Managing Water Quality to Enable Future Irrigation Development in the Kimberley Region

Three-Dimensional Hydrodynamic Modelling to Evaluate the Effect of Farm Chemicals on the Lower Pools of the Keep River

Department of Primary Industries and Regional Development

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→ The Power of Commitment

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Executive Summary

The National Water Grid Authority awarded the Department of Primary Industries and Regional Development a project entitled ‘Managing Water Quality to Enable Future Irrigation Development in the Kimberley Region’. The purpose of the project is to review the current and future risk profile of agrichemicals (pesticides) in the Keep River catchment (Ord - East Kimberley) in the context of irrigation development across the last decade and proposed in the medium term. The results of the review were to define prospective mitigation and risk management practices, which were developed in consultation with the Goomig and Knox Plains Independent Review Group and local agricultural community. One element of this funding was to update an existing numerical hydrodynamic model of the lower Keep River system to improve understanding of the implications of current and future agricultural practices.

This investigation builds on a previous 2011 modelling assessment of the lower Keep River system with the following key improvements:

– Inclusion of a 2014 bathymetry survey of the lower Keep River system.
– Use of spatially varying winds and the inclusion of additional meteorology inputs (shortwave-longwave radiation, temperature, humidity, pressure, rainfall) to allow simulation of water temperatures.
– Spatial and temporal varying currents, water temperatures and salinities along the open ocean model boundary.
– Use of several ‘actual’ hydrology events representative of high risk chemical toxicity conditions to the lower Keep River pools at the end of the wet season and at any time during the dry season.
– Incorporation of a chemical module to simulate the transport, dispersion and degradation of farmland chemicals that are released into the lower Keep River system.

The focus of the investigation was on four (4) pools in the lower Keep River system. The upper pool (K4) is not tidally influenced, however the other three (3) pools are. Any farmland discharge from the existing Goomig farmlands flows into Border Creek and then to pool K3 (the uppermost tidally influenced pool). Any discharge from the future Knox Plains farmlands will flow into the Keep River and then pool K4 (not tidally influenced).

Hydrodynamic simulations were run from March-November 2019. This period was preceded by the lowest discharge water year (July-June) in the past 24 years. The 2013 dry season was preceded by the second lowest discharge water year, and had measurements of water level, temperature and salinity in the three (3) tidal pools. Given the similarity in preceding hydrological conditions, the 2013 measurements were compared to the 2019 simulations to verify the hydrodynamic model. The simulated and measured water levels, water temperatures and salinities in these three (3) pools compared well.

There was an unplanned farmland tailwater release incident into Border Creek with concomitant releases of irrigation water to mitigate elevated atrazine levels in the lower Keep River pools from July-October 2019, which was regularly monitored in the creek and three (3) tidally influenced pools. Hydrology and chemical concentration model inputs were estimated from the available data. The hydrodynamic-chemical simulations compared well with the measured atrazine levels in the three (3) tidally influenced pools.

A number of scenarios were then run with the hydrodynamic-chemical model to improve understanding of the interaction between chemical releases, transport and dispersion in and between the pools, chemical degradation rates, and mitigation measures (i.e. primarily flushing with good quality irrigation water). Recommendations and guidance for consideration in the management of farmland chemical risks of the lower Keep River system for such events and incidents on the basis of the scenario modelling include:

– Where possible, use chemicals with rapid degradation rates (shorter half-lives) and/or lower toxicity as this substantially decreases the ecological risks to the lower Keep River system. It is recommended that the use of persistent (long half-lives) **‘and’** high toxicity chemicals, such as metolachlor, be discontinued and replaced with suitable alternatives.
– If the volume of farmland chemicals released to the lower Keep River system is small and largely contained in the two (2) upper pools (K3, K4), consider natural degradation as a management option (i.e.

do nothing but monitor) if the chemical rapidly degrades with concentrations in the pool(s) that are not much greater than the relevant environmental criteria. Under such conditions this may reduce risk of chemical exposure to the down-river K2 and K1 pools.

– For dry season incidents similar to July-October 2019 from the existing Goomig farmlands for chemicals with slow to moderate degradation rates that have relatively low toxicity, consider reducing the duration of flushing releases at ~50 megaliters per day (upper flushing discharge limit during the dry season) from ~2 months to ~1 month. However, if the chemical has relatively high toxicity, then flushing at ~50 megaliters per day for at least ~2 months is recommended.
– For slowly degrading chemicals in pools K3 and/or K4 with levels greater than relevant environmental criteria, release sufficient good quality irrigation water to flush high chemical concentrations well down-river of pool K1. If the lower reach of the Keep River is not flushed adequately, subsequent up-river tidal transport may pose a toxicity risk to pool K1 later in the dry season. Semi-quantitative guidelines in terms of the discharge rate and release duration of high quality irrigation water to flush the lower Keep River system are provided.
– In the event of an infrastructure failure incident with unplanned farmland water releases to Border Creek (from the Goomig farmlands) and/or Keep River (from the future Knox Plains farmlands), where possible identify alternative higher quality waters for preferential release.
– As pool K4 has no tidally induced flushing, it is particularly at risk from farmland releases from the future Knox Plains farmlands when Keep River flows are low (i.e. end of wet season and dry season). Periodic monitoring of pool K4 from the end of the wet season throughout the dry season is recommended to manage this risk.
– There was a lag of ~10 days in the release of M2 flushing flows after the start of the dry season incident. Similarly, a lag of ~10 days was assumed in the simulated M2 releases after the end of the high chemical loading event for the end of wet season event scenarios. Decreasing this flushing response lag time after such events/incidents will reduce toxicity risks to the lower Keep River system. An adaptive monitoring strategy over the end of the wet season is recommended when high risk hydrological events may occur in effort to reduce the flushing response (if needed) lag time.
– This investigation used concentration thresholds and cumulative exposure to evaluate toxicity risks to the lower Keep River system. It is recommended that numeric chemical exposure criteria are developed to improve quantification of toxicity risks to ecological receptors.
– Consider the use of the hydrodynamic-chemical modelling framework as a quasi-real-time decision support tool to assist with management of future incidents/events associated with farmland chemical risks to the lower Keep River system.

This report is subject to, and must be read in conjunction with, the limitations, assumptions and qualifications contained throughout the Report.

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Abbreviations and Acronyms

Abbreviation / Acronym	
3D	Three-dimensional
AHD	Australian height datum
ANZG	Australia and New Zealand Guidelines
CFSv2	Climate Forecast System, version 2
C_i	Concentration of chemical greater than PC99
cm	Centimeter
DHI	Danish Hydraulic Institute
DPIRD	Department of Primary Industries and Regional Development
E	Exposure
EC	Electrical conductivity
FM	Flexible mesh
GL	Gigaliters
hr	Hour
HYCOM	Hybrid Coordinate Ocean Model
L	Liter
LiDAR	Light Detection And Ranging
LoR	Limit of reporting
LSP	Level of species protection
m	Meter
m^3	Cubic meters
mg	Milligrams
MLD	Megaliters per day
mm	Millimeter
mS	Millisiemens
n	Number of water samples
N	Number of 30 minute model output time steps C_i greater than PC99
NCEP	National Centres for Environmental Prediction
NRETAS	NT Department of Natural Resources, Environment, the Arts and Sport
NT	Northern Territory
PC99	Concentration of a substance protective of 99% l of species
PDST	Pesticide Decision Support Tool for the sugar cane industry
ppb	Parts per billion
PPDB	Pesticide Properties DataBase
ppt	Parts per thousand
PSU	Practical Salinity Units (equivalent to ppt)
Q	Discharge
R	Rainfall
RH	Relative humidity
S	Second

Abbreviation / Acronym	
T	Temperature
WL	Water level
WQ	Water quality
Y	Year
°C	Degrees Celsius
µg	Microgram

1. Introduction

The National Water Grid Authority awarded the Department of Primary Industries and Regional Development (DPIRD) a project entitled 'Managing Water Quality to Enable Future Irrigation Development in the Kimberley Region'.

The purpose of the project is to review the current and future risk profile of agrichemicals (pesticides) in the Keep River catchment (Ord - East Kimberley) in the context of irrigation development across the last decade and proposed in the medium term. The results of the review were to define prospective mitigation and risk management practices to be developed in consultation with the Goomig and Knox Plains Independent Review Group and local agricultural community.

1.1 Purpose of this report

One element of this funding was to update an existing numerical hydrodynamic model of the lower Keep River system and to apply it to improve understanding of the implications of current and future agricultural practices of the existing Goomig and proposed Knox Plains farmlands. This report outlines the methodology and findings of the updated hydrodynamic modelling.

1.2 Scope of report

This report's scope is to provide key inputs into the review of the Keep River agrichemicals risk profile through the following tasks:

- Update and verify a past (GHD 2011) hydrodynamic model of the Keep River with recent available flow, survey and chemistry data.
- Evaluate mitigation and management options of key Keep River contaminants of concern to protected species through scenarios with the hydrodynamic model.

1.3 Limitations

This report has been prepared by GHD for DPIRD and may only be used and relied on by DPIRD for the purpose agreed between GHD and DPIRD as set out in Sections 1.1 and 1.2 of this report.

GHD otherwise disclaims responsibility to any person other than DPIRD arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report. GHD disclaims liability arising from any of the assumptions being incorrect.

GHD has prepared the three-dimensional (3D) Keep River hydrodynamic model ("Model") for, and for the benefit and sole use of, DPIRD to support this project's scope as defined in Section 1.2 and must not be used for any other purpose or by any other person.

The Model is a representation only and does not reflect reality in every aspect. The Model contains simplified assumptions to derive a modelled outcome. The actual variables will inevitably be different to those used to prepare the Model. Accordingly, the outputs of the Model cannot be relied upon to represent actual conditions without due consideration of the inherent and expected inaccuracies. Such considerations are beyond GHD's scope.

The information, data and assumptions ("Inputs") used as inputs into the Model are from publicly available sources or provided by or on behalf of the DPIRD (including possibly through stakeholder engagements). GHD has not independently verified or checked Inputs beyond its agreed scope of work. GHD's scope of work does not include review or update of the Model as further Inputs becomes available.

The Model is limited by the mathematical rules and assumptions that are set out in the Report or included in the Model and by the software environment in which the Model is developed.

The Model is a customised model and not intended to be amended in any form or extracted to other software for amending. Any change made to the Model, other than by GHD, is undertaken on the express understanding that GHD is not responsible, and has no liability, for the changed Model including any outputs.

GHD has prepared this report on the basis of information provided by DPIRD and others who provided information to GHD (including Government authorities)], which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

1.4 Assumptions

The following assumptions have been adopted in this modelling study:

– The bathymetry data of the Keep River system below the rock bar at the down-river end of pool K1 is uncertain and largely relies on the Gray and Williams (2006) longitudinal profile. The focus of this investigation is on the lower Keep River pools above the rock bar.

– The lower Keep River is a dynamic system with likely large changes in bathymetry due to seasonal and interannual sediment transport dynamics. This investigation does not address these changes and assumes a static bathymetry throughout the model domain. Small changes to the elevations of physical control points (e.g. rock bar and sand bar) can affect the tidally induced flushing of pools K1 to K3.

– There is insufficient information to tailor model inputs in terms of hydrology and chemical concentrations of the future Knox Plains farmlands. Here it is assumed that the release of farmland water from the future Knox Plains farmlands is the same as the Goomig farmlands. Similarly, when irrigation water supply via the M2 drain from the Ord Irrigation Cooperative is used as a mitigation measure to flush the lower Keep River pools, it is applied equally for scenarios that include both farmlands.

– Chemical degradation is modelled on the basis of literature half-life times at temperatures of ~25°C and pH ~7 with no modifications due to variations in temperature, salinity, turbidity, organic matter or any other constituents that may influence degradation rates. Turbidity levels are elevated in the lower Keep River pools (Bennett and George 2014) so that enhanced degradation rates from photolysis are not considered.

– The gauging station below the Goomig farmlands (DW1GS) measures flow from both farm and non-farm portions of the catchment (e.g. uncleared buffer and hills of the Pincombe Range). This will be similar in future for drainage waters that are released from the future Knox Plains farmlands. For the end of wet season scenarios considered in this investigation (small rainfall events when on-farm water retention infrastructure is at capacity), most of the releases from the farmlands are assumed to be from the farm portions of the catchment.

2. Data

2.1 Overview

The study area is located within the lower reaches of the Keep River catchment. 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 into the Joseph Bonaparte Gulf. The existing Goomig and future Knox Plains farmlands drain into the lower portion of the Keep River. Permanent water within the lower Keep River occurs in the tidal reaches that include a series of three sheltered pools down-river of Legune Road (pools K3, K2 and K1) that retain water during the dry season. Additionally, there is a pool above Legune Road bridge (pool K4) that retains water during the dry season. Border Creek is a major tributary in the lower Keep River system and it also receives Goomig farmland waters that are discharged primarily during the wet season via the DW1 drain. At the Border Creek confluence with pool K3, ~250 m north of Legune Road, the Keep River opens into a tidal water body ~50-100 m wide, which becomes progressively wider and more tidal towards the river mouth.

As Goomig farmland water discharges into Border Creek, the lower Keep River pools are of concern in terms of toxicity effects from agricultural chemicals. The fourth pool (K4) immediately up-river of pool K3 has the potential to be impacted by the future Knox Plains farmlands, but it is above the confluence of Border Creek with pool K3 and therefore is not affected by discharge from the Goomig farmland.

Table 2.1 provides summary of the locations and periods of available measurements that were used in this study, and Figure 2.1 spatially illustrates these locations.

Table 2.1 Overview of monitoring site locations, date range of measurements, and measurement parameters used in this investigation.

Station ID	Latitude GDA94 Zone 52	Longitude GDA94 Zone 52	Start	End	Frequency and Parameter(s)	Notes
Hydrology – rainfall (R) and discharge (Q)						
BoM 14803 (Legune Station)	548331	8318397	1-Jan-57	3-Oct-22	Daily R	
G8100106 (lower Border Creek)	501231	8297621	27-Jan-71	29-Nov-86	Sub-daily Q	Border Creek below DW1GS
			24-Oct-97	23-Oct-22		
G8100225 (Keep River at K4)	506915	8297031	11-Jan-65	8-May-86		Keep River at pool K4
			31-Oct-97	23-Oct-22		
DW1GS (drain DW1 existing Goomig farmlands)	494610	8296652	2-Aug-18	9-Jun-22		Discharge from farmlands
October-November 2004 water level (WL) measurements of lower Keep River pools						
G8100110	513573	8316477	11-Oct-04	14-Nov-04	Sub-daily WL	At Barramundi Flats (Gray & Williams 2006)
G8100111	513850	8306645	12-Oct-04	14-Nov-04		Down-river of Rock Bar (Gray & Williams 2006)
G8100109 (near K1)	508915	8303974	11-Oct-04	14-Nov-04		Up-river of Oakes Creek (Gray & Williams 2006)
2010-2014 WL, temperature (T), electrical conductivity (EC) and water quality (WQ) measurements of lower Keep River pools						
Border Creek (G8100106)	501231	8297621	13-Jun-10 (T) 15-Oct-10 (EC)	20-Jul-14 (T) 23-Oct-13 (EC)	Sub-daily T, EC ~Monthly WQ	Bennett & George (2014)
K4	506941	8297061	10-Jun-10	21-Jul-14		
K3	508469	8298138	9-Sep-10	20-Jul-14		
K2	509280	8300569	9-Sep-10	23-Jul-14		
K1 (near G8100109)	508923	8303810	8-Sep-10	22-Jul-14		
E3	513175	8316268	19-Nov-11	22-Jul-14		
2016-2022 WQ measurements of Border Creek, farmland drain (DW1GS) and irrigation channel (M2)						
Border Creek (G8100106)	501231	8297621	29-Nov-17	11-Sep-20	~2 days-1 week (17 July-22) WQ August 2019) ~Monthly to quarterly WQ at other times	Between with pool K3 and drain DW1
DW1GS	494610	8296652	21-Jun-16	16-Mar-22		Farmland drainage gauge
M2	492190	8292780	29-Jul-19	30-May-20		Irrigation channel releases

