mm culverts	×
S04s	As S04 with spillway at VDD offtake	×
S04s	As S04 with spillway at VDD offtake and Causeway Rd bridge upgrade	✓
S05	VDD fully connected to the LVR	×
S06	VDD offtake two 900 mm culverts open only Aug–Oct	✓
S07	Recycled water discharged to LVR year-round	✓
S08	Vasse and Wonnerup barriers check boards set at 0.6 mAHD	✓
S09	SDD weir with one 450 mm culvert	✓
S10	SDD weir with one 900 mm culvert	✓
S10a	SDD weir with two 900 mm culverts	✓
S11	SDD fully connected to the LSR	×
S12	Surge barriers removed	×
S13	Two 900mm culverts on VDD offtake, one 900 mm culvert on SDD weir	✓
S14	No Butter Factory Weir, partially fill LVR, VDD offtake two 900 mm culverts	✓

The construction of the spillway on the Vasse Diversion Drain to direct peak flows to the Lower Vasse River would not affect maximum flood water levels due to the timing of the peak flows. This initiative, which would protect the levees of the Vasse Diversion Drain, does not change the flood risk in any of the scenarios modelled.

The flood modelling confirmed that the major structures – Vasse Diversion Drain, Sabina Diversion Drain and associated compensation basins, as well as the surge barrier – are necessary to prevent flooding in the low-lying areas of Busselton and adjacent to the Vasse Estuary. The surge barrier also stops the inflow of sea water, which would salinise surrounding pastures. The IPCC (2013) predicts sea-level rise by 2050 of 170–380 mm. The surge barriers will become increasingly important for flood protection as ocean water levels rise.

Full connection of the Vasse Diversion Drain to the Lower Vasse River and/or the Upper Sabina River to the Lower Sabina River would pose unacceptable risks. The largest reconnection options modelled – two 900 mm culverts at Upper Sabina River diversion and three 900 mm culverts at the Vasse Diversion Drain offtake – represent ‘bank-full’ flows (more for the Sabina), and thus reconnection options that redirect more flow to the lower rivers would also pose an unacceptable flood risk. Installation of three 900 mm culverts at the Vasse Diversion Drain offtake showed the potential for unacceptable flooding with the current

Causeway Road bridge. Flood risk for this option would only be acceptable if the bridge were upgraded to reduce afflux. Although reconnection of the two 900 mm culverts at the Sabina diversion caused flooding out of the lower Sabina River channel, the risk was deemed acceptable because buildings were not affected.

Scenario S14, which models two 900 mm culverts at the Vasse Diversion Drain offtake, filling of the Lower Vasse River to remove pools, and removing the Butter Factory weir, resulted in an acceptable flood risk. However, if this option were to be considered further, detailed modelling would be required.

5.4 Hydrological simulation results

This section presents hydrological modelling results from MIKE11 for all scenarios. The results may be used to assess the effectiveness of the management options for achieving different goals; for example, reducing nutrient concentration, improving flushing, or mobilising sediment.

The hydrological simulations were run from 2001–14 inclusive using the same flow and meteorological input data for all scenarios unless otherwise specified. The results presented here are calculated from the MIKE11 model output at an hourly timestep for the entire period.

The hydrological simulations calculate changes to the hydrology of the rivers and estuary under typical flow conditions. Results are reported for discharge, residence time, water level, velocity and bed shear stress, as well as changes to the nutrient balance for nitrogen and phosphorus. Table 5-5 lists the variables used in the analysis.

Table 5-5: Variables and descriptions reported for hydrological simulations

Variable		Units	Description
Discharge	Q	m^3/s ML/month GL/yr	Discharge time-series were extracted at an hourly timestep from MIKE11 at relevant Q points. These are presented in the form of averages (annual or monthly).
Residence time	*t*	days	Residence time is the average amount of time that a drop of water will spend in a control volume (e.g. a river reach). It is calculated by dividing the capacity of the control volume by the discharge through the system. Residence time was calculated for the Lower Vasse River assuming a control volume of 57 ML based on a water level of 0.4 mAHD.
Water level	*H*	mAHD	Water level time-series were extracted at an hourly timestep from MIKE11 at relevant cross-section locations. These are presented in the form of average levels (annual or monthly).
Velocity	*v*	m/s	Velocity time-series were extracted at an hourly timestep from MIKE11 at relevant Q or H points between model cross-sections.
Bed shear stress	*T*	N/m^2	Bed shear stress is the measure of force of moving water against the channel bed. It indicates the capacity of flow to entrain and move sediment. Sediments can become mobile when the shear stress in the river channel exceeds the critical bed shear stress for a certain particle size. This parameter is calculated in MIKE11 as a function of flow velocity, water depth and resistance. It was extracted at an hourly timestep from relevant H points from the model. Bed shear stress gives an indication of the capacity of flow to move sediment, but actual erosion and deposition of a river is influenced by the availability of sediment (sediment load in inflows), sediment cohesion and the settling velocity of entrained particles.
Nutrient concentration		mg/L	Nutrient concentration calculated using the methods described in Section 5.4.1.4
Nutrient load		Kg/yr	Nutrient load calculated by multiplying flow by nutrient concentration.

5.4.1 Lower Vasse River reconnection scenarios S02 to S07, S13, S14

This section discusses the scenarios which relate to the Lower Vasse River:

- S00: Base case Vasse Diversion Drain offtake, one 900 mm culvert assumed three-quarters open
- S02: Vasse Diversion Drain offtake one 900 mm and one 450 mm culvert
- S03: Vasse Diversion Drain offtake two 900 mm culverts
- S04: Vasse Diversion Drain offtake three 900 mm culverts
- S05: Vasse Diversion Drain fully connected to the Lower Vasse River
- S06: Vasse Diversion Drain offtake two 900 mm culverts open only in spring
- S07: Recycled water discharged to Lower Vasse River year-round
- S13: Two 900 mm culverts on Vasse Diversion Drain offtake, one 900 mm culvert on Sabina Diversion Drain weir
- S14: No Butter Factory weir, partially fill Lower Vasse River, Vasse Diversion Drain offtake two 900 mm culverts

These scenarios relate to increasing flow to the Lower Vasse River, either by adding additional capacity at the offtake structure or by discharging treated wastewater directly to the river.

5.4.1.1 Changes to average annual flows, seasonality of flows and residence time

Increasing the offtake structure's capacity allows for more water to be diverted to the Lower Vasse River – assuming there is sufficient flow in the Vasse Diversion Drain. Figure 5-20 clearly illustrates that a larger offtake structure could substantially increase flow through the river. S03 is the largest culvert sizing deemed feasible due to flooding. This scenario shows that even with restrictions due to flooding, a 45% increase in flow through the river could be achieved on average. S07 shows a relatively small increase in flow resulting from the recycled water, and S13 illustrates that even with some diversion of flow to the Lower Sabina River further upstream, a substantial increase in flow could still be achieved on the Lower Vasse River. S14 results in the same increase in flow as S03 since the culvert sizing is identical.

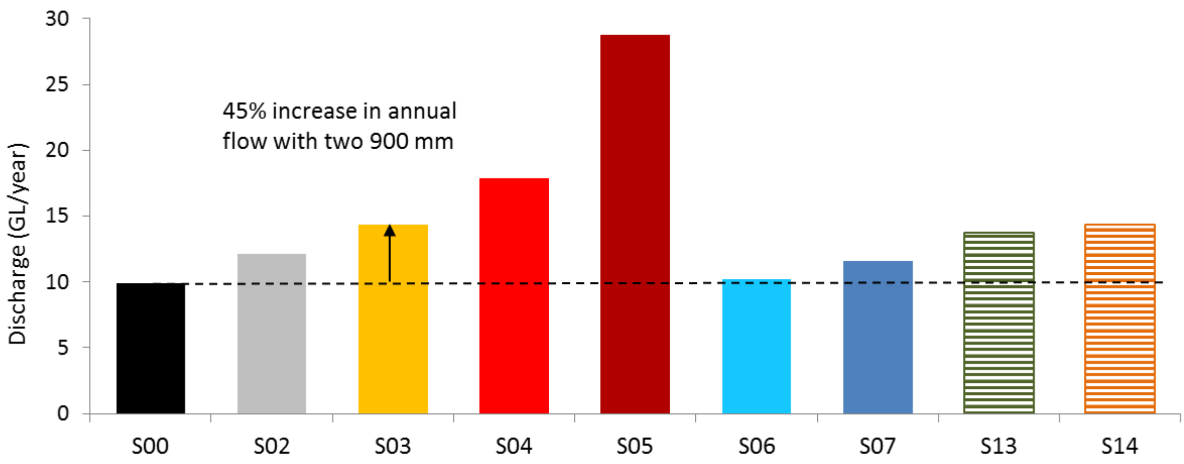


Figure 5-20: Average annual flows in the Lower Vasse River

The seasonality of flow for each scenario is shown in in Figure 5-21. Except for S07, all scenarios resulted in an increase in flows during winter and spring only, which is the time of year the Vasse Diversion Drain is flowing. Scenario S06 only increased flow for the period of time that the culverts are open, with a substantial reduction in flow in winter. Scenario S07 – recycled water discharged to the Lower Vasse River year round – increased flow year-round by around 100 ML/month.

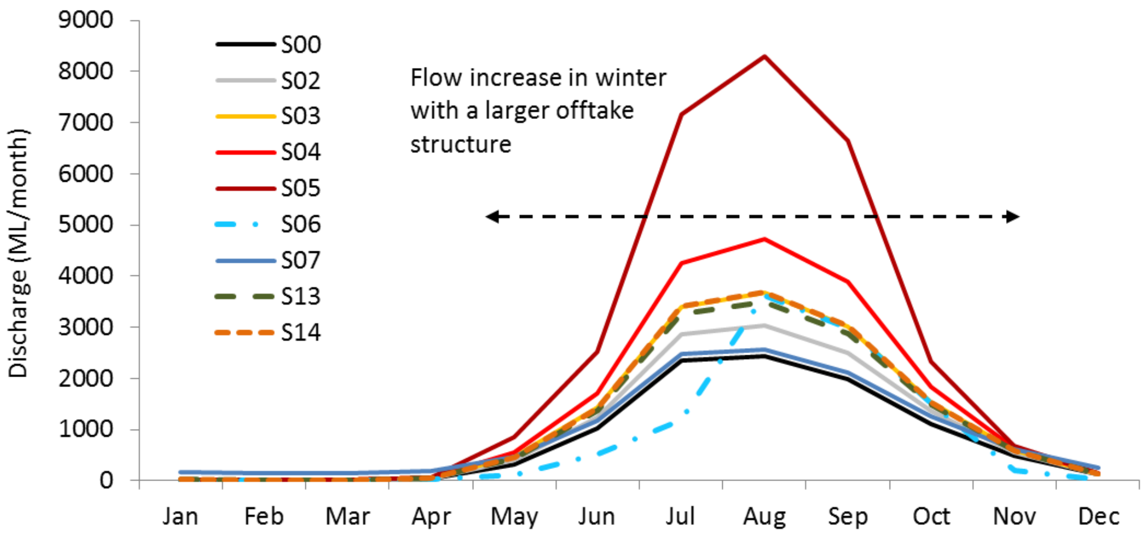


Figure 5-21: Monthly flows in the Lower Vasse River

The seasonal delivery of flow has a direct impact on the residence time of water in the Lower Vasse River, as shown in Figure 5-22. Because flow is only diverted through the offtake structure during winter, these scenarios did not result in a beneficial reduction in residence time in the Lower Vasse River; that is, the river would still remain stagnant during summer and autumn. The exception is S07 which would introduce a steady baseflow of water through the Lower Vasse River year-round, lowering residence time to around 10 days during summer.

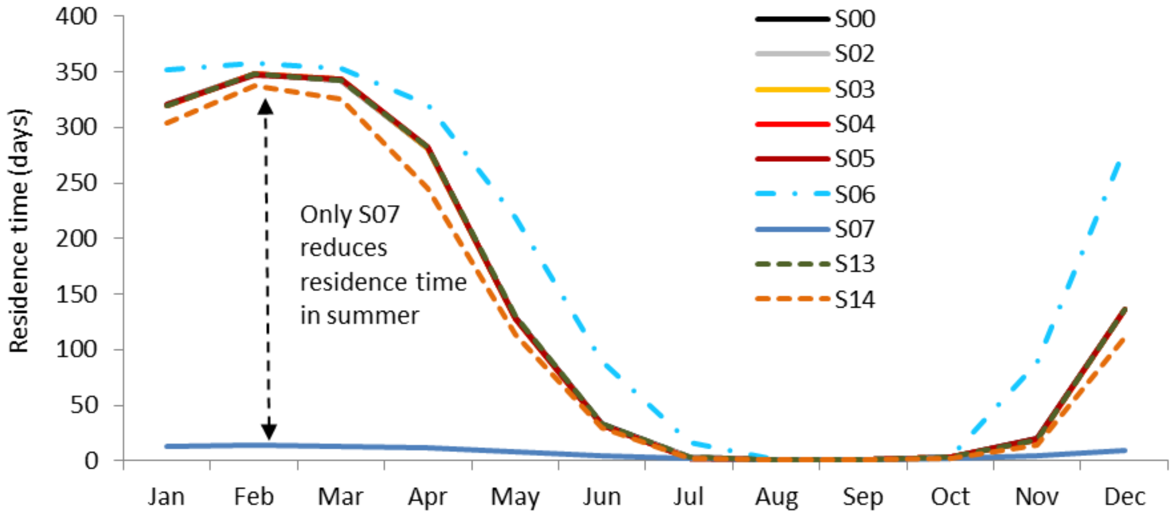


Figure 5-22: Residence time in the Lower Vasse River

5.4.1.2 Changes in seasonal water level

Average monthly water levels for each scenario are shown in Figure 5-23 for the Lower Vasse River near the river wetlands (Lower Vasse River 7). These show the time of year that water levels are influenced by each scenario. The base case indicated higher water levels in winter and the influence of evaporation in summer. For scenarios S02 to S05 there was no change in water level during summer and autumn because this is a period of no-flow or very low flow on the Vasse Diversion Drain. During winter, average water levels increased with the additional flow: S04, for example, resulted in an additional 20 cm of water in August, but by December little difference in water level was found.

For scenario S14 flow volumes through the Lower Vasse River were comparable to scenario S03. However, water levels were substantially lower throughout the year, which is related to removal of the Butter Factory weir. For this scenario water levels were controlled by the water level in the estuary. This means that in lower rainfall years the river would likely dry completely during summer.

Water-level results at the Vasse surge barrier (Vasse Estuary 3) are shown in Figure 5-24. Changes in water level were similar to those on the Lower Vasse River, with an increase in winter and no change in summer. For S05 the peak water level in the main body of the estuary was only 15 cm higher than for the base case. For S07 water levels were around 10 cm higher in summer – indicating that a portion of the recycled water would reach the surge barrier.

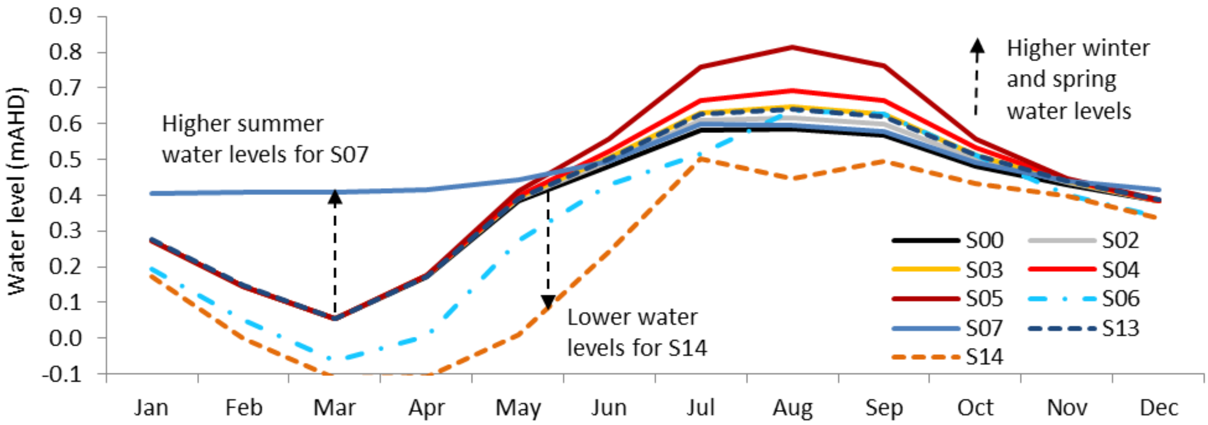


Figure 5-23: Average monthly water levels in the Lower Vasse River

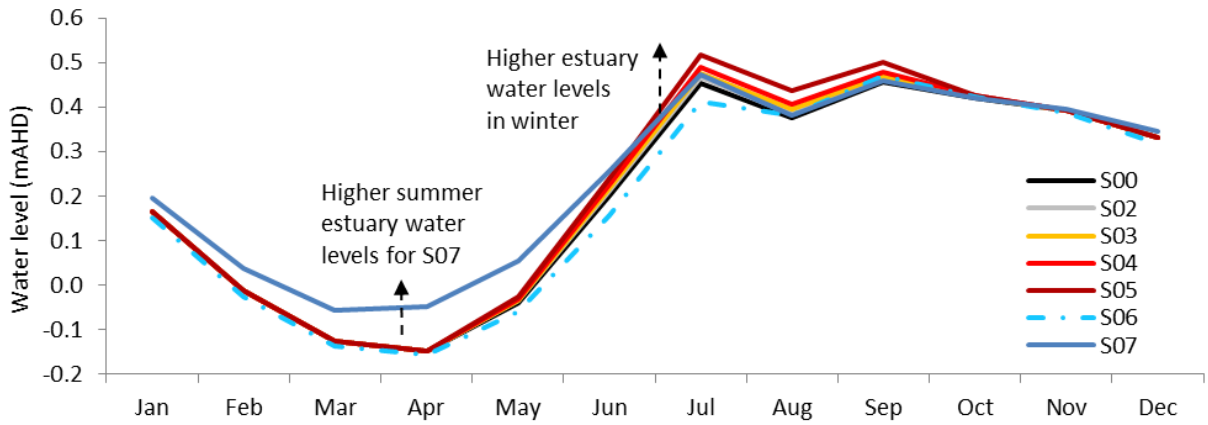


Figure 5-24: Average monthly water levels in the Vasse Estuary

5.4.1.3 Changes in bed shear stress – would the scenarios move sediment?

To assess the capacity of each scenario to move sediment, bed shear stress on the Lower Vasse River was compared with the critical shear stress for different sediment sizes (average values from Julien 2002). Because bed sediment is usually mobilised only in higher flow conditions, an exceedence curve has been used to illustrate changes to bed shear stress on the Lower Vasse River (Figure 5-25). This shows the proportion of time a particular shear stress was exceeded.

Generally increasing flow increases the *potential* to move sediment, due to increases in water depth and velocity. Scenario S03 indicated that finer sediments might be mobilised more often with a larger capacity at the offtake structure. However, for scenarios S00 to S04 the river flows clearly had very limited capacity to move sediment in the lower reaches; that is, most of the time flows were insufficient to move even very fine particles. Further to this, cohesive fine silts require much higher bed shear stress for mobilisation compared with much larger particle sizes (Julien 2002). The threshold for movement of ‘medium silt’ shown in Figure 5-25 is for non-cohesive sediments, which is unlikely to apply in the Lower Vasse River.

Net erosion or deposition in a river reach depends not just on the energy available to move sediment, but also on the incoming sediment load. So higher bed shear stress does not necessarily indicate that net erosion would happen in the Lower Vasse River. It is possible that increasing flow could cause further sedimentation either from bed and bank erosion on the steeper sections; or with the increased load associated with flow. To illustrate this, Figure 5-26 shows a long-section of simulation results for bed shear stress with a steady inflow of 10 m^3/s to the Lower Vasse River – shear stress is up to three orders of magnitude higher in the upper reaches compared with the lower reaches.

To further assess the likelihood of net erosion/deposition in the Lower Vasse River, a simple uncalibrated HEC RAS sediment transport model was constructed. Results indicated that under both normal and increased flow conditions, the upper reaches would erode and deposition would occur in the lower reaches.

It is worth highlighting that S14 resulted in higher flow velocities and shear stress relative to the other scenarios, implying a greater capacity to carry sediment to the estuary. This is caused by increases in the slope of the river bed and removal of flow restrictions. This scenario also reduced residence time because a smaller volume of water was stored in the river and flow velocities were higher.

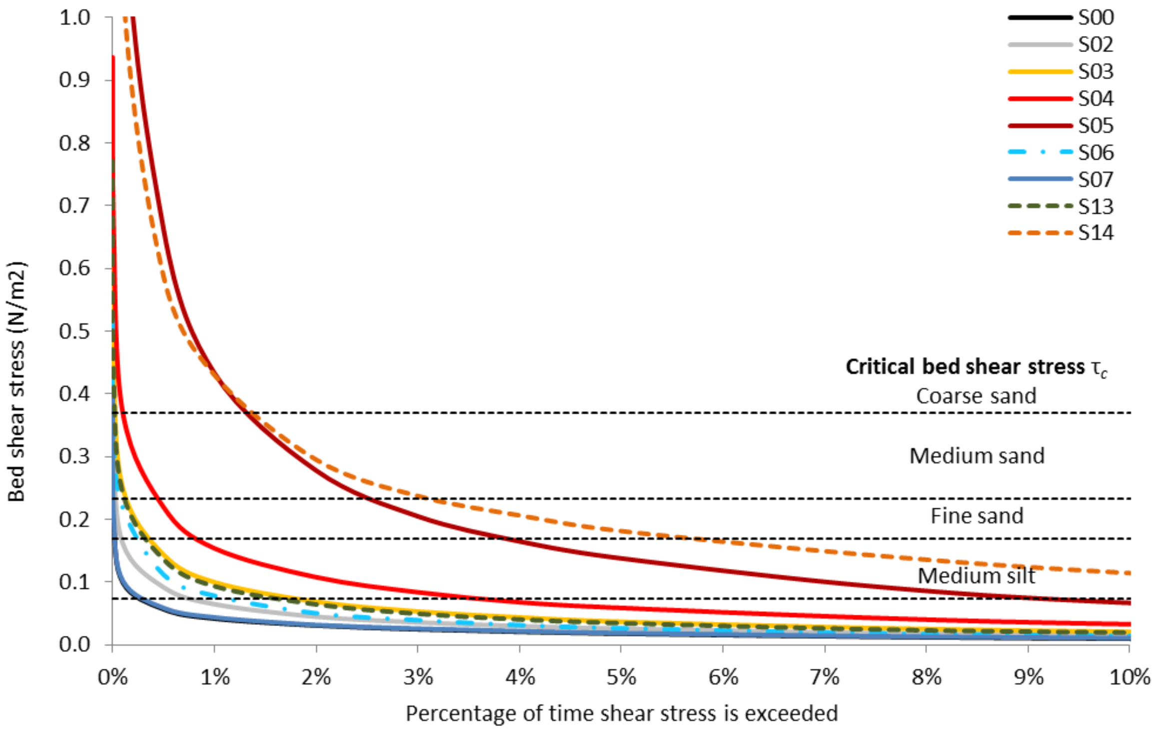


Figure 5-25: Bed shear stress exceedence in the Lower Vasse River (Lower Vasse River 7)

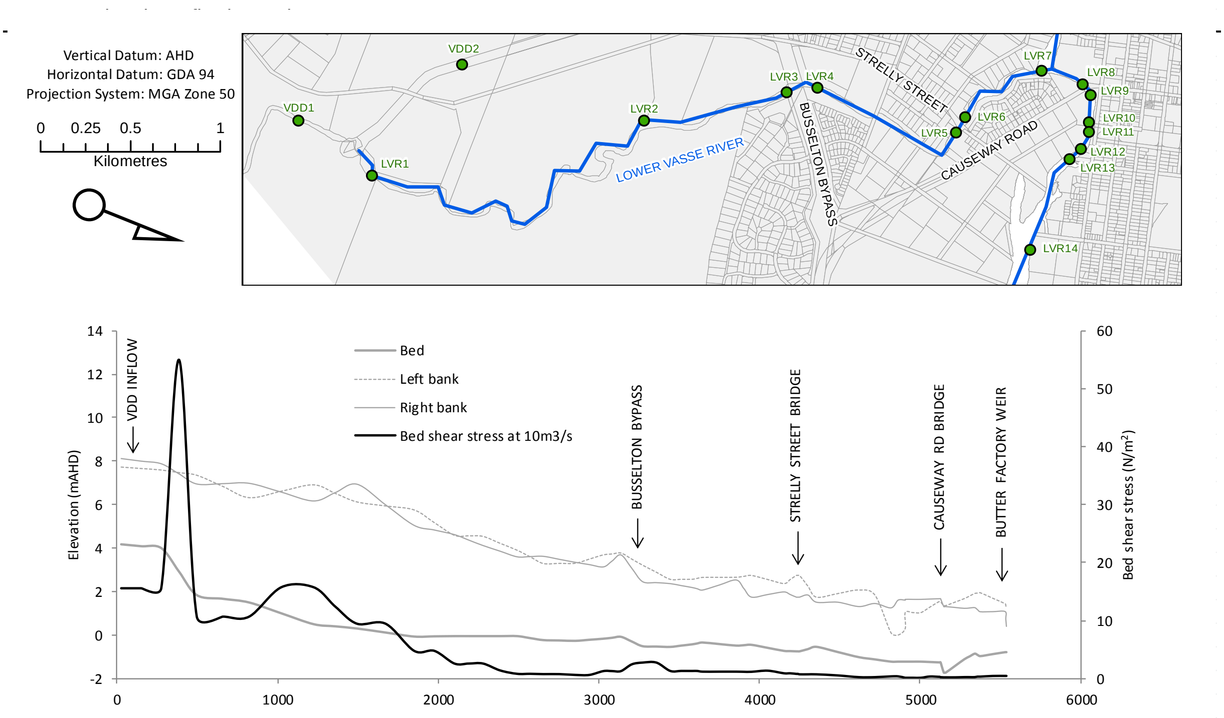


Figure 5-26: Long-section of bed shear stress for steady-state conditions with an inflow of 10 m^3/s for the Lower Vasse River. Where the river is steep and narrow, bed shear stress is highest

5.4.1.4 Changes to nutrient load and concentration

A simple nutrient mass balance was used to estimate nutrient concentrations in the rivers and the total nutrient loading to the estuary. The mass balance was calculated using a box model of the Lower Vasse River using measured nitrogen and phosphorus concentrations and the modelled flow regime for the different scenarios. For full details of the calculations, see Appendix L.

Figure 5-27 and Figure 5-28 show the influence of each scenario on seasonal nutrient concentrations and total nutrient load to the Lower Vasse River. The increase in flow associated with the scenarios resulted in a proportional increase in nutrient load. For example, the addition of three 900 mm culverts (S04) would increase the TN load by 80%, and increase the TP load delivered to the Lower Vasse River by around 40%. Full reconnection of the Lower Vasse River would result in an almost tripling of TN load and a doubling of TP load.

With spring releases only (S06), more flow was released in spring but none was released during the rest of the year, resulting in little change to the total annual nutrient load. Release of treated wastewater (S07) would result in an 8% increase in TN and TP load, assuming that the water was treated to meet a TP concentration of 0.1 mg/L and a TN concentration of 1.0 mg/L.

All scenarios would alter nutrient concentrations in the Lower Vasse River to some extent, generally with reductions in winter and spring as flows increased. For example, in S03 TP concentrations in winter and spring are between 11 and 16% lower than the base case, but in late summer and early autumn the difference is less than 3%. For TN there is little difference in nutrient concentration for the reconnection scenarios because TN concentrations in the Vasse Diversion Drain and Lower Vasse River catchment are comparable.

The largest reduction in concentration arises from scenario S07 because the additional flow of 4.5 ML/day is sufficient to fully replace water in the Lower Vasse River every two weeks, causing a reduction in concentration for both TN and TP during summer-autumn. S06 showed a large increase in concentration from November to June. Although an increase would be expected, the magnitude of change is probably overestimated due to simplifications in the box model.

