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Report for Phase 2 Ord River Irrigation Area Expansion of the Weaber Plain

Keep River Catchment-River and Hydrodynamic Modelling

October 2010

INFRASTRUCTURE | MINING & INDUSTRY | DEFENCE | PROPERTY & BUILDINGS | ENVIRONMENT

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Executive Summary

The Western Australia Minister for State Development proposes to expand the existing Ord River Irrigation Area (ORIA) across the Weaber Plain farmlands (WPF). This study focuses on the 8,000 ha of Phase 2 WPF. A summary of the main water quality outcomes of this modelling study from the proposed WPF development include:

- The Total Dissolved Solids (TDS) concentrations in the least saline, permanent pool (K3) of the receiving Keep River does not exceed the lower trigger value of 675 mg/L. This has been determined to be an appropriate site specific lower concentration, though an upper trigger level of 1,275 mg/L has been recommended;
- At the onset of the dry season the concentrations of nutrients and farm chemicals in the Keep River pools and the estuary will be below environmental trigger values; and
- Additional safeguard management measures are available to ensure compliance with the trigger values should extreme or unusual circumstances occur.

The proposed WPF development involves an irrigation tailwater management system, meaning that irrigation runoff from irrigated land will be reused on farms. Retained tailwater will be reused for irrigation most of the time; however, if the surface runoff exceeds the tailwater system retention capacity, the excess water will overflow at a designated point via a controlled discharge (hereafter referred to as stormwater). It is proposed that the stormwater be directed into Border Creek, which ultimately discharges into the Keep River. The stormwater may contain sediment, organic matter, nutrients and farm chemicals.

As a result of the development groundwater accession is expected. Groundwater will be reused for irrigation or alternatively discharged into the Keep River system during the wet season, depending on its water quality. The groundwater discharge option considered here assumed a 200-500 L/s release rate, a groundwater TDS of 3,000 mg/L and a target release volume of 3.7 GL into the Keep River. The rate of release of groundwater into Keep River will be such that instantaneous dilution with the receiving waters at the discharge point maintains a TDS less than 675 mg/L, which was determined to be the appropriate lower trigger value based on available evidence. Nutrients, farm chemicals and salt may also occur in the groundwater discharge.

Catchment-river and hydrodynamic models were developed in this study to evaluate dilution and flushing, and thereby potential changes to water quality in the lower Keep River and upper Keep River estuary from the proposed WPF development. Both high (2006) and low (2007) runoff years were considered. The application of conservative tracers in this modelling investigation is deemed sufficient to ascertain whether salt, nutrient and contaminant loads from the proposed development will be of concern to the receiving riverine and estuarine waters. The catchment-river modelling indicated that tracers of farmland-origin stormwater can attain peak concentrations of 5-28% (of initial concentrations) of the Keep River flows prior to entering pool K3 for short durations. To a large degree these peak concentrations depend upon the amount of dilution below the release point with a higher proportion of stormwater when Keep River flows are low.

For the hydrodynamic modelling the Keep River bathymetry was approximated with available information. The tidal regime in the river is highly dependent on the river bed elevation with shallow sections of the river dampening the tides as they propagate upstream. Given the assumptions to

construct the bathymetry, hydrodynamic modelling in the narrow regions of the estuary is considered approximate. Nonetheless, simulated and measured tidal water levels over approximately 1.5 months at the end of the 2004 dry season compared well at three upper estuarine locations.

Overflow of WPF stormwater into Border Creek and managed releases of groundwater into Keep River will generally occur during flow events. These flow events flush the stormwater and groundwater through the lower Keep River including a series of 3 pools that are freshwater (pool K3), brackish (pool K2) and saline (pool K1). Generally, peak groundwater tracers of 10-15% (i.e. 10-15% of the volume comprised of groundwater) are predicted in the pools and upper estuary, while peak WPF stormwater can typically comprise 4-8%. In the worst case when stormwater retention capacity of the WPF is low (or non-existent) prior to a small rainfall event, then low dilution can result in up to 25% of the waters in the pools and upper estuary comprised of stormwater.

Stormwater and groundwater quality were approximated with extensive measurements from Ivanhoe districts' D4 drain and groundwater as proxies for the proposed WPF development. Though the farm chemicals atrazine and endosulfan have been detected in the D4 drain, 'characteristic' values are below the ANZECC & ARMCANZ (2000) 99% species protection trigger levels. Endosulfan has also been recently banned from use in Australia. Characteristic TDS, Total Nitrogen (TN) and Total Phosphorus (TP) background levels of the Keep River and lower Border Creek were developed from end of wet season (start of dry season) available data. Predicted concentrations of TN, TP and TDS in the pools and upper estuary were estimated from the simulated proportion of Keep River, Border Creek, WPF stormwater and groundwater; and their characteristic water quality concentrations.

The predicted water quality in the pools and upper estuary was compared to relevant ANZECC & ARMCANZ (2000) trigger values (TN and TP) or interim site specific freshwater trigger values for pool K3 (TDS, TP). Predicted TDS was always considerably below the interim trigger values (lower trigger value of 675 mg/L, upper trigger value of 1,275 mg/L) in the freshwater pool K3. Stormwater was estimated to increase TP in pools K3 and K2 (but not pool K1 or upper estuary) slightly above the ANZECC & ARMCANZ (2000) trigger value of 0.01 mg/L for approximately 1 cumulative month over the 5 month simulation (20% time exceedance), but not exceed the interim site specific trigger value of 0.02 mg/L. The combination of groundwater releases and stormwater was estimated to slightly (~10%) to moderately (~50%) increase TN and TP in the pools and upper estuary over the relevant ANZECC & ARMCANZ (2000) trigger values for 1 to 4 cumulative months (20-80% time exceedance), but only slightly (~10%) for 1 cumulative month (20% time exceedance) during the high runoff year (2006) over the site specific TP trigger value (0.02 mg/L) for pool K3. However, at the onset of the dry season TN and TP was predicted to be equal or less than all trigger values because riverine flows effectively flush the pools after the cessation of groundwater releases. Further, tidal flushing of the upper estuary also assists in reducing the proportion of stormwater and groundwater, so that trigger levels are met at the onset of the dry season.

The end of the wet season is the period of greatest environmental sensitivity to the pools, as this sets the initial water quality for the long dry season with low riverine flushing thereafter. Typically, the proportion of stormwater and groundwater at the onset of the dry season is below 1% in the pools and upper estuary. Further, several proposed management measures can readily mitigate atypical circumstances when elevated proportions of groundwater and/or stormwater occur in the pools, including:

- Limited releases of excess groundwater during the tail of late wet season flow events; and
- Provision to flush pools with M2 water if required.

1. Introduction

1.1 Project Context

The Western Australia Minister for State Development proposes to expand the existing Ord River Irrigation Area (ORIA). This proposed expansion (hereafter referred to as 'Ord Irrigation Expansion Project' or OIEP) ultimately covers 30,500 ha of land for irrigated agriculture on the Weaber, Keep River and Knox Creek Plains. Over 42,000 ha surrounding the farmlands will also be managed for conservation purposes. The OIEP will be implemented in a staged approach. This study focuses on the first development of approximately 8,000 ha within the OIEP on the Weaber Plains (hereafter referred to as 'Weaber Plains Farmlands; or WPF).

The farm design in the development is based on the use of an irrigation tailwater management system, meaning that irrigation runoff from irrigated land will be reused on farms. The system consists of constructed channels to collect tailwater, a storage area, and return pumps and pipelines for reuse as irrigation water.

The management of the tailwater system will be seasonal. During the dry season or between intermittent rainfall events, the farms will be irrigated, thus the tailwater system will retain tailwater for reuse as irrigation. During the wet season, the tailwater system along with other on-farm storage will function to retain the first 25 mm of stormwater runoff. When the surface runoff exceeds the tailwater system retention capacity, the excess runoff will overflow from the farm at a designated point via a controlled discharge. It is proposed that this excess runoff along the internal buffer area be transported via various internal drains into the upper reaches of Border Creek to mix with runoff water from the undeveloped 100,000 ha, which ultimately discharges into the Keep River with a 319,000 ha catchment.

As a result of the development, groundwater accession is expected to occur, although the precise extent and rate of such depends on many factors including wet season rainfall, crop types and an adaptive groundwater management strategy. The groundwater levels will be monitored and, where required, managed with a network of dewatering bores (likely year-round). Where possible, groundwater extracted as part of the groundwater management strategy will be reused for irrigation. When groundwater cannot be reused for irrigation purposes (i.e. if irrigation is in low demand, as in the wet season, or if long-term groundwater salinity exceeds the limits for shandying) then excess pumped groundwater (hereafter 'excess groundwater') will be collected in a storage reservoir and/or discharged during periods of 'wet season' stream flow into Border Creek and Keep River. A groundwater Total Dissolved Solids (TDS) threshold of approximately 1,500–2,000 mg/L is the anticipated upper limit for shandying groundwater with irrigation water from Lake Kununurra. The expected extraction of groundwater is likely to be an annual average of between 800 L/s depending on a wide range of likely climatic and cropping scenarios (KBR 2010). An expected TDS range of 3,000 mg/L for low yield bores to 1,000 mg/L for paleo-channel bores is predicted for the WPF pumped groundwater (KBR 2010). Operation rules for the discharge of excess groundwater during the wet season into the Keep River system will be selected to allow sufficient dilution with these receiving waters to minimise the impact on the downstream riverine and estuarine environments. This strategy has been devised so that no surface discharge of excess groundwater occurs into the Keep River system during the dry season when potential impacts to the hydrology and water quality of the downstream riverine and estuarine receiving water are likely to be measurable. Monitoring of the excess groundwater quality and surface water discharge will inform decisions on the timing of release so that sufficient dilution occurs with the receiving riverine waters. Groundwater quality is likely to decrease over time from the proposed development (KBR 2010), so the groundwater management strategy has been developed to provide flexibility in decision making and ongoing management in terms of wet season excess groundwater release.

1.2 Scope of Study

It is a condition from the Western Australian Minister of the Environment that a Hydrodynamic Survey Plan for the Keep River, Border Creek and Sandy Creek be prepared prior to discharging excess (pumped) groundwater or stormwater runoff from the WPF development area into the downstream portions of the Keep River system.

Surveys of the flushing characteristics of the Keep River have previously been undertaken (KBR 2006) as part of the requested Hydrodynamic Survey Plan, as specified in Condition 10 of the Ministerial Statement 830 (amended from Statement 585). The hydrodynamic investigations of the estuarine portion of the Keep River also stated in Condition 10 of Statement 830 are now required to fulfil the outstanding requirements of the Hydrodynamic Survey Plan.

This modelling investigation's scope was the following:

- Collate and review existing hydrology, hydrodynamic and water quality data;
- Establish a one-dimensional (1D) catchment-river model of the Keep River region (including Border Creek) that includes the catchment and stream network response to typical wet season rainfall-runoff patterns to the permanent tidal boundary;
- Establish two- (2D) and three- (3D) dimensional hydrodynamic models of the Keep River system from the confluence of Border Creek that extends downstream well into the Joseph Bonaparte Gulf to evaluate flushing and dilution from riverine flows and tides; and
- With these catchment-river and hydrodynamic models evaluate any potential impacts to receiving surface waters from wet season releases of stormwater and pumped excess groundwater discharge from the WPF (8,000 ha of the OIEP) for a plausible management strategy during representative 'low' and 'high' runoff years.

The catchment-river modelling focuses primarily on the initial dilution of stormwater as it is released into Border Creek and subsequent dilution with the Keep River at the confluence. The hydrodynamic modelling focuses on the subsequent flushing and dilution of these waters downstream of the Border Creek-Keep River confluence to the estuary via stream discharge and tidal dynamics.

Stormwater runoff from the WPF is expected only during the wet season, unless the occurrence of a dry season rainfall event generates stormwater runoff, which is rare. Hence, representative high and low runoff 'wet' seasons were used to evaluate the proportion of WPF stormwater that comprised these receiving surface waters.

Release of excess groundwater is proposed primarily above threshold wet season flows for Keep River that yield sufficient dilution to minimise potential impacts on the downstream riverine and estuarine environments. Therefore, modelling of the flushing and dilution of excess groundwater was carried out to predict the proportion these waters comprise of the downstream pools and upper estuary.

A particular emphasis is placed on the proportion of these WPF derived waters in the 3 pools below Legune Road crossing at the onset of the 'dry season' as this sets the initial water quality conditions for the subsequent dry season (7-8 months) with minimal base flow and resultant low rates of flushing.

Conservative (i.e. non-decaying, non-reactive) numerical tracers are used to assess the proportion of either WPF stormwater or excess groundwater in the pools and upper estuary below Legune Road crossing. The predicted spatial and temporal variations in the composition of waters in the pools and upper estuary serve as the basis to evaluate potential water quality impacts from the proposed development.

1.3 Overview of Report

This report includes the following:

- Literature and data review (section 2);
- Relevant guidelines and adopted trigger values (section 3);
- Overview of water quality potential impacts and approach to mitigate (section 4);
- Catchment-river model simulations (section 5);
- Hydrodynamic model simulations (section 6);
- Potential water quality impacts to riverine and estuarine systems (section 7);
- Summary and conclusions (section 8); and
- Recommendations (section 9).

2. Literature and Data Review

A literature and data review has been undertaken to evaluate existing information on the Keep River system. The review was particularly focused on characteristic hydrology, hydrodynamics, water quality and key sensitive environments of Border Creek, and Keep River at and below Legune Road crossing.

2.1 Study Site

Figure 1 Satellite image of the lower Keep River catchment (source: Google Earth).

The study area (Figure 1) is located within the lower reaches of the Keep River catchment. Keep River is the most significant water course draining the WPF and its major tributaries include the Knox, Border and Oakes Creeks. The Keep River headwaters flow south of the Victoria Highway, through the gorges and low hills of the Keep River National Park, to the cracking-clay plains of the Weaber, Knox and Keep, then north and north-east to drain into the Joseph Bonaparte Gulf (KBR 2006).

2.2 Winds

Half hourly wind data from 1993 to 2010 was sourced from the Bureau of Meteorology (BoM) station 2056 (Kununurra Airport). The wind roses for each month over this record are presented in Appendix A. From May to September, the 'Trade Winds' (prevailing south-easterlies) dominate the wind climate. During this period, almost all wind speeds above 5 m/s are south-easterly. These reliable and dry winds are predominantly responsible for fine conditions during this period. Towards the end of the dry season (September and October), the 'build up' to the wet season (December to April) occurs. A tropical low pressure system, referred to as the monsoon trough, dominates the wind climate during the wet season. During the 'build up' period, the monsoon trough is usually weak and results in light—but at times gusty—winds that are generally northerly in this area. The transition to monsoonal conditions occurs at different times on an interannual basis.

2.3 Bathymetry

Permanent water within the study area is restricted to the tidal reaches near the river mouths and a series of sheltered pools, separated by sand bars and rock bars downstream from the Legune Road crossing that retain water during the dry season (KBR 2006). At the confluence with Border Creek (located approximately 250 m north of the Legune Road crossing), the Keep River opens into a tidal water body approximately 50-100 m wide. Oakes Creek discharges into the Keep River in this reach, which becomes progressively wider and tidal to the river mouth (KBR 2006).

2.4 Tides

The maximum tidal range at the Keep River mouth is approximately 8 m (KBR 2006). Water level measurements during October-November 2004 at 3 locations along the Keep River (Figure 2) indicate spring tide ranges of 2, 1 and 0.2 m at the seaward, middle and landward stations, respectively (Figure 3, Gray and Williams 2006). Tidal bores also occur in the region with characteristic heights of 0.5 m (Tickell et al 2006).

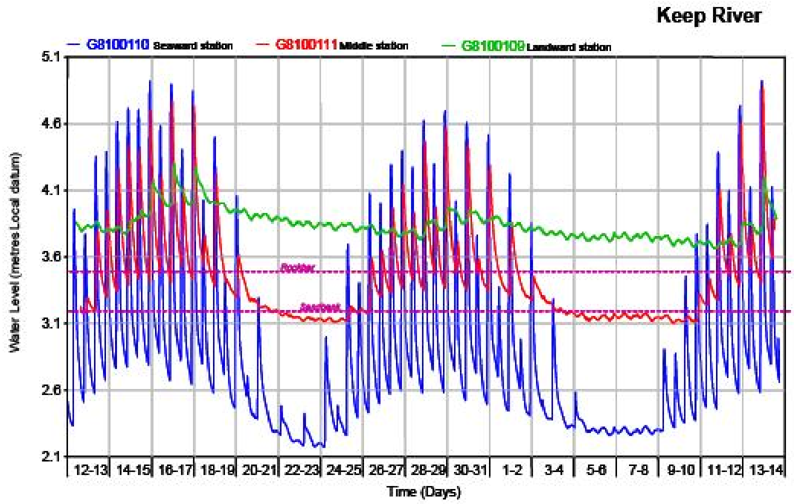
2.5 Hydrology[1]

NRETAS (2010a) operate permanent and automated stream (stage and calculated flow) gauging stations on the Keep River approximately 1 km upstream of the confluence with Border Creek at the Legune Road crossing (gauging station number G8100225) and on Border Creek approximately 6 km upstream of its confluence with the Keep River (gauging station number G8100106). Continuous measured stage and calculated flow rate data is available from these stations for the periods 1965-1986 and 1998-2010 for the Keep River; and 1971-1986 and 1998-2010 for Border Creek (NRETAS 2010a). Measured stage versus discharge relations have been developed for low and moderate flows (up to 2.5 m of stage), however the relation for higher stages is theoretically based on cross-sectional area. The records show that the Keep River and Border Creek are ephemeral with discharge restricted to the wet season. There is virtually no flow from the upper reaches of the Keep River at station G8100225 from June to November. Additionally, NRETAS (2010a) also has records obtained during the 1970s from additional stage measuring stations on the Keep River located upstream and downstream of G8100225.

[1] Hydrological overview provided in Bennett and George (unpubl.).

Figure 2 Locations of tidal level measurements along the Keep River below the sand bar (G8100110-seaward station), below the rock bar (G8100111-middle station) and above the rock bar (G8100109-landward station, south of figure as noted) (Gray and Williams 2006).

Figure 3 Keep River water levels at 3 locations from October-November 2004 (Gray and Williams 2006).

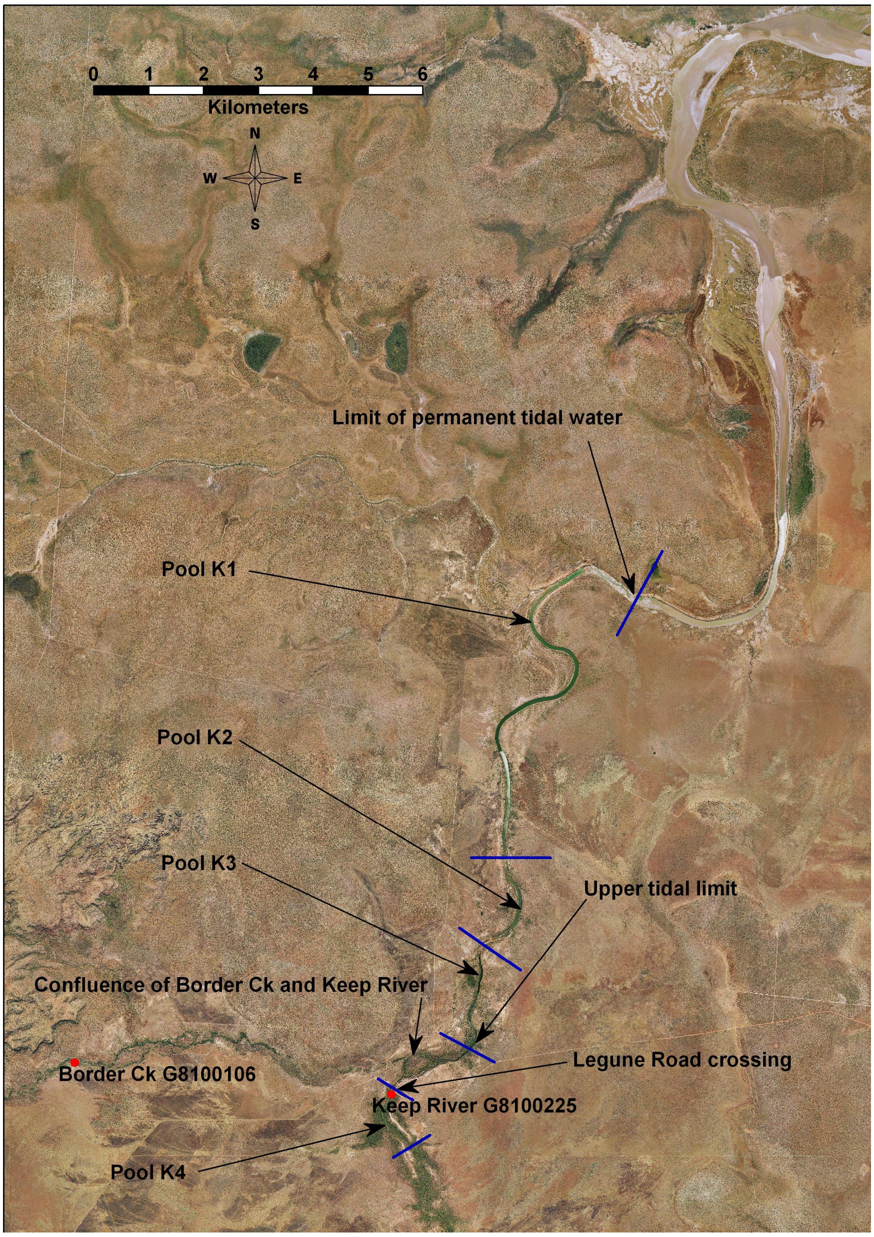


The mean annual flow of the Keep River at Legune Road crossing is approximately 428 GL and has varied between 16 and 1,613 GL in response to the amount of wet season rainfall. Analysis of the relative daily flow volumes recorded at the Border Creek (100,000 ha catchment) and Keep River (319,000 ha catchment) gauging stations indicates that on average the total flow from Border Creek is only 10% of the Keep River (i.e. sum of flows during the entire period when both stations were operational). The median of the daily ratio between the discharge of Border Creek and Keep River (measured over 5846 days when both were flowing) is 0.11 which indicates that on a per unit area basis the Border Creek catchment is much less responsive to rainfall than the Keep River catchment, and contributes a relatively small volume.

During the dry season the Border Creek bed is dry and contains no significant permanent pools. Three significant pools are maintained in the Keep River during the dry season between Border Creek and the upper limit of permanent tidal water in the Keep Estuary, approximately 12 km downstream (Figure 4). The pools are named K1 (lower), K2 (middle) and K3 (upper) with their location described in KBR (2005) and shown in Figure 4 with further description in sections 2.5.1 to 2.5.3. The pools are defined by rock and sand bars. Gray and Williams (2006) used continuous recording tide gauges to show that the potential upper extent of tidal influence (high spring tides) extends to the uppermost pool (located approximately 1.5 km downstream of the outflow from Border Creek) as discussed previously in section 2.4 where it was shown that the 2 lower pools, in particular, receive periodic tidal inflows depending on the spring tide height (KBR 2005) whereas the upper pool appears to be influenced by only the highest tides.

A permanent pool also extends for approximately 1.5 km upstream of the Legune Road crossing (pool K4, Figure 4), where GS G8100225 is located. This pool is separated from pool K3 by approximately 1.5 km of river bed which is crossed by an outcropping basement rock bar (on which Legune Road crossing is located). Anecdotal evidence indicates that there was no dry season flow out of this pool prior to 2000. WRM (2010a) (and A. Storer, pers. comm.) report that since then there has been dry season discharge from this pool across the Legune Road crossing every year at flow rates greater than 5 L/sec. The discharge was approximately 25 L/sec in July, August and September 2010 (D. Bennett, pers. comm.). This suggests that this pool is now permanently discharging groundwater, possibly as a consequence of rising groundwater levels of approximately 4 m under the Keep Plain to the south and west. A 4 m rise would result in the river bed now intersecting the watertable in this area on the basis of cross-sections detailed in Humphreys et al (1995).

Figure 4 Approximate locations of the pools of the Keep River and anecdotal evidence of limit of permanent tidal water (Bennett and George, unpubl.).



A water-salt balance model (Appendix B) indicates that evapoconcentration is not a likely dominant process in the pools, especially during periods with river discharge similar to observations over the past several years.

2.5.1 Pool K1

Pool K1 begins just upstream of the rock bar (roughly corresponds to 'limit of tidal water' in Figure 4) and is subject to tidal inundation during spring tides. As a spring tide cycle lasts 14 days, pool K1 is subject to tidal inundation for periods of about 12 hours during 14 days every month. This pool is approximately 6 km long, 35–55 m wide and 1.8 m deep on average with a maximum depth of 3.8 m (KBR 2006).

During the end of the dry season (11-17 October 2004 (KBR 2006) and October 2009 (Table 3)) conductivity measurements indicated that salinity in K1 was approximately 50% of seawater. KBR (2006) found at two of the five monitoring sites within this pool, temperature and conductivity increased with increasing depth, which indicated that the stable salinity stratification across the halocline (i.e. lower salinity waters overlying higher salinity waters) had overcome the unstable thermal stratification of the thermocline (i.e. cooler waters overlying warmer waters) at these sites (KBR 2006). pH was inversely proportional to conductivity and this was most prominent at the same two monitoring sites that exhibited increasing salinity and temperature with depth and dissolved oxygen decreased with depth (KBR 2006).

No monitoring during the wet season is available; however it is likely that the salinity of K1 approaches freshwater due to the influence of high freshwater runoff events.

2.5.2 Pool K2

Pool K2 is subject to occasional tidal inflow only during the highest peak spring tidal cycles. This pool is approximately 1.25 km long, 35–50 m wide and 2.0 m deep on average with a maximum depth of 2.9 m (KBR 2006).

The most noticeable difference between K1 and K2 is salinity (KBR 2006). Based on the same water quality sampling period as pool K1, salinity was substantially lower at K2 (mean ~2.0 ppt [2]) than K1 (mean ~17.6 ppt [3]), which suggests that K2 has substantially less salt water inputs from tidal inputs (KBR 2006), which is in agreement with October 2009 measurements (Table 3). Temperature, pH, conductivity and dissolved oxygen typically decreased with increasing depth at the monitoring sites within this pool.

No monitoring during the wet season is available; however it is likely that the salinity of K2 approaches freshwater values due to the influence of elevated riverine freshwater discharge.

2.5.3 Pool K3

Pool K3 is at the upper end of the tidally influenced portion of the river. As such, this pool is minimally subject to saline inputs from tidal inflow. Water sources are mainly from the upstream catchment, rainfall and possibly groundwater. This pool is approximately 2.25 km long, 10–40 m wide and 3.9 m deep on average with a maximum depth of 5.5 m (KBR 2006).

Based on the same water quality sampling period as pools K1 and K2 (KBR 2006), salinity was again lower at K3 (mean ~1.0 ppt [4]) than at both K2 and K1. The October 2009 monitoring event indicated a TDS of ~600 mg/L (Table 3). Dissolved oxygen decreased with increasing water column depth and indicated that the water was anoxic (DO = 0.0 mg/L) at a depth of 5.0 m at one of the monitoring sites within this pool, which was attributed to the decay of organic material (KBR 2006). Temperature and pH were greater at the surface, as compared to the bottom of the water column in this pool (KBR 2006).