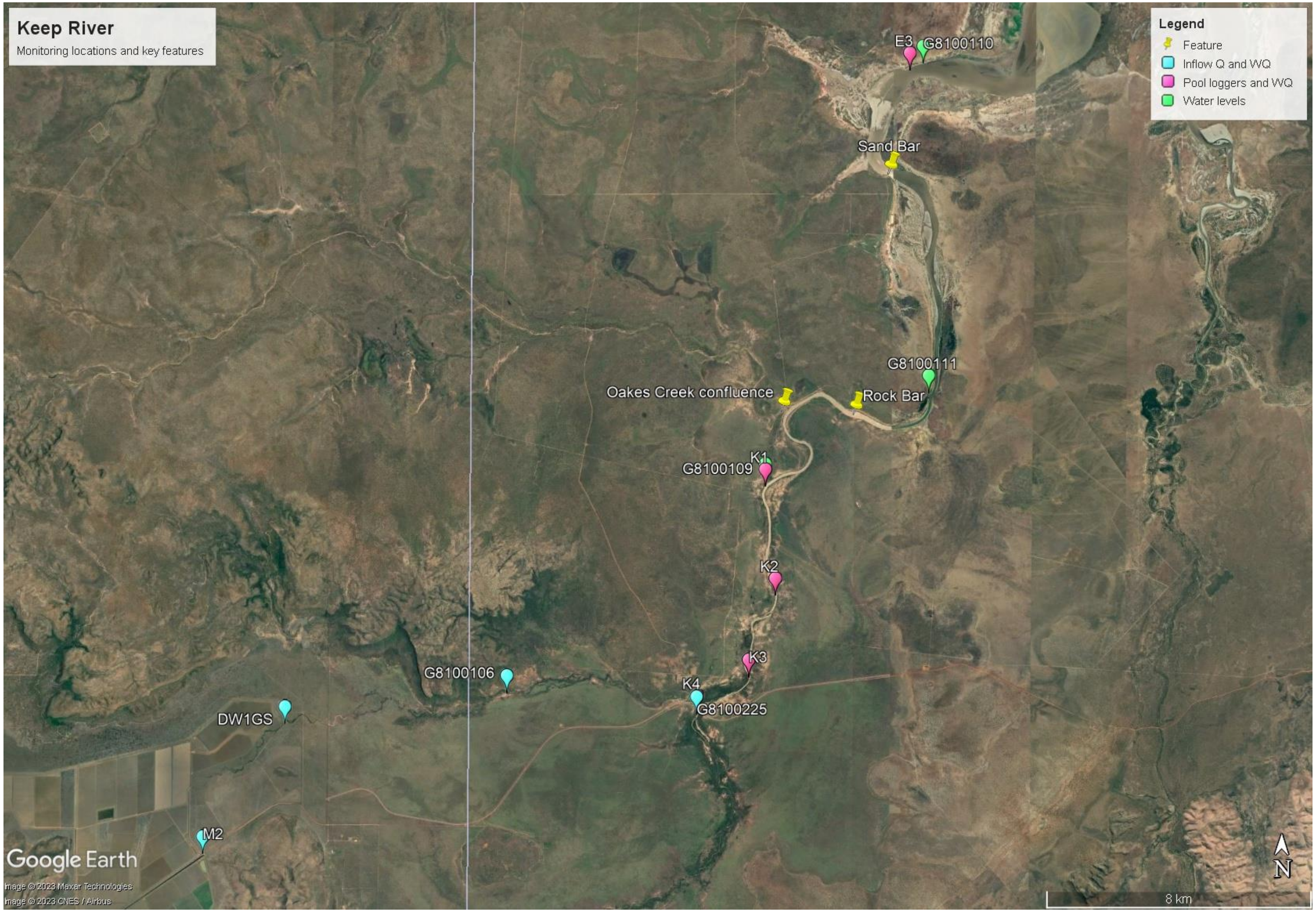

Figure 2.1 ***Satellite image of the lower Keep River catchment with locations of available measurements and key features (source: Google Earth).***

2.2 Hydrology

2.2.1 Discharge and rainfall

Two Northern Territory (NT) Natural Resources, Environment, the Arts and Sport (NRETAS) gauging stations on the Keep River system are located ~1 km up-river of the confluence with Border Creek at Legune Road (station number G8100225) and on Border Creek ~6 km upstream of the Keep River confluence (station number G8100106). Discharge data for the Keep River spans from November 1965-November 1986 and October 1997-October 2022; and for Border Creek from January 1971-November 1986 and October 1997-October 2021 (Figure 2.2). Keep River and Border Creek typically only flow during the wet season (~December-April). Discharge at both gauging stations during the first period of measurements during the 1960/1970s to 1980s was generally much lower than the second period of measurements after 1997, particularly for Border Creek. Further, the discharge of high flow events of Border Creek after 1986 was often greater than the maximum gauge rating of ~180 m^3/s. The annual rainfall at the Bureau of Meteorology (BoM) station at Legune Station (BoM Station 14803) was generally greater after 1997 than during 1965-1986 (Figure 2.3). On this basis the hydrology and rainfall measurements from 1997 onwards were considered in this investigation.

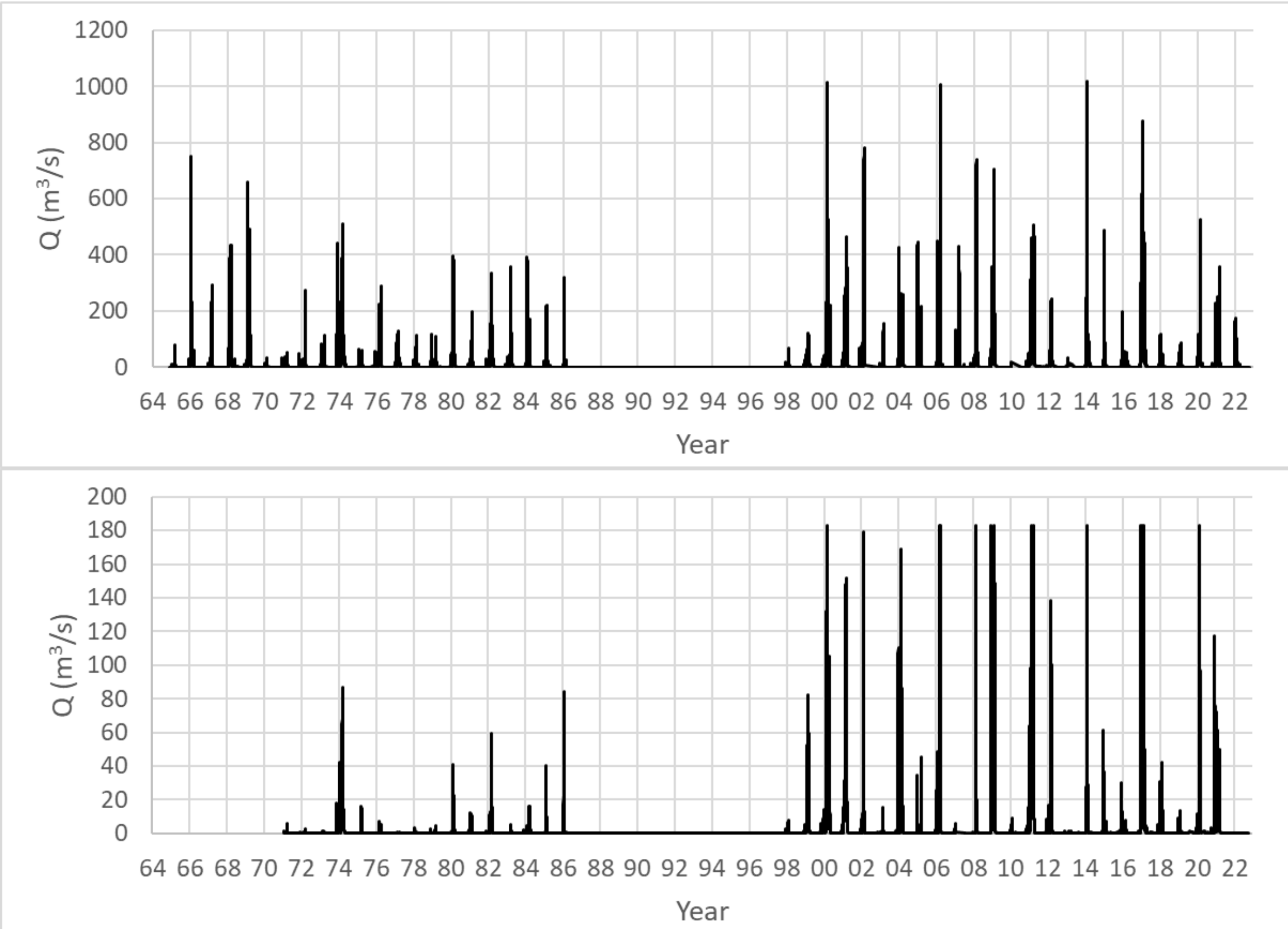

Figure 2.2 ***Discharge (Q) measurements at the Keep River (top, 1964-1987, 1997-2022, station G8100225) and Border Creek (bottom, 1970-1987, 1997-2021, station 8100106) gauging stations.***

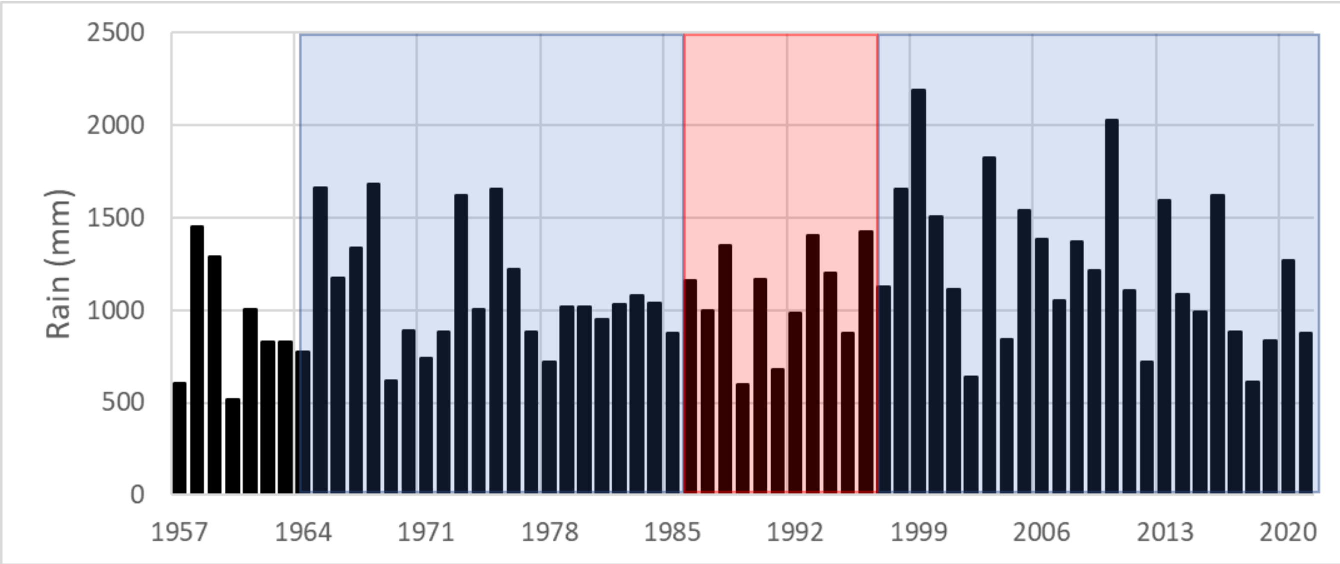

Figure 2.3 ***Annual rainfall at Legune Station (BoM station 14803) (blue and red shading denote available and missing Keep River discharge data periods, respectively) over the water year (July to June).***

Annual (July-June) Legune Station rainfall (lower Keep River catchment) is significantly linearly correlated to annual Keep River (r^2=0.58, Figure 2.4) and Border Creek (r^2=0.56, Figure 2.5) discharge from 1998-99 to 2020-21. Though the rank of annual Legune Station rainfall (in order from highest to lowest) was generally correlated to the annual Keep River of (r^2=0.63, Figure 2.4) and Border Creek (r^2=0.57, Figure 2.5) discharge, clearly interannual spatial variability in rainfall throughout the catchment (and resultant river discharge) was not reliably captured by this one (1) meteorology site (e.g. rank 4 of annual Legune Station rainfall corresponded to rank 16 Keep River discharge). Simple statistics of the annual Legune Station rainfall and Keep River and Border Creek discharge are summarised in Table 2.2. There is a strong linear correlation (r^2=0.90) between the annual discharge of Keep River and Border Creek (i.e. Border Creek ~25% of Keep River, Figure 2.6).

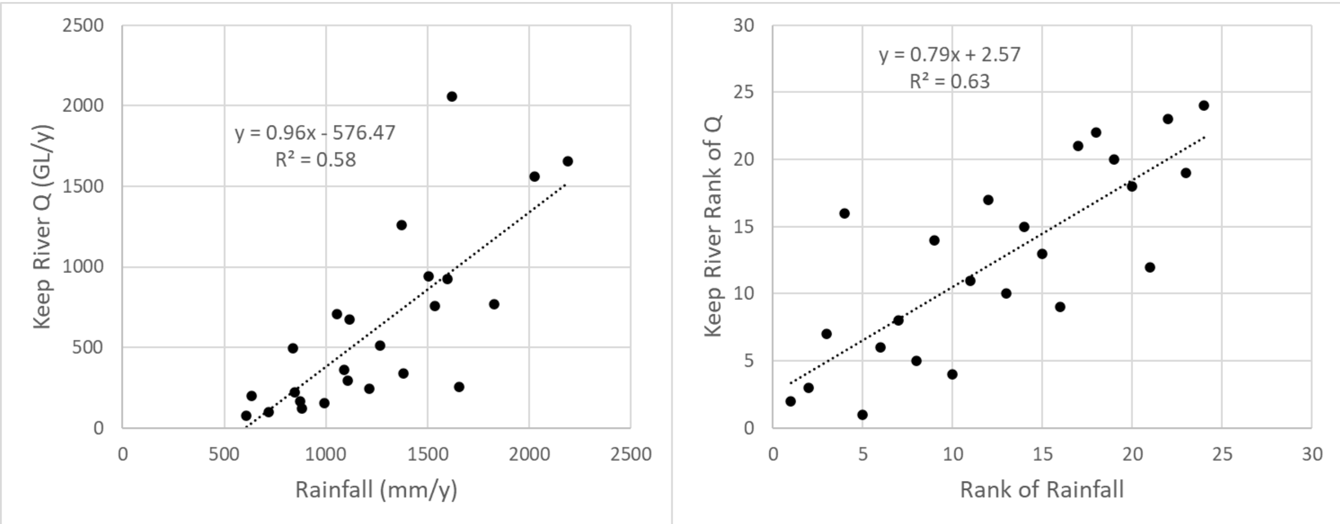

Figure 2.4 ***Linear relations between annual Legune rainfall and Keep River discharge (Q) (left) and the ranks of Legune rainfall and Keep River discharge (right) over the period of 1998-99 to 2021-22.***

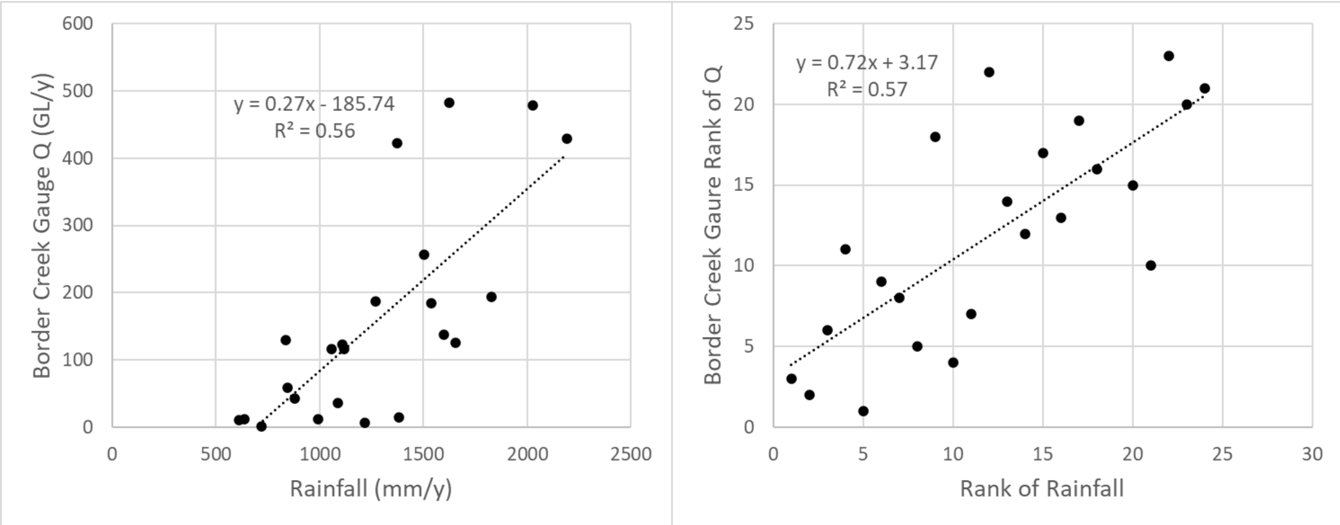

Figure 2.5 *As Figure 2.4 for Border Creek gauge over the period of 1998-99 to 2020-21.*

Table 2.2 *Simple statistics of annual Legune Station rainfall, and Keep River and Border Creek discharge (Q) from 1998-99 to 2020-21.*

Statistic	Rainfall (mm/y)	Keep River Q (GL/y)	Border Creek Q (GL/y)
Maximum	2,190	2,059	482
90th percentile	1,793	1,503	428
75th percentile	1,567	849	190
Median	1,215	493	123
25th percentile	936	233	26
10th percentile	742	129	11
Minimum	609	77	2

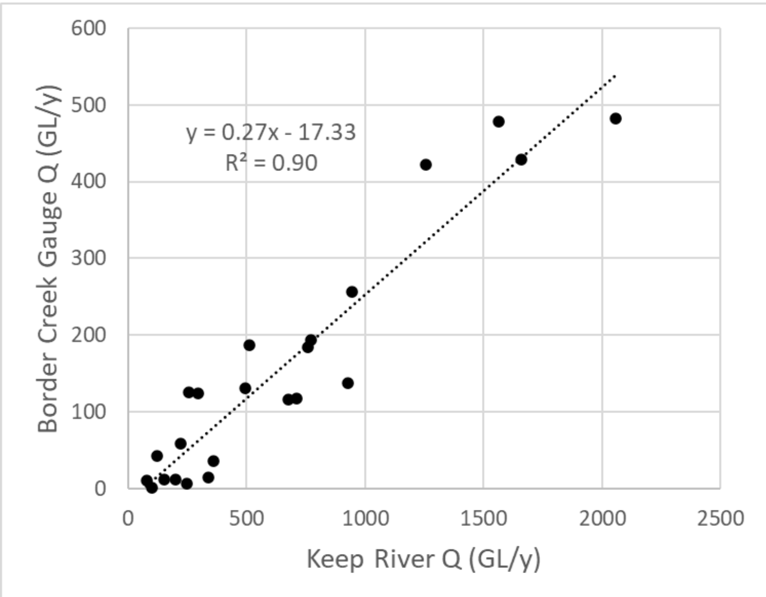

Figure 2.6 *Relation between Border Creek and Keep River annual discharge (Q) over the period of 1998-99 to 2020-21.*

2.2.2 Selection of modelling scenario periods

The selection of modelling scenario periods to predict farm chemical concentrations in the lower Keep River pools and to evaluate potential management strategies to ameliorate potential toxicity risks have the following constraints:

- Spatially varying meteorological and open ocean boundary inputs for the three-dimensional (3D) hydrodynamic model span July 2017-July 2022.
- Discharge measurements from the existing Goomig farmlands at the DW1GS gauging station span from August 2018-June 2022.