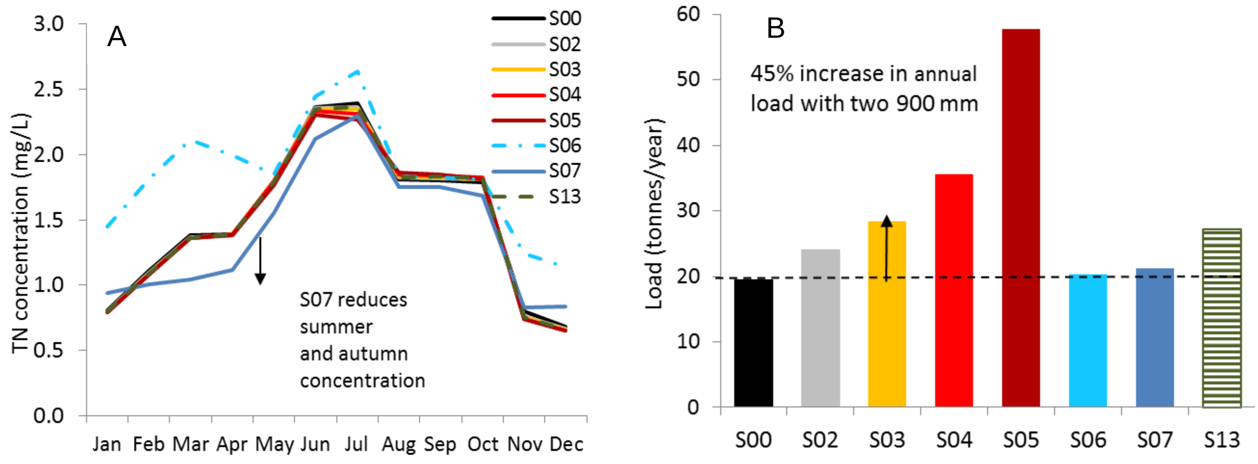


Figure 5-27: Monthly TN concentration (A) and annual nitrogen load (B) for the Lower Vasse River

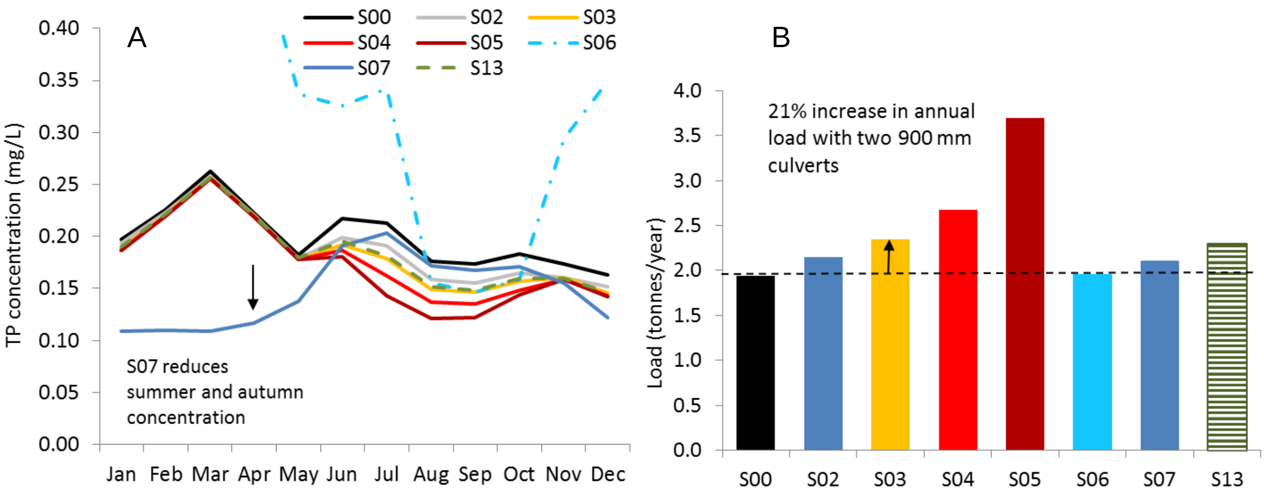


Figure 5-28: Monthly TP concentration (A) and annual phosphorus load (B) for the Lower Vasse River

5.4.2 Lower Sabina River reconnection scenarios S09 to S11

This section discusses the scenarios which relate to the Lower Sabina River:

- S00: Base case – no inflow from the Sabina Diversion Drain
- S09: Sabina Diversion Drain weir with one 450 mm culvert
- S10: Sabina Diversion Drain weir with one 900 mm culvert
- S10a: Sabina Diversion Drain weir with two 900 mm culverts
- S11: Sabina Diversion Drain fully connected to the Lower Sabina River

The culvert sizing is small relative to the scenarios for the Lower Vasse River because less water is available for diversion. The Lower Sabina River does not contain a weir structure holding water in summer and dries completely every year, so calculations of residence time are not relevant. Similarly, increases to bed shear stress or scouring is not one of the desired outcomes and is not reported for the Sabina scenarios.

5.4.2.1 Changes to average annual flows and water levels

Diverting all of the available flow from the upper catchment to the Lower Sabina River made it possible to increase the total flow volume from about 5.7 GL/year to 9 GL/year. With a restricting 900 mm culvert, annual flow would total about 8 GL/year (Figure 5-29). Most of this water would be delivered in July to September (Figure 5-30) and result in an increase in average August water levels of about 7 cm (Figure 5-31). In the absence of significant flood flows, this would be well below bank level for this section of the river.

Diverting flow to the Lower Sabina River had a much smaller impact on discharge and water levels compared with the scenarios for the Lower Vasse River – for the simple reason that much less water is available from the Sabina Diversion Drain. Even with all of the water diverted (S11), there was almost no change in average winter water levels in the estuary.

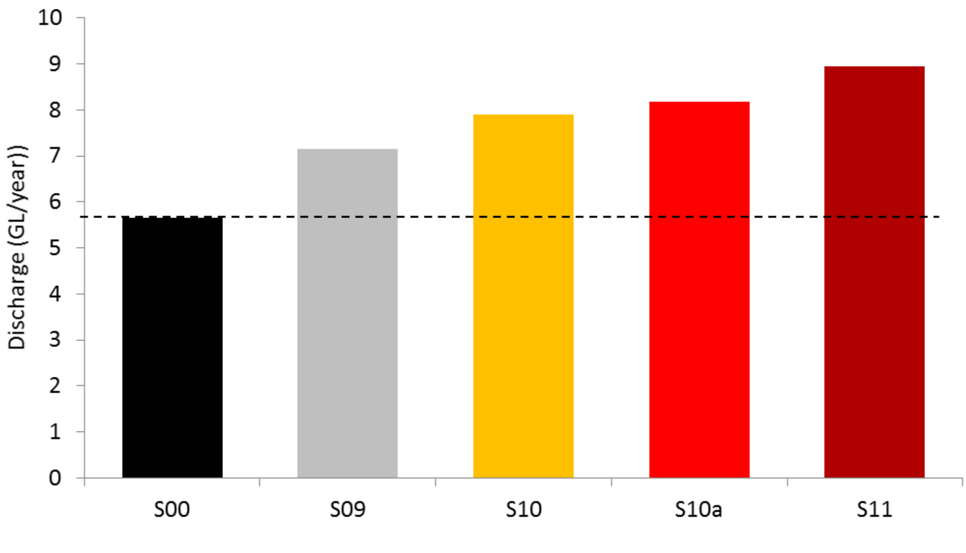


Figure 5-29: Average annual flows in the Lower Sabina River

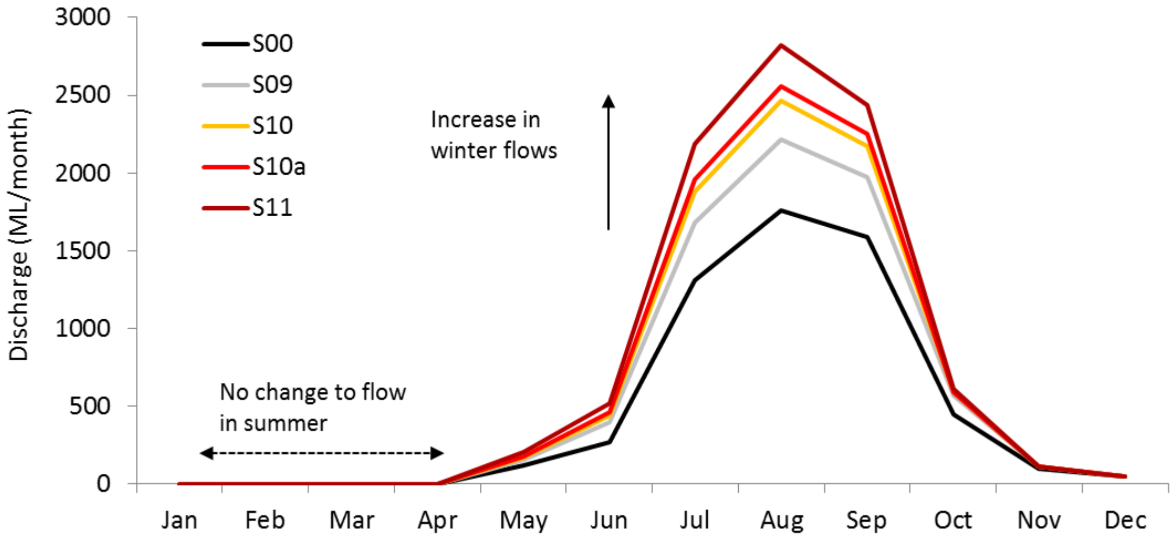


Figure 5-30: Average monthly flows in the Lower Sabina River

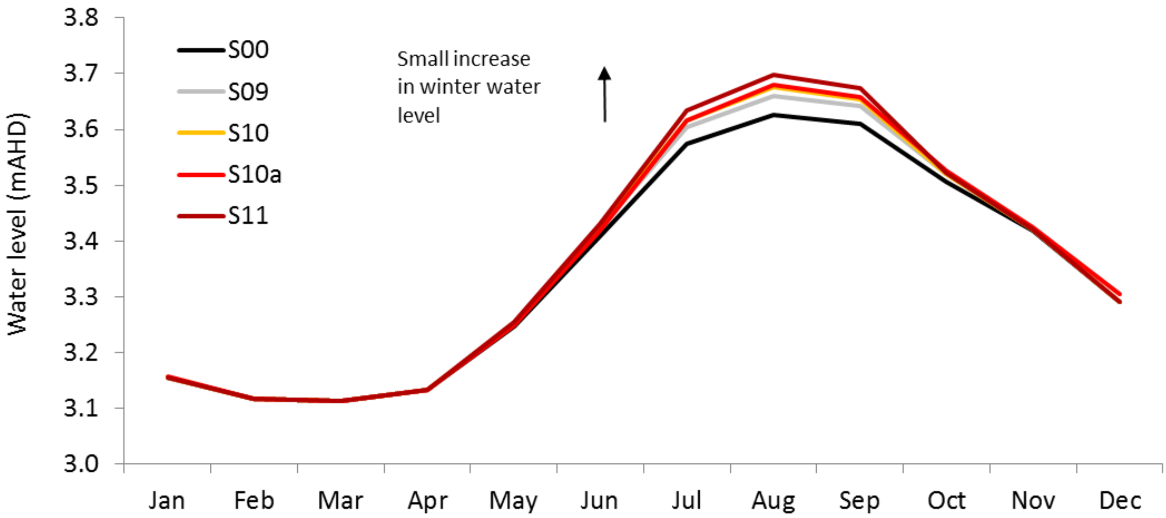


Figure 5-31: Average monthly water levels in the Lower Sabina River

5.4.2.2 Changes to nutrient load and concentration

For the Lower Sabina River, the mass balance was calculated directly from the modelled flows using measured nutrient concentrations. Refer to Appendix L for full details of the calculations. See Figure 5-32 and Figure 5-33 for the estimated changes to load and concentration for the Sabina River scenarios.

Since the TP concentrations in the Sabina Diversion Drain are low, introducing additional flow to the Lower Sabina River results in small increases in load – 7% for S10 (one 900 mm culvert) and 11% for S11 (full reconnection). However, water in the Sabina Diversion Drain has relatively high TN concentrations, so the increase in load is about 50% for S10 and 150% for S11.

Increased flow diversion would result in a decrease in TP concentrations on the Lower Sabina River during the flow season, and possibly a small increase in TN concentration. In most years there is no flow in the Sabina River or drain during summer, so changes to nutrient concentrations in this season are negligible.

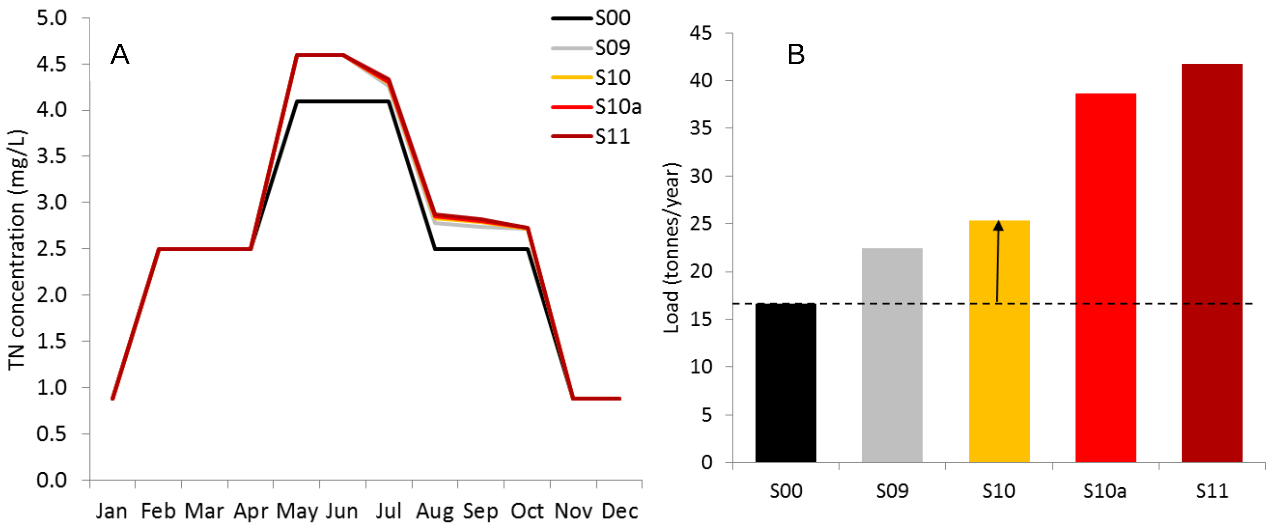


Figure 5-32: Monthly TN concentration (A) and annual nitrogen load (B) for the Lower Sabina River for various scenarios

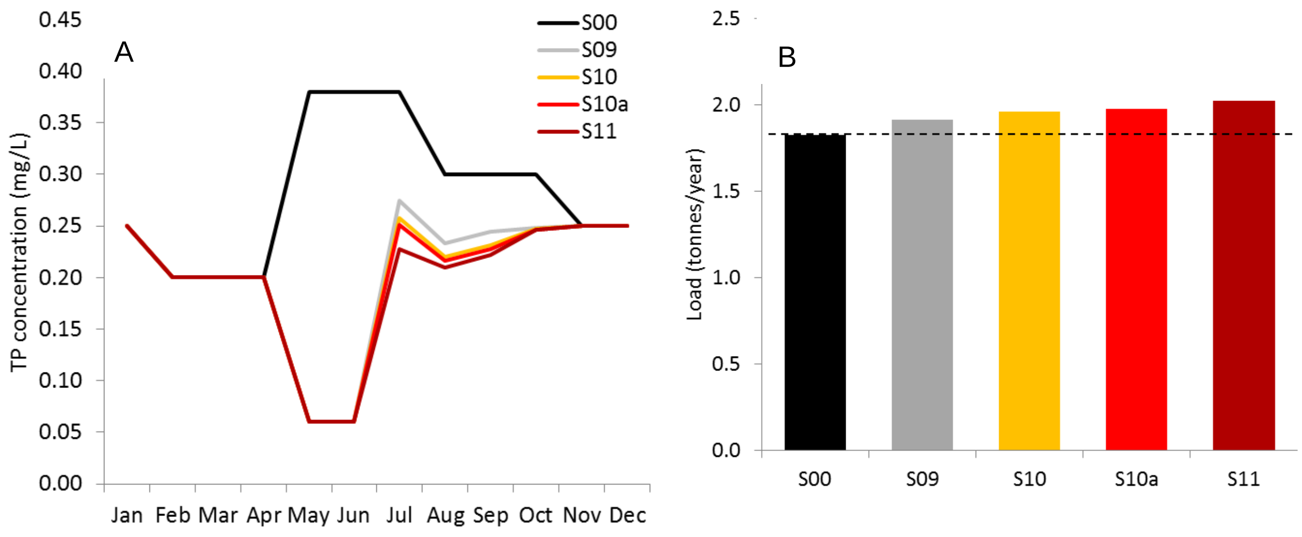


Figure 5-33: Monthly TP concentration (A) and annual phosphorus load (B) for the Lower Sabina River for various scenarios

5.4.3 Surge barrier scenarios S08 and S12

The two scenarios related to the surge barrier are:

- Increasing the check board height on the Vasse and Wonnerup surge barriers to 0.6 mAHD (S08). Boards in place from 1 September to 1 May
- Completely removing both surge barriers (S12)

These scenarios primarily influence water levels in the main body of the estuary. Results for the recycled water scenario S07 are also discussed in this section given the increase in flow during summer influences water levels in the main body of the estuary.

5.4.3.1 Changes to estuarine water level

Changes relative to the base case are illustrated by the monthly average water levels in Figure 5-34.

Increasing the check board height (S08) meant the estuary filled to 0.6 mAHD by the end of October (on average). This resulted in a greater volume of water being stored in the estuary for the duration of summer. The peak water level recorded in the simulation period was recorded in October 2005 while the check boards were in place, resulting in a peak that was 11 cm higher for S08 relative to the base case.

For S12 the range in water levels in the estuary was substantially altered. This was because the main influence becomes the tide in the absence of the surge barrier with the sandbar kept open. Relative to the base case this resulted in higher water levels from January to June, and lower water levels for the remainder of the year.

The treated wastewater scenario S07 increased water levels during summer but made little difference for the remainder of the year.

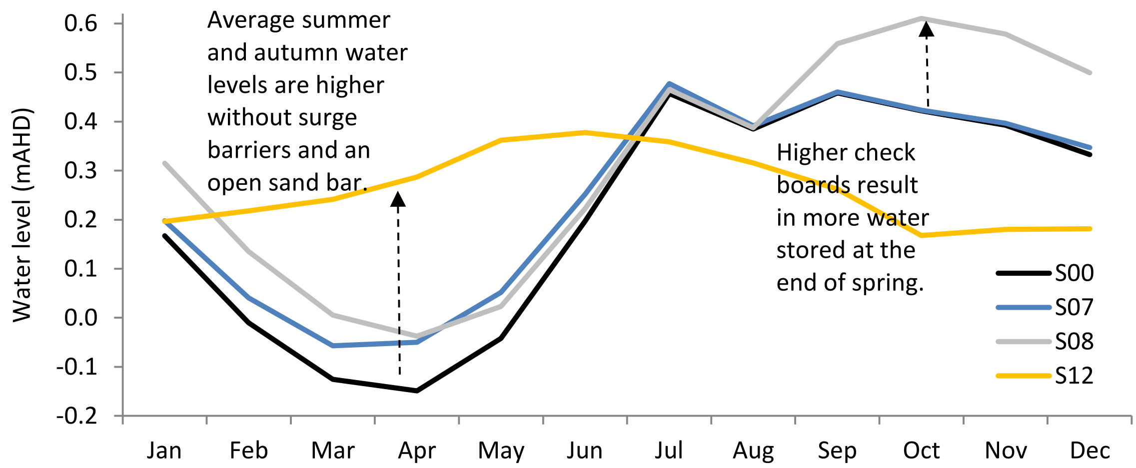


Figure 5-34: Average monthly water level in the Vasse Estuary

5.4.3.2 Changes to salinity and inundation without surge barriers

With the surge barriers removed, sea water is free to enter the estuaries if the sand bar is kept open. Discharge through the entry channel to the Vasse Estuary was extracted from the model to estimate the volume of water that would enter the estuary and the total discharge from the estuary in an average year for S12 (Figure 5-35). The average monthly net discharge (inflows less outflows) is shown in the same figure and indicates whether net inflow or outflow of seawater occurs in a given month. Average annual inflows from the ocean would be 25 GL/year, with much of this water returning to the ocean within a tidal cycle. The monthly flows show that during summer there is a net inflow of sea water. Outflows average 51 GL/year and result from river flows, rainfall and tidal outflows.

Although this modelling did not include solute-transport, it is reasonable to assume that tidal exchange in combination with evapo-concentration would result in estuarine waters being saline to hyper-saline during summer. The greatest difference in water levels between the base case and S12 was for April, when much of the estuary would normally dry out. To illustrate this the modelled median maximum April water level of 0.42 mAHD (at Vasse Estuary 2) was mapped to the bathymetry of the Vasse Estuary between the Butter Factory and Wonnerup Inlet (Figure 5-36). In the highest individual year, April water levels would reach 0.62 mAHD and inundate farmland adjacent to the estuary with sea water. In comparison, the base case maximum April water level was 0.06 mAHD.

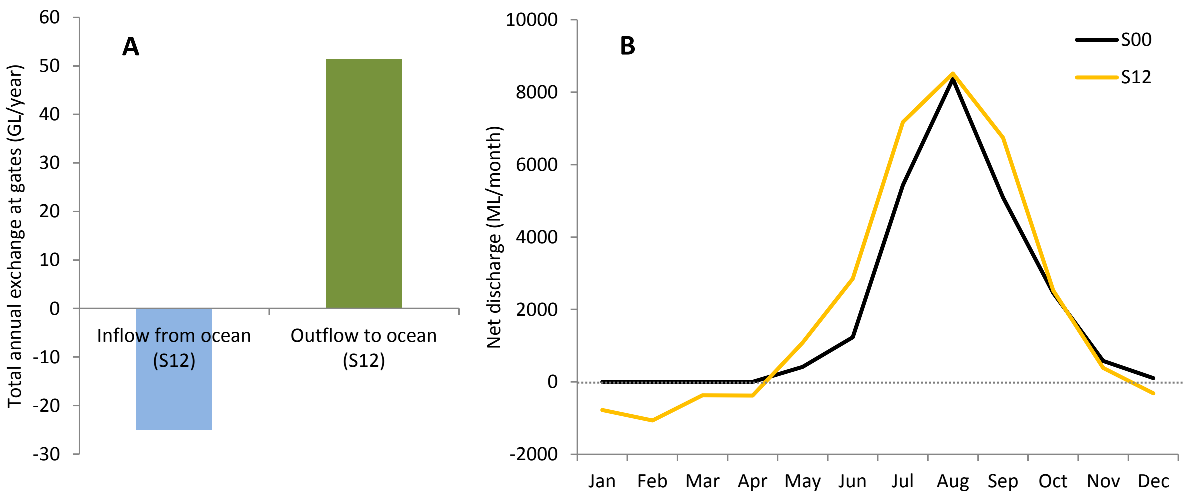


Figure 5-35: Total average volume of water exchanged between the ocean and Vasse Estuary in the absence of surge barriers (A) and average monthly net discharge (B). Negative discharge indicates inflow from the ocean

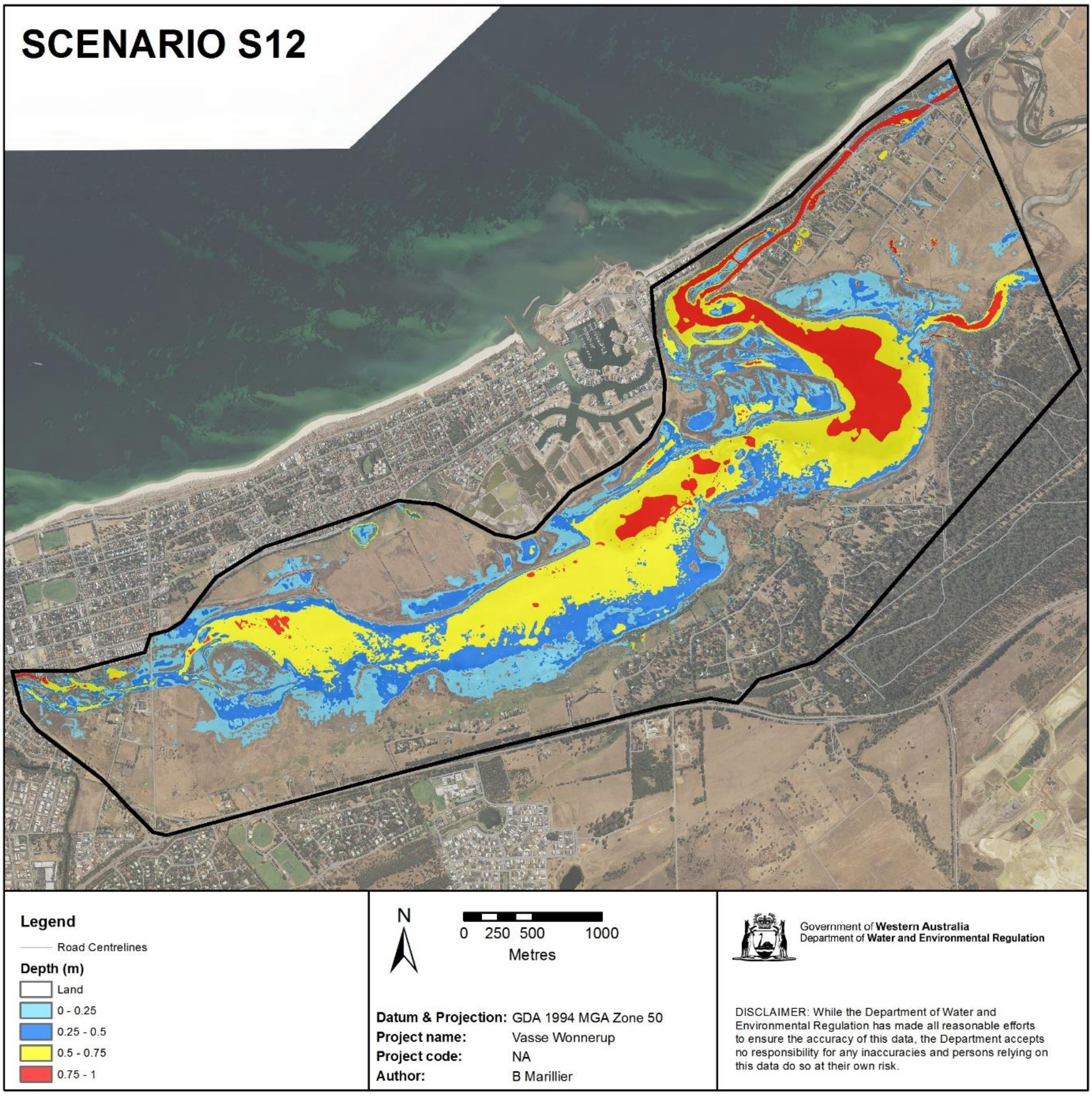


Figure 5-36: Estimated average maximum extent of seawater inundation in April with water level at 0.42 mAHD, surge barriers removed (S12)

6 Discussion and conclusions

6.1 Summary of results

Many scenarios were modelled to examine flood and long-term hydrological and water quality impacts. A selection of these are discussed here:

ID	Description
S00	Base case Vasse Diversion Drain offtake, one 900 mm culvert assumed three-quarters open
S03	Vasse Diversion Drain offtake of two 900 mm culverts
S04	Vasse Diversion Drain offtake of three 900 mm culverts
S04sb	Same as S04 with spillway at Vasse Diversion Drain offtake and Causeway Road bridge upgraded
S05	Vasse Diversion Drain fully connected to the Lower Vasse River
S14	No Butter Factory weir, partially fill Lower Vasse River, Vasse Diversion Drain offtake two 900 mm culverts
S07	Recycled water discharged to Lower Vasse River year-round
S10a	Two 900 mm culverts to direct flow from the Upper Sabina to the Lower Sabina River
S11	Upper Sabina fully connected to the Lower Sabina River
S12	Estuary surge barriers removed
S08	Vasse and Wonnerup surge barrier check boards raised to 0.6 mAHD

Table 6-1 summarises the modelling results for these scenarios, which are discussed below (sections 6.1.1 to 6.1.5). A similar table containing the results for all the scenarios is in Appendix M.

6.1.1 Reconnection scenarios (S03, S04, S04b, S05, S10a, S11)

Flood risk

- Complete reconnection of the Vasse Diversion Drain to the Lower Vasse River would result in severe flooding in Busselton, which would be unacceptable.
- Increasing the capacity of the Vasse Diversion offtake to the Lower Vasse River to two 900 mm culverts (S03) would be acceptable based on the current floodplain development strategy and building floor levels in the area. It is estimated that this would increase the 1% AEP design flood level upstream of Causeway Road by 6 cm.
- Increasing the capacity of the Vasse Diversion offtake to the Lower Vasse River to three 900 mm culverts (S04) would pose an unacceptable flood risk, with the current Causeway Road bridge. If the bridge were upgraded appropriately, then three 900 mm culverts would not pose a flood risk. (This assumes no reconnection at Sabina Diversion Drain.)
- Redirection structures at the Vasse Diversion Drain offtake to the Lower Vasse River consisting of more than the equivalent of three 900 mm culverts would pose an unacceptable flood risk, even with the Causeway Road bridge upgrade.

Table 6-1: Summary of modelling results

Legend

- Acceptable flood risk (blue)
- High risk for flood or increased nutrient pollution (orange)
- Potential benefit (green)
- Negligible change (yellow)

Scenario	Flood risk	Annual river loads (% increase)		% time medium silt is mobilised in the LVR	Water residence time (days) in the LVR		November nutrient concentration (% change)		
		N	P		JAN–MAR	AUG–SEP	TN	TP	Comments
LOWER VASSE RIVER SCENARIOS									
Base case				0.2	> 300	1			
2 x 900 mm culverts	(blue)	45	20	1.8	> 300	1	-6	-8	Nutrient load increase
3 x 900 mm culverts	(orange)	80	40	3.5	> 300	1	-8	-9	Flood risk; excessive nutrient load increase
3 x 900 mm + bridge upgrade	(blue)	80	40	3.5	> 300	1	-8	-9	Excessive nutrient load increase
FULL	(orange)	200	90	9	> 300	< 1	-8	-9	Flood risk; excessive nutrient load increase
2 x 900 mm + remove butter boards	(blue)	45	20	NA[2]	NA[2]	1	NA[2]	NA[2]	Nutrient load increase
Recycled WW to LVR	(blue)	8	8	0.2	13–14	1	3	-11	Reduces water residence time in LVR in summer
SABINA RIVER SCENARIOS									
2 x 900 mm culverts	(blue)	130	8	NA	NA	NA	0	0	Excessive nutrient load increase
FULL	(orange)	150	11	NA	NA	NA	0	0	Flood risk; excessive nutrient load increase
OTHER									
Check boards raised to 0.6 mAHD		NA	NA	NA	> 300	1	NA	NA	Being considered in Review Surge Barrier project
Removal of surge barriers	(orange)	NA	NA	NA	NA	NA	NA	NA	Unacceptable risk of flooding farmland with salt water; increases Busselton's flooding potential

FULL = full reconnection; NA = not applicable; LVR = Lower Vasse River; NA[2] = not applicable because LVR would dry out in summer

2 x 900 mm culverts re-grade LVR[1] – Note that sediment mobilised from the LVR will flow to the Vasse Estuary with potential adverse impact

- Full connection of the Upper Sabina River to the Lower Sabina River would pose an unacceptable flood risk. Flood levels would increase by 38 cm near dwellings located upstream of Tuart Drive and would likely affect several properties adjacent to the river. The flood peak in the main body of the Vasse Estuary and the Lower Vasse River would also increase.
- Adding up to two 900 mm culverts to the Sabina Diversion weir to divert more flow to the Lower Sabina River would not pose an unacceptable flood risk. With two culverts, water would spill from the Lower Sabina River to the surrounding area, but this was considered acceptable because buildings were not affected. A 4 cm increase in flood levels near residences located upstream of Tuart Drive would also result. The existing floodplain development strategy for the area would provide adequate protection from this increase in level. (This assumes no reconnection at the Vasse Diversion Drain.)
- Structures to divert water from the Upper Sabina River to the Lower Sabina River larger than the equivalent of two 900 mm culverts would pose an unacceptable flood risk.