[2] For indicative purposes only, this salinity was estimated from the measured mean conductivity of 3.8 mS/cm assuming a temperature of 25°C.

[3] For indicative purposes only, this salinity was estimated from the measured mean conductivity of 29.2 mS/cm assuming a temperature of 25°C.

[4] For indicative purposes only, this salinity was estimated from the measured mean conductivity of 2.0 mS/cm assuming a temperature of 25°C.

2.5.4 Previous Modelling of Flushing and Nutrient Dynamics in River Pools

Water quality modelling by Tropical Water Solutions (TWS) with the coupled CAEDYM water quality and DYRESM 1D hydrodynamic models, predicted that nutrient levels in the Keep River pools are heavily influenced by flow rates, which in turn are affected by rainfall.

During periods of high flow there is no nutrient deposition as the flows are sufficient to completely flush the pools (KBR 2006). If these high flows end abruptly, then the nutrient composition within the pool is equal to that of the influent water (generally low). Nutrients may increase in these pools when, after major flow events, reduced flows continue to transport nutrients into the pools, but are not sufficient to flush out the pools (KBR 2006).

2.6 River and Pool Water Quality

2.6.1 KBR (2005) Pool K4 Water Quality[5]

Various sporadic water sampling has been undertaken in the Keep River upstream of Legune Road crossing in pool K4 over the years with a summary provided by KBR (2005) reproduced in Table 1, where the quality of much of this data is regarded as uncertain. This historical data set has a large range of N and P with some quite high levels.

Table 1 Summary of past water quality data of Keep River in K4 upstream of Legune Road crossing (KBR 2005).

Parameter	Wet Season	Dry Season
Conductivity (mS/m)	4.5 - 31.3	18.2 - 74
pH	7.2 – 8.4	7.2 – 8.6
Turbidity (NTU)	22	1 – 39
Dissolved Oxygen (mg/L)	6.55	6.60 – 9.05
TN (mg/L)	0.281	0.355
Total Kjeldahl N (mg/L)	0.280 – 2.25	0.35
NO_3 and NO_2 (mg/L)	0.001 – 19	0.005 – 1.0
TP (mg/L)	0.008 – 0.540	0.018
Reactive P (mg/L)	0.003 – 0.057	0.002 – 0.056

The NRETAS (2010b) database lists only limited water quality data that has a quality control rating for Keep River at Legune Road crossing (station number G8100225). Nutrient data is mostly limited to single observations made during the dry seasons of 1975 and 1995. Copies of correspondence contained in KBR (2005) refer to the deployment of automatic water samplers at gauging stations at Legune Road crossing (G8100225), as well as gauging stations G8100106 and G8100210 for a period in 1998. However due to several problems no reliable water quality information is available from these sites.

2.6.2 KBR (2006) Pool Measurements of TN, TP and Salinity

Concentrations of nutrients sampled in the Keep River and its tributaries during the wet season have ranged from 0.01 mg/L to 0.54 mg/L for Total Phosphorus (TP) and 0.12 mg/L to 0.48 mg/L for Total Nitrogen (TN) (KBR 2006). During the wet season salinity levels in the non-tidal portions of the Keep

[5] This water quality summary provided in Bennett and George (unpubl.).

River are generally less than ~0.1 ppt [6] (KBR 2006). During the dry season, salinity levels up to ~0.4 ppt[7] have been recorded in pools upstream of the Legune Road crossing (KBR 2006). Total suspended solids (TSS) data is consistent with field observations that wet season discharge in all rivers and streams typically have high turbidity levels and high sediment loads (KBR 2006).

2.6.3 Overview of River Pool Conductivities[8]

Upstream of Border Creek the Keep River is permanently freshwater. Conductivity measurements at Legune Road crossing (station number G8100225) between 1975 and 1995 were always less than 30 mS/m inclusive of the dry season (NRETAS 2010b). More recent measurements indicate higher dry season conductivities in this pool of 78 mS/m in 2009 (WRM 2010a), and 52 mS/m in 2010 (G. Stainer pers comm.). This apparent increase in conductivity after 1995 is consistent with the hypothesis that this pool is now influenced by groundwater flows from the Keep Plain.

Several salinity studies undertaken downstream have occurred during the dry season when discharge from upstream had essentially ceased. Therefore, salinity levels are influenced by the previous last wet season event in addition to any groundwater contributions and/or tidal inflows. The results from these studies are summarised in Table 2.

Table 2 Recent Keep River pool conductivities.

Reference	K1 (µS/cm)	K2 (µS/cm)	K3 (µS/cm)	Sample Date
Field (1988)	37,600	13,888	2,400	June 1988
KBR (2005)	29,180	3,850	2,000	October 2004
WRM (2010)	30,520	5,190	1,170	October 2009

The gradient from high to lower conductivities from pools K1 to K3 observed in all of these studies indicate a diminishing but observable tidal influence up to pool K3. This is consistent with the observations of tide level measurements (Gray and Williams 2006, see section 2.4). WRM (2010a) analysed the ionic composition of pools K1–K3, as well as other pools upstream of Border Creek, and found that Na and Cl dominated (80%) in pools K1 - K3, possibly reflecting the influence of the inflow of seawater from tidal movement. By contrast in pool K4, upstream of Border Creek, the dominant ions were Mg and HCO_3.

The permanent gauging stations on Keep River and Border Creek were fitted with instruments to continuously log EC in June 2010. When coupled with flow gauging this will provide additional information of the load and timing of salt transport to the tidally influenced pools (Bennett and George, unpubl.).

2.6.4 WRM (2010a,b) Data of Salinity, TN and TP

Recent measurements during the start (May 2009, WRM 2010a) and end (October 2009, WRM 2010b) of the 2009 dry season are shown in Table 3.

[6] For indicative purposes only, this salinity was estimated from the measured mean conductivity of 0.2 mS/cm assuming a temperature of 25°C

[7] For indicative purposes only, this salinity was estimated from the measured mean conductivity of 0.74 mS/cm assuming a temperature of 25°C

[8] The water quality summary provided in Bennett and George (unpubl.).

Table 3 Keep River water quality during the May and October 2009 (WRM 2010a,b).

Site	Site Description	E Cond (µS/cm)	TDS (mg/L)	TN (mg/L)	TP (mg/L)	Comments
May 2009 Sampling						
KE5	Keep River, downstream Legume Road crossing	775	318	0.13	0.01	WRM (2010a) as reported, TDS summed from major anions/cations
SBE2	Border Creek at Legume Road crossing	307	76	0.28	0.02	WRM (2010a) as reported, TDS summed from major anions/cations
October 2009 Sampling						
K1	Lower Tidal Pool	29,800	19,000	0.25	<0.01	WRM (2010b), Median of 5 reported measurements
K2	Middle Brackish Pool	4,920	2,900	0.22	<0.01	WRM (2010b), Median of 5 reported measurements
K3	Upper Freshwater Pool	1,190	630	0.14	0.01	WRM (2010b), Median of 5 reported measurements
SBE	Border Creek near WA border	351	180	0.3	0.01	WRM (2010b), Median of 3 reported measurements
Keep	Keep River u/s of Legune Road crossing	818	410	0.15	0.01	WRM (2010b), Median of 3 reported measurements

In brief these data indicate the following water quality during low discharge in the study area immediately below the proposed discharge locations of the WPF stormwater and excess groundwater releases into Border Creek and excess groundwater releases into Keep River:

- Border Creek salinity is low (76-180 mg/L TDS) and approximately a third to a half of that of Keep River at Legune Road crossing (318-410 mg/L TDS). A TDS gradient below Legune Road crossing is evident from K3 (upper freshwater pool) with a TDS of 630 mg/L through K2 (middle brackish pool with a TDS of 2,900 mg/L) to the greater tidally influenced K1 (19,000 mg/L);
- TN in Border Creek is elevated relative to the other sites (0.28-0.3 mg/L), is lowest in Keep River above Legune Road (0.13-0.15 mg/L) and the upper freshwater K3 pool (0.14 mg/L), and intermediate in the brackish K2 and tidal K3 pools (0.22-0.25 mg/L); and
- TP in the study area was observed to be higher in Border Creek (0.01-0.02 mg/L), Keep River above Legune Road (0.01 mg/L) and the upper freshwater K3 pool (0.01 mg/L) than the middle brackish K2 and lower tidal K1 pools that were below the 0.01 mg/L detection level.

2.6.5 Overview of TN and TP Dry Season Concentrations in River Pools[9]

Sampling and analysis of the Keep River pools was undertaken during the dry seasons of 2004 (KBR 2005), 2009 (WRM 2010a,b) and 2010 (Bennett and George, unpubl.), which comprise the most recent available data when flow from upstream had essentially ceased. The mean TN and TP from these studies are summarised in Table 4. Because no substantial data is available under wet season flow conditions, intensive flow proportional sampling periods at Legune Road crossing (station number G8100225) are planned to coincide with the commencement and end of the 2010-2011 wet season (Bennett and George, unpubl.)

[9] TN, TP, Ec, endosulfan and atrazine overview provided Bennett (unpubl., a,b).

Table 4 Recent TN and TP measurements in mg/L during the dry season in Keep River pools.

Reference	Date	K1 TN	K2 TN	K3 TN	K4 TN	K1 TP	K2 TP	K3 TP	K4 TP
KBR (2005)	Oct. 2004	0.312	0.252	0.390		0.006	0.007	0.007	
WRM (2010b)	Oct. 2009	0.25	0.26	0.18	0.18	0.005[10]	0.005[10]	0.009[10]	0.01
Bennett and George, unpubl.	June 2010				0.14				0.02

2.7 Irrigation Drain Water Quality[11]

The Ord Irrigation Cooperative and Department of Water have measured stream discharge and water quality at a site in the D4 Drain (Station 809334) since 1999. The total catchment area at the measuring site is 13,000 ha. The catchment includes 5,300 ha of irrigation development and 7,600 ha of dry land agriculture. The irrigation farms in the catchment do not capture the first flush stormwater, nor is tailwater recycling implemented. Stream discharge at the site is a combination of stormwater runoff, irrigation tailwater and groundwater seepage into the D4 drain.

Preliminary analysis of the data (Table 5) has been made by Bennett (unpubl., a, b) with the following recommended values for characteristic concentrations of TDS, nutrients (TP, TN) and other contaminants (endosulfan, atrazine) of concern from farm runoff (see Table 5 for overview of D4 Drain water quality):

- Wet season (rainfall induced) runoff is typically fresh (39 mS/m or a TDS of 240 mg/L, on average). While there are higher EC observations, they correspond to periods when flow is likely largely derived from baseflow (groundwater discharge into D4). This is unlikely to be a factor in the WFD as depth to groundwater is to be managed by pumping, no deep drains (e.g. D4) are to be constructed and the water during these low flow periods is to be retained on farm. It is recommended that the long term mean TDS be the basis for the dilution modelling of approximately 240 mg/L TDS.
- The long term median TN from the D4 drain is 0.54 mg/L. While there are indications that higher TN concentrations may arise early in the wet season (rain induced runoff), they were only relatively short lived. Long term data indicates no statistical difference between wet and dry seasons;
- The long term median TP from the D4 drain is 0.079 mg/L. Long term data indicates no statistical difference between wet and dry season mean TP. Data from 1998/99 suggests that while higher concentrations may arise early in the wet season (rain-induced runoff), they were relatively short-lived in the context of the wet season flows. Importantly, the preceding period also had atypically high TP concentrations that were similar to those at the commencement of rainfall induced runoff;
- Conservative characteristic concentrations during the wet season (when application is not likely) are taken to be the medians of 0.1 µg/L for atrazine and 0.01 µg/L for endosulfan. Numerous other chemical species have been monitored, but these are the only 2 substances that have been detected. Further, endosulfan has recently been de-registered in Australia so will not be available for use in WPF development. These recommended concentrations should be considered to be conservative because:

[10] Note values reported by Bennett (unpubl., a, b) are a mean where the limit of reporting value of >0.01 mg/L in WRM (2010a) is given a value of 0.005 in Table 3.

[11] Irrigation water quality overview provided primarily in Bennett (unpubl., a, b).

- o They are mainly derived from samples of direct and uncontrolled irrigation runoff under relatively low discharge during the dry (irrigation) season;
- o On the WPF all dry season flows are to be retained on-farm plus the first 25 mm of wet season runoff, and the wet season flows are expected to have much higher discharge and hence be more diluted; and
- o These are derived with the detection limit for samples that have been reported as being lower than these concentrations.

Table 5 Drain D4 water quality with bold numbers recommended characteristic values (medians) for use in the EIS assessment to represent WPF drain water quality.

	TN (mg/L)	TP (mg/L)	Atrazine (µg/L)	Endosulfan (µg/L)
Mean	0.68	0.106	0.84	0.018
95% confidence interval of the mean	0.57-0.78	0.087-0.125	0.39-1.29	0.012-0.024
Median	**0.54**	**0.079**	**0.1**	**0.01**
Minimum	0.18	0.018	0.1	0.01
Maximum	4.2	0.52	13	0.203
Default ANZECC & ARMCANZ (2000) trigger values for tropical rivers	0.3	0.01		
ANZECC & ARMCANZ (2000) 99% species protection level trigger values			0.7	0.03

2.8 Groundwater Quality[12]

Recent (June and November 2006) CSIRO groundwater sampling under the nearby Ivanhoe irrigation district in 12 deep (>10 m) bores are summarised in Table 6 where median values have been adopted for this EIS assessment.

Table 6 Ivanhoe irrigation district groundwater quality with bold numbers recommended characteristic values (medians) for use in the EIS assessment to represent WPF groundwater quality.

	TN (mg/L)	TP (mg/L)
Mean	1.76	0.169
95% confidence interval of the mean	0.92-2.59	0.058-0.279
Median	**1.30**	**0.07**
Minimum	0.12	0.032
Maximum	7.30	0.980
Default ANZECC & ARMCANZ (2000) trigger values for tropical rivers	0.3	0.01

[12] Irrigation water quality overview provided primarily in Bennett (pers. comm..).

3. Relevant Guidelines and Adopted Trigger Values

Water quality trigger values in an environmental management context are ideally based upon extensive pre-development monitoring. For example, ANZECC & ARMCANZ (2000) recommends 2 years of monthly monitoring. Ideally monitoring provides the normal water quality range, which through appropriate statistical analysis of the data can then be used to establish trigger values for management purposes.

However, if such pre-development monitoring is not available and the historical water quality data is limited, then 'default' trigger values from the ANZECC & ARMCANZ (2000) guidelines need to be applied. Recognising that ANZECC & ARMCANZ (2000) default trigger values are derived on the basis of regional data sets, deviations from the 'default' trigger values often occur as a specific catchment or estuary may have higher or lower levels than the regional value. In contrast, toxicant trigger values in ANZECC & ARMCANZ (2000) are on the basis of ecotoxicological studies, and hence values for freshwater and marine ecosystem protection are relevant across regions.

The current water quality monitoring data is not sufficiently comprehensive to derive definitive site specific values. Seasonal water quality monitoring would be required to define the natural range of water quality to form definitive site (i.e. pool) specific trigger values. Generally, development of site specific trigger values is based on monthly measurements for a period of several years where the 80th percentile of the data set is defined as the trigger value (ANZECC & ARMCANZ 2000). Regular measurements of TN, TP and TDS are recommended, while toxicants (specifically atrazine and endosulfan) can potentially be measured on one occasion to verify they do not exist in the receiving waters.

3.1 Toxicants

The ANZECC & ARMCANZ (2000) 99% species protection level has been adopted as appropriate for atrazine and endosulfan trigger values, which are the only toxicants detected in the water quality monitoring of the D4 drain (Table 5).

3.2 TDS

Salinity is a key water quality variable in the Keep River and estuary. ANZECC & ARMCANZ (2000) guidelines suggest a conductivity range 20-250 µS/cm, which is approximately a range of 15–175 mg/L TDS[13], for upland and lowland tropical rivers. Occasional dry season measurements of salinity (or TDS) in the Keep River clearly show that pools K1, K2 and K3 receive salt, either from the estuary via tidal exchange in the case of pools K1 and K2 (Field 1988, KBR 2005, WRM 2010, KBR 2006) or via flows from the upstream catchment and groundwater sources in the case of pool K3. The data available is insufficient to determine the full background range of salinity (or TDS) in the pools, although a clearly decreasing trend in salinity is observed with distance from the estuary in proportion to the degree of tidal influence (sections 2.6.3 and 2.6.4).

Given the information available, a TDS trigger value well above the ANZECC & ARMCANZ (2000) default for upland and lowland tropical rivers is appropriate for pools K1 and K2 due to the tidal influence.

[13] For indicative purposes only, this TDS was estimated from the conductivity at 25°C in µS/cm to TDS in mg/L with a factor of characteristic conversion factor of 0.7.

Furthermore, pool K3 (farthest upstream) recorded a TDS of 630 mg/L (Table 3), which is ~4 fold greater than the upper ANZECC & ARMCANZ (2000) trigger value range. Hence, development of a site-specific TDS trigger values is appropriate for pool K3.

The critical period to set a TDS trigger values is at the 'onset of the dry season' in the upper 'freshwater' K3 pool. The range of TDS in pool K3 over the dry season is likely primarily driven by:

- Initially the TDS at the 'tail' of the last wet season flow event, which sets the initial concentration;
- Dry season baseflow TDS of the Keep River inflow into the pool; and
- The TDS of the local groundwater inputs.

A lower interim TDS trigger value of 675 mg/L has been adopted on the basis of recent measurements (sections 2.6.3 and 2.6.4). WRM (2010c) recommend a conductivity trigger value of 1,824 µS/cm, which is the 80th percentile value of a larger data set that extends back to 2004-2005. This is approximately a TDS of 1,275 mg/L[13], which has been adopted as the upper interim TDS trigger value for pool K3.

Pools K2 (brackish) and K1 (saline) are strongly influenced by tidally-induced salinity inputs, hence TDS trigger values are not appropriate at these locations.

3.3 TN and TP

The default TN and TP trigger values from ANZECC & ARMCANZ (2000) guidelines for relevant tropical Australian environments are shown in Table 7.

Table 7 ANZECC & ARMCANZ (2000) trigger values of TN and TP for tropical lowland rivers and estuaries.

	TP (mg/L)	TN (mg/L)
Lowland River[14]	0.01	0.3[15]
Estuary[14]	0.02	0.25

WRM (2010c) recommend the following TN and TP trigger values on the basis of the 80th percentile values of the combined data sets of lower Border Creek and pool K3:

- Adoption of the ANZECC & ARMCANZ (2000) TN trigger value for tropical lowland rivers of 0.3 mg/L, which was similar to the 80th percentile value of 0.28 mg/L;
- Adoption of a site specific TP trigger value of 0.02 mg/L on the following basis:
  - 80th percentile is 0.016 mg/L;
  - 90th percentile is 0.02 mg/L; and
  - Both of these percentiles are well above the ANZECC & ARMCANZ (2000) TP trigger value for tropical lowland rivers of 0.01 mg/L, so a site specific trigger value is appropriate.

[14] No data available for tropical WA estuaries or rivers. A precautionary approach should be adopted when applying default trigger values to these systems.

[15] A value of 0.2 mg/L suggested for river draining forested catchments.

In this report the following trigger values are adopted for TN and TP:

- The adopted TN trigger value for pools K3 and K2 are those in the ANZECC & ARMCANZ (2000) guidelines for tropical lowland rivers of 0.3 mg/L;
- Lower and upper interim TP trigger values of 0.01 mg/L and 0.02 mg/L are adopted for pools K3 and K2 on the basis of ANZECC & ARMCANZ (2000) guidelines for tropical lowland rivers and WRM (2010c) recommendations for pool K3, respectively; and
- The ANZECC & ARMCANZ (2000) guidelines for tropical estuaries of 0.25 mg/L and 0.02 mg/L, respectively, have been adopted for pool K1 and the upper estuary in the absence of site specific data for TN and TP, respectively.

4. Overview of Potential Impacts from Excess Groundwater and Stormwater Discharge during the Wet Season

4.1 Potential Impact Summary

Most of the literature and data review in Section 2 focus on the Keep River system during the dry season. The proposed WPF stormwater and excess groundwater disposal strategy involves only releases into Border Creek (stormwater) and Keep River (excess groundwater). Any potential impacts to the Keep River system that may occur from 'wet season' WPF stormwater runoff and excess groundwater releases need to address the following:

- Are most of the releases of WPF stormwater and excess groundwater flushed through the 3 pools (K3, K2 and K1) into the estuary?
- What is the proportion of WPF stormwater and excess groundwater in the pools and upper estuary at the onset of the dry season? The end of the wet season after the final runoff event and cessation of groundwater releases is a critical period as it sets the 'initial' water quality of the pools at the onset of the dry season assuming no further substantive riverine flushing until the next wet season.
- What is the duration and time-varying proportion of WPF stormwater and excess groundwater over the 'wet season' in the environmentally sensitive areas (i.e. river pools) in the study area?

Because of the ephermal nature of Border Creek below the proposed WPF stormwater outlet, and the short distance to the upper pool K3 from the excess groundwater release point at Legune Road crossing, both of these reaches are not assessed for water quality impacts. Hence, the following is noted throughout the remainder of the report:

- Excess groundwater will be released at Legune Road crossing (also referred to as 'above the confluence' or 'release point');
- The excess groundwater will then traverse a short section of Keep River (250 m) until it reaches the Border Creek confluence (also referred to as the 'confluence'); and
- A short distance below the confluence is the uppermost pool K3.

4.2 Water Quality Assumptions

The assessment of potential impacts to the water quality (and hence riverine and estuarine ecology) requires adoption of a number of assumptions, in particular the concentrations of TDS, TN and TP of source waters (Keep River, Border Creek, groundwater and stormwater) and the relevant trigger values for receiving environments (pools and estuary). These assumptions and adopted trigger values are summarised in Table 8. Selection of median concentrations for characteristic stormwater (from D4 irrigation channel data) and groundwater (from Ivanhoe irrigation district) are based on weak seasonality of these water sources. In contrast, use of the 25th percentile data for the seasonal Border Creek and Keep River systems was based on favourable comparisons with typical values early in the dry season (no wet season data available). Further, adopted trigger values to evaluate potential impacts are based on lowland tropical river systems (i.e. pools K3 and K2) and tropical estuarine environments (i.e. pool K1 and upper estuary).

Table 8 Water quality concentrations of source waters (Keep River, Border Creek, WPF stormwater, paleo-channel and low yield groundwater) and adopted trigger values for the pools and upper estuary.

	TDS (mg/L)	TN (mg/L)	TP (mg/L)	Atrazine (μg/L)	Endosulfan (μg/L)	References
WPF Stormwater	240	0.54	0.079	0.39	0.012	Median (TDS, TN, TP) in D4 drain as section 2.7 In section 2.7 lower bound 95th confidence interval of mean (atrazine, endosulfan)
Groundwater	3,000[16] 1,000[17]	1.30	0.07	0[18]	0[18]	KBR (2010) modelling for TDS Median CSIRO data for Ivanhoe groundwater in section 2.8 (TN, TP)
Keep River	175	0.15	0.01	0[18]	0[18]	25th percentile (TDS, TN, TP) of available data above Legune Road Crossing or pool K4 that is representative of the end of the wet season Assume atrazine and endosulfan not in Keep River waters
Border Creek	150	0.235	0.01	0[18]	0[18]	25th percentile (TDS, TN, TP) of available data from lower Border Creek that is representative of the end of the wet season Assume atrazine and endosulfan not in external Border Creek catchment waters
K3 and K2 Trigger Values	675 (lower for K3 only) 1,275 (upper for K3 only)	0.3	0.01 (lower) 0.02 (upper)	0.7	0.03	80th percentile (TDS) of K3 data, ANZECC & ARMCANZ (2000) trigger values for tropical lowland rivers (TN, TP) where TN for lowland rivers taken as upper value as not a rainforest catchment and 99% species protection level (atrazine, endosulfan)
K1 and Upper Estuary Trigger Values	NA	0.25	0.02	0.7	0.03	ANZECC & ARMCANZ (2000) trigger values for tropical estuaries (TN, TP) and 99% species protection level (atrazine, endosulfan)

[16] Low yield bore TDS.

[17] Paleo-channel bore TDS.

[18] Assumed

5. Catchment-River Modelling

This section presents the methodology and results of the catchment-river simulations of stormwater overflows and a spreadsheet model of excess groundwater discharge to just below Legune Road crossing during the wet season. This involved development of a 1D Mike SHE model for the entire Keep River catchment that included the developed farmland area of the WPF. Though the catchment-river model extended into the Keep River Estuary, it was primarily used to predict the discharge (or flows) and directly simulate the proportion of WPF stormwater to a point just below the confluence of Border Creek and Keep River. Simulated flows in the Keep River were used to determine excess pumped groundwater release regime above Legune Road crossing with a spreadsheet model. Thereafter, the hydrodynamic modelling (section 6) was used to simulate the subsequent dilution and flushing in the pools and upper estuary.

5.1 Methodology

Simulations of the 2005-2006 (hereafter 2006) and 2006-2007 (hereafter 2007) wet seasons correspond to characteristic high and low runoff years, respectively. An event in March 2006 was the largest recorded at the Keep River gauge. Catchment hydrology was simulated with the Mike SHE framework while the drain and stream network was represented in Mike 11 HD.

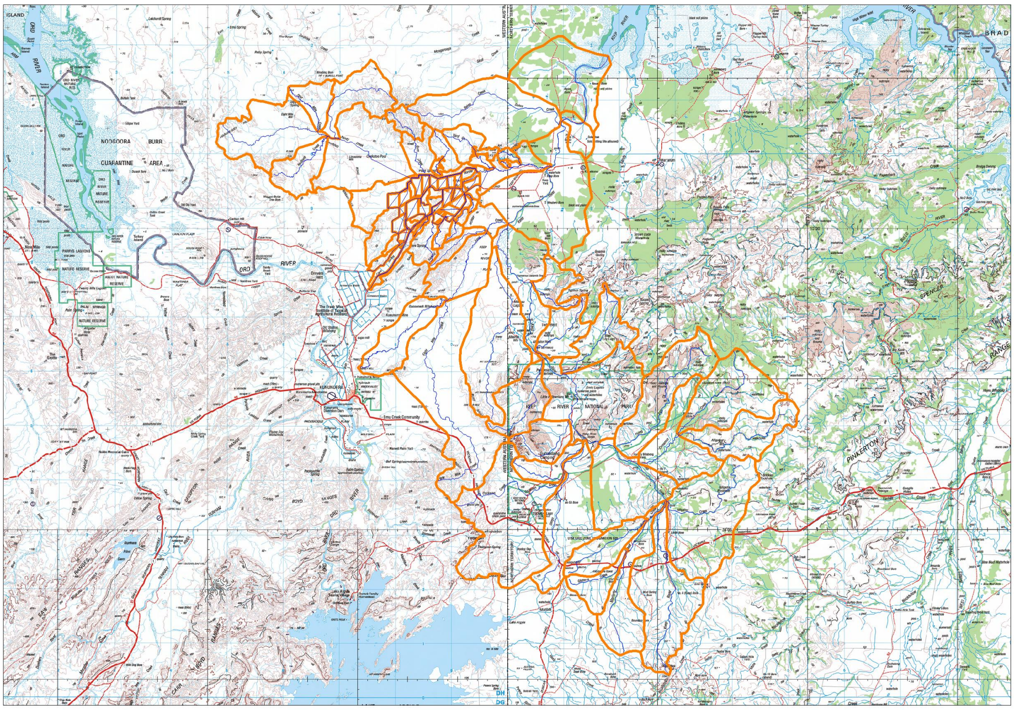
Network and cross-section data from a number of models developed for the design of the OEIP (GHD 2010) were merged and simplified to form the 1D catchment-river model. The GHD (2010) design models were developed to simulate short duration design rainfall events with 1D model representations for the farmlands and the Keep River catchments, and a coupled 1D and 2D model for Border Creek. For the seasonal catchment-river model simulations here, the 2D components were converted to 1D and run at a daily time step. Accordingly, this model's representation of the farmlands and the Border Creek floodplain is simpler than the design models. Catchment hydrology was represented with a simplified initial and continuing loss model, which was based on the calibrated design models and varied across the catchments with land use. Catchments and reaches represented in the catchment-river model are shown in Figure 5. Daily rainfall sequences (SILO data drill, BoM 2010) were used for wet season simulations and design rainfall (Pilgrim 2001) for simulation of design events. An oragraphic effect of reducing rainfall to the southeast in the Keep River catchment was represented with a simple reduction in rainfall total. Daily rainfall served as inputs.

