Chapter 4: RIVERINE FLOOD HAZARD

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2.1 Introduction

This chapter examines flood estimation associated with heavy rainfall, resulting in the overbank flows from rivers or streams onto the floodplain. In general, the factors that influence whether or not a flood will occur include:

- volume, spatial distribution, intensity and duration of rainfall over the catchment;
- catchment and weather conditions prior to the rainfall event;
- ground cover;
- topography;
- the capacity of the watercourse or stream network to convey the runoff; and
- tidal influence.

The Department of Environment (DOE) is Western Australia's lead agency responsible for floodplain mapping and floodplain management. The Department provides advice on development of floodplains to promote wise use of floodplains while minimising flood risk and damage. Previous to this study, the Department undertook floodplain mapping for the 1% annual exceedence probability (AEP) event for the Swan River and other rivers. Though the DOE have only mapped the 1% AEP flood event, flood levels for the 10%, 4% and 2% AEP events have also been determined.

The work undertaken in this study significantly increases the number and range of scenarios modelled and mapped. Eight scenarios are modelled, ranging from the 10% AEP to the 0.05% AEP. This study updates the floodplain geometry to account for changes to the floodplain. It also models the effect of tributaries on flooding in the Swan River and flooding in the tributaries themselves. Through the use of the dynamic hydraulic model HEC-RAS, this study also adds on the information available for the 1% AEP flood through introducing the temporal aspects of inundation. Put simply, it enables changes of flood inundation extent, depth and velocity to be modelled over the period of the flood event. The results shown in this chapter will, however, focus on the maximum depth of inundation. Future work will incorporate the temporal aspects of inundation available from the model with a building database in order to model flood damages and estimate losses.

This chapter focusses on flood estimation. The physical setting of the study area is described and an overview given of historical riverine flooding. The development of the design hydrographs for flood estimation is then described and the reader is referred to previous reports where appropriate. The report then focusses on the hydraulic modelling of the Swan and Canning Rivers and tributaries. Model development is described, followed by the calibration and validation of the model. The impact of the tributaries, simulated inflow hydrographs and tidal cycle variation are covered. Finally, floodplain maps are presented showing maximum water-depth contours.

Flood estimation

Flood estimation for planning purposes aims to estimate the long-term probability of flood impacts so that appropriate planning decisions can be made to minimise that impact. As a complex set of factors influences whether or not flooding occurs in a catchment, it is difficult to define the causes or the effects of an ‘average’ flood. Put simply, no two floods in the same catchment are ever identical. To overcome this problem, floodplain managers and hydraulic engineers rely on a series of design flood events and historical rainfall and flood level information. It is upon these that this chapter is based.

Six data sets are important in predicting floods:

- historical rainfall and runoff data across a catchment;
- historical river height and discharge information;
- catchment topography and land use;
- surveys of river and floodplain levels and cross sections;
- models of the hydrologic processes (rainfall, runoff, infiltration, concentration etc.);
- models of the hydraulic processes (propagation, attenuation etc.).

Typically, these analyses are undertaken by hydrologists and specialist engineers skilled in the physical understanding of rainfall patterns and the behaviour of floods. The results of such studies are often used to set freeboards for proposed development (such as housing) or public works like roads, bridges and levee systems.

Items (1) and (2) are essential for describing the statistical nature of the flood hazard. Using this data the various models derived in (3), (4), (5) and (6) can be calibrated and validated. Using statistical analyses of the historical rainfall data, a well-calibrated model is then capable of predicting the impact of floods unlike those experienced in the past. It can also be used test potential flood mitigation strategies, such as the construction of new channels, levees and detention basins. The model may be used to establish planning zones, with regulations that may stipulate that a property be built to a minimum property floor level. The limit of infilling in a floodplain to prevent the raising of flood levels can also be determined by the model.

The data collection and modelling process leads to a statistical description of flooding for a specific community. Planning regulations must then be adopted which aim to limit the social, economic and environmental impact of flooding on a community. Typically, the 1% AEP level is used as the ‘designated flood’ level for planning purposes. A freeboard allowance, typically 0.5 m, is then applied above the designated level to provide a measure of safety and to allow for wind and wave set-up and the tidal effect caused by vehicles and vessels. The AEP is a statistical benchmark used for flood comparison. Average recurrence interval (ARI) is another commonly used statistical benchmark, and is often referred to interchangeably with AEP. The 1% AEP, for example, is often referred to being the same as the 100 year ARI., Technically, the two terms are not interchangeable. ARI is the average interval in years which would be expected to occur between exceedances of flood events of a given magnitude. AEP is the probability of a flood event of a given magnitude being equalled or exceeded in any one year (Institute of Engineers, 1987).

The definition given for the probable maximum precipitation (PMP) by the World Meteorological Organisation (WMO, 1986) is

> *the greatest depth of precipitation for a given duration meteorologically possible for a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends.*

The PMP is used for estimating the probable maximum flood (PMF). The PMF is the limiting-value flood which can reasonably be expected to occur. It is usually perceived as having an AEP of between 0.01% and 0.00001% (Nathan and Weinmann 1999, Laurenson 1994 cited in SCARM, 2000). This report however does not examine the effects of the PMF.

4.2 Physical Setting

Catchment description

The major tributaries of the Swan–Canning estuary are the Swan/Avon River, Ellen Brook, Susannah Brook, Helena River, Jane Brook, Canning River and the Southern River–Wungong Brook (Figure 4.1). The Swan River is tidal to its confluence with Ellen Brook, which is approximately 60 km from the mouth of the Swan River at Fremantle. The Kent St weir (Plate 4.1) on the Canning River in the suburb of Wilson limits the extent of the tidal excursion in all but the most extreme storm surge situations.

Plate 4.1: Kent St weir on the Canning River generally looking upstream (Photo: Middelmann, 2003)

Avon River

The Avon River, with a catchment area of more than 120,000 km^2, is by far the largest catchment that drains into the Swan–Canning estuary (Figure 4.2). Two major systems of inter-connected lakes (Lockhart and Yilgarn systems) account for approximately 75% of the entire catchment area and combine within the Yenyenning Lakes subcatchment to overflow into the Avon River upstream of Beverley during major flood events. The Walyunga gauging station on the Avon River has been operational since 1970. Officially the Avon River changes into the Swan River at the confluence of Wooroloo Brook; but in reality, both the Avon River and Wooroloo Brook flow into a pool which overflows into the Swan. Of the tributaries, the Avon River carries by far the greatest volume of water to the Swan–Canning estuary.

Ellen Brook

Ellen Brook is located west of the Darling Scarp between the town of Gingin, some 70 km north of Perth, and the outlet to the Swan River at Upper Swan (Figure 4.3). Ellen Brook has a catchment area of approximately 640 km^2. More than 70% of the diverse, low-forest native vegetation has been cleared since the 1950s for sheep and cattle grazing, vineyards and orchards. The streamflow gauging station, Railway Parade, is located 7.5 km upstream of the confluence with the Swan River.

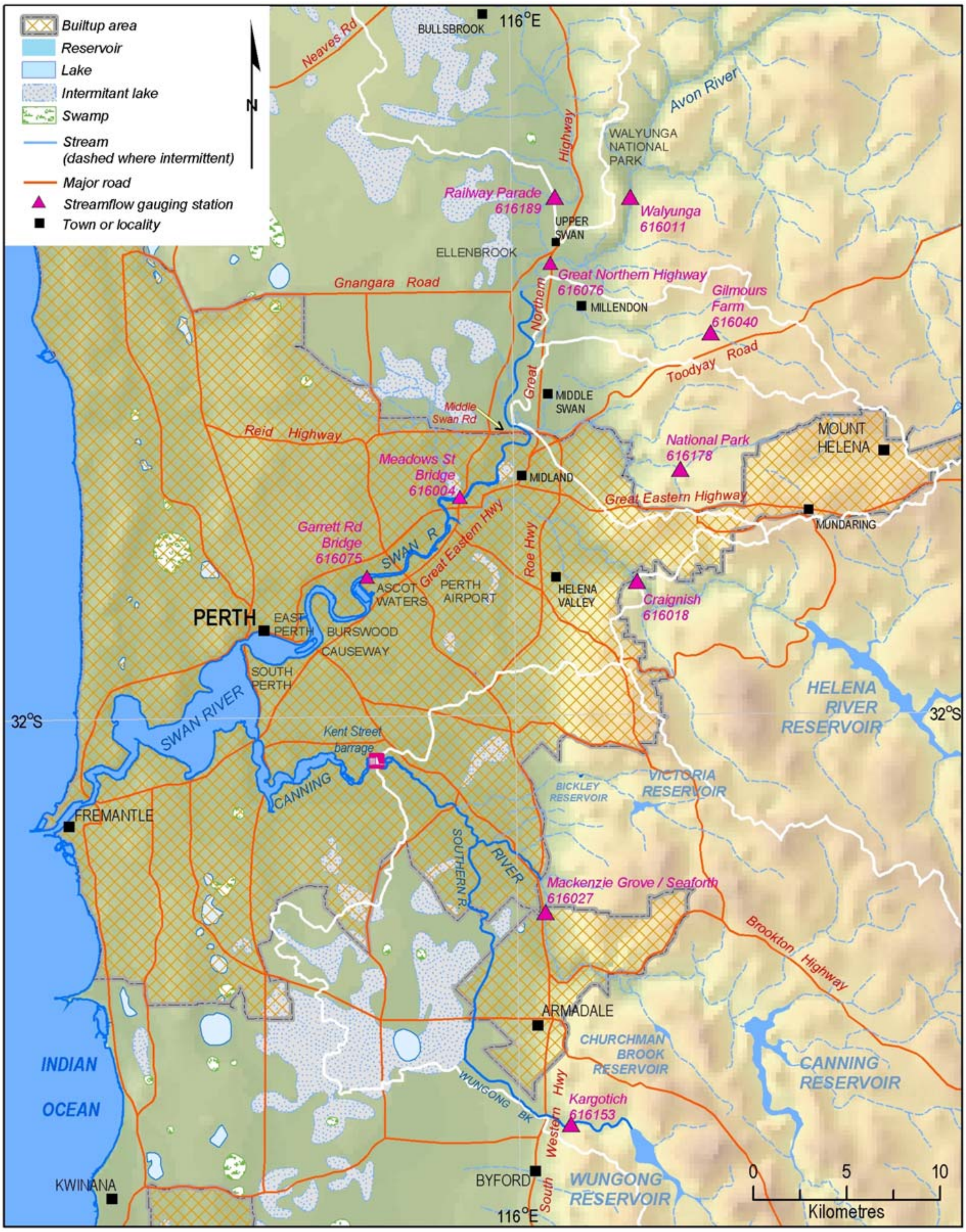

Figure 4.1: The Swan–Canning catchment

Susannah Brook

Susannah Brook has a catchment area of approximately 55 km^2, and is located west of the Darling Scarp about 25 km northeast of Perth (Figure 4.4). Over than 70% of the native vegetation has been cleared since European settlement and is currently used as pasture, orchards and hobby farms. Portions of the catchment have been taken up by suburban developments, particularly in the lower reaches. A streamflow gauging station at Gilmours Farm has monitored the flow from the upper half of the catchment since 1981.

Jane Brook

Jane Brook has a catchment area of approximately 131 km^2, and is located west of the Darling Scarp, about 30 km northeast of Perth (Figure 4.5). Roughly half of the native Jarrah forest vegetation has been cleared since European settlement and is now mainly used for pasture, orchards and hobby farms. Portions of the catchment have been taken up by suburban developments, particularly in the lower reaches. The streamflow gauging station at National Park has been operational since 1962.

Helena River

The Helena River has a catchment area of approximately 1,860 km^2 (Figure 4.6). Almost 75% of the catchment (1476 km^2) is above Mundaring Weir which has a capacity of around 64 GL. Located about 20 km northeast of Perth, the weir supplies water for metropolitan domestic use and also by pipeline to the goldfields, some 600 km east of Perth. The Helena River catchment above Mundaring Weir is completely within the Darling Plateau and has no significant clearing of the natural vegetation. Below Mundaring Weir, about 50% of the catchment has been cleared for pasture and orchards. The streamflow gauging station of Craignish is located 15.5 km upstream from the Swan River confluence and has been operational since the mid-1970s.

Canning River

The Canning River has a catchment area of approximately 1,300 km^2, extending about 70 km southeast of Perth into the Darling Scarp (Figure 4.7). The lower foothills and flat plains west of the Scarp have largely been cleared for agriculture and urbanisation. In the section of the catchment within the Scarp, the majority of the native vegetation is still present.

Three-quarters of the catchment is regulated, largely by the Canning Reservoir, though Wungong and Churchman Brooks, and the Victoria and Bickley Reservoirs also have some influence. Approximately 6 km downstream of Wungong Reservoir, 40% of flow is diverted into the Birrega Drain within the adjacent Serpentine River catchment (Waugh, 1986). Kangaroo Gully diversion weir and contour channel diverts flow from Kangaroo Gully into the Canning Reservoir. Any flow in excess of 2.2 m^3/s spills over the weir and continues down Kangaroo Gully, which joins the Canning River just downstream of the Canning Reservoir.

A number of streamflow gauging stations monitor the flow in the Canning River and its tributaries, the earliest of which commenced operation in the 1950s. Streamflow records from the Mackenzie Grove gauging station, which were used in this study for model calibration, began in 1974. In April 1997, Mackenzie Grove was replaced as the primary gauging station by Seaforth, 520 m downstream.