Long-term hydrological and water quality impacts

The upper Vasse and Sabina catchments, whose flows are now mostly diverted to the ocean, would have provided very little flow to the estuary in their natural state. Catchment clearing, and subsequent agricultural and urban land uses, have not only increased flow volumes, but also greatly increased the nutrient concentrations in the flows. The extensive artificial drainage network efficiently conveys these large volumes of nutrient-rich water to the estuary. The estuary’s ecological condition has progressively worsened as its catchment has developed and nutrient inflows have increased. Increasing nutrient concentrations are still apparent in recent estuary data due to ongoing land use intensification (Kelsey pers. comm.).

The reconnection proposals would deliver increased nutrient loads to the estuary, and judging by the estuary’s historical response to such increased loads, further detrimental effects are likely. Even though water sensitive urban design (WSUD) is generally applied at a smaller scale than large-scale catchment management, some of the underlying principles can be used as a guide. The underlying tenet of WSUD is that water should be retained and treated at ‘source’ and not be conveyed in pipes to receiving waterbodies. Water that is retained in the environment, infiltrated or treated in purpose-built bio-retention structures or wetlands, can have nutrient concentrations reduced before reaching the receiving waterbody.

Reconnecting the upper and lower Sabina and Vasse rivers is being considered to improve water quality. The main poor-water-quality areas are the Lower Vasse River upstream of the Butter Factory weir and the Vasse Estuary in the exit channel upstream of the surge barriers, with the water quality being generally poor in spring, summer and autumn (i.e. November–April). During the summer of 2016–17, however, poor water quality was evident in the main body of the estuary. A succession of algal blooms prevailed from November onwards, with the algal species responding to the different conditions in the estuary.

Increasing flows through the Lower Vasse River and to the Vasse Estuary may provide a water quality benefit in the following ways:

- Dilution: lower-nutrient-content water flowing into the Lower Vasse River and estuary will dilute the nutrient-rich water in the river and estuary.

- Decreased water residence time: algal blooms are less likely to establish in flowing waters, and flow will carry (disperse) algae downstream. Decreasing the residence time of water in the Lower Vasse River and Vasse Estuary would help to prevent algal growth.
- Sediment mobilisation: algal growth is fuelled by nutrients in the water, as well as by nutrients released from sediments on the river and estuary beds. Increased flow may mobilise nutrient-rich sediments downstream of the Lower Vasse River and out of the Vasse Estuary.

Dilution

Poor water quality occurs in the Lower Vasse River and Vasse Estuary in the dry season from November to April, when there is little or no flow available in the Upper Sabina River and Vasse Diversion Drain for redirection (Figure 2-7). A simple nutrient balance model was used to estimate changes to nutrient concentrations (Section 5.4). Changes to November–April nutrient concentrations were small for all the reconnection scenarios modelled (Figure 5-27, Figure 5-28, Figure 5-32 and Figure 5-33). The expected average monthly TN and TP concentrations for the scenarios being discussed are shown in Figure 6-1.

The average monthly TN concentrations in the Lower Vasse River changed negligibly, and in the Lower Sabina rivers increased slightly, when more water was redirected into them from the upper catchments. The pattern was different for TP: concentrations were similar during dry months, but were reduced in June–December in the Lower Vasse River and May–October in the Lower Sabina River. The modelled reduction in TP concentration in the Lower Vasse River with the reconnection flows in October–December (when the weather is heating up and algal growth is starting) was 0.01–0.03 mg/L (reduction of 12–17%). This may be of benefit to the Lower Vasse River. The difference in average monthly TP concentration in October–December between the two and three 900 mm culvert reconnection scenarios (S03 and S04sb) was, at the most, 0.01 mg/L.

Residence time

Water residence time in the Lower Vasse River was estimated (Figure 5-22). None of the reconnection scenarios changed the residence time appreciably. The only scenario in which residence time changed was the addition of recycled water to the Lower Vasse River year-round.

Sediment mobilisation

For the base case, the bed shear stress required to mobilise medium silt occurs about 1% of the time in the Lower Vasse River. The bed shear stress required to mobilise fine, medium and coarse sand occurs less than 0.1% of the time. Most of the scenarios modelled had bed shear stress in the Lower Vasse River that was the same as the base case, except for the S04, S05 and S14 scenarios. The S04 scenario (three 900 mm culverts) could mobilise medium silt 4% of the time and fine sand 1% of the time. The S14 scenario re-engineered the Lower Vasse River to remove the pools, thus greatly increasing bed shear stress. (Scenario S05 – full reconnection – was not acceptable due to flood risk).

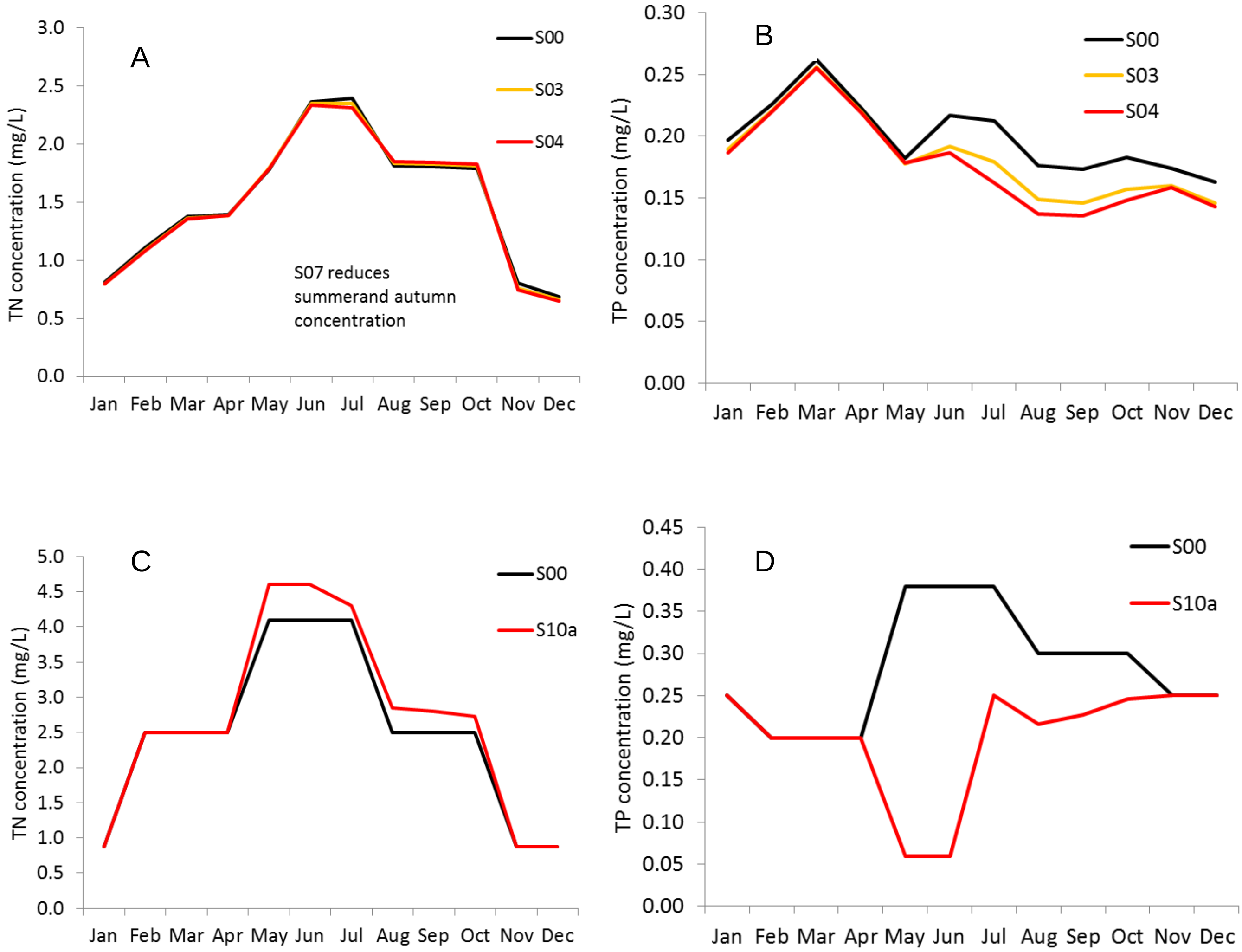


Figure 6-1 Average monthly TN and TP concentrations for the Lower Vasse River (A & B) and the Lower Sabina River (C & D)

However, sediment mobilised in the Lower Vasse River will flow to the estuary and be deposited there. This will worsen the estuary's water quality. Note that algal blooms in summer are fuelled by nutrient sediment release and nutrient cycling (growing and decaying algae).

In 2004, sediments were removed from the Vasse Estuary in the area upstream and downstream of the surge barrier (for about 30 m) before construction of the new barrier. A recent sediment survey (November 2016) revealed that the area upstream of the barrier contained about 300 m^3 of sediment at 50–60 cm depth, while the area downstream had little sediment. This highlights the tendency for particulate matter (whether from river inflows or dead algae) to become trapped in the estuary instead of flowing to Wonnerup Inlet. The increased flow volumes from different reconnection options are unlikely to increase flows at the surge barrier enough to 'push' accumulated sediments into Wonnerup Inlet.

Increased nutrient loads

Redirecting more flow into the estuary would result in a higher nutrient load to the estuary, which could be detrimental.

The reconnection scenarios that are acceptable in terms of flood risk[3] – two 900 mm culverts connecting the Upper Sabina River to the Lower Sabina River, and two or three 900 mm culverts connecting the Vasse Diversion Drain to the Lower Vasse River – have average annual flow increases to their downstream water body of about 25, 55 and 98%, nitrogen load increases of 34, 45 and 81% and phosphorus load increases of 5, 21 and 38% respectively. These increased flows and loads would be transported to the Lower Vasse River and Vasse Estuary during winter, so soluble nutrients in these flows would be likely to flow with the water to Wonnerup Inlet and the ocean. Particulate matter in the inflows may deposit in the Lower Vasse River and Vasse Estuary as the flows slow when they reach these waterbodies. Large amounts of deposition has been observed recently upstream of the Butter Factory weir and the Vasse surge barrier.

Although most of the nitrogen in the water that would be redirected into the estuary is in soluble form, more than half the phosphorus is in particulate form (Figure 6-2). In winter, this particulate phosphorus would readily deposit and thus increase the store of phosphorus in bed sediments available to fuel algal growth during spring, summer and autumn (November–April). This is of particular concern because phosphorus has been shown to be the limiting nutrient in the estuary in recent statistical analyses (da Silva, pers. comm.). Many algal species that grow in the estuary are nitrogen-fixers (can obtain nitrogen from the atmosphere) and phosphorus supply is crucial to them.

The re-connection scenarios of two and three 900 mm culverts connecting the Vasse Diversion Drain to the Lower Vasse River could increase the supply of particulate phosphorus to the estuary (via the Lower Vasse River) on an average annual basis by about 10 and 20% respectively. This represents large increases to phosphorus load to the estuary that could have a detrimental effect.

6.1.2 Partially fill Vasse River pools, remove the Butter Factory weir and reconstruct the river channel (S14)

This scenario was modelled with a reconnection structure of two 900 mm culverts at the Vasse Diversion Drain offtake. The Vasse River pools were filled so that an even grade resulted and the Butter Factory weir was removed. Even with the two-culvert diversion, the flooding risk was acceptable. Most of the nutrients in the increased inflows would flow to the estuary.

[3] Note: if reconnection were undertaken at both the Vasse Diversion Drain and the Sabina Diversion Drain, then the proposed culvert capacity would need to be smaller.

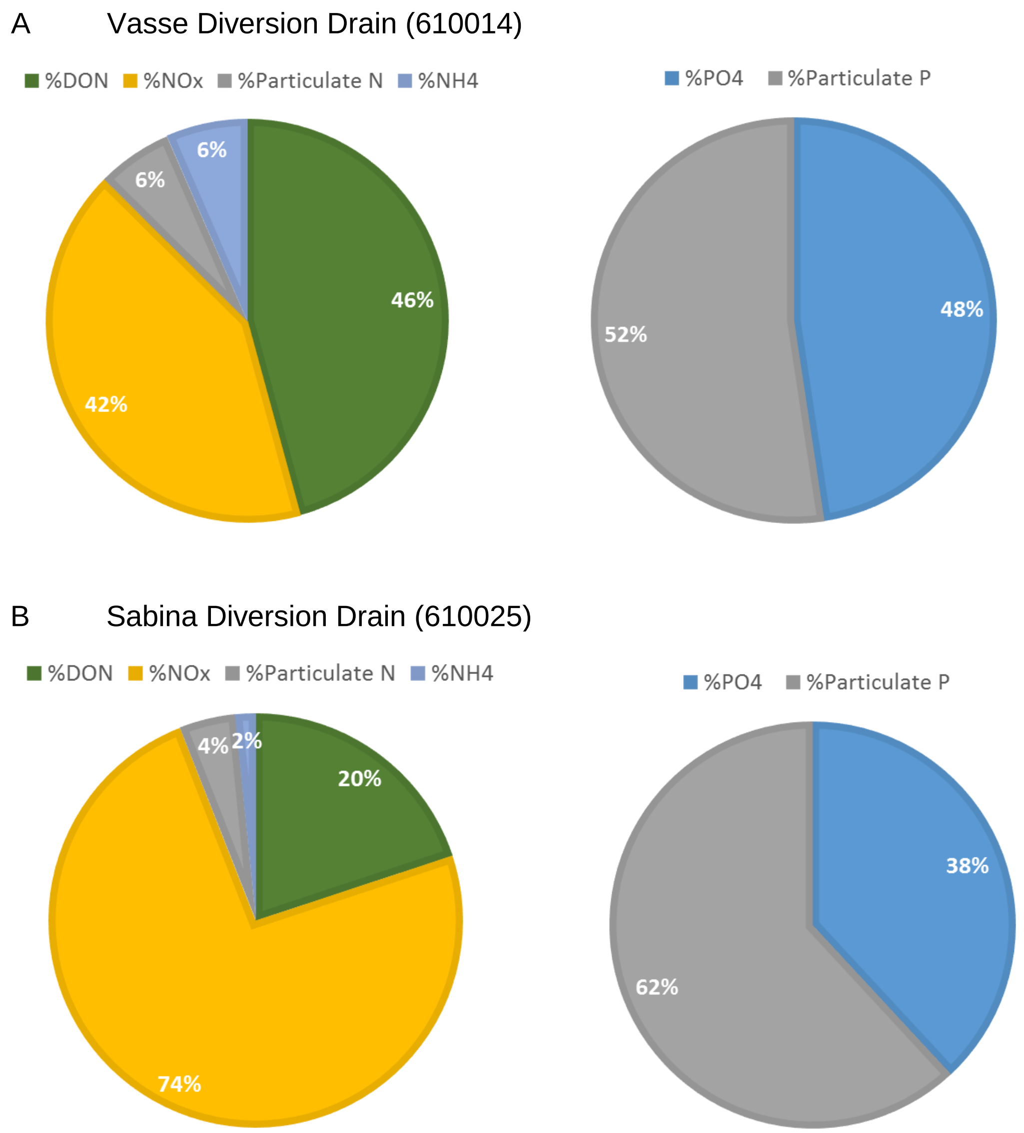


Figure 6-2 Average nitrogen and phosphorus fractions for the Vasse (A) and Sabina (B) diversion drains for 2011–16

The current weir pool in the Lower Vasse River in the centre of Busselton has algal blooms (which are potentially toxic) almost continuously during spring, summer and autumn, thus providing a seeding source for algae growth in the main estuary. The Lower Vasse River also traps and processes nutrients that would otherwise flow to the estuary. Although reconstructing the Lower Vasse River channel and removing the Butter Factory weir could be of large benefit to amenity in the centre of Busselton, the potential impact on the estuary is unclear. A comprehensive study to further assess flood risk, and ecological and social benefits would be required to support further consideration of this scenario. The study could also asses the effect of reducing flows from the Vasse Diversion Drain to the Lower Vasse River and estuary.

6.1.3 Recycled water discharged to Lower Vasse River year-round (S07)

This scenario had no impact on the river's flood regime, and was the only scenario able to increase flow during summer – reducing summer water residence times and reducing nutrient concentrations. Note that the nitrogen and phosphorus concentrations in the recycled water were assumed to be 1 mg/L and 0.1 mg/L respectively in the modelling.

If this scenario were to be pursued, a detailed investigation into the availability and cost of recycled water, and whether it was of suitable quality for discharge to the Lower Vasse River and estuary, would be required – taking into consideration potential human and ecological health effects.

6.1.4 Removal of the estuary surge barriers (S12)

Removing the surge barriers would result in flooding (from the ocean) during significant storm surges, and is associated with a 4 cm increase in the modelled flood level for the 1% AEP event. Seawater flooding would salinise low-lying land adjacent to the estuary. With sea-level rise of 0.17–0.38 m anticipated by 2050 (IPCC 2013), the surge barriers will become increasingly important for flood protection and should not be removed.

Aside from the significant flood risk associated with removal of the surge barriers, this scenario would completely alter the estuary's ecological character through the introduction of large volumes of sea water. This has implications for fringing vegetation, farmland and the ecological function of the estuary. It is highly likely that a large extent of the estuary would be inundated with saline to hyper-saline water during late summer and autumn, if no surge barriers were in place.

Further modelling of this scenario – using the estuary model being developed by DWER – should be undertaken to assess the potential extent of land salinisation and estuary salt concentrations.

6.1.5 Increase estuary check board height to 0.6 mAHD (S08)

Increasing the Vasse and Wonnerup estuary surge barrier check board heights to 0.6 mAHD (0.2 m higher than present) would increase the risk of spring flooding. The 1% AEP flood modelling assumes the water level in the estuary before the event is 0.6 mAHD. Even small rainfall events in September would result in slightly higher water levels than 0.6 mAHD. For example, if the estuary had a water level of 0.8 mAHD before a 1% AEP event, this would result in a peak flood level of 1.49 mAHD, compared with a peak flood level of 1.45 mAHD for the 0.6 mAHD starting level.

Retaining more fresh water in the Vasse Estuary may provide ecological benefits. Increasing the height of the check boards and the timing of their installation at the end of the flow season is being investigated in another project (Vasse Estuary surge barrier management).

6.2 Conclusions

The Water Corporation is planning to build a spillway from the Vasse Diversion Drain to the Lower Vasse River in the summer of 2018–19 to reduce the risk of levee failure. The modelling showed the proposed spillway was unlikely to influence peak flood levels in the Lower Vasse River or Vasse Estuary due to differences in time-to-peak on the drain compared with the estuary. This assumed the spillway would be designed with a peak capacity of 7 m^3/s during the critical six-hour duration 1% AEP event on the Vasse Diversion Drain, and would not flow in events more frequent than 5% AEP.

The flood modelling confirms that the major structures – Vasse Diversion Drain, Sabina Diversion Drain and associated compensation basins, as well as the surge barrier – are necessary to prevent flooding of low-lying areas in Busselton and adjacent to the Vasse Estuary.

If the surge barrier was removed, the peak flood level for the 1% AEP event would increase by about 4 cm under current sea-level conditions. The main role of the surge barrier is to prevent salinisation of low-lying land. However, the surge barrier will become increasingly important for flood prevention as the sea level rises (0.17–0.38 m anticipated by 2050).

To prevent flooding of Busselton, the Wonnerup Inlet sand bar must be kept open so floodwater can flow to the ocean. Ongoing management of the sand bar is required.

A large amount of additional water could be directed into the Lower Vasse River and Vasse Estuary without increasing the flood risk. Three 900 mm culverts at the Vasse Diversion Drain offtake to the Lower Vasse River and an upgrade to the Causeway Road bridge would allow flow in the Lower Vasse River to be almost doubled, from an average of 10 GL/year to 18 GL/year. The maximum reconnection configuration in the Sabina Diversion Drain that would not increase flood risk (two 900 mm culverts) would increase average annual flow by 44%, from 5.7 GL/year to 8.2 GL/year. If reconnection is proposed for both the Vasse and Sabina diversion drains, then the culvert configuration would be different. For example, two 900 mm culverts at the Vasse Diversion Drain offtake in combination with one 900 mm culvert at the Sabina Diversion Drain weir would have an acceptable flood risk.

This preliminary study found a reduction in TP concentration (9–19%) during October–December following reconnection, which may benefit the Lower Vasse River. The difference in TP concentration between the two scenarios considered (two and three 900 mm culverts) was very small, at the most 0.01 mg/L. The reconnection scenarios had a negligible effect on TN concentration in the Lower Vasse River and caused an increase in TN concentration in the Lower Sabina River.

The reconnection scenarios showed no decrease in spring, summer and autumn water residence times. The three-culvert connection scenario showed an increase in sediment mobilisation in the Lower Vasse River, however the sediment would flow to the Vasse Estuary. None of the reconnection scenarios are likely to 'push' sediment from the Vasse Estuary into the Wonnerup Inlet.

The potential increased nutrient loads associated with increased flows following reconnection are large, and are likely to further damage the ecological health of the Lower Vasse River and estuary. As more than half of the inflowing phosphorus is in particulate form, the increased deposition of phosphorus in the Lower Vasse River upstream of the Butter Factory weir and in the Vasse Estuary is potentially large: approximately 10% for the two 900 mm culvert and 20% for the three 900 mm culvert scenarios respectively.

6.3 Recommendations

Culvert design and management

The Water Corporation's proposed installation of a concrete spillway from the Vasse Diversion Drain would allow for an upgrade of the offtake structure from the drain to the Lower Vasse River. As further investigations may reveal some benefits to having more water in the estuary, it is recommended that the offtake structure be upgraded to have flow capacity equivalent to two 900 mm culverts. This would enable the status quo to be maintained and the winter inflow to be increased by 50%, if desired in the future.

The offtake structure should have a design that enables it to be closed, by varying amounts, to control the flow volume to the Lower Vasse River. This is important both for flood control and if redirection of water from the Vasse Diversion Drain to the Lower Vasse River is determined to be having a detrimental effect on the Lower Vasse River and Vasse Estuary. If the proposed structure has only 'fully-open' or 'fully closed' operational modes, then two structures (at least) will be required to give flexibility to the water volume that can be re-directed.

Three 900 mm culverts are not recommended because of the large risk they would pose to the health of the Lower Vasse River and Vasse Estuary ecosystems due to the large increases in average annual nitrogen (~80%) and phosphorus (~40%) load that would result. As more than half the phosphorus in these inflows would be in particulate form, a large proportion would be deposited in the Lower Vasse River and Vasse Estuary and be available to fuel algal growth during spring, summer and autumn (November–April).

If reconnection culverts are constructed, an operational strategy should be developed with clearly defined roles and responsibilities. First-flush flows, which generally have high nutrient concentrations, should not be directed into the Lower Vasse River. The culverts should be closed if harmful flooding is likely to occur.

To improve the condition of the Lower Vasse River and Vasse Estuary, nutrient concentrations in inflows must decrease. The catchment management initiatives being undertaken at present should be strongly supported, including those concerning fertiliser management, dairy management, WSUDs and infill sewerage programs.

As the upgrade of the Causeway Road bridge by Main Roads WA would have a regional benefit in terms of flood risk, it is recommended that this project goes ahead.

Future studies

There is little information available on the characteristics and functioning of sediment in the beds of the Lower Vasse River and estuaries. Further research in this area is needed. In particular, more understanding of the contributions to water column nutrients from sediment nutrient release and groundwater is needed. This would help with determination of the relative impact of inflows from the Vasse Diversion Drain.

Ongoing monitoring of water quality in the main rivers, Lower Vasse River and estuaries is needed, along with an understanding of sediment characteristics in the inflows.

It is recommended that some of the scenarios that investigated long-term hydrology and water quality are revisited once the estuary model being developed by DWER is complete, and more information about and knowledge of the Vasse Estuary is available. The estuary model should be used to:

- investigate the impact of different inflow volumes, which will increase flow velocities (and bed shear stress) and may mobilise sediments
- assess the management of the Vasse Estuary surge barrier, including check board height
- model surge barrier removal.

If other options besides the upgrade of the Vasse Diversion Drain offtake are pursued, such as removing the Butter Factory weir and reconfiguring the Lower Vasse River or addition of recycled water to the estuary, comprehensive studies to assess possible impacts should be undertaken.

Appendices

Appendix A The 1990 guidelines for operating the floodgates and managing the sand bar (Lane et al. 1997)

APPENDIX 2. The 1990 guidelines for operating the floodgates and managing the sand bar.

The Water Authority's "Update to Hand Book of Basic Data" (August 1990) reads as follows with respect to operation of the floodgates and management of the sand bar at the mouth of Wonnerup Inlet.

2.9 Vasse and Wonnerup Floodgates

2.9.1 General

"The Vasse and Wonnerup floodgates protect the low lying agricultural land surrounding the Vasse and Wonnerup Estuaries from flooding with sea water".

"They also have a check board facility on each flood-gate to allow fresh water to be retained at the end of winter to control the drop in water table on these flats. This is done to maintain water in the estuary system for as long as possible and to hold back any summer run-off".

"Due to high temperatures and low levels in the estuaries, there is a strong possibility that fish fatalities will occur in the Vasse estuary and between the floodgates if the bar is closed, with resultant criticism of the Authority".

"The Authority's major obligation is the interest of the drainage ratepayers and this will be the overriding consideration. It will however, be necessary to take action to facilitate better environmental management where the interest of the ratepayers can be protected".

2.9.2 Maintenance

"The gates must be lifted each year and scraped clear of marine growth and any corrosion on steel work protected. The structures should be annually sprayed for protection against white ants and fire".

2.9.3 Operation

2.9.3.1 WINTER

"Immediately after the first rains produce run-off, the boards can be removed. To prevent vandalism, these boards should be stored in the Depot."

"Due to the fact that the ocean outlet for these two structures will block easily, it may be necessary to open this bar by mechanical means on several occasions throughout the winter. Experience has shown that to attempt to open the bar without sufficient head is a waste of time, and the gauge board at the Vasse Floodgate should attain a reading of at least 0.7m AHD, or the attempt will probably fail (unless the sea is extremely quiet with low tides. This is unlikely at times when the bar is blocked and the Estuaries are between 0.4m and 0.7m AHD in height)".

"Before the run-off has finished for the season, it is necessary to fix the stopboards to a height of 0.40m AHD so that the fresh water is retained, to facilitate the breeding of waterfowl. (It is desirable - but difficult - to keep the water at 0.40m AHD)".

2.9.3.2 SUMMER

"The water levels should be monitored at the Vasse Floodgates on a minimum monthly basis until the level reaches 0.1m AHD and then on a minimum weekly basis. If three consecutive days of temperatures in excess of 30 degrees occur, preparation should be made to allow fish to pass through the gates if they show any signs of stress (swimming on surface)".

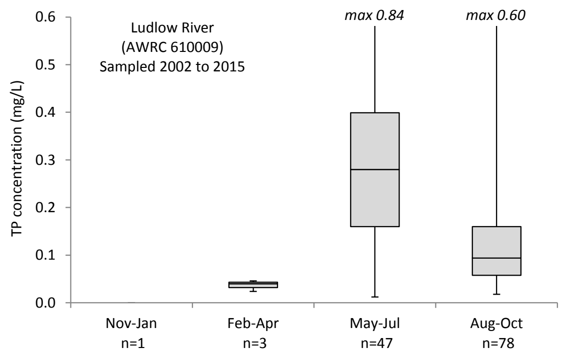
"When the level reaches -0.1m AHD, farmers on the Vasse estuary should be notified and the gates opened to maintain the level at -0.1m AHD".

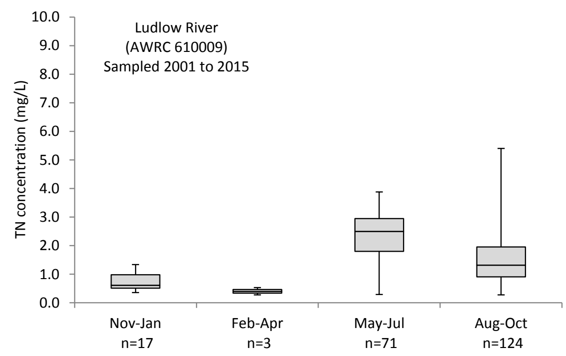
"Under no circumstances should salt water be allowed to come back behind the gates to allow the levels to become higher than -0.1m AHD"

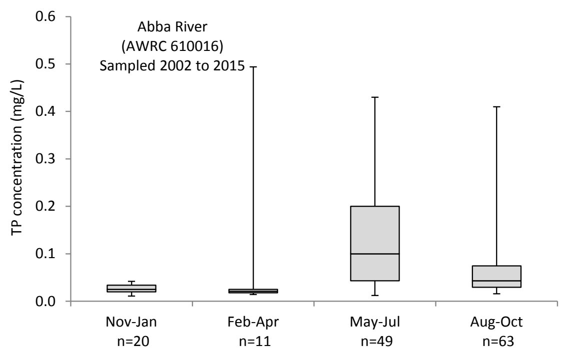
"The level of -0.1m AHD has been found to be acceptable by farmers in the area and appears to be satisfactory to relieve stress on the fish. It should be reviewed periodically with interested parties. Tests have also shown that at this level the salt is diluted to acceptable levels when the Vasse estuary fills with run-off water so that no damage is done to surrounding pastures"

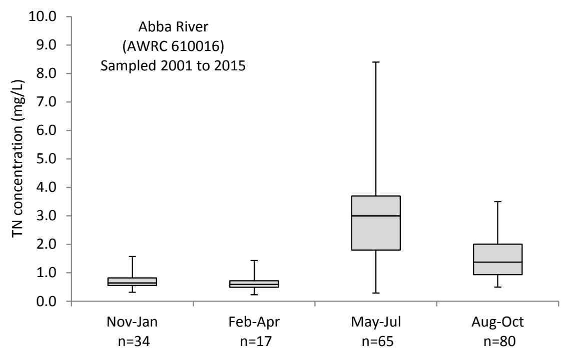
"In the event of the sand bar being closed and no water available to come back, a decision to open the sand bar must be made in conjunction with the Regional Operations Engineer as a matter of urgency".