2.2.2.1 End of wet season event

Figure 2.7 shows the sub-daily discharge measurements at the Keep River, Border Creek and DW1GS gauges from July 2018-June 2022 and plots of each wet season period (December to April). The 2018-19 (77 GL/y Keep River, 10 GL/y Border Creek) wet season had much lower discharge than 2019-20 (493 GL/y Keep River, 130 GL/y Border Creek), 2020-21 (510 GL/y Keep River, 187 GL/y Border Creek) and 2021-22 (167 GL/y Keep River, no data for Border Creek). In fact, 2018-19 had the lowest annual (July-June) discharge in the Keep River since 1998-99.

GHD (2011) evaluated the following conditions that defined a high risk event from farmland chemical toxicity on the lower Keep River pools:

- Late in the wet season farmland water retention infrastructure is at capacity.
- A small rainfall event(s) generates farmland discharge over the DW1GS gauging station into Border Creek.
- This small rainfall event(s) generates low (if any) non-farmland flows in Keep River and Border Creek.
- Hence, farmland discharge undergoes limited dilution in Border Creek prior to pool K3 thereby posing an elevated toxicity risk to the lower Keep River pools.

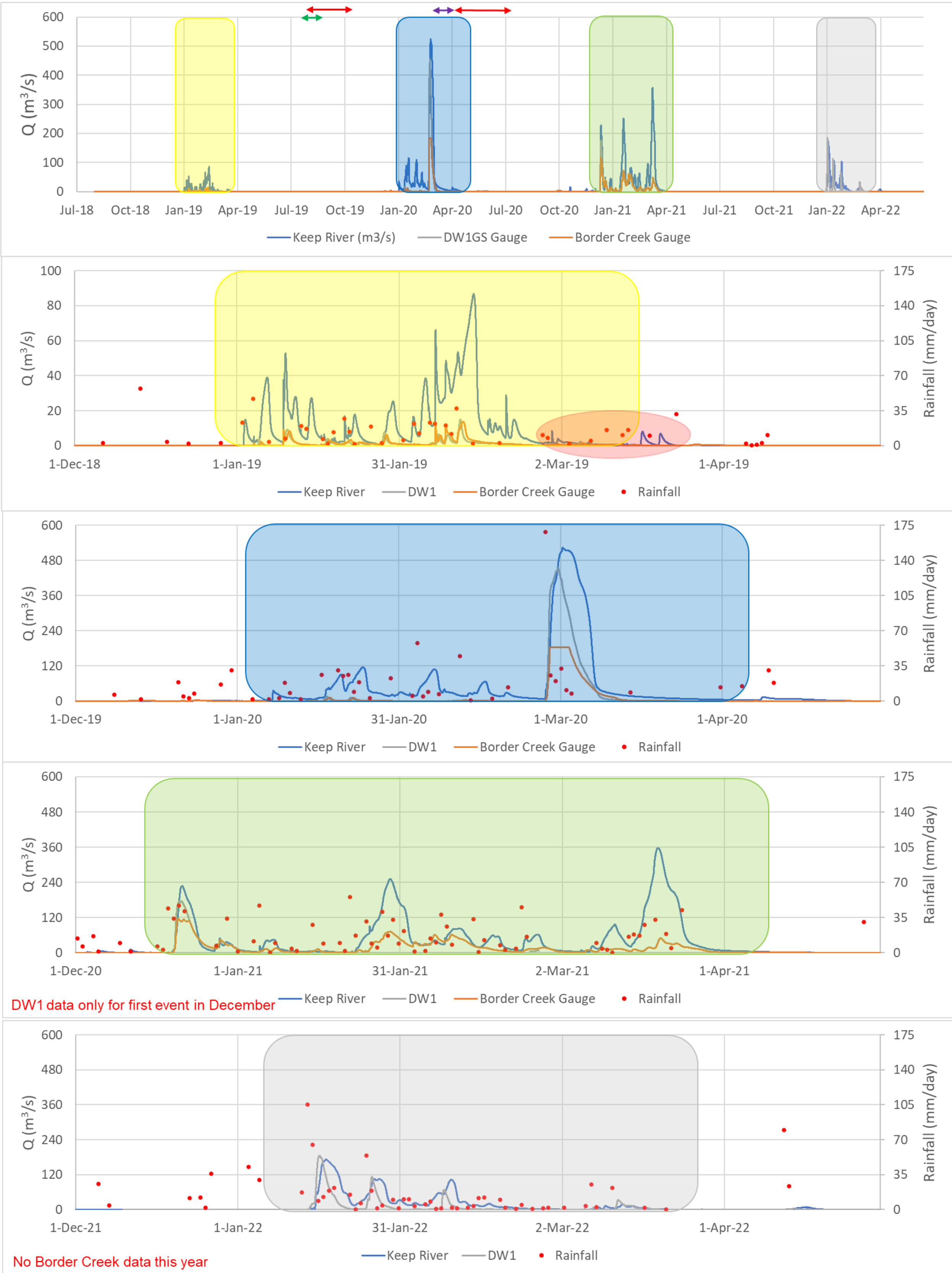

Figure 2.7 ***July 2018 to June 2022 sub-daily discharge (Q) at Keep River, Border Creek gauge and DW1GS gauging stations, and daily rainfall at Legune Station (top) with zooms of the wet seasons (1 December-1 May) during 2018-19 (upper middle), 2019-20 (middle), 2020-21 (lower middle) and 2021-2022 (bottom). Note 2018-19 wet season plots has different y-axis scale, purple arrow depicts breach of D8 drain flow to DW1 from April-June 2020, green arrow depicts release of farmland tailwater directly into Border Creek from July-October 2019, red arrows depict periods of M2 irrigation water releases to flush lower Keep River pools, and shaded red oval outlines high toxicity risk event at the end of the 2019 wet season event due to a high proportion of DW1 inputs into pool K3.***

Surrich (2014) estimated the volumes of the lower Keep River pools as 923, 141, 201 and 68 ML for K1, K2, K3 and K4, respectively. Hence, relatively low farmland discharge under such conditions can pose a high toxicity risk to the lower Keep River pools, particularly pools K2 and K3 due to their relatively small volumes and their proximity to the Border Creek confluence. One such event occurred during 2018-2022 when DW1GS flow measurements were available at the end of February to early April of 2019 (Figure 2.8). Over this period from 27 February-14 April 2019 Keep River discharge was low with several small flow events in response to small late wet season rainfall events. Most of the measured Border Creek discharge was from flows also measured upstream at the DW1GS gauging station, albeit at low flows <1 m^3/s. Though the rainfall events generated Keep River flows and farmland discharge, Border Creek discharge was estimated to be near zero except for the flows from the DW1 drain (as measured at the DW1GS gauging station). Keep River discharge was greater than 100 MLD from 17-22 March (total of ~1,390 ML over period sufficient to potentially flush pools K1 to K3), but was only ~5-50 MLD from 23-30 March (total of ~180 ML) and ~0.3-3 MLD from 31 March- 14 April (total of ~10 ML). In contrast farmland discharge was low from 17-22 March (~0.5-20 MLD, total ~36 ML), elevated from 23 March-3 April (~10-45 MLD, total of 344 ML), and ~0.2-7 MLD (total of ~26.5 ML) from 3-14 April after which flow ceased.

The proportion of farmland water of the total inflows into pool K3 ranged from:

– ~15-80% from 27 February-16 March.
– Nearly 0% during the two elevated river flow events from 17-23 March.
– ~40-95% over the final 3 weeks of the period to 14 April.

<u>This is an example of a high risk event that was identified by GHD (2011), and has been selected as the end of wet season hydrological case.</u>

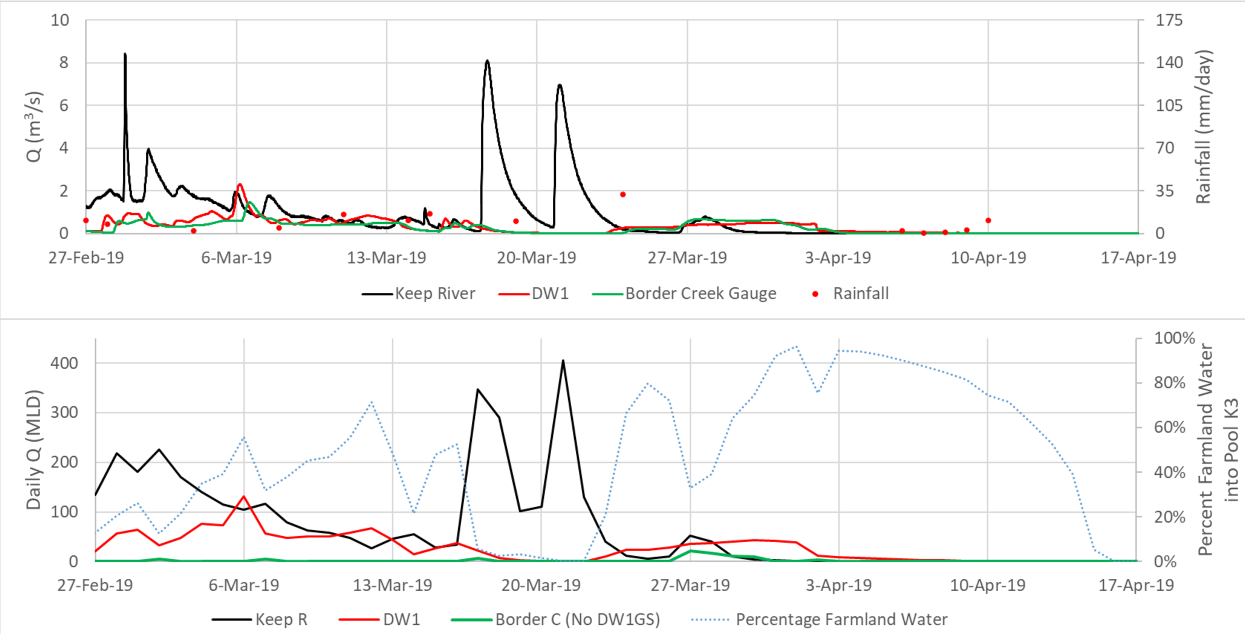

Figure 2.8 ***End of 2019 wet season (27 February-14 April 2019) sub-daily measurements (top) and daily estimates (bottom) of discharge (Q) in the Keep River, Border Creek (sub-daily measurements in top panel, daily estimates of Border Creek catchment flows with no farmland releases included in the bottom panel) and DW1; daily rainfall at Legune Station (top) and percentage of farmland water of total inputs (Keep River + Border Creek catchment + farmland inputs) discharged into pool K3 (bottom).***

2.2.2.2 Farm water retention infrastructure failure case

A second hydrological case was evaluated to emulate an engineering/infrastructure failure that occurs in the dry season. One such event occurred recently from 12 July-7 October 2019 when stored farmland tailwater was released into Border Creek to manage insufficient storage capacity at the time (George 2019). This was, in fact, tailwater from adjoining Ord Stage 1 farmland stored in temporary infrastructure within the environmental buffer of the Goomig farmland. However, it is nonetheless representative/informative of a scenario of a tailwater infrastructure failure for the purpose of modelling and predictive purposes. To manage ecological risks to the lower

Keep River pools associated with farm chemicals in the released tailwater, M2 flows were released via the DW1GS gauge.

Hydrological measurements and estimates of source waters during this dry season event (i.e. there were no Border Creek catchment flows) are illustrated in Figure 2.9 where:

– DW1GS gauge measurements are considered to be reasonably accurate at these discharge levels (red line).
– Most of the water at the Border Creek gauging station was comprised of M2 flushing flows from mid-September onwards. A 0.13 m^3/s (~11 MLD) reduction in the Border Creek gauge measurements (yellow line) was necessary to align the DW1GS and Border Creek gauging measurements over this period (purple line, i.e. at these low discharge levels the Border Creek gauging station overestimates flows by ~0.13 m^3/s).
– The difference between the corrected Border Creek flow estimates (purple line) and DW1GS measurements (red line) yields the estimate of the Border Creek flows upstream of the confluence with the DW1 drain (green line, note DW1GS measurements were shifted 12 hours later to account for the duration to reach the Border Creek gauging station). These Border Creek flow estimates above the DW1 confluence (green line) are the tailwater release discharge estimates due to the infrastructure failure (water retention capacity) event.

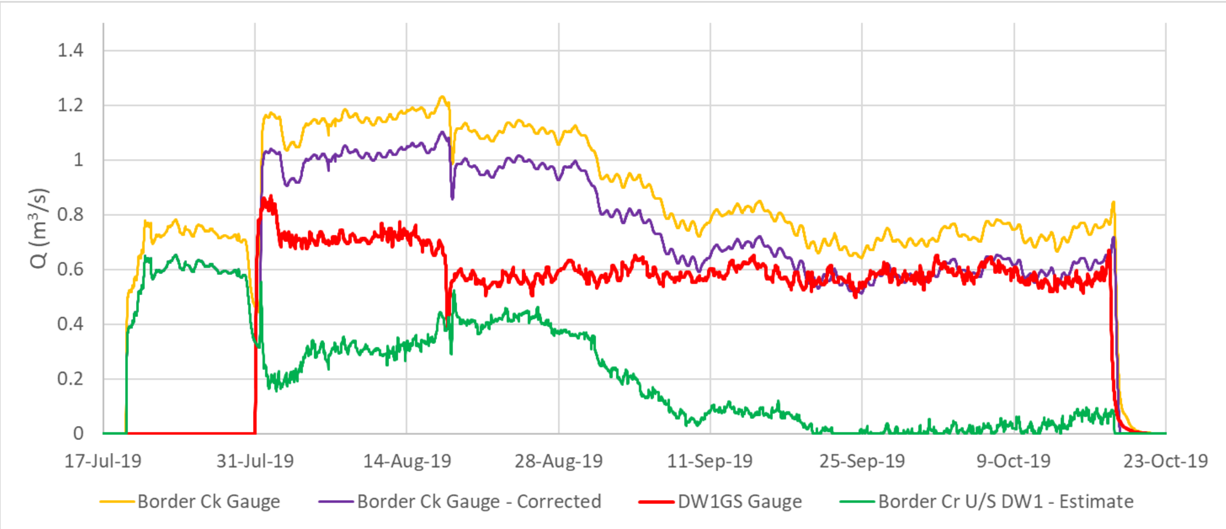

Figure 2.9 ***Sub-daily (15 minute) measurements and estimates of Border Creek discharge (Q) during July-October 2019 over the period of tailwater releases into the creek and M2 irrigation water releases via DW1GS.***

Idealised daily discharge estimates are provided in Figure 2.10 and Table 2.3 that emulate the sub-daily measurements and estimates (Figure 2.9), where:

– The corrected Border Creek gauge measurements (purple line, -0.13 m^3/s reduction in measurements) match well with the idealised Border Creek gauge estimates, which were the combination of M2 irrigation water releases via DW1GS (43.2 MLD, 0.5 m^3/s), farmland releases via DW1GS (range of 4.3-17.3 MLD, 0.05-0.2 m^3/s), and estimates of tailwater releases into Border Creek above the DW1 drain confluence (range of 1.7-51.8 MLD, 0.02-0.6 m^3/s).
– The DW1GS gauge measurements (red) match well with the idealised DW1GS estimates that are comprised of the estimates of the M2 irrigation water releases (43.2 MLD, 0.5 m^3/s) and farmland releases via DW1GS (range of 4.3-17.3 MLD, 0.05-0.2 m^3/s).
– The estimates of Border Creek discharge above the DW1 confluence (green line) match well with the idealised farmland releases directly into Border Creek (range of 1.7-51.8 MLD, 0.02-0.6 m^3/s).