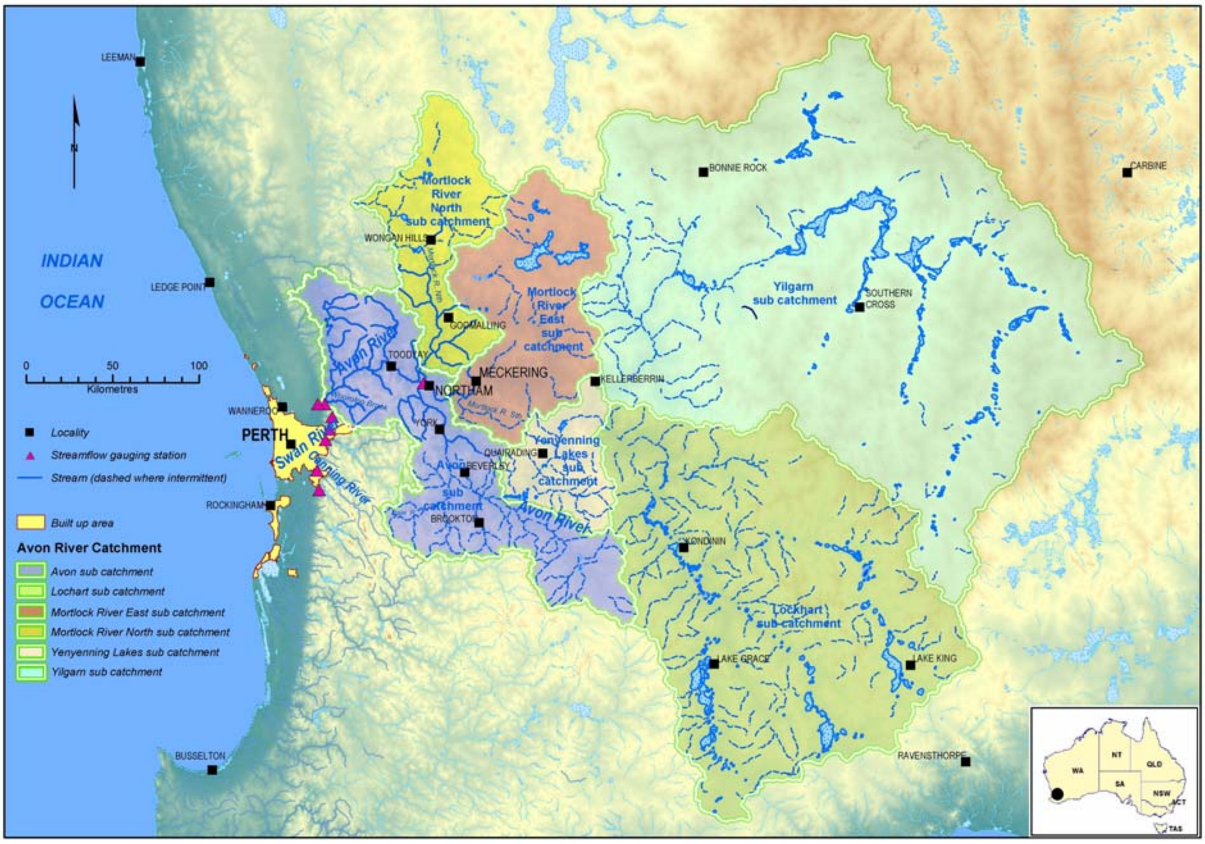

Figure 4.2: The Avon River catchment

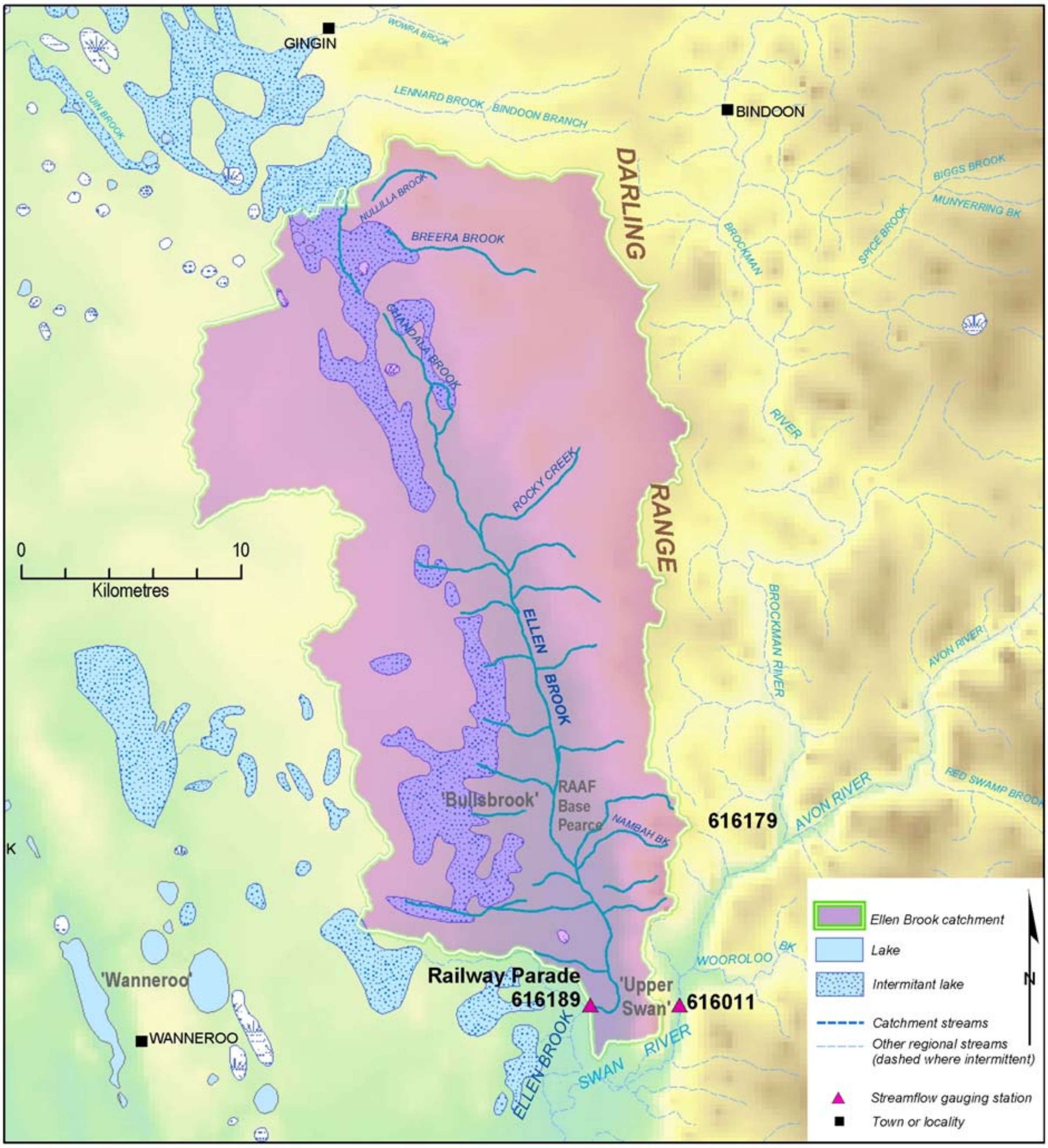

Figure 4.3: The Ellen Brook catchment

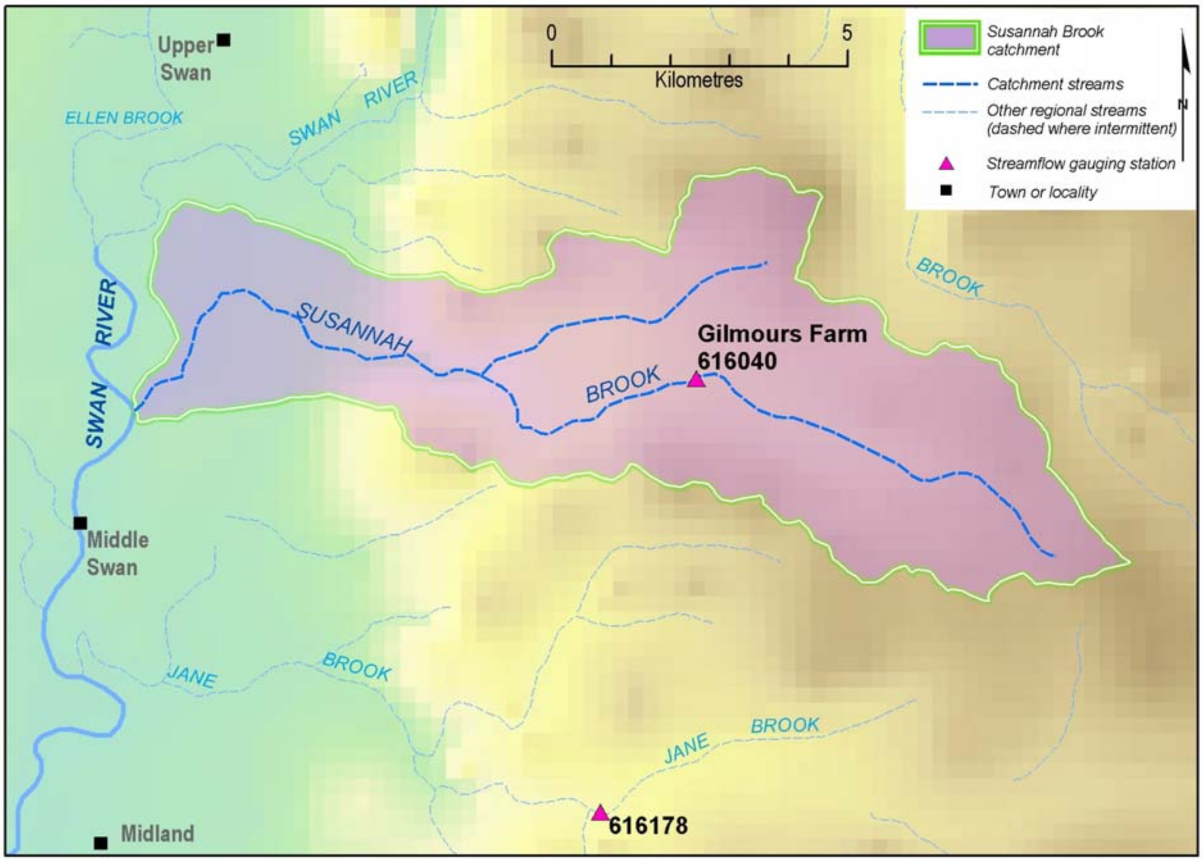

Figure 4.4: The Susannah Brook catchment

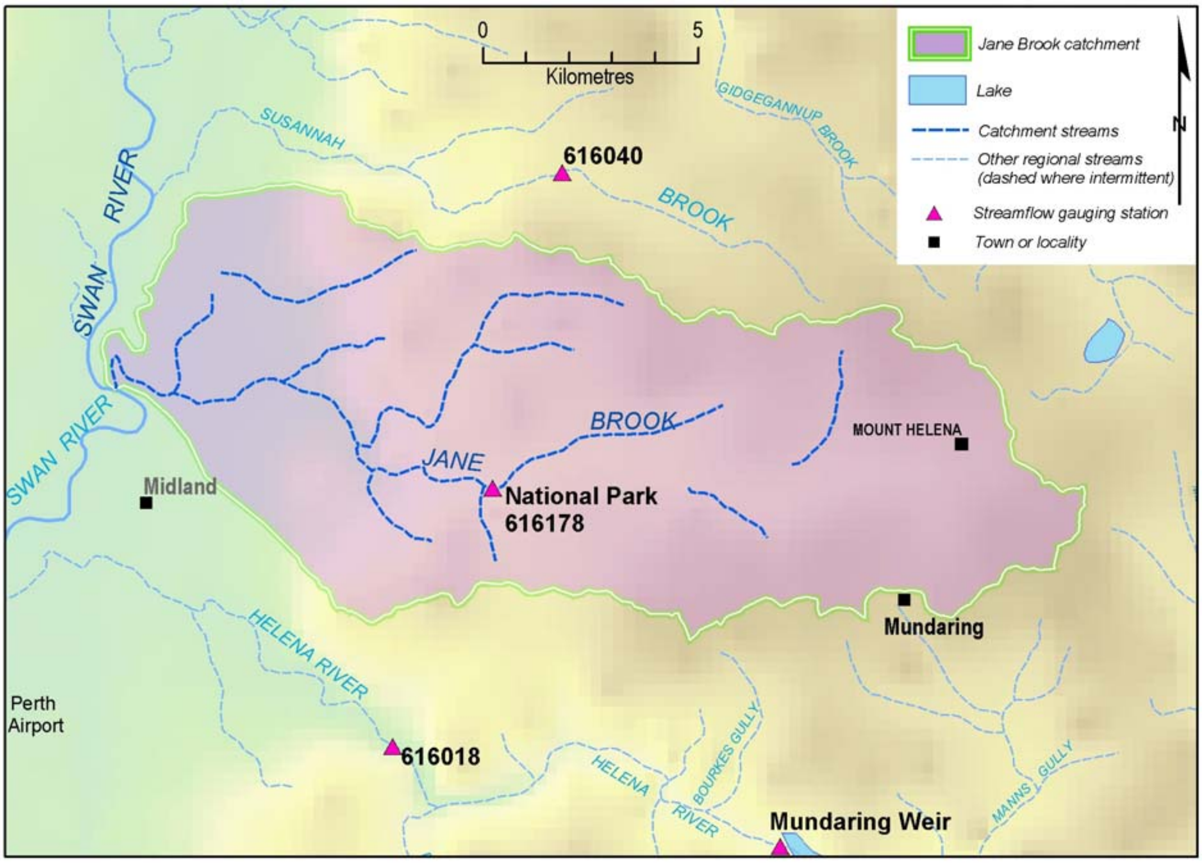

Figure 4.5: The Jane Brook catchment

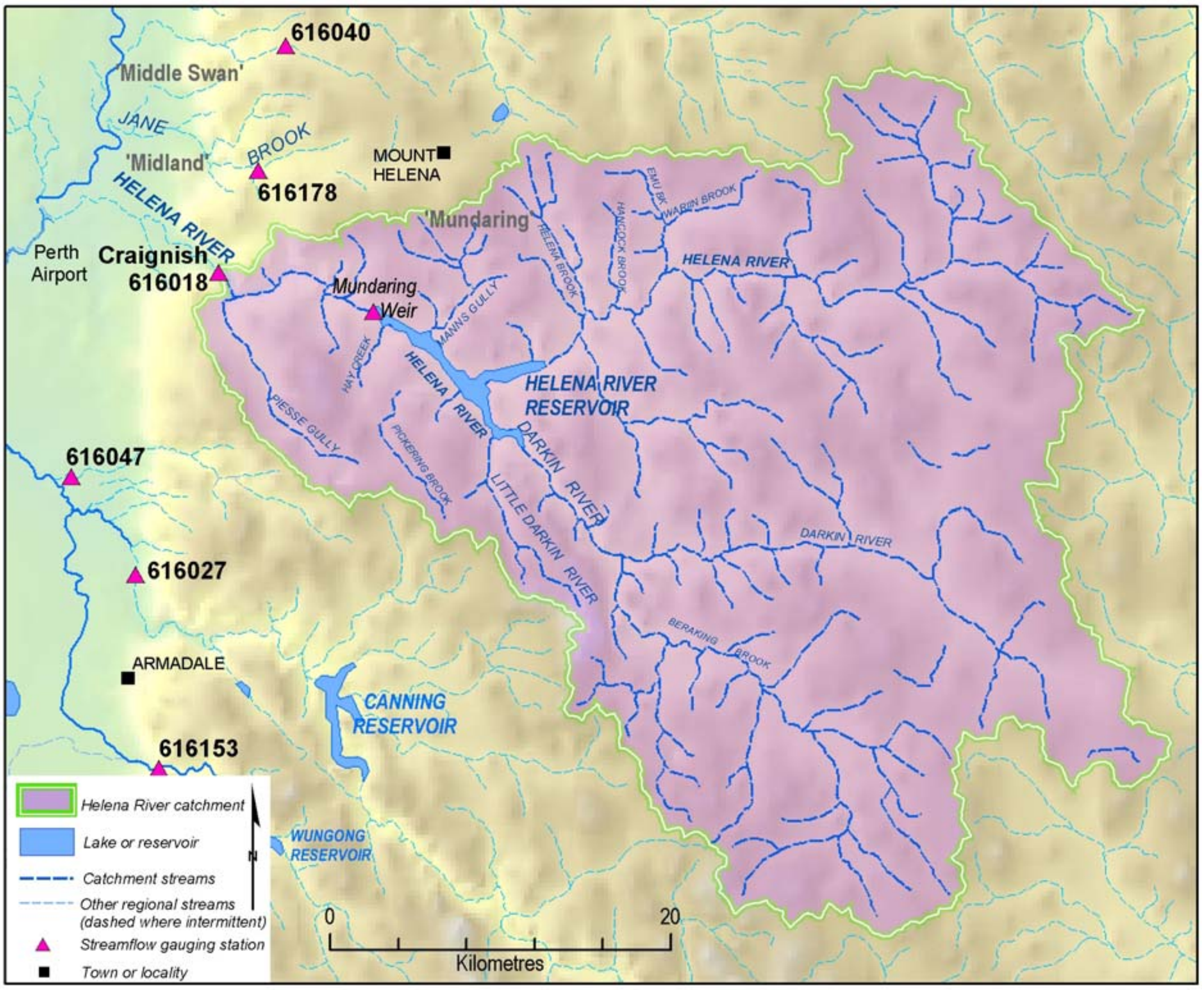

Figure 4.6: The Helena River catchment

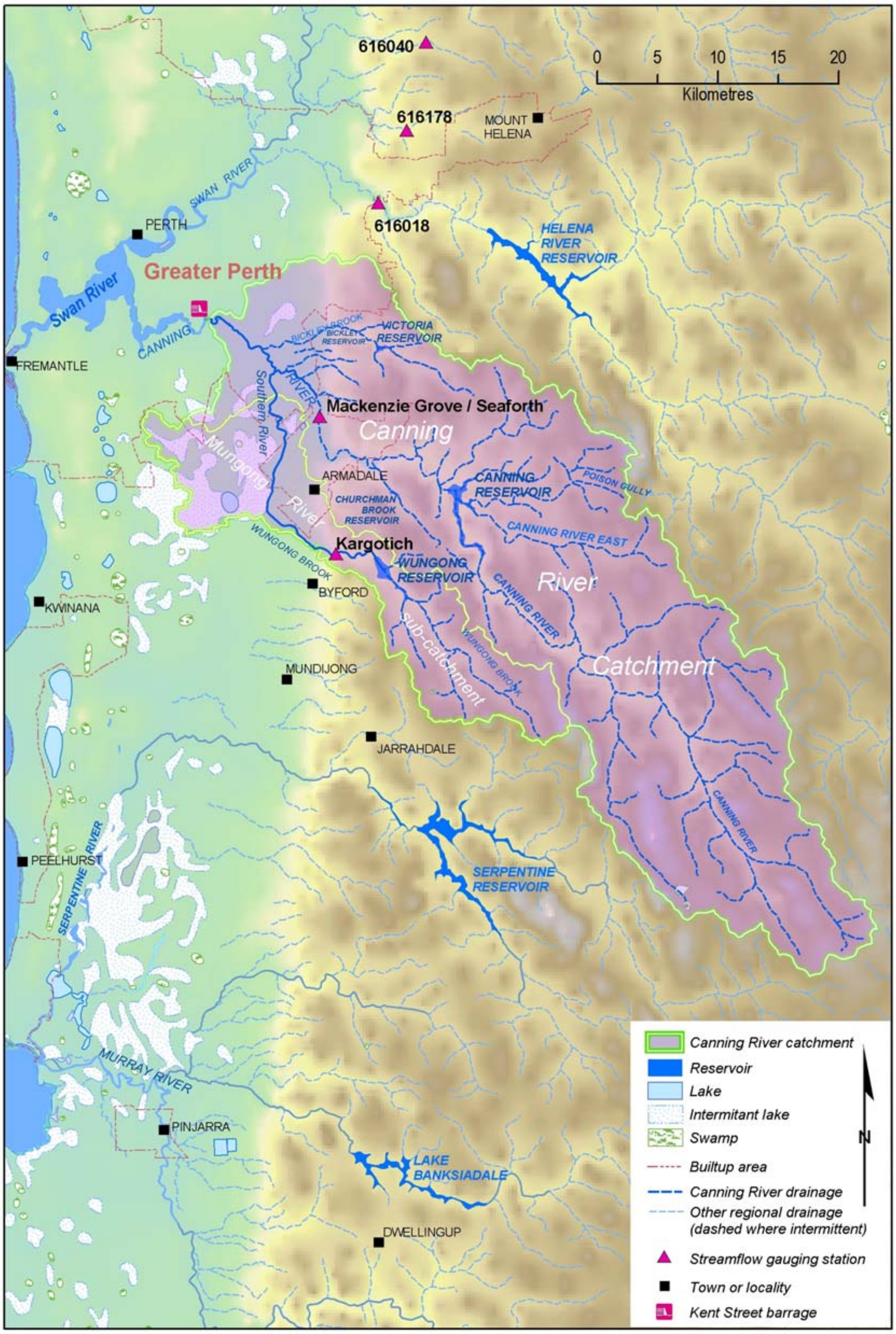

Figure 4.7: The Canning River catchment

4.3 Historical Flooding

Historical flood records and information for the Swan River extend back as far as July 1830.

In July 1830, the Swan River rose more than 6 m above its usual level, doing considerable damage (Bureau of Meteorology (BOM), 1995). In July–August 1847, flooding of the low-lying areas around Perth forced some residents to evacuate their homes (BOM, 1929). On 24 August 1860, the *Perth Gazette* reported extensive flooding along the Avon and Swan Rivers, following a very wet period during the preceding three months. On the Canning River, a flood with a 4% AEP was recorded in July 1987.

Table 4.1 gives the years of major floods from 1862 to 2004 and their estimated return period. The absence of major river flooding since the early 1960s has kept flood damage costs low in Perth.

Table 4.1: Floods in the Swan River, Perth, and their estimated ARI (PWD, 1986)

Year	1862	1872	1910	1917	1926	1930	1945	1946	1955	1958	1963	1964	1983
ARI	60	100	20	20	30	15	20	10	20	20	15	10	10

Losses from the flood in July 1862 were reported on 12 March 1934 in the *West Australian* at an estimated 30,000 pounds (1862 values), a considerable sum at the time. Since then, considerable infrastructure and buildings have been constructed on the floodplain. The 1862 flood, estimated to have an ARI of 60 years, was said by some sources to be unprecedented. The *Perth Gazette* (11 July 1862) reported that much property was destroyed, with gardens backing onto the river between the Causeway and Mt Eliza largely underwater. A contemporary account of the flood, describing the extent, depth and duration of flooding follows:

> *To show the enormous accumulation of water in the Estuary, we may state that the area occupied by Perth and Melville Waters, as laid down in the maps of the Survey Office, is given as 7,100 acres, over all of which the rise of seven feet took place; but in addition, we have to take into consideration the large extent of lowland (but lying above the usual water level) which was also covered to a depth of several feet. The flood maintained its highest level until about 10 pm on 7th (Sunday), when a slight ebb commenced and continued until Wednesday morning, the fall being about one foot. A reaction then commenced (probably owing to spring tides having set in outside) and on the 10th at North Fremantle the whole of the Pensioners Cottages and allotments were under water… The flats on the Swan were flooded for some time, the bridge over the Helena was covered above its top rails, and the Causeway had between seven and eight feet of water upon it. In places the only means of communication was a small boat. Two of the police force, when trying to get across the river on horseback, were swept by the current among the trees on the flat and had a narrow escape from drowning. At Strelly an entire farm and its contents were swept away… the flood maintained its height for fourteen days, and reached two feet above that of 1830… Several losses of life through the floods were reported: - Lieutenant Oliver, 12th Regiment, at Perth; a shepherd at York; one person at Toodyay and two on the Greenough Flats… In the southern districts parts of the bridge over the Canning River disappeared, leaving the centre standing.*

The largest flood in the known record occurred ten years later in July 1872 and has an estimated AEP of 1%. The flood reportedly caused considerable property damage along the Swan–Avon River (BOM, 1995). A contemporary account of the flood from the *Perth Gazette and WA Times* (26 July 1872) follows:

> *In and about Perth, the water owing to the force of the incoming seas at the mouth of the river presented a scene of a great lake, all the jetties were submerged, the high roads to Fremantle covered, and passage traffic rendered impossible quantities of sandalwood lying along the banks of river were washed away, and the inhabitants of the suburban villas on the slopes of Mt Eliza obliged to scramble up the hill sides to get into Perth. In some of them, especially Mr C Watson's, the water*

rose two feet inside, that gentleman getting in and out only by means of his boat. From Guildford and the Swan we hear of serious injury, the Helena Bridge causeway has been much damaged – a large extent of land remains unsown and fortunately as compared with those that have been sown will give no returns… Much live stock has been lost, and but for the noble exertions of police, constable James McCourt a loss of human life also had been incurred. The rise in the Helena was two feet three inches higher than in the great flood of 1862.