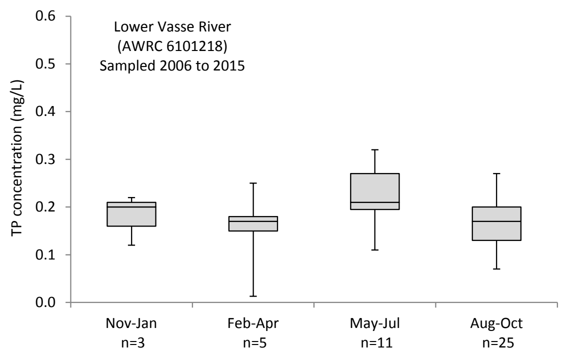
Appendix B Total nitrogen and phosphorus concentrations in waterways

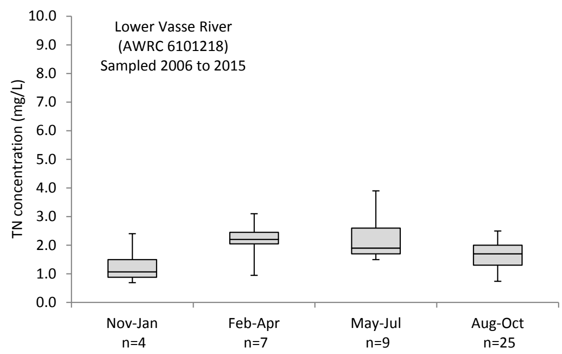


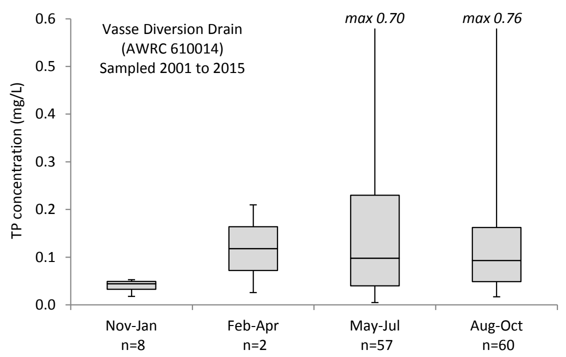


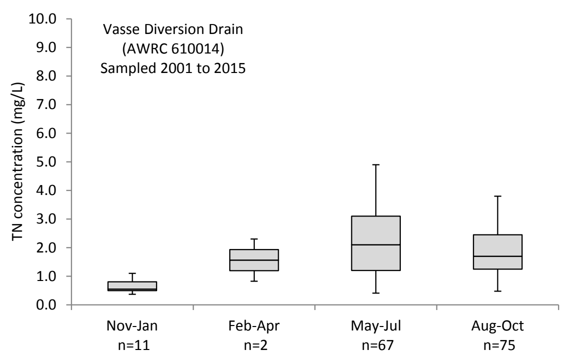


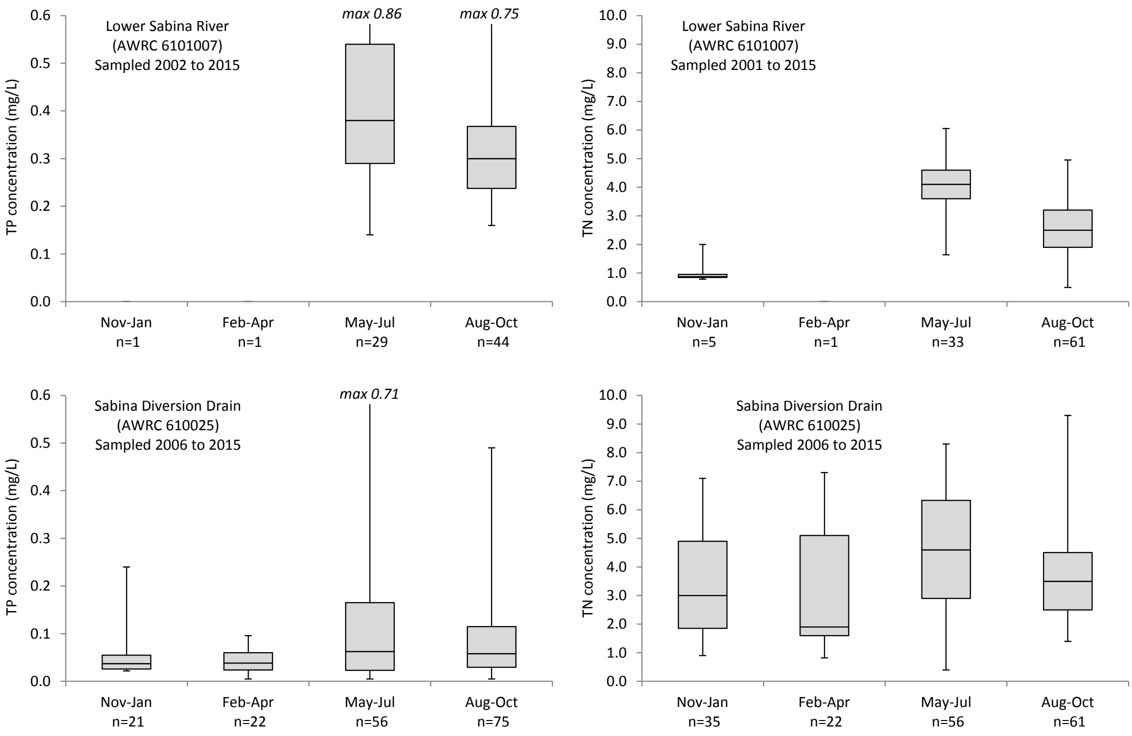











Lower Sabina River
(AWRC 6101007)
Sampled 2002 to 2015
max 0.86
max 0.75
TP concentration (mg/L)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Nov-Jan
n=1
Feb-Apr
n=1
May-Jul
n=29
Aug-Oct
n=44
Lower Sabina River
(AWRC 6101007)
Sampled 2001 to 2015
TN concentration (mg/L)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Nov-Jan
n=5
Feb-Apr
n=1
May-Jul
n=33
Aug-Oct
n=61
Sabina Diversion Drain
(AWRC 610025)
Sampled 2006 to 2015
max 0.71
TP concentration (mg/L)
Nov-Jan
n=21
Feb-Apr
n=22
May-Jul
n=56
Aug-Oct
n=75
Sabina Diversion Drain
(AWRC 610025)
Sampled 2006 to 2015
TN concentration (mg/L)
Nov-Jan
n=35
Feb-Apr
n=22
May-Jul
n=56
Aug-Oct
n=61

Appendix C Literature review

This section summarises the findings of some previous hydrological, estuarine, flood and drainage studies for the Vasse-Geographe catchment. The listing is in chronological order.

1978 Bunbury Engineering District: effects of storm of April 4, 1978
Public Works Department (1978)

This report describes the impact of the degenerating ex-tropical Cyclone Alby which passed through the Bunbury and Busselton area on the evening of Tuesday, 4 April 1978.

During the storm, barometric pressure dropped to 994 millibars, with strong north-north-east winds reaching a peak of 130 km/h, coincident with the day's normal high tide.

Storm surge and the lunar tide combined to create a record high water level, which caused flooding in Bunbury and Busselton and erosion of coastal beaches. Analysis of monthly high tides based on 47 years of data indicated there was a 95% probability that tides would not reach the levels of 4 April in an 800-year return period.

Significant rain was not present with the event, and there was no flooding within the Vasse Estuary because of the presence of the surge barriers.

1984 Busselton regional flood study: hydrological Investigations
Public Works Department (1984)

This report gives estimates of design flows for six rivers in the Busselton drainage district. The ARIs considered are 25, 50 and 100 years (equivalent to 4%, 2% and 1% AEP) for the Buayanyup, Vasse, Sabina, Abba, Ludlow and Capel rivers. A runoff-routing model, RORB, was calibrated using gauged data and local knowledge in three catchments, with extrapolation to the ungauged catchments. Flood observations from local landholders were used to characterise flooding on the coastal plain for the 1964 and 1965 flood events. It was noted that data were sparse and of poor quality and attempts to use a regional runoff relationship using catchment characteristics were unsuccessful.

The report includes calibrated RORB parameters, design rainfall estimates and design flood estimates.

The peak flood levels estimated in the Vasse and Wonnerup estuaries was 1.25 mAHD for the 4% AEP event, and 1.35 mAHD for the 1% AEP event. These were calculated with a hydraulic model, using the Cyclone Alby recorded sea levels and the 1% AEP design flows for the catchment. It is noted that even though Cyclone Alby produced the highest recorded tide level in Geographe Bay, the duration of the event was not sufficient to significantly restrict outflow from the surge barriers.

1987 Busselton regional flood study
Water Authority of Western Australia (1987)

This study was carried out to assess flood impacts, provide technical information, and support development of management strategies for protection of existing and future developments in Busselton. It builds on the hydrological investigations completed earlier (PWD 1984).

Key recommendations in the report were:

- Establishment of a floodway through the lower reaches of the Vasse River.
- Complete containment of 1% AEP floods within the rivers, which may be achieved by raising the levees along the Buayanyup Drain, the Vasse Diversion Drain, the Ludlow River and the Capel River.
- Roads and bridges below the 1% AEP flood line should be raised so that bridge decks are 600 mm above flood level.
- Given the issues associated with stability and overtopping of river levees, all future developments should leave a 50 m buffer around the levee or river reserve boundary to ensure adequate flood protection in the event of levee failure.
- A 0.5 m clearance above natural ground level for developments.

The report includes a description of flood behaviour in the catchment, and lists peak flows for the 1% AEP event for the different rivers. It also includes 1% AEP floodplain mapping. For the rivers that discharge to the Vasse Estuary, the 1% AEP design flows were estimated as follows:

- Lower Vasse River: 15 m^3/s assuming no spilling from the Vasse Diversion Drain, and 42 m^3/s with spilling
- Lower Sabina River: 34 m^3/s
- Abba River: 87 m^3/s

The report notes that the Butter Factory checkboards maintain water levels in the Lower Vasse River at 0.45 mAHD during summer, but that water levels are not allowed above 0.7 mAHD due to the risk of interaction with septic systems.

1994 Busselton Drainage District

Water Authority of Western Australia (1994)

This report outlines the state of drainage infrastructure in 1994 and gives a history of drainage in the region.

The Busselton Drainage District was proclaimed under the Land Drainage Act of 1925. As at 1993, 530 km of drains and watercourses were maintained in the district to allow settlement and agricultural development.

Before the drainage works, the Buayanyup, Vasse, Abba, Ludlow and Capel rivers all drained into the Vasse and Wonnerup estuaries, and eventually to Geographe Bay through the Wonnerup Inlet (when the sand bar is open).

From 1840–1900 demand rose for drainage works. Large areas of the coastal plain were regularly inundated by up to 30 cm of water for several months. In 1900 the first Land Drainage Act was enacted by Parliament. It allowed for funding to be directed to farmers to carry out their own drainage work, with supervision by the Public Works Department.

The first work began in 1904 on the Stirling Estate west of Capel near the Capel River. In the following years the south drain was extended to discharge into the Wonnerup Estuary.

In 1907 a scheme began to alleviate flooding in Busselton and Wonnerup that included construction of surge barriers at the mouths of the Vasse and Wonnerup rivers to prevent salt water ingress. The work was completed 1908 but more work was needed.

In 1925 the Land Drainage Act was passed, giving more control to government to undertake drainage works. In the 1920s improvements to the drainage systems were substantial. New surge barriers were constructed at the mouth of the Vasse and Wonnerup estuaries during 1928–29.

Between 1954 and 1986 capital works included enlargement of the main drains.

1997 Vasse River Diversion Drain: flood hydrology
Water Authority of Western Australia (1997)

This unpublished report was completed in response to the August 1997 flood event, which resulted in overtopping of the Vasse Diversion Drain. The report reviews the 1% AEP event for the drain. Peak flow on the drain was recorded as 128 m^3/s for the 1997 event. Using flood-frequency analysis, it was determined that the 1997 event was approximately a 6% AEP event, and the 1% AEP design flow was between 160 and 175 m^3/s. RORB modelling was also done as part of this study, and the 1% AEP design flow was estimated at between 170 and 250 m^3/s. The report recommended an interim 1% AEP design flow of 190 m^3/s.

1997 Management of the Vasse-Wonnerup wetland system in relation to sudden mass fish deaths
Lane (1997)

This report was completed on behalf of the Vasse Estuary Technical Working Group. It describes the features of the Vasse-Wonnerup wetland system, summarises historical water level and water quality data, discusses in detail the influence of the surge barriers and sandbar on the system, and describes fish kills and management options.

The function of the sand bar is of particular interest for the current modelling study, as it has the potential to influence water levels within the estuary and river system. The report notes that the opening and closing of the bar may occur as a result of ocean conditions and discharge from the estuary. The bar is artificially opened periodically one or more times a year, with the earliest occasion recorded in 1905. The report highlights occasions when closure of the bar has resulted in very high water levels in the estuary.

The report discusses the impact of the surge barriers on the estuary, and notes three major effects. Firstly, the flap gates prevent water entering the estuary from the ocean at any time of year, lowering salinity. Secondly, water levels in the estuary became generally lower due to the reduced tidal influence. Thirdly, the estuaries are now able to dry completely during summer. From a flooding perspective, the gates were considered a success, as they reduced the influence of storm surge, reduced waterlogging of farmland, and reduced seawater intrusion into farmland. However, the ecological function of the system was substantially altered as a result of these changes to the flow regime.

Seasonal installation of stop-boards in the Vasse Estuary is described, as is the opening of the estuary surge barriers in summer or autumn. The report also provides a detailed history of water levels and water quality in the estuary from settlement to 1997.

1998 Busselton regional flood study review and appendices

JDA (1998)

This report reviewed and revised the Busselton flood study completed in 1984. It involved analysis of catchment hydrology and flooding of Busselton under several scenarios.

Flood estimation used flood-frequency analysis and a rainfall-based method in combination with RORB. The report lists calibrated parameters for the RORB model. Flood-frequency analysis and the results of RORB modelling were combined to generate a flood-frequency curve. Peak flows for the 1% AEP events in the main rivers were as follows:

- Vasse Diversion Drain: 188 m^3/s
- Abba River: 86 m^3/s (JDA 1998)
- Lower Vasse River: 16 m^3/s
- Lower Sabina River: 35 m^3/s (JDA 1998)

The study also used the numerical model HEC RAS to assess the hydraulic capacity of the Vasse Diversion Drain and flooding characteristics of the Lower Sabina River. A reservoir-routing technique was used to determine the extent of flooding in the Vasse and Wonnerup estuaries. The peak water level for the 1% AEP event in the Vasse Estuary was 1.50 mAHD assuming some overbank spilling from the Vasse Diversion Drain, and 1.46 mAHD with no spilling. These scenarios assumed a starting water level of 0.8 mAHD.

One of the review’s key findings was that the capacity of the Vasse Diversion Drain was insufficient to convey a 1% AEP flood event. JDA completed a cost-benefit analysis of several options for reducing peak discharge in the drain and lowering the level of flood risk for Busselton. The options included upgrading of the Vasse Diversion Drain to meet the peak flow requirement of 188 m^3/s, construction of compensation basins (this option was ultimately adopted by the Water Corporation), reconnection of the Upper Sabina to the Lower Sabina River, partial upgrade of the Vasse Diversion Drain with some compensation basins, and a combination of upgrade, detention basins, and diversion to the Sabina.

The report includes useful calibration parameters for RORB, and Manning’s roughness coefficients for the main rivers. Design hydrographs are tabulated for the major rivers.

1999 Water and Rivers Commission letter from Rick Bretnall to resident on Bunyip Road near the Lower Sabina

Water and Rivers Commission (1999)

A resident contacted Rick Bretnall to highlight flooding issues in 1997, 1998 and 1999. Flood levels reached building floors on Bunyip Road with no precedent from the previous 28 years.

Rick advised that the Busselton Flood Management Steering Committee:

> *‘agreed that the diversion of more floodwaters into the Lower Sabina River should not be further pursued due to technical, environmental and social factors’*
>
> *‘the flooding regime of the Lower Sabina River area has changed over time and appears to be mainly due to the construction of roads and a railway line in the area’*

Flooding was attributed to concentration of flows under the new Bussell Highway, directing more water down the Sabina River, whereas previously floodwater was directed as sheet flow northwards towards the estuary.

2002 Rural Drainage Services customer information brochure
Water Corporation (2002)

This brochure lists general information for customers in the south-west. Flood mitigation service standards are listed as follows:

- Vasse River Diversion Drain: 5% AEP
- Buayanyup Drain: 1% AEP
- Vasse and Wonnerup floodgates (surge barriers): 1% AEP
- Capel River levees: 1% AEP

These are the maximum design capacities of the drains for conveyance of flood flows at the time of publication.

2003 Engineering design report: Vasse and Wonnerup estuaries: surge barrier replacement
GHD (2003)

This report outlines the design of the replacement surge barriers installed during 2004 on the Vasse and Wonnerup estuaries. The previous surge barriers were 70 years old, and had deteriorated to a point that necessitated replacement. The report includes schematics of the gates, survey information and descriptions of gate operation.

The Department of Water (now DWER) requested that GHD's surge barrier design show no increase in peak estuary water level for the 1% AEP event. The previous headwater level defined by JDA (1998) was 1.46 mAHD; GHD completed a steady-state analysis which estimated the headwater level would be 1.29 mAHD with a combined flow rate for both estuaries of 155 m^3/s and tide level of 1.02 mAHD. It is worth noting that this method was not consistent with either JDA (1998) or WAWA (1987), as both of these studies used a storage routing method in combination with time-varying water level and inflow boundaries. The previous studies also used catchment inflows that were substantially higher, so it is possible that GHD underestimated the peak water level.

2005 Ernest Hodgkin's Swanland: Estuaries and coastal lagoons of south-western Australia
Brearley (2005)

Swanland provides a literature review of publications related to the Vasse and Wonnerup estuaries, including descriptions of drainage and land development throughout the catchment from European settlement onwards. Water quality and ecological deterioration is described for the Vasse-Wonnerup system, highlighting the issues of nutrient enrichment in the estuaries and waterways. The Lower Vasse River and the Vasse Estuary both have high to very high concentrations of TN and TP. The availability of nutrients in combination with suitable environmental conditions has led to toxic and non-toxic algal blooms, de-oxygenation events and fish kills in the system.

A summary of major fish-kill events in the system includes events from as early as 1905. The events generally occur in summer and can be in all parts of the system (Vasse and Wonnerup estuaries, the Deadwater, Wonnerup Inlet and the Vasse River).

Swanland describes the many strategies which have been employed over the years to provide habitat, reduce algal problems and prevent fish kills, which at the time of publication were:

- opening of the sandbar between January and February to improve water quality in the Wonnerup Inlet
- opening of the surge barrier fish gates to allow fish to escape unfavourable conditions
- maintaining summer water levels at no less than -0.1 mAHD.

The operational regime has had mixed success: managing to prevent fish kills at some times and failing at others.

2007 Ecological character description Vasse-Wonnerup wetlands Ramsar site in south-west Australia

Wetland Research and Management (2007)

This report provides a detailed description of the Vasse-Wonnerup wetlands in the context of their Ramsar listing. The wetlands and their catchment have a long history of modification and intervention, and a thorough literature review and conceptualisation describes the change in the river geomorphology, hydrology and ecology from before European settlement to the present. A chapter on wetland processes describes the interactions between physical and biological processes, and their implications for the long-term health of the system.

The report highlights several detrimental changes to the system since its Ramsar listing in 2000, including increased frequency of severe phytoplankton blooms, and no decline in nutrient concentrations in tributary rivers. Several management actions are suggested which include a combination of direct intervention (such as dredging of target areas and foreshore management) and ongoing research and monitoring.

The complexity of the wetland processes and interactions is highlighted by the report. The use of Bayesian Belief Networks is suggested as a potential decision-support tool to prioritise management measures based on the chance of success for a targeted process or outcome (i.e. prevention of algal blooms).

2010 Vasse Wonnerup Wetlands and Geographe Bay: water quality improvement plan

Department of Water (2010)

This study outlines the current water quality status throughout the Vasse-Geographe catchment and identifies sources of nutrient pollution on a subcatchment basis. The plan recommends catchment interventions to reduce nutrient loading to the estuary and Geographe Bay.

A process-based conceptual model SQUARE (Stream Quality Affecting Rivers and Estuaries) was calibrated to measured flows and nutrient concentrations to quantify nutrient sources and problem areas within the catchment. The Abba, Ludlow, Lower Vasse and Lower Sabina rivers were all found to have nutrient concentrations above recommended concentrations for Swan Coastal Plain catchments, and the Vasse and Sabina rivers delivered several times the 'acceptable' nitrogen and phosphorus load to the estuary.

The sources that contribute the most to nutrient loads are diffuse sources of beef and dairy cattle grazing, and point sources including dairy sheds and feedlots. Nutrient loads from urban areas are relatively less because of the smaller urban area, but are expected to increase with planned land development.

2011 Depth, salinity and temperature profiling of Vasse-Wonnerup wetlands in 1998–2000
Department of Environment and Conservation (2011)

This report describes the collection of physical data from the Vasse and Wonnerup estuaries from 1998 to 2000. The focus is on the presentation and description of the data. The report provides a useful description of seasonal changes in salinity, temperature and water levels in the Vasse Estuary, with winter generally having higher water levels, cooler temperatures and fresh water; and summer having hyper-saline conditions, very low water levels and high temperatures.

2013 Hydrologic review of Busselton Flood Protection – Vasse Diversion Drain catchment area
GHD for Water Corporation (2013)

This report is the most recent and comprehensive flood study of the Vasse Diversion Drain, and builds on the work undertaken since the earlier *Busselton regional flood study* (WAWA 1987) and flood study review (JDA 1998). GHD completed the work on behalf of the Water Corporation, with the aim of assessing drainage capacity for the Vasse Diversion Drain and its tributaries. The Water Corporation constructed three large compensation basins on the Upper Sabina River and Vasse Diversion Drain from 2001 to 2009, and this study assessed their efficacy in reducing peak flows for flood events.

This study used a combination of RORB and hydraulic modelling to identify the capacity of the drainage network.

Some key findings which are relevant to modelling the Vasse Estuary are:

- In the Vasse Diversion Drain 1% AEP peak flows before and after compensation basin installation were 183 m^3/s and 144 m^3/s respectively.
- Any flows above 144 m^3/s would overtop the drain into the Lower Vasse River catchment.
- When flows reach 137 m^3/s in the Vasse Diversion Drain, the water levels are close to bank level.
- The weir installed at the junction of the Upper and Lower Sabina River is not likely to overtop in a 1% AEP flow. However, some bypass flow may occur from the overtopping of subdrains higher in the Sabina River catchment.

The area of interest for this study does not extend to the catchments of the Lower Vasse River, Lower Sabina River or Vasse Estuary. However, the design rainfall, flows and RORB parameters used in this study are directly applicable to the current modelling work.

2014 Current and future climate inundation modelling for Busselton, Western Australia
Martin et al. (2014)

Geoscience Australia completed storm-surge modelling using Global Environmental Modelling System's (GEMS) 2D Coastal Ocean Model (COM2D) coupled with a riverine flood model developed with the Geoscience Australia and Australian National University inundation model (ANUGA).

The study focused on the modelling of Cyclone Alby, sea-level rise, and coincident riverine flooding for a 4% and 1% AEP event.

As the storm surge associated with Cyclone Alby was included for each scenario, it is difficult to determine the change in inundation extent resulting from sea-level rise or the 1% AEP event alone. With 0.9m sea-level rise and a worst-case track version of Cyclone Alby, all of Busselton and most of Dunsborough would be inundated. It is also worth noting that the surge barriers were 'assumed open' which would result in an overestimation of inundation within the estuary compared with the more likely closure of the flap-gates during a storm surge event.

Estimates of coastal recession were included for time horizons of 2030, 2070 and 2100 and these were assigned a likelihood for a range of impact magnitudes. Coastal recession scenarios were not coupled to the ANUGA modelling due to issues with DEM resolution.

The Vasse Diversion Drain, Sabina River and Abba River flood hydrographs for the 4% and 1% AEP events were sourced from previous studies (Water and Rivers Commission 1997; JDA 1998).

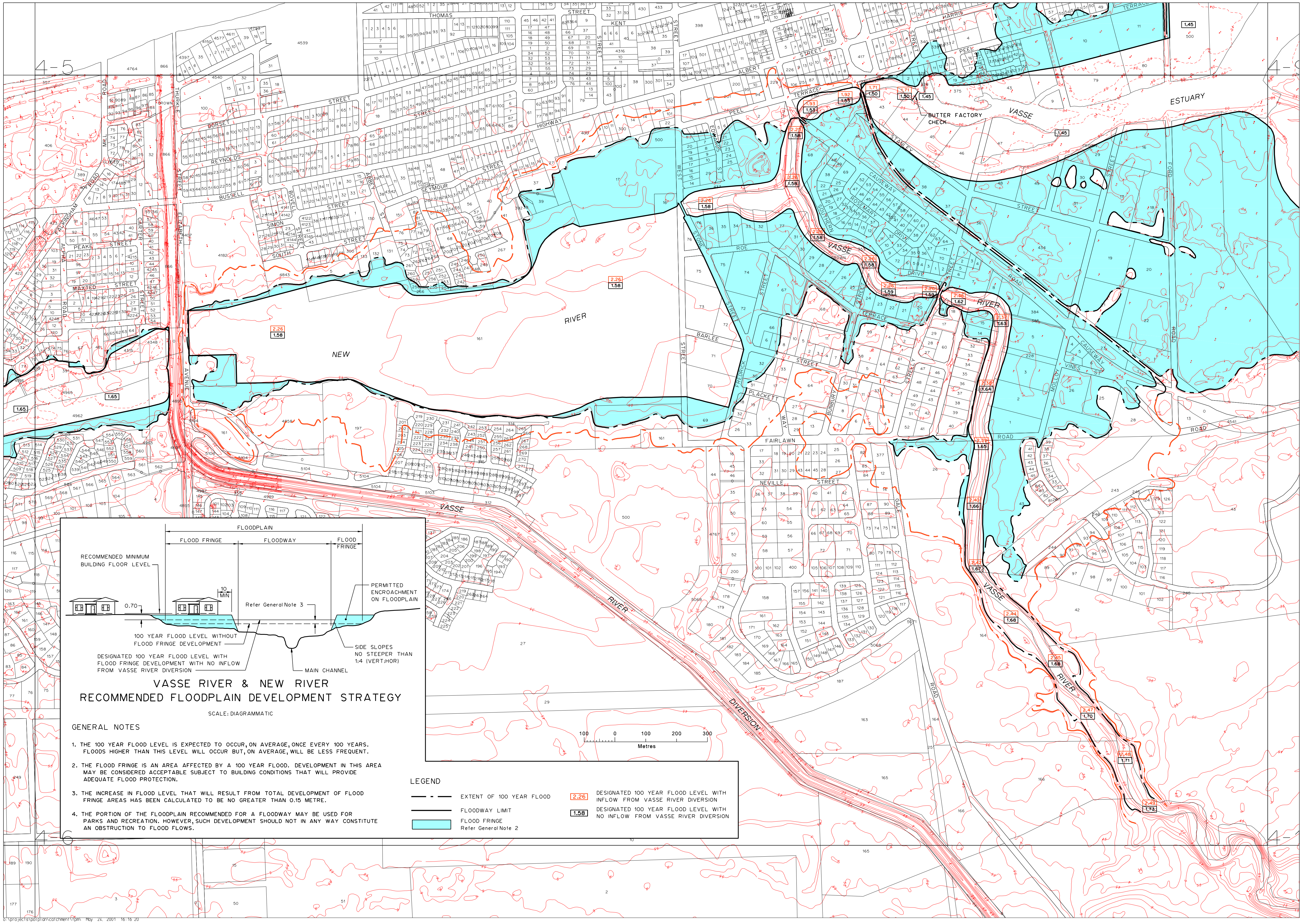
2015 Busselton storm surge response plan
Shore Coastal (2015)

This study used the results from storm-surge and flood modelling in Busselton completed by Martin et al. (2014). Peak flood levels were assessed in GIS for flood impacts on infrastructure. The four scenarios considered are listed below by increasing flood magnitude.

- Tropical Cyclone Alby: minor coastal flooding with sea levels of 1.8 mAHD.
- Mid-level scenario: direct hit of Cyclone Alby less 0.8 m, so an assumed water level of 2.6 mAHD. This resulted in flooding of around 1000 buildings.
- Direct hit of Alby: ocean water level of 3.4 mAHD. Water depths of up to 1.5 m in the town with around 7000 buildings affected.
- Direct hit of Alby with coincident river flooding: combined 1% AEP event with Alby. Results are similar to the direct hit of Alby alone.

The study highlights the vulnerability of coastal Busselton to flooding in extreme storm surge events, which will become increasingly likely as sea levels rise. Nevertheless, the scenarios considered in this report are based on very rare events. For example, the high water level associated with cyclone Alby has been estimated as a 1 in 200 AEP (Worley Parsons 2013). Thus the chance of flooding from a coincident direct hit of a tropical cyclone and a 1% AEP riverine flooding event is extremely low.