A 12-month tidal elevation record, which was developed as part of the hydrodynamic modelling in Section 6, served as the downstream boundary conditions for the catchment-river simulations.

5.1.1 Stormwater Discharge to Border Creek

Stormwater dilution was simulated with a conservative tracer with the Mike 11 AD (advection-dispersion) module. The stormwater tracer was applied with a value of 1.0 for all runoff from the 21 farms in the Stage II development area with the model predicting subsequent dilution through the drainage network, Border Creek, and the remainder of the Keep River system. Hence, tracer values represent the fraction (or proportion) of water at any location that is comprised of 'farm-origin' stormwater.

Figure 5 Catchments in 1D catchment-river model.



5.1.2 Excess Pumped Groundwater Releases to Keep River

The proportion of released excess pumped groundwater throughout the Keep River system was estimated with a spreadsheet model that utilised the simulated Keep River flows above Legune Road crossing at the proposed release location. The proposed option (Figure 6) is based upon the following assumptions:

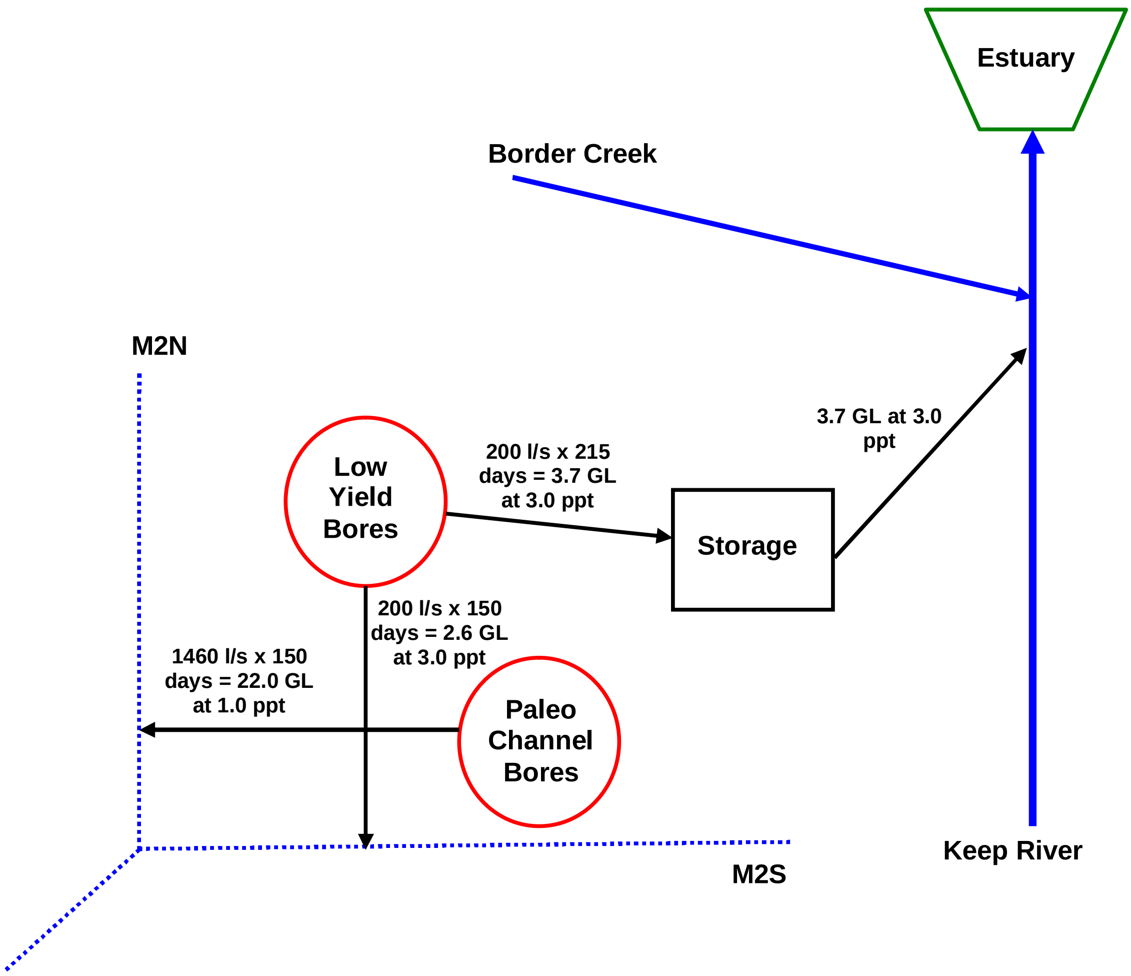
- An annual average of 25 GL groundwater extraction;
- A 150 day irrigation season[19] from May 1 to September 30 with:
  - No dry season discharge of excess pumped groundwater into receiving Keep River waters after April 30;
  - No shandying of pumped groundwater with irrigation channels (M2N and M2S) after September 30;
- Paleo-channel bores pump at 1.46 m^3/s (1,460 L/s):
  - For the 150 day irrigation season flow directly into the M2N drain (18.9 GL);
  - Otherwise no pumping with no resultant discharge to the Keep River;
- Low yield bores pump at 0.2 m^3/s (200 L/s) for the entire year and:
  - For the 150 day irrigation season flow directly into the M2S channel (2.6 GL);

[19] Irrigation season officially from April 1 though to October 31, for purposes of EIS this has been assumed to be compressed into 5 month period (May 1 to September 30) at 100% irrigation demand when 'shandying' pumped groundwater is reasonable.

- o For the other 215 days flow into a storage for delayed or direct release to the Keep River above Legune Road Crossing (3.7 GL);

- Excess pumped groundwater release to the Keep River will be at an average TDS of 3,000 mg/L. Evapo-concentration in the storage has not been considered as increases in salinity will be offset by decreases in volume, hence the same salt (and nutrient) load will be introduced at the river release point; and
- Release rates were varied between 0.2 m^3/s and 0.5 m^3/s depending on stream discharge at a rate where maximum TDS in the receiving Keep River does not exceed the adopted trigger value of 675 mg/L.

Figure 6 Schematic of proposed option for groundwater release into the Keep River.



Estimates from a spreadsheet model of excess pumped groundwater release rates from the WPF were based on the following assumptions (see Table 8):

- Keep River TDS of 170 mg/L (25th percentile of data representative of start of dry season);
- Border Creek TDS of 150 mg/L (25th percentile of data representative of start of dry season);

- Allowable maximum stream TDS in Keep River at the point of discharge of 675 mg/L at the adopted lower interim TDS trigger value in section 3;
- TDS of excess pumped groundwater of 3,000 mg/L; and
- Excess groundwater released only during the wet season when the Keep River is flowing.

Table 9 summarises the excess groundwater release statistics for the preferred option (Figure 6) to maintain a threshold TDS of 675 mg/L in Keep River at the point of discharge (above Legune Road crossing and the Border Creek confluence) during 2006 (low runoff year) and 2007 (high runoff year). During the high runoff year the release target of 3.72 GL could be readily met with a high proportion of the release days (40%) consisting of direct releases to the river (i.e. bypass empty storage with direct discharge at pump rate of 0.2 m^3/s). In contrast 80% of the release target (3.0 GL) could be discharged during the low runoff year of 2007 with no direct release days (i.e. storage could not be depleted completely at any period over the wet season). However, increasing the maximum groundwater release rate from 0.5 m^3/s (500 L/s) to 0.65 m^3/s (650 L/s) during 2007 would yield a predicted total groundwater release of 3.6 GL (not simulated).

Table 9 Groundwater release statistics for both simulated years.

Year	Target GW Release Volume (GL)	Initial GW Storage Volume (GL)	GW Release Volume (GL)	Number of GW Release Days	Number of Direct GW Release Days	Average GW Release Discharge (m^3/s)	Average Keep River Discharge during GW Release (m^3/s)	Final GW Storage Volume on May 1 (GL)
2006	3.72	1.31[20]	3.67	125.2	51.6	0.34	107.54	0.05
2007	3.72	1.69[21]	3.01	85.7	0	0.43	49.42	0.73

5.2 River Discharge Characteristics of Selected Wet Season Scenario Periods

A brief overview of the simulated hydrology of the 2 selected wet seasons is shown in Table 10. The 2006 wet season was one of the highest runoff years on record with 75% of the annual discharge occurring during one large event in March 2006. In contrast the 2007 season was a low runoff year where during a small flow event in February 2007 approximately 25% of the Keep River flow into the pool K3 was predicted to consist of WPF-derived stormwater. The 2006 and 2007 wet seasons are representative of high and low flow years, respectively, and the March 2006 and February 2007 events are representative extreme high and low flow events, respectively. These wet seasons and flow events represent a wide range of riverine flows through the Keep River system.

[20] Estimate on 17 December 2005 at start of hydrodynamic simulation.

[21] Estimate on 3 January 2007 at start of hydrodynamic simulation.

Table 10 Overview of simulated surface hydrology of the 2006 and 2007 wet seasons and March 2006 and February 2007 events with values in parentheses discharge from existing catchment model runs.

Event / Period	Rainfall (mm)	Q of WPF Outlet (GL)	Q of Border Creek Below WPF Outlet (GL)	Q of Keep River below Confluence with Border Creek (GL)
November 2005 - May 2006 wet season	1,405	77	302 (297)	1,177 (1,243)
March 2006 event	378	49	202 (193)	875 (882)
January - July 2007 wet season	746	33	125 (122)	397 (492)
February 2007 event	66	8	32 (8)	40 (24)

5.3 Peak Stormwater Proportion during the Large March 2006 Event

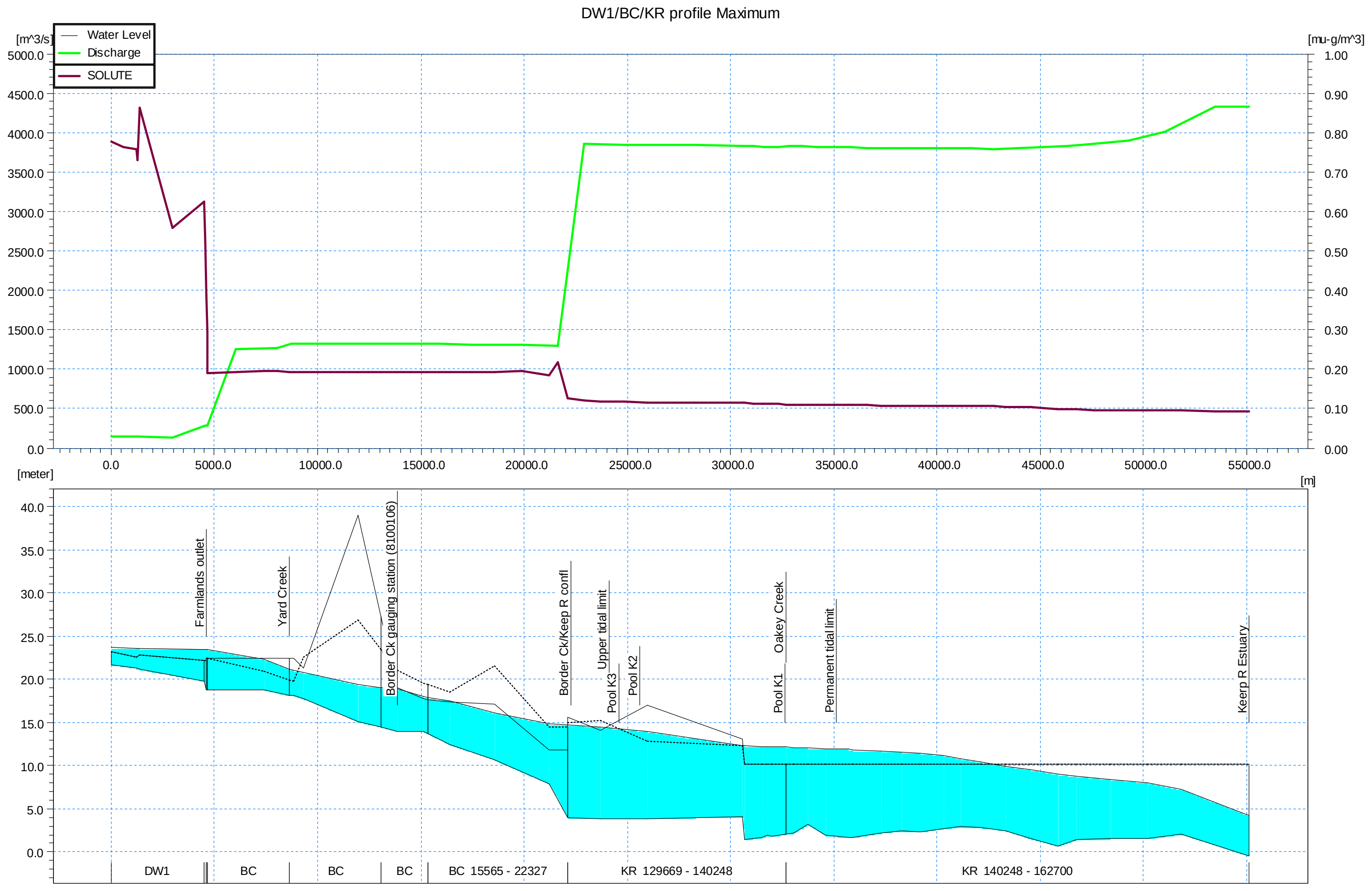
To illustrate the extent of the river-catchment model, simulated peak stormwater tracer levels (as well as discharge and water levels) along a longitudinal profile from the WPF stormwater drain DW1 to the Keep River Estuary during the high 2006 runoff year are shown in Figure 7, which mostly corresponds to the March 2006 event. A brief overview of this large runoff event in terms of peak tracer levels, discharge and water levels includes:

- The maximum proportion (or tracer levels) of stormwater in the DW1 drain was 0.86 (86%), but a lower value of 0.62 (62%) was predicted just prior to discharge into Border Creek because of dilution with non-farm runoff in the development area;
- Dilution with Border Creek flow below the outlet with the WPF stormwater outlet decreased the maximum proportion (or tracer levels) of stormwater to 0.2 (20%);
- Further dilution with Keep River flows lowered the peak proportion (or tracer levels) of stormwater to 0.11 (11%); and
- Further dilution of stormwater downstream of the Border Creek confluence yielded a further slight decrease in tracer levels to 0.1 (10%).

The river-catchment model does not represent tidal flushing, the volumetric capacity of the pools, and the bathymetric features (i.e. rock bar and sand bar) as well as the hydrodynamic model. So the proportion (or tracer levels) of groundwater and stormwater in the pools and upper estuary are considered in section 6

Generally, maximum tracer levels do not occur simultaneously in the model domain. Temporal snapshots of the March 2006 flow event (not shown) illustrate that peak tracer levels (i.e. proportion of stormwater) can occur more or less at a particular instance or time. In contrast, during low flow events (i.e. February 2007) the spatial and temporal variability in peak stormwater tracer levels is much greater (not shown). The hydrodynamic modelling in section 6 investigates the temporal and spatial evolution of stormwater tracers in the 3 pools and upper estuary below the Border Creek confluence in greater detail with improved representation of the bathymetry and tidal dynamics than is captured with the 1D catchment-river model.

Figure 7 Predicted maximum instantaneous stormwater tracer, discharge and water level over the 2006 wet season simulation.



5.4 Groundwater and Stormwater Proportions for the Proposed Option above Pool K3

The simulated discharge, TDS and tracers (stormwater and excess pumped groundwater) at the WPF outlet, Border Creek above the confluence, and Keep River below the confluence for the 2006 and 2007 wet seasons are shown in Figure 8 and Figure 9, respectively. The peak TDS of ~600 mg/L remained below the lower trigger value of 675 mg/L during both simulations below the confluence of Border Creek and Keep River.

Peak stormwater tracer levels at the WPF outlet generally ranged from 0.3-0.4 (30-40% stormwater composition) during the high 2006 runoff year and 0.5-0.6 (50-60% stormwater composition) during the low 2007 runoff year. Generally dilution of the stormwater tracer was predicted to be 2-3 fold from the WPF outlet into Border Creek, and another 2-3 fold by the Keep River. Peaks in WPF stormwater tracer tended to occur in advance of the peak Keep River discharge with levels dropping off during and after the peak from dilution by this dominant flow. During the high 2006 runoff year, peak stormwater tracer levels below the confluence ranged from 0.05-0.1 (5-10%), but generally were less than 0.05 (<5%) for the low 2007 runoff year.

Atypical high stormwater tracer levels were simulated as a result of consecutive small rainfall events in late January and then early February of 2006. The first rainfall event filled the on-farm stormwater storages with no discharge into the DW1 drain. The subsequent small rainfall event then caused stormwater discharge into the DW1 drain with low dilution within the WPF (peak level of 0.6 or 60% at the stormwater outlet), along Border Creek (peak level of 0.5 or 50% at the confluence), and with the Keep River (peak level of 0.28 or 28% below the confluence). This event is considered in greater detail in section 6.

Peak groundwater tracer levels in Keep River above and below the confluence were generally greater during the low 2007 runoff year (0.08-0.16 or 8-16%) than the high 2006 runoff year (0.06-0.14 or 6-14%). These peaks generally occurred between flow events, when lower river discharge yielded less dilution at the point of groundwater release. Unlike stormwater, groundwater tracer levels were higher not only at the beginning of a flow event, but also at the 'tail' (or recession) of a flow event as groundwater was still released to maintain the 675 mg/L lower TDS trigger value. Groundwater tracer levels were inversely proportional to flow and were considerably less than 0.01 (1%) for discharge in excess of 100 m^3/s.

The proportion of excess groundwater and stormwater (and exposure durations) from the WPF to the downstream pools and estuarine environments are evaluated with the hydrodynamic modelling in section 6 for the pools and lower estuary.

Figure 8 Predicted discharge (top panel), TDS (upper middle panel), and groundwater (lower middle panel) and stormwater (lower panel) tracers during the 2006 simulation.

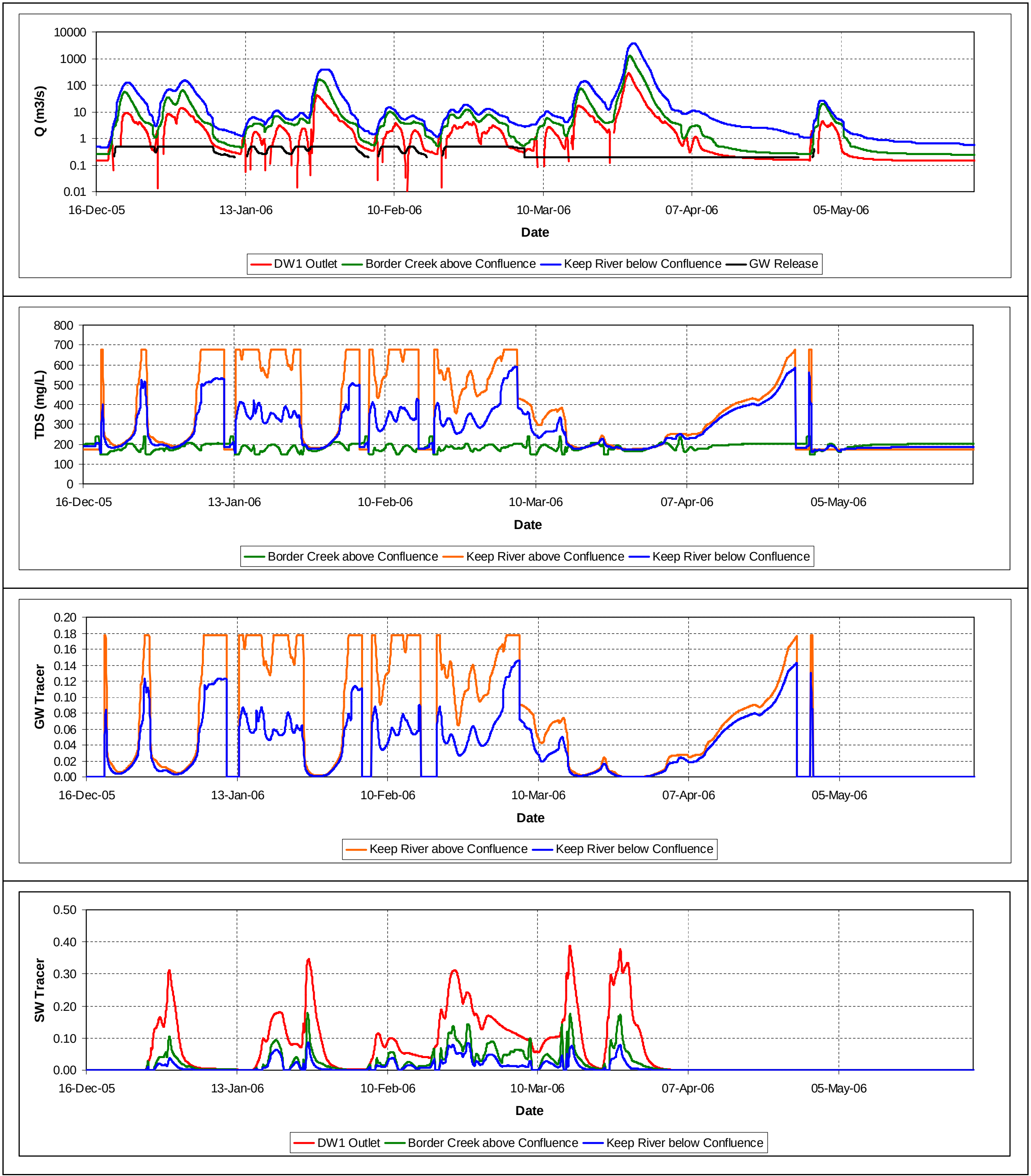
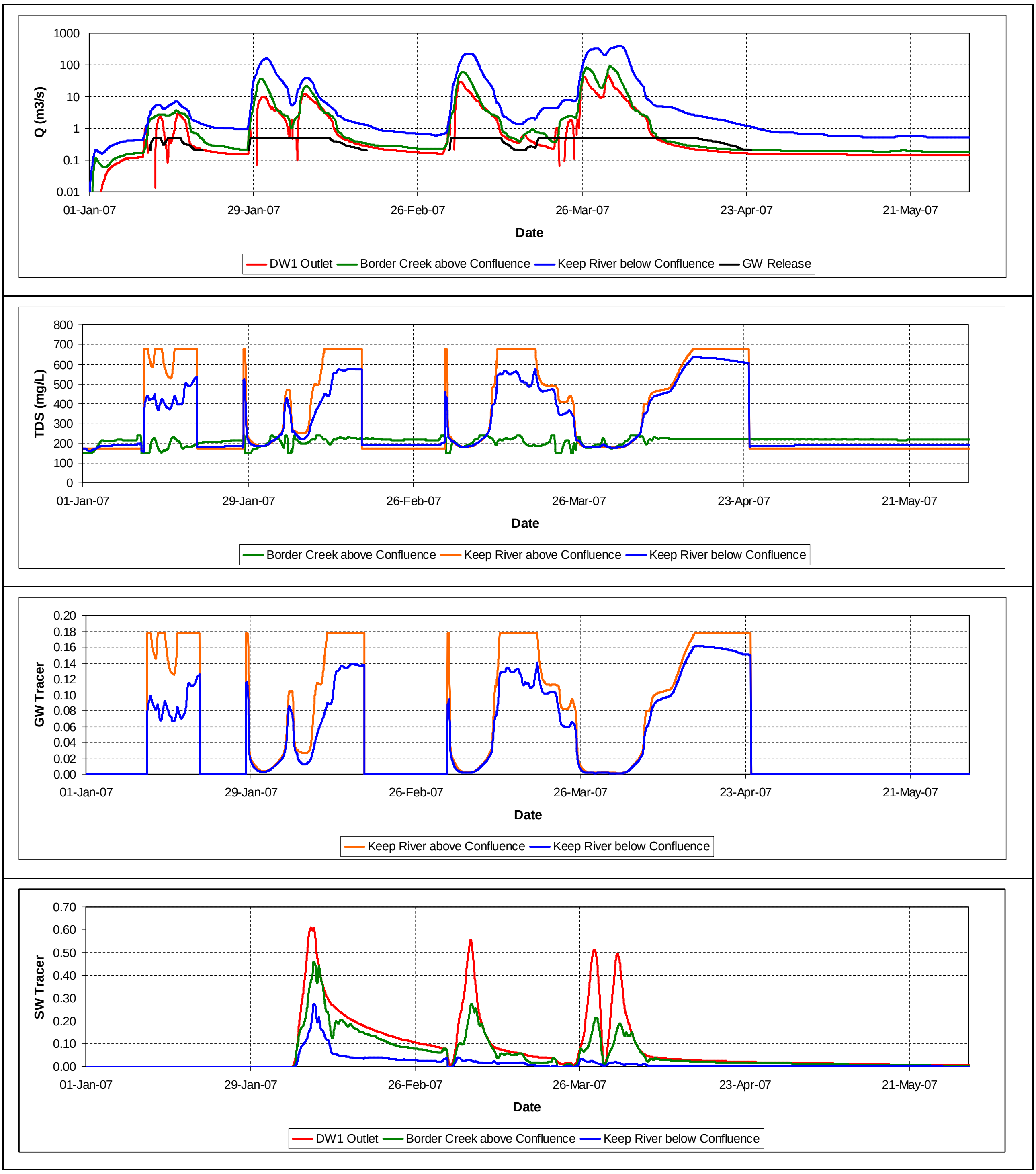


Figure 9 As Figure 8 for 2007 simulation.