The idealised total volumetric discharge during this event at the Border Creek gauge (6,479 ML), M2 releases via the DW1GS gauge (3,802 ML), and tailwater releases into Border Creek (1,899 ML) are similar to the George (2019) estimates (Border Creek 6,054 ML, M2 3,850 ML, tailwater 2,095 ML) (Table 2.3).

<u>This ~2 GL release of farmland tailwaters into Border Creek was selected as an infrastructure failure case study.</u>

Table 2.3 Idealised hydrology of the 2019 dry season infrastructure failure incident.

Date	m³/s					MLD					Comment
	Tailwater Release	M2 Flush	Farmland Water via DW1GS	Border Creek Gauge	DW1GS Gauge	Tailwater Release	M2 Flush	Farmland Water via DW1GS	Border Creek Gauge	DW1GS Gauge	
1-Jul-19	0	0	0	0	0	0	0	0	0	0	
18-Jul-19	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	
19-Jul-19	0.6	0	0	0.6	0	51.8	0.0	0.0	51.8	0.0	Start tailwater releases as measured at Border Creek gauge
30-Jul-19	0.6	0	0	0.6	0	51.8	0.0	0.0	51.8	0.0	
31-Jul-19	0.35	0.5	0.2	1.05	0.7	30.2	43.2	17.3	90.7	60.5	M2 flushing flows reach Border Creek gauge
15-Aug-19	0.35	0.5	0.2	1.05	0.7	30.2	43.2	17.3	90.7	60.5	
19-Aug-19	0.35	0.5	0.1	0.95	0.6	30.2	43.2	8.6	82.1	51.8	
31-Aug-19	0.35	0.5	0.1	0.95	0.6	30.2	43.2	8.6	82.1	51.8	
8-Sep-19	0.08	0.5	0.1	0.68	0.6	6.9	43.2	8.6	58.8	51.8	
17-Sep-19	0.08	0.5	0.1	0.68	0.6	6.9	43.2	8.6	58.8	51.8	
21-Sep-19	0.02	0.5	0.05	0.57	0.55	1.7	43.2	4.3	49.2	47.5	End tailwater releases into Border Creek at Border Creek gauge
17-Oct-19	0.02	0.5	0.05	0.57	0.55	1.7	43.2	4.3	49.2	47.5	M2 flushing flows cease
18-Oct-19	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	
25-Oct-19	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	
Total	-	-	-	-	-	**1,849**	**3,413**	**711**	**5,972**	**4,123**	
George (2019)	-	-	-	-	-	**2,095**	**3,850**	-	**6,054**	-	

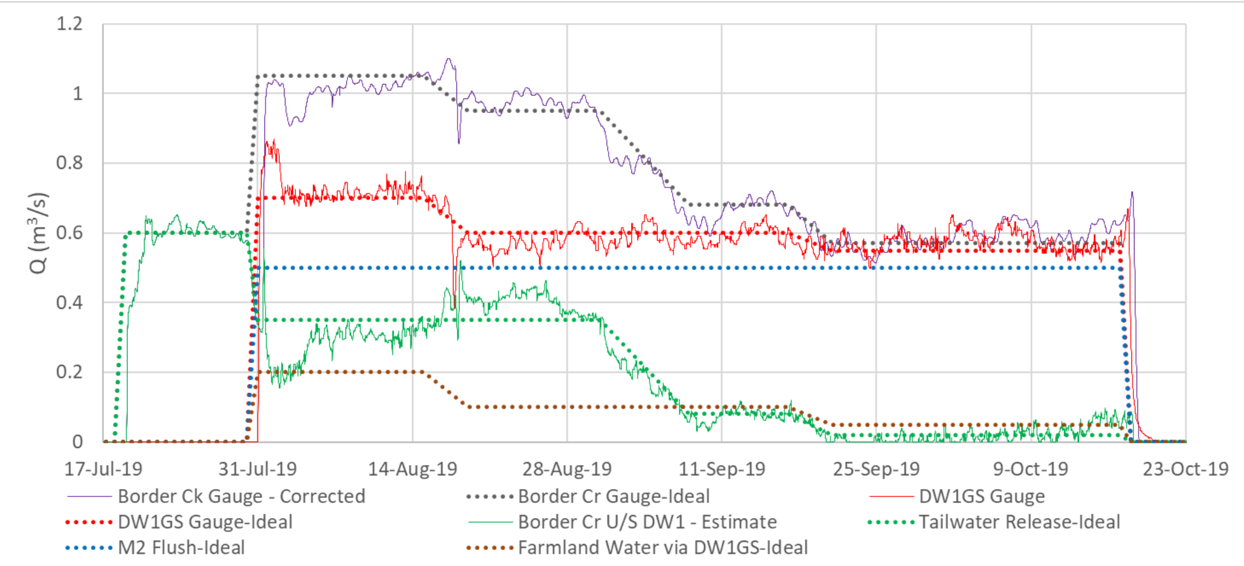

Figure 2.10 Sub-daily estimates and measurements (solid lines), and daily estimates for model inputs (dashed lines), of Border Creek discharge (Q) from 17 July-23 October 2019.

2.2.3 Temperature and conductivity of Keep River and Border Creek

Hourly water temperatures and electrical conductivity (at 25°C) of the Keep River at pool K4 and Border Creek at the gauging station were measured from August 2010-August 2014 (Figure 2.11) (refer to Bennett and George (2014) for details on loggers and deployment methodology).

Water temperatures in pool K4 ranged from a minimum of 20°C from July-August and maximum of 30-35°C from January-February. Though Border Creek water temperature measurements were similar during the wet season (December-April) when typically the stream had water, the large variations in temperature through much of the dry season likely reflects air temperature measurements when Border Creek had no water. Therefore, pool K4 water temperature measurements were adopted as model inputs for both Keep River and Border Creek.

Electrical conductivity measurements were typically lower during the wet season in Keep River (~10-20 mS/m) and Border Creek (~10-50 mS/m) than peak values in the dry season (~60-100 mS/m). These measurements are well below 1 PSU in terms of salinity.

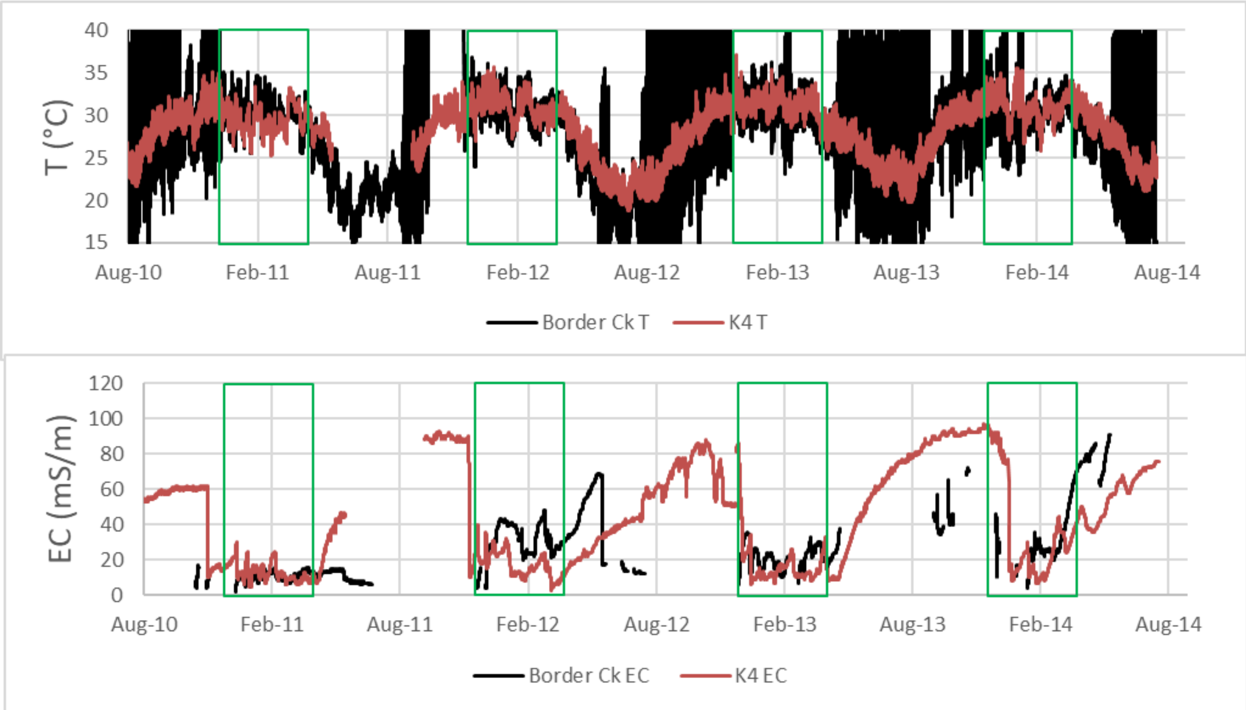

Figure 2.11 ***2010-2014 Keep River (at pool K4) and Border Creek measurements of water temperature (T, top) and electrical conductivity (EC, bottom). Green outline denotes December-April (wet season).***

2.3 Pools

2.3.1 Tides

Tidal water level variations become progressively less for pools K1, K2 and K3 with distance up-river. The degree that tides affect these pools is largely controlled by a rock bar at the down-river end of pool K1, and the sill between pools K1 and K2. Dry season water level measurements at sites K1 (G1800109), K2 and K3 from 2010-2014 from Bennett and George (2014) are illustrated in Figure 2.12 where:

– The three pools primarily undergo tidal flushing during spring tides.
– Maximum tidal ranges are 0.6-0.7 m, 0.5-0.6 m and 0.4-0.5 m in pools K1, K2 and K3, respectively.
– Pool K1 has some degree of tidal forcing during every spring tide.
– Pools K2 and K3 typically undergo some degree of tidal forcing during spring tides.

Figure 2.12 ***Measured hourly water levels in pools K1, K2 and K3 from August 2010-July 2014 (shaded blue denotes dry season) (top) and during the dry seasons (May-October) of 2011 (upper middle), 2012 (middle), 2013 (lower middle) and 2014 (bottom).***

2.3.2 Water temperature

A summary of dry season water temperatures in pools K3, K2 and K1 over the 2010-2014 measurement period (Figure 2.13) includes:

– Maximum temperatures occurred in October in the range of 29-33°C.
– Minimum temperatures occurred in June-July in the range of 20-25°C.

These seasonal and diel variation in water temperatures are similar to those shown for pool K4 in Figure 2.11 of section 2.2.3.

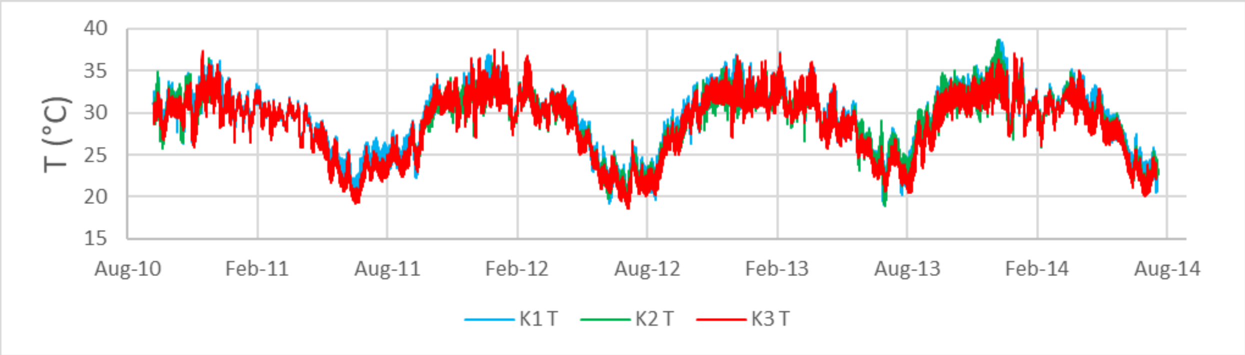

Figure 2.13 Hourly water temperature (T) measurements in pools K1, K2 and K3 from August 2010-July 2014.

2.3.3 Electrical conductivity

Temporal variations in the dry season electrical conductivities (at 25°C) in pools K3, K2 and K1 over the 2010-2014 measurement period responded to the interplay between remnant catchment inflows that maintained low salinity and tidal forcing which introduced marine waters with elevated salinity (Figure 2.14). A summary each year includes:

– The 2011 dry season had relatively high inflows over the previous wet season (Keep River discharge volume of 1,564 GL with rank 3 of 24 years over 1998-2022) with substantial discharge well into the dry season so conductivity in pool K1 increased slowly from mid-July to mid-September in response to tidal forcing.
– The 2012 dry season had relatively low inflows over the previous wet season (Keep River discharge volume of 294 GL with rank 15 of 24 years over 1998-2022) with low discharge at the start of the dry season that resulted in rapidly increasing electrical conductivity in pool K1 from May.
– The 2013 dry season had very low inflows over the wet season (Keep River discharge volume of 100 GL with rank 23 of 24 years over 1998-2022) with no discharge at the start of the dry season that resulted in increasing electrical conductivity at the end of April and May in pools K1 and K2, respectively. Further, in contrast to 2011, conductivity in pool K3 increased at the beginning of July in response to tidal forcing.
– The 2014 dry season had high inflows over the wet season (Keep River discharge of 927 GL with rank 6 of 24 years over 1998-2022) that maintained low electrical conductivity through the end of the measurement record in mid-July in the three lower Keep River pools.

These electrical conductivities are substantially greater than those in the pool K4 of the Keep River (<100 mS/m, see Figure 2.11 of section 2.2.3), which is located above the tidally influenced region.

The 2013 dry season (Keep River discharge of 100 GL over 2012-13 water year with a rank of 23 of 24 years) electrical conductivity measurements were used as a qualitative comparative verification measure of those simulated over the 2019 dry season (Keep River discharge of 77 GL over 2018-19 water year with a rank of 24 of 24 years) that was the selected modelling scenario period of this investigation.

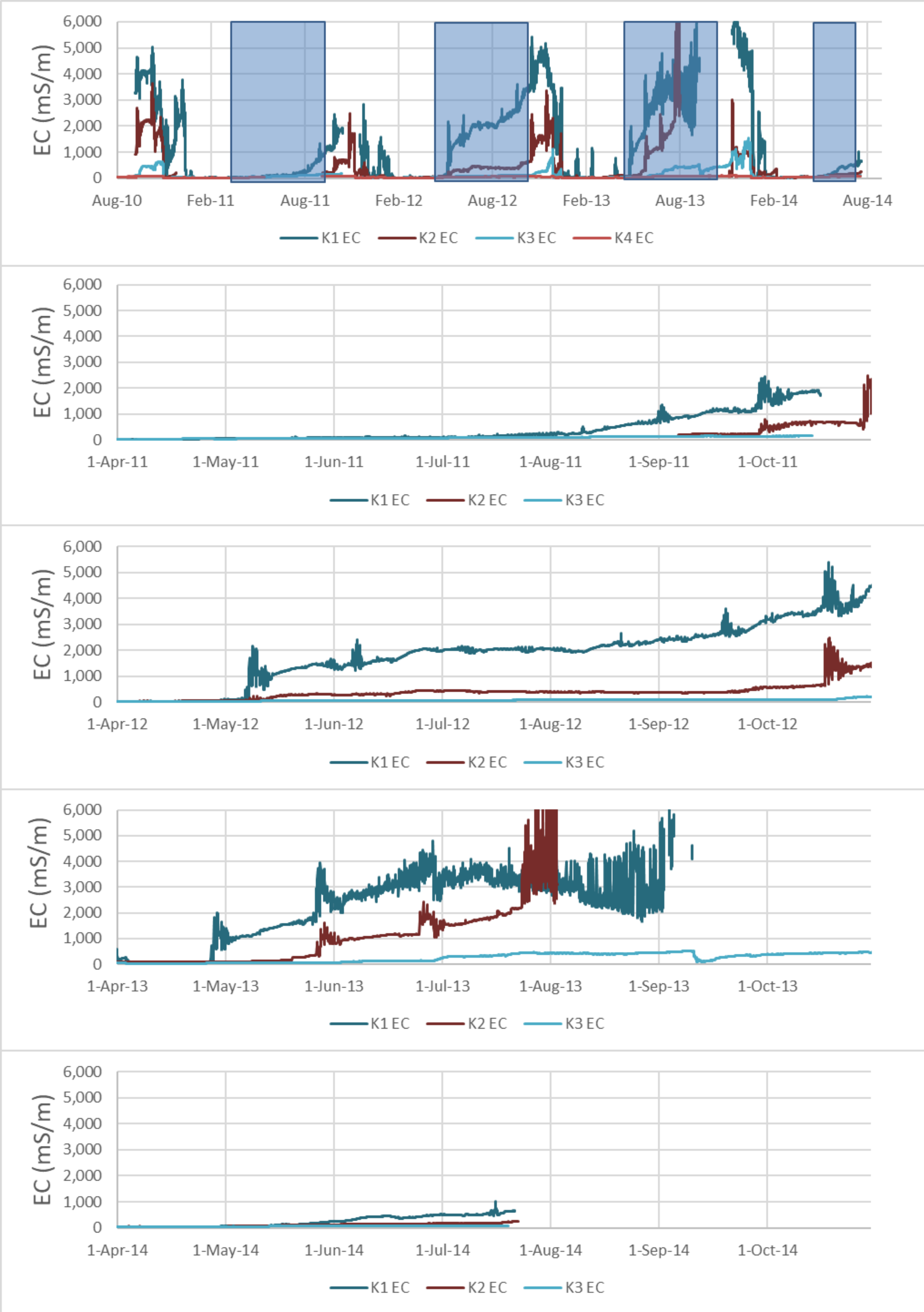

Figure 2.14 ***As Figure 2.12 for hourly electrical conductivity (EC) measurements in pools K1, K2 and K3.***

2.4 Farmland chemicals

Bennett and George (2014) described the 2010-2014 water quality data of the lower Keep River system. Bennett and George (2011) reported on the available water quality data prior to 2010 from various sources in the lower Keep River system. Additional data since Bennett and George (2011, 2014) have been collected since 2016 in Border Creek, DW1 drain and the M2 irrigation channel along with additional measurements in the lower Keep River pools.