Appendix D Floodplain development strategies

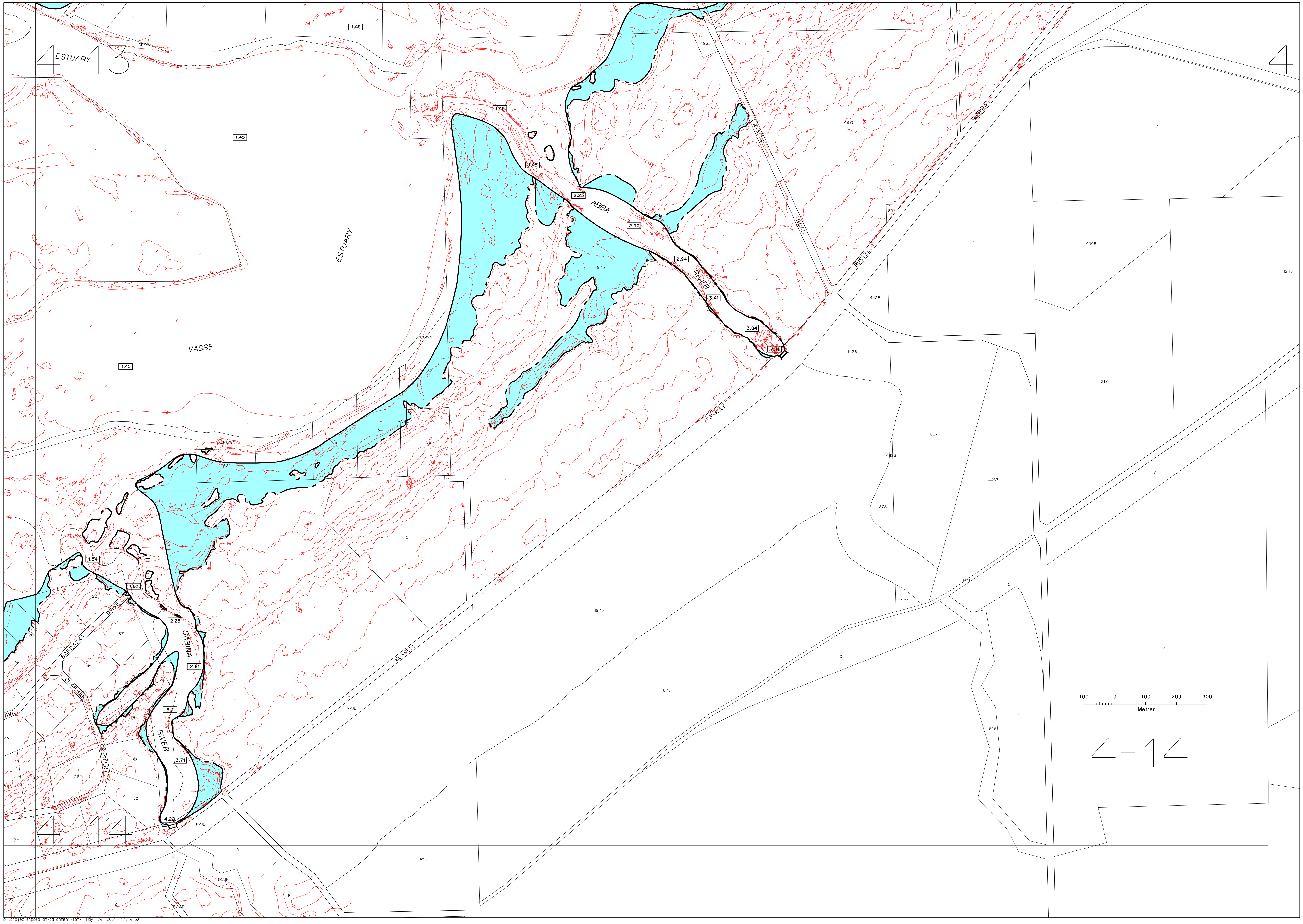


VASSE RIVER & NEW RIVER
RECOMMENDED FLOODPLAIN DEVELOPMENT STRATEGY

SCALE: DIAGRAMMATIC

GENERAL NOTES

1. THE 100 YEAR FLOOD LEVEL IS EXPECTED TO OCCUR, ON AVERAGE, ONCE EVERY 100 YEARS. FLOODS HIGHER THAN THIS LEVEL WILL OCCUR BUT, ON AVERAGE, WILL BE LESS FREQUENT.
2. THE FLOOD FRINGE IS AN AREA AFFECTED BY A 100 YEAR FLOOD. DEVELOPMENT IN THIS AREA MAY BE CONSIDERED ACCEPTABLE SUBJECT TO BUILDING CONDITIONS THAT WILL PROVIDE ADEQUATE FLOOD PROTECTION.
3. THE INCREASE IN FLOOD LEVEL THAT WILL RESULT FROM TOTAL DEVELOPMENT OF FLOOD FRINGE AREAS HAS BEEN CALCULATED TO BE NO GREATER THAN 0.15 METRE.
4. THE PORTION OF THE FLOODPLAIN RECOMMENDED FOR A FLOODWAY MAY BE USED FOR PARKS AND RECREATION. HOWEVER, SUCH DEVELOPMENT SHOULD NOT IN ANY WAY CONSTITUTE AN OBSTRUCTION TO FLOOD FLOWS.


4-13
ESTUARY
VASSE
ESTUARY
ABBA
RIVER
SABINA
RIVER
LAYMAN
ROAD
BUSSELL
HIGHWAY
BARRACKS
DRIVE
CHAPMAN
CRESCENT
RAIL
CROWN
1.45
2.25
2.57
2.94
3.41
3.84
1.54
1.80
2.61
3.11
3.71
4.22
100 0 100 200 300
Metres
4-14

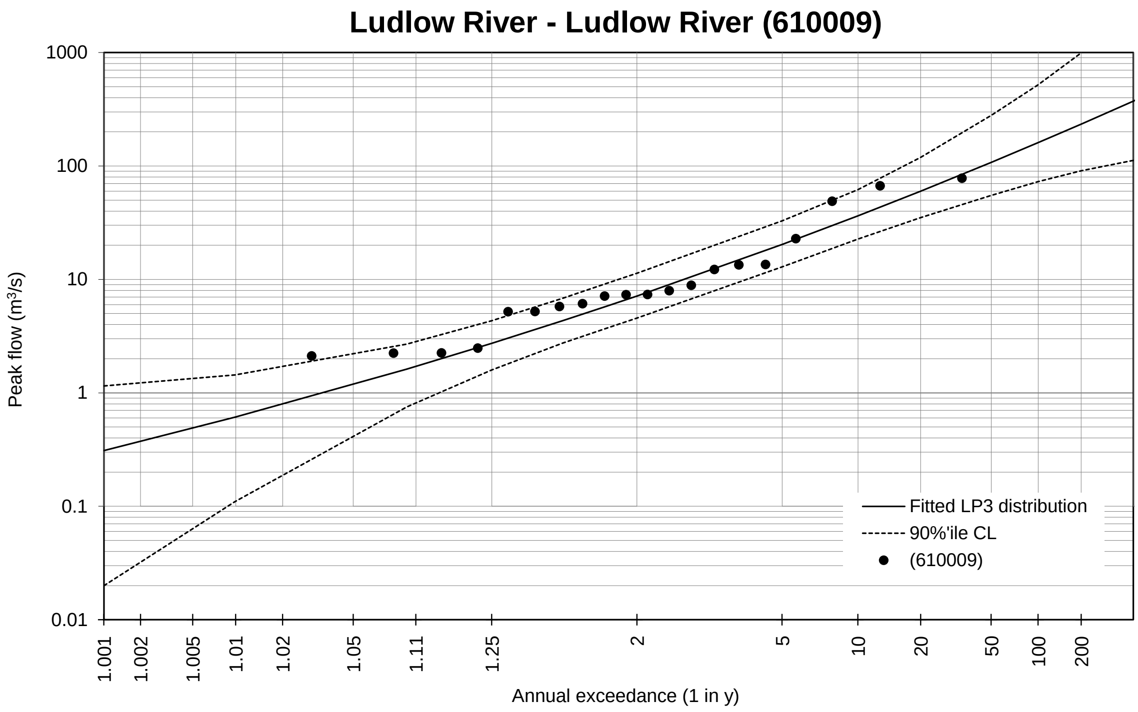
Appendix E Design hydrology

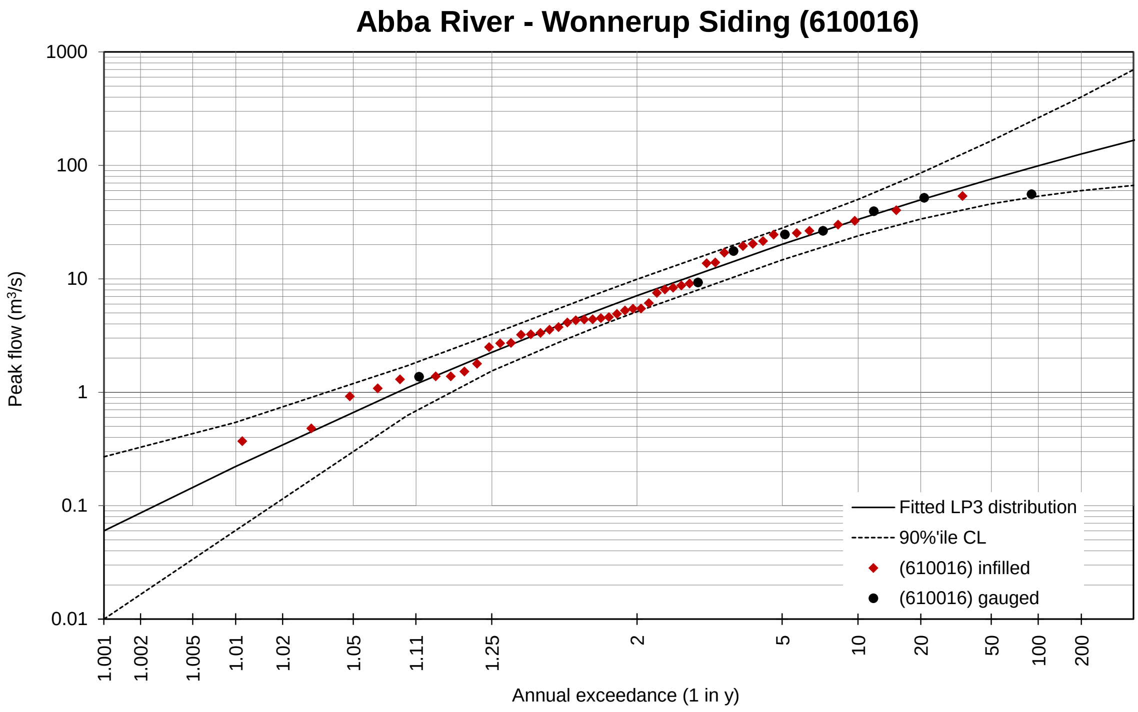
Infilling of gauged record for Abba River flood-frequency analysis

	Abba Wonnerup Siding	Ludlow	Happy Valley	Capel (Yates & Scott)	Capel Yates	Capel Scott
Catchment area (km^2)	128	208	109	315	315	336
Scaling factor	1.00	0.62	1.17	0.41	0.41	0.38
AWRC reference	610016	610009	610005	na	610219	610129

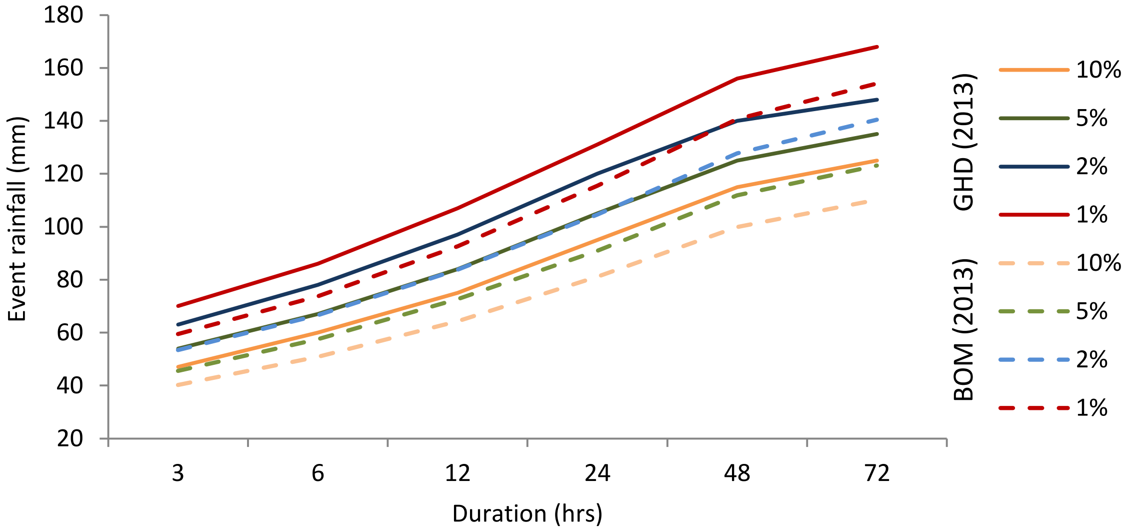
Year	Abba infilled (m^3/s)	Ludlow (m^3/s)	Happy Valley (m^3/s)	Capel infill (m^3/s)	Capel Yates (m^3/s)	Capel Scott (m^3/s)	Data source
1959	4.3			4.3		11.3	Capel infill
1960	13.9			13.9		36.6	Capel infill
1961	17.0			17.0		44.5	Capel infill
1962	24.4			24.4		64.1	Capel infill
1963	32.4			32.4		85.0	Capel infill
1964	40.2			40.2		105.6	Capel infill
1965	8.0			8.0		21.1	Capel infill
1966	9.1			9.1		23.8	Capel infill
1967	26.4			27.0	66.3	69.3	Capel infill
1968	25.3			14.6	35.9		Capel infill
1969	13.7			2.9	7.1		Capel infill
1970	2.7			9.3	22.9		Capel infill
1971	8.7			22.9	56.3		Capel infill
1972	21.5			6.5	16.0		Capel infill
1973	6.1			24.5	60.2		Capel infill
1974	53.5		45.6		71.8		Happy Valley
1975	3.3		2.8		33.6		Happy Valley
1976	2.7		2.3				Happy Valley
1977	1.8		1.5				Happy Valley
1978	3.2		2.8				Happy Valley
1979	0.5		0.4				Happy Valley
1980	2.5		2.1				Happy Valley
1981	19.4		16.6				Happy Valley
1982	4.6		3.9				Happy Valley
1983	30.0		25.6				Happy Valley
1984	5.4		4.6				Happy Valley
1985	4.1		3.5				Happy Valley
1986	1.1		0.9				Happy Valley
1987	0.4		0.3				Happy Valley
1988	20.3		17.3				Happy Valley
1989	0.9		0.8				Happy Valley
1990	4.4		3.7				Happy Valley
1991	5.3		4.5				Happy Valley
1992	8.3	13.5	5.7				Ludlow
1993	7.5	12.2	2.9				Ludlow
1994	3.8	6.1	0.7				Ludlow
1995	39.3	48.9	6.2		34.4		Abba
1996	26.4	22.9	5.5		38.3		Abba
1997	55.7	66.7	13.1		19.4		Abba
1998	17.5	7.4	2.0		19.2		Abba
1999	51.6	78.0			80.6		Abba
2000	24.5	13.4			19.6		Abba
2001	1.4	1.3			3.2		Abba
2002	9.3	5.2			11.5		Abba
2003	4.5	7.3			32.8		Ludlow
2004	3.2	5.2			11.1		Ludlow
2005	5.5	8.9			55.8		Ludlow
2006	1.4	2.2			10.1		Ludlow
2007	3.6	5.8			35.7		Ludlow
2008	4.9	7.9			17.8		Ludlow
2009	4.4	7.1			25.0		Ludlow
2010	1.4	2.2			2.6		Ludlow
2011	1.3	2.1			10.0		Ludlow
2012	1.5	2.5			4.6		Ludlow

Flood-frequency analysis plots





Comparison of design rainfall with Bureau of Meteorology 2013 IFD data



Design rainfall temporal patterns

	Temporal pattern for events <30 yr ARI (3% AEP)					Temporal pattern for events >30 yr ARI (3% AEP)				
Duration	**6**	**12**	**24**	**48**	**72**	**6**	**12**	**24**	**48**	**72**
Time step	**0.5hr**	**0.5hr**	**1hr**	**2hr**	**4hr**	**0.5hr**	**0.5hr**	**1hr**	**2hr**	**4hr**
1	9%	14%	14%	14%	33%	9%	11%	12%	12%	27%
2	18%	27%	26%	28%	17%	16%	22%	21%	23%	14%
3	4%	9%	9%	8%	10%	5%	7%	7%	7%	9%
4	31%	4%	7%	6%	8%	25%	4%	6%	6%	8%
5	13%	7%	5%	6%	5%	12%	6%	5%	6%	6%
6	6%	6%	7%	5%	7%	7%	5%	7%	5%	7%
7	4%	4%	4%	5%	3%	5%	5%	4%	5%	3%
8	5%	5%	6%	3%	4%	6%	5%	6%	4%	5%
9	3%	4%	3%	1%	1%	5%	4%	4%	2%	2%
10	2%	2%	4%	1%	2%	3%	2%	4%	2%	3%
11	2%	2%	3%	2%	2%	3%	3%	3%	3%	3%
12	1%	1%	2%	1%	0%	3%	2%	3%	2%	1%
13	0%	3%	2%	1%	1%	0%	4%	3%	1%	1%
14	0%	3%	2%	4%	1%	0%	3%	2%	5%	1%
15	0%	2%	1%	1%	1%	0%	3%	2%	2%	1%
16	0%	2%	1%	2%	3%	0%	3%	2%	3%	4%
17	0%	1%	1%	1%	1%	0%	2%	2%	2%	2%
18	0%	1%	1%	2%	1%	0%	2%	1%	3%	2%
19	0%	0%	1%	1%	0%	0%	1%	2%	1%	0%
20	0%	1%	0%	3%	0%	0%	2%	0%	3%	0%
21	0%	1%	1%	1%	0%	0%	2%	1%	1%	0%
22	0%	1%	1%	1%	0%	0%	1%	2%	1%	0%
23	0%	1%	1%	1%	0%	0%	1%	1%	1%	0%
24	0%	0%	1%	1%	0%	0%	1%	1%	1%	0%

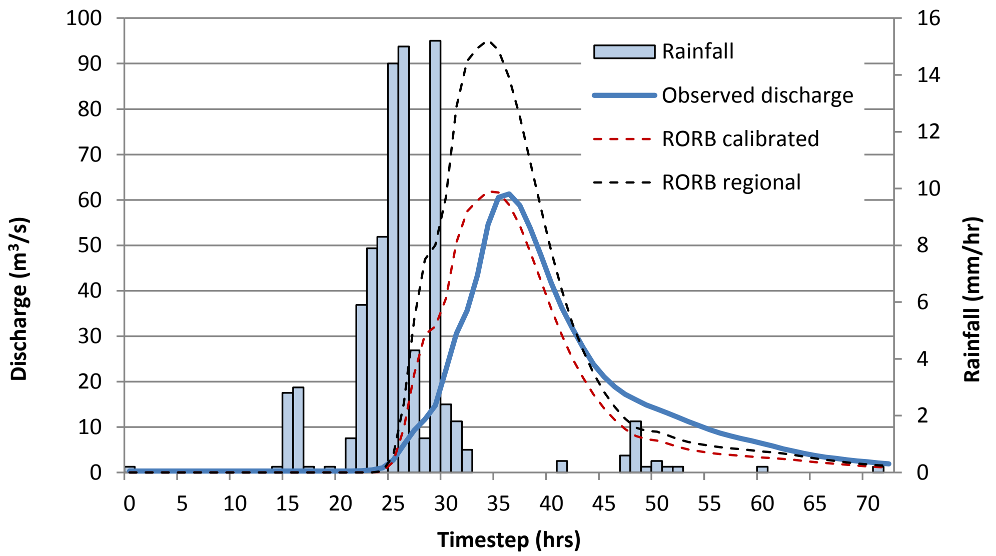
RORB model calibration

1997 event (3 August to 5 August)

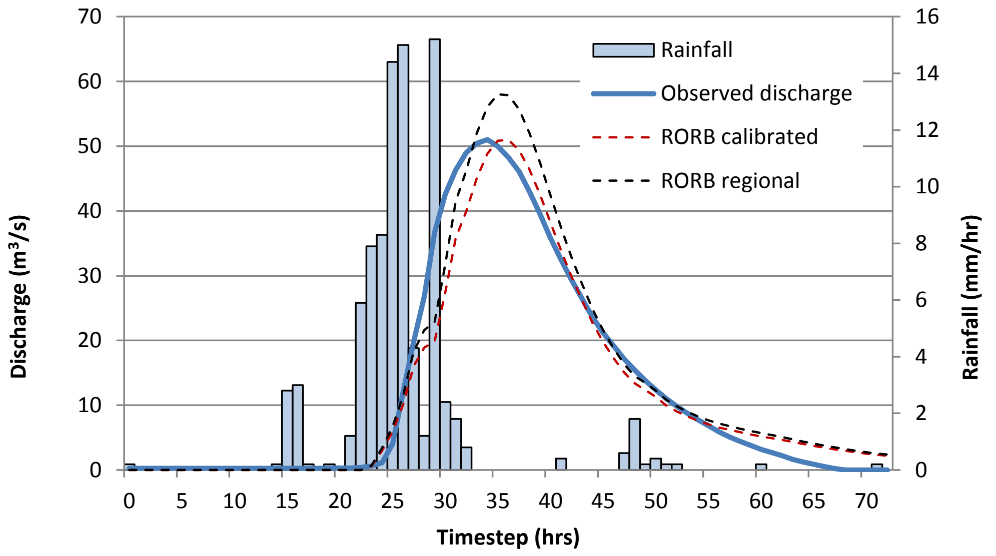
Calibration parameters

1997 event *Total rainfall 89mm at Happy Valley*			Validated parameters			Calibrated parameters		
Catchment	Area (km^2)	Clearing	*IL*	*RoC*	*Kc*	*IL*	*RoC*	*Kc*
Ludlow River	228	41%	20	0.32	14	20	0.26	14
Abba River	137	64%	10	0.37	18	10	0.33	18
Sabina River	50	100%	10	0.29	15	10	0.24	15
Vasse River	18	100%	10	0.29	12	10	0.29	12

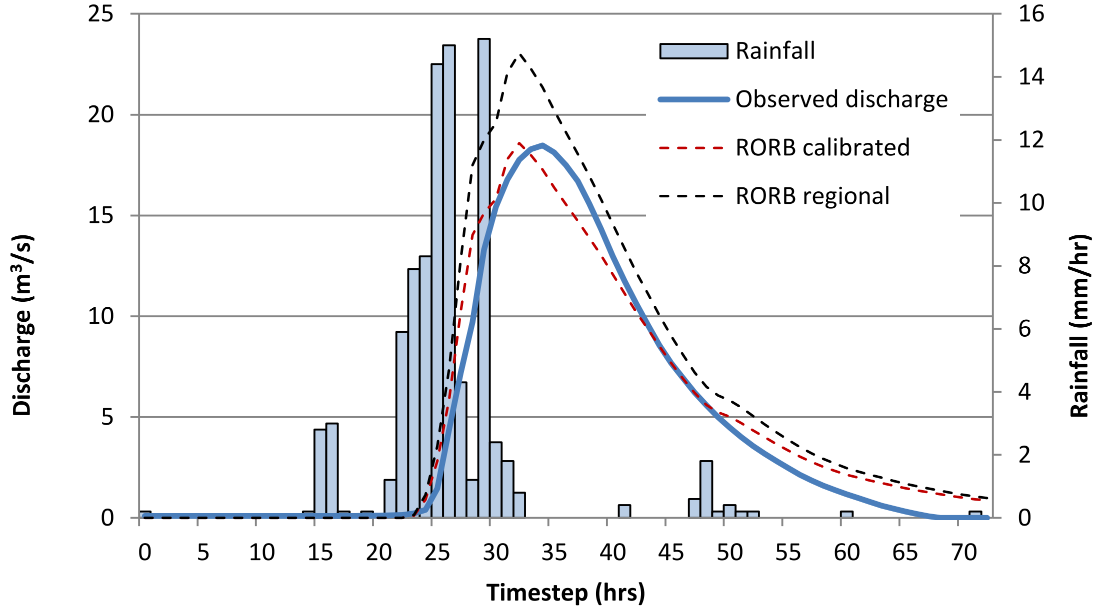
Ludlow River (610009)



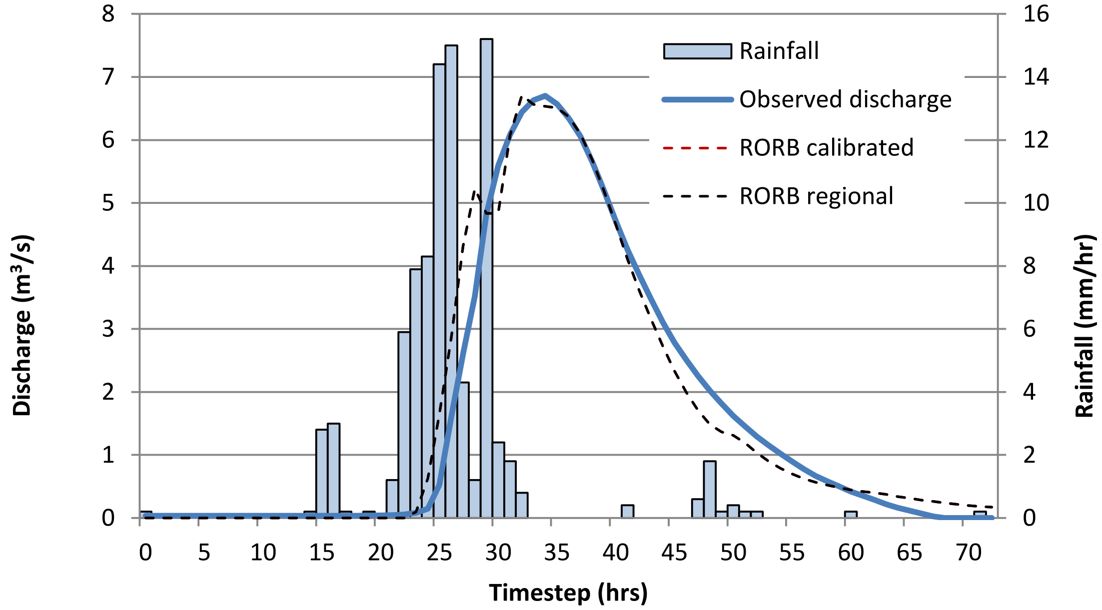
Abba River (610016)



Lower Sabina River (using area weighted flow from 610016)



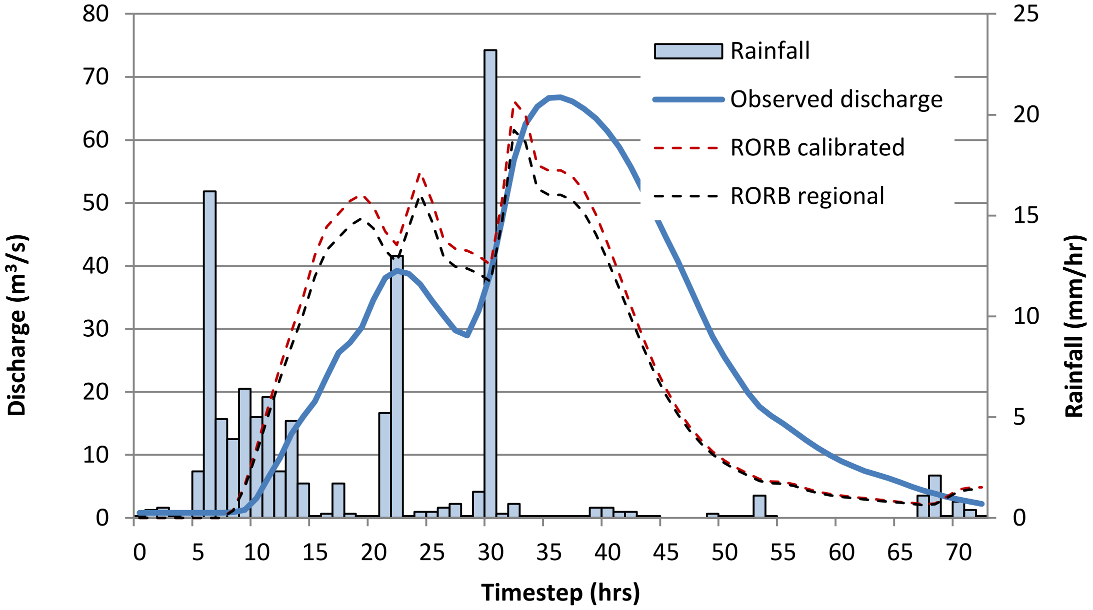
Lower Vasse River (using area weighted flow from 610016). Note that the regional and calibration parameters were identical for this event.