6. Hydrodynamic Modelling

To reiterate, it is envisaged that groundwater extraction from the WPF will be needed and either reused for irrigation (via shandying) or released to the Keep River during the wet season. Groundwater salinity is predicted to decrease over time (KBR 2010), but here it has been assumed that it remains constant. Overflows of stormwater from the WPF into Border Creek will also occur primarily during the wet season.

Low water quality impacts to the downstream pools and upper estuary are expected from WPF stormwater and excess groundwater because of high dilution with receiving waters, effective flushing during runoff events, and subsequent tidally-induced dilution and flushing with marine-origin waters. The hydrodynamic modelling here evaluates the flushing and dilution of both excess groundwater and WPF stormwater in the pools and upper estuary during the wet seasons of several representative runoff year wet seasons.

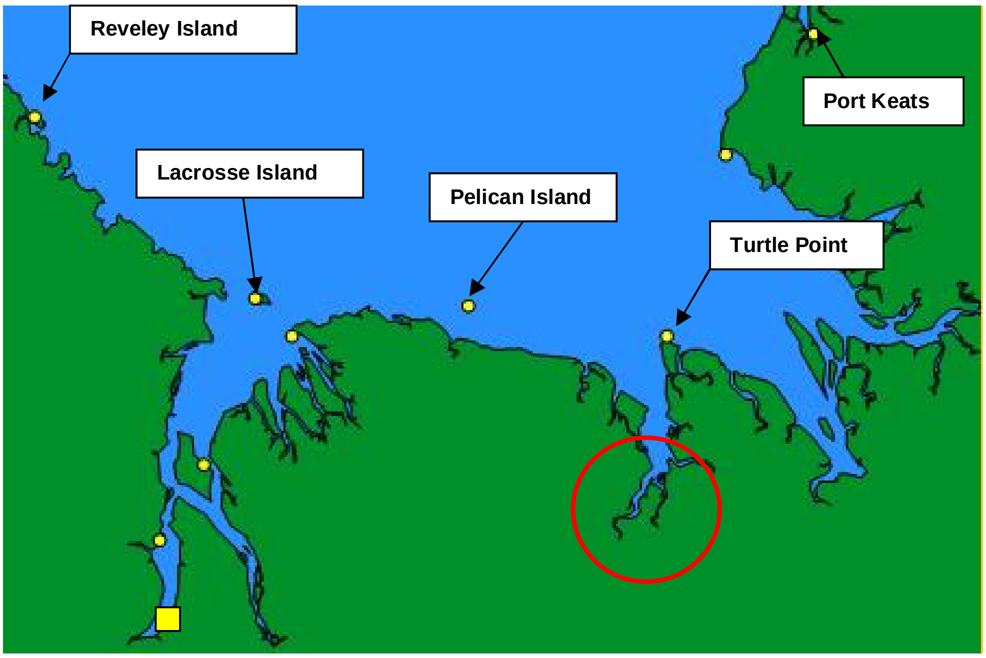
6.1 Methodology

Hydrodynamic modelling was carried out with DHI's MIKE 21 HD (two-dimensional or 2D) and MIKE 3 HD (three-dimensional or 3D) hydrodynamic models. Non-decaying conservative tracers that were representative of the proportion of WPF stormwater overflows and excess pumped groundwater releases served as inputs to the hydrodynamic modelling below the confluence of the Keep River and Border Creek. Flushing and further dilution with estuarine and marine waters were simulated with hydrodynamic modelling.

6.1.1 Set Up of 2D Regional Model

Firstly, a 2D regional hydrodynamic model was set up with MIKE 21 HD. Harmonic tidal constituents from 2 secondary ports were used to generate a time series of water levels at the open boundary of the 2D model domain with the open ocean. The 2D model simulations were then run to calibrate the appropriate bed friction coefficient via comparisons with the predicted astronomical water levels at 2 tidal stations. Calibration was achieved by adjusting the bed friction coefficient through comparisons of modelled surface elevations with predicted astronomical tides at Lacrosse Island and Pelican Island (see Figure 10). The other secondary ports and tide stations were not considered in the calibration as either the harmonic constituents from these stations were not available (e.g. Turtle Point) or they are located some distance from the region of interest, namely the Keep River estuary. These calibration simulations were run with no wind or inflow forcing because 'predicted' (or astronomical) tides do not consider meteorological, hydrological or non-tidal oceanographic processes by definition.

Figure 10 Tide stations near the Keep River Estuary (yellow circles) and the primary port at Wyndham (yellow square) with area of interest highlighted by a red circle.



6.1.2 Open Boundary Conditions for High Spatial Resolution Modelling

After the bed friction coefficient was calibrated with the regional scale 2D model, tidal surface elevations were extracted near Turtle Point (see Figure 10) to provide open boundary conditions for the high spatial resolution 2D and 3D models of the Keep River Estuary. Tidal harmonic constituents were derived from this time series so that predicted tides could be determined for any date, inclusive of the 2 representative wet season periods that were used to assess potential impacts from the proposed stormwater and excess groundwater management strategies.

6.1.3 High Spatial Resolution Modelling

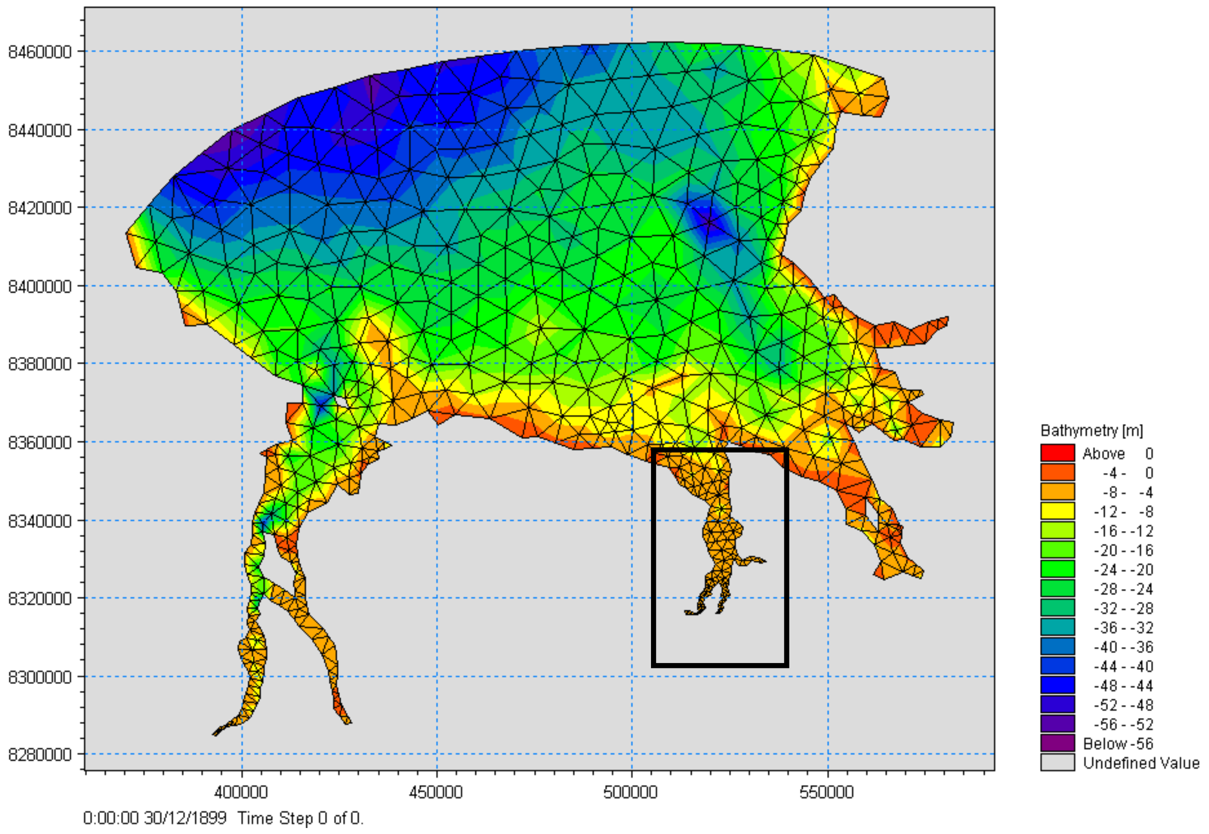
High spatial resolution bathymetry in the region of interest (red circle in Figure 10) was developed as inputs for 2D and 3D hydrodynamic modelling with MIKE 21 HD and Mike 3 HD, respectively. Model validation was carried out with available tidal records. To investigate the dilution and flushing of excess pumped groundwater releases and WPF stormwater discharge in the Keep River system. Discharge and tracer levels from the 1D catchment-river model below the confluence of Keep River and Border Creek (see Section 5) served as the upstream boundary inputs for the high spatial resolution hydrodynamic modelling. First, the importance of vertical salinity (or density) stratification was simulated to evaluate the need for 3D (i.e. simulate salinity stratification) versus 2D (i.e. assume vertically homogeneous water column) modelling. Afterwards, 2 separate conservative tracers for the WPF stormwater overflows and excess groundwater releases, respectively, were simulated to assess potential impacts to the water quality of the Keep River system below the confluence with Border Creek.

6.2 Regional Hydrodynamic Model

6.2.1 Regional Model Domain, Bathymetry and Horizontal Grid

To minimise errors caused by open boundaries, a large model domain was selected for the 2D regional hydrodynamic model. Bathymetry data was sourced from the software package MIKE CMap (DHI's digital global ocean depth repository). The 2D regional model domain, bathymetry and horizontal grid used in the simulations are shown in Figure 11. The black rectangle delineates the region of the high spatial resolution model domain, which is a small proportion of the overall 2D regional model domain. The much larger regional model domain enables greater accuracy of the tidal conditions in the region of interest because it is considerably less impacted by tidal level inputs along the open ocean that are difficult to define precisely.

Figure 11 2D regional model domain, bathymetry (referred to AHD) and grid with area of high spatial resolution model domain highlighted by a black rectangle.



6.2.2 Vertical Discretisation

By definition, only 1 vertical layer is used to represent the entire water column for the 2D regional model as the water column is assumed to be vertically homogeneous.

6.2.3 Tidal Forcing

Astronomical tides at half-hourly intervals served as the forcing inputs at the open boundary between Reveley Island and Port Keats. The time series of tidal levels was generated with the IOS method included in the Mike 21 toolbox for the tidal harmonic constituents published in the Australian National Tide Tables (Department of Defence 2008).

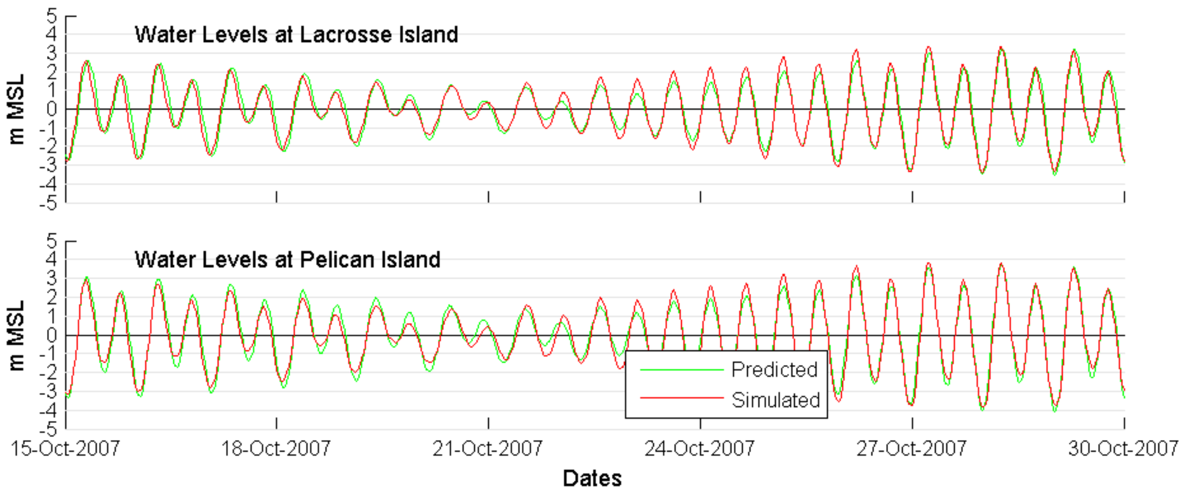
6.2.4 Modelling Period

The 2D regional modelling period spanned 244 days from 1 March 2007 to 31 November 2007.

6.2.5 Modelling Validation

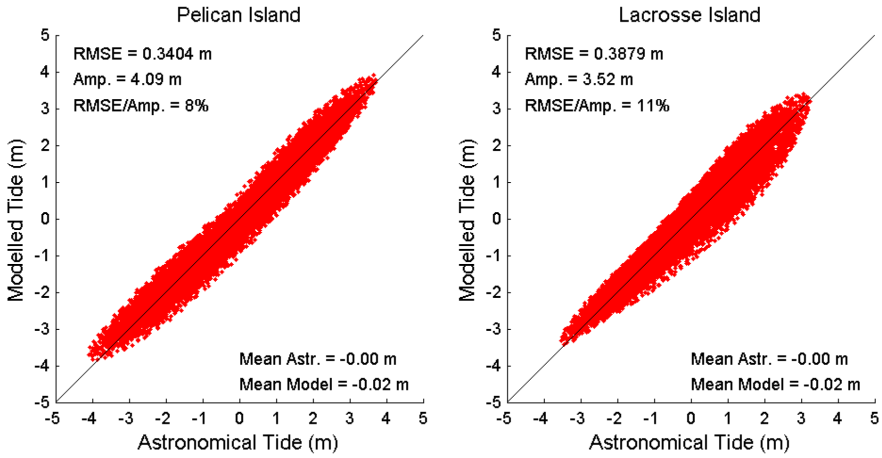
The 2D regional hydrodynamic model was validated with predicted astronomical tides at Lacrosse Island and Pelican Island over the 244 simulated days. Calibration consisted of adjusting the bed friction coefficient in the standard quadratic friction law within practical ranges. Model runs were tested with the Manning's number (*M*) in the range of 22-65 $m^{1/3}/s$. The calibration runs were only forced with tidal elevations at the open boundaries (i.e. no wind or atmospheric pressure). Comparisons of the simulated and predicted water levels at the selected stations are shown in Figure 12 for $M = 38\ m^{1/3}/s$ over the last 15 days of the simulation.

Figure 12 Comparison between the 2D regional simulation (red) and predicted (green) tidal levels at Lacrosse Island and Pelican Island.



To further investigate the accuracy of the model, correlations between modelled and predicted (or astronomical) water levels at Lacrosse Island and Pelican Island are shown in Figure 13. Red dots correspond to half-hourly outputs during the 244 day simulation. No correction for phase lags was applied in Figure 13, hence the correlations reflect the combined tidal phase and amplitude accuracy of the model, a more rigorous comparison than the standard correlations to 'amplitude' or 'phase' independently. These figures also present a quantitative assessment of the model accuracy with root-mean-square-error (RMSE) to amplitude (Amp) ratios of 8% and 11% at each station, respectively. Both of these values are within the industry-standard acceptable range.

Figure 13 Quantitative representation of regional hydrodynamic model water level accuracy.



6.3 High Spatial Resolution Hydrodynamic Modelling

6.3.1 High Spatial Resolution Bathymetry and Output Locations

As no detailed survey data is available for the upper portion of the Keep River Estuary (i.e. upstream of the Sandy Creek confluence in Figure 14), the bathymetry of the high spatial resolution domain was constructed with available information as descried in this sub-section.

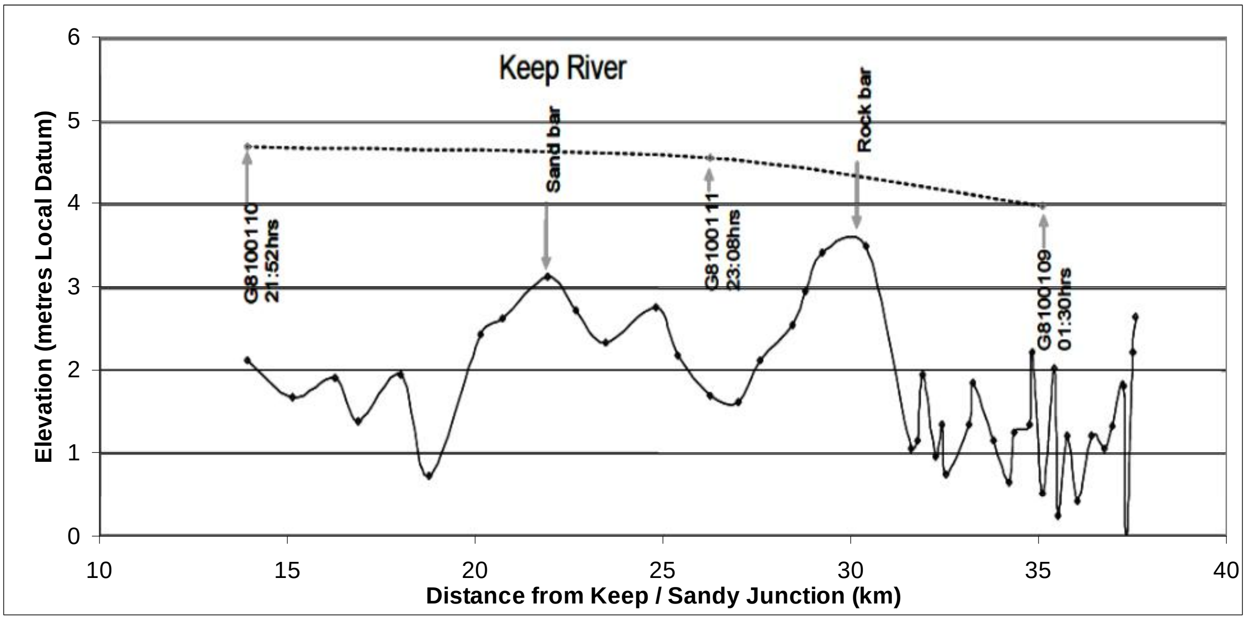
First, a satellite image at high tide was used to define the upper tidal boundary of the Keep River system (Figure 14). The edge of the water was extracted from the image file via GIS that allowed the waterline to be accurately mapped. Next, bottom elevations from one available longitudinal profile along a limited reach of the Keep River from 14 km to 38 km upstream of the Sandy River confluence (Gray and Williams 2006, Figure 15) served as the primary data to construct the bathymetry.

The Gray and Williams (2006) longitudinal Keep River bed profile, the satellite image derived high tide waterline, and available CMap data of the northern extent of the high spatial resolution model served as the primary data to construct the bathymetry. It was not possible to align both the sand bar and the rock bar as measured by Gray and Williams (2006) (Figure 15), so the sand bar was assumed to be ephemeral and the rock bar was selected as the fixed reference point. The remaining downstream bathymetry from 14 km upstream of the Keep River and Sandy Creek confluence was assumed to linearly decrease to the confluence, after which sparse CMap data was used. Upstream of 38 km from the Keep River and Sandy River confluence (i.e. upstream extent of Gray and Williams 2006 longitudinal depth profile), no bathymetric information was available. Hence, for pools K1, K2 and K3 the morphology information (characteristic lengths, widths and depths of pools) from section 2.5 were used in conjunction with aerial photography of the pool locations.

Because of the uncertainty in the local datum reported by Gray and Williams (2006), comparisons with initial model validation simulations indicated that the local datum was 0.9 m higher than AHD. Hence, the depths in the longitudinal profile Figure 15 (Gray and Williams 2006) were corrected by -0.9 m to convert from the local to the AHD datum.

Figure 14 Satellite image of the lower Keep River catchment at high tide (Gray and Williams 2006).

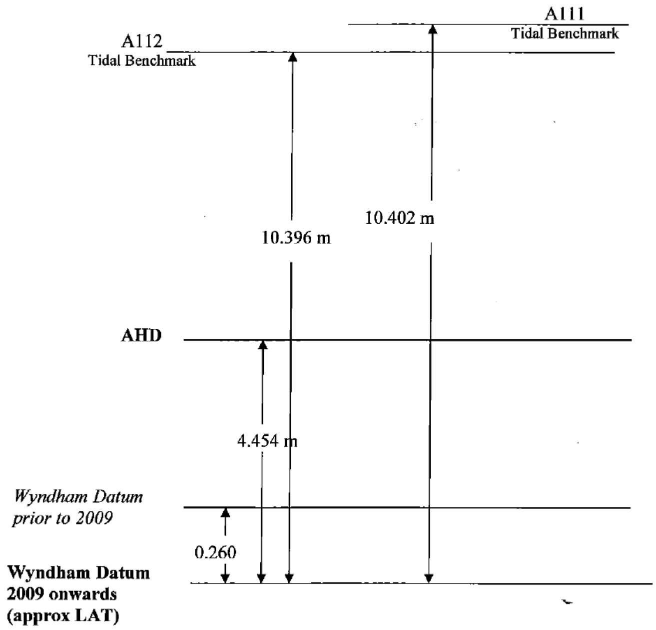
Figure 15 Longitudinal depth profile of the Keep River bathymetry (Gray and Williams 2006).



The construction of a bathymetry from multiple datasets with various datum (i.e. Gray and Williams 2006 longitudinal depth profile, CMap data) required a single height datum, namely the Australian Height Datum (AHD; equivalent to Mean Sea Level). As mentioned previously, a -0.9 m correction was applied to the local datum reported by Gray and Williams (2006). The CMap data is relative to the Lowest Astronomical Tide (LAT) height, which was converted to AHD as shown in Figure 16.

Lastly, to carry out wet season simulations the incorporation of the Keep River floodplain into the model domain was necessary. For the upper reach above Oakes Creek the floodplain was delineated on the basis of a 25K photogrammetry survey, while the lower floodplain extent was delineated on the basis of a 250K map with spot heights and inferences based on vegetation types from aerial photos (Figure 17).

Figure 16 Datum conversion between LAT to AHD (Department of Transport).



A 3D mesh with 27465 Elements and 19572 Nodes and a 2D mesh with 5580 Elements and 3380 Nodes were constructed for the high spatial resolution model domain from the derived bathymetry (Figure 17). The horizontal mesh is also shown in Figure 17.

During the simulations time series information was outputted at 11 locations (Table 11, Figure 17) as well as areal snapshots over the entirety of the model domain.

![GHD logo]

Table 11 Time series output locations in high spatial resolution model domain.

Time Series Location	Description
NO	Near open boundary
LE	Lower estuary
ME	Middle estuary near Sandy Creek confluence
UE	Upper estuary corresponding to Gray and Williams (2006) seaward station G100110
DS	Downstream of sand bar
US	Upstream of sand bar corresponding to Gray and Williams (2006) middle station G100111
BR	Below of rock bar
UR	Upstream of rock bar
K1	Pool K1 corresponding to Gray and Williams (2006) landward station G100109
K2	Pool K2
K3	Pool K3

Figure 17 High spatial resolution model domain bathymetry (AHD), time series output locations and floodplain delineation sources (left panel), and mesh and boundary conditions (right panel).

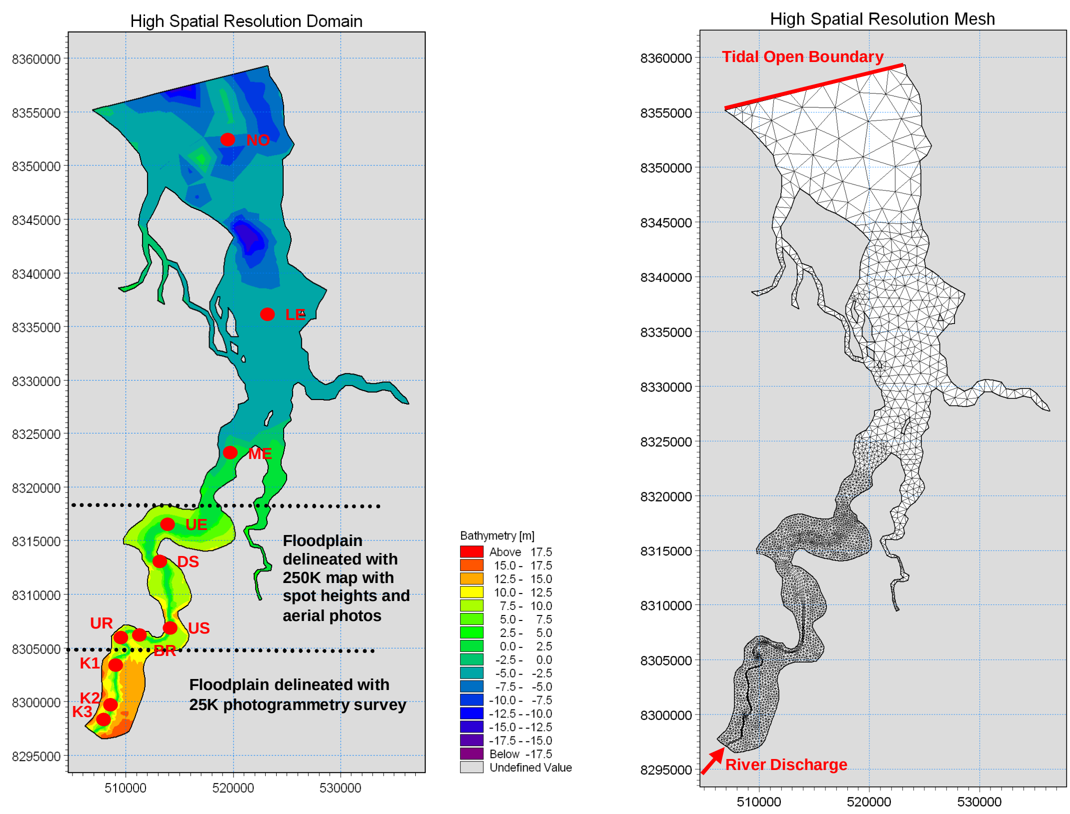
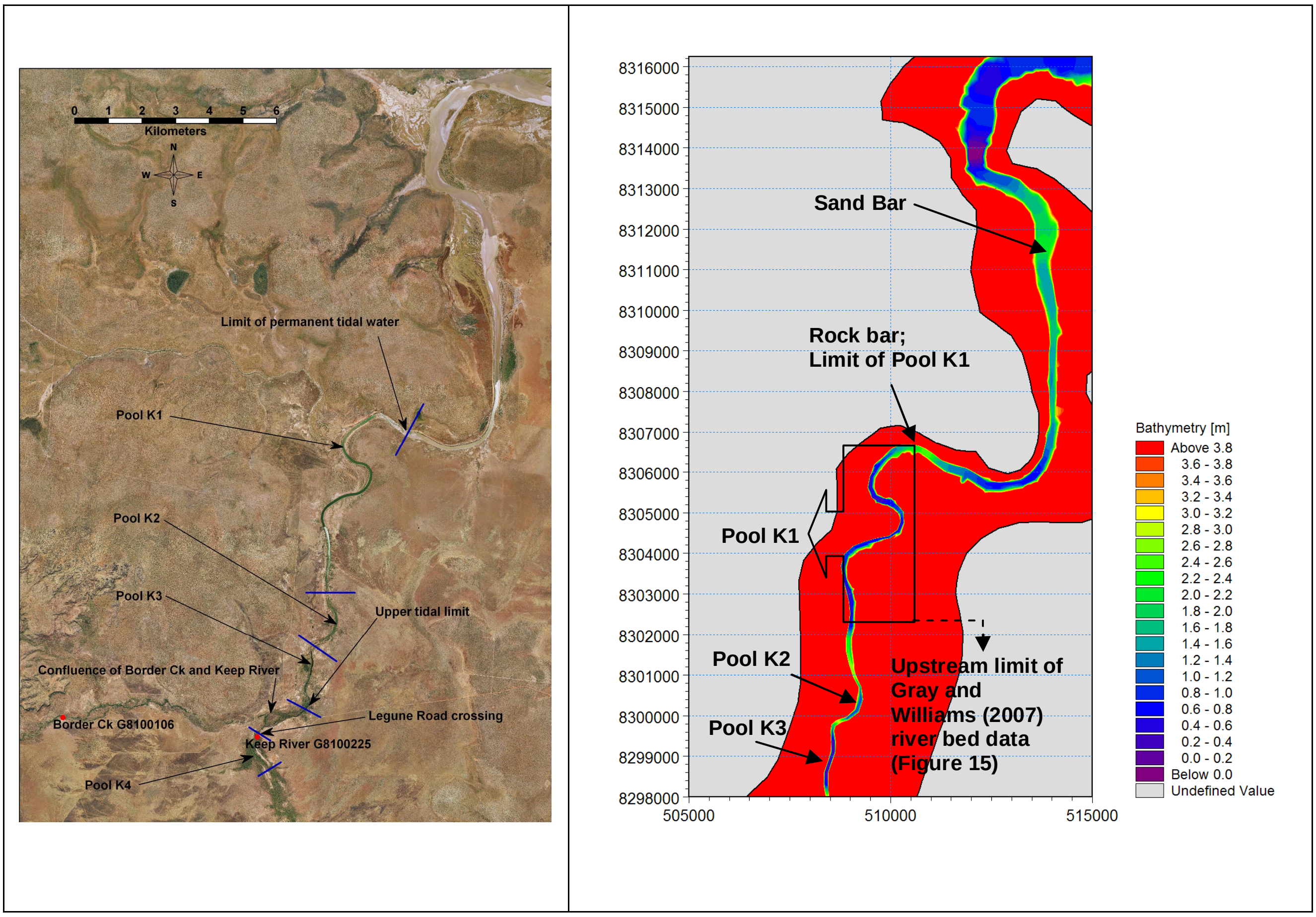


Figure 18 shows an enlarged view of the model bathymetry along with a map of key locations including the sand bar and rock bar.