Between 1910 and 1963 there were ten floods ranging between 15–30 years ARI, after which, the area has experienced a much drier period. The flood of July 1926 is perhaps the best-documented case of flooding of the Swan River, though its estimated ARI is only 30 years. The Fremantle Railway Bridge (Plate 4.2) and the Upper Swan Bridge collapsed. Significant flooding of property occurred in South Perth (Plates 4.3 and 4.4) and in the Upper Swan–Guildford areas. Freight costs rose as a consequence of the collapse of the Fremantle Railway Bridge because goods traffic between Perth and Fremantle had to be diverted through Armadale (*Western Mail,* 29 July 1926). A description of the flood follows from the *West Australian* (July 23 1926):

The North Fremantle railway bridge was sagging yesterday as a train passed over it. Shortly afterwards, when it was only by a miraculous piece of good fortune that there was no passenger train on it, the structure began to collapse, and the effect of the swirling flood waters soon put it hopelessly out of commission. This is by far the most serious result of the recent floods, as it means that the ordinary Fremantle train service will be disorganised for at least a month…..the disaster will have far reaching effects on the shipping and commerce of the Port… the southern side of the harbour was practically isolated as far as cargoes coming from Perth were concerned, at any rate, until the railways in the country districts were reorganised and goods trains could be frequently sent to Fremantle via Armadale.

Plate 4.2: Fremantle Railway Bridge destroyed by the July 1926 floods (Courtesy of the Battye Library 54902P)

Plate 4.3: Mill Point, South Perth, in the July 1926 flood (Courtesy of the Battye Library 225145P)

Plate 4.4: View of South Perth showing Point Belches under water during the July 1926 floods (Courtesy of the Battye Library 225147P)

The estimated ARI for the flood of 1917 is less than the 1926 flood (see Table 4.1), and the following extract indicates that at many locations the water levels in the 1926 flood may have been higher than the 1917 flood. This extract from the *Western Mail* (29 July 1926) shows the significant impact of the 1926 flood in the South Perth and Guildford areas:

At the foot of Barrack Street the river had burst its banks, and the water was swirling over the garden plots and roadways on the foreshore to a distance of 150 yards from the jetties and ferry offices. The jetties were completely submerged, and the flood had burst into the offices, driving the officials out and causing a certain amount of damage... …an expanse of water varying from a few inches to a foot in depth.

… The people of the Mill Point area [South Perth] were in dire need of practical assistance… During the night no fewer than fourteen houses situated in Suburban Road between Scott Street and the Point, were invaded by the rising waters. Two houses in Stone Street and one in Melville Terrace were also flooded… Along the whole road to Mill Point, from the Scott Street intersection as far as eye could see, water flowed – flowed not dully and placidly, but actively, in high surging currents flecked with foam and breaking here and there into actual waves. A yacht in full sail went up Suburban road…

Several dwellings in the vicinity of the bridge over the Helena River at South Guildford were submerged to within three or four feet of their roofs. Half a window pane peeped over the flood surface… A dead dog and a couple of dead cats floated nearby. The abomination of desolation marked the whole locality. At Barkers Bridge, on Caversham road just out of Guildford, to the northeast a rowing boat was seen arriving with some Caversham residents who had come in for provisions…

The playing field [at Guildford] *was eleven feet below the surface of the waters. Floodwaters prevailed on Wednesday throughout the whole district of Guildford. Almost as much land was under water as was above it. From some points extraordinary panoramic views were obtained, vistas of enormous sheets of water, extending for three or four miles, the surface of the floods broken by tree tops which emerged disconsolately and the roofs of sheds, and much floating debris of all kinds…*

When the flood was at its top most crest the Helena River at East Guildford had risen three feet six inches higher than its level during the deluge of 1917, while the Swan River in the flats below the Guildford Grammar School, and in the vicinity of Barkers Bridge on Caversham road had actually reached a level seven feet higher than the 1917 maximum.

That the recent floods, however, at all events so far as the Guildford district is concerned, did not reach the height of the flood waters of 1862, was a fact pointed out to the Government Meteorologist (Mr Curlewis). One of the oldest Guildford residents affirmed that while on this occasion the ancient and well known Preston farmhouse had been surrounded by the deluge, in 1862 the waters were right up to the windows. There is little doubt said Mr Curlewis that the 1917 floods have been everywhere eclipsed, but we have every reason to believe that in 1862 the waters were considerably higher generally speaking than the levels of last week.

Washaways on the railway line between Northam and Perth and on the Great Southern Line reduced supplies to the Midland Junction market on 21 July, increasing prices as reported in the *Western Mail* (29 July 1926):

The effect on the sheep market was a rise from 2s to 4s per head, all lambs were 1s to 5s per head dearer but [the price of] *pigs remained firm at the preceding weeks rate… Among the sufferers through the torrential rains are the Chinese gardeners who cultivate vegetables along the river at Mount Bay's road South Perth, Belmont and Maylands. All these gardens are flooded, in some cases three or four feet deep.*

Flash floods in Perth have also resulted in large losses, though they are not modelled here. In July 1987, for example, the WA state government declared Perth's southeastern suburbs a natural disaster zone. The *West Australian* (4–5 August 1987) estimated flood damages to local government public facilities at $500,000 – $1 million. Flood damage to roads in the Armadale City Council district was estimated at nearly $500,000. More than 140 houses were damaged by flooding in the suburbs of Westfield, Armadale, Kelmscott, Forrestfield and Kardinya. The *Daily News* (29 July 1987) describes cars being abandoned, and a tow truck which had been responding to the calls for assistance due to the flash floods also breaking down. The following two extracts from the *West Australian* (30–31 July 1987), illustrate the loss sustained to home and contents:

> *Families lose homes… Kim Daykin, awoke about 5am yesterday to find knee-deep water swirling around her bed. The roof had also partly caved in… Another house in the next street had three walls washed away and a teenage boy was almost crushed as he tried to rescue family possessions.*
> *Once a lake – now dozens of homes… Those families in Excalibur Close, and nearby Lancelot Close, Camelot Place and Ivanhoe Way, were yesterday attempting to clear mud and water from their homes after Tuesday night's deluge… Their home in Excalibur Close had 20 cm deep water flowing through it… "The carpets, lounge suites and beds are ruined – they will go straight to the tip. When I open a cupboard, water gushes out"… The home of Geraint Griffiths, in Ivanhoe Way, escaped the flood waters by centimetres, but the family car floated away.*

Another flash flood occurred on 6 December 1987, severely affecting the Armadale and Kelmscott areas again, causing flooding up to 30 cm deep from a 45-minute downpour. One of the Hill residents described this as the second time that he had lost his back fence to flashflooding in just over four months, with the earlier fence destroyed by a wall of water a metre high (*West Australian,* 7 December 1987).

4.4 Hydrology of the Swan and Canning Rivers Catchments

The hydrologic component of the flood study involved hydrographs being determined for floods of a range of frequencies. Hydrographs were developed in order to run an unsteady flow model, in which changes in area of inundation, depth of inundation and velocity with time could be estimated in the hydraulic component of the study. Peak design flows of varying probability were developed and used to predict floods of the same magnitude. An estimate for the 1% AEP design flow, for example, was used to estimate the 1% AEP design flood. The main focus of the report, however, is on the hydraulic modelling. While we acknowledge that there are uncertainties associated with the hydrology component which is the input to the hydraulic model, they are not discussed in detail here. The interested reader can refer to the original reports which are referenced in the following section, to establish the associated uncertainties for each individual hydrologic model. This section describes the development of the design hydrographs for each catchment.

Design hydrograph development for flood estimation

Where available, the design flows and hydrograph shape used in this study were based on the results of the previous studies undertaken by/for the DOE or its predecessors. In most cases these studies involved running design catchment rainfall through a calibrated RORB (Laurenson and Mein, 1985) runoff routing model of the catchment. For flood events between 10% and 1% AEP, a flood frequency approach, coupled with runoff routing models, was used to estimate peak design flood estimates and hydrograph shape.

Floods between the 1% AEP and the PMP design floods were estimated by interpolating from a flood frequency curve. The flood peak between the 1% AEP and the PMP design flood was determined by calculating the magnitude of two events at designated AEPs based on the methods described in Institution of Engineers (1987, 1999). This method provides estimates of magnitudes ranging from 0.5% to 0.0005% AEP events. The peak estimates produced for all the catchments are for AEPs = 10%, 4%, 2%, 1%, 0.5%, 0.2%, 0.1% and 0.05%, and the PMP. As the probability of the PMP for a catchment is directly related to the catchment area over which it is applied (Institution of Engineers, 1999), the approximate AEP of the PMP design flood varies between the catchments as is shown in Table 4.2.

Hydrograph shape for design flows equal to or less than the 1% AEP was derived using the RORB (Laurenson and Mein, 1985) or URBS (Carroll, 1995) models for each catchment. Hydrograph shape for peak estimates ranging between the 0.5% and 0.05% AEPs were determined based on the shape of the 1% AEP hydrograph for each respective catchment. The shapes of the hydrographs were scaled by standardising discharges in the 1% AEP flood hydrograph to 1.

Table 4.2: AEP estimates for the PMP design flood at selected locations

Catchment	Location	AEP estimate	ARI estimate[1]
Avon below Yenyenning Lakes	Swan River at Gt Nthrn Hwy	3.3×10^{-5}	30,300 year
Ellen Brook	Swan River confluence	6.4×10^{-7}	1,562,500 year
Susannah Brook	Swan River confluence	1.0×10^{-7}	10,000,000 year
Jane Brook	Swan River confluence	1.3×10^{-7}	7,692,300 year
Helena River	Swan River confluence	1.9×10^{-6}	537,600 year
Canning River	Swan River confluence	1.3×10^{-6}	769,200 year

Note: [1] Please note that technically AEP and ARI are not interchangeable (see Introduction to this chapter). However, in the interests of being understood by the majority of people, both are included.

The PMP for all catchments for the Swan–Canning estuary is of tropical origin, most likely occurring between October and April. In the southwest of Western Australia the rainfall during this period is typically infrequent and evaporation rates are high. As a result, the PMP for each of the streams is likely to coincide with relatively dry antecedent catchment conditions. Therefore, a high initial loss (100 mm) and moderate proportional runoff (45%) was adopted for application of the PMP event to the URBS model of the Avon River catchment and calibrated RORB runoff routing models for the Ellen, Susannah, Jane, Helena and Canning streams. The output from the URBS and RORB models provided an estimate of both the peak discharge and the hydrographs for the PMP design flood.

Table 4.3 shows the design flood estimates for the common AEPs modelled across all catchments. There is a sharp increase in the design flood estimates for the PMP, with an average eleven-fold increase in peak discharge over the modelled 1% AEP

Table 4.3: Summary of peak design flow estimates (m^3/s) at selected locations

	Location on Stream						
AEP	Avon River	Ellen Brook	Susannah Brook	Jane Brook	Helena River	Canning River	Wungong Brook
Gauging station	616011	616189	616040	616178	616018	Brookton Hwy	616153
10%	640	68	10	19	90	38	10
4%	990	75	15	25	140	49	12
2%	1,300	83	19	27	185	53	13
1%	1,700	97	23	34	225	61	15
0.5%	2,200	125	29	44	300	80	19
0.2%	3,000	170	38	61	420	115	25
0.1%	3,750	200	46	76	530	145	30
0.05%	4,550	250	55	95	635	180	37
PMP design flood*	11,750	2,220	240	510	6950	2740	310

* **Note**: The AEP for the PMP design flood varies, as shown in Table 4.2.

In addition to developing design hydrographs for each of the gauging stations, additional hydrographs were developed in order to capture changes in hydrograph shape and discharge downstream of the gauging stations to account for additional flow from the urban area. The location of these additional simulated inflow hydrographs can be seen in Figure 4.8. The total change (%) in peak flow between the gauging station and the outlet for each tributary is shown in Table 4.4. The peak flow estimate at the most upstream locations were shown in Table 4.3. The one exception is on the Canning River where the upstream boundary is 7.4 km upstream of the gauging station. Table 4.4 shows that the simulated inflow hydrographs can contribute significantly to the predicted peak flow at the outlet of a tributary. As distance increases away from the gauging stations at the upstream boundaries of the model, the time to peak also increases. Table 4.5 shows the percentage change in peak discharge between the upstream boundary hydrograph H_1 and the nearest downstream modelled lateral inflow hydrograph H_2. The change (%) between hydrograph H_2 and the next most downstream hydrograph H_3 is then shown. While there is significant increase in inflow between some locations, there is minimal change at others.

Table 4.4: Change (%) in peak flow over the stream within the study area for various AEPs

Stream	Annual Exceedance Probability (%)							
	10	**4**	**2**	**1**	**0.5**	**0.2**	**0.1**	**0.05**
Ellen Brk	3	1	6	2	4	3	5	4
Susannah Brk	60	53	42	43	45	47	48	51
Jane Brk	53	48	59	47	43	36	32	26
Helena R	0	0	0	0	0	0	0	0
Canning R	182	192	202	192	175	173	134	139
Southern R–Wungong Brk	350	400	377	340	300	260	233	197

In some locations the peak discharge between some of the modelled hydrographs for the tributaries appears to decrease rather than increase downstream. This is an artefact of the model. The flow has been routed relatively long distances without the addition of sufficient tributary inflow to counteract the attenuation resulting from the flow routing. The differences estimated may or may not exist in a real-life situation and will depend on the magnitude and timing of the actual inflows from the small tributaries along the reaches in question.

The generic aspects in the design hydrograph development have been covered. The unique aspects in the development of the hydrographs for each of the major catchments of the Swan–Canning estuary are described in the following sections.

Table 4.5: Change (%) in peak flow between modelled inflow hydrographs for the tributaries to the Swan River for various AEPs

Stream	Inflow Hydrograph: Upstream	Inflow Hydrograph: Downstream	AEP (%) 10	4	2	1	0.5	0.2	0.1	0.05
Ellen Brk	Railway Parade GS[1] (616189)	Swan confluence	3	1	6	2	4	3	5	4
Susannah Brk	Gilmours Farm GS[1] (616040)	Moore Rd	60	53	47	52	55	61	65	69
	Moore Rd	Railway Line	0	4	4	3	2	2	1	1
	Railway Line	Gt Northern Hwy	0	0	-3	-6	-7	-6	-9	-10
	Great Northern Hwy	Swan confluence	0	-4	-4	-3	-2	-3	-3	-2
Jane Brk	National Park GS[1] (616178)	Toodyay Rd	32	28	33	26	25	20	18	16
	Toodyay Rd	Swan confluence	16	16	19	16	15	14	11	9
Canning R	Brookton Hwy	Mackenzie Grove GS[1] (616027)	11	10	13	13	13	9	7	8
	Mackenzie Grove GS[1] (616027)	Canning U/S Southern R	5	6	7	7	-6	-8	-6	-8
	Canning U/S Southern R	Canning D/S Southern R	73	75	72	64	81	74	69	64
	Canning D/S Southern R	Canning at Nicholson Rd	41	43	45	47	43	40	39	46
Southern R–Wungong Brk	Kargotich GS[1] (616153)	Southern River D/S of Neerigen Bk Sth confluence	150	194	198	195	168	148	137	116
	Southern River D/S of Neerigen Bk Sth confluence	Southern River outlet	80	70	60	49	49	45	41	38

Note: [1] GS = Streamflow gauging station

Avon River

Studies by the Public Works Department (PWD, 1986) and Waugh (1985) employed a flood frequency analysis approach to estimate the design peak flows for AEPs between 50% and 1% at the streamflow gauging station at Walyunga. The observed peak flow data set (1970–1983) was extended using catchment rainfall in conjunction with a Sacramento (Burnash, Ferral and McGuire, 1973) model of the catchment. The Sacramento model was calibrated using the gauged Walyunga streamflow data from 1970 to 1983.

As a result of the flood frequency method employed in these studies, hydrographs for the design flood events were unavailable. To produce hydrographs for these events design catchment rainfall was applied to the flood forecasting model developed by Rodgers (1998). The URBS runoff routing model of the Swan–Avon catchment was used to estimate hydrographs at the towns of Beverley, York, Northam and Toodyay, and at the Walyunga gauging station.

During the runoff routing modelling three design rainfalls were applied to groups of sub-catchments depending on their location. The eastern sub-catchments of Yenyenning Lakes, Yilgarn, Lockhart and Mortlock River East above Meckering, have been grouped together and assigned relatively low design rainfalls. The more centrally located sub-catchments on the eastern part of the Scarp, from Beverley through to Toodyay in the Avon subcatchment and all of Mortlock River North and Mortlock River East below Meckering, make up the second group. The sub-catchments below Toodyay were the final grouping and were assigned slightly higher design rainfalls than the central group. The design rainfall estimates applied to each of these three areas corresponded to the design rainfall estimates for a representative location within each, namely Kellerberrin (East), Northam (Central) and Walyunga (Lower).

An initial loss of 10 mm was adopted for the entire catchment. The proportional runoff coefficients suggested in Rodgers (1998) ranged between 0.5% and 30%. In this study the model was simplified by using only three runoff coefficients across the entire Avon catchment. A runoff coefficient of 1% was adopted for the Yilgarn and Lockhart systems and the flat areas at the top of both the Mortlock River East and North Branches. A runoff coefficient of 15% was adopted for the downstream Mortlock River East and Mortlock River North sub-catchments. For the remaining sub-catchments, a runoff coefficient of 20% was adopted. The design peak flows for AEPs between 10% and 1% obtained from the runoff routing modelling were within 2% of the flood frequency analysis results quoted PWD (1986) and Waugh (1985).

The Lockhart and Yilgarn systems account for approximately 75% of the Avon River catchment area. However, these systems are likely to be only a small contributor to the peak flow discharging from the Avon River at Walyunga because the Lockhart and Yilgarn systems lie within a lower rainfall zone. The catchment is a relatively flat, low relief region with a series of lake formations distributed evenly throughout. These lakes trap a large proportion of the runoff, with runoff averaging <0.3 mm/year. The large flood storage provided by the lake formations also results in significant attenuation of flows during major events when the lake formations interconnect. By comparison the runoff generation in the areas downstream is significantly larger (>20 mm for catchments west of Yenyenning).

The passage of storms within the catchment generally ranges between south-southeast (for summer, ex-tropical events) to northeast (for winter frontal systems). The passage of the storms combined with the sheer size of the Lockhart and Yilgarn systems and the flood storage available within them suggest that it is unlikely that peaks from these sub-areas will coincide with the peak from the smaller catchment downstream of Yenyenning. For catchments the size of the Swan–Avon this temporal variation in the design rainfall should be considered.

The PMP for the entire catchment (~120 000 km^2 to Walyunga) is significantly smaller than the PMP estimate for the ~ 30 000 km^2 catchment below Yenyenning, which is the junction of these two systems (see Figure 4.2). Due to the high losses, low runoff rates, flood storage and attenuation in the

Lockhart and Yilgarn systems, the resulting PMP for the area downstream of Yenyenning has been assumed to be higher than simply applying a PMP to the entire catchment. Therefore, rather than applying a PMP event to the entire Avon catchment which would produce a smaller PMP design flood, a PMP event was applied to the remaining 25% of the catchment (ie, Avon catchment below Yenyenning Lakes). A large flood event (1% AEP) in the Yilgarn and Lockhart systems was then assumed to occur concurrently.