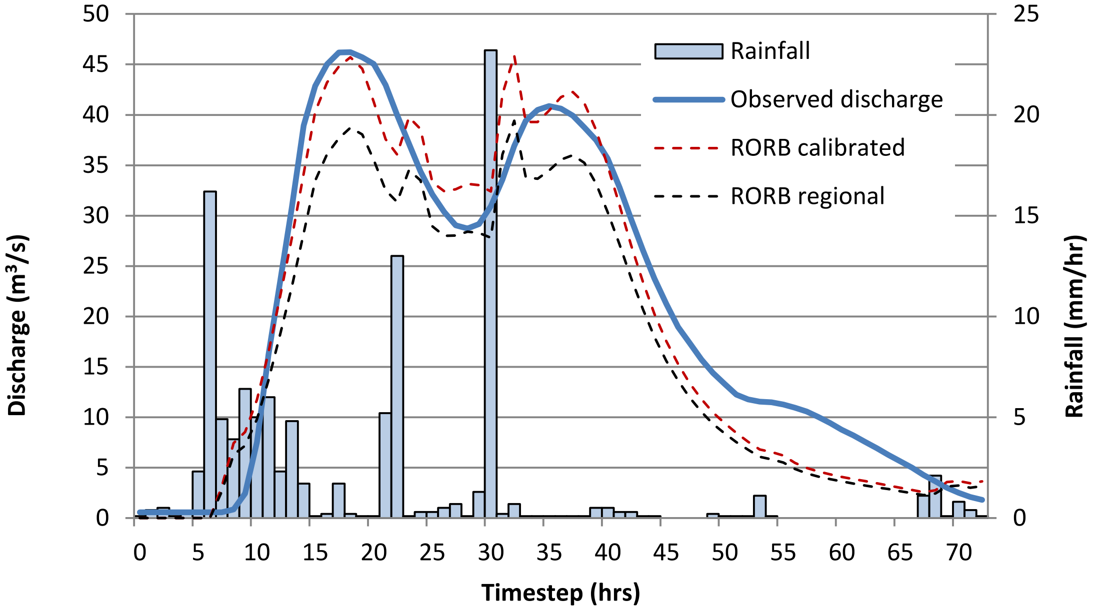
1999 event (3 September to 7 September)

1999 event *Total rainfall 116mm at Aston Downs*			Validated parameters			Calibrated parameters		
Catchment	Area (km^2)	Clearing	*IL*	*RoC*	*Kc*	*IL*	*RoC*	*Kc*
Ludlow River	228	39%	20	0.34	14	20	0.41	14
Abba River	137	64%	10	0.39	15	10	0.43	15
Sabina River	50	100%	10	0.31	15	10	0.28	15
Vasse River	18	100%	10	0.31	12	10	0.37	12

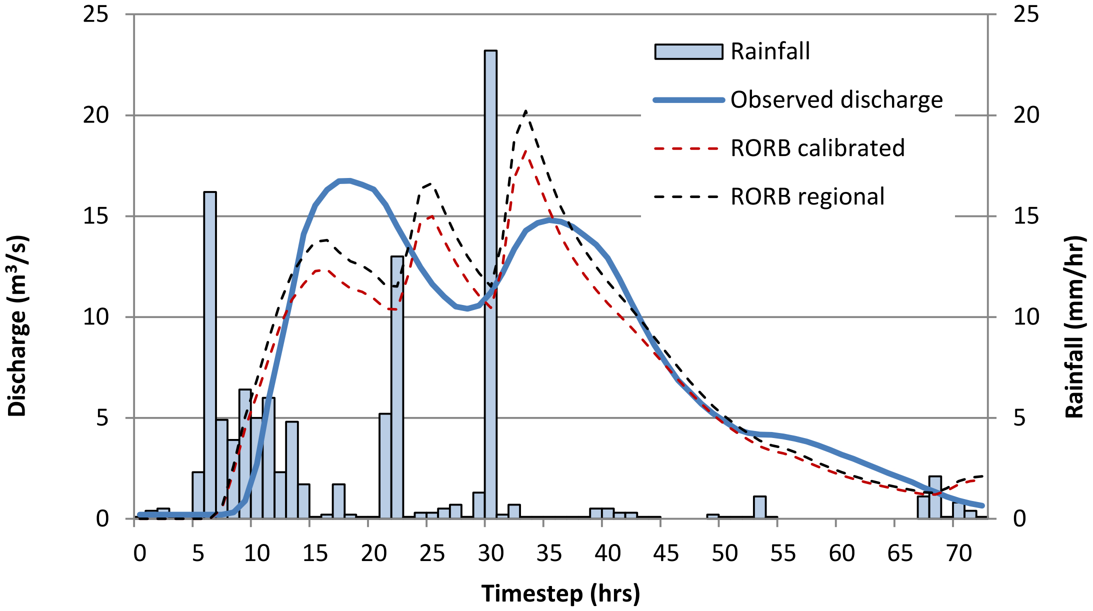
Ludlow River (610009)



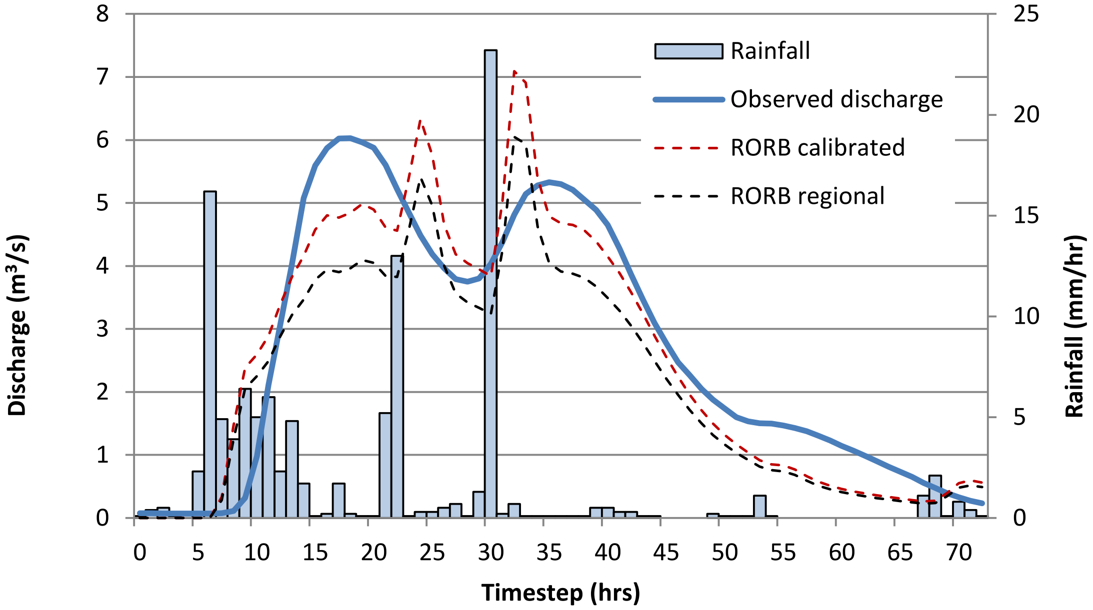
Abba River (610016)



Lower Sabina River (using area weighted flow from 610016)



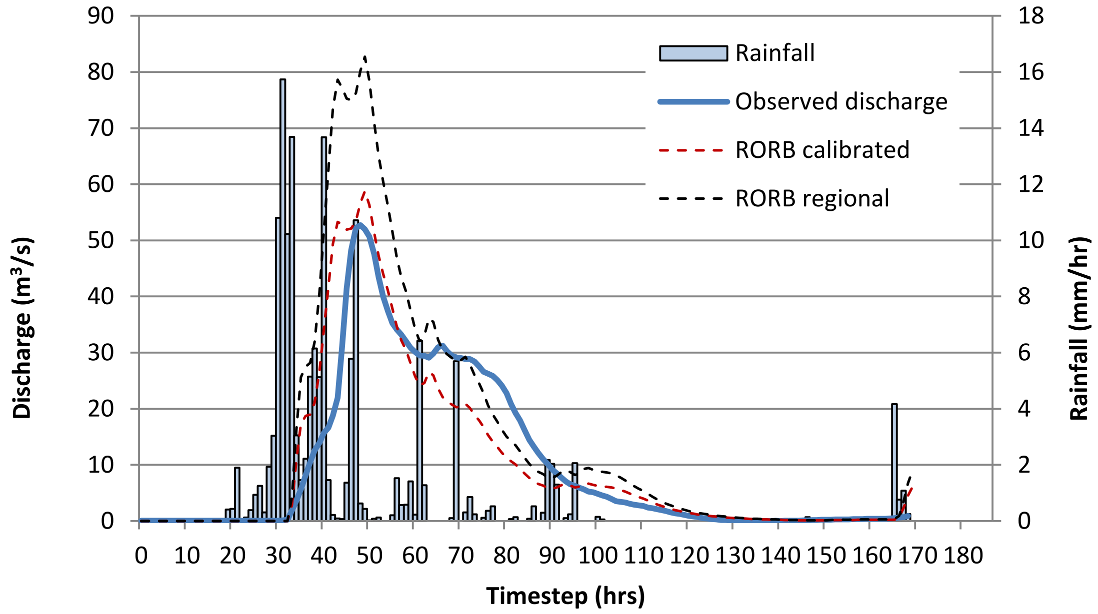
Lower Vasse River (using area weighted flow from 610016)



2016 event (14 July to 21 July)

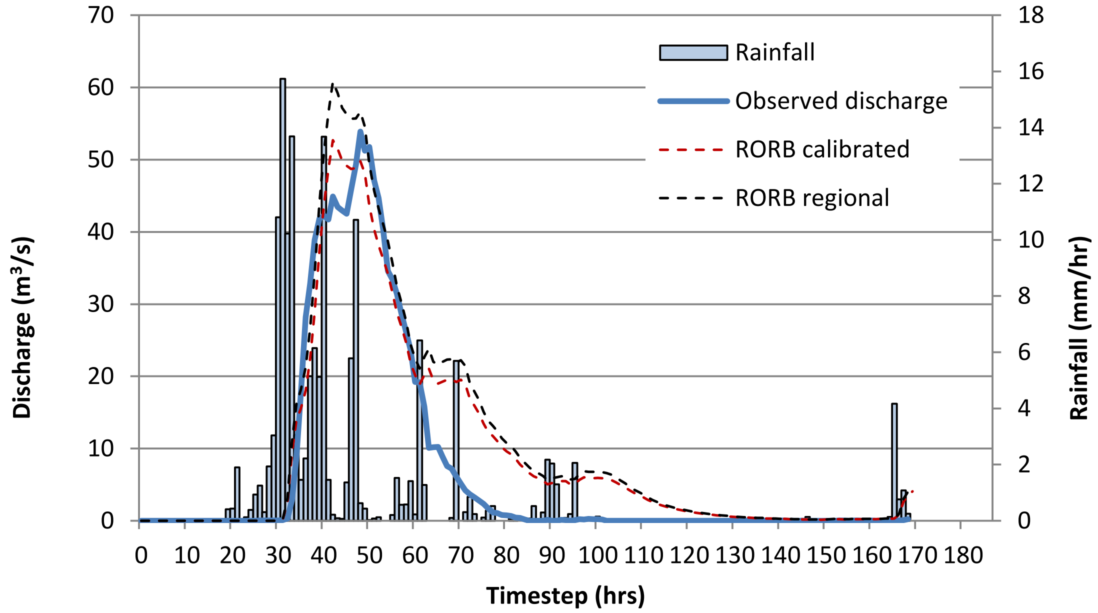
2016 event Total rainfall 155mm at Ludlow			Validated parameters			Calibrated parameters		
Catchment	**Area (km^2)**	**Clearing**	***IL***	***RoC***	***Kc***	***IL***	***RoC***	***Kc***
Ludlow River	228	41%	30	0.35	16	30	0.25	16
Abba River	137	64%	20	0.36	15	20	0.41	15

Ludlow River (610009)

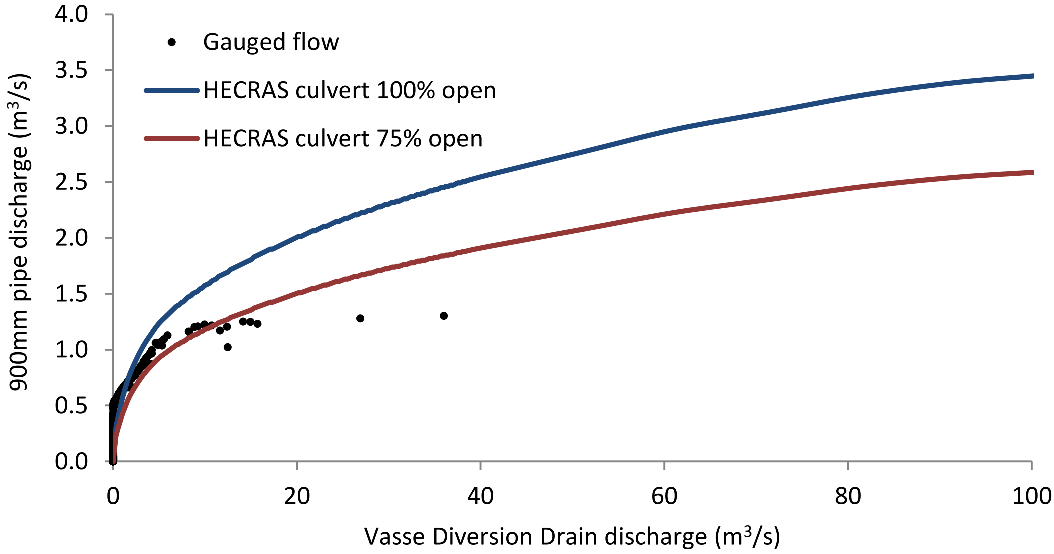


Abba River (610062)

Note: theoretical rating used to derive discharge from recorded stage at new Abba River gauging station (Wonnerup South Road).



Appendix F Rating curve for 900 mm culvert



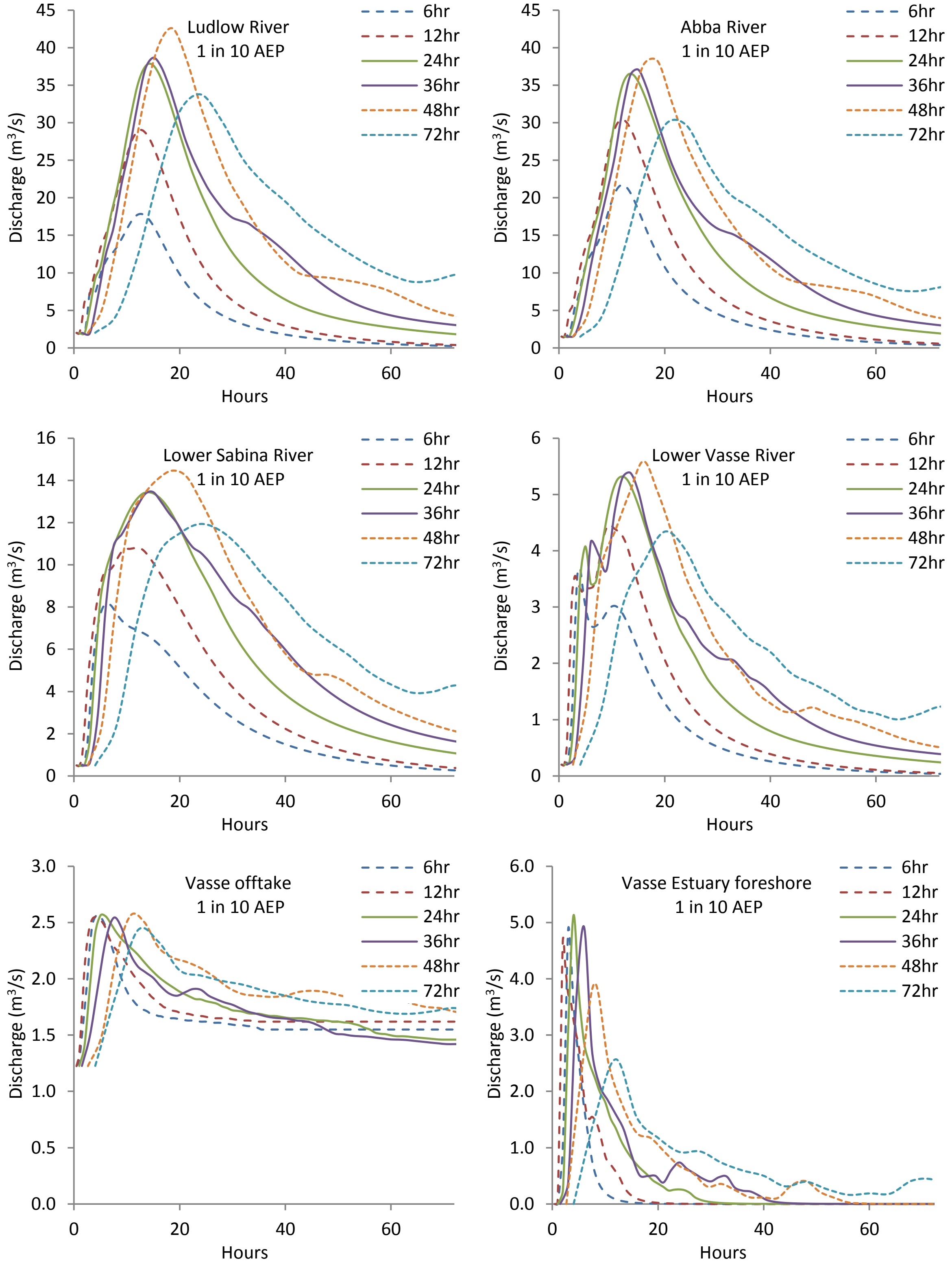
Rating curve generated using a HEC RAS model of a section of the Vasse Diversion Drain with a lateral outflow culvert 900 mm in diameter. Black data points indicate gauged flow on the Vasse Diversion Drain (610014) and on the offtake structure (610045) for data collected between 2012 and 2014.

RORB parameters for all design events

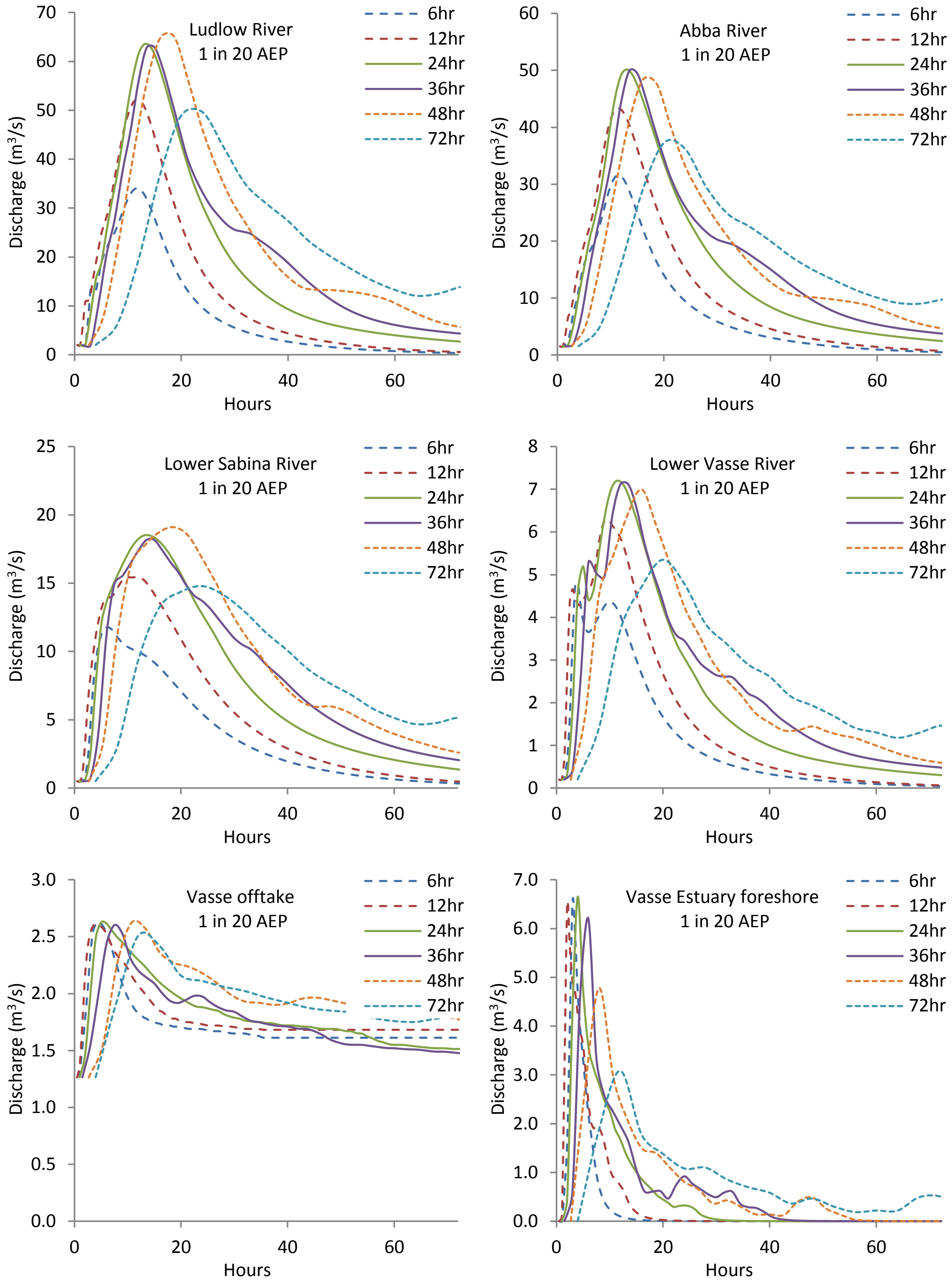
		Adopted parameters				Regional parameters			
Event duration Hours	1% AEP rainfall (mm)	Ludlow River RoC	Abba River RoC	Sabina River RoC	Vasse River RoC	Ludlow River RoC	Abba River RoC	Sabina River RoC	Vasse River RoC
6	70	0.36	0.38	0.38	0.38	0.31	0.36	0.28	0.28
12	93	0.37	0.39	0.39	0.39	0.32	0.37	0.29	0.29
24	120	0.39	0.40	0.40	0.40	0.34	0.39	0.31	0.31
36	136	0.40	0.41	0.41	0.41	0.35	0.40	0.32	0.32
48	147	0.41	0.42	0.42	0.42	0.36	0.41	0.32	0.32
72	160	0.42	0.43	0.43	0.43	0.36	0.42	0.33	0.33
Event duration Hours	2% AEP rainfall (mm)	Ludlow River RoC	Abba River RoC	Sabina River RoC	Vasse River RoC	Ludlow River RoC	Abba River RoC	Sabina River RoC	Vasse River RoC
6	64	0.29	0.33	0.33	0.33	0.30	0.36	0.26	0.26
12	85	0.30	0.34	0.34	0.34	0.31	0.37	0.28	0.28
24	110	0.32	0.35	0.35	0.35	0.33	0.38	0.30	0.30
36	121	0.33	0.36	0.36	0.36	0.34	0.39	0.31	0.31
48	132	0.33	0.37	0.37	0.37	0.34	0.40	0.31	0.31
72	141	0.34	0.37	0.37	0.37	0.35	0.40	0.32	0.32
Event duration Hours	5% AEP rainfall (mm)	Ludlow River RoC	Abba River RoC	Sabina River RoC	Vasse River RoC	Ludlow River RoC	Abba River RoC	Sabina River RoC	Vasse River RoC
6	55	0.18	0.22	0.22	0.22	0.30	0.35	0.26	0.26
12	73	0.19	0.23	0.23	0.23	0.31	0.36	0.28	0.28
24	96	0.20	0.24	0.24	0.24	0.33	0.38	0.29	0.29
36	107	0.21	0.25	0.25	0.25	0.33	0.39	0.30	0.30
48	118	0.22	0.25	0.25	0.25	0.34	0.39	0.31	0.31
72	129	0.23	0.26	0.26	0.26	0.34	0.40	0.32	0.32
Event duration Hours	10% AEP rainfall (mm)	Ludlow River RoC	Abba River RoC	Sabina River RoC	Vasse River RoC	Ludlow River RoC	Abba River RoC	Sabina River RoC	Vasse River RoC
6	49	0.12	0.18	0.18	0.18	0.30	0.35	0.26	0.26
12	66	0.13	0.19	0.19	0.19	0.31	0.36	0.28	0.28
24	87	0.14	0.20	0.20	0.20	0.32	0.37	0.29	0.29
36	98	0.15	0.21	0.21	0.21	0.33	0.38	0.29	0.29
48	108	0.16	0.22	0.22	0.22	0.33	0.39	0.30	0.30
72	119	0.17	0.23	0.23	0.23	0.34	0.39	0.31	0.31

Design hydrographs for various AEP and duration events

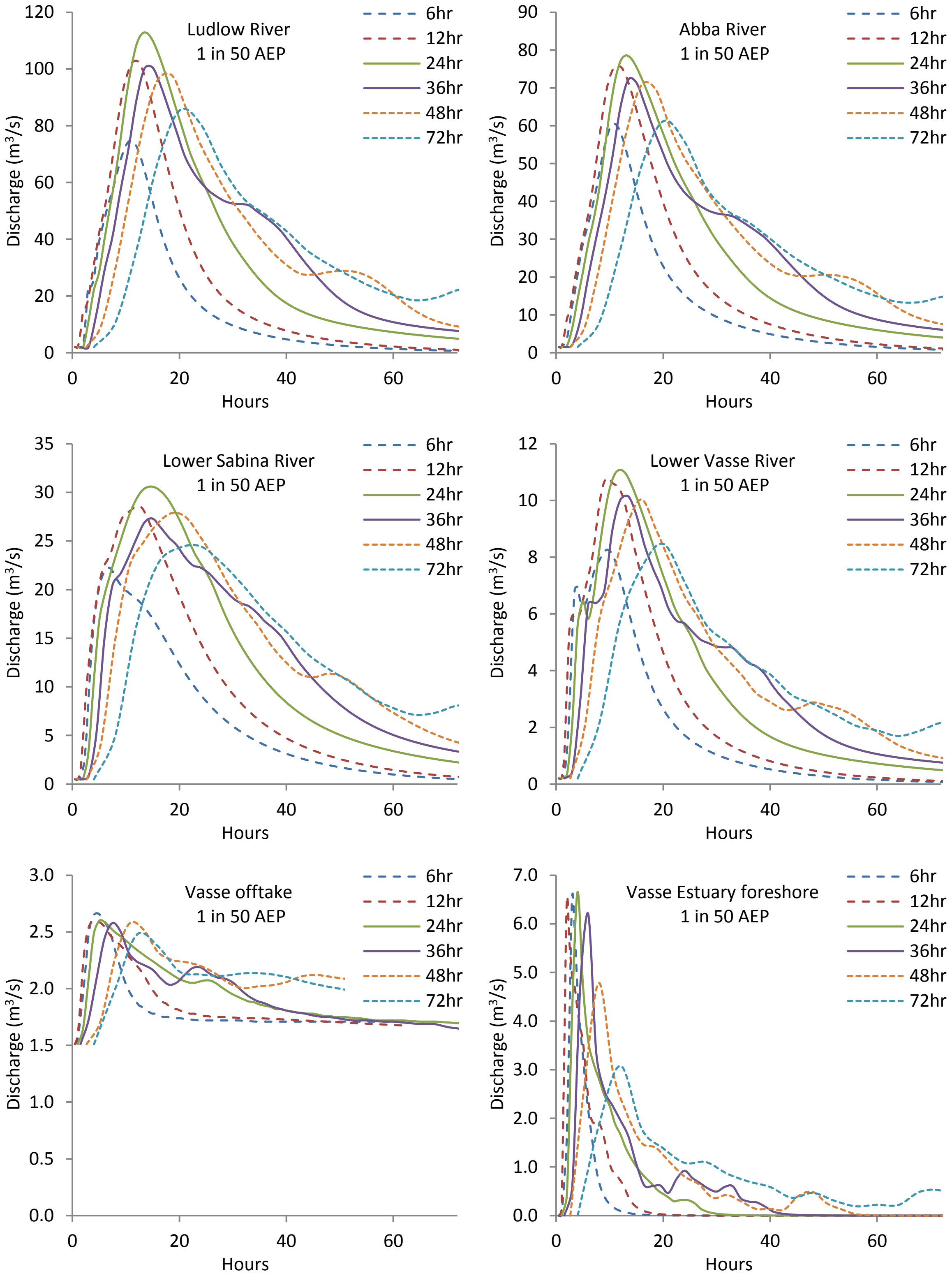
1 in 10 (10%) AEP design hydrographs including baseflow



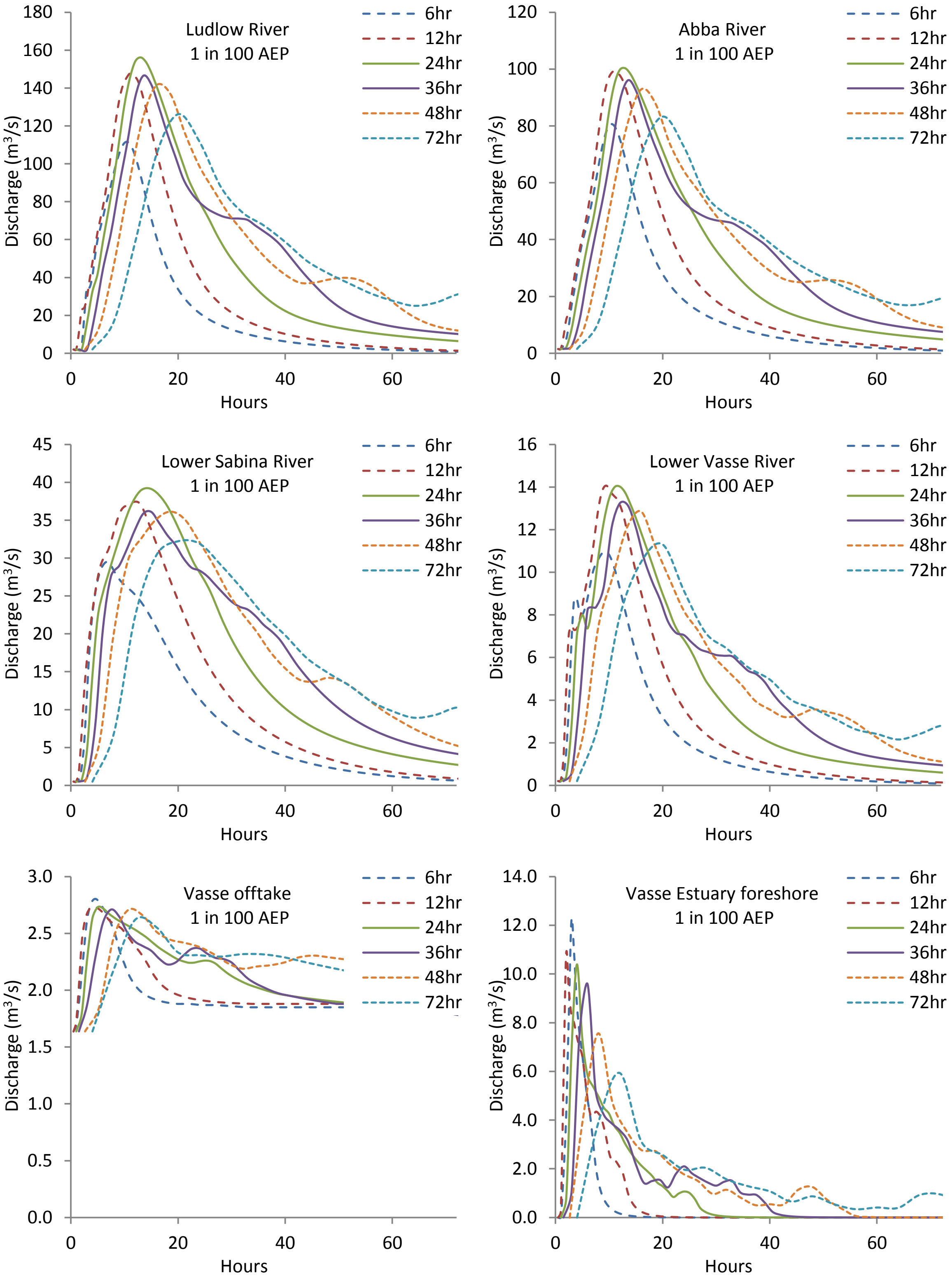
1 in 20 (5%) AEP design hydrographs including baseflow



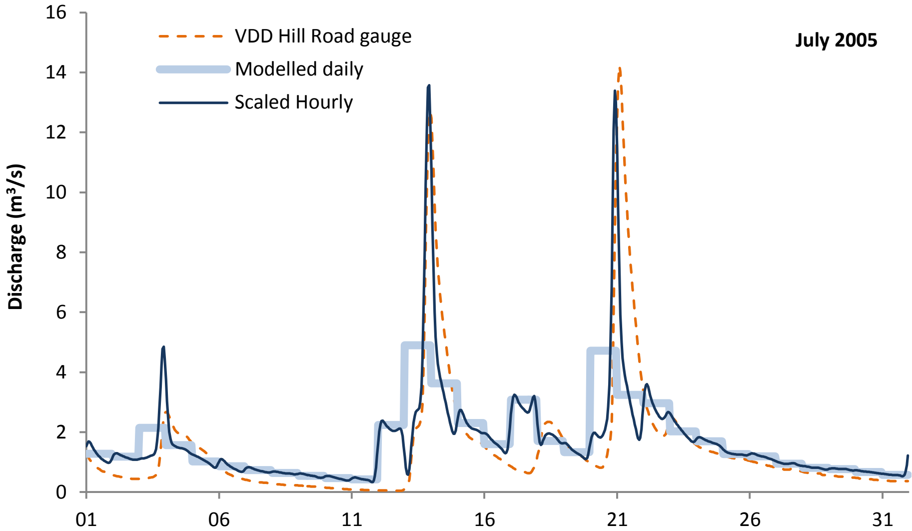
1 in 50 (2%) AEP design hydrographs including baseflow



1 in 100 (1%) AEP design hydrographs including baseflow



Appendix G Conversion from daily to hourly flows

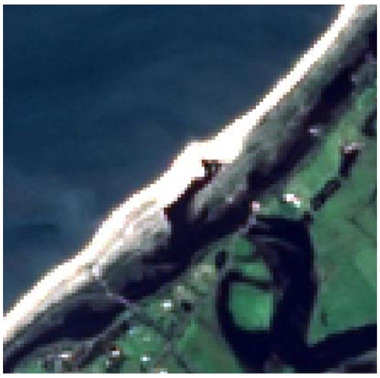


Example of daily to hourly scaling of flows based on gauged hourly flow and modelled daily flow

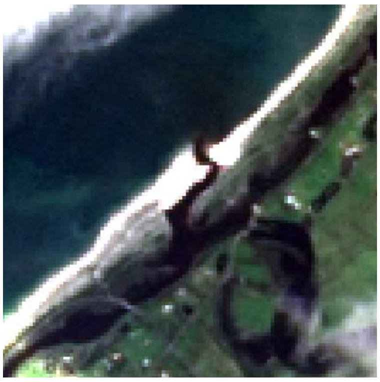
Daily flows from the Source model (light blue) were converted to hourly flows (dark blue) by proportionally scaling the modelled flows according to the measured hourly flows on the Vasse Diversion Drain at Hill Road gauging station (610014). For example, if 50% of flow recorded for the day was in a single hour, then 50% of the daily modelled flow would be assigned to that hour in the synthetic hourly time-series, with the remaining 50% distributed among the other 23 hours of the day. This gives a more realistic estimate of peak flows, although it can also introduce false variability into the hydrograph due to inconsistencies between the modelled daily flows and the observed hourly flows. A spline smoothing filter was applied over the hydrograph after the hourly scaling to remove any sharp jumps in discharge.