Figure 18 Approximate locations of the pools of the Keep River and anecdotal evidence of limit of permanent tidal water (Bennett and George, unpubl., left panel) and corresponding model bathymetry (right panel).



6.3.2 Vertical Discretisation

A sigma-coordinate vertical grid with 5 layers was configured in the 3D model, which allowed simulation of vertical salinity (or density) gradients that are induced by the interaction between freshwater and marine waters. By definition the 2D model has only 1 layer representing the entire vertical water column, and therefore does not simulate vertical stratification.

6.3.3 Model Initialization and Output Time Step

High spatial resolution simulations were initialised with a constant water level (generally approximately 3.5 m AHD near high tide). A half hourly (i.e. dry season validation simulations) or hourly (i.e. wet season scenarios) time step was selected for outputs from the 11 locations and areal distributions.

6.3.4 Modelling Periods

The following three periods were selected for high spatial resolution modelling:

- 2004 dry season validation: September 1 to November 30 2004, which coincides with the period of water level measurements by Gray and Williams (2006) from 12/10/2004 to 14/11/2004. This period was also used to evaluate applicability of 2D versus 3D modelling and the influence of wind forcing in the region of interest;
- 2006 wet season scenario: December 11 2005 to May 31 2006, which had the largest recorded flood on record during March 2006 (Figure 20); and
- 2007 wet season scenario: January 3 to May 31 2007, which was a relatively low runoff year.

The 2 wet season scenarios were initiated prior to major flow events to allow the model to 'spin up' and establish tidal dynamics. Simulations through May 31 allowed assessment of the groundwater proportions in the pools and upper estuary after 1 month from the cut-off date for releases into the Keep River on April 30.

6.3.5 Boundary Conditions

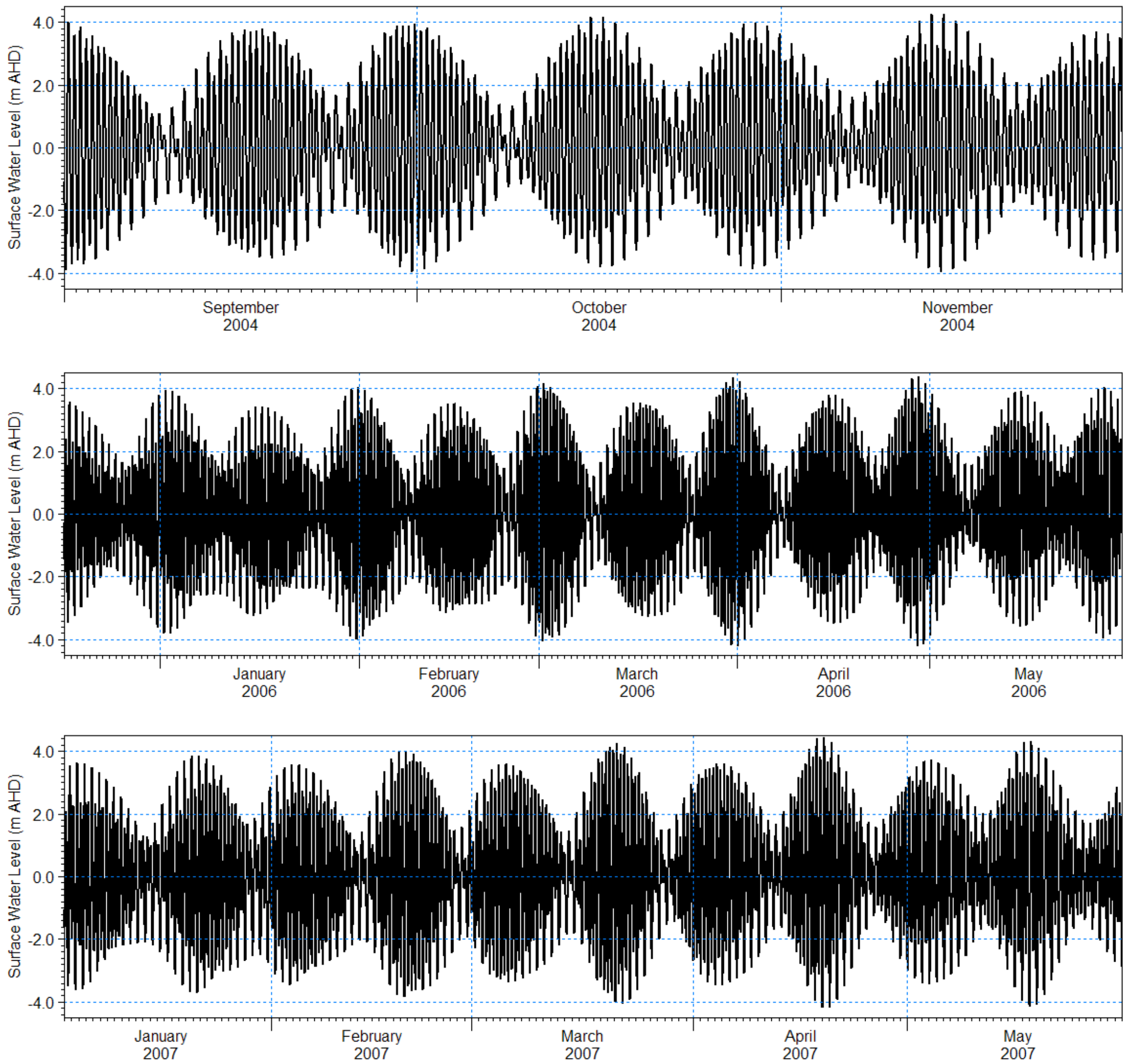
Tidal Forcing

Neither the tidal record nor the tidal harmonic constituents from Turtle Point (see Figure 10) were available to force the water levels at the high spatial resolution model open boundaries. Water levels from the 2D regional model simulation were extracted and directly served as inputs for the dry season high spatial resolution validation simulations. Harmonic constituents were computed from the 2D regional simulated tidal levels near Turtle Point to determine predicted tides for application along the northern open boundary of the high spatial resolution simulations for the 2 wet season scenarios (Figure 19). A tidal range of up to 8 m is predicted along the open boundaries.

Temperature and Salinity

The initial temperature and salinity throughout the model domain and at the open ocean boundary was set to a constant 30°C and 35 ppt, respectively. The temperature and salinity of the Keep River discharge into the high spatial resolution model domain was set to 30°C and 0.3 ppt, respectively.

Figure 19 **Tidal water level inputs into high spatial resolution modelling along the marine open boundary during the 2004 dry season (upper panel), and the 2006 (middle panel) and 2007 (lower panel) wet seasons.**



Inflow Discharge and TDS

A dry season discharge of approximately 0.025 m^3/s on the basis of recent (July, August and September 2010) flow measurements (D. Bennett, pers. comm.) of the Keep River at Legune Road crossing (station G8100225) served as inputs for the validation simulation.

For the 2006 and 2007 wet season simulations, the Keep River discharge was based on the catchment-river model flows below the confluence of Border Creek and Keep River as detailed in section 5 and reproduced here in Figure 20. The TDS was estimated on the basis of the mixture waters from the various sources (groundwater, stormwater, Border Creek, Keep River) with their respective characteristic salinities.

Tracers were also used to track the proportion of Keep River and external Border Creek (i.e. not WPF origin) waters in the pools and upper estuary.

WPF Stormwater and Excess Groundwater Tracers

The WPF stormwater and groundwater tracers detailed in section 5 served as inputs at the upstream boundary above pool K3 for the 2006 and 2007 scenarios (Figure 21). These tracer levels represent the volumetric dilution of the WPF stormwater and excess groundwater with the Keep River and Border Creek above pool K3. For example, a groundwater tracer value of 0.06 indicates that 6% of the water volume is comprised of excess groundwater. Subsequent decreases in tracer levels in the hydrodynamic simulations are from further dilution with riverine, estuarine and/or marine waters, and/or tidal or riverine-induced flushing. Generally peak groundwater and stormwater tracers were 12-15% and 6-9%, respectively. The proportion of stormwater below the Border Creek confluence attained a peak of 28% in early February as discussed previously in section 5.4.

Figure 20 Discharge (m^3/s) and TDS (g/L) at the confluence of Border Creek and Keep River for the 2006 (left panel) and 2007 (right panel) scenarios.

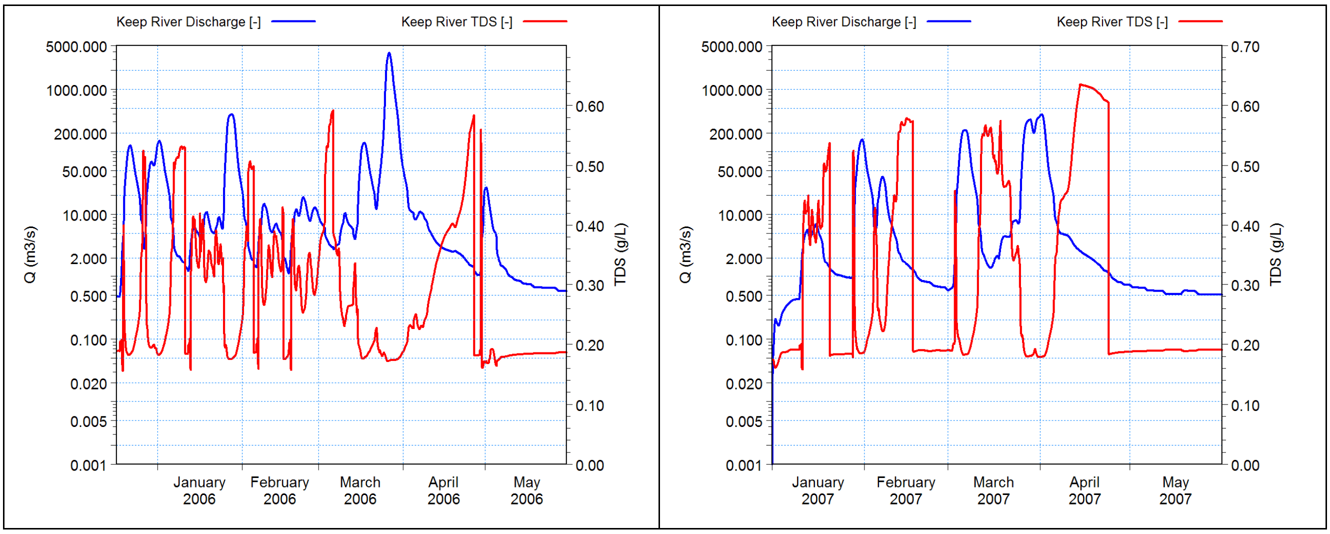
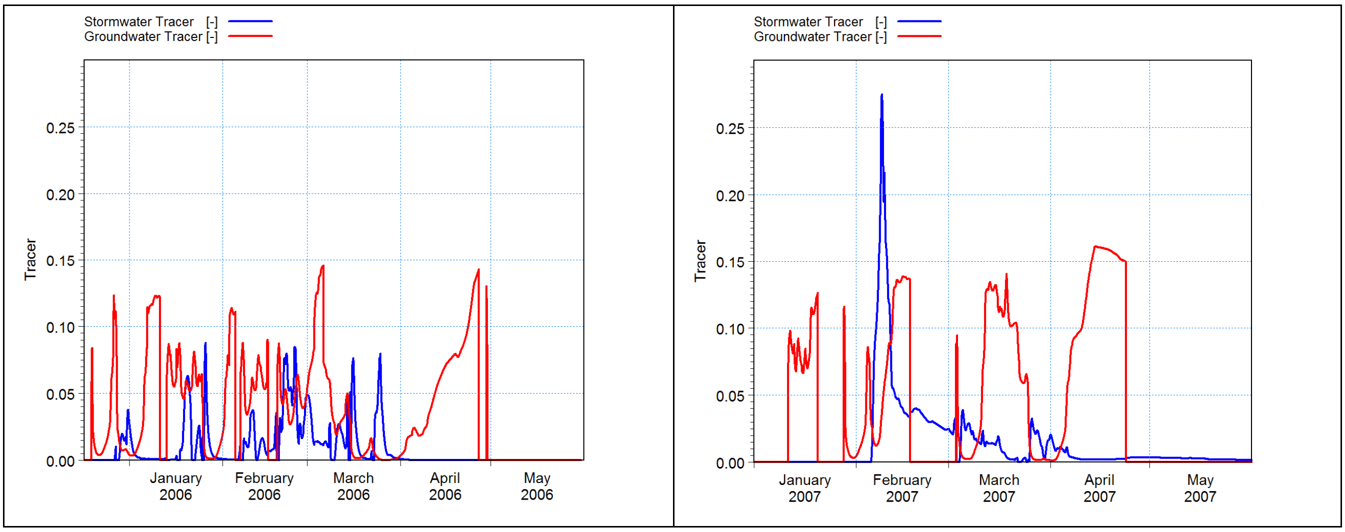


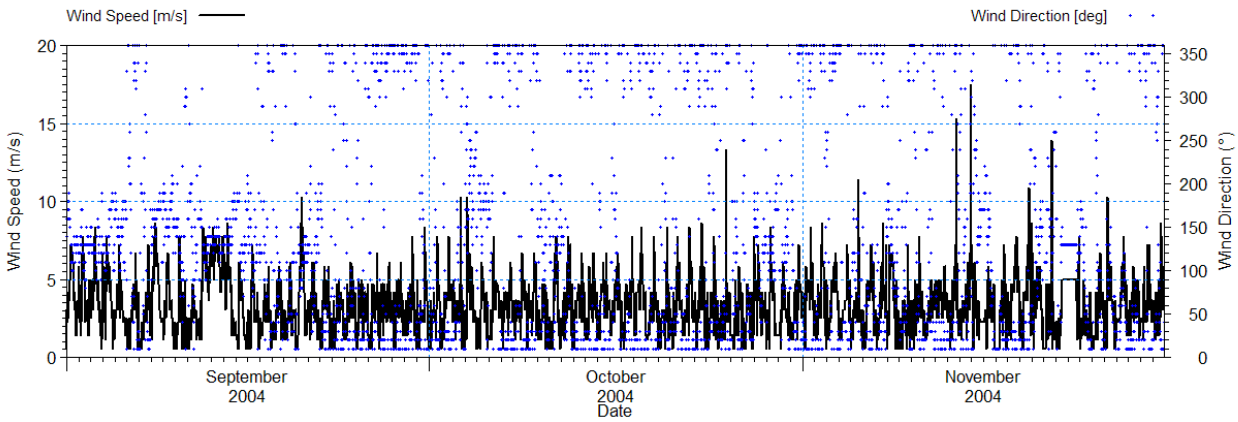
Figure 21 Groundwater and stormwater tracers at the confluence of Border Creek and Keep River for the 2006 (left panel) and 2007 (right panel) scenarios.



Wind Speed and Direction

For the validation period simulations were run with and without wind speed and direction from Kununurra Airport to assess their impact on the region of interest (Figure 19).

Figure 22 Half hourly wind speed and direction from September-November 2004 for the high spatial resolution model validation simulation.



6.3.6 Other Modelling Considerations

Other modelling considerations included:

- The effect of the earth's rotation on currents (i.e. Coriolis force) was simulated in the model;
- The stress terms in the equations of motion were resolved using the Smagorinsky formula with a coefficient of 0.28;
- Scaled eddy formulation was used with a scaling factor of 1.1; and
- Surface heat exchange was not considered a dominant factor in this system relative to salinity variations, riverine flushing and tidal-induced exchanges.

6.4 Validation of High Spatial Resolution Models

6.4.1 Bed Resistance

Several 3D hydrodynamic model runs were carried out to validate the bed resistance with roughness heights (z_0) between 0 and 0.25 m. A z_0 of 0.02 m yielded the best 3D hydrodynamic simulation comparison with water levels at the Gray and Williams (2006) seaward station. For the 2D simulations a corresponding Mannings Number (M)[22] of M = 50 $m^{1/3}/s$ was estimated from the z_0 of 0.02 m of the 3D simulations with the relation $M=25.4/z_0^{1/6}$.

6.4.2 Water Level Validation

Comparison of the simulated water levels with the 2D model (Figure 23) over the range of measurements of Gray and Williams (2006) in Figure 3 compared well on the basis of the following:

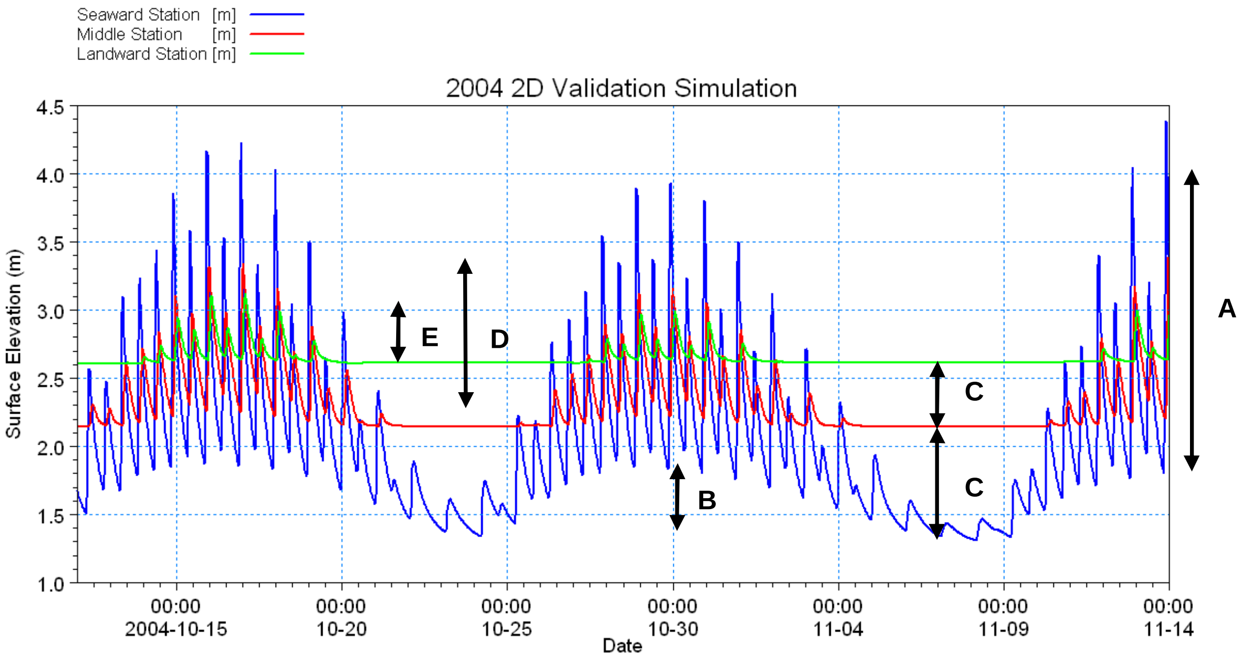
[22] Note Mannings Number used in Mike 21 FM 2D hydrodynamic simulations is the reciprocal of Mannings Number described in some text books.

- A - Observed and simulated surface fluctuations from tides at the seaward station both had a maximum range just over 2 m;
- B - The observed 0.4-0.5 m increase in minimum surface levels between spring and neap tides is captured by the simulation;
- C – The observed differences in minimum water levels between the 3 stations was captured well;
- D – The simulated surface fluctuations from tides at the middle station had a maximum range of approximately 1 m, which was slightly lower than the observations of 1.2-1.3 m; and
- E – The simulated surface fluctuations from tides at the landward station had a maximum range of approximately 0.4 m, which were slightly greater range than the observations of up to 0.3 m.

The seaward station indicates that the propagation of tides from Joseph Bonaparte Gulf is captured well by the model. The crests of the sandbar (3.1 m local datum, 2.2 m AHD) and rock bar (3.5 m local datum, 2.6 m AHD) controlled the tidal level fluctuations at the middle and landward stations, respectively.

Given the constraints of the limited availability of bathymetric information, the high spatial resolution modelling captures the primary features in the tidal portions of the Keep River system well, namely the correct tidal amplitude variations at the 3 stations monitored by Gray and Williams (2006) during October 2004. This validation provides confidence that the model accurately simulates the tidally influenced regions sufficiently to capture the tidal flushing and dilution with marine-origin waters.

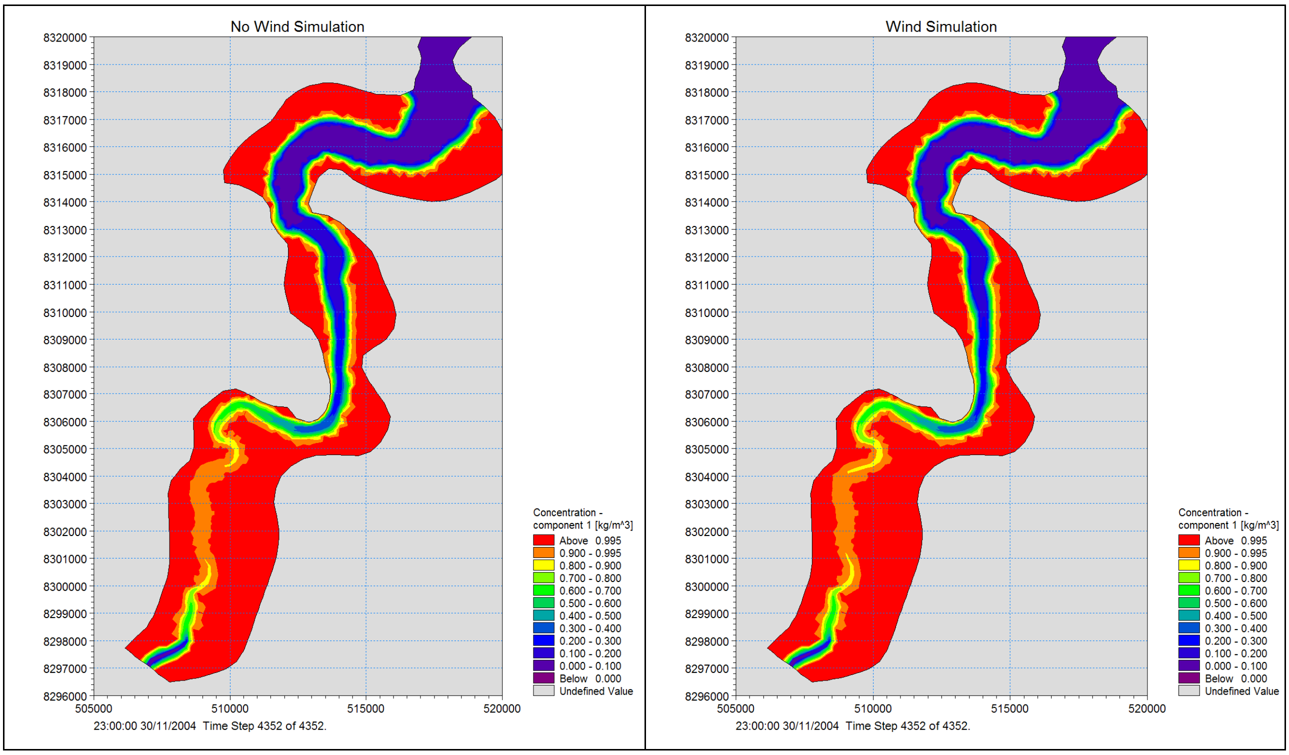
Figure 23 Simulated seaward (blue line), middle (red line) and landward (green line) stations at same locations as measurements by Gray and Williams (2006) with key comparisons to measured time series (Figure 3) highlighted by capital letters and arrows.



6.4.3 Impact of Winds

In order to assess the impact of winds on the region of interest, simulations with and without wind forcing were compared with a time series of areal snapshots of the 2D model runs with a conservative tracer that was initialised with a value of 1.0 at the onset of the simulation. Inputs via riverine inflows with a discharge of 0.025 m^3/s were set to 0.0 as was the exchange of water through the marine open boundary. After the 3 month simulation the difference between the tracer distributions in the region of interest with and without wind was minimal (Figure 24). This indicates wind forcing is not a dominant process on the time scale of weeks to months in the area of interes, so wet season simulations were run with no wind forcing.

Figure 24 Comparison of 2D simulations without (left panel) and with (right panel) wind forcing at the end of the 3 month validation simulation.



6.5 Flushing and Dilution of Stormwater and Excess Groundwater

6.5.1 Methodology

The validated high spatial resolution hydrodynamic model was then coupled with an advection-dispersion transport module to 'track' two conservative tracers that 'mark' the proportion of the water at any point in the model study area that is comprised of WPF stormwater and excess groundwater. As mentioned previously, discharge and TDS (Figure 20), and stormwater and groundwater tracer levels (Figure 21) from the catchment-river model over the 2006 and 2007 wet seasons along with predicted tides at the open boundaries (Figure 19) served as inputs for these scenario simulations.