A crude estimate of the PMP for the reduced catchment area downstream of Yenyenning Lakes (approximately 33,000 km^2) was determined based on estimates provided by the BOM for the Ord River Dam (BOM, 1999) and Wellington Dam (BOM, 1996) catchments. The PMP for these two catchments was used because they are the two largest catchments for which estimates of PMP were available at the time that the hydrology for this report was undertaken, with areas of approximately 45,000 km^2 (BOM, 1999) and 2,850 km^2 (BOM, 1996) respectively.

Improved estimates of the PMP are now available following the release of the BOM's generalised tropical storm method revision (GTSMr). A comparison between the original estimates and the estimates based on the GTSMr have not been undertaken, however, the difference is likely to be relatively small in comparison to adopting a different loss model to the simple method applied within this study (initial loss = 100 mm proportional runoff = 0.45). The release of the CRC FORGE database for WA will enable improved estimates of rare event floods (between 1% and 0.05% AEP). It is not yet clear what impact these recent advances will have on the rare and extreme design flood estimates for Swan River and tributaries.

Ellen Brook

The most recent study was undertaken by Waugh and Ng (1987) and employed two runoff routing models (Flout and RORB) to determine design peak flows for AEPs between 4% and 1% at a number of locations along Ellen Brook.

The RORB model of the catchment from Waugh and Ng's (1987) study was adapted to enable estimates to be obtained for a number of additional locations within the catchment. The calibrated model parameters from the study were applied, including an initial loss of 0 and a runoff coefficient of 12.1%. The adapted RORB model successfully reproduced the hydrographs for the 4%, 2% and 1% AEP events at the locations common between the two models. An estimate of the 10% AEP rainfall for the catchment at the critical duration of 48 hours was applied to the RORB model to determine design flows for an event of this probability.

The PMP estimates for Ellen Brook catchment were derived using a relationship between catchment area and the unadjusted January PMP estimates for 15 catchments in southwestern Western Australia provided by the BOM. The estimates were based on a generalised method incorporating depth–area–duration (DAD) curves that had been derived directly from the Australian tropical storm data. The final PMP estimates were estimated by applying adjustment factors for moisture, barrier height, topography and distance from the coast. PMP estimates for Susannah Brook, Jane Brook and the Canning River catchments were derived using the same method.

Susannah Brook

The most recent study was undertaken in August 1992 (McLaughlin, 1992). It employed the RORB model and flood frequency analysis on the gauged data to determine design peak flows for AEPs between 10% and 1% at locations along Susannah Brook.

The RORB model of the catchment from McLaughlin's (1992) study was adapted to allow for estimates at additional locations within the catchment. The calibrated model parameters determined in the previous study were applied and resulted in the successful reproduction of the hydrographs for the 10%, 4% and 1% AEP events. An estimate of the 2% AEP rainfall for the catchment at the critical duration of 18 hours was applied to the RORB model to determine design flows for an event of this probability.

Jane Brook

The most recent study was carried out in January 1988 by Davies (1988). It employed a RORB runoff routing model to reproduce design peak flows determined by flood frequency analysis for AEPs between 10% and 1% at the Jane Brook National Park streamflow gauging station.

The RORB model of the catchment from Davies (1988) study was adapted to allow for estimates at additional locations within the catchment. The calibrated model parameters determined in the previous study were applied, including an initial loss of 0 and runoff coefficients varying from 12.5% to 17%. The calibrated RORB model successfully reproduced the hydrographs for the 10%, 4% and 1% AEP events at the locations common between the two models. An estimate of the 2% AEP rainfall for the catchment at the critical duration of 24 hours was applied to the RORB model to determine design flows for an event of this probability.

Helena River

The most recent flood study for the Helena River downstream of Mundaring Weir was undertaken in October 1984 (Waugh, 1984). It involved a flood frequency analysis on estimated peak annual flows at Fyfe Road to determine design peak flows at the site for AEPs ranging between 10% and 1%. The estimated flows were based on overflow data for Mundaring Weir and gauged data below the dam.

A study on extreme flood estimation for the Helena River is currently underway as part of Dam Safety Reviews for Mundaring Weir and at the Lower Helena pumpback site. This study involved calibrating the RORB runoff routing model and soil water loss model of the Helena River catchment. Design rainfall information has then been applied to determine the appropriate design peak flows for the 2% AEP to the PMP. Estimates of the PMP were supplied by the BOM.

The design outflow peaks from Mundaring Weir obtained during the recent modelling of the 2% and 1% AEP events were slightly different to the earlier flood frequency results. The flood frequency results from the earlier study were preferentially adopted during this study because they are based on observed data (1905–1983) and the runoff routing results are still only preliminary. Despite the preliminary nature of the runoff routing results, the shape of the design hydrographs have been adopted as the Waugh (1984) study produced peak design flows only.

Canning River

The most recent study was undertaken in April 1989 by Davies (1989). It employed a RORB runoff routing model and a flood frequency analysis to determine design peak flows for AEPs between 10% and 1% at a number of locations along the Canning and Southern Rivers.

The RORB model of the catchment from Davies (1989) study was adapted to allow for estimates at additional locations within the catchment. The calibrated model parameters and median reservoir starting dam levels determined in Davies (1989) were applied. The calibrated RORB model successfully reproduced hydrographs for the 10%, 4% and 1% AEP events. An estimate of the 2% AEP rainfall for the catchment at the critical duration of 48 hours was applied to the RORB model to determine design flows for an event of this probability.

Though estimates of the PMP had previously been supplied by the BOM for the Canning, Wungong and Churchmans' Brook catchments, and for the Victoria and Bickley Reservoir catchments, no PMP was available for the entire Canning River catchment. Therefore, an estimate for the PMP was derived using the same method as used for the Ellen, Susannah and Jane Brook catchments.

4.5 Hydraulic Modelling of the Swan and Canning Rivers and Tributaries

Model development

Hydraulic models are used for predicting the impact of floods. The hydraulic model used in this study is the US Army Corps of Engineers Hydraulic Engineering Center's (2003) River Analysis System (HEC-RAS). HEC-RAS is a one-dimensional steady and unsteady flow water surface model, publicly available from the US Army Corps of Engineers Hydrologic Engineering website. HEC-RAS version 3.1.1 was used for modelling unsteady flows through the river network to estimate the duration and extent of inundation, and changes in water surface elevation and velocity through time at any location. HEC-RAS was interfaced closely with geographical information systems (GIS) for developing additional cross-sections and for visualising the flooding scenarios. Two-dimensional models were not considered as the area modelled is too large. However, the results of the one-dimensional model could be used to identify areas where a two-dimensional model may produce more detailed results.

The key data required for developing the unsteady flow model included geometric data, streamflow hydrographs and tidal data, and are described below. A representation of the model for the Swan River system is shown in Figure 4.8.

Cross-section data

Spatially located cross-section information is required throughout the stream network to capture the geometry of the stream channel and floodplain. Surveyed cross-section data was supplemented with cross-sections derived using GIS.

Surveyed

The surveyed cross-sectional information came from nine separate studies undertaken by the DOE and its predecessors between 1981 and 1990. The studies include:

- Swan River Flood Study, Causeway to Middle Swan Road, Review 1985
- Swan River Flood Study, Middle Swan Road to Walyunga National Park, Review 1985
- Susannah Brook Flood Study, Swan River to Millendon, 1995
- Jane Brook Flood Study, Swan River to Wexcombe, 1989
- Helena River Flood Study, Swan River to Helena Valley, 1987
- Ellen Brook Flood Study, Swan River to Bullsbrook, 1989
- Canning River Flood Study, Canning Bridge to Nicholson Road Bridge, 1981
- Canning River Flood Study, Nicholson Road Bridge to Brookton Highway, 1990; and
- Southern River – Wungong Brook Flood Study, Canning River to South Western Highway, 1988.

Several hundred cross-sections were transformed from hardcopy format into the same spatially referenced digital format (AGD66). The locations of the cross-sections were digitised as northings and eastings from the DOE's flood study survey plans. The spatial location of the cross-sections and the elevation data for each cross-section was entered into HEC-RAS.

The spatial extent of the survey data is limited to the area extending from the Causeway on the Swan River upstream to Walyunga National Park (Figure 4.8). On the tributaries the survey data falls short of the gauging stations used in the model by 1.5 km on the Southern River – Wungong Brook, 6.4 km on Susannah Brook, 3.3 km on Jane Brook and 2.9 km on the Helena River.

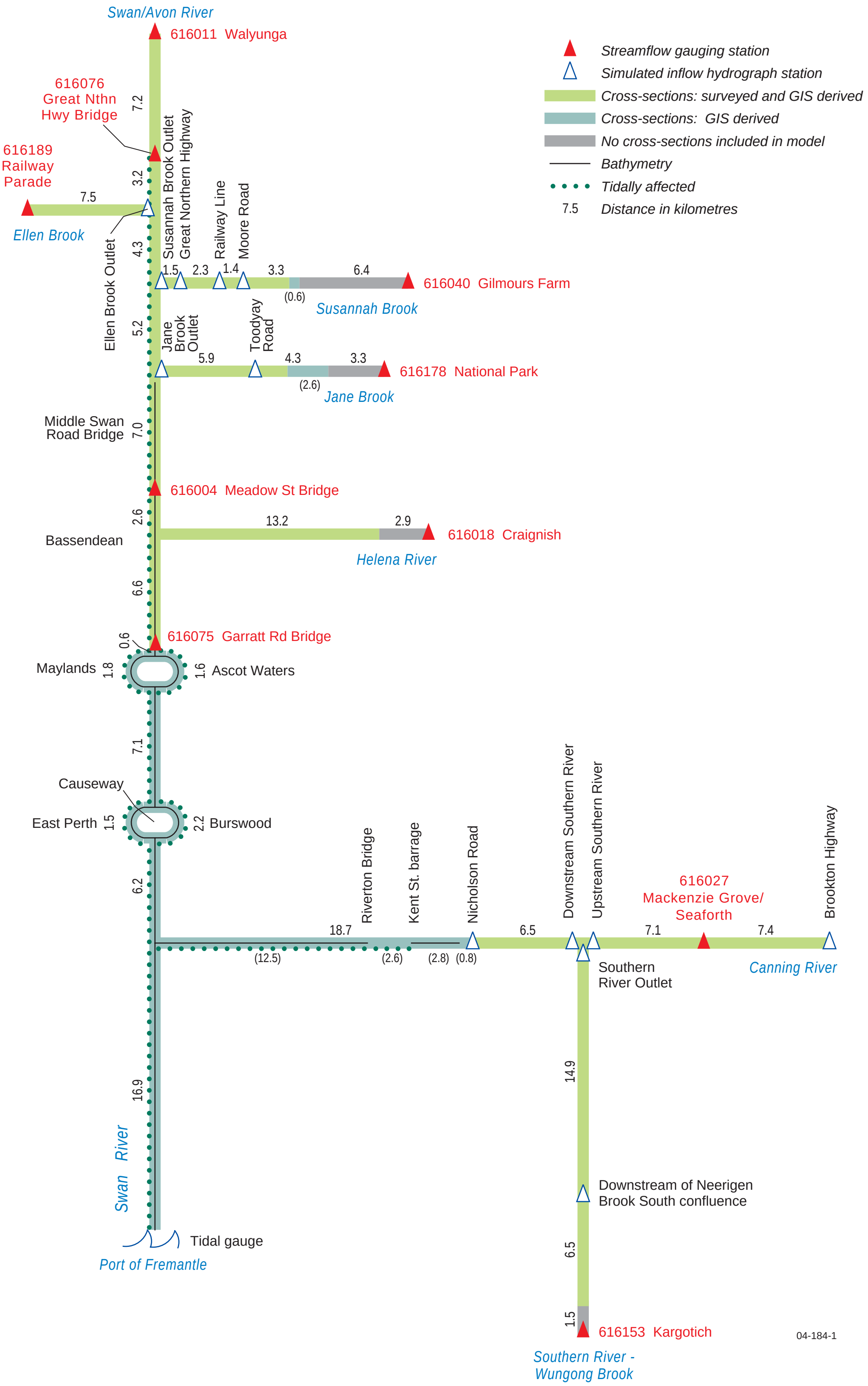

Figure 4.8: A representation of the hydraulic model

Bridges

Detailed modelling of the bridges was not undertaken because the amount of data required to input into the HEC-RAS bridge function was not available for many of the bridges. Where bridges were included, the bridge was treated as a simple surveyed cross-section. Previous studies (Water Authority of Western Australia, 1985a, 1985b, 1986) have also shown that the affluxes for the bridges on the Swan River in a 1% AEP flow are low (i.e. ~0.1 m – 0.2 m), and are considered insignificant when considering the accuracies/sensitivities of the modelling work.

GIS derived

GIS was used as a tool for supplementing and extending the surveyed cross-sections. Additional cross-sections were needed to extend the area modelled over previous studies, to reduce the distance between the surveyed cross-sections and to lengthen the surveyed cross-sections to cover the width of the floodplain for flows greater than the 1% AEP event. Extension of the cross-sections was necessary as the model assumes a vertical wall where a cross-section does not fully extend across the flooded area, underestimating the aerial extent of flooding and overestimating the depth of flooding. The extension of surveyed cross-sections and cross-section supplementation increased the accuracy of water levels and velocities, improved floodplain visualisation (particularly where streams are winding), and increased model stability.

Cross-sections derived solely in GIS were used between the Causeway and the mouth of the Swan River at the Port of Fremantle, a distance of some 23.1 km (Figure 4.8). Although surveyed cross-sectional data was available for the Canning River, the spatial orientations of the cross-sections below the Nicholson Road Bridge at Langford were unknown. Where bathymetry data was available, these cross-sections were not used and cross-sections derived in GIS were used. Where bathymetry data was unavailable, the orientation of these surveyed cross-sections was estimated in GIS.

The floodplain geometry was also updated where there had been substantial changes in topography since the original surveys had been undertaken. Only one major area was identified: the section of the Swan River flowing between the suburbs of Ascot Waters and Maylands. At this location a second channel has been formed, and the adjoining area has been raised for the new residential development of Ascot Waters.

HEC-RAS's companion package, HEC-GeoRAS for ArcView was used for processing geospatial data for use with HEC-RAS. HEC-GeoRAS requires data in TIN format (triangulated irregular network). However, it was found that the cross-sections produced using the TIN did not adequately reflect the channel geometry, largely because of insufficient data sampling points extracted by the program. In order to improve the representation of the channel geometry, an Arc Macro Language (AML) script was written to extract elevations at 5 m intervals along each cross-section from a 5 m Arc-Info grid of the digital elevation model (DEM). Where there was no bathymetry available, channel width was estimated using the orthophotos and channel depth was estimated by interpolating between the surveyed cross-sections. These cross-sections were then incorporated back into the DEM for the damage analysis.

River and channel delineation

The spatial location of the river reaches were derived using a combination of water course data available from the Department of Land Information in Western Australia, the othophotos, the TIN and the survey data. The stream channel was differentiated from the floodplain by manually locating the left and right channel banks for each cross-section. Where the location of the left and right channel banks of the GIS derived cross-sections were unclear from the channel geometry, they were estimated in conjunction with the 2001 orthophotos. However, the location of the stream channel was still sometimes difficult to determine because of dense tree coverage in the orthophotos. On the Swan River around the suburbs of Maylands and Ascot Waters, and the Causeway, the flow in the channel was split around each island. The levee on Wungong Brook, a tributary of the Canning River, was also added.

Floodplain roughness

Manning's 'n' was used to estimate channel and floodplain roughness for each of the cross-sections, which is used as a measure of the resistance of the channel to the flow. One Manning's 'n' value was used for the combined channel and overbank areas in earlier flood studies, which were calibrated to match actual flood levels. In this research, three roughness values were assigned for each cross-section, namely the left and right overbank areas and the main channel. Roughness was initially estimated using Chow's (1959) book on *Open Channel Hydraulics*, which describes numerous channel and floodplain types and gives a range of recommended values of 'n' for each. These channel and floodplain types were estimated using 2001 orthophotos. However, Manning's 'n' was then calibrated against 47 recorded flood levels from the 1983 and 1987 flood events, to establish the Manning's 'n' values used in the modelling of the design floods.

Digital elevation model

The 5 m DEM and digital terrain model in Arc-Info TIN format was developed for the whole study area using a combination of bathymetry point data in the stream channels, and detailed contour and/or dense spot height data for the remaining floodplain area. This provided significant improvements in resolution over the 10 m DEM initially developed. Availability of computer memory (influenced by the detail of the data used and computational capacity), limit the resolution of the DEM, as the memory required for processing the DEM is thirteen times the size of the final product. The resolution used in the model was more than adequate for the purposes of the flood assessment undertaken.

The bathymetry data used in the DEM was provided by the DPI. The contour and spot height data was obtained from the Department of Land Information in Western Australia. The contours ranged from 1 m in the built-up areas to 10 m in the country. Non-terrestrial artefacts (e.g. tall buildings and trees) were filtered from the input contour and spot height data by comparing cross-sections in HEC-RAS with the DEM and othophotos. Limited fieldwork was also undertaken. As Figure 4.8 shows, the bathymetry data extends from the Indian Ocean, up the Swan River to Middle Swan Road Bridge, Middle Swan, with a small gap in the data in Perth Waters, near South Perth. Up the Canning River the bathymetry data extends to Fern Road at Riverton Bridge, Riverton where there is a gap for 2.6 km until the Kent St barrage. From the barrage the bathymetry data extends for a further 2.8 km upstream. The concentration of points varies on the Swan–Canning, it is typically higher in areas around bridges, where dredging has occurred, or where there has been a history of flooding.

Where no bathymetry data were available, the geometry of the stream channel was estimated by interpolating manually between the nearest surveyed cross-sections. There were only two areas where this was difficult: in the upper Jane and Susannah tributaries, where cross-sections derived in GIS were used to extend the cross-sections beyond the surveyed cross-sections for a further 2.6 km and 0.6 km respectively (Figure 4.8).

The surveyed cross-section data were incorporated into the DEM to reduce anomalies in the floodplain mapping. The anomalies are caused by slight differences in elevation between the DEM and the surveyed data at the same location, resulting in inaccuracies in the modelled spatial extent of flooding and water depths.

Streamflow hydrographs and tidal data

Streamflow and tidal data are used at all external boundaries of the model and establish the flows in the system. The tidal cycle is used as the lower boundary condition at the outlet of the model. Streamflow data is used for the upstream boundary conditions and at a number of locations downstream. Streamflow data can either be historical or can be estimated during the hydrologic component of the model. Boundary conditions can be input in a variety of ways, including flow and/or stage hydrographs, or rating curves.

Initial conditions

Initial conditions establish the starting water surface at the upstream ends of the river system and at the beginning of each reach. These are necessary for the program to begin its calculations. Where the flow is divided, such as around an island, initial conditions were based on the volume of flow estimated to flow on either side of the island, with the main channel (Maylands and Burswood sides) having higher initial conditions (Figure 4.8).