To meet the objectives of this investigation, credible maximum concentration estimates of farmland chemicals of concern are needed for the following:

– Keep River at pool K4, to characterise background levels in the river prior to the lower tidally influenced pools.
– Border Creek catchment above the confluence with the DW1 drain from the Goomig farmlands (i.e. the natural catchment concentrations), which flows bypass the Goomig farmland, including the DW1 drain.
– Releases from the Goomig farmlands via the DW1 drain at site DW1GS.
– M2 irrigation channel, which is an available management tool to flush the lower Keep River pools.

Identified farmland chemicals of concern from the available monitoring data in the DW1 drain, Border Creek and lower Keep River pools were metolachlor, atrazine, diuron and methomyl with a simple statistics summary in Table 2.4. Key points to note from Table 2.4 include:

– Metolachlor and atrazine were frequently detected at most sites (DW1 drain, Border Creek, K3, K2 and K1) except at pool K4 on the Keep River and the M2 irrigation water. Because the limit of reporting (LoR) of metolachlor (0.01 µg/L) is greater than the protective concentration of 99% of species protection (PC99, 0.0084 µg/L), when detected in a sample it was always greater than the PC99. This contrasts with atrazine with a LoR (0.01 µg/L) that is substantially lower than the PC99 (0.7 µg/L) with many detections at the various locations between LoR and the PC99.
– Maximum diuron levels in the DW1 drain and Border Creek have been detected above the PC99 though it has not been detected (i.e. <LoR) in the M2 irrigation water, Keep River at pool K4 or any of the other lower Keep River pools (K3, K2 and K1). Further, the 95th percentile in the DW1 drain was above the PC99.
– Though methomyl has not been sampled to the extent of the other three farm chemicals, it does have a high frequency of detection at all of the sampling sites except for the M2 irrigation water and the Keep River at pool K4. Though detected at the remaining sites there has been no measured exceedances of the PC99.

Table 2.4 Summary statistics of available measurements of selected farmland chemicals in the DW1 drain at DW1GS, Border Creek, Keep River (at pool K4) and the lower Keep River pools (K3, K2, K1). Pink, yellow and blue shading denotes concentrations that are greater than, within 10%, and <10% but greater than LoR of the PC99s, respectively.

Parameter/Chemical	ANZG (2018) PC99 (PC99 from King et al 2017)	Maximum	95th Percentile	90th Percentile	80th Percentile	Median	n >LoR	n LoR
DW1 drain (station DW1GS)								
Atrazine (µg/L)	0.7	4.1	1.1	0.3	0.1	<0.01	23	39
Diuron (µg/L)	0.08	0.9	0.14	0.03	<0.02	<0.02	7	49
Metolachlor (µg/L)	0.0084	4.2	3.1	1.1	0.4	0.1	37	20
Methomyl (µg/L)	0.5	0.22	-	0.04	0.02	<0.01	5	12
Border Creek Gauge (station G8100106)								
Atrazine (µg/L)	0.7	9.7	2.4	1.3	0.5	0.03	36	25
Diuron (µg/L)	0.08	0.33	<0.02	<0.02	<0.02	<0.02	2	54
Metolachlor (µg/L)	0.0084	4.9	1.5	0.6	0.2	<0.01	22	34
Methomyl (µg/L)	0.5	0.08	-	0.03	0.01	<0.01	4	11
Keep River at pool K4 (station G8100225)								
Atrazine (µg/L)	0.7	0.1	<0.01	<0.01	<0.01	<0.01	2	73
Diuron (µg/L)	0.08	<0.02	<0.02	<0.02	<0.02	<0.02	0	61
Metolachlor (µg/L)	0.0084	0.04	<0.01	<0.01	<0.01	<0.01	2	59
Methomyl (µg/L)	0.5	<0.01	<0.01	<0.01	<0.01	<0.01	0	15
M2 irrigation channel								
Atrazine (µg/L)	0.7	0.21	<0.01	<0.01	<0.01	<0.01	3	24
Diuron (µg/L)	0.08	<0.02	<0.02	<0.02	<0.02	<0.02	0	27
Metolachlor (µg/L)	0.0084	0.15	0.05	0.02	<0.01	<0.01	3	24
Methomyl (µg/L)	0.5	<0.01	-	-	<0.01	<0.01	0	6
Pool K3								
Atrazine (µg/L)	0.7	6.1	0.8	0.4	0.3	<0.01	31	47
Diuron (µg/L)	0.08	<0.02	<0.02	<0.02	<0.02	<0.02	0	65
Metolachlor (µg/L)	0.0084	3.1	0.5	0.08	0.04	<0.01	18	48
Methomyl (µg/L)	0.5	0.06	-	0.03	0.01	<0.01	4	11
Pool K2								
Atrazine (µg/L)	0.7	3.1	1.1	0.6	0.5	0.2	28	24
Diuron (µg/L)	0.08	<0.02	<0.02	<0.02	<0.02	<0.02	0	39
Metolachlor (µg/L)	0.0084	2.90	2.29	0.64	<0.01	0.01	8	31
Methomyl (µg/L)	0.5	0.15	-	0.03	0.03	<0.01	5	7
Pool K1								
Atrazine (µg/L)	0.7	3.5	1.08	0.7	0.5	0.3	33	16
Diuron (µg/L)	0.08	<0.02	<0.02	<0.02	<0.02	<0.02	0	35
Metolachlor (µg/L)	0.0084	5.20	1.51	0.75	0.21	<0.01	9	27
Methomyl (µg/L)	0.5	0.09	-	-	0.04	0.02	5	5

2.4.1 2019 dry season incident

The selected 2019 dry season incident described in Section 2.2.2.2 to emulate a farmland water retention infrastructure failure event was well monitored for atrazine, which was the contaminant of concern at the time of the incident (George 2019).

Figure 2.15 illustrates the time series of atrazine measurements at the Border Creek gauging station from the peak on 22 July 2019 and an idealised exponential decay relation where:

– The zero-intercept of 2.1 µg/L is similar to the peak concentration of 2.4 (µg/L).
– The exponential decay coefficient is 0.078 1/day.
– The exponential relation explains 97.5% of the variability in the measurements.

These atrazine measurements and the exponential relation over time from the tailwater releases into Border Creek (i.e. the incident) also account for dilution by M2 flows via DW1GS that started on 31 July, approximately 9 days after Border Creek flows into pool K3 started to occur. Recall that Border Creek flows upstream of the confluence with DW1 are solely from tailwater releases as there were no natural flows from the catchment over this period of the dry season.

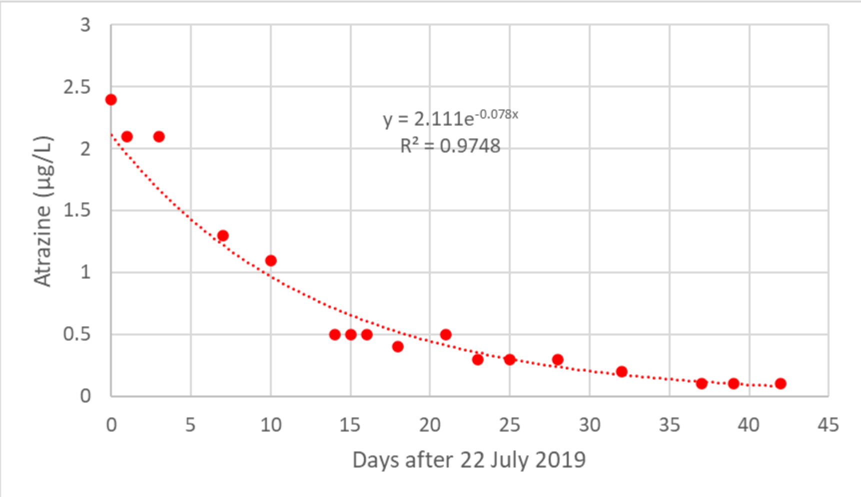

Figure 2.15 Exponential decay relation of Border Creek gauge atrazine measurements in days after the peak level on 22 July 2019.

Atrazine measurements at the Border Creek and Keep River gauging stations, M2 irrigation water and in pools K3, K2 and K1 are illustrated in Figure 2.16 along with the exponential decay relation of the Border Creek measurements. The M2 irrigation water releases via the DW1 drain (as measured at DW1GS) had atrazine measurements of LoR and thereby diluted the tailwater releases into Border Creek (the incident) from which a time series of tailwater atrazine levels was estimated as presented in Figure 2.16. At the onset of the M2 flushing flows on 31 July 2019 the estimated tailwater concentration was ~2.1 µg/L, which decreased until 29 July, then increased to ~3 µg/L on 31 July, and then decreased thereafter.

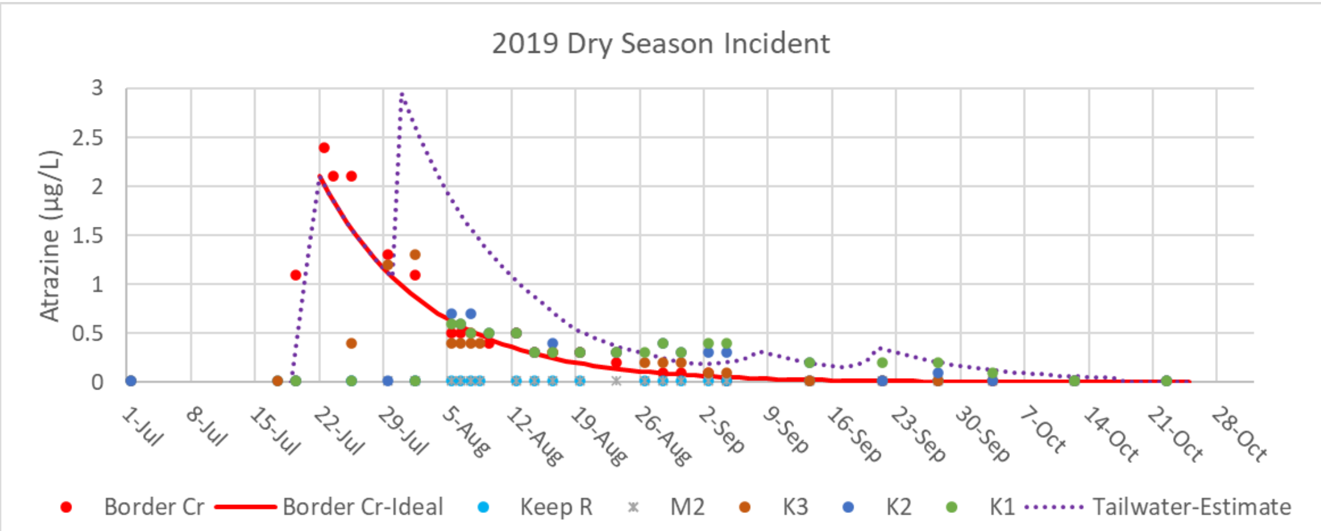

Figure 2.16 Atrazine levels in at the Border Creek and Keep River gauging stations, M2 irrigation water and the lower Keep River pools K3, K2 and K1. The red line is the estimated atrazine concentration at the Border Creek gauging station on the basis of the idealised exponential decay (Figure 2.15). The purple dashed line is the estimate of the tailwater release concentration on the basis of the water balance presented in Section 2.2.2.2, atrazine concentrations measured in the M2 irrigation water (always below limit of reporting), and the idealised exponential decrease of atrazine concentrations at the Border Creek gauging station (red line).

3. Modelling framework

3.1 Overview

A conceptual schematic of the modelling framework for this investigation is provided in Figure 3.1, which is used to evaluate current (Goomig farmland) and future (Knox Plains farmland) risks from farmland-derived chemicals on the lower Keep River pools, and management measures to ameliorate these risks. The framework is comprised of:

– A three-dimensional (3D) hydrodynamic model of the lower Keep River system that includes the tidally influenced pools of K1, K2 and K3, and pool K4 immediately up-river of tidal influences. The 3D hydrodynamic model inputs include meteorology (solar insolation, longwave radiation, winds, air temperature, relative humidity, rainfall, air pressure), the open ocean boundary (water level, temperature, salinity, currents, chemicals), Border Creek confluence at the up-river portion of pool K3 (discharge, temperature, salinity, chemicals), and the Keep River confluence just up-river of pool K4 (discharge, temperature, salinity, chemicals).

– A stream input generator tool that determines the inputs (discharge, temperature, salinity, chemicals) via Border Creek into pool K3 and farmland drain that discharges into the Keep River above pool K4.

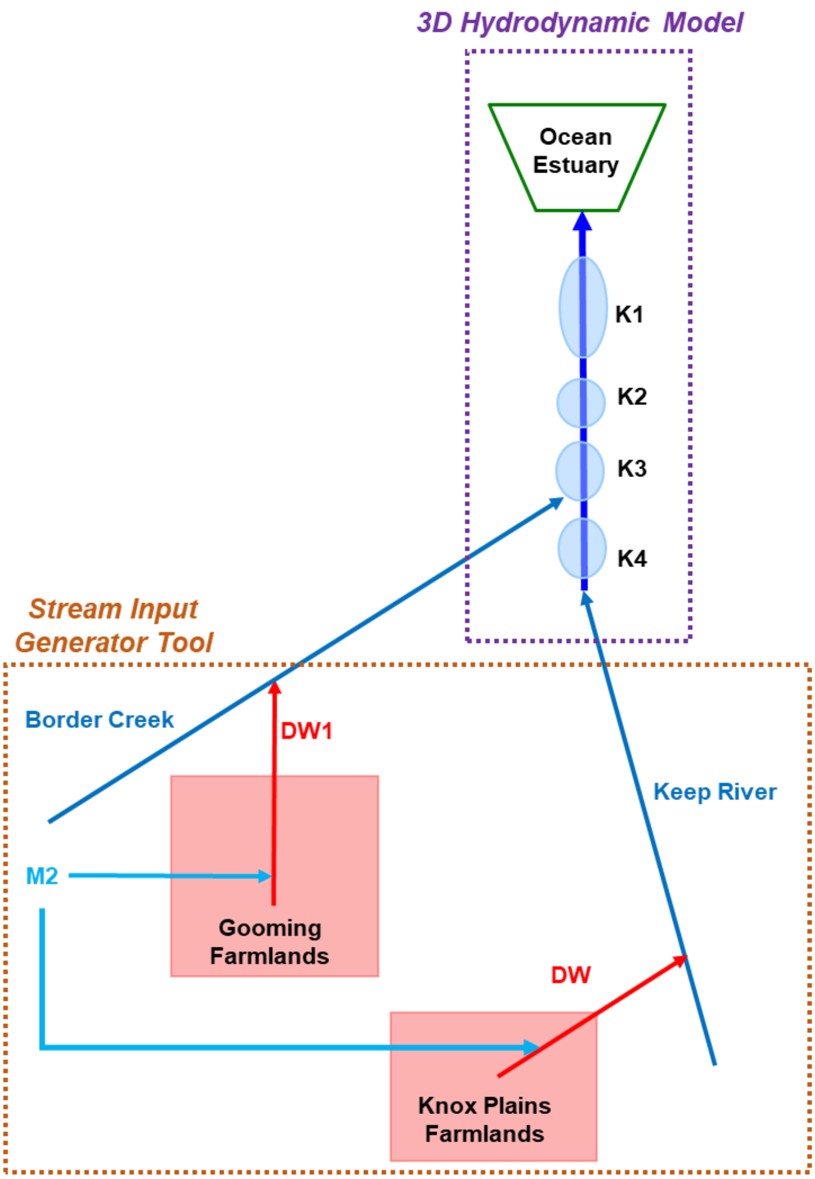

Figure 3.1 Conceptual schematic of modelling framework.