The resulting hourly hydrographs were compared with the original modelled hydrographs to ensure there were no mass balance errors introduced by the scaling process.

Appendix H Sand bar state from Landsat 8 imagery 2013–15



18 Jul 2013 Closed



19 Aug 2013 Open

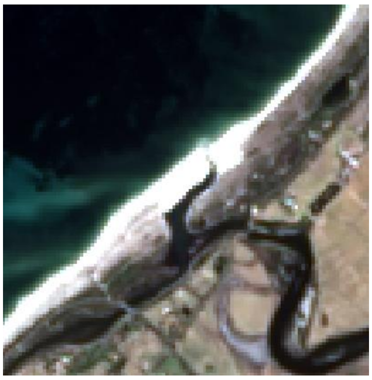
4 Sep 2013 Open

22 Oct 2013 Closed

23 Nov Closed

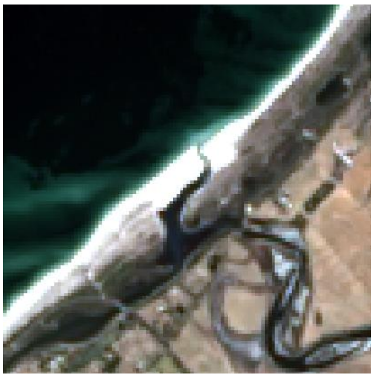
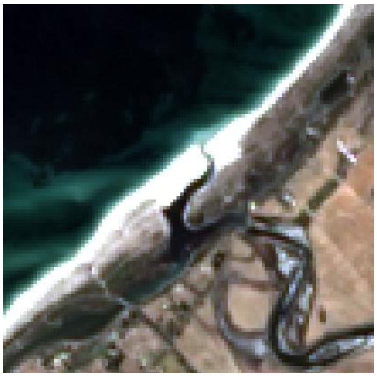
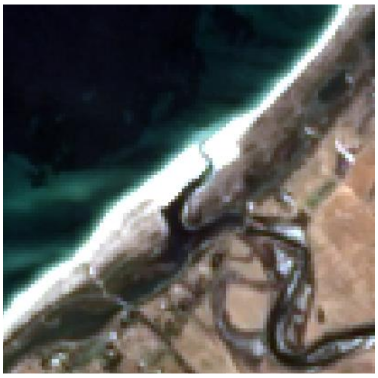
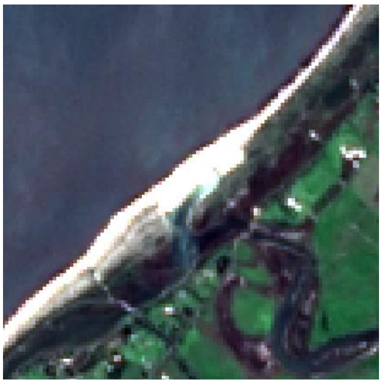
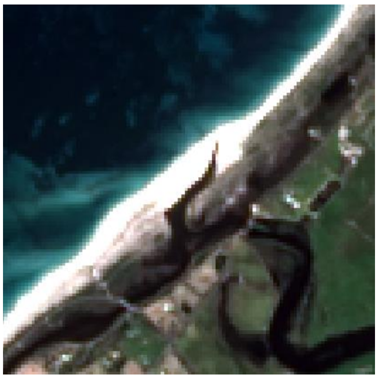
9 Dec 2013 Closed

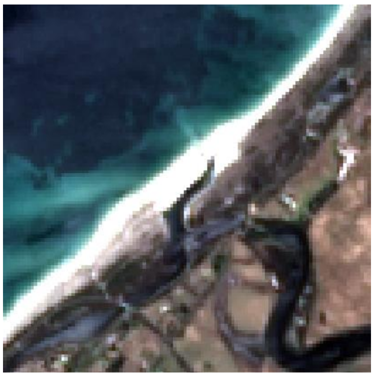
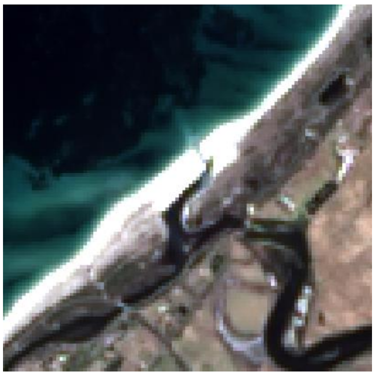
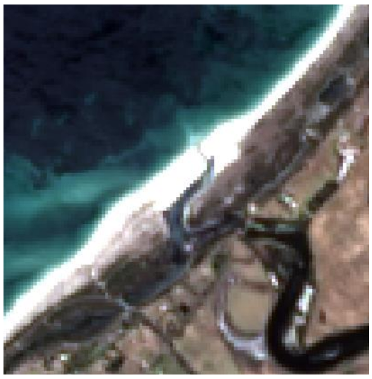
1 Jan 2014 Open



10 Jan 2014 Open

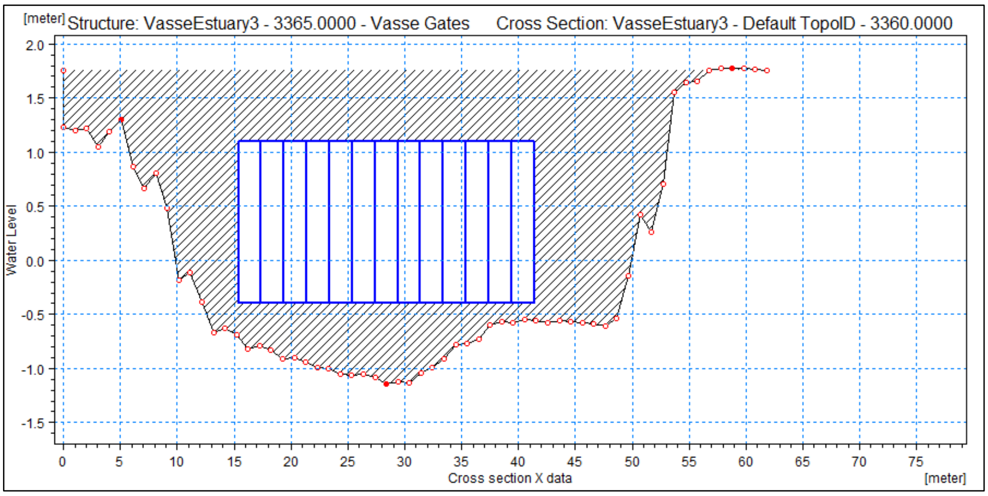
11 Feb 2014 Open

 27 Feb 2014 Open	 3 Mar 2014 Open	 22 Mar 2014 Open
 6 Jun 2014 Closed	 12 Jul 2014 Open	 6 Aug 2014 Closed
 16 Oct 2014 Closed	 1 Nov 2014 Closed	 17 Nov 2014 Closed

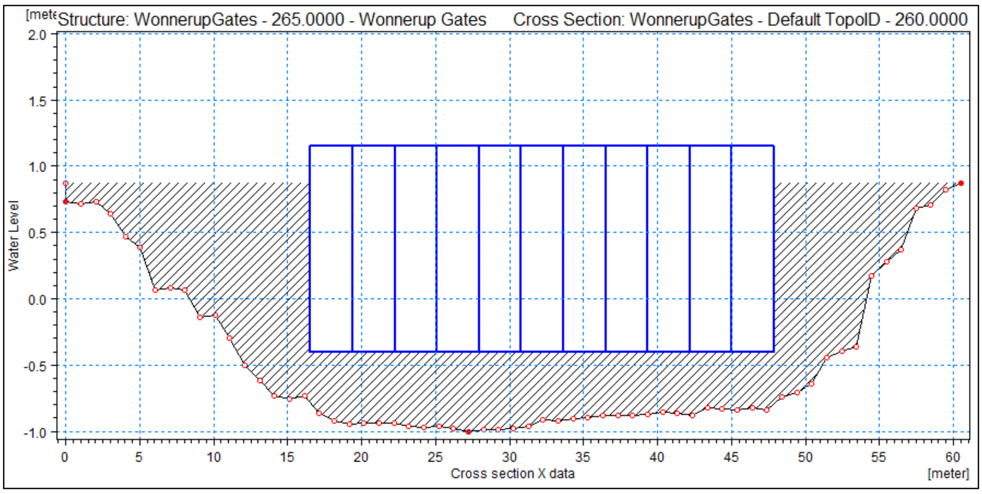
		
19 Dec 2014 Closed	28 Dec 2014 Open	4 Jan 2015 Open

Appendix I Structures implemented in MIKE11

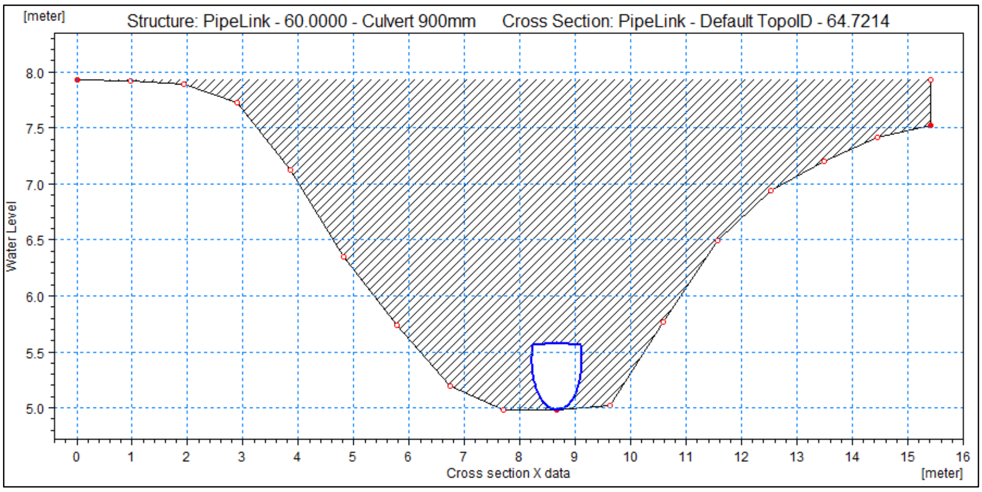
Vasse Floodgates - Vasse Estuary



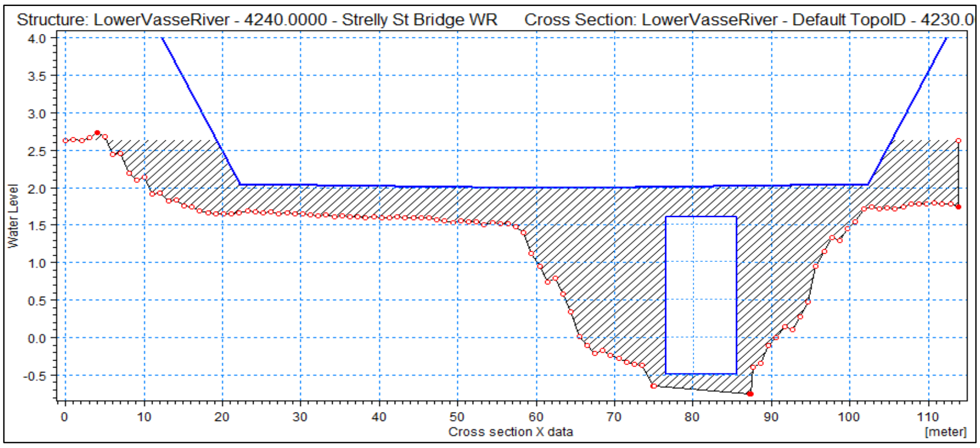
Wonnerup Floodgates - Wonnerup Estuary



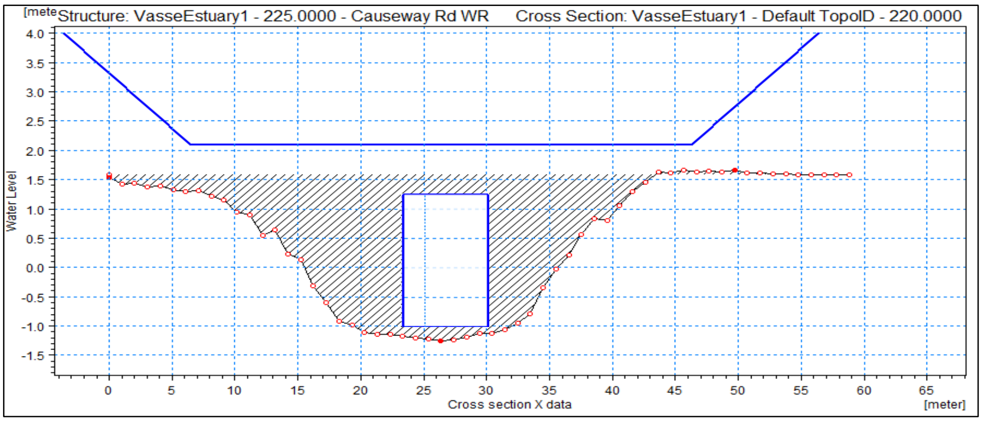
900mm pipe - Vasse Diversion Drain to Lower Vasse River



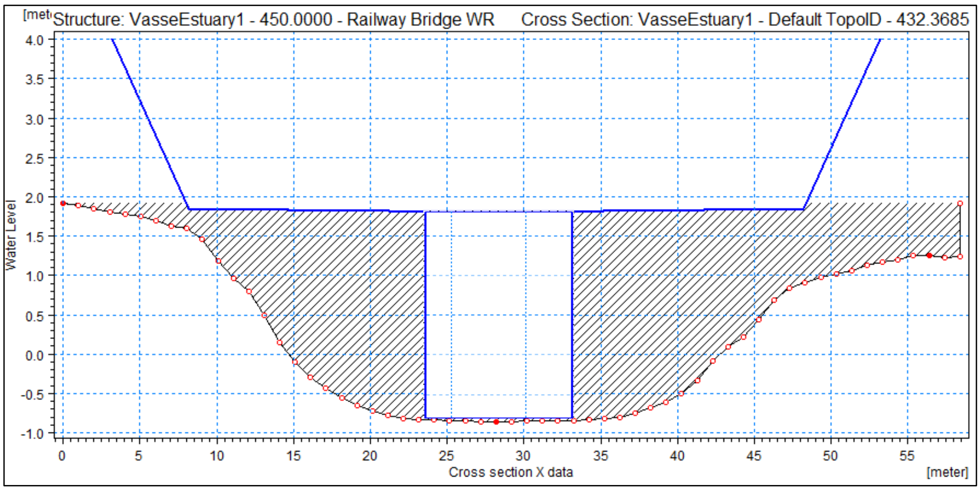
Strelly Street Bridge - Lower Vasse River



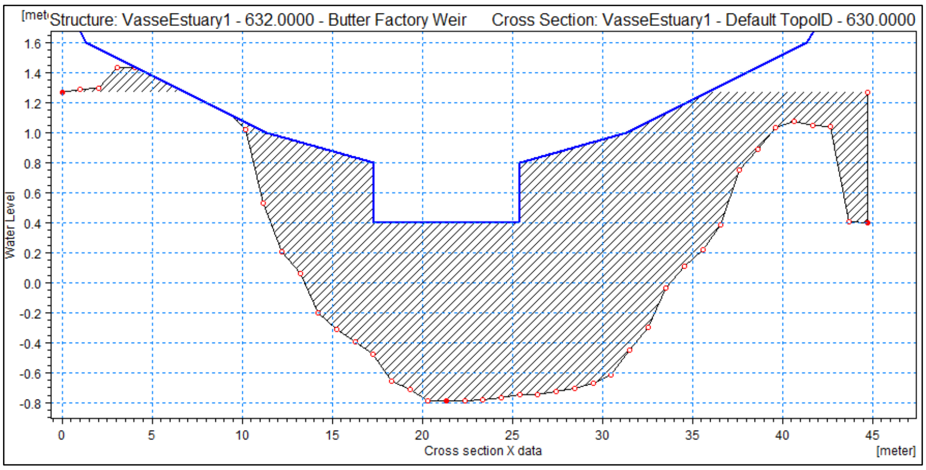
Causeway Road Bridge - Lower Vasse River



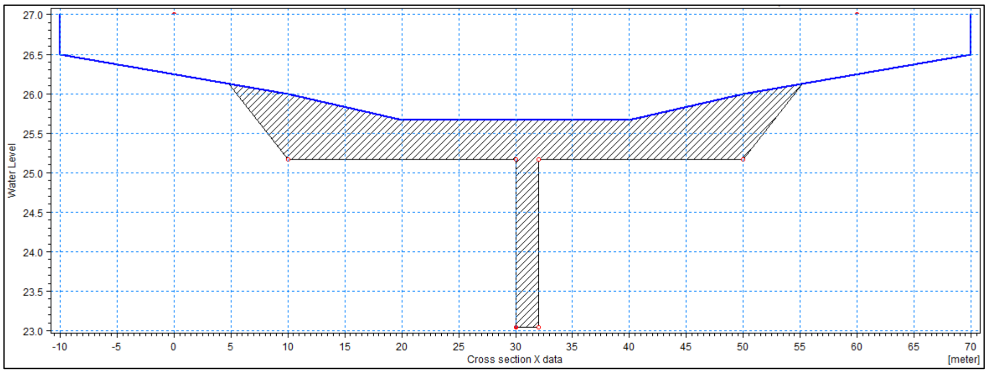
Railway Bridge - Lower Vasse River



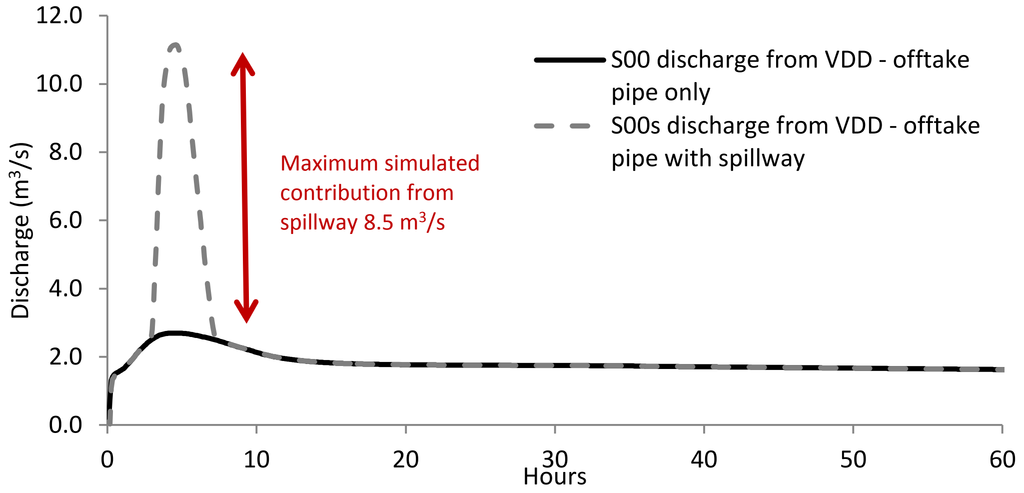
Butter Factory Weir - Lower Vasse River



Sabina Diversion Weir - Lower Sabina River



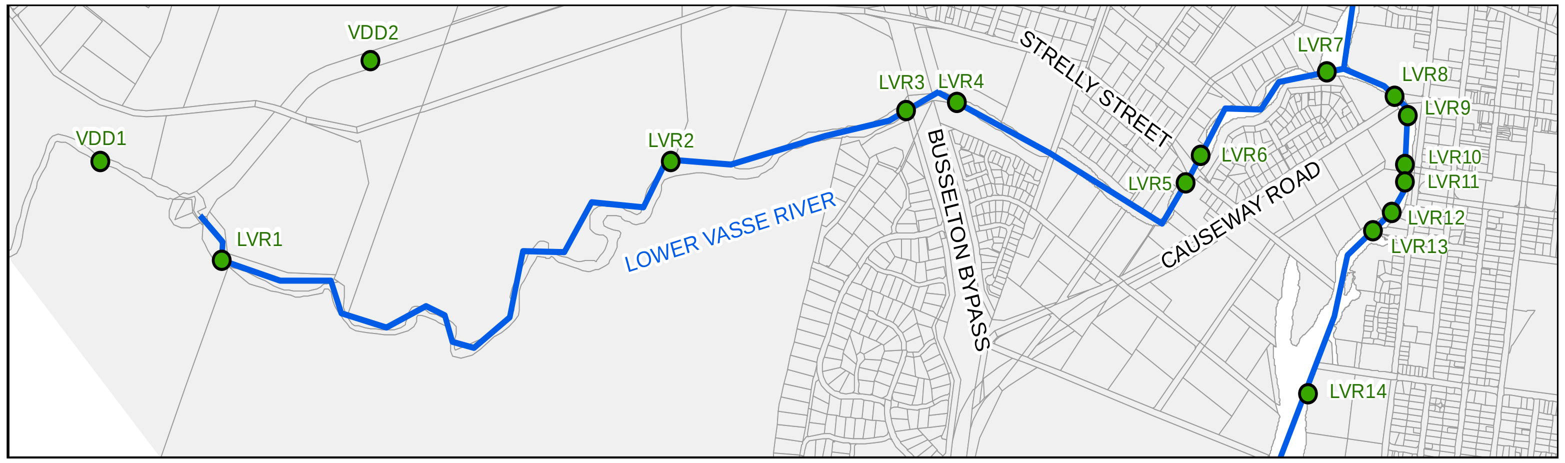
Appendix J Discharge from Vasse Diversion Drain offtake structure with and without spillway for six-hour 1% AEP event

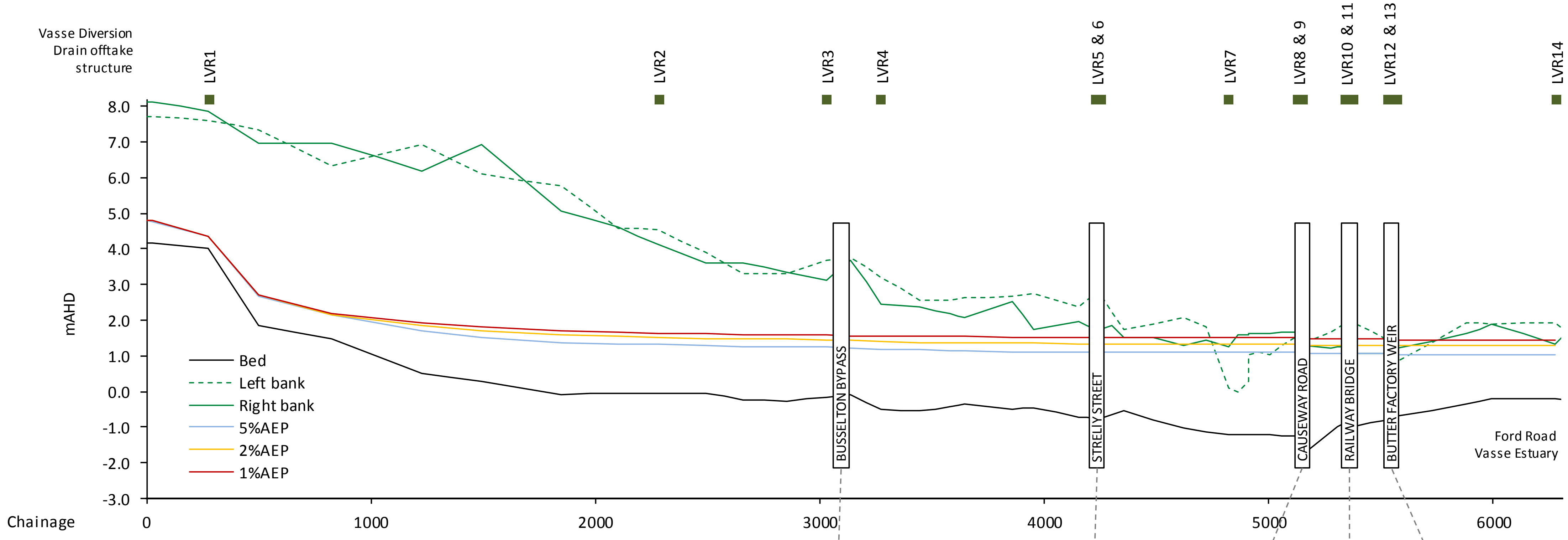


The target spillway peak discharge was 7 m^3/s but a 20% safety factor was applied, resulting in a conservative spillway contribution of 8.5 m^3/s, and a total contribution through the offtake structure and spillway of 11.1 m^3/s.