Model stability and uncertainties

Initially a lot of problems were encountered with model stability because of the complexities of the model geometry and rapid changes in discharge in the tributaries. One of the first steps in reducing the instabilities was to adopt a 5 minute time step for all the flow hydrographs, reducing the change in discharge between individual time steps.

Rapid changes in elevation between cross-sections, particularly in the steep upper reaches of the tributaries, also caused instabilities. To reduce the sharp changes in elevation, additional cross-sections were interpolated using the surveyed and GIS derived cross-sections. In the upper reaches of the Susannah and Jane Brooks, the changes in elevation were so rapid (an average drop in elevation of 30 m per kilometre), that the model remained unstable even when the number of interpolated cross-sections was significantly increased. A stable model was attained only when the very steep upper reaches of the Susannah and Jane tributaries, which flow through native bush and farmland, were not included in the model. The discharges recorded at the Gilmours Farm and National Park gauging stations were still used, but were applied 6.4 km and 3.4 km respectively downstream from the gauging stations where the gradients were not as steep. Therefore, though these gauging stations have been tied into AHD, the historical stage hydrographs could not be used.

Although the addition of interpolated cross-sections can improve model stability, the interpolated channel may not necessarily reflect the actual channel geometry. The model assumes a straight line between the two measured cross-sections; therefore, the interpolated channel may not be in the same location as the real channel. The problems become particularly evident when visualising the flooding spatially in GIS, using the othophotos as a backdrop, and when calculating water depths using a DEM. The appropriateness of the interpolated cross-sections was therefore checked using the DEM and othophotos to see if these cross-sections were realistic. Where necessary, additional cross-sections were derived from the DEM at strategic locations to reduce the number of interpolated cross-sections and associated inaccuracies.

A flow minimum of 1 m^3/s was assigned to hydrographs on the Helena, Susannah and Wungong tributaries where the initial flow was lower to help avoid instability problems. This was necessary as the model becomes unstable where there is no flow but made no difference to the impact of flooding. During the 1987 event, a minimum flow of 40 m^3/s was adopted for the Avon River at Walyunga, because the model became unstable for lower initial flows.

A restart file was used to establish initial conditions to keep model from going unstable at the beginning of the simulation. All the inflow hydrographs were set at a constant flow (which was base flow). The stage hydrograph downstream boundary was set up with high tailwater, which was then decreased gradually to the water level of the tidal cycle over a period of 36 hours. A high initial tailwater condition for the restart file was not needed for all the scenarios, though a restart file was.

Model calibration

The primary purpose of model calibration is to replicate the historical water level and/or discharge and volume, the time to peak and hydrograph shape. A properly calibrated model may then be used to estimate the impact of flood events beyond the period of record. In order to calibrate an unsteady flow model, historical streamflow and/or historical stage hydrographs are required for the upstream boundaries of the model, and preferably for at least one location downstream. The historical tidal cycle is used as the downstream boundary of the model. For calibrating the model along the stream network, historical peak water levels at a number of locations along the Swan and Canning Rivers are necessary.

Streamflow gauging stations in the study area were identified and examined to determine the availability of data for model calibration. The gauging stations in the study area, their length of record, data format available and other associated information is shown in Table 4.6.

The location of the gauging stations (616011, 616189, 616040, 616178, 616018, 616153) shown in Figure 4.8 and included in Table 4.6 delimit the upstream boundaries of the model for calibration purposes with the exception of the gauging stations on the Swan River (ie, Meadow St Bridge, 616004; Garratt Road Bridge, 616075 and the Great Northern Highway, 616076). The lower boundary of the model is delineated by a tidal cycle for the Port of Fremantle. The spatial extent of the model for calibration was slightly smaller than for the design flood events as no historical data was available upstream of Mackenzie Grove gauging station (616027). The design flood events however were modelled as far as the Brookton Highway on the Canning River, another 7.4 km upstream (see Figure 4.8).

A major limiting factor in the calibration of the model is that the streamflow data for the larger flood events was not recorded. Of the six gauging stations at the upstream boundaries of the model, historical streamflow data is only available since 1981. The period since then has been relatively dry, with only two flood events estimated to be equal to or greater than a 10% AEP as shown in Table 4.1. The 1983 flood was estimated to have a 10% AEP on the Avon River at Walyunga (616011). The 1987 flood event was estimated to have a 4% AEP on the Canning River at MacKenzie Grove (616027). The estimated peak discharge for these events is given in Table 4.7.

Table 4.7: Peak discharge and estimated AEP for the July 1983 and 1987 floods

Stream	Gauging station	Peak discharge (m^3/s) 1983	Peak discharge (m^3/s) 1987	AEP (%) 1983	AEP (%) 1987
Avon	616011	650	158	10	60
Canning	616027	9	55	40	4

Only the Meadow St Bridge site (616004) can be used for calibration as the Garratt St Bridge (616075) and Great Northern Highway (616076) gauging stations on the Swan River became operational in the 1990s. At the Meadow St Bridge (616004) gauging station only stage hydrograph may be calibrated as this site is tidally affected, which excludes discharge or volume measurements. Unfortunately, due to equipment problems at the Meadow St (616004) gauging station during the 1987 flood event, water levels were not recorded. Historical tidal fluctuations were also not available at the Port of Fremantle during the 1987 flood event. Tidal levels were calculated using tidal modelling software developed by the DPI. This software employs basic astronomical factors, and does not consider the prevailing meteorological factors.

The calibration of the model to the 1983 and 1987 events is described in the following two sections. These two flood events have been previously used in the calibration of earlier flood studies of the Avon River (Waugh, 1985) and Canning River (Water Authority of Western Australia, 1990).

Table 4.6: Streamflow gauging stations within the Swan River catchment study area

Gauging station	Stream	Station name	Managing authority	Longitude	Latitude	Catchment area (km^2)	Discharge	Stage (m AHD)	Site commenced	Site ceased
616004	Swan River	Meadow St Bridge	DOE[2]	115.972	-31.895			√	17/07/1978	29/10/2002
616011	Avon River	Walyunga[1]	DOE[2]	116.067	-31.756	119,000.0	√	√	01/04/1970	
616018	Helena River	Craignish[1]	WC[3]	116.068	-31.937	1600.0	√		c1975	
616027	Canning River	Mackenzie Grove[1]	DOE[2]	116.014	-32.097	920.0	√		01/04/1974	10/11/1999
616027[4]	Canning River	Seaforth[1]	DOE[2]	116.021	-32.097		√	√	22/04/1997	
616040	Susannah Brk	Gilmours Farm[1]	DOE[2]	116.110	-31.818	24.8	√	√	22/05/1981	20/6/2001
616075	Swan River	Garratt Rd Bridge	DOE[2]	115.917	-31.933			√	12/07/1995	28/09/1999
616076	Swan River	Great Northern Highway	DOE[2]	116.018	-31.787		√	√	01/01/1994	
616189	Ellen Brk	Railway Parade[1]	DOE[2]	116.023	-31.752	590.0	√		3/10/1959	
616178	Jane Brk	National Park[1]	DOE[2]	116.091	-34.882	73.0	√	√	17/08/1962	
616153	Wungong Brk	Kargotich[1]	WC[3]	116.028	-32.199	146.0	√		c1980 (post dam)	

Notes: [1] These gauging stations form the upstream boundaries of the model for calibration purposes.

[2] DOE = Department of Environment, formerly the Water and Rivers Commission.

[3] WC = Water Corporation

[4] The gauging station at Seaforth replaced Mackenzie Grove as the primary gauging station when it became operational in 1997, and adopted the same gauging station number as had been used at Mackenzie Grove.

1983 flood event

Two flood events were recorded in the winter of 1983 on the Swan River, though the West Australian (28 July 1983) reported that there was little property damage. The second and larger of the floods is used for model calibration, peaking at the Walyunga gauging station (616011) on the Avon River on 27 July 1983 at 06:00. This event was approximately a 10% AEP at Walyunga and a 40% AEP on the Canning River at MacKenzie Grove (616027). The same event at the Gilmours Farm (616040) and National Park (616178) gauging stations on the Susannah and Jane tributaries was estimated to be about a 20% AEP event. However, as these gauging stations are well up in the Susannah and Jane catchments (~50% of the catchment), the AEP at the gauging stations may not be indicative of the AEP of the flood event on the tributaries near the confluence with the Swan River. The AEP estimates for the Craignish gauge (616018) on the Helena River is complicated by the presence of Mundaring Weir further upstream, however flow for this flood event would also be well below a 10% AEP event.

Figure 4.9 depicts the flood hydrograph at Walyunga (616011) over the time period 23 July 1983, 24:00 – 7 August 1983, 08:00. The tidal data at the downstream boundary of the model over the corresponding time period is shown in Figure 4.10. Figure 4.11 depicts the historical hydrographs over the equivalent time period on the tributaries. Rather than experiencing a single hydrograph as at Walyunga, the tributaries experienced a series of smaller, peaky hydrographs during the corresponding period.

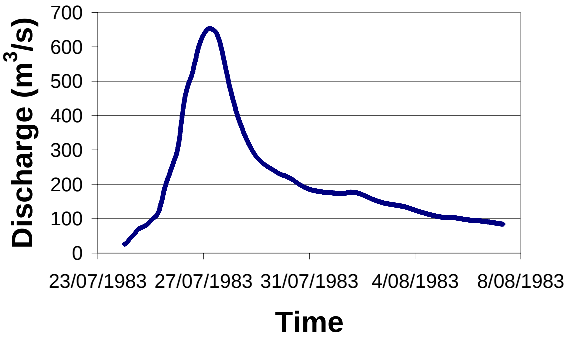

Figure 4.9: Flood hydrograph on the Swan–Avon River at Walyunga gauging station (616011), 23 July 1983, 24:00 – 7 August 1983, 08:00

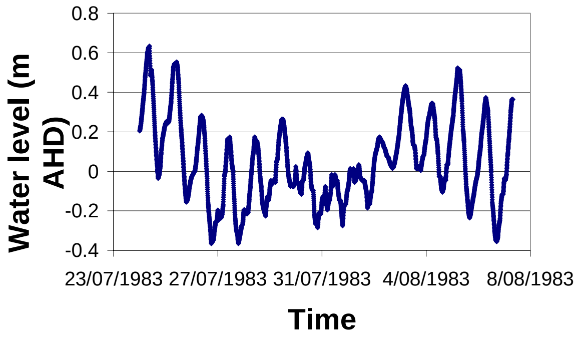

Figure 4.10: Tidal cycle at the Port of Fremantle, 23 July 1983, 24:00 – 7 August 1983, 08:00 (Data courtesy of DPI)

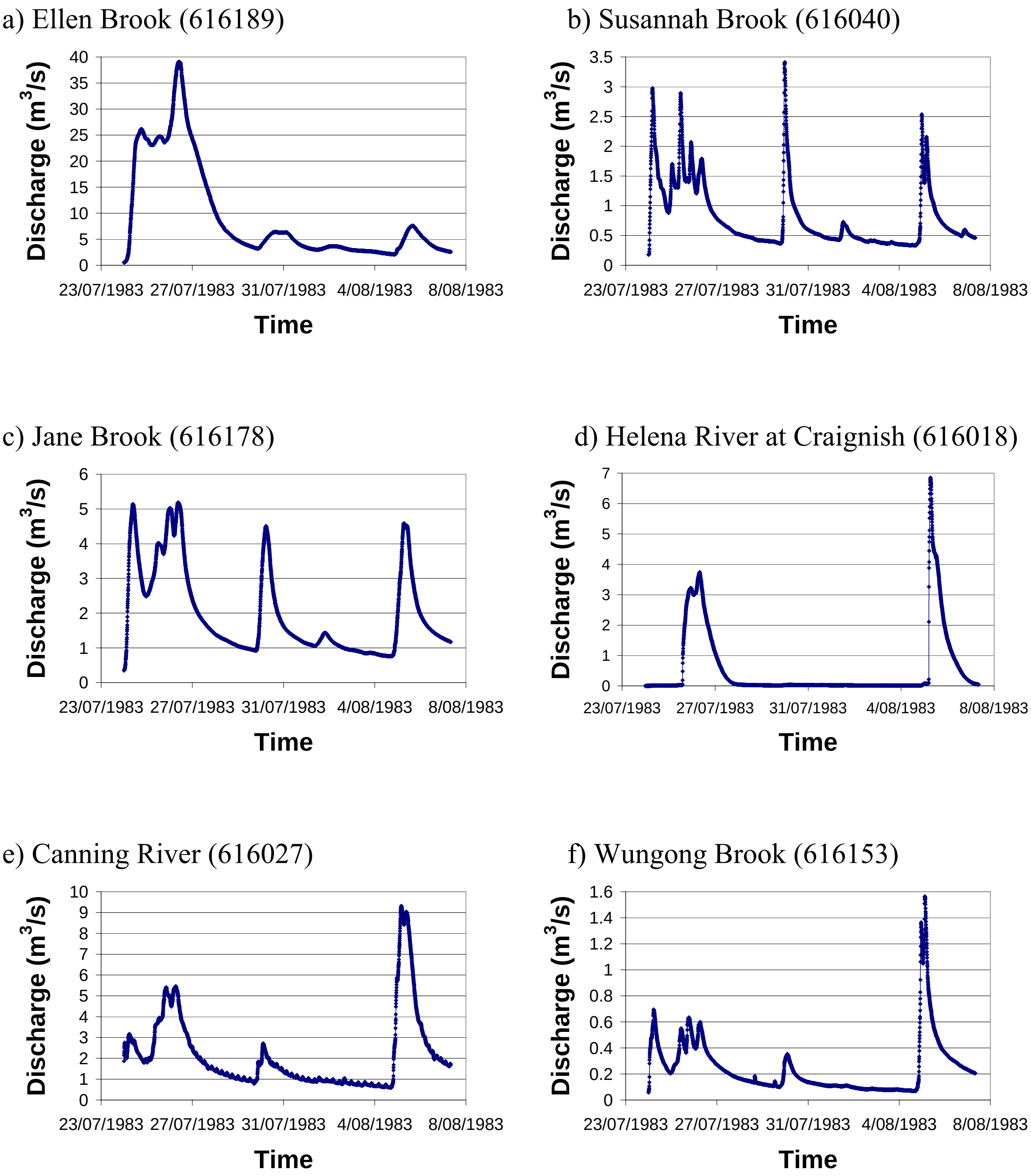

Figure 4.11(a–f): Hydrographs for the streamflow gauging stations on the major tributaries to the Swan River for the period 23 July 1983, 24:00 – 7 August 1983, 08:00

Before the model was calibrated at the Meadow St gauging station (616004) on the Swan River, the peak flow was too low and the time to peak too short. In order to increase the modelled flood peak a trial and error approach was adopted. Small amounts of lateral inflow were added, however, the resulting peak stage was vastly overestimated. Manning's 'n' was then calibrated to 39 peak recorded water levels on the Swan River between the Causeway and the Great Northern Highway Bridge, a distance of 40.1 km. The observed and modelled (after calibration) stage hydrograph at Meadow St (616004) gauging station is shown in Figure 4.12. The calibrated model reduced the difference between the observed and modelled peak water level at the Meadow St (616004) gauging station by 0.4 m and a time of 1.5 hours. Figure 4.13 is a longitudinal profile of the Swan River upstream of the Causeway showing modelled peak flood levels after calibration and the observed peak flood levels.

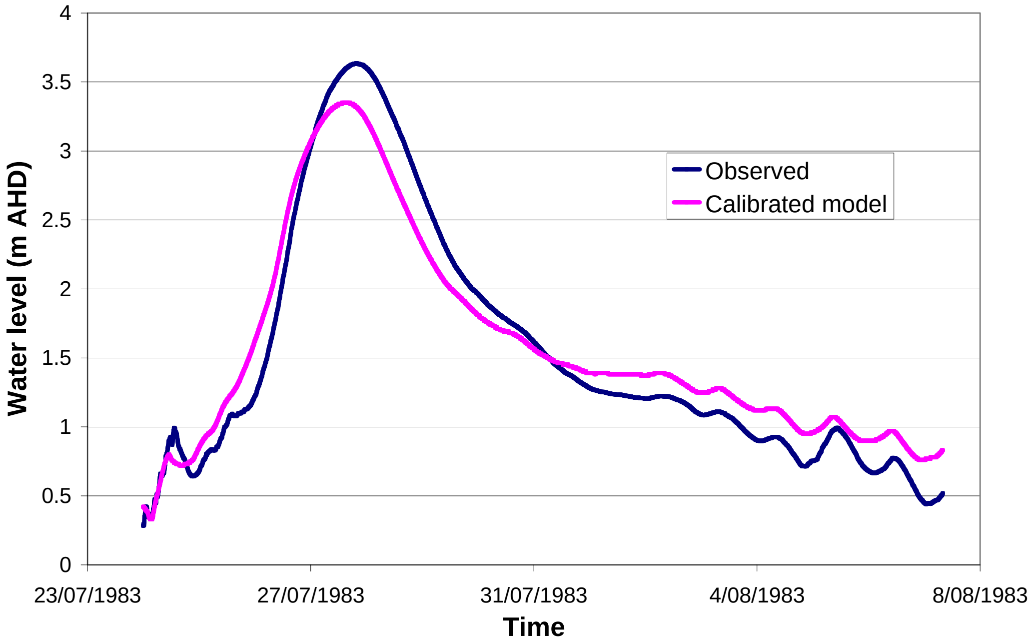

Figure 4.12: Hydrographs at Meadow St gauging station (616004) on the Swan River between 23 July 1983, 24:00 – 7 August 1983, 08:00 (Observed versus modelled)

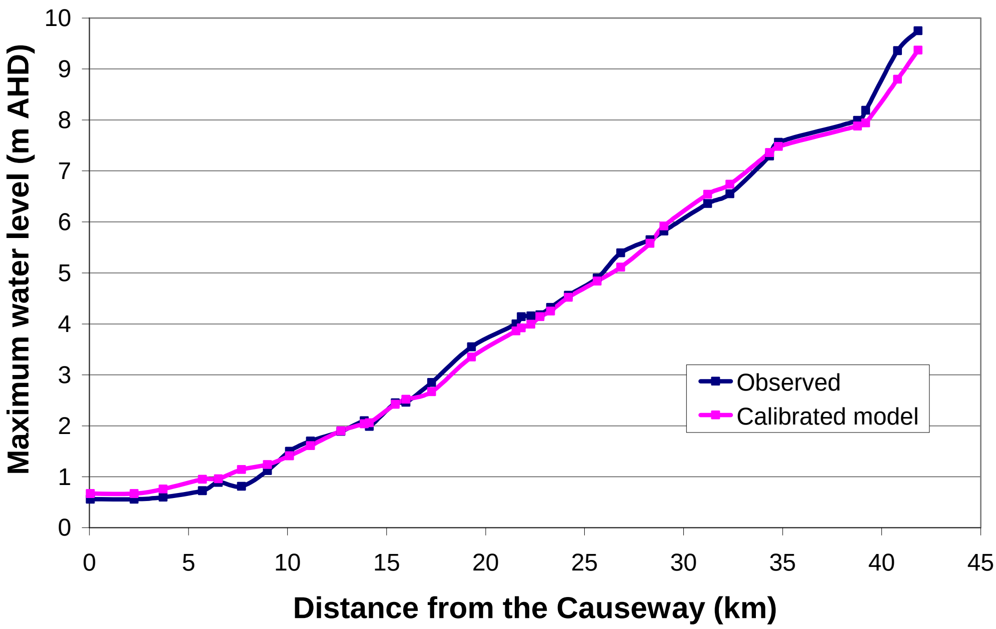

Figure 4.13: Maximum water levels on the Swan River during the July–August 1983 flood event (Observed versus modelled at the corresponding locations)

1987 flood event

The 1987 flood on the Canning River has an estimated AEP of 4%, peaking at the MacKenzie Grove (616027) gauging station on 29/07/1987 at 10:00. The equivalent event on the Avon River is estimated to be roughly a 60% AEP at Walyunga gauging station.