This investigation builds on the previous GHD (2011) modelling assessment of the lower Keep River system as summarised in Table 3.1, where key improvements include:

- Updates to the bathymetry of the lower Keep River system with Surrich (2014) survey data (Section 3.2.1).
- Spatially varying winds with additional meteorological forcing (shortwave and longwave radiation, air temperature, relative humidity, air pressure, rainfall) (Section 3.2.2) that allows the implementation of the surface heat flux module and the simulation of water temperatures.
- In addition to spatially varying surface water level inputs along the open ocean boundary, this investigation also incorporates spatial and temporal varying currents, temperatures and salinities along the ocean boundary (Section 3.2.3).
- Selection of several 'actual' flow events that represent high potential ecological risk conditions to the lower Keep River pools (Section 2.2.2). These selected events serve as the basis to predict 'worst case' risks to lower Keep River pools on the basis of a range of farm chemicals (Section 2.4) and potential management measures (e.g. M2 releases, selection of lower chemical toxicity, chemical application).
- Development of a stream input generator tool to configure the model inputs (discharge, temperature, salinity, chemicals) for Border Creek into pool K3 and Keep River into pool K4 (Section 3.2).

Table 3.1 Comparison of GHD (2011) and this investigation's modelling framework

Aspect	GHD (2011)	This Investigation
3D model	Model domains: 2 (large and small) Lower Keep Bathymetry: Gray and Williams (2006) Meteorology: uniform winds Ocean boundaries: water levels Model output: water levels, salinity, currents Model verification: October-November 2004 water levels	Model domains: 1 (integrated ocean-estuary-pools simulation) Lower Keep Bathymetry: Gray and Williams (2006), Surrich (2014), LiDAR Meteorology: spatially varying winds, insolation, longwave radiation, air temperature, relative humidity, rainfall Ocean boundaries: water levels, temperature, salinity, currents Model output: water levels, salinity, currents, water temperature Model verification: October-November 2014 water levels, 2010-2014 water levels and pool temperatures and salinities
Hydrology	Keep River and Border Creek: Measurements through 2010 Goomig farmland discharge: One-dimensional (1D) hydraulic model to predict discharge to Border Creek when on-farm water management infrastructure (i.e. capture of first 25 mm of rainfall on farm) at capacity Knox Plains farmland discharge: Not considered	Keep River and Border Creek: Measurements through 2022 Goomig farmland discharge: Selection of 'focus' events from 2018-2022 DW1GS measurements that represent high risk. Knox Plains farmland discharge: Assume same as Goomig farmland discharge
Chemicals	Goomig farmland loads: Concentrations assumed the same as several Ord River Irrigation Area (ORIA) farms Knox Plains farmland loads: Not considered Prediction in pools K1-K3: Assumed chemical only undergoes dilution (conservative substance)	Goomig farmland loads: Concentrations based on 2019-20 measurements Knox Plains farmland loads: Assumed to be the same as Goomig farmlands Prediction in pools K1-K4: Capacity to model chemical degradation rates and addition of pool K4 to the model

3.2 Hydrodynamic model

Three-dimensional (3D) simulations were carried out with Danish Hydraulic Institute's (DHI's) MIKE 3 Flexible Mesh (FM) hydrodynamic model to evaluate the dispersion and transport of farm chemicals from the existing and proposed farmlands on the lower Keep River system. The model was configured with meteorology, Keep River and Border Creek inflows, and tidal-oceanographic currents and water levels at the open ocean boundaries.

The MIKE 3 FM is an industry standard for 3D hydrodynamic modelling. The model domain in MIKE 3 FM is defined horizontally by an irregular network of triangles (the model 'cells') that are split into vertical 'layers' by either a z-level (defined layer thicknesses), sigma coordinate (fixed number of vertical layers throughout the model domain), or a combined sigma and z-level configuration. For each model cell, MIKE 3 FM simulates a range of hydrodynamic properties including, but not limited to, current speed, current direction, water level and salinity. MIKE 3 FM is driven by user-defined environmental inputs (e.g., tidal level variations at open boundaries, wind speeds and directions over the surface).

MIKE EcoLab is DHI's water quality module with a number of 'templates' to model a wide range of applications ranging from simple (dissolved oxygen and biochemical oxygen demand dynamics) to complex (zooplankton, algae, nutrients, sediments). These EcoLab templates can be readily modified to suit investigations. An EcoLab template was tailored for this investigation to simulate the selected farmland chemicals (Section 2.4) in the lower Keep River pools assuming that degradation rates are exponential decay coefficients.

3.2.1 Model domain

The mesh and bathymetry are shown in Figure 3.2 and Figure 3.3 for the entire model domain and the lower Keep River system, respectively. Mesh element sizes ranged from ~10 km at the offshore boundaries (Figure 3.2) to ~50 m along the river and ~10 m across the river in the lower Keep River system (Figure 3.3). The GHD (2011) model bathymetry was updated as follows:

- In addition to DHI's C-MAP data of digitised nautical charts and the Gray and Williams (2006) longitudinal survey transect of the lower Keep River system that was used by GHD (2011), in this investigation more recent survey (bathymetry) data by Surrich (2018) of Keep River pools K1, K2, K3 and K4; and LiDAR data (10 m horizontal resolution) of the lower Keep River system were incorporated.
- GHD (2011) had two model domains (large coarse resolution of marine waters, small fine resolution of the lower Keep River), the updated model has a single model domain.
- The GHD (2011) model domain extended up-river to pool K3, but now includes pool K4.
- The updated horizontal and vertical resolution of the lower Keep River is much finer than GHD (2011).

The vertical domain in the 3D model is configured as follows:

- Sigma coordinate system of 4 layers in the upper 10 m of the water column that expand and contract in response to tidal and non-tidal water level variations. As the lower Keep River system is much shallower than 10 m, the vertical resolution of this portion of the model domain is 4 layers.
- Fixed coordinate system of 4 layers below 10 m of 5, 10, 20 and 25 m thicknesses. The vertical resolution below 10 m depth is not overly important for this investigation as the lower Keep River system is relatively shallow (<-3 m AHD) that decouple it from the dynamics of the deeper waters in the Joseph Bonaparte Gulf.

The updated model bathymetry of pools K1-K4 compares favourably with the Surrich (2014) survey for pool K1 (Figure 3.4) and pools K2 to K4 (Figure 3.5).

Surrich (2014) established the following rock bar heights at the down-river end of each pool, which was incorporated into the model bathymetry:

- Pool K4 at 5.3 m AHD.
- Pool K3 at 3.7 m AHD.
- Pool K2 at 3.65 m AHD.
- Pool K1 at 3.45 m AHD.

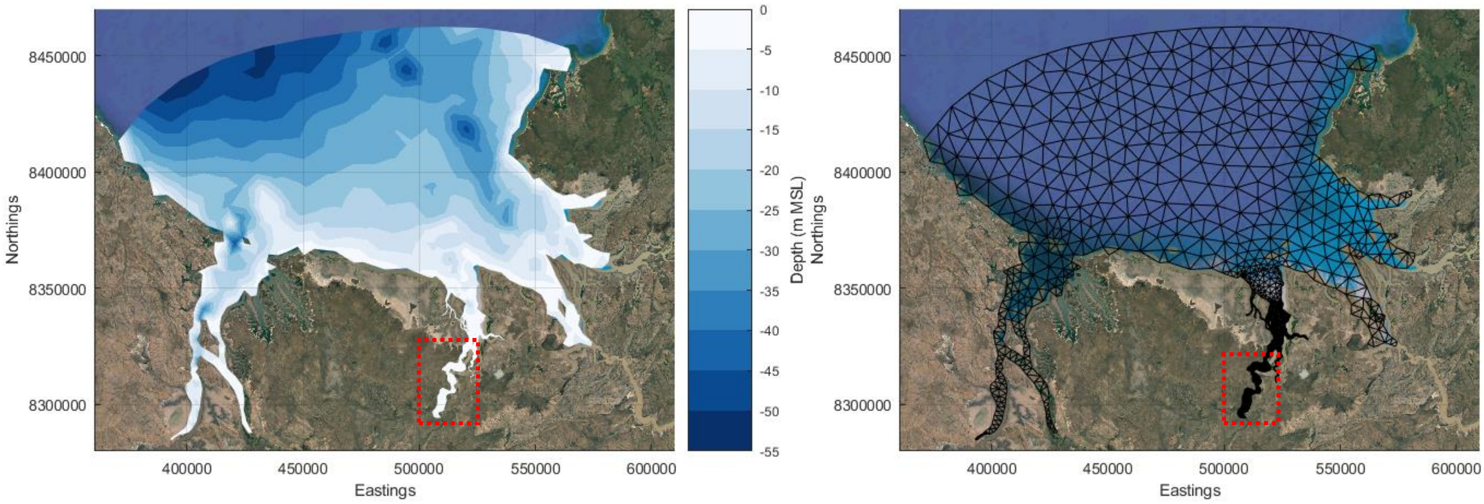

Figure 3.2 ***Model bathymetry (left) and mesh (right) of the entire model domain. Red rectangle denotes lower Keep River system.***

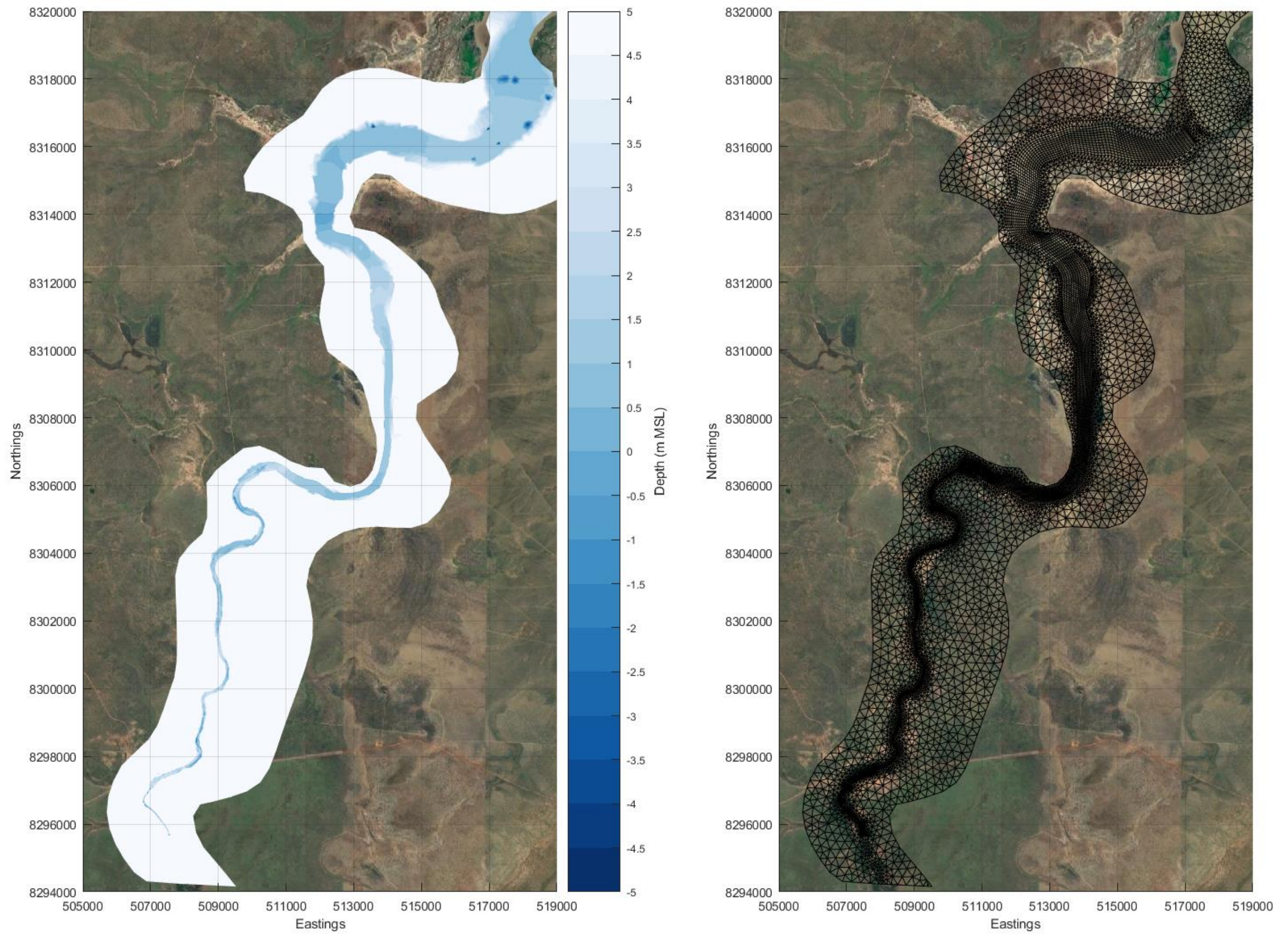

Figure 3.3 ***Model bathymetry (left) and mesh (right) of the lower Keep River.***

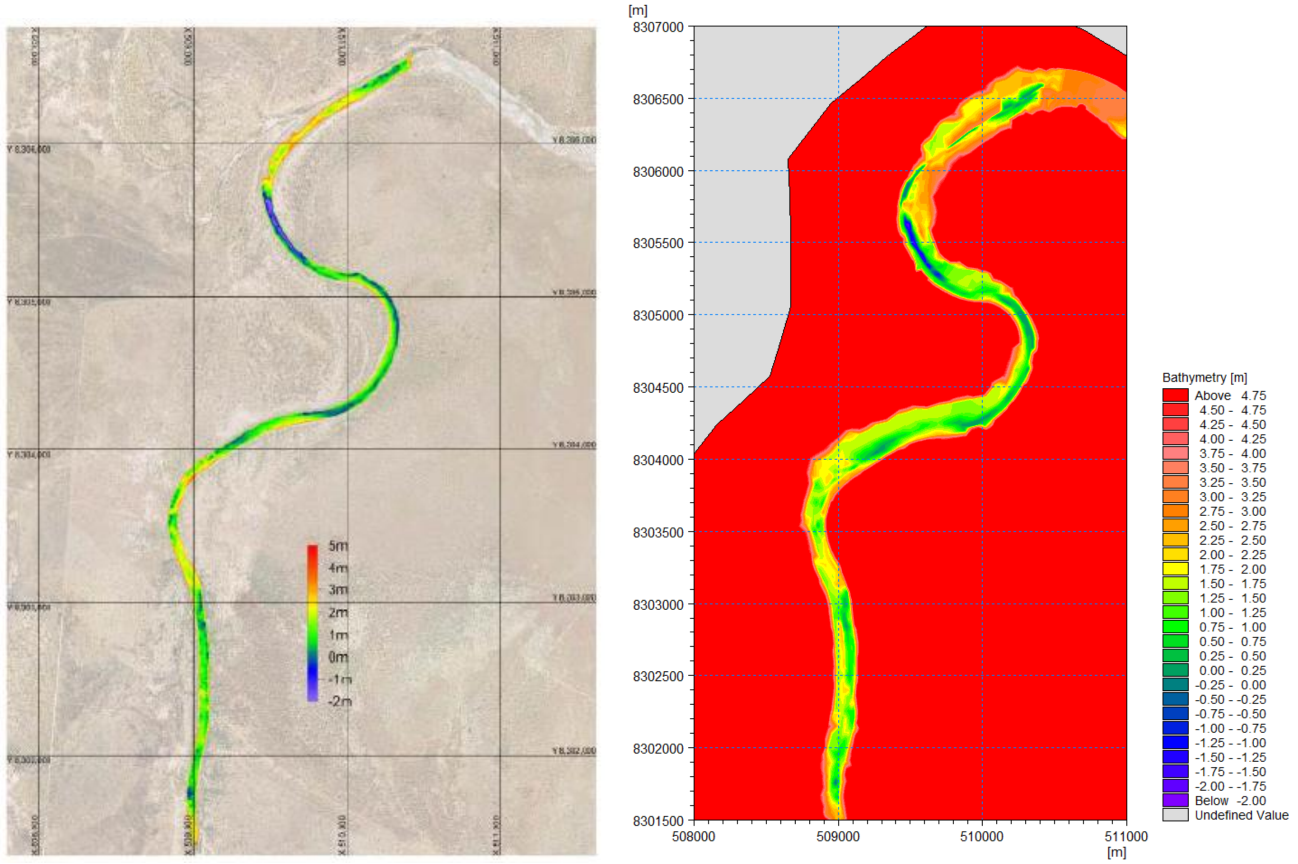

Figure 3.4 ***Comparison of Surrich (2014) (left) and model (right) bathymetry of pool K1.***