Appendix K Detailed long-sections for the Lower Vasse River

Vertical Datum: AHD
Horizontal Datum: GDA 94
Projection System: MGA Zone 50





Size (mm)														
Chainage (m)	276	2279	3028	3272	4230	4250	4819	5128	5148	5340	5375	5530	5572	6276
Left bank level (mAHD)	7.59	4.54	3.69	3.21	2.74	2.74	1.59	1.53	1.35	1.91	1.94	1.44	0.85	1.94
Right bank level (mAHD)	7.88	4.12	3.13	2.46	1.74	1.74	1.61	1.67	1.31	1.26	1.07	1.08	1.21	1.35
5%AEP HGL (mAHD)	4.35	1.31	1.25	1.19	1.11	1.10	1.09	1.09	1.07	1.07	1.07	1.07	1.05	1.05
2%AEP HGL (mAHD)	4.36	1.52	1.45	1.39	1.34	1.33	1.33	1.32	1.30	1.30	1.29	1.29	1.28	1.28
1%AEP HGL (mAHD)	4.36	1.64	1.58	1.55	1.52	1.51	1.50	1.50	1.47	1.47	1.46	1.46	1.46	1.46
Invert level (mAHD)	4.00	-0.05	-0.17	-0.51	-0.75	-0.75	-1.22	-1.26	-1.73	-0.86	-0.97	-0.79	-0.70	-0.20
5%AEP discharge (m^3/s)	2.52	6.50	9.06	9.23	9.08	9.07	8.88	5.15	5.15	5.15	5.15	5.15	5.17	5.32
2%AEP discharge (m^3/s)	2.62	8.93	12.89	13.17	13.00	12.98	12.71	6.70	6.70	6.72	6.73	6.73	6.79	7.33
1%AEP discharge (m^3/s)	2.64	10.71	15.77	16.13	15.94	15.93	15.62	7.79	7.79	7.84	7.85	7.86	8.09	9.05

Lower Vasse River - Offtake structure to Ford Road

LONGITUDINAL SECTION

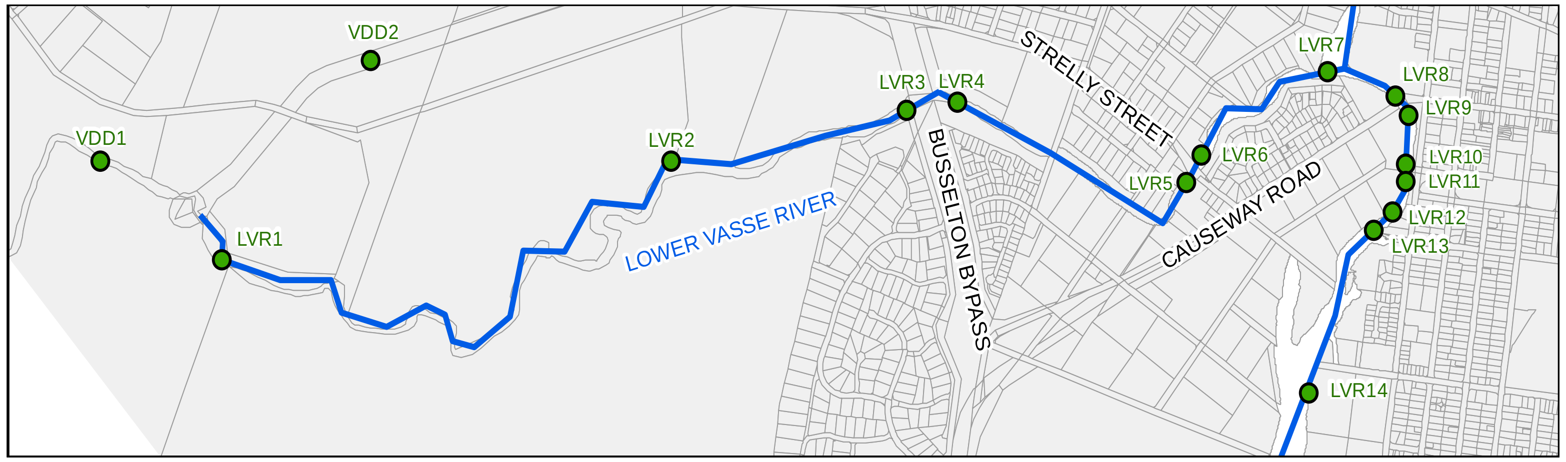
Base case S00 HGLs & flows

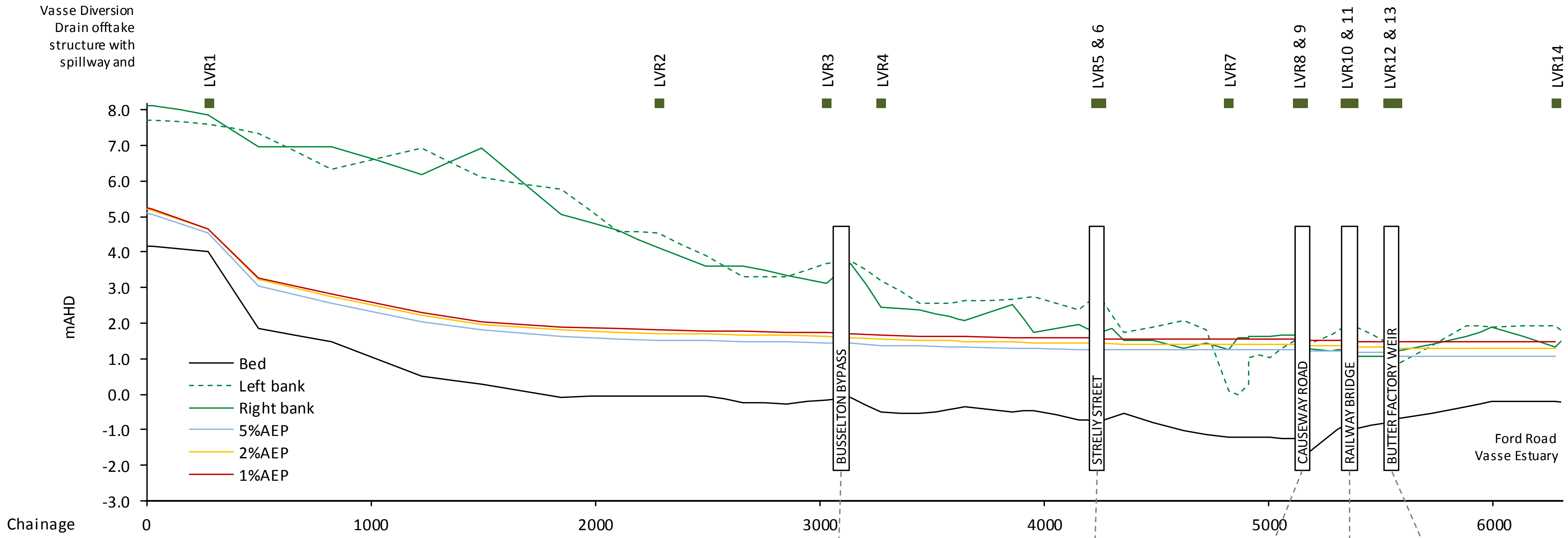
Figure I-1

Author: B. Marillier
Date: 9/11/2016

The Department of Water acknowledges the following datasets and their custodians in the analysis of data and production of the maps: Water Corporation Pipes, Water Corporation, 2009; Cadastre, Landgate, 2013.

Vertical Datum: AHD
Horizontal Datum: GDA 94
Projection System: MGA Zone 50





Size (mm)														
Chainage (m)	276	2279	3028	3272	4230	4250	4819	5128	5148	5340	5375	5530	5572	6276
Left bank level (mAHD)	7.59	4.54	3.69	3.21	2.74	2.74	1.59	1.53	1.35	1.91	1.94	1.44	0.85	1.94
Right bank level (mAHD)	7.88	4.12	3.13	2.46	1.74	1.74	1.61	1.67	1.31	1.26	1.07	1.08	1.21	1.35
5%AEP HGL (mAHD)	4.54	1.53	1.46	1.38	1.27	1.26	1.24	1.24	1.21	1.21	1.20	1.20	1.06	1.06
2%AEP HGL (mAHD)	4.64	1.71	1.64	1.56	1.44	1.42	1.41	1.41	1.35	1.35	1.33	1.33	1.30	1.30
1%AEP HGL (mAHD)	4.66	1.81	1.74	1.65	1.59	1.57	1.56	1.56	1.50	1.50	1.48	1.48	1.47	1.47
Invert level (mAHD)	4.00	-0.05	-0.17	-0.51	-0.75	-0.75	-1.22	-1.26	-1.73	-0.86	-0.97	-0.79	-0.70	-0.20
5%AEP discharge (m^3/s)	7.12	10.60	13.15	13.32	13.19	13.18	12.99	8.04	8.04	8.04	8.04	8.04	8.07	8.45
2%AEP discharge (m^3/s)	10.43	13.63	17.36	17.64	17.37	17.36	16.99	11.12	11.12	11.23	11.22	11.30	11.26	11.11
1%AEP discharge (m^3/s)	11.40	15.51	20.34	20.71	20.26	20.24	19.69	11.29	11.29	11.32	11.32	11.33	11.40	12.20

Lower Vasse River - Offtake structure to Ford Road

LONGITUDINAL SECTION

Scenario S03s HGLs & flows

Figure I-2

Author: B. Marillier
Date: 9/11/2016

The Department of Water acknowledges the following datasets and their custodians in the analysis of data and production of the maps: Water Corporation Pipes, Water Corporation, 2009; Cadastre, Landgate, 2013.

Appendix L Nutrient mass balance calculations

A nutrient mass balance is a simple method used to estimate nutrient concentrations in rivers and the total nutrient loading to the estuary. The mass balance was calculated using a box model of the Lower Vasse River, using as inputs the measured total nitrogen and phosphorus concentrations for the rivers and drains, and the modelled flow regime for the different scenarios. For the Lower Sabina River, the mass balance was calculated directly from the modelled flows, without use of a box model since the river does not operate as a store in summer.

By adjusting the ratio of inflows from different waterways – such as introducing more flow from the Vasse Diversion Drain to the Lower Vasse River – the change in nutrient concentration and loading can be quantified.

Although the results are reported quantitatively, it is important that they be interpreted more generally given the uncertainty surrounding the interaction of flow regimes and nutrient concentrations and the simplicity of the method. For example:

- *Are we likely to see an increase in nutrient load?*
- *At what time of year will nutrient concentrations be reduced?*

The following headings describe the steps used to calculate the mass balance.

Measured nutrient concentrations in waterways

Median TN and TP concentrations were calculated from measured concentrations for the Vasse Diversion Drain, Lower Vasse River, Sabina Diversion Drain, Lower Sabina River over four 'seasons' as shown in Appendix B. These were Feb–Apr, May–Jul, Aug–Oct and Nov–Jan. This grouping was designed to separate the early flow season from the late and account for the first flush signal.

Measured median TP and TN concentrations used for mass balance modelling

	Lower Vasse River		Vasse Diversion Drain		Lower Sabina River		Sabina Diversion Drain	
Season	**TN mg/L**	**TP mg/L**	**TN mg/L**	**TP mg/L**	**TN mg/L**	**TP mg/L**	**TN mg/L**	**TP mg/L**
Feb-Apr	2.20	0.17	1.57	0.12	na	na	1.90	0.04
May-Jul	1.90	0.21	2.10	0.10	4.10	0.38	4.60	0.06
Aug-Oct	1.70	0.17	1.70	0.09	2.50	0.30	3.50	0.06
Nov-Jan	1.07	0.20	0.56	0.05	0.88	na	3.00	0.04

Calculating nutrient concentrations in runoff from the Lower Vasse River catchment

The measured nutrient concentrations in the Lower Vasse River are influenced by inflows from the local catchment and the Vasse Diversion Drain. There are sampling sites on the Vasse Diversion Drain and the Lower Vasse River, but the concentrations in runoff from the local catchment of the Lower Vasse River are an unknown – that is, what is measured in the river is a combination of multiple sources.

Two methods were used to estimate these concentrations – land use mapping and calibration to the measured values in the Lower Vasse River.

Land use mapping

Land use mapping was combined with published estimates of nutrient concentrations for soils and land uses on the Swan and Scott coastal plains (Marillier 2010; Hall 2011). The table below lists the land uses and associated nutrient concentrations for the Lower Vasse River catchment. Land uses that are responsible for the most nutrient inputs are beef grazing, urban and horticultural.

Using this method, the areally weighted nutrient concentration for the catchment is 0.48 mg/L for TP and 1.62 mg/L for TN.

Land use and nutrient concentration for the Lower Vasse River catchment

Land use	Area (km^2)	Per cent	TN (mg/L)	TP (mg/L)
Bare soil	0.5	3%	0.32	0.01
Beef	10.1	56%	1.75	0.30
Horticulture	0.5	3%	5.64	9.90
Industrial	0.8	4%	0.50	0.02
Native vegetation	1.0	6%	0.65	0.01
Orchard	0.0	0%	1.28	0.00
Public open space	0.5	3%	2.52	0.04
Road reserve	1.3	7%	0.38	0.02
Rural living	0.5	3%	1.15	0.11
School	0.6	3%	2.52	0.04
Urban residential	1.9	11%	1.85	0.20
Water	0.2	1%	0.01	0.01
Totals/weighted average	18	100%	1.62	0.48

Box model of the Lower Vasse River

This method involved calibrating the box model of the Lower Vasse River using observed concentrations in the river. The box model considers the process of mixing from different catchment sources, stage-volume and stage-surface area relations for the Lower Vasse River and New River wetlands, and evapo-concentration. Nutrient release and deposition within the system and biological processes were not considered.

It was assumed that the Lower Vasse River acts as a store which receives water and nutrients from the local catchment and the Vasse Diversion Drain. The store discharges through the Butter Factory weir based on a rating table, and water can also be lost via evaporation. No nutrient cycling was considered, and nutrients were assumed to be lost from the system only with discharge (i.e. as the product of discharge and concentration in the store).

The input nutrient concentrations from the Vasse Diversion Drain and Lower Vasse River catchment were adjusted within sensible bounds to meet the measured median concentrations in the Lower Vasse River. Calibrated concentration parameters for TP and TN are shown below. The parameters adopted for the modelling are consistent with the estimated concentrations from the land use mapping and measurements in the Vasse Diversion Drain and Sabina Diversion Drain.

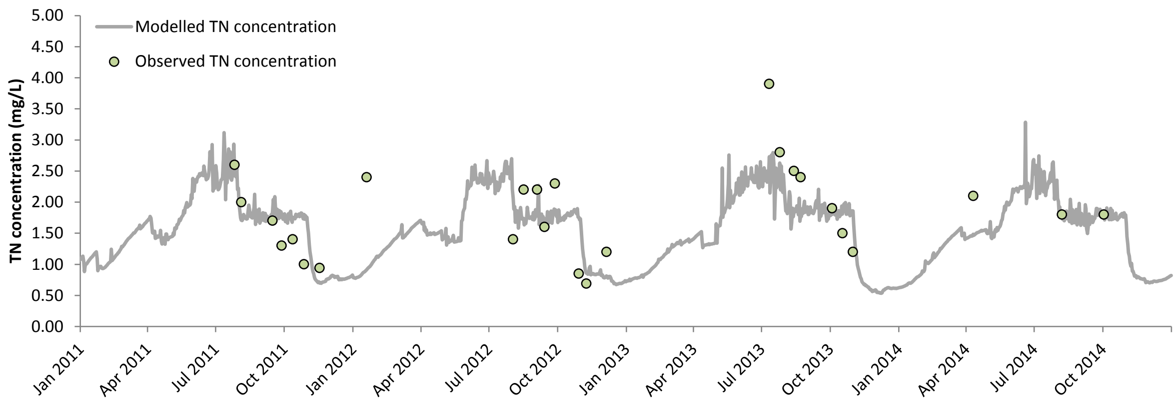
Modelled versus observed TN and TP concentrations for the box model are shown in the figures below.

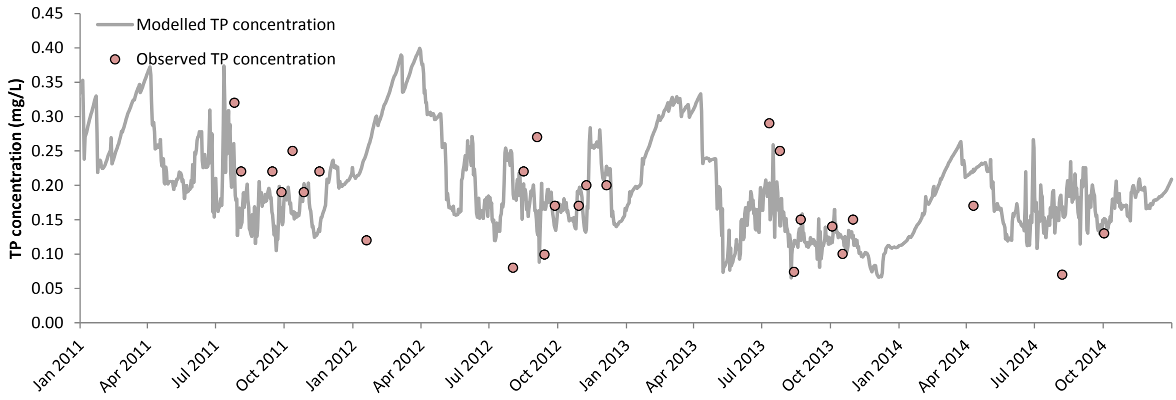
Calibrated seasonal nutrient concentrations used in mass balance modelling for the Lower Vasse River

	Lower Vasse River catchment		Vasse Diversion Drain	
	TN mg/L	**TP mg/L**	**TN mg/L**	**TP mg/L**
Feb-Apr	2.20	0.35	1.56	0.12
May-Jul	2.70	0.35	2.19	0.10
Aug-Oct	1.63	0.30	1.95	0.09
Nov-Jan	1.00	0.35	0.49	0.05

Calculating nutrient concentrations in runoff from the Lower Sabina River catchment

The Sabina River receives no flow from the upper catchment so water quality sampled in the lower reaches of the river are reflective of the lower catchment only. Therefore, the measured concentrations were used in the nutrient mass balance for scenarios on the Sabina.





Modelled and measured TN and TP concentrations for the Lower Vasse River (2011–14)

Nutrient mass balance for scenario modelling

The mass balance was calculated for each scenario by adjusting the inflows from the Vasse Diversion Drain or the Sabina Diversion Drain for the lower river reaches. The average annual nutrient load is the sum product of flow and concentration from the different sources.

For the Lower Vasse River, the seasonal concentration was calculated as the median modelled concentration of the box model, which accounts for the effects of storage in the Lower Vasse River.

For the Lower Sabina River, seasonal concentration was calculated as the median flow-weighted concentration from inflows.

Appendix M Summary of modelling results

Legend

- Acceptable flood risk (blue)
- Potential benefit (green)
- High risk for flood or increased nutrient pollution (orange)
- Negligible change (yellow)

Scenario	Flood risk	Annual river loads (% increase) N	Annual river loads (% increase) P	% time medium silt is mobilised in the LVR	Water residence time (days) in the LVR JAN–MAR	Water residence time (days) in the LVR AUG–SEP	November nutrient concentration (% change) TN	November nutrient concentration (% change) TP	Comments
LOWER VASSE RIVER SCENARIOS									
S00 Base case				0.2	> 300	1			
S00s S00 + spillway at VDD offtake		0	0	0.2	> 300	1	0	0	
S00sb S00 + spillway at VDD offtake + bridge upgrade		0	0	0.2	> 300	1	0	0	
S01 1 x 900 mm culvert fully open		2	1	0.5	> 300	1	0	-1	
S02 1 x 900 mm + 1 x 450 mm culverts		23	11	0.8	> 300	1	-5	-8	Nutrient load increase / slight Nov concentration reduction / slightly increased sediment mobilisation
S03 2 x 900 mm culverts		45	20	1.7	> 300	1	-6	-8	Nutrient load increase / slight Nov concentration reduction / slightly increased sediment mobilisation
S03s 2 x 900 mm culverts + spillway at VDD offtake		45	20	1.7	> 300	1	-6	-8	Nutrient load increase / slight Nov concentration reduction / slightly increased sediment mobilisation
S03sb 2 x 900 mm culverts + spillway at VDD offtake + bridge upgrade		45	20	1.7	> 300	1	-6	-8	Nutrient load increase / slight Nov concentration reduction / slightly increased sediment mobilisation
S04 3 x 900 mm culverts		80	40	3.5	> 300	1	-8	-9	Flood risk / excessive nutrient load increase = not recommended

Legend

- Acceptable flood risk (blue)
- High risk for flood or increased nutrient pollution (orange)
- Potential benefit (green)
- Negligible change (yellow)

Scenario	Flood risk	Annual river loads (% increase)		% time medium silt is mobilised in the LVR	Water residence time (days) in the LVR		November nutrient concentration (% change)		Comments
		N	P		JAN–MAR	AUG–SEP	TN	TP	
S04s 3 x 900 mm culverts + spillway at VDD offtake		80	40	3.5	> 300	1	-8	-9	Flood risk / excessive nutrient load increase = not recommended
S04sb 3 x 900 mm culverts + spillway at VDD offtake + bridge upgrade		80	40	3.5	> 300	1	-8	-9	Excessive nutrient load increase = not recommended
S05 FULL		200	90	9	> 300	< 1	-8	-9	Excessive flood risk / excessive nutrient load increase = not recommended
S06 2 x 900 mm culverts open Aug–Oct		3	1	1.1	> 300	1	54	69	Excessive increase in November nutrient concentration = not recommended
S07 Recycled WW to LVR		8	8	0.2	13–14	1	3	-11	Reduces water residence time in LVR in summer
S14 2 x 900 mm + remove butter boards		45	20	NA[2]	NA[2]	NA[2]	NA[2]	NA[2]	Nutrient load increase
S13 VASSE: 2 x 900 mm culverts; SABINA 1 x 900 mm culvert		39	18	1.7	> 300	1	-6	-8	
SABINA RIVER SCENARIOS									
S09 1 x 450 mm culvert		35	5	NA	NA	NA	0	0	
S10 1 x 900 mm culvert		52	7	NA	NA	NA	0	0	
S10a 2 x 900 mm culverts		130	8	NA	NA	NA	0	0	Excessive nutrient load increase = not recommended
S11 FULL		150	11	NA	NA	NA	0	0	Flood risk / excessive nutrient load increase = not recommended

Scenario	Flood risk	Annual river loads (% increase)		% time medium silt is mobilised in the LVR	Water residence time (days) in the LVR		November nutrient concentration (% change)		Comments
		N	P		JAN–MAR	AUG–SEP	TN	TP	
S13 VASSE: 2 x 900 mm culverts; SABINA 1 x 900 mm culvert		52	7	NA	NA	NA	0	0	
OTHER									
S08 Check boards raised to 0.6 mAHD		NA	NA	NA	> 300	1	NA	NA	Being considered in Review Surge Barrier project
S12 Removal of surge barriers		0	0	0.2	> 300	1	0	0	Unacceptable risk of flooding land with salt water / increases Busselton's flooding potential = not recommended

Legend

- Acceptable flood risk
- High risk for flood or increased nutrient pollution
- Potential benefit
- Negligible change

FULL = full reconnection; NA = not applicable; LVR = Lower Vasse River; NA[2] = not applicable because LVR would dry out in summer

Notes

1 S06 2 x 900 mm culverts open Aug–Oct. In this scenario the culvert is open during Aug–Oct and closed during the rest of the year. Concentrations during Aug–Oct are the same as for S03. For the rest of the year LVR TN and TP concentrations are no longer diluted by inflows from the Vasse Diversion Drain and are much higher than those of the base case.

2 S14 2 x 900 mm culverts re-grade LVR – note that sediment mobilised from the LVR will flow to the Vasse Estuary with potential adverse impact.

3 S13 VASSE: 2 x 900 mm culverts; SABINA 1 x 900 mm culvert affects both the Lower Vasse and Lower Sabina rivers so is listed twice. It produces the same result in the Lower Sabina River as S10, but the result in the Lower Vasse River is slightly different to S03 because there is less water available for diversion at the Vasse Diversion Drain offtake in S13 compared with S03.

Shortened forms

AEP	annual exceedence probability
ANUGA	Australian National University Geoscience Australia
ANZECC	Australia and New Zealand Environment and Conservation Council
AR&R1987	Australian Rainfall and Runoff 1987
ARF	areal reduction factor
ARI	average recurrence interval
BoM	Bureau of Meteorology
COM2D	2D Coastal Ocean Model
CRC-FORGE	Cooperative Research Centre – Focussed Regional Growth Estimation
DEC	former Department of Environment and Conservation
DoW	former Department of Water
DEM	digital elevation model
DPAW	former Department of Parks and Wildlife
ELCOM	Estuary and Lake Computer Model
FFA	flood-frequency analysis
GEMS	Global Environmental Modelling Systems
HEC RAS	Hydrologic Engineering Center River Analysis System
IFD	intensity–frequency–duration
IL	initial loss
JDA	Jim Davies and Associates
LiDAR	Light Detection and Ranging
LPIII	Log-Pearson type three probability distribution
LSR	Lower Sabina River

Lower Vasse River	Lower Vasse River
mAHD	metres Australian height datum
MDBMC	Murray–Darling Basin Ministerial Council
PWD	Public Works Department
RoC	Runoff Coefficient
RORB	Runoff Routing B
RTK	real-time kinematic
SDD	Sabina Diversion Drain
SQUARE	Stream Quality Affecting Rivers and Estuaries
TN	Total Nitrogen
TP	Total Phosphorus
Vasse Diversion Drain	Vasse Diversion Drain
Vasse Estuary	Vasse Estuary
WAWA	Water Authority of Western Australia

Terminology

The Australian Rainfall Runoff 2016 preferred terminology was adopted for this report as shown in the table below. For consistency in terminology ARIs of 1 in 5 and 1 in 10 years were assumed equivalent to the 20% and 10% AEP events.

AEP (%)	AEP (1 in x)	ARI	Frequency of observation
20%	5	4.48	Frequent
10%	10	9.49	
5%	20	20	Infrequent
4%	25	25	
2%	50	50	
1%	100	100	Rare
0.5%	200	200	
0.2%	500	500	

References

ANZECC 2000, *Australian water quality guidelines for fresh and marine waters*, Australian and New Zealand Environment and Conservation Council, Kingston.

Brearley, A 2005, *Ernest Hodgkin's Swanland; Estuaries and coastal lagoons of south-western Australia*, University of Western Australia Press, Crawley, Western Australia.

Brookes J 2012, *River Torrens water quality improvement trial – summer 2011/12*, Goyder Institute for Water Research Technical Report Series no. 12.

Department of Environment and Conservation 2011, *Depth, salinity and temperature profiling of Vasse-Wonnerup wetlands in 1998–2000,* Department of Environment and Conservation.

Department of Water 2010, *Vasse Wonnerup Wetlands and Geographe Bay water quality improvement plan*, Department of Water.

Department of Water 2014, *Floodplain management,* Water Facts 14, Department of Water.

Durrant, J & Bowman, S 2004, *Estimation of rare design rainfalls for Western Australia – Application of the CRC-FORGE method*, Surface water hydrology series, report no. HY17, Department of Environment, Western Australia.

Eckhardt, K 2005, 'How to construct recursive digital filters for baseflow separation', *Hydrological Processes*, no. 19, pp. 507–515.

GHD 2003, *Engineering design report: Vasse and Wonnerup estuaries: surge barrier replacement*, Water Corporation.

GHD 2013, *Hydrologic review of Busselton Flood Protection – Vasse Diversion Drain catchment area*, Report CD000116, prepared by GHD for the Water Corporation, Oct 2013, Perth.

Hall, J 2011, *Scott River catchment hydrological and nutrient modelling – Supporting document for stage 1 of the Hardy Inlet water quality improvement plan*, Water Science Technical Series, report no. 37, Department of Water, Western Australia.

Hall, J in prep., *Geographe Bay catchment hydrological and nutrient modelling*, Water Science Technical Series, report no. x, Department of Water and Environmental Regulation, Western Australia.

Intergovernmental Panel on Climate Change 2013, *Climate change 2013: the physical science basis, summary for policymakers, Contribution of Working Group I to the IPCC Fifth Assessment Report, Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York.

JDA 1998, *Busselton regional flood study review and appendices,* JDA consultant hydrologists for the Water and Rivers Commission.

Julien, P 2002, *River mechanics*, Cambridge University Press, United Kingdom.

Kuczera, G 2001, FLIKE Bayesian flood frequency analysis, software, version 4.5, University of Newcastle, New South Wales, Australia.

Lane, JAK, Hardcastle, KA, Tregonning, RJ & Holtfreter, GJ 1997, Management of the Vasse-Wonnerup wetland system in relation to sudden, mass fish deaths, unpublished report for the Vasse Estuary Technical Working Group, WA Department of Conservation & Land Management, Busselton.

Lane, J, Clarke, A & Winchcombe, Y 2011, *Depth, salinity and temperature profiling of Vasse-Wonnerup wetlands in 1998–2000,* Department of Environment and Conservation.

Marillier, B 2010, *WaterCAST nutrient modelling of the Leschenault catchment,* Water Science Technical Series, report no. 15, Department of Water, Western Australia.

Martin, S, Moore, D & Hazelwood, M 2014, *Coastal inundation modelling for Busselton, Western Australia, under current and future climate*, Record 2014/03, Geoscience Australia, Canberra.

MDBMC 1994, *The Algal Management Strategy for the River Murray*, Murray–Darling Basin Ministerial Council, Canberra.

Mitrovic, M, Hardwick, L & Forugh, D 2011 'Use of flow management to mitigate cyanobacterial blooms in the Lower Darling River', *Journal of Plankton Research*, vol. 33, no. 2, pp. 229–241.

Pilgrim, DH 2001, *Australian rainfall and runoff: A guide to flood estimation: Volume 1*, The Institution of Engineers Australia, Barton.

Public Works Department 1984, *Busselton regional flood study: hydrological investigations*, Public Works Department, Western Australia.

Public Works Department1978, *Bunbury Engineering District – effects of storm of April 4, 1978*, Public Works Department, Western Australia.

Shore Coastal 2015, *Busselton storm surge response plan*, technical report prepared for the City of Busselton, Shore Coastal.

Water and Rivers Commission 1999, Letter from Rick Bretnall to resident on Bunyip Road near the Lower Sabina, Water and Rivers Commission.

Water Authority of Western Australia 1987, *Busselton regional flood study*, Water Authority of Western Australia.

Water Authority of Western Australia 1994, *Country drainage: Busselton Drainage District*, Water Authority of Western Australia.

Water Authority of Western Australia 1997, *Vasse River Diversion Drain: flood hydrology*, Water Authority of Western Australia.

Water Corporation 2002, Rural Drainage Services customer information brochure, Water Corporation.

Watts, J, Allan, C, Bowmer, K, Page, K, Ryder, D & Wilson, T 2009, *Pulsed flows: a review of environmental costs and benefits and best practice,* Waterlines report, National Water Commission, Canberra

Water Research and Management 2007, Ecological character description for the Vasse-Wonnerup wetlands Ramsar Site in south-west Western Australia, unpublished report to the Department of Environment and Conservation and Geographe Catchment Council Inc. by Wetland Research & Management. September 2007

Worley Parsons 2013, Extreme water level analysis to support Port Geographe reconfiguration of coastal structures, Technical note, Worley Parsons for the Department of Transport.

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