6.5.2 Water Surface Elevations

The simulated peak and mean surface elevations from the 2006 (Figure 25) and 2007 (Figure 26) simulations provide the following insights:

- Extensive floodplain inundation from the March 2006 event was predicted (up to 11 m in upper model domain), whereas peak water levels during the 2007 simulation were much lower (up to 6 m in upper model domain). The peak water surface elevations during the 2006 scenario simulation were comparable to those modelled by the 1D catchment-river model for the March 2006 event (see Figure 7 in section 5.2); and
- However, mean surface water elevations were substantially lower and similar for both scenario simulations, indicative that episodic flooding occurs for only short periods of elevated surface water elevations.

Figure 25 Statistical maximum (left panel) and mean (right panel) water surface elevations over the duration of the 2D 2006 wet season simulation.

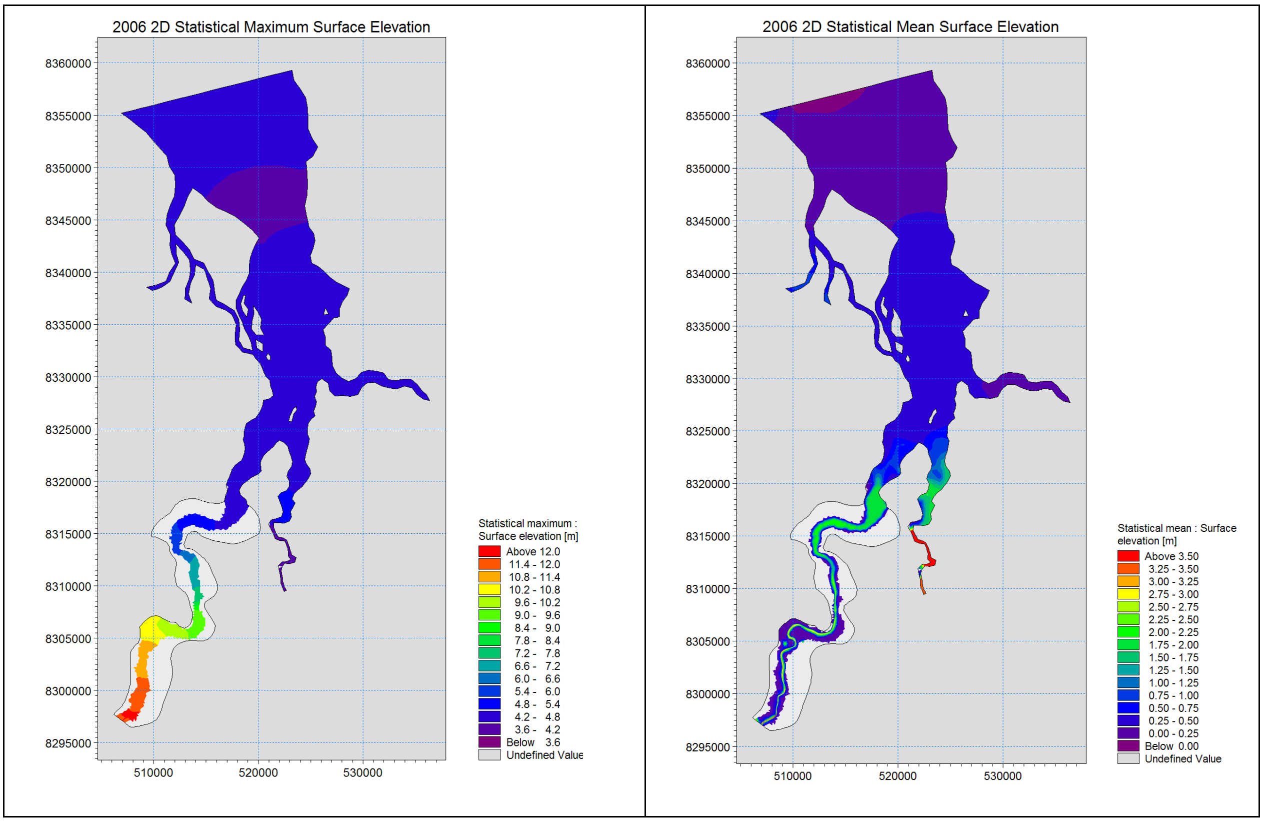
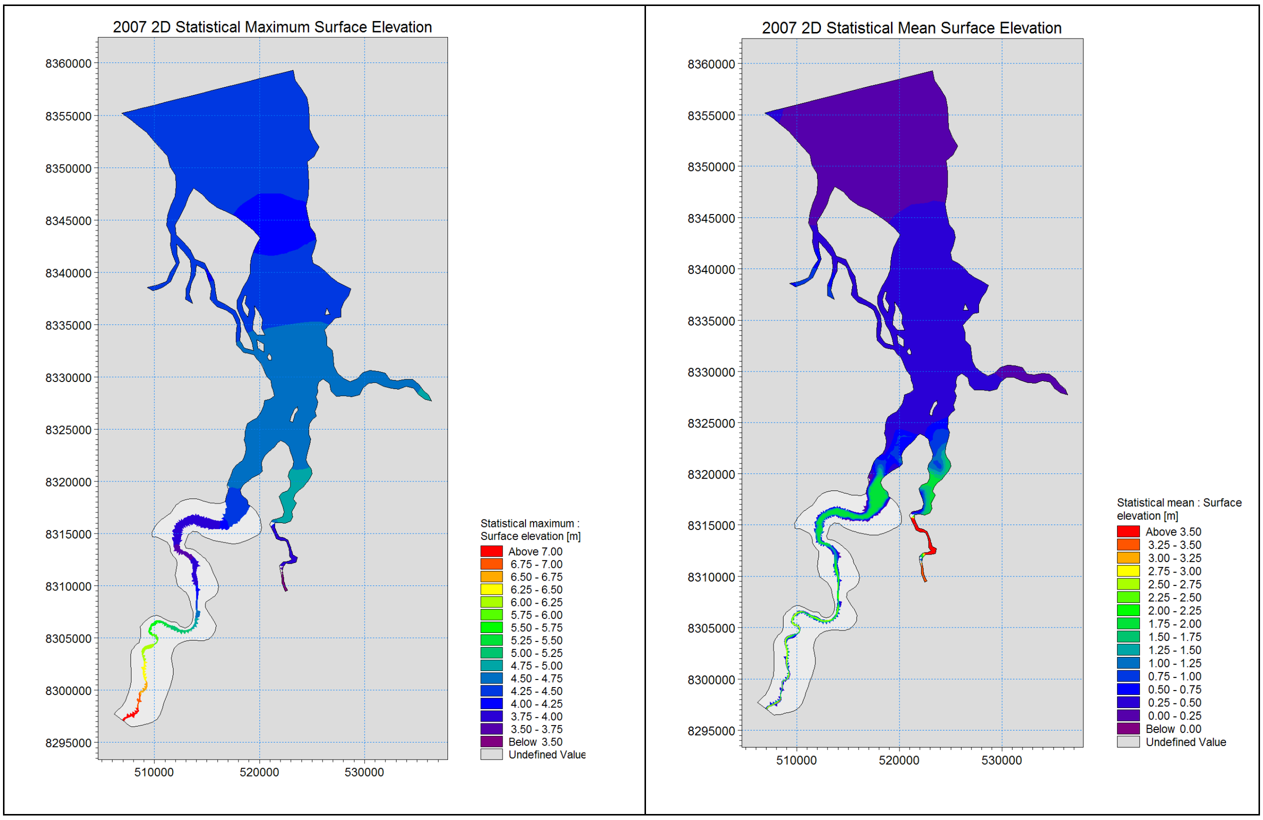


Figure 26 As Figure 25 for the 2007 wet season simulation

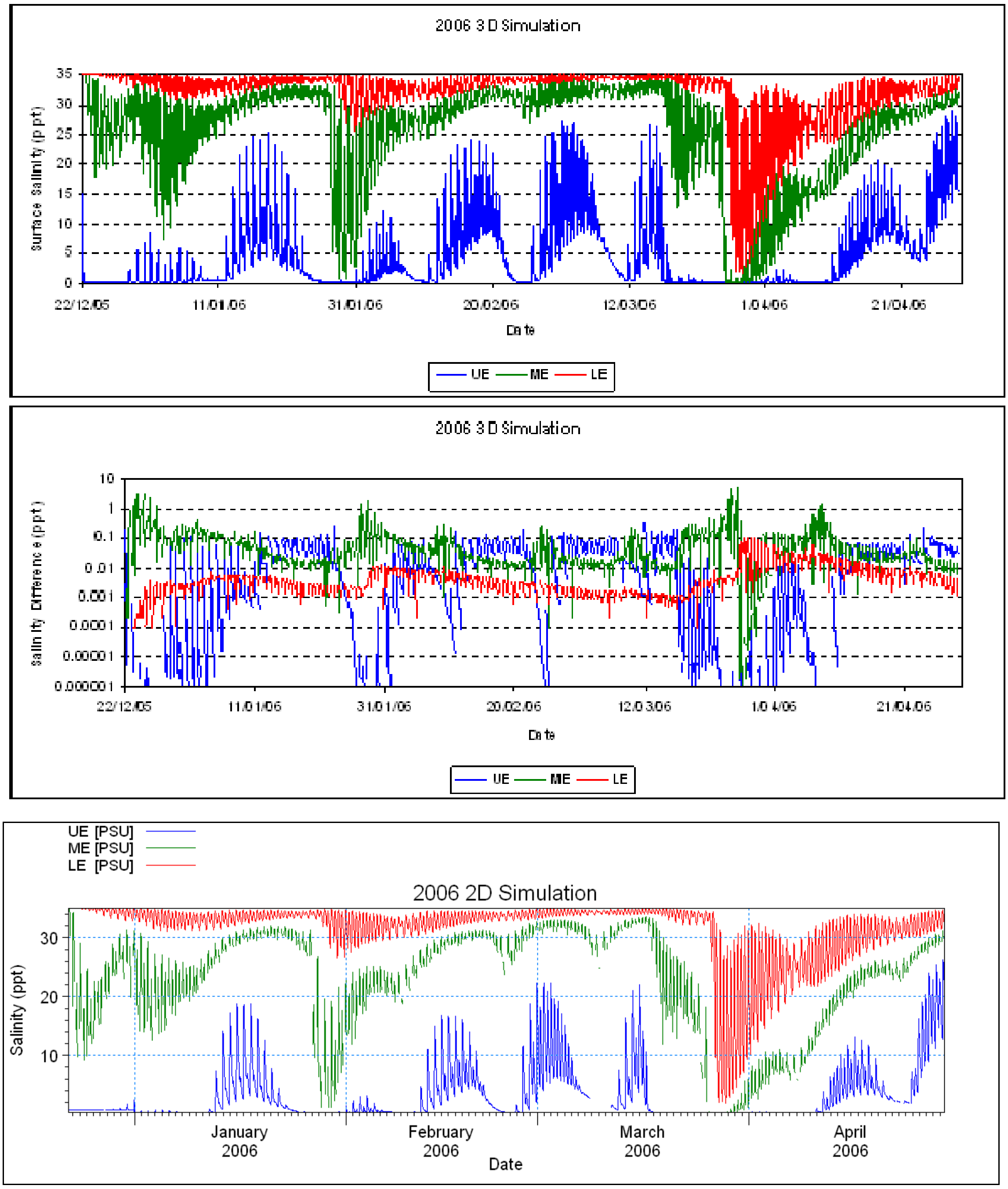


6.5.3 Salinity Dynamics

The simulated salinity dynamics at 3 representative locations in the estuary (see Figure 17) for the 2006 3D wet season scenario are shown in Figure 27 and provide the following insights:

- Surface salinity at the lower estuary (station LE) time series location (see Figure 17 and Table 11 for time series locations and identifiers) is generally near 35 ppt (the open boundary condition salinity), but decreases to ~30 ppt during moderate-sized Keep River flood events (i.e. late January 2006 of 100-200 m^3/s) and to 5 ppt during the large March 2006 event (i.e. up to 3,800 m^3/s). Salinity differences between the surface and bottom layers were 0.001-0.01 ppt except briefly to 0.1 ppt immediately after the March 2006 flood event;
- Surface salinity at the middle estuary location near the confluence with Sandy Creek (station ME) decreased to 5-15 ppt during moderate sized floods, and was essentially freshwater during the large March 2006 flow event. Salinity differences between the surface and bottom layers were 0.01-0.1 ppt except briefly to 1 ppt after the arrival of the March 2006 peak flows; and
- Surface salinity at the upper estuary location (station UE) was essentially freshwater during small floods (i.e. 100-200 m^3/s) at the start of the simulation with salinity increasing during low flow periods. Salinity differences between the surface and bottom layers were generally about 0.1 ppt except after flow events when essentially the entire water column was freshwater.

Figure 27 **Surface salinity (top panel) and salinity difference between top and bottom layers (middle panel) during the 2006 3D wet season scenario simulation, and salinity for the 2006 2D wet season scenario simulation (bottom panel) at 3 estuarine locations.**



Though weak salinity stratification is generally simulated with the 3D model (0.001-0.1 ppt) at the selected locations in the estuary, the 2D model captures the same salinity variations at these 3 locations (lower panel in Figure 27), which indicates that a 2D modelling approach is valid during the wet season.

Time series (Figure 28) and spatial distributions of mean salinities (Figure 29) during both low (2007) and high (2006) runoff years illustrate that predominantly freshwater occurs above the sand bar (station US) during the wet season. However, time series (Figure 28) and spatial distributions of mean salinities (Figure 29) show that for the low runoff year (2007) higher salinities occur below the sand bar (station BS) than the high runoff year (2006) because of lower volumetric freshwater discharge that allowed further upstream migration of saline waters.

Figure 28   Salinity for the 2006 (left panel) and 2007 (right panel) 2D wet season scenario simulations in the sand bar region.

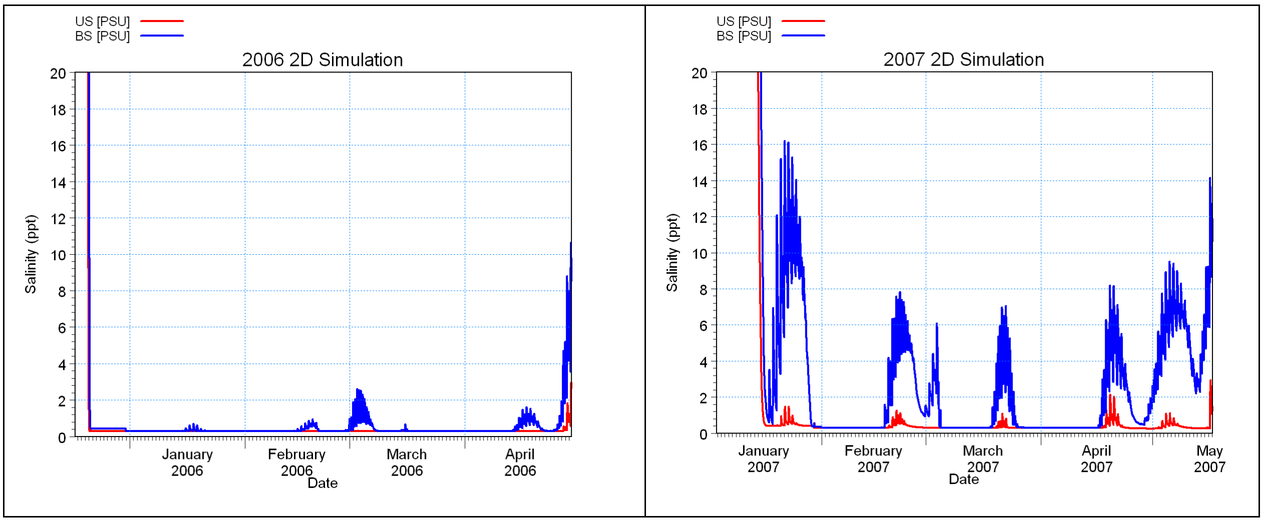
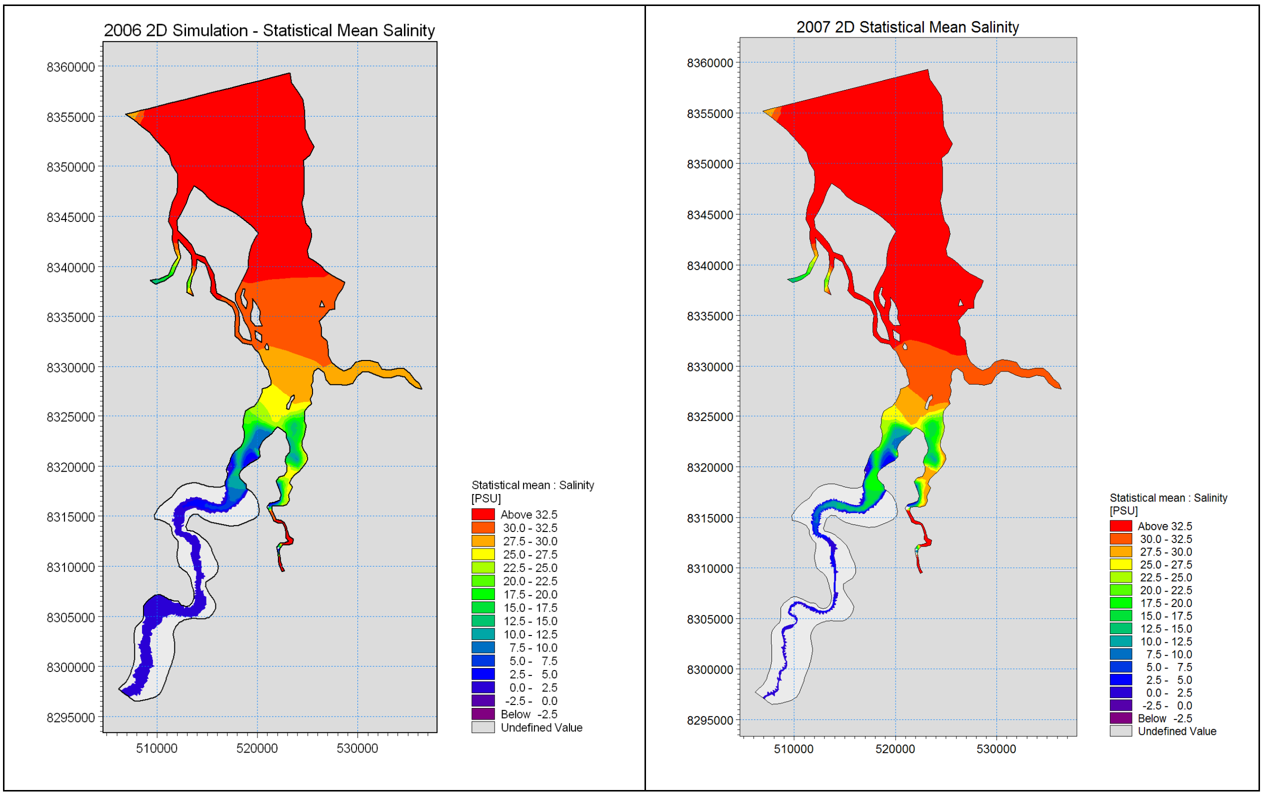


Figure 29   Statistical mean salinity during high (2006, left panel) and low (2007, right panel) runoff years over the duration of the 2D scenario simulations.



In short, 2D and 3D modelling approaches simulate similar salinity dynamics in terms of capturing horizontal variations in salinity during the wet season. This is particularly the case in the important regions for assessment of potential impacts from WPF stormwater and excess groundwater (i.e. narrow Keep River reaches above the sand bar) during the wet season when most of this region is essentially riverine freshwater. The validity of a 2D modelling approach is further demonstrated in the next section with 2D versus 3D comparisons of the spatial tracer distributions.

6.5.4 2D versus 3D Spatial Tracer Distributions

Though these simulations illustrate an earlier groundwater option whereby 12 GL per annum of groundwater was pumped with 6.8 GL per annum discharged to the Keep River and Border Creek, it demonstrates that the 2D and 3D models yield comparable predictions. The middle layer (layer 3) has been illustrated in the spatial figures for the 3D simulations.

Comparisons between the 2D and 3D simulations of the groundwater tracers were very similar for the 2006 and 2007 wet seasons for both the mean (Figure 30) and maximum (Figure 31) values over each grid cell over the model run duration. Key findings include:

- Peak mean groundwater tracer levels tend to occur between the rock bar (station BR) in 2006 or downstream of the sand bar (station DS) in 2007 and the upper (station UE) to middle (station ME) estuary stations; and
- Maximum groundwater tracer levels were generally higher throughout the narrow portion of the upper Keep River model domain in 2006 than in 2007, and decreased due to dilution with marine waters between the upper (station UE) and middle (station ME) estuary stations both years.

The 2D and 3D simulations of the stormwater tracers were also very similar for the 2006 and 2007 wet seasons for both the mean (Figure 32) and maximum (Figure 33) values over each grid cell over the model run duration. Key findings include:

- Peak mean stormwater tracer levels occurred beyond the sand bar (station DS) in 2007, but tended to occur between the rock bar (station BR) and sand bar (station DS) in 2006; and
- Maximum stormwater tracer levels were lower throughout the narrow portion of the upper Keep River model domain between the upper (station UE) and middle (ME) stations in 2006 than in 2007 because of greater volumetric discharge.

In short, a 2D modelling approach yields similar tracer dynamics as the 3D simulations in terms of capturing horizontal variations in tracers during the wet season (note different from the proposed option considered in the EIS). Next simulations of the proposed option are used to evaluate the potential impacts on water quality, with particular emphasis on TDS, TN and TP.

Figure 30 Statistical mean groundwater tracers for 3D (left panels) and 2D (right panels) for 2006 (upper panels) and 2007 (lower panels) wet season scenarios with a preliminary option of 6.8 GL of excess groundwater release.

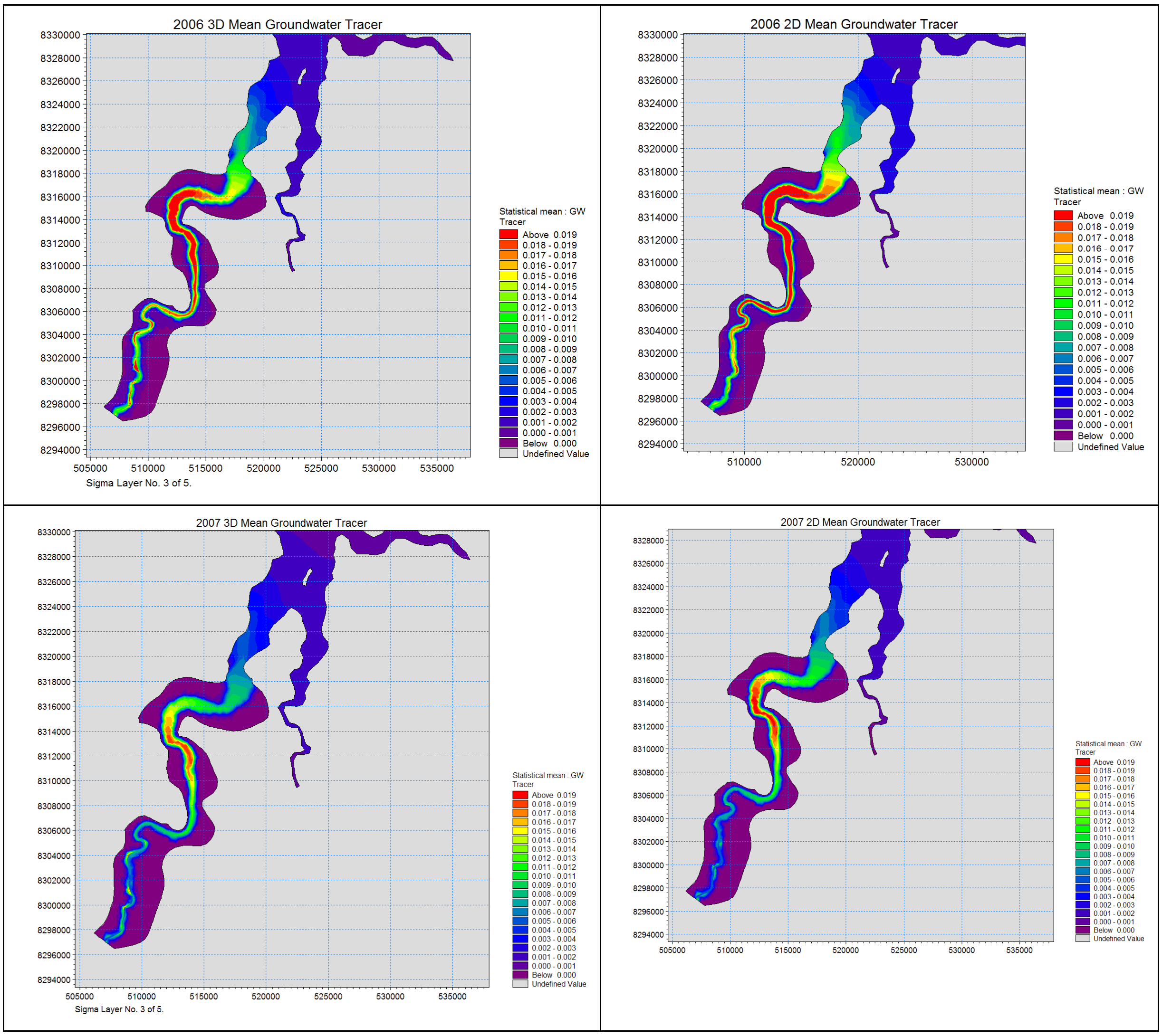


Figure 31 As Figure 30 for the statistical maximum groundwater tracers.