The geometric data which were calibrated to the 1983 flood event on the Swan River were used as the basis for calibrating the geometric data for the Canning River using the 1987 flood event. A longitudinal profile for the Canning River showing modelled peak flood levels after calibration and observed peak flood levels is shown in Figure 4.14. Peak flood values were recorded on the Canning River from Old Nicholson Road, 17.7 km upstream of the junction with the Swan River, for a distance upstream of 16.7 km. No flood levels were available for the Swan River or the other tributaries.

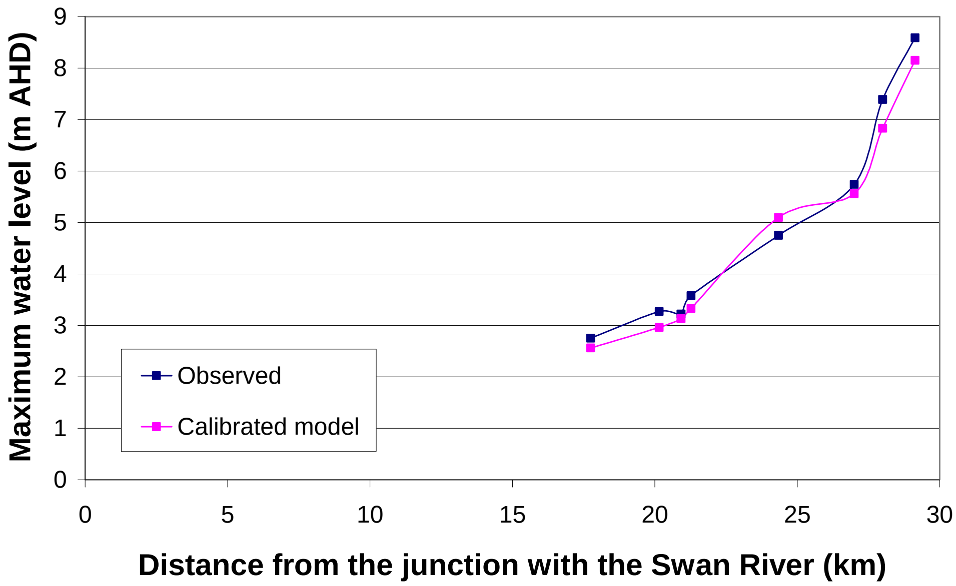

Figure 4.14: Maximum water levels on the Canning River during the 1987 flood event (Observed versus modelled at the corresponding locations)

After calibration the difference between the modelled and historical water levels was reduced by between 0.18–1.08 m. To increase modelled peak flows simulated inflow hydrographs were added to account for increased flows through the urban area. As the 1987 event was equivalent to a 4% AEP event on the Canning River at MacKenzie Grove (616027), the modelled simulated inflow hydrographs for the 4% AEP event were used to calibrate the model. As Table 4.5 shows, lateral inflow has a major effect on flows between the junction with the Southern River and the Nicholson Road Bridge. Adding the simulated design inflow hydrographs increased peak flow and delayed the hydrograph peak, resulting in a calibrated modelled hydrograph much closer in shape, peak and timing to the observed. Minor adjustments to Manning's 'n' further improved calibration.

Model validation

There have been no large historical flood events on the Swan and Canning Rivers since gauging stations in the Swan River system have been operational. Therefore, model validation was difficult because major floods have not been recorded in the system. An alternative approach to model validation is to compare the results from different models. Floodplain modelling carried out by the DOE for the Swan River (Water Authority of Western Australia, 1985) was used to compare the results of the unsteady flow model.

Comparison against the DOE flood model

The 1% AEP floodplain of the Swan River has been mapped by the DOE, and is used as the basis for the provision of floodplain management advice. A comparison of peak water levels for the 1% AEP flood for the Swan River upstream of the Causeway between the two models is shown in Figure 4.16. The locations used for the comparison are the same as those used for calibration (see Figure 4.13).

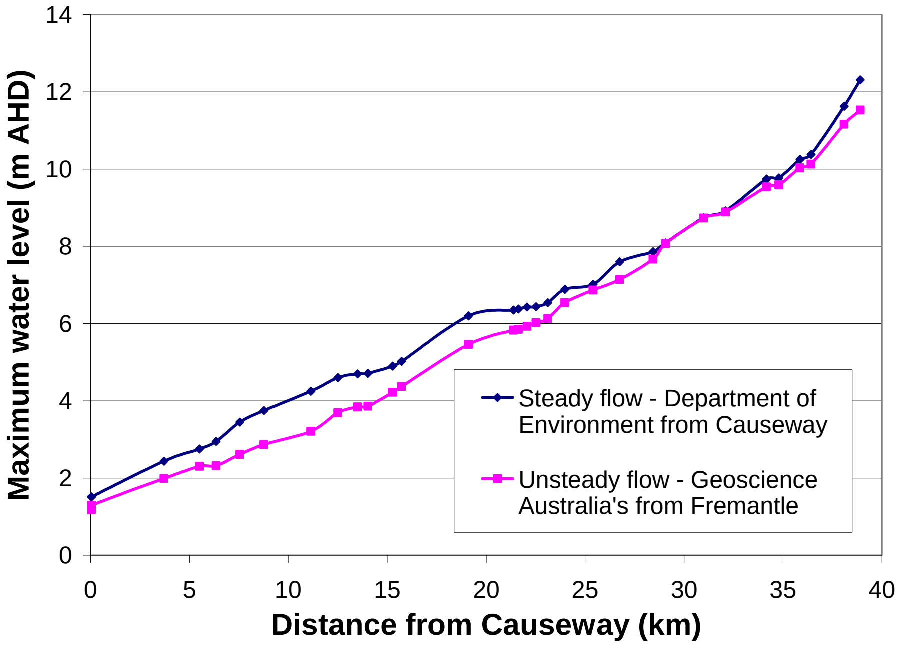

Figure 4.16: Modelled maximum water levels on the Swan River for the 1% AEP event. DOE's results using a steady flow model versus GA's results using an unsteady flow model at the corresponding locations

Flood levels in this study are generally lower than those predicted by the DOE's model at the same location. The greatest difference in water levels is just upstream of the Garrett Road Bridge at the Ascot Racecourse, where peak flood levels are predicted to be 1 m lower than that modelled by the DOE (Figure 4.16). It is important to note that significant differences exist between the two models as shown in Table 4.8, and when these differences are removed, then the results from both studies are similar as shown in Figure 4.17. The inclusion of the tributaries in this study, in particular, played a significant role. The use of the whole flood hydrograph, rather than just peak flow, also played a role in lowering the water levels in places in this study.

As both models have not been validated against high flow events it is difficult to assess the accuracy of the results. There are now sufficient gauging stations operational on the Swan and Canning Rivers and their tributaries to enable proper validation of the models using the flood levels and hydrographs recorded during a future major flood event. However, it is recommended that major river flooding in the Swan and Canning Rivers is reviewed following the next major flood event.

Impact of Tidal Cycle Variation on Flood Flows

Examination of the 19 years of predicted tidal record between 1 January 1992 and 31 December 2010 from the Tides and Waves Section of the DPI, shows seasonal variation in the tidal cycle. As seen in Figure 4.18, the highest astronomical tide (HAT) at the Port of Fremantle tidal gauge (62230) occurs in the winter months and the lowest astronomical tide (LAT) occurs during the summer months, though there is no seasonal variation in the range of water heights. Similar seasonal variations in the tidal cycle are seen at the Barrack St and Guildford tidal gauges on the Swan River as shown in Figure 4.19. During the winter months, flood flows coming down the Swan River can push the tidal cycle up even higher than would be seasonally typical at Guildford. No station numbers are available for Barrack St and Guildford as they are minor tidal gauges.

Table 4.8: Differences between the model employed in this study and the model used by DOE

This study	Earlier study: DOE
Modelled the Swan, Canning and Helena Rivers, and the Ellen, Susannah, Jane and Southern River–Wungong Brooks.	Swan River flood modelling included inflow from Ellen Brook, Jane Brook and the Helena River
Unsteady flow model, hydrographs	Steady flow model, peak discharge
Extended model geometry to Fremantle	Model geometry commenced at the Causeway
Used tidal cycle as lower boundary condition at the Port of Fremantle	Constant 1.5 m AHD was used for downstream boundary condition at the Causeway
Total number of cross-sections used was 2,786 for the Swan River and tributaries; of which 424 were surveyed, 784 were supplementary cross-sections derived in GIS, and 1977 were interpolated cross-sections derived in HEC-RAS	Used 1985 Swan River survey data comprising 128 cross-sections
Treated bridges as surveyed cross-sections	Affluxes through bridges were calculated
Updated floodplain and channel geometry where significant changes	Used 1985 Swan River survey data
Lengthened surveyed cross-sections to extend across the floodplain	Used 1985 Swan River survey data
Manning's values for channel, and left and right overbank areas. Calibrated against 39 recorded flood levels on Swan River for the 1983 flood event and 8 recorded flood levels on Canning River for the 1987 flood event	Average Manning's value for channel and overbank areas were calibrated using 39 recorded 1983 peak Swan River flood levels
Verified against DOE model	Other historical recorded peak flood levels (1872,1926, 1945, 1955, 1963, 1974) were used to verify predicted flood levels

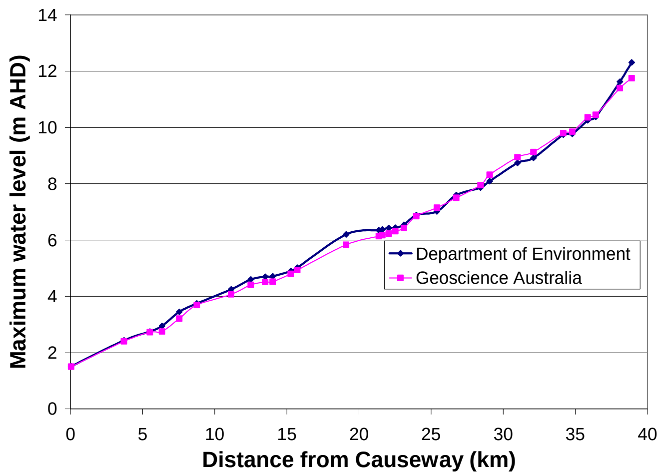

Figure 4.17: Modelled maximum water levels on the Swan River for the 1% AEP event. DOE's results are compared with those of GA's model using the same parameters. In order for GA's model to cover the same geographical location as the DOE's model, the tributaries have been excluded and the Causeway is used as the lower boundary condition rather than Fremantle. In this comparison, GA's model was also run under steady flow conditions

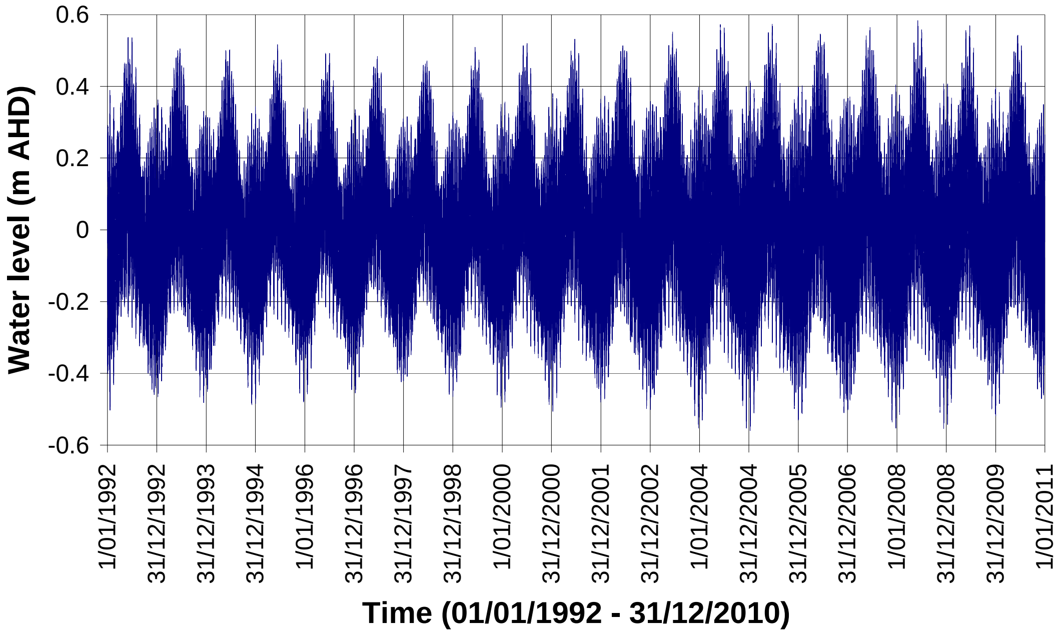

Figure 4.18: Nineteen years of tide predictions for the Port of Fremantle (62230), 1 January 1992 – 31 December 2010 (Data courtesy of DPI)

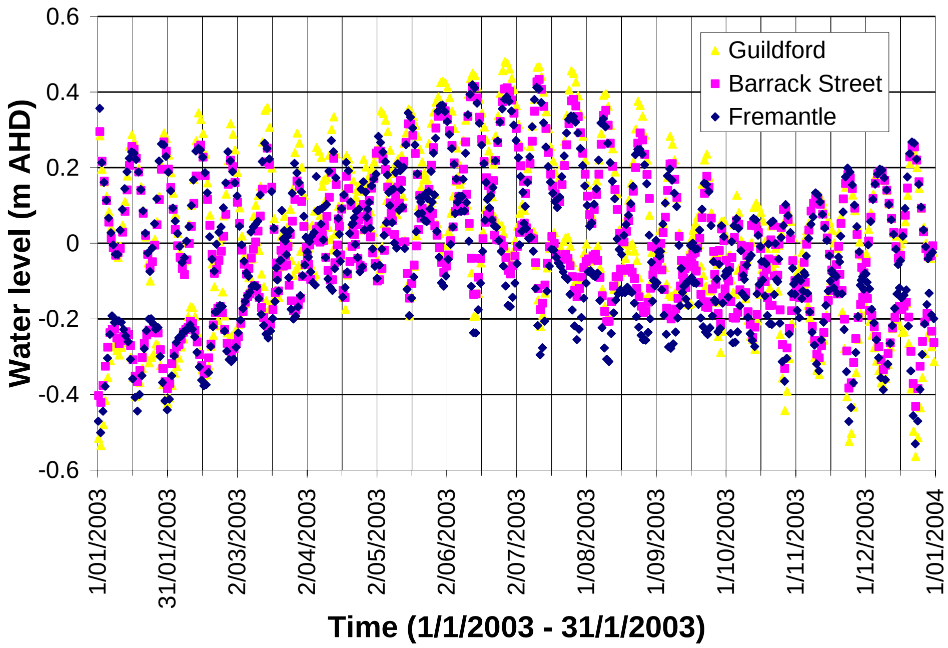

Figure 4.19: Tide predictions for the Port of Fremantle (62230), Barrack St and Guildford for 2003 (Data courtesy of DPI)

In order to assess what impact, if any, the tidal cycle has on water levels in the Swan–Canning River system, the HAT and LAT were assumed to occur simultaneously with the peak of the 1% AEP flood. In 2003, the HAT was predicted to occur on 15 June, 09:10 – 09:30 and the LAT on 24 December, 07:00 – 07:15 (Figure 4.20). The 1% AEP flood was chosen to compare the affect of the tidal cycle as the 1% AEP flood is used as the basis for floodplain management planning in Perth.

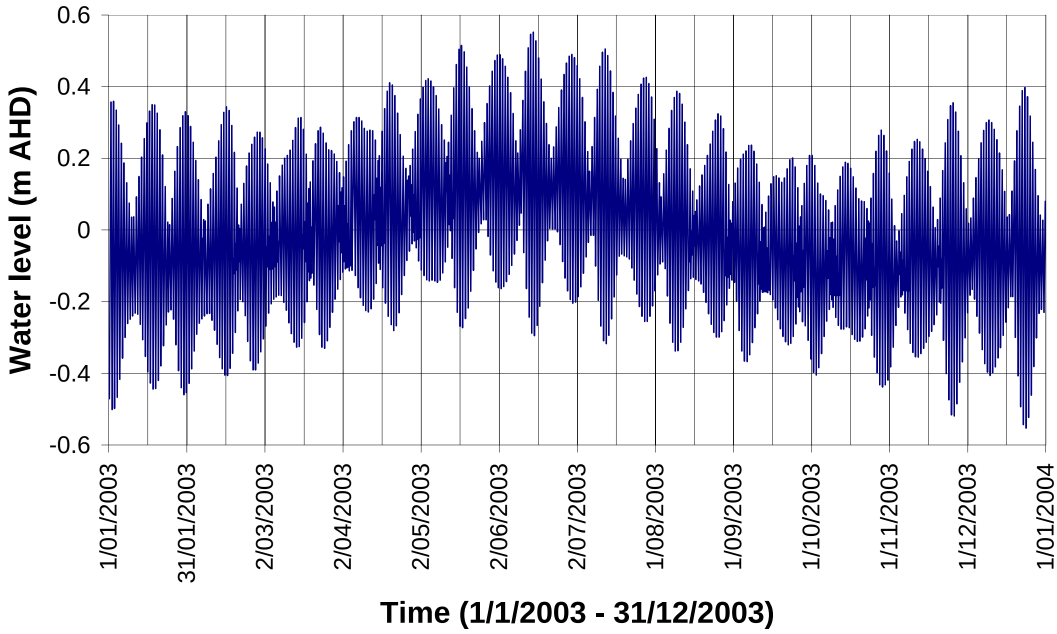

Figure 4.20: Tide predictions for the Port of Fremantle (62230) for 2003 (Data courtesy of DPI)

Figures 4.21 and 4.22 show that varying the tidal cycle has a slight impact on maximum water surface elevations, with maximum differences of 0.16 m and 0.2 m on the Swan and Canning Rivers respectively. The results modelled using the winter tide are slightly higher than those modelled using the summer tide. Upstream of the Causeway, located 25 km from the mouth of the Swan River, the variation in the maximum water surface elevation is less than 0.1 m. Approximately 45 km upstream of the mouth of the Swan River there is no variation in maximum water surface levels. On the Canning River the variation in maximum water surface levels decreased to less than 0.1 m within 12 km from the junction with the Swan River, with no variation 14 km from the junction.