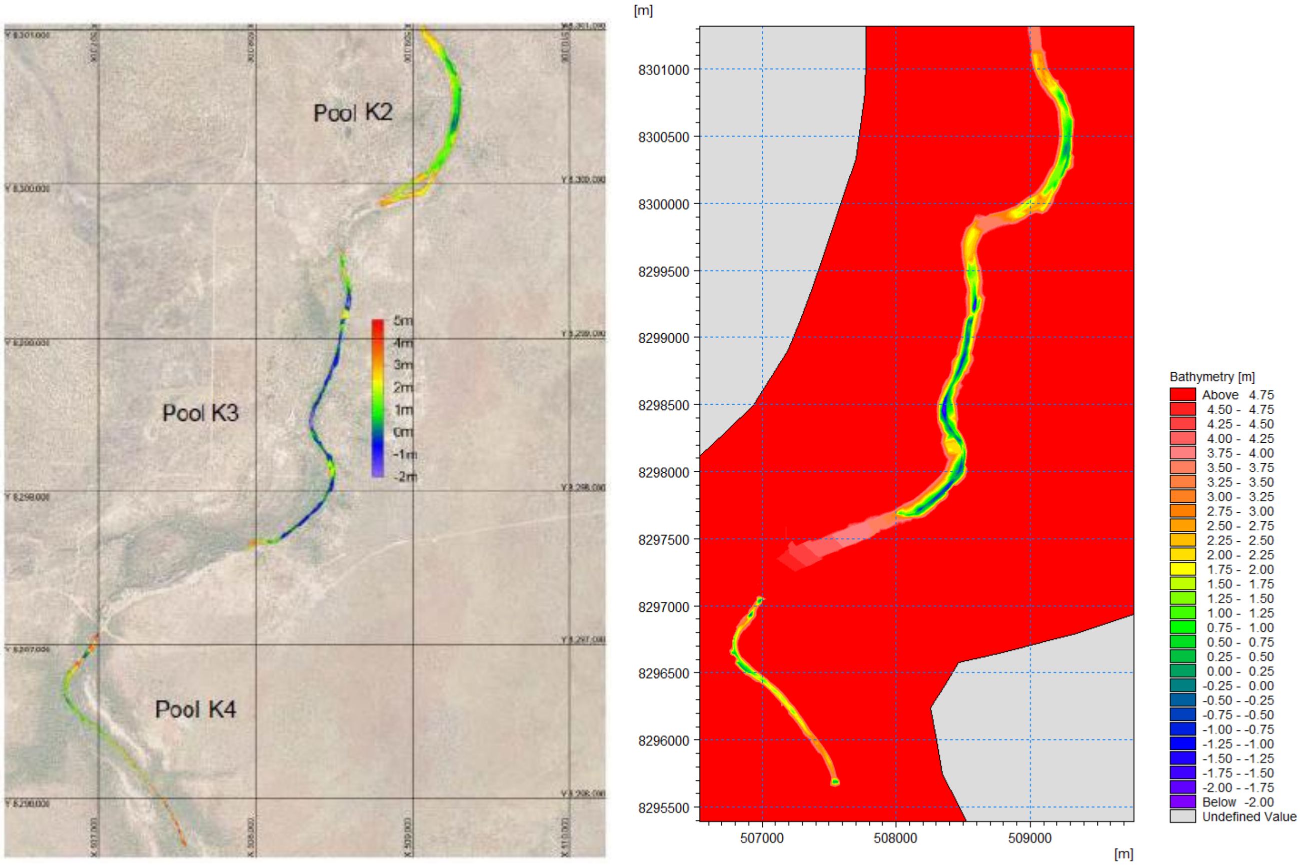

Figure 3.5 ***Comparison of Surrich (2014) (left) and model (right) bathymetry of pools K2, K3 and K4.***

3.2.2 Meteorological inputs

Spatially and temporally varying meteorology (solar insolation, incoming longwave radiation, air pressure, air temperature, relative humidity, rainfall, wind speed and wind direction) were applied to the sea surface of the hydrodynamic model. These data were sourced from the National Centres for Environmental Prediction's (NCEP's) Climate Forecast System, version 2 (CFSv2), at 0.2° spatial resolution and an hourly temporal resolution (Suranjana *et al.* 2014). CFSv2 is an operational climate model that includes nearly all up-to-date forecasting and data assimilating techniques. This allows a surface heat flux model to be implemented in the simulations to simulate water temperatures. GHD (2011) only applied winds across the surface and assumed a constant water temperature. The CFSv2 meteorology spans from July 2017-July 2022. Figure 3.6 and Figure 3.7 illustrate an example of the hourly meteorology over pool K1 during a 3 month period at the end of the 2018-2019 wet season.

Figure 3.6 ***Example of hourly CFSv2 meteorological data of shortwave radiation, incoming longwave radiation and air pressure over pool K1 from February-April 2019.***

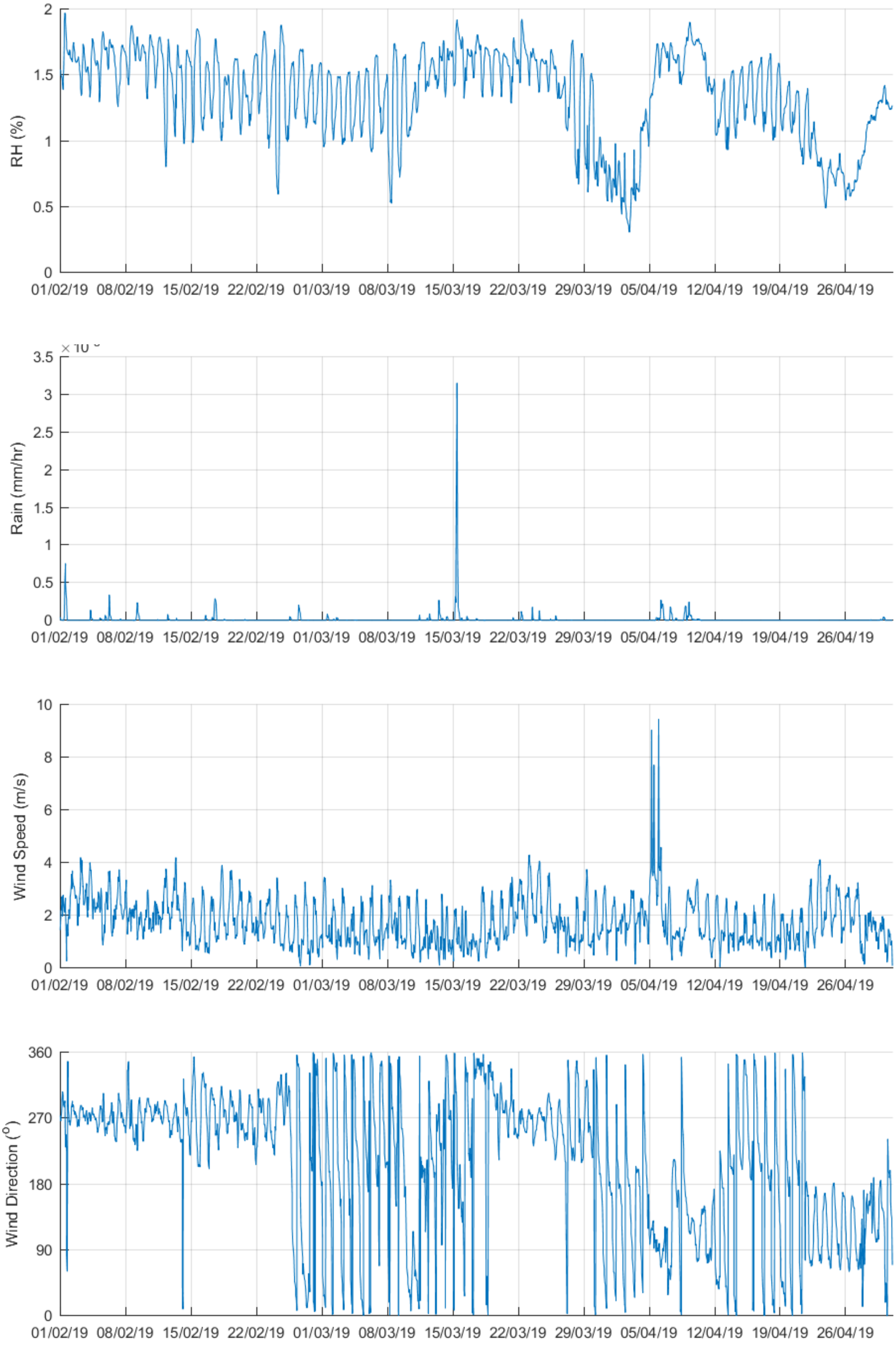

Figure 3.7 ***Example of hourly CFSv2 meteorological data of relative humidity (RH), rainfall, wind speed and wind direction over pool K1 from February-April 2019.***

3.2.3 Open ocean boundary inputs

Model inputs at the open ocean boundary that include spatially varying surface levels, and water temperatures, salinity and water currents through the water column, were generated from a combination of astronomical tides from the global tide model TPXO7.2 (Egbert and Erofeeva, 2002) and non-astronomical water levels from the Hybrid Coordinate Ocean Model (HYCOM) at 1/12° horizontal resolution and 3-hourly temporal resolution (Chassignet *et al*., 2007). Further, horizontal, vertical and temporal varying currents at the model open ocean boundary were generated from the combination of oceanographic (non-tidal) HYCOM and tidal TPXO7.2 currents. Lastly, temporally varying water temperatures and salinities through the water column at the model open ocean boundary was generated from HYCOM data.

An example of the offshore model inputs at the middle of the open ocean boundary is illustrated in Figure 3.8 for surface levels, and in Figure 3.9 for water temperature, salinity and currents (where v- and u- currents are the north (positive)-south (negative) and east (positive)-west (negative) component of water currents through the water column at this location, respectively) through the water column.

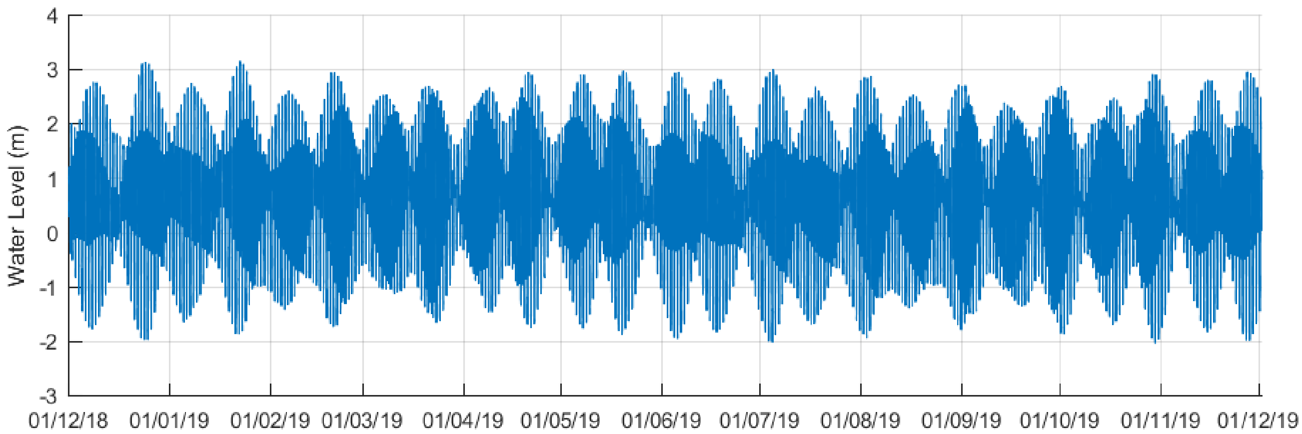

Figure 3.8 ***Water levels at the middle of the open ocean boundary from 1 December 2018 to 1 December 2019.***

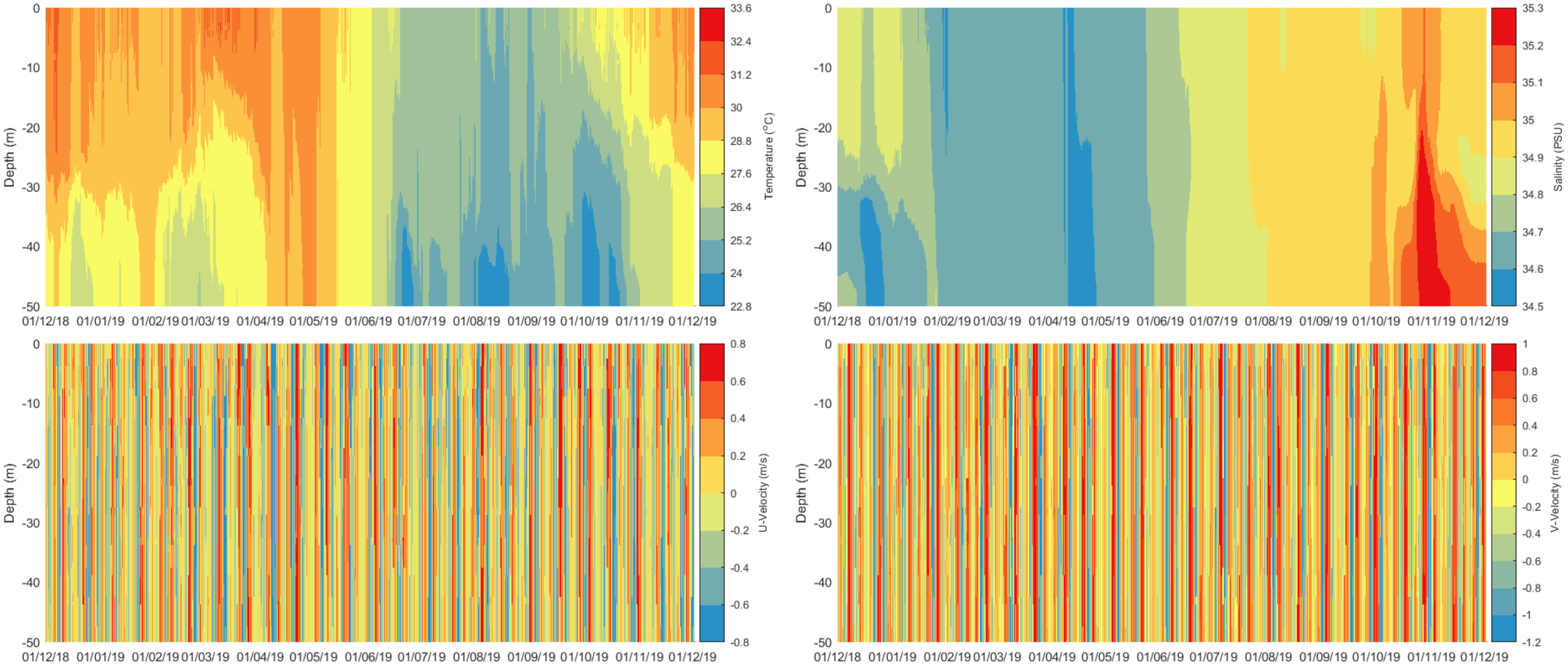

Figure 3.9 ***Water temperatures (upper left), salinities (upper right), and U- (positive east, negative west, lower left) and V- (positive north, negative south, lower right) currents at a middle location along the open ocean boundary from 1 December 2018 to 1 December 2019.***

3.2.4 Stream inputs of discharge, temperature and salinity

Two major streams of the lower Keep River system, the Keep River and Border Creek, are configured into the model. Model inputs of these two streams for the range of scenarios evaluated in this investigation were prepared via the stream input generator tool in terms of discharge, salinity, temperature and chemical concentrations, which is described in the next section.

There are several improvements in terms of stream input data in this investigation relative to GHD (2011), which include:

– Measurements of DW1 drain discharge from the Goomig farmlands are available from 2018-2022 (Section 2.2.1). The DW1GS gauging station was established after the GHD (2011) assessment, and thereby provides a marked improvement on characterising inputs from the Goomig farmlands to Border Creek than the previous investigation.

– Estimates of the Border Creek discharge above the confluence with the DW1 channel that conveys the Goomig farmland releases were estimated as the Border Creek measurements (station G8100106) less those of station DW1GS. If DW1GS discharge is greater than G8100106, then Border Creek flows above confluence are assumed to be zero.

– Stream water temperatures were based on measurement of Keep River at station G8100225 (Section 2.2.3).

– Dry and wet season salinities of DW1GS, Border Creek and Keep River were estimated from available measurements at the three (3) gauging sites of DW1GS, G8100106 and G8100225, respectively.