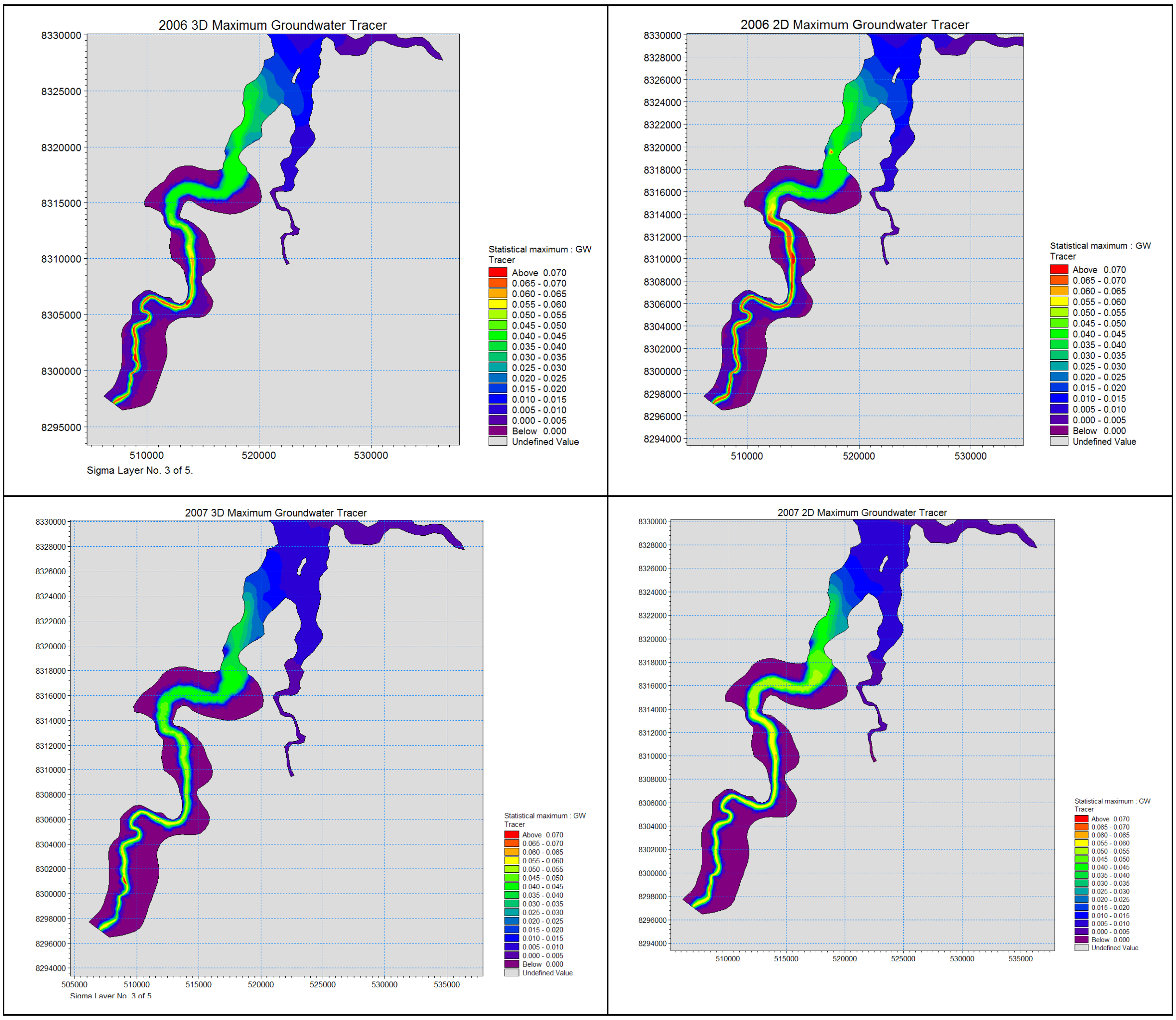


Figure 32 As Figure 30 for the statistical mean stormwater tracers.

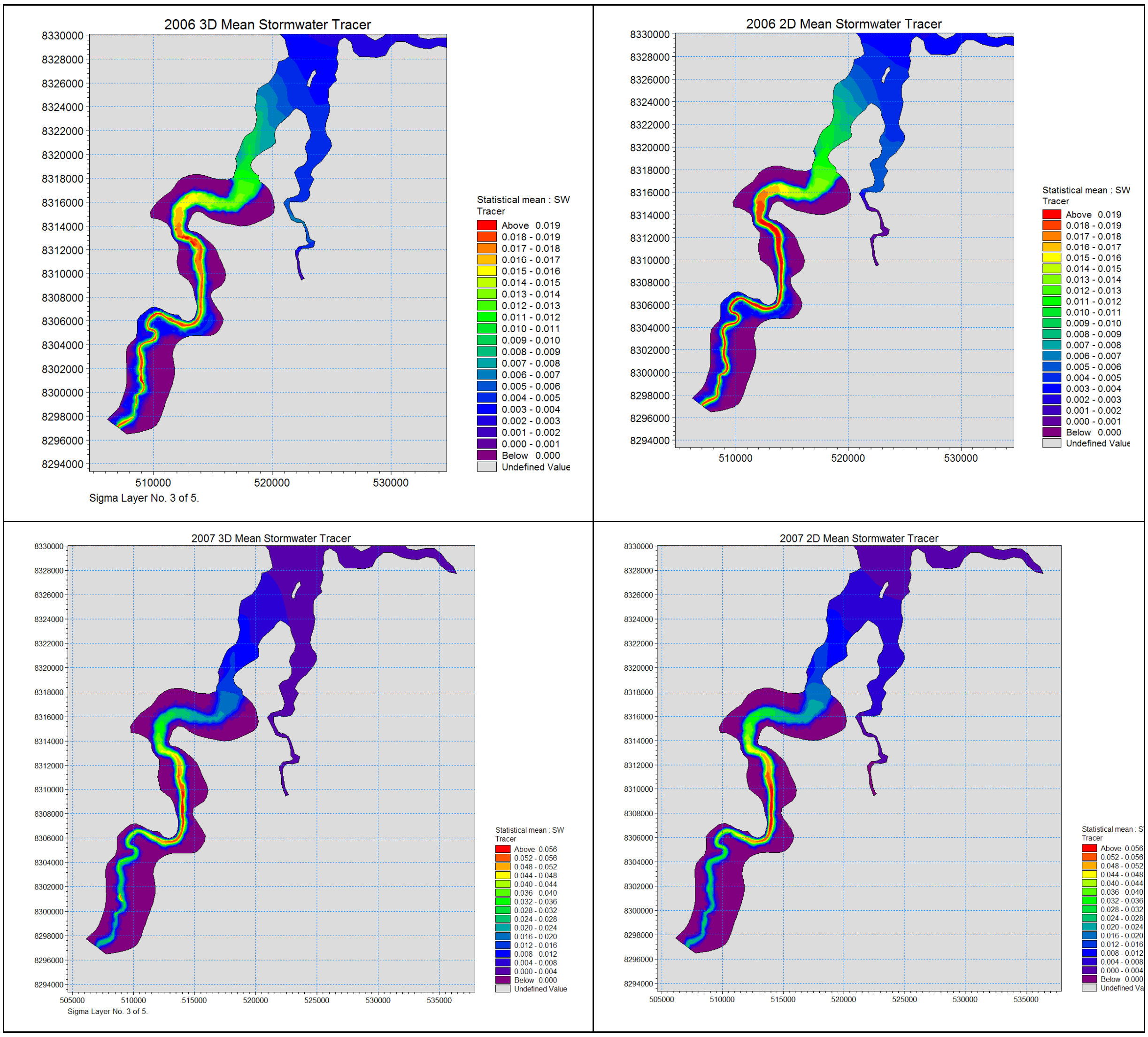
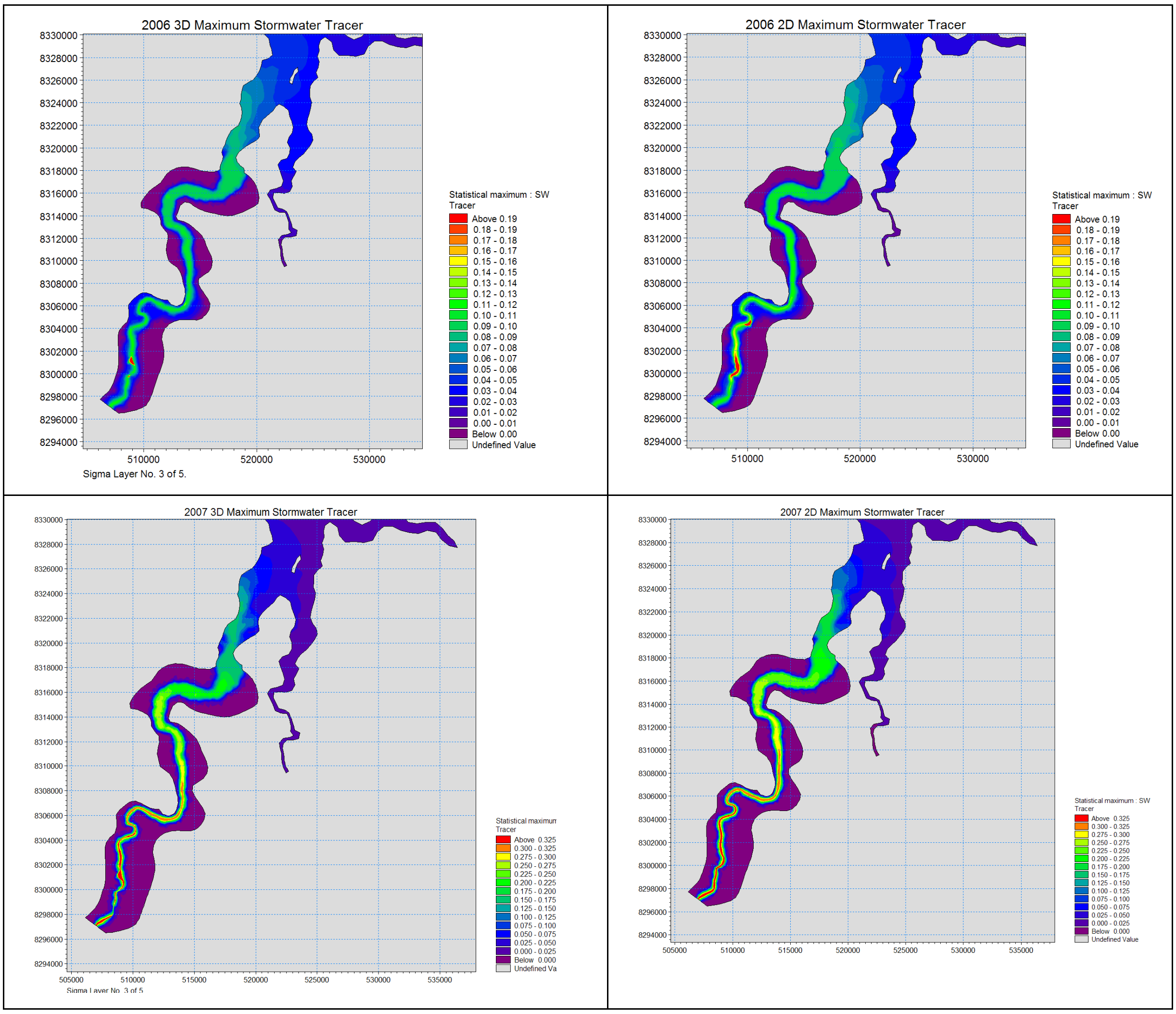


Figure 33 As Figure 30 for the statistical maximum stormwater tracers.



6.5.5 Tracer Dynamics: Proposed Option

Conservative tracers in the Keep River inflow have been used to investigate the dilution and flushing of the WPF stormwater and excess groundwater in the pools and upper estuary of the Keep River system. Tracers from the catchment-river model for the WPF stormwater and from the spreadsheet model for excess groundwater served as inputs (Figure 21). The hydrodynamic model domain was initialised with tracer values of 0.0. Therefore, an excess groundwater tracer concentration of 0.1 indicates 1 in 10 parts or 10% of the water at a particular location is comprised of this water source. Similarly, a value of 0.1 for the stormwater tracer indicates that 10% of the water is comprised of WPF 'on farm' origin stormwater.

Time Series and Probability Exceedance of Tracer Levels

The model runs are presented in the following forms:

- Time series of stormwater and groundwater tracer levels throughout the approximately 5 month duration simulations at the following 6 locations:
  - The K3 (upper), K2 (middle) and K1 (lower) pools;
  - Station BR immediately below the rock bar that forms the downstream extent of pool K1;
  - Station DS immediately downstream of the sand bar;
  - Station UE, which is just upstream of the confluence with the Sandy River; and
- Probability exceedance plots that express the percentage of time that a tracer level was above a certain value at each of these same 6 stations. For example, a groundwater tracer value of 0.05 for the 20th percentile exceedance is interpreted as '5% or more of the water is comprised of groundwater for 20% of the time at this location'.

The probability exceedance plots were evaluated over set periods for each simulation. The start of this period for each year was when the first excess groundwater release occurred, which were:

- December 29 2005 for the high runoff year simulation; and
- January 12 2007 for the low runoff year simulation.

These dates correspond to approximately 10-12 days after the start of the model runs.

The following dates mark the end period over which the probability exceedances were computed:

- May 15 2006 for the high runoff year simulation (15 days prior to end of simulation); and
- May 31 2007 for the low runoff year simulation (end of simulation).

For the 2006 high runoff year, all of the tracers were effectively flushed from the 3 pools and upper estuary stations from riverine-induced flushing by mid-May; hence an earlier cut-off date was selected. In contrast, elevated groundwater tracer levels persisted throughout much of May for the 2007 low runoff year. Further, as the simulation of the 2006 high runoff year started approximately 2 weeks earlier than the 2007 low runoff year, the probability exceedance plots for both simulations are computed over a similar duration of 5 months.

The time series plots and probability exceedances plots of the simulated tracer levels are illustrated for the 6 stations in Figure 34 and Figure 35 for the 2006 and 2007 wet seasons, respectively. The following key features were simulated:

- The time series plots of the excess groundwater tracers indicate:
    - Generally, excess groundwater tracers were simulated to be well flushed from the 3 pools (i.e. K3, K2 and K1) after large stream flow events during both years. However, during the tail of these events tracer levels increased as groundwater releases comprised a larger proportion of the total flow. Subsequent flow events then rapidly flushed these remnant tracers;
    - There was sufficient river flow after the cessation of groundwater releases on April during both years to flush the 3 pools by May 31, though this occurred more rapidly during the high runoff year of 2006 than the low runoff year of 2007;
    - There was sufficient riverine flow to flush the estuarine locations (BR, DS, UE) during the high runoff year of 2006, in large part because of the late modest-sized flow event at the beginning of May after the cessation of groundwater releases. In contrast, during the low runoff year of 2007 the slower tidal flushing mechanism decreased tracer levels more gradually during May after the cessation of groundwater releases;
    - The duration of relatively elevated excess groundwater was shortest in the 2 upper pools (stations K3 and K2), whereas the duration was progressively longer for K1, below the rock bar (BR) and downstream of the sand bar (station BS);
- The probability exceedance plots of the excess groundwater tracers indicate:
    - During the high runoff year of 2006, the 3 upper pools had very similar exposure durations and comparable tracer levels. However, for the 3 estuarine stations tracer levels decreased with distance downstream due to dilution with marine/estuarine waters;
    - In contrast, during the low runoff year of 2007, the 3 pools along with station BR (immediately below the rock bar) had similar exposure durations and comparable tracer levels over the 0 to 30th percentile exceedance range. However, there was a divergence above the 30th percentile with tracer levels decreasing markedly for pools K3 and K2 relative to pool K1 and station BR. In large part this was an artefact of the substantially increased duration of relatively elevated tracer levels (0.15 or 15% excess groundwater composition) at pool K1 and below the rock bar (station BR) from mid-April to mid- to end of May after the final wet season flow event. Stations DS (downstream of the sand bar) and UE (upstream of the confluence with Sandy Creek) had considerably lower tracer levels;
- The time series plots of the WPF stormwater tracers indicate:
    - Typically stormwater tracers were readily flushed through the system. As the response of the WPF stormwater and external Border Creek catchment is more rapid than the Keep River catchment, generally peak stormwater tracer levels preceded peak flows from the Keep River. The typically longer duration of flows in Keep River served not only to dilute the remnant Border Creek and WPF stormwater water volumes, but also effectively flushed the pools and upper estuarine portions of the system;
    - Peak tracer levels of 0.08 (8% stormwater composition) occurred for short durations (days to a week) during the high runoff year of 2006;
    - Under certain conditions stormwater can comprise a significant proportion of the water volume in the pools and upper estuary as exemplified by the following 2 cases:

- From mid-February to mid-March 2006 tracer levels over 5-6 weeks were approximately or greater than 0.02 (>2% stormwater composition) and as high as 0.06-0.08 (6-8%) in the pools and estuary;
- A higher proportion of WPF stormwater resulted after the 2 consecutive small rainfall events at the end of January and beginning of February 2007, which induced a several day period when peak levels of 0.2-0.25 (20-25%) of the water volume was comprised of stormwater in the pools. A relatively elevated proportion of stormwater (>5%) persisted for approximately 3 weeks thereafter;
- These types of events occur when on-farm stormwater storage is at capacity and small rainfall events generate stormwater flows from the WPF with limited dilution by the external Border Creek catchment and upper Keep River. This is illustrated in Table 10 where the early February 2007 event generated a modest 8 GL of stormwater that was diluted with 24 GL of Border Creek flow and only an additional 8 GL of Keep River flow;
- The duration of these relatively elevated proportions of stormwater flow in the pools and upper estuary are largely dependent on the timing of the next flushing flow event;

- The probability exceedance plots of the stormwater tracers indicate:
  - During the high runoff year of 2006, the 3 pools and 3 upper estuarine stations had very similar exposure durations and comparable tracer levels. Stormwater tracers were nearly zero at the 40th percentile exceedance; and
  - In contrast, the impact of high tracer levels (~0.25 or 25%) from the atypical high stormwater event in early February 2007 yielded substantive differences below the 20th percentile exceedance. However, for the 20th percentile and higer exceedance values, all 6 stations had similar exposure durations and comparable tracer levels. Stormwater tracers were nearly zero at the 50th percentile exceedance.

Figure 34 Time series of groundwater (upper panel) and stormwater (middle panel) tracers, and probability exceedance plots for groundwater (lower left panel) and stormwater (lower right panel) tracers during 2006. Blue line in top panel delineates the period over which probability exceedance calculated since the first storm of the wet season.

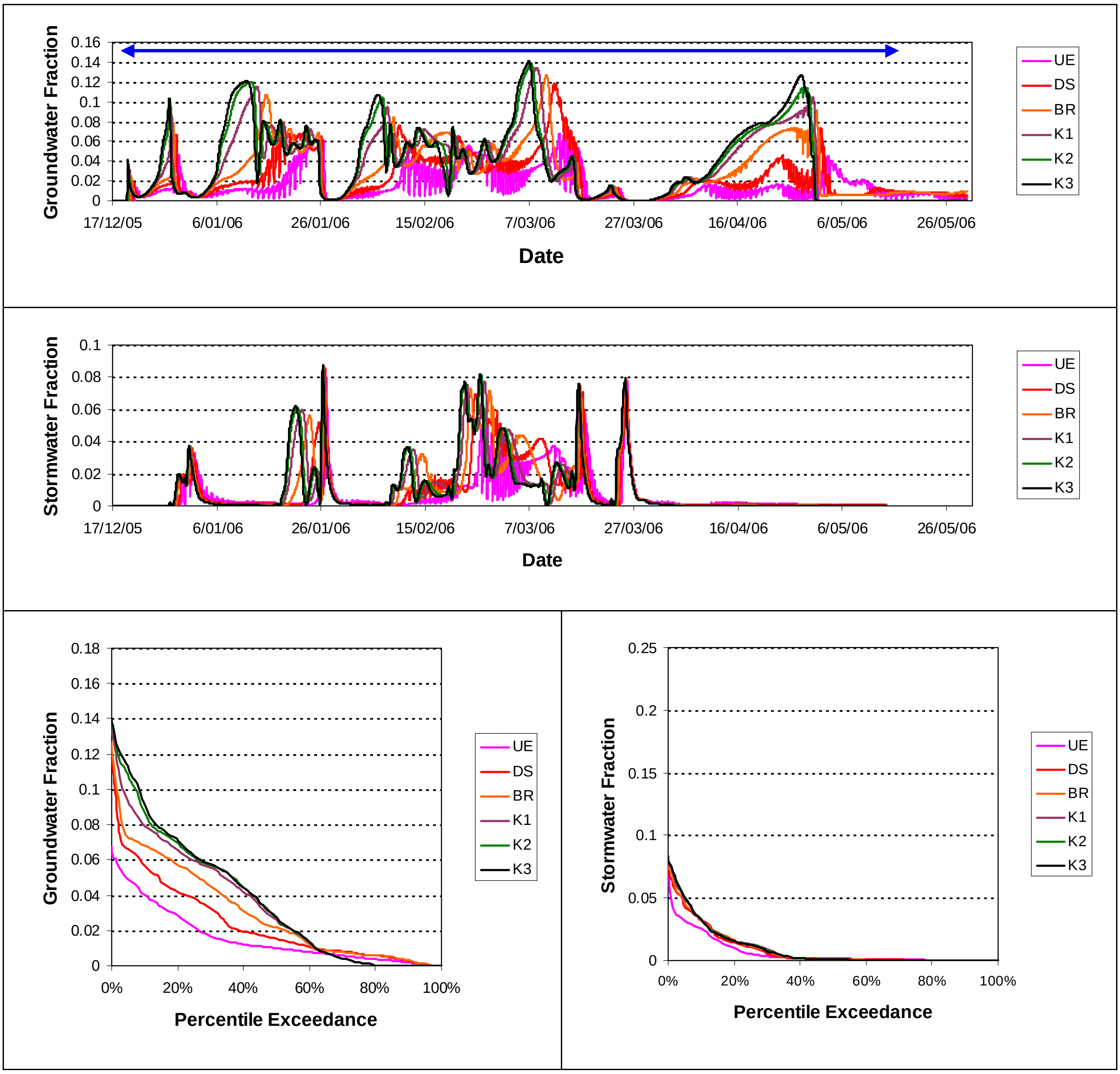
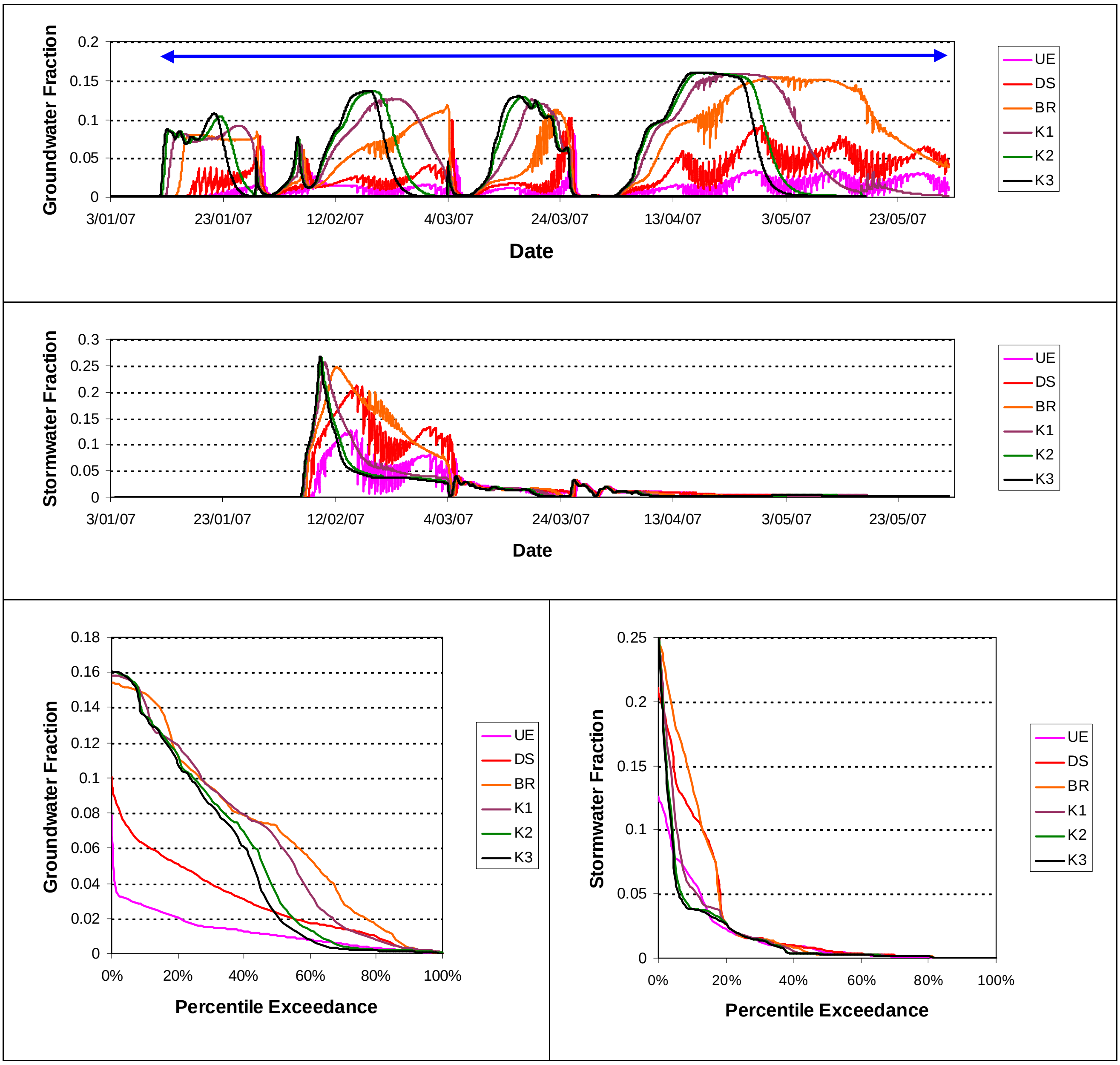


Figure 35 As Figure 34 for 2007.

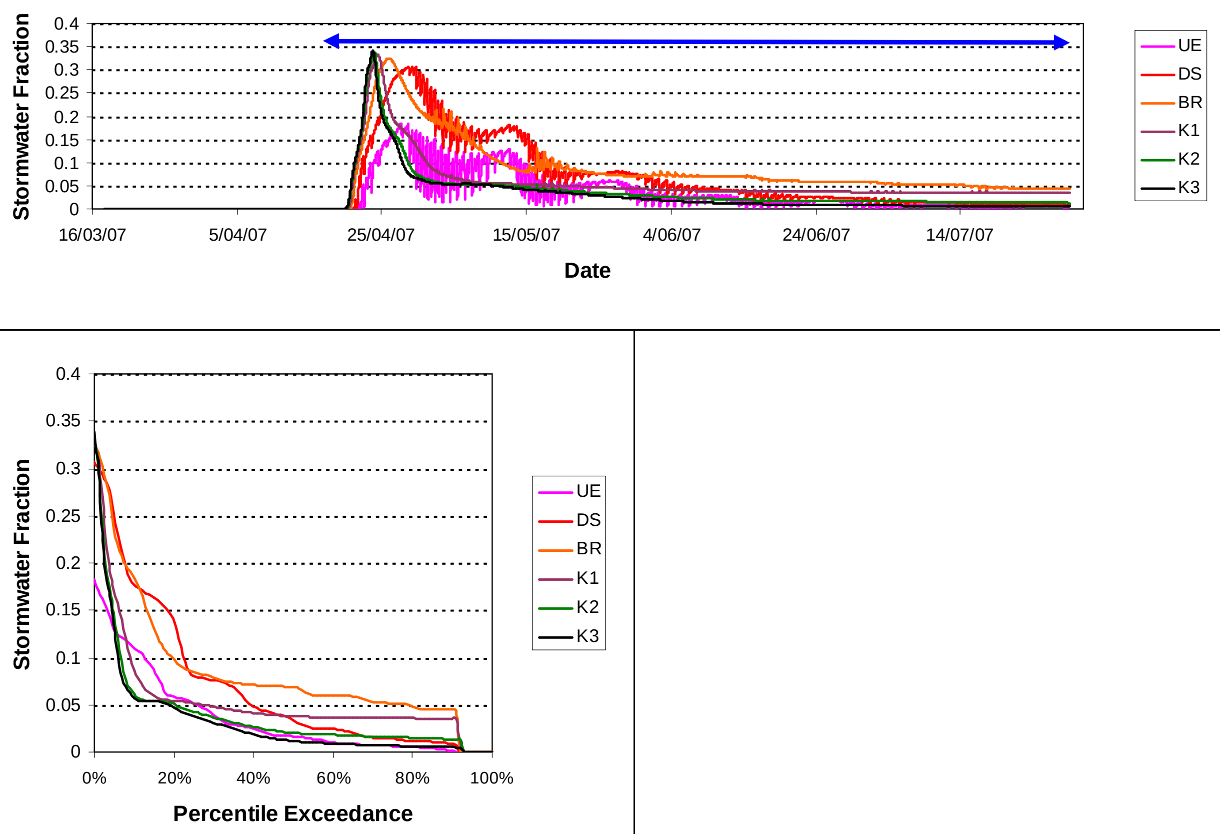


Worst Case Stormwater Scenario

Next, a simulation of the sequence of rainfall events during late January and early February 2007 that led to the high stormwater proportion in the pools and upper estuary (~25%) is evaluated as if it had occurred at the end of the wet season with no subsequent riverine flushing flow events. The sequence of these two flow events were simulated assuming their occurrence late in the wet season (mid-April) with no subsequent flow events and a baseflow of 0.025 m^3/s by the beginning of July. The time series and probability exceedance of simulated tracers (Figure 36) demonstrated the following:

- The stormwater tracer in the pools decreased to less than 0.05 (5%) in approximately 15 days; and
- The stormwater tracer persisted at 0.05 (5%) below the rock bar (station BR), 0.04 (4%) at pool K1, and less than 0.015 (<1.5%) at all other locations by the end of the simulation.