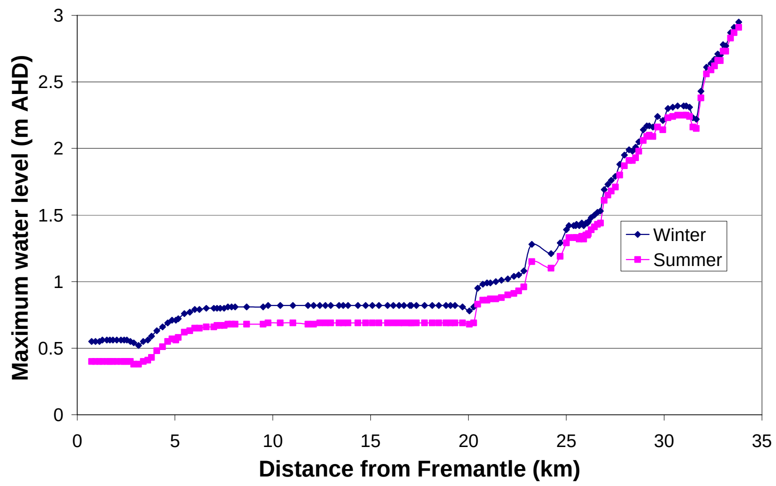

Figure 4.21: Comparison in maximum water surface elevation using the winter and summer tides, from the mouth of the Swan River to Ascot Waters

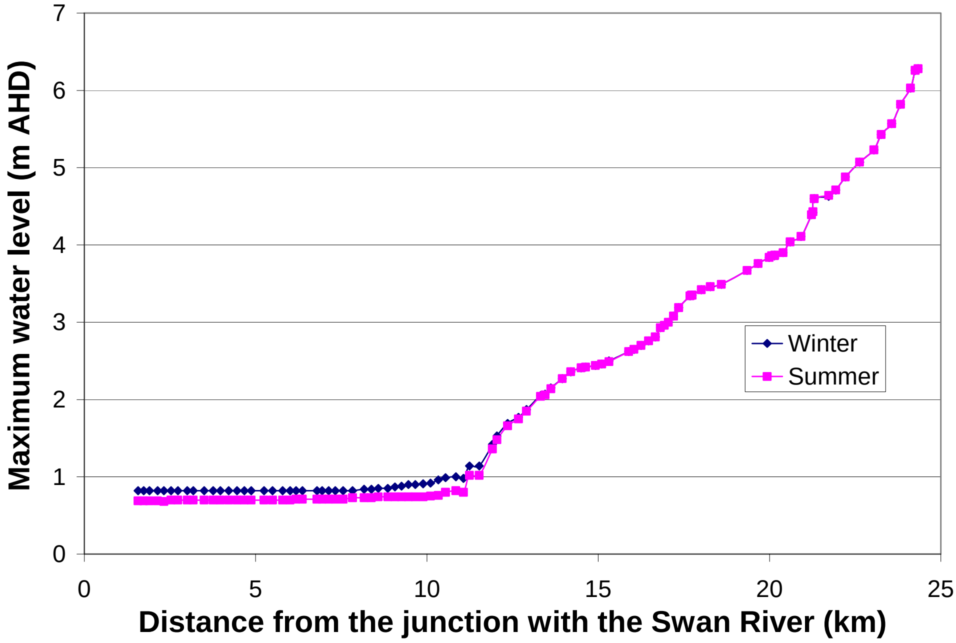

Figure 4.22: Comparison in maximum water surface elevation using the winter and summer tides on the Canning River, between the junctions with the Swan and Southern Rivers

Figure 4.23 shows the impact of varying the tidal cycle on water surface elevation over the simulation period on the Swan River. The impact of tidal cycle variation is greatest downstream of the Causeway, where the peaks and troughs in water surface elevation are reversed between the use of the HAT and the LAT (Figure 4.23). The affect decreases upstream, becoming insignificant just downstream of the Swan and Helena river junction, 40 km upstream from the mouth of the Swan River. On the Canning River there is a noticeable difference in water surface levels only on the falling limb of the hydrograph, 12.7 km upstream of the Swan and Canning river junction (Figure 4.24). As with the maximum water surface levels, the results modelled using the winter tide are only marginally higher than those modelled using the summer tide.

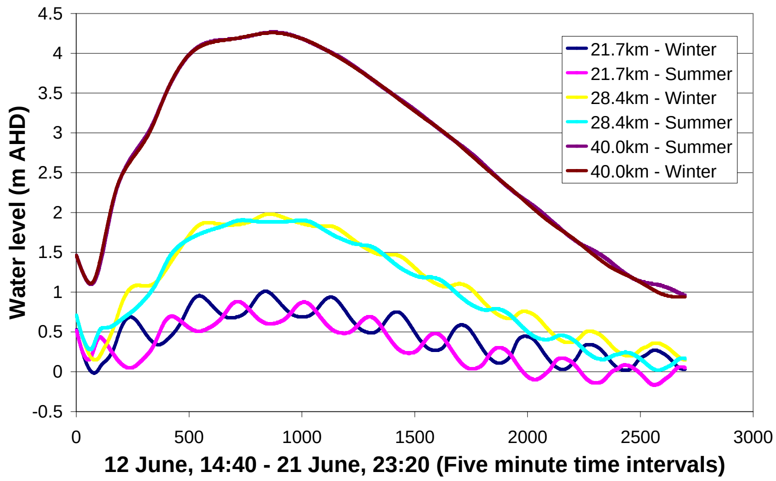

Figure 4.23: Comparison in water surface elevation over time (12 June 2003, 14:40 – 21 June 2003, 23:20) using the winter and summer tides, at distances of 21.7 km, 28.4 km and 40.0 km upstream of the mouth of the Swan River

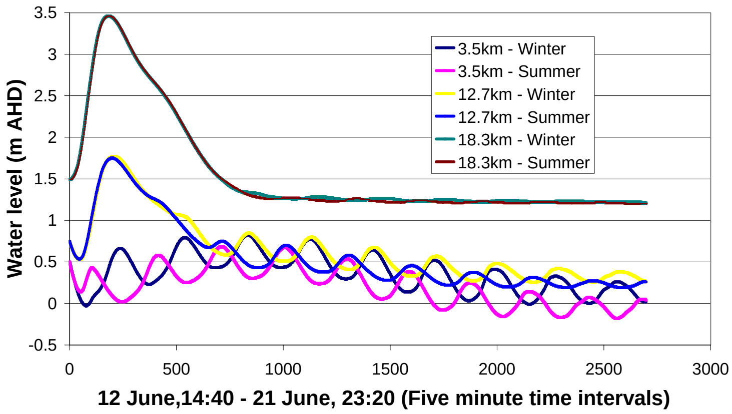

Figure 4.24: Comparison in water surface elevation over time (12 June 2003, 14:40 – 21 June 2003, 23:20) using the winter and summer tides, at distances of 3.5 km, 12.7 km and 18.3 km along the Canning River upstream of the junction with the Swan River

The areas where the variation in maximum water surface levels are the greatest on both the Swan and Canning rivers, coincides with the suburbs which are not affected by flooding during the 1% AEP event.

Impact of a storm surge

High ocean storm surges and large riverine floods generally occur as a result of low-pressure systems crossing the coast. Where the riverine flood and storm surge occur as a result of the same low pressure system, peak riverine flood levels would not occur at the mouth of the Swan River until 3–5 days after the peak ocean storm surge, due to the size of the Swan–Avon catchment. However, a storm surge of any magnitude associated with a later low pressure system than one which has caused flooding has the effect of reducing the discharge capacity of the river mouth, causing flow to back up and raise water levels beyond those identified through the modelling. This has not been studied due to the lack of data on coincident occurrence of both phenomenon. The frequency of storm surge occurrence and the probability of it happening jointly with riverine flooding need separate study.

Modelling of design floods

This section presents the flood inundation mapping for eight scenarios ranging from 10% AEP to the 0.05% AEP for the Swan and Canning Rivers and their tributaries. The modelling used the inflow hydrographs at each of the seven gauging stations, and additional simulated inflow hydrographs at 13 other locations. As floods in Perth occur most commonly during winter, the winter tidal cycle was adopted as the lower boundary condition. The winter tide was also used in the comparison of flood modelling shown in Figure 4.16 earlier.

Each AEP simulation was done with the tributaries experiencing the same event magnitude as the Swan–Avon River at Walyunga (616011), for example, the 1% AEP flow. The flood hydrographs at Walyunga (616011) typically lasted for nine days, with the peak occurring on the third day. The flood hydrographs on the tributaries typically reach base flow on the third day, peaking on either the first or second day. Base flow was assumed on the tributaries for the rest of the simulation. The peak design flow estimates for the hydrographs at the upstream boundaries of the model were shown in Table 4.3, and the difference in flow (%) between the different locations on a single stream in Table 4.5. The PMF was not modelled because of the huge uncertainties involved in modelling the extreme event.

Figures 4.25 to 4.32 show maximum water depth contours for the 10% AEP to 0.05% AEP scenarios.

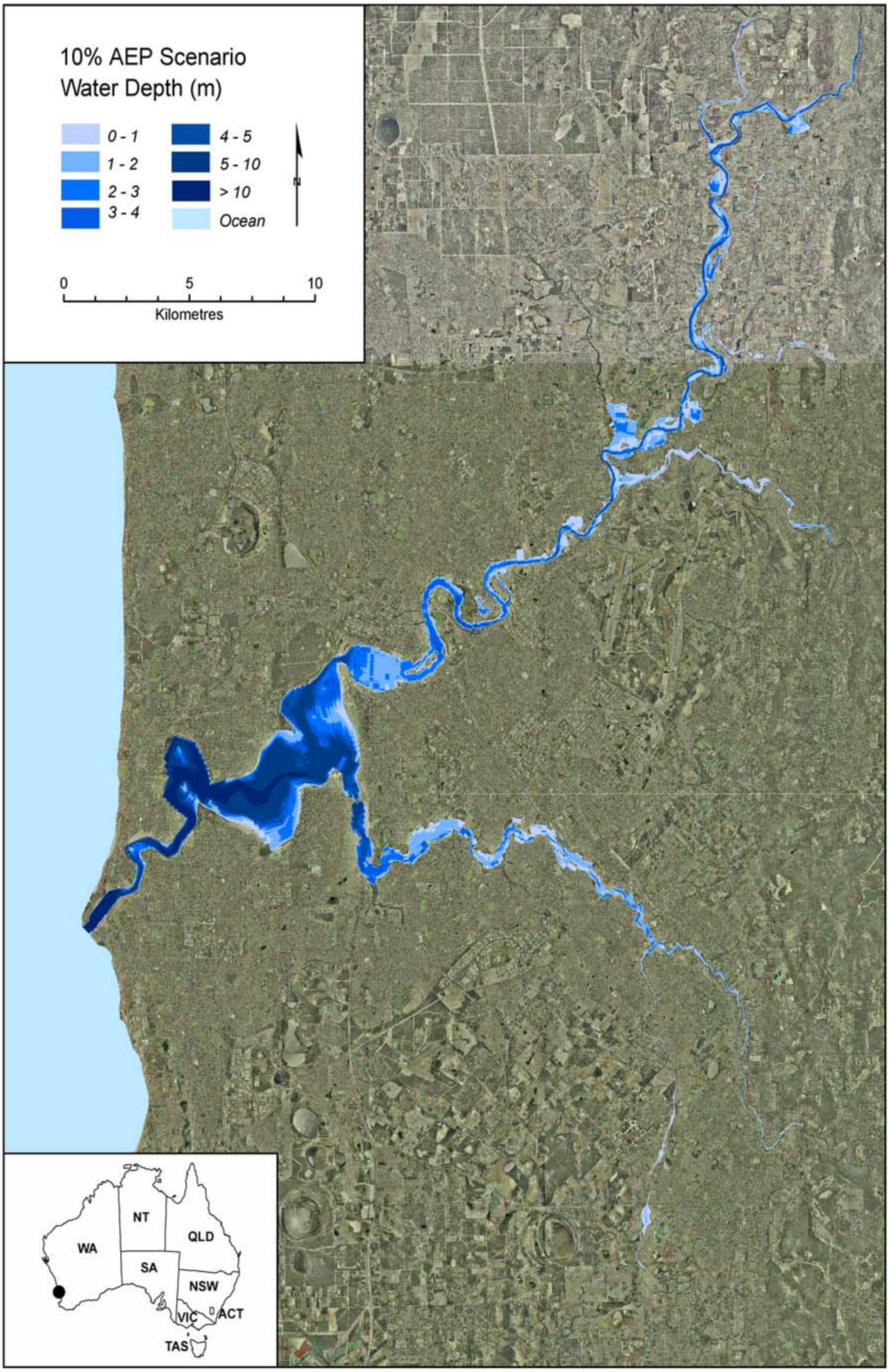

Figure 4.25: Flood inundation mapping for the 10% AEP scenario showing maximum water depth contours

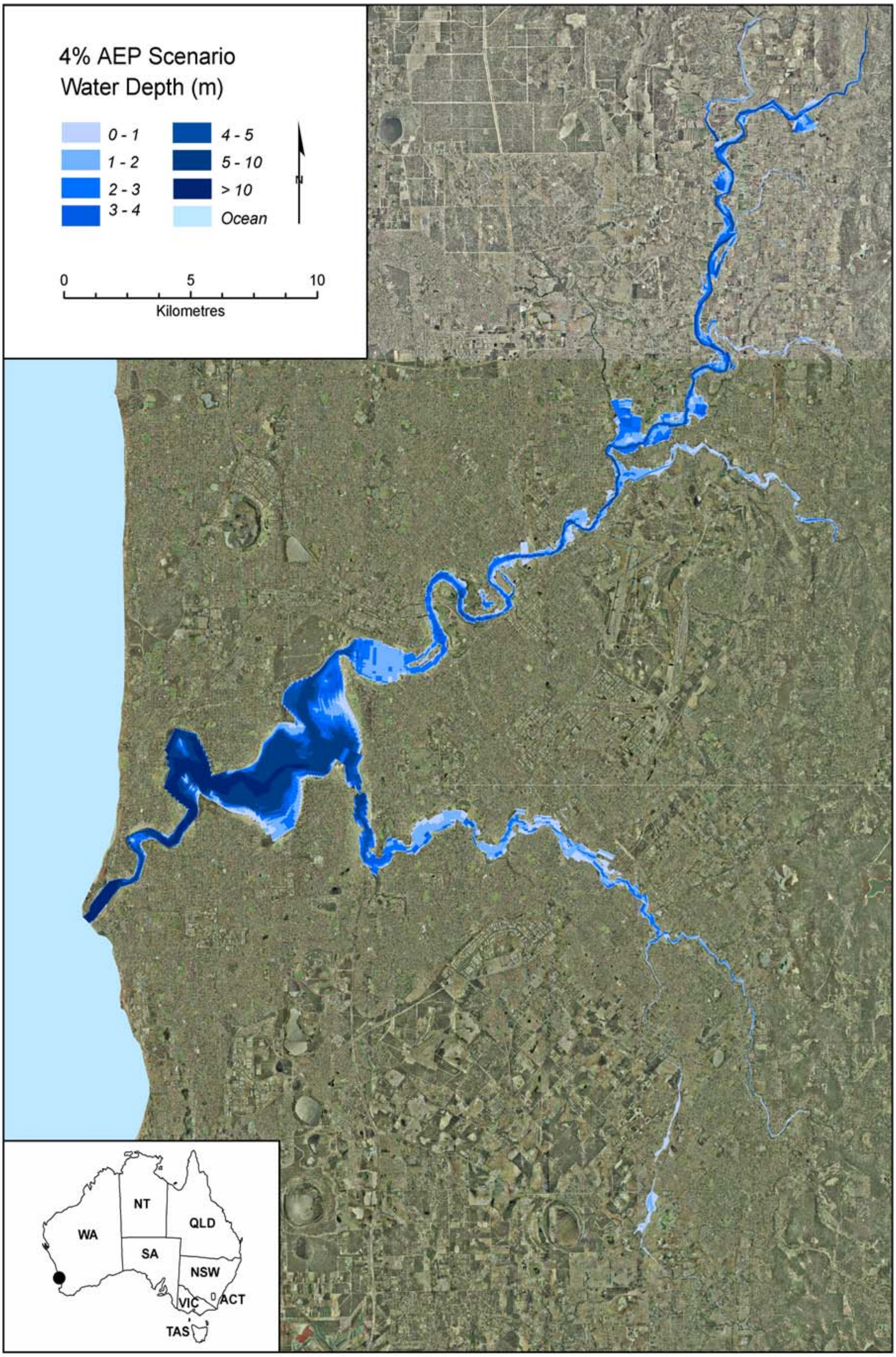

Figure 4.26: Flood inundation mapping for the 4% AEP scenario showing maximum water depth contours

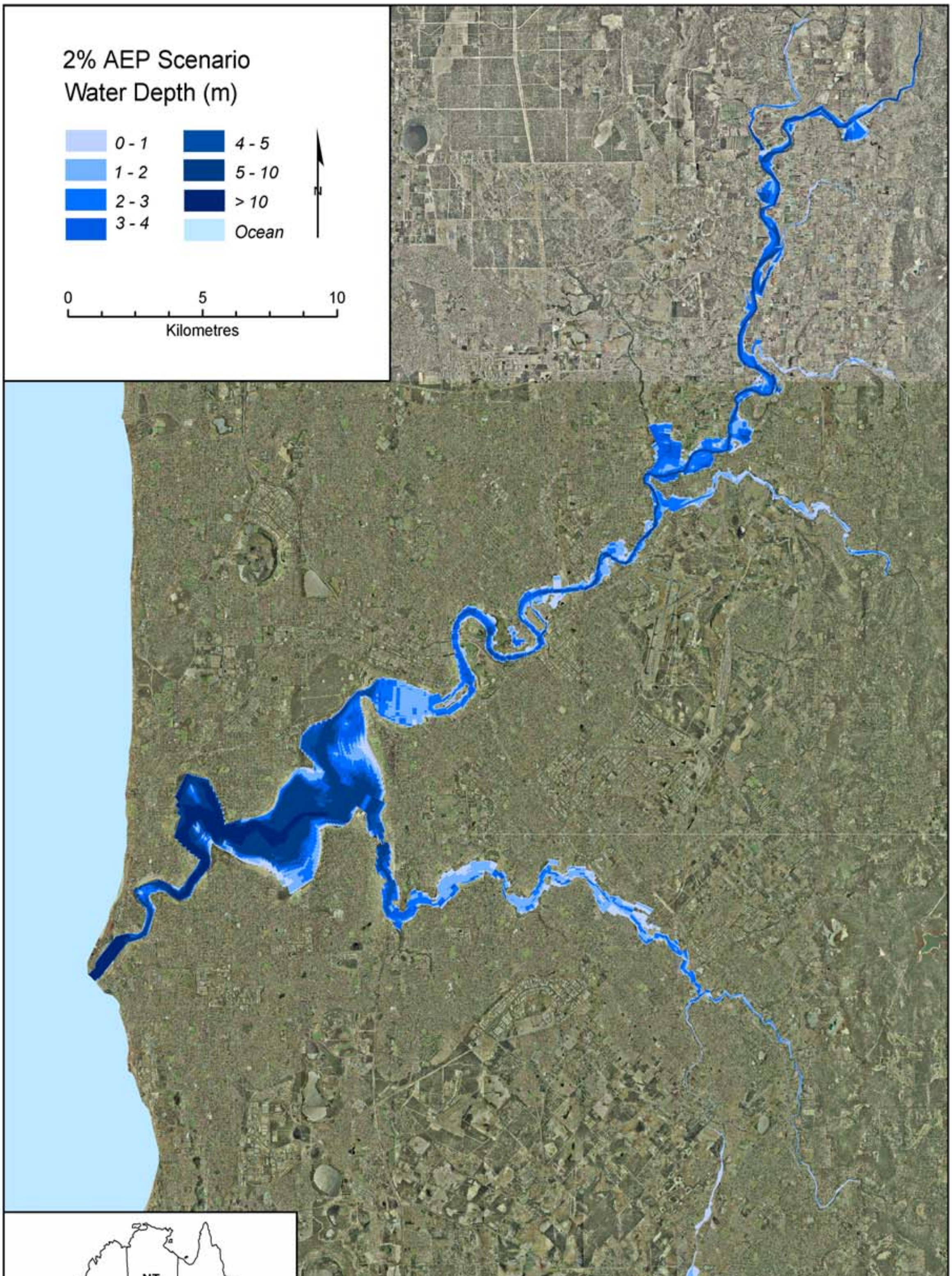

Figure 4.27: Flood inundation mapping for the 2% AEP scenario showing maximum water depth contours

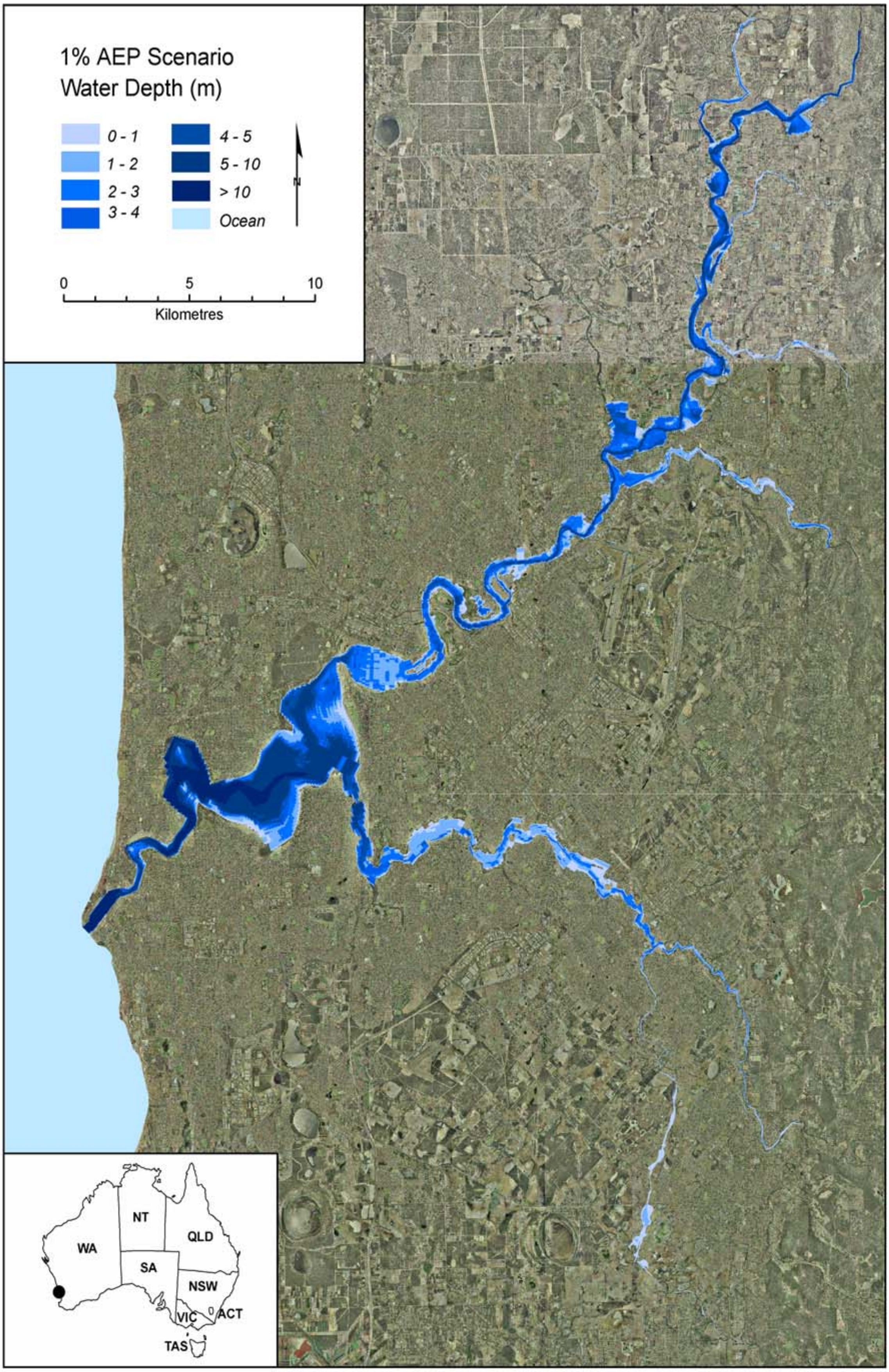

Figure 4.28: Flood inundation mapping for the 1% AEP scenario showing maximum water depth contours

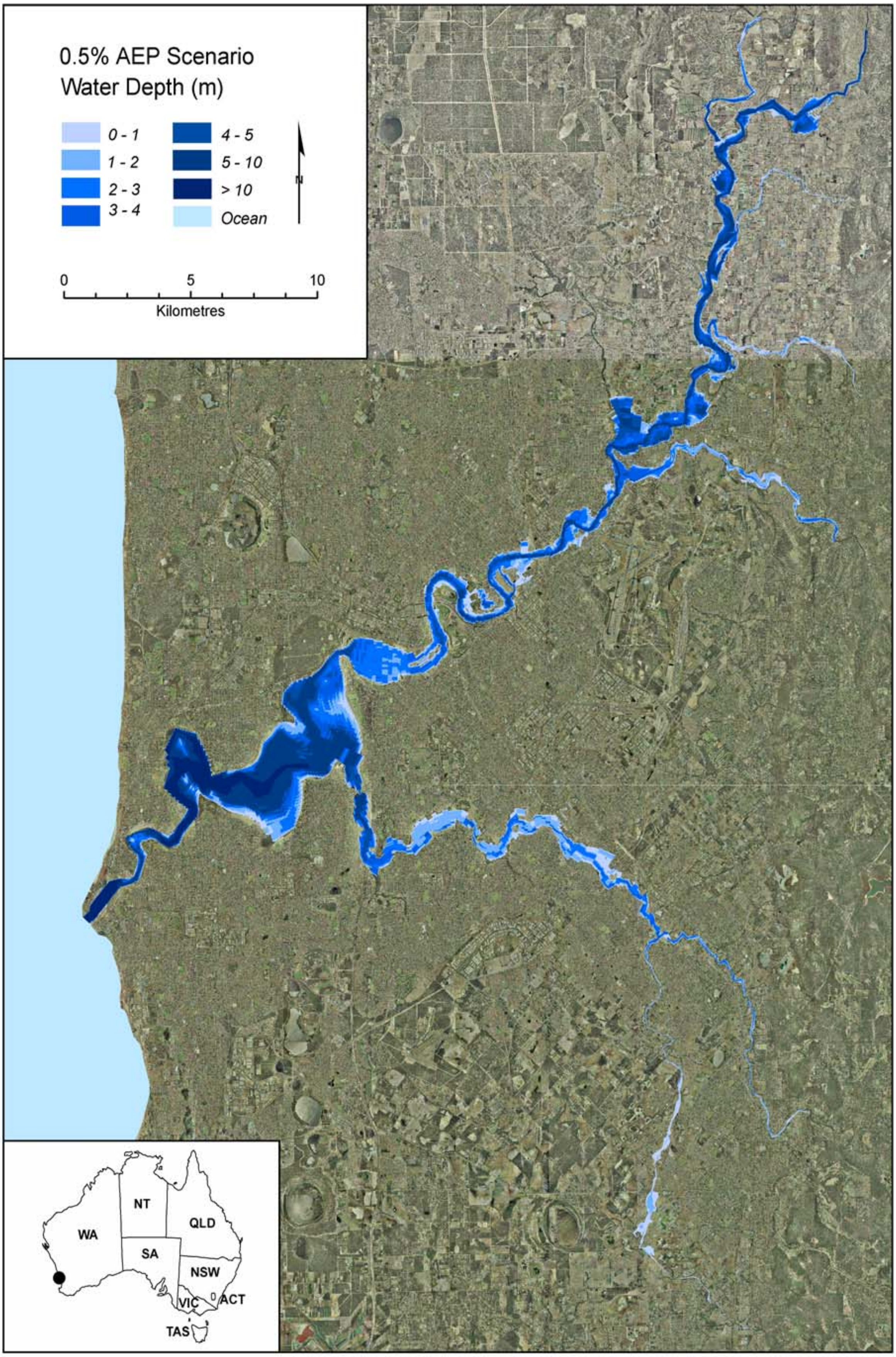

Figure 4.29: Flood inundation mapping for the 0.5% AEP scenario showing maximum water depth contours

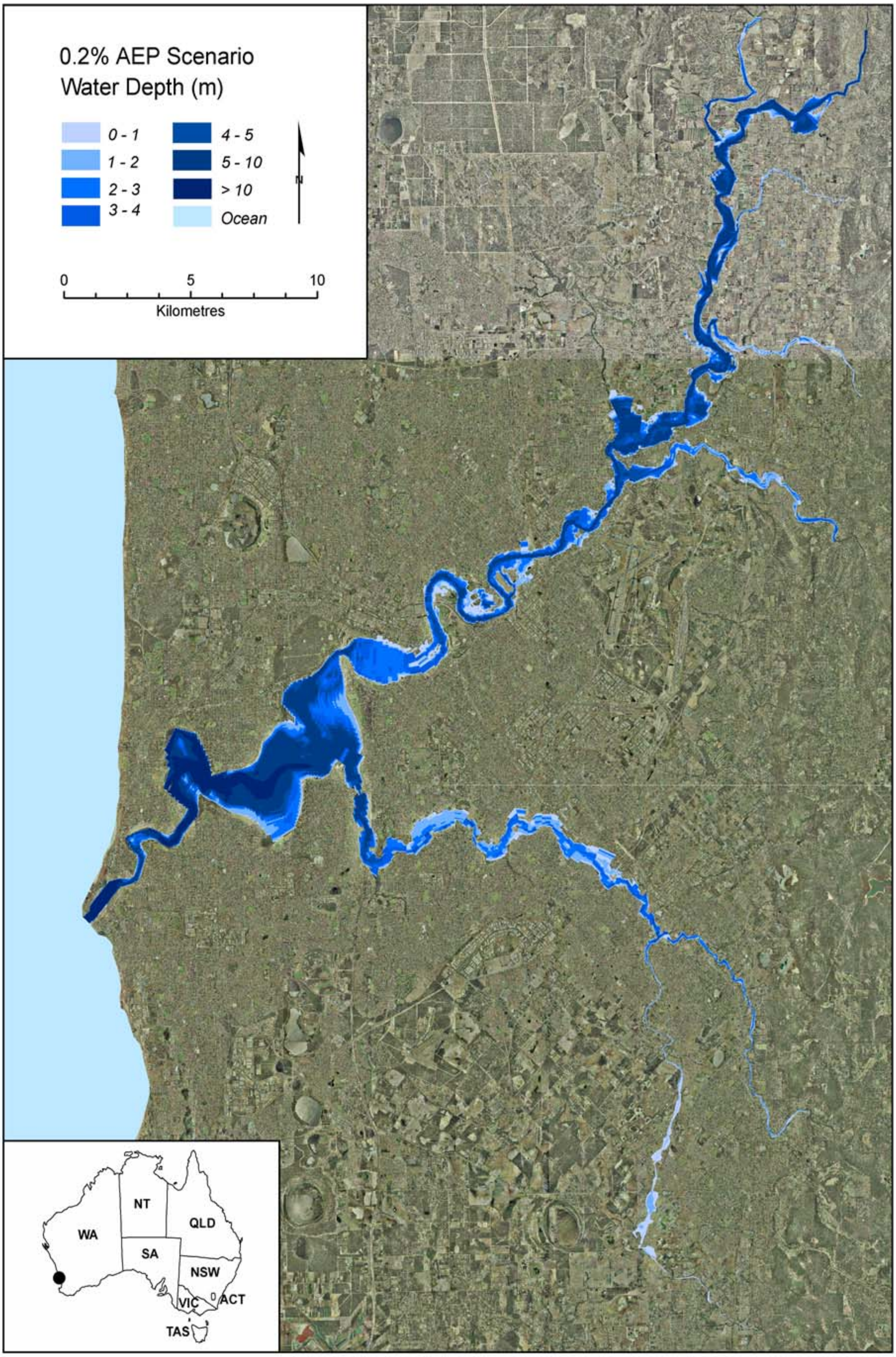

Figure 4.30: Flood inundation mapping for the 0.2% AEP scenario showing maximum water depth contours

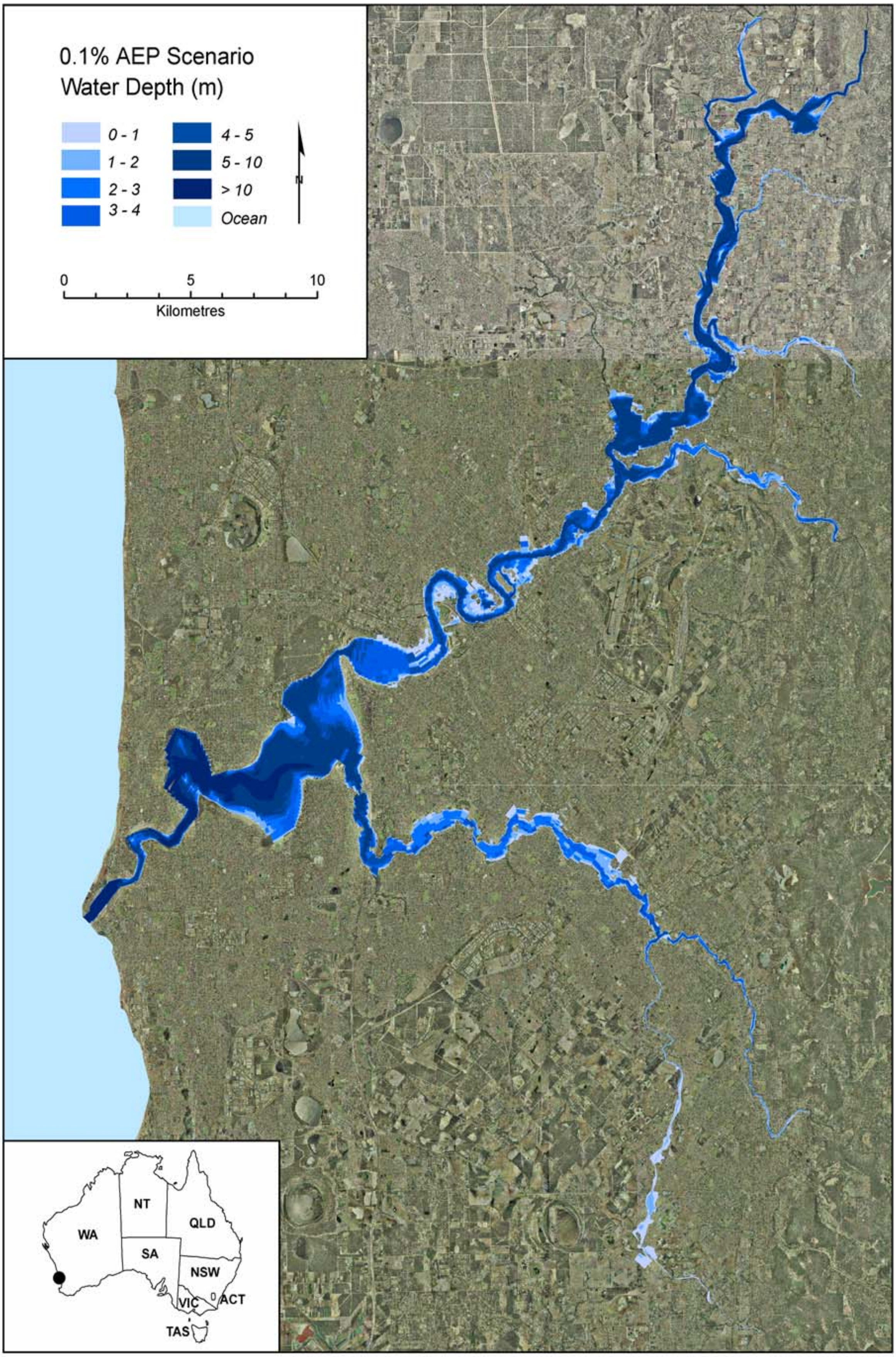

Figure 4.31: Flood inundation mapping for the 0.1% AEP scenario showing maximum water depth contours

Figure 4.32: Flood inundation mapping for the 0.05% AEP scenario showing maximum water depth contours

4.6 Conclusions

This chapter covered both the hydrologic and hydraulic aspects of flood estimation for the Swan River and its tributaries in Perth, Western Australia. It has incorporated hydrologic estimates and surveyed cross-sections used in previous individual studies into a single study and modelled the interactions of the tributaries with the Swan River. The geometry of the model was significantly enhanced by the addition of many cross-sections derived using a detailed DEM, which was developed specifically for the modelling of flood flows.

There are six major catchments in the study area that contribute flow to the Swan River, of which the Avon catchment is by far the largest. Unsurprisingly, the hydrologic estimation of flows showed that the Avon River at Walyunga (616011) was by far the most dominant flow contributor to the Swan River. Simulated inflow hydrographs (accounting for urban runoff), on the whole provided a significant source of additional flow to the tributaries, particularly on the Canning and Southern Rivers.

HEC-RAS was the hydraulic model used for the modelling of unsteady flows through the Swan River and its tributaries. The season of the tidal cycle was found to marginally influence flood flows, with water levels slightly higher in winter, when peak flood levels at Walyunga were made to coincide with the HAT. As expected, the influence of the tidal cycle decreases with distance upstream from the Port of Fremantle.

Perth has experienced a lengthy dry period. Only two major flows have occurred since all the streamflow gauging stations at the outer boundaries of the model became operational. These events, the 1983 flood on the Swan River and the 1987 flood on the Canning River, were used for model calibration, having estimated AEPs of 10% and 4% respectively. The dry conditions have made validation of the model even more difficult. Therefore, the results of the model were verified against the results of the DOE and found to produce similar results when the differences between the models were removed.

Water levels in this study were found to be up to a metre lower than those modelled previously for the 1% AEP flood event. The variation in water levels can be explained by the significant differences between the two models. Of these, the inclusion of the tributaries, followed by the use of an unsteady flow model rather than a steady flow model provide the best explanation for the differences.

Eight flood scenarios have been modelled for the Swan River and its tributaries ranging from AEPs of 10% to 0.05%. It is recommended that the DOE’s 1% AEP floodplain mapping is continued to be used as the basis for ensuring that future development has adequate flood protection. However, it is recommended that major river flooding in the Swan and Canning Rivers is reviewed following the next major flood event.

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