Figure 36 Time series (upper panel) and probability exceedance (lower panel) plots of stormwater tracers during the 2007 worst case scenario. Blue line in top panel delineates the period over which probability exceedance calculated since the onset of stormwater tracer into the model domain.



Characteristic Stormwater and Groundwater Proportions in Pools and Estuary on May 31

Table 12 and Table 13 provide a summary of the simulated stormwater and groundwater tracers in the 3 pools and upper estuary locations on May 31 at the end of both simulations. This end date was purposefully selected because:

- It is 1 month after the final allowable day in the simulations to release groundwater into the Keep River; and
- This is assumed to be the onset of the dry season. Critical evaluation of the water quality at this time is needed as the occurrence of any further dry season riverine flushing flow events is unlikely.

Tracers of the proportion of Keep River and external Border Creek waters were also tracked in the 3 pools and upper estuary during the simulations and are also reported in these tables.

Table 12 Groundwater and stormwater tracer levels (as percentage composition of water type) at the start of the 2006 dry season (May 31). Keep River and Border Creek tracer levels also reported.

Percentile Exceedance	K3	K2	K1	BR	DS	UE
Groundwater Proportion	0.0%	0.0%	0.0%	0.9%	0.5%	0.3%
Stormwater Proportion	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Keep River Proportion	61.1%	62.2%	63.6%	49.6%	17.1%	7.9%
Border Creek Proportion	38.9%	37.8%	36.4%	46.8%	22.7%	9.7%

Table 13 As Table 12 for 2007.

Percentile Exceedance	K3	K2	K1	BR	DS	UE
Groundwater Proportion	0.0%	0.1%	0.2%	4.0%	4.2%	1.4%
Stormwater Proportion	0.2%	0.2%	0.3%	0.3%	0.1%	0.1%
Keep River Proportion	65.1%	66.0%	66.4%	75.2%	33.8%	11.7%
Border Creek Proportion	34.9%	34.0%	33.6%	23.3%	5.4%	1.7%

The pools all had similar compositions of Keep River and Border Creek waters at the end of the simulation for both high and low runoff years. However, the proportion of Keep River waters was higher and Border Creek waters lower at the 3 estuarine stations during 2007 (low runoff year) than 2006 (high runoff year).

Importantly, the stormwater tracer levels at all 6 stations were zero and the groundwater tracers were less than 1% during the high runoff year of 2006. In contrast, though the stormwater tracers at all 6 stations are less than 0.4% during the low runoff year of 2007 along with the groundwater tracers in the 3 pools, relatively elevated groundwater tracers levels of 4% were predicted in the upper estuary below the rock bar (BR) and downstream of the sand bar (DS) stations.

7. Potential Water Quality Impacts from Excess Groundwater and Stormwater

Table 8 in section 4.2 provides a summary of the characteristic concentrations of TDS, TN, TP, atrazine and endosulfan that occur in the excess pumped groundwater, WPF stormwater, Keep River and the external Border Creek catchment. These water quality concentrations and the simulated tracer levels were used to estimate the water quality over the simulation period. Tracers were simulated to track the proportion of these 4 types of water throughout the 3 pools (K3, K2 and K1) and 1 of the upper estuary stations (station BR). Estimates of the water quality at each of these 4 locations were estimated as:

$$C = C_{GW}T_{GW} + C_{SW}T_{SW} + C_{KR}T_{KR} + C_{BC}T_{BC}$$

where C is the concentration of a substance (TN, TP, TDS) at a station, C_i is the characteristic water quality concentration of the source water, T_i is the tracer value (i.e. the proportion of the source water i at the station), GW is the groundwater source, SW is the stormwater source, KR is the Keep River source, and BC is the Border Creek source. For example, supposing at a station the composition of the source water was T_{GW}=0.05, T_{SW}=0.02, T_{KR}=0.7, and T_{BC}=0.23; then the estimated TN would be:

$$C = 1.30mg/L \times 0.05 + 0.54mg/L \times 0.02 + 0.15mg/L \times 0.7 + 0.235mg/L \times 0.23$$

which gives an estimated TN of 0.235 mg/L.

This approach was applied to the hourly outputs at each of the six locations to derive a time series of TN, TP and TDS estimates. Atrazine and endosulfan were not evaluated because characteristic stormwater concentrations were below the ANZECC & ARMCANZ (2000) 99% species protection trigger levels (see Table 8 in section 4.2). The 20th, 50th and 80th percentile exceedances were computed from the derived hourly TN, TP and TDS time series at the 3 pools (K1, K2, K3) and below the rock bar (station BR) as summarised in Table 14 and Table 15 for high (2006) and low (2007) runoff years, respectively. These percentile exceedances were selected because:

- The 20th percentile exceedance represents the minimum concentration that occurs for a cumulative total of 1 month over the 5 month wet season assessment period;
- The 50th percentile exceedance represents the minimum concentration that occurs for a cumulative total of 2.5 months over the 5 month wet season assessment period; and
- The 80th percentile exceedance represents the minimum concentration that occurs for a cumulative total of 4 months over the 5 month wet season assessment period.

The TN, TP and TDS on May 31 are also reported, which corresponds to the onset of the dry season. Hence comparisons to trigger values are critical at this time as no subsequent flushing flows from the Keep River (or Border Creek) are anticipated.

Estuarine stations DS and UE were not included because they had a strong marine/estuarine water influence (composition). As no water quality data (i.e. TN or TP) were available to characterise these waters, these stations were excluded from this water quality assessment.

Recognising that groundwater releases may not occur for several years after the implementation of the development, Table 16 and Table 17 provide the water quality assessment for the occurrence of only stormwater inputs and no groundwater releases into the Keep River.

Table 14 Predicted TN, TP and TDS for the preferred option at pools and upper estuary (BR) for 2006 where bold red indicates exceedance of the single or upper trigger value, and bold indicates exceedance of the lower trigger value only.

Percentile Exceedance		Cumulative Duration	K3	K2	K1	BR
TN						
	20%	1 month	0.29	0.28	**0.28**	**0.27**
	50%	2.5 months	0.24	0.24	0.24	0.22
	80%	4 months	0.19	0.19	0.19	0.19
On May 31			0.18	0.18	0.20	0.21
ANZECC & ARMCANZ (2000) trigger values			0.30	0.30	0.25	0.25
TP						
	20%	1 month	**0.016**	**0.016**	0.015	0.015
	50%	2.5 months	**0.013**	**0.013**	0.013	0.012
	80%	4 months	**0.011**	**0.011**	0.011	0.011
On May 31			0.010	0.010	0.010	0.010
ANZECC & ARMCANZ (2000) trigger values			0.010	0.010	0.020	0.020
WRM (2010c) upper interim trigger value			0.020	0.020		
TDS						
	20%	1 month	266	263	257	246
	50%	2.5 months	219	219	217	205
	80%	4 months	176	176	176	176
On May 31			167	167	162	166
Lower interim site specific trigger value			675	675	675	675
Upper interim site specific trigger value			1,275			

Table 15 As Table 14 for 2007.

Percentile Exceedance		Cumulative Duration	K3	K2	K1	BR
TN						
	20%	1 month	**0.34**	**0.34**	**0.35**	**0.36**
	50%	2.5 months	0.21	0.23	**0.28**	**0.29**
	80%	4 months	0.18	0.18	0.19	0.19
On May 31			0.18	0.18	0.18	0.22
ANZECC & ARMCANZ (2000) trigger values			0.30	0.30	0.25	0.25
TP						
	20%	1 month	**0.020**	**0.020**	**0.021**	**0.021**
	50%	2.5 months	**0.013**	**0.014**	0.015	0.016
	80%	4 months	0.010	0.010	0.011	0.012
On May 31			0.010	0.010	0.010	0.013
ANZECC & ARMCANZ (2000) trigger values			0.010	0.010	0.020	0.020
WRM (2010c) upper interim trigger value			0.020	0.020		
TDS						
	20%	1 month	334	341	351	347
	50%	2.5 months	207	225	271	276
	80%	4 months	173	175	183	201
On May 31			167	168	170	227
Lower interim site specific trigger value			675	675	675	675
Upper interim site specific trigger value			1,275			

Table 16 As Table 14 for stormwater only (no groundwater releases) during 2006.

Percentile Exceedance		Cumulative Duration	K3	K2	K1	BR
TN						
	20%	1 month	0.21	0.21	0.21	0.21
	50%	2.5 months	0.18	0.18	0.18	0.17
	80%	4 months	0.16	0.16	0.16	0.16
On May 31			0.18	0.18	0.20	0.21
ANZECC & ARMCANZ (2000) trigger values			0.30	0.30	0.25	0.25
TP						
	20%	1 month	**0.011**	**0.011**	0.011	0.011
	50%	2.5 months	0.010	0.010	0.010	0.010
	80%	4 months	0.010	0.010	0.010	0.010
On May 31			0.010	0.010	0.010	0.010
ANZECC & ARMCANZ (2000) trigger values			0.010	0.010	0.020	0.020
WRM (2010c) upper interim trigger value			0.020	0.020		
TDS						
	20%	1 month	169	169	169	169
	50%	2.5 months	160	160	160	162
	80%	4 months	152	152	154	156
On May 31			167	167	162	156
Lower interim site specific trigger value			675	675	675	675
Upper interim site specific trigger value			1,275			

Table 17 As Table 14 for stormwater only (no groundwater releases) during 2007.

Percentile Exceedance		Cumulative Duration	K3	K2	K1	BR
TN						
	20%	1 month	0.19	0.19	0.20	0.20
	50%	2.5 months	0.18	0.18	0.18	0.17
	80%	4 months	0.16	0.16	0.16	0.16
On May 31			0.18	0.18	0.18	0.17
ANZECC & ARMCANZ (2000) trigger values			0.30	0.30	0.25	0.25
TP						
	20%	1 month	**0.012**	**0.012**	0.012	0.012
	50%	2.5 months	0.010	0.010	0.010	0.010
	80%	4 months	0.010	0.010	0.010	0.010
On May 31			0.010	0.010	0.010	0.010
ANZECC & ARMCANZ (2000) trigger values			0.010	0.010	0.020	0.020
WRM (2010c) upper interim trigger value			0.020	0.020		
TDS						
	20%	1 month	176	176	177	177
	50%	2.5 months	171	171	172	172
	80%	4 months	167	168	168	166
On May 31			167	167	167	167
Lower interim site specific trigger value			675	675	675	675
Upper interim site specific trigger value			1,275			

An overview of this water quality assessment includes:

- For the combined stormwater and preferred groundwater release option:
  - All stations and both years were predicted to below the lower TDS trigger value of 675 mg/L for the 20th, 50th and 80th percentile durations on May 31;
  - All 4 locations for both years were predicted to be at or below the TN and the lower TP trigger values at the onset of the dry season on May 31;
  - The 20th percentile exceedance (at least 1 cumulative month over the 5 month wet season simulation) was slightly (5-15%) to moderately (40-100%) above the TN and the lower TP trigger values during both years, except for:
    - TP at stations K1 and BR;
    - TN at pools K3 and K2 during the high runoff year of 2006;
    - TP in pools K3 and K2 though above the lower trigger value (ANZECC & ARMCANZ 2000) were below the upper trigger value (WRM 2010c);
  - The 80th percentile exceedance (at least 4 cumulative months over the 5 month wet season simulation) was slightly (10%) above the lower TP trigger value (ANZECC & ARMCANZ 2000) at pools K3 and K2 during the high runoff year of 2006, but well below the higher TP trigger value (WRM 2010c);
  - The 50th percentile exceedance (at least 2.5 cumulative months over the 5 month wet season simulation) was moderately (30-40%) above the lower TP trigger value (ANZECC & ARMCANZ 2000) at pools K3 and K2 during the low runoff year of 2007, but well below the higher TP trigger value (WRM 2010c);
  - The 50th percentile exceedance (at least 2.5 cumulative months over the 5 month wet season simulation) was slightly (10-15%) above the TN trigger value at pool K1 and below the rock bar (BR) during the low runoff year of 2007;
- If only stormwater overflows occur with no groundwater releases then:
  - All 4 locations for both years were predicted to be at or below the TN, the lower TDS and the lower TP trigger values at the onset of the dry season on May 31;
  - The only 20th percentile exceedance (at least 1 cumulative month over the 5 month wet season simulation) was for TP at pools K3 and K2 during both the high (2006) and low (2007) runoff years, which was slightly (20%) above the lower TP trigger value (ANZECC & ARMCANZ 2000), but well below the higher TP trigger value (WRM 2010c); and
  - All other stations during both years were below the TN and lower TDS trigger values for the 20th, 50th and 80th percentile exceedances.

The lower TP trigger value (ANZECC & ARMCANZ 2000) will only be met in the pools with the occurrence of low proportions of stormwater and groundwater, because it is equivalent to the characteristic TP concentration of the Keep River and Border Creek of 0.01 mg/L. In contrast, because the characteristic TN concentrations of the Keep River (0.15 mg/L) and Border Creek (0.235 mg/L) are well below the trigger value (i.e. 0.3 mg/L in pools K1 and K2, and 0.25 mg/L in pool K1 and upper estuary), a greater proportion of stormwater and groundwater in the pools and upper estuary does not cause an exceedance for TN. Similarly, exceedance of the upper TP trigger value (WRM 2010c) is approximately 1 cumulative month over the 5 month simulation period only for the low runoff year, when a higher proportion of groundwater with a TP of 0.07 mg/L is predicted to occur.

8. Summary and Conclusions

The catchment-river modelling indicates that stormwater from the farmlands area is diluted in the WPF prior to undergoing further dilution with Border Creek and Keep River. The peak proportion of stormwater during any particular event generally occurs in advance of the Keep River peak discharge, and then decreases with the arrival of the elevated flow from this primary river.

Discharge of mildly saline groundwater (3,000 mg/L TDS) into the Keep River and maintenance of instantaneous peak TDS below 675 mg/L at the point of release yields 3.7 GL and 3.0 GL of total groundwater discharge during high (2006) and low (2007) runoff years. Increasing the maximum groundwater release rate from 0.5 m^3/s (500 L/s) to 0.65 m^3/s (650 L/s) during 2007 would yield a predicted total groundwater release of 3.6 GL.

The Keep River bathymetry was approximated with remote sensing data, limited longitudinal depth data and relatively coarse coastal bathymetric data. Further, incorporation of the floodplain above pool K1 utilised reasonable quality 25K aerial photogrammetry, whereas below pool K1 reliance was on a 250K coarse map. Hence, the resultant bathymetry and floodplain for the hydrodynamic modelling is considered an approximation. Nonetheless, comparisons of simulated and measured tidal levels at 3 upper estuary locations indicated the model captured water level variations well during the dry season.

The hydrodynamic modelling indicates that the flushing during the wet season in the Keep River is primarily influenced by catchment flow events and secondarily by tidal dynamics. The tidal dynamics in the river are highly dependent on the bathymetry with the shallow water regions dampening the tides as they propagate upstream. Given these observations, an improved representation of the Keep River bathymetry would improve confidence in simulations of tidally induced flushing. However, during the wet season the need for accurate bathymetry is lessened because of the dominance of riverine flushing through the lower Keep River system.

Hydrodynamic simulations of the ‘controlled’ release of excess groundwater into the Keep River during the wet season on the basis of TDS thresholds (i.e. instantaneous dilution to <675 mg/L TDS) can yield up to 7% (high runoff year) to 11% (low runoff year) of this water type in the pools for 1 cumulative month over the 5 month simulation duration (i.e. 20% of the wet season). Excess groundwater is flushed out of the pools during both high and low runoff years within a month of cessation of releases on April 30. Typically at the onset of the dry season on June 1, stormwater and groundwater proportions are below 1% of the pool volumes.

Hydrodynamic simulations of WPF stormwater overflows into Border Creek during the wet season predict 1.5% (high runoff year) to 2.5% (low runoff year) of this water type in the pools for 1 cumulative month over the 5 simulated months (i.e. 20% of the wet season). Stormwater is generally flushed out from the pools by the longer duration of Keep River discharge relative to Border Creek and WPF stormwater runoff after flow events. At the onset of the dry season the proportion of stormwater in the pools is well below 1% except under an atypical hydrological sequence.

This sequence occurs when the on-farm stormwater storage capacity is full, and a small rainfall event generates stormwater overflow into Border Creek. Under these conditions of low runoff from the external Border Creek and Keep River catchments, low dilution prior to the pool K3 occurs that results in a large proportion of the pools comprised of stormwater. Subsequent flow events effectively flush the pools. A model run was carried out to predict the case where this sequence of hydrological events occurs at the end of the wet season (mid-April) without any subsequent flushing riverine flows. The model run indicated that approximately 1.5-4% of the pools and upper estuary are comprised of stormwater by the end of July in the midst of the dry season.

TN and TP estimates in the pools and upper estuary over the wet season were typically slightly (~20%) to moderately (~50%) greater than the ANZECC & ARMCANZ (2000) default trigger values for 1 to 2.5 cumulative months over the 5 month simulation with the proposed groundwater release option. The exceedance of an interim site specific TP trigger value of 0.02 mg/L (WRM 2010c) reduces the duration of exceedance from 2.5-4 months to 0-1 month. For the case of stormwater discharge only (i.e. prior to the need for groundwater pumping), TP (not TN) is slightly (~10%) above the ANZECC & ARMCANZ (2000) default trigger value only in the upper 2 pools (K3 and K2) with no exceedance of the upper trigger value of 0.02 mg/L. For both cases (with and without groundwater release) at the onset of the dry season there are no anticipated water quality issues as the pools and upper estuary are comprised primarily of Keep River and Border Creek water. Atrazine and endosulfan have been detected in irrigation waters in the D4 drain, but the appropriate characteristic concentrations are below the relevant ANZECC & ARMCANZ (2000) 99% species protection trigger levels. TDS is predicted to not be a water quality issue, as it is typically well below the lower interim site specific trigger value of 675 mg/L.

9. Recommendations

Because the primary influence of flushing of WPF stormwater and excess groundwater from the Keep River system is river flow, reduction of risks can be accomplished in the following manner:

- Carry out wet season monitoring of Border Creek and Keep River upstream of Legune Road crossing to improve characterisation of typical concentrations of these source waters;
- Carry out wet season monitoring of the groundwater and WPF stormwater quality once the development is implemented to verify the use of current D4 drain water quality and Ivanhoe groundwater quality data as surrogates to characterise water quality of releases from the development;
- Tidal flushing and dilution below the rock bar is strongly controlled by the bathymetry of the rock bar, sand bar and reaches upstream of the confluence with Sandy Creek. Further, there is currently a lack of bathymetric information for pools K2 and K3. Collection of bathymetric data would improve confidence in the hydrodynamic simulations. However, the current modelling does predict that regardless of the bathymetry, stormwater and groundwater in the pools are readily flushed even in low runoff years;
- The following operational strategies can prevent or mitigate elevated stormwater or groundwater proportions in the pools at the onset of the dry season:
  - Groundwater releases during the tail of late wet season flow events need to be managed carefully with lower release rates than the beginning and middle portion of the wet season; and
  - Pool K3 can be flushed by releasing M2 water into Border Creek or Keep River if the proportion of stormwater or excess groundwater is deemed excessive in this or further downstream pools.

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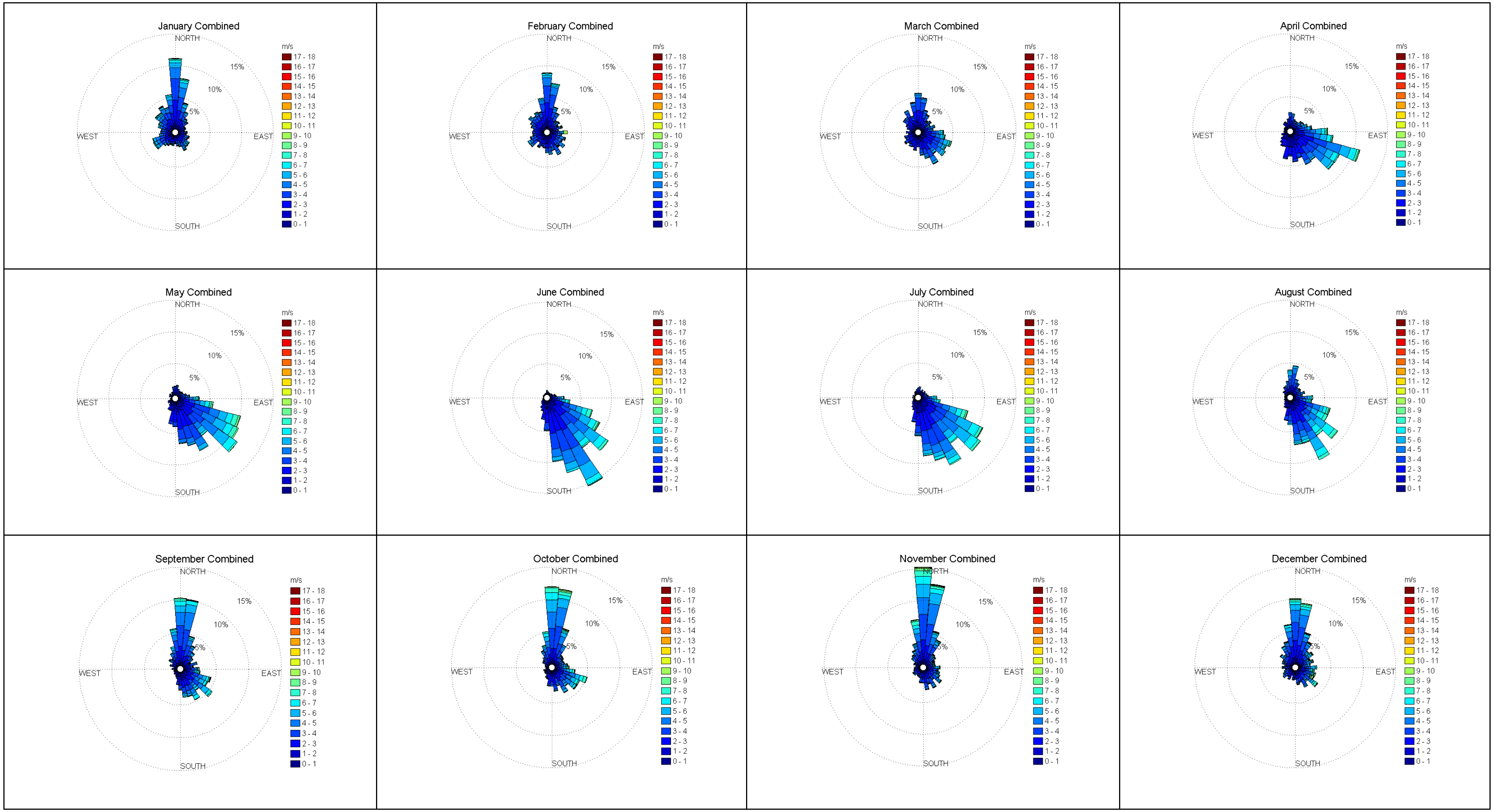
Appendix A

Wind Roses

Based on half-hourly wind data between 1993 and 2010 as sourced from BoM station 2056 (Kununurra Airport)

Figure 37 Appendix A: Monthly wind roses



Appendix B

Importance of Evapo-concentration in Pool K3

Keep River Pool K3 Box-Model

Keep River Pool K3 Box-Model

Dry Season Mass Balance Modelling of Keep River Pool K3

Pool K3 on the Keep River is at the upper end of the tidally influenced portion of the river. The pool is approximately 2.25 km long, 10–40m wide, and has an average depth of approximately 3.9 m (KBR 2006).

During the dry season, flows along the Keep River are limited. Flows recorded at the Northern Territory Department of Natural Resources, Environment and the Arts (NRETA) station G8100225, upstream of pool K3, indicate flow rates of 10,000 – 20,000 m^3/day (0.11 – 0.23 m^3/s) since the 2004 dry season. However, the accuracy of these dry season low flow measurements . is questionable.

Hence, a dry season discharge of approximately 0.025 m^3/s on the basis of recent (July, August and September 2010) measurements (D. Bennett, pers. comm.) for the Keep River at Legune Road crossing (station G8100225) was used here.

In this section, a simple mass balance approach is used to determine the potential for evapo-concentration in pool K3.

Current Potential for Evapo-concentration

Evapo-concentration occurs when a water mass containing salts undergoes evaporation. As water is removed, the salts (which do not evaporate) increase in concentration in the reduced water mass. The effect is most pronounced in terminal systems or systems where evaporation is large compared to inflows and outflows. As dry season flow rates in the Keep River are low, the potential for significant evapo-concentration is investigated.

An analysis of Class A Pan Evaporation data extracted from the Bureau of Meteorology SILO system indicates an average dry season evaporation rate of 7.48 mm/day. This is very close to the average dry season evaporation of 7.55 mm/day recorded at the Kimberley Research Station. For the purposes of this discussion, an evaporation rate of 7.5 mm/day has been assumed.

To estimate the evaporation from pool K3, an estimate of the surface area is required. Mapping from a scaled photo and GIS yielded a pool area of 72,000 m^2.

Using this estimate, evaporation can be estimated using the area and the average evaporation rate. Using an area of 72,000 m^2 and an average evaporation rate of 7.5 mm/day, evaporative losses from pool K3 are estimated as 540 m^3/day. Evaporation from water bodies often occurs at a rate lower than that predicted by the Class A Pan evaporation rate. Increasing the evaporation rate by 50% yields an evaporation rate of 810 m^3/day.

This estimated rate of evaporation from pool K3 is 25-33% of the dry season flow rate (2,160m^3/day), and hence significant evapo-concentration is not expected to occur.

GHD

GHD House, 239 Adelaide Tce. Perth, WA 6004
P.O. Box 3106, Perth WA 6832
T: 61 8 6222 8222   F: 61 8 6222 8555   E: permail@ghd.com.au

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