3.3 Stream input generator tool

As illustrated in the conceptual diagram of the modelling framework in Figure 3.1, the stream input generator tool was developed to prepare Keep River and Border Creek model inputs on the basis of available baseline hydrology (Section 2.2), stream water quality (Section 2.4), and farmland water and chemical management scenarios.

The key aspects of the stream input generator tool include:

– Ability to select either the end of wet season event (Section 2.2.2.1) and dry season infrastructure failure incident (Section 2.2.2.2) that represent high risk conditions to the lower Keep River system’s environment from farm chemical toxicity. The stream input generator tool produces the Border Creek and Keep River model inputs of discharge, salinity and water temperature.

– Border Creek discharge into pool K3 is determined on the basis of:
  - Measurements of Goomig farmland discharge via the DW1GS gauging station.
  - Estimates of Border Creek discharge above the confluence with DW1 drain discharge estimated as the measurement at G8100106 gauging station less those of DW1GS.
  - Additional M2 discharge can be specified to predict the effect of controlled releases to flush the lower Keep River pools.
  - DW1GS discharge can be modified to predict the effect of different release strategies on the lower Keep River pools.

– Keep River discharge into pool K4 is determined as:
  - Keep River discharge above the proposed Knox Plains farmlands, which is established as the flow measurements at G8100225 gauging station at pool K4.
  - The option to generate scenarios of drain water discharge from the proposed Knox Plains farmlands, which is assumed to flow into the Keep River above pool K4.
  - Additional M2 discharge can be specified to predict the effect of controlled releases to flush pools.

– The farmland chemical concentrations of each of the sources (i.e. natural Border Creek catchment, Keep River, M2 channel, DW1 drain, future Knox Plains drain) can be modified to evaluate a particular scenario where:

- For each scenario Keep River concentrations above pool K4 are determined on the basis of specified concentrations for each source (Keep River at pool K4, Knox Plains drain water and M2 releases, see Sections 3.4.2 and 3.4.3) and their discharge.
- For each scenario Border Creek concentrations prior to the confluence with pool K3 are determined on the basis of specified concentrations for each source (Border Creek above the DW1 confluence, DW1 drain and M2 releases, see Sections 3.4.2 and 3.4.3) and their discharge.
- The chemical levels of releases from the future Knox Plain farmlands are assumed to be the same as the Goomig farmlands.

In short, the stream input generator tool is used to systematically configure the 3D model inputs to allow evaluation of the effect of on-farm management actions (e.g. M2 releases) and/or preventative measures (e.g. selection of farm chemicals with reduced aquatic toxicity) to manage ecological risks to the lower Keep River pools.

3.4 Farmland chemicals

3.4.1 Toxicity guideline values and degradation half-lives

Section 2.4 identified four farmland chemicals that were regularly detected in Border Creek, DW1 drain and/or lower Keep River pools, namely metolachlor, atrazine, diuron and methomyl. Table 3.2 provides a summary of the adopted PC99 values on the basis of ANZG (2018) and King et al (2017), and adopted degradation half-lives in water on the basis of the scientific literature.

Table 3.2 Adopted (bold red) PC99 values used to assess ecotoxicity in the lower Keep River pools and the adopted (bold red) degradation half-lives of the simulated farmland chemicals (note F – freshwaters, E – estuary, W – water, GW – groundwater).

Chemical	Concentration (µg/L)					Half-Life (days)			
	ANZG (2018) 99% LSP	ANZG (2018) 95% LSP	ANZG (2018) Unknown	King et al (2017) 99% LSP	King et al (2017) 95% LSP	ANZG (2018)	PDST[1] (Warne et al 2023)	PPDB[2] (University of Hertfordshire 2013)	Adopted PC99 value in this Investigation
Metolachlor	**0.0084 (F)**	0.46 (F)				>200	88 (W)	88 (W)	**90**
Atrazine	**0.7 (F)**	13 (F)				~60 (F), ~<30 (E)	80 (GW)	80 (GW), - (W)	**30**
Diuron			0.2 (F)	**0.08 (F)**	0.23 (F)	-	8.8 (W)	8.8 (W)	**9**
Methomyl	**0.5 (F)**	3.5 (F)				-	-	2.9 (W)	**3**

3.4.2 End of wet season event concentrations

Section 2.2.2.1 describes the hydrology of the selected end of wet season event that is evaluated in this investigation as a case example of potential toxicity risks to the lower Keep River pools and mitigation measures to reduce these risks. The following approach was adopted to assign farmland chemical concentrations to the Border Creek and Keep River model inputs:

– During the wet season event from 23 March-3 April 2019 high farmland chemical concentrations are prescribed for the existing Goomig and future Knox Plains drain waters that discharge into Border Creek and Keep River, respectively. The maximum concentration of each farmland chemical that has been measured from DW1GS, Border Creek gauging station or any of the lower Keep River pools (Table 2.4 of Section 2.4) is adopted as a worst case representative value. The Goomig farmlands have only been farmed since 2014, and not to full capacity, hence the use of the maximum concentrations in this investigation is considered a conservative worst case given the current pesticide application and use.

[1] Pesticide decision support tool for the Queensland sugar cane industry.
[2] Pesticide properties database.

– At other times a typical background concentration for Border Creek, Keep River and M2 irrigation water was assumed to be the median of available measurements of each farmland chemical (Table 2.4 of Section 2.4).
– A simple dilution model based on discharge is used to calculate the resultant farmland chemical concentration that is discharged into the Keep River (mix of drain water and M2 irrigation water) and Border Creek (mix of Border Creek, drain water and M2 irrigation water) by the stream input generator (Section 3.2).

Table 3.3 provides a summary of these adopted chemical concentrations.

Table 3.3 ***Adopted background farmland chemical concentrations of surface water sources to the lower Keep River during the end of wet season scenarios, and adopted concentrations in the drainage water during the high risk discharge event (Drain – Event) to Border Creek (Goomig farmlands) and Keep River above pool K4 (Knox Plains farmlands).***

Chemical	Drain – Event (µg/L) (maximum measurement in M2, DW1GS, Border Cr Gauge or river pools)	Background (µg/L) (median, if <LoR then assumed 0 (µg/L)				
		Drain	Border Creek	Keep River	M2 Irrigation Water	Open Ocean Boundary
Metolachlor	5	0.1	0	0	0	0
Atrazine	10	0	0.03	0	0	0
Diuron	1	0	0	0	0	0
Methomyl	0.25	0	0	0	0	0

3.4.3 Dry season infrastructure failure incident concentrations

Section 2.2.2.2 describes the hydrology of the selected infrastructure failure incident during the dry season that is evaluated in this investigation as an example of potential toxicity risks to the lower Keep River pools and mitigation measures to reduce these risks. The tailwater releases in Table 2.3 and Figure 2.10 of Section 2.2.2.2 are the adopted baseline hydrology for this event. For each of the four farmland chemicals considered in this study (atrazine, metolachlor, diuron, methomyl) idealised (simplified) concentrations of the tailwater releases to Border Creek during the incident is illustrated in Figure 3.10, which is based on that of atrazine measurements during the event in Figure 2.16 of Section 2.4.1. The model input of chemicals into pool K3 from Border Creek is the tailwater release concentration estimates (red line in Figure 3.10) that are diluted by the M2 flushing flows that start on 31 July. The resultant concentrations of Border Creek input concentrations into pool K3 (dashed blue line in Figure 3.10) are similar to the exponential curve fitted to the atrazine measurements at the Border Creek gauge that was described in Figure 2.16 of Section 2.4.1.

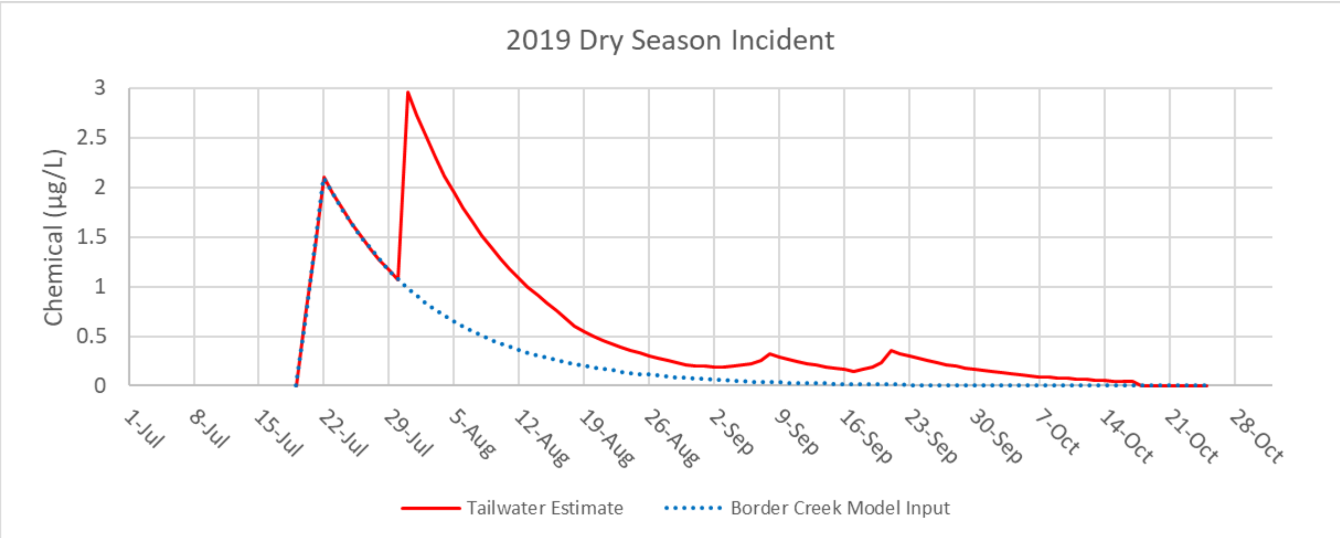

Figure 3.10 ***Idealised tailwater release concentrations of farmland chemicals for dry season infrastructure failure incident case into upper Border Creek (red line) and Border Creek levels into pool K3.***

3.5 Scenarios

3.5.1 Approach

The four farm chemicals evaluated in this investigation all have PC99 values on the basis of ANZG (2018) (metolachlor, atrazine, methomyl) or King et al (2017) (diuron) as described in Section 3.4.1. In Section 2.2.2 several periods in 2019 were identified with hydrological conditions that may pose high toxicity risks to the lower Keep River system (i.e. small rainfall events at the end of the wet season, dry season tailwater releases into Border Creek) if released farmland drainage waters have high chemical concentrations. Simulations of these periods were carried out to evaluate whether the PC99 toxicity criteria are predicted to be met if accompanied by high chemical concentrations in the drainage water during these events. If the PC99 criteria are not met, then the duration of exceedance prior to being diluted or degraded to environmentally acceptable levels is predicted.

3.5.2 Model inputs

Each of the scenarios were defined as follows:

- Selection of one of the two hydrological events that were identified in Section 2.2.2 (i.e. end of wet season event or dry season infrastructure failure event).
- Scenarios were configured with a range of M2 irrigation water releases into Border Creek (via DW1GS for Goomig farmlands) and/or Keep River (via the Knox Plains farmlands main drain) to evaluate the effectiveness of flushing/dilution of the lower Keep River pools to reduce chemical concentrations in these sensitive environmental receptor settings.
- If the future Knox Plains farmlands were included in a scenario, then it was assumed farmland releases from this development's drain (confluence with Keep River above pool K4) were equivalent to the Goomig farmlands (via DW1GS). Similarly, the volume of M2 irrigation water (if configured) to flush the lower Keep River pools (including pool K4, which is not affected by flushing releases from the Goomig farmland via Border Creek) was defined.
- Chemical model inputs were based on the following:
  - For the end of wet season event, the maximum and median farm chemical concentrations from available data (Section 3.4.2) were used as the model inputs over the critical ~10 day high risk release period (23 March-3 April 2019 with high concentrations in the farmland releases) and at other times (i.e. background levels), respectively. The use of the maximum available concentration is a conservative measure to estimate the potential toxicity risks to the ecology of the lower Keep River pools from such an event.
  - For the dry season infrastructure failure case, the time series of released tailwater atrazine estimates into Border Creek above the confluence with DW1 (Section 3.4.3) was used as the concentrations for metolachlor, diuron and methomyl as well. Simulations of these three (3) additional chemicals in addition to atrazine allows an evaluation of the effect of degradation rates on toxicity risks to the lower Keep River pools as all other inputs (e.g. input chemical concentrations) for the dry season infrastructure failure case are the same across the four (4) chemicals. For example, how do the predicted concentrations of diuron with a faster degradation half-life of ~10 days in the lower Keep River pools differ to those of atrazine with a slower degradation half-life of ~30 days?

3.5.2.1 Dry season incident

A summary of this investigation's scenarios of Border Creek model inputs of discharge and chemical concentrations into pool K3 during the dry season tailwater release incident scenarios is provided in Figure 3.11. The four (4) scenarios with differing Border Creek inputs were:

- **Verify** scenario is comprised of the idealised Border Creek gauge hydrology (see Section 2.2.2.2) and estimated atrazine chemical levels (see Section 2.4.1) for the 'actual' 2019 event with M2 flushing flows.
- **50% Less Flushing** scenario is the same as the **Verify** scenario inputs with only the first half of M2 flushing flows with a concomitant slight increase in atrazine concentrations from 7 September as a result.

– **No Flushing** scenario assumes no M2 flushing flows with a concomitant large increase in atrazine concentrations from 30 July relative to the **Verify** scenario (no M2 releases).

– **Reduce TW** (tailwater) **Conc** (concentration) scenario assumes tailwater releases with no second peak in atrazine concentrations around 1 August of the **No Flushing** scenario (see red line in concentration plot of Figure 3.11) and the M2 flushing flows of the **Verify** scenario. This scenario assumes that water quality monitoring identifies tailwater releases with high chemical concentrations and alternative tailwater basins of lower toxicity (lower chemical concentrations) are available to release water. These so-called tailwater basins are hypothetical in the context of the model, but my be available in future as the Knox Plains farmlands will require compensating basins, and the proposed Sorby Mine by Boab Metals (if it proceeds) is likely to have stormwater and dewatering basins.

To evaluate the effect of a range of degradation half-lives on chemical levels in the lower Keep River pools, metolachlor, diuron and methomyl were simulated with the same Border Creek concentrations and loads as atrazine for each of the four (4) dry season tailwater release (infrastructure failure) scenarios (see Figure 3.11).

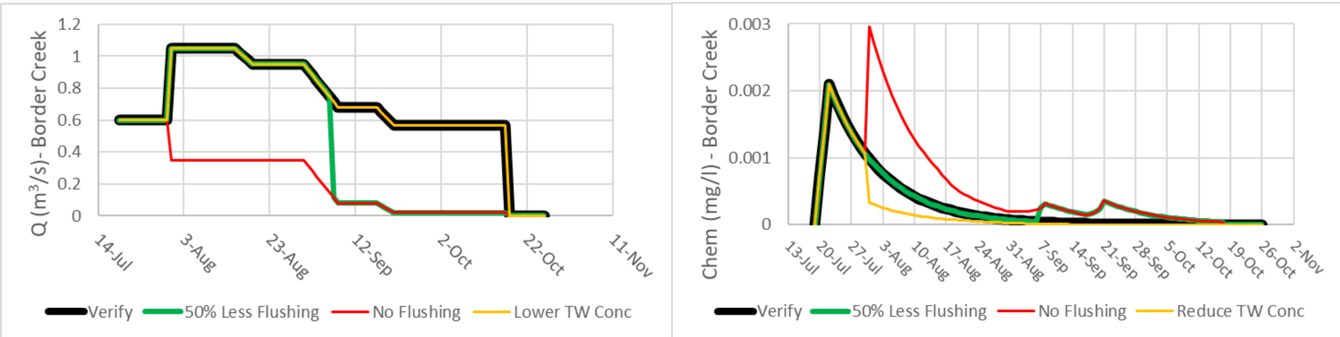

Figure 3.11 ***Dry season tailwater release (infrastructure failure) model inputs for Border Creek discharge (Q) and chemical concentrations into pool K3 of four (4) scenarios.***

3.5.2.2 Wet season event

A summary of the hydrology and chemical model inputs for Border Creek (including any Goomig farmland contributions and M2 flushing flows) and Keep River (including any Knox Plains farmland contributions and M2 flushing flows) that were used in various combinations to construct the end of wet season scenarios is provided in Figure 3.12. M2 flushing flows of 0 MLD (baseline), 50 MLD, 100 MLD and 150 MLD of 1 month duration that started ~10 days after the end of the high chemical loading event on 3 April 2019. Concentrations of the four (4) chemicals over the period when a high proportion of Border Creek and Keep River flows were farmland drainage (i.e. 23 March-3 April 2019) was estimated with a mass balance from discharge and characteristic chemical concentrations (see Table 3.3 of Section 3.4.2). The end of wet season event scenarios predict the toxicity risk to the lower Keep River from the four (4) chemicals assuming credible maximum estimates of the farmland drainage concentrations during such an event (Table 3.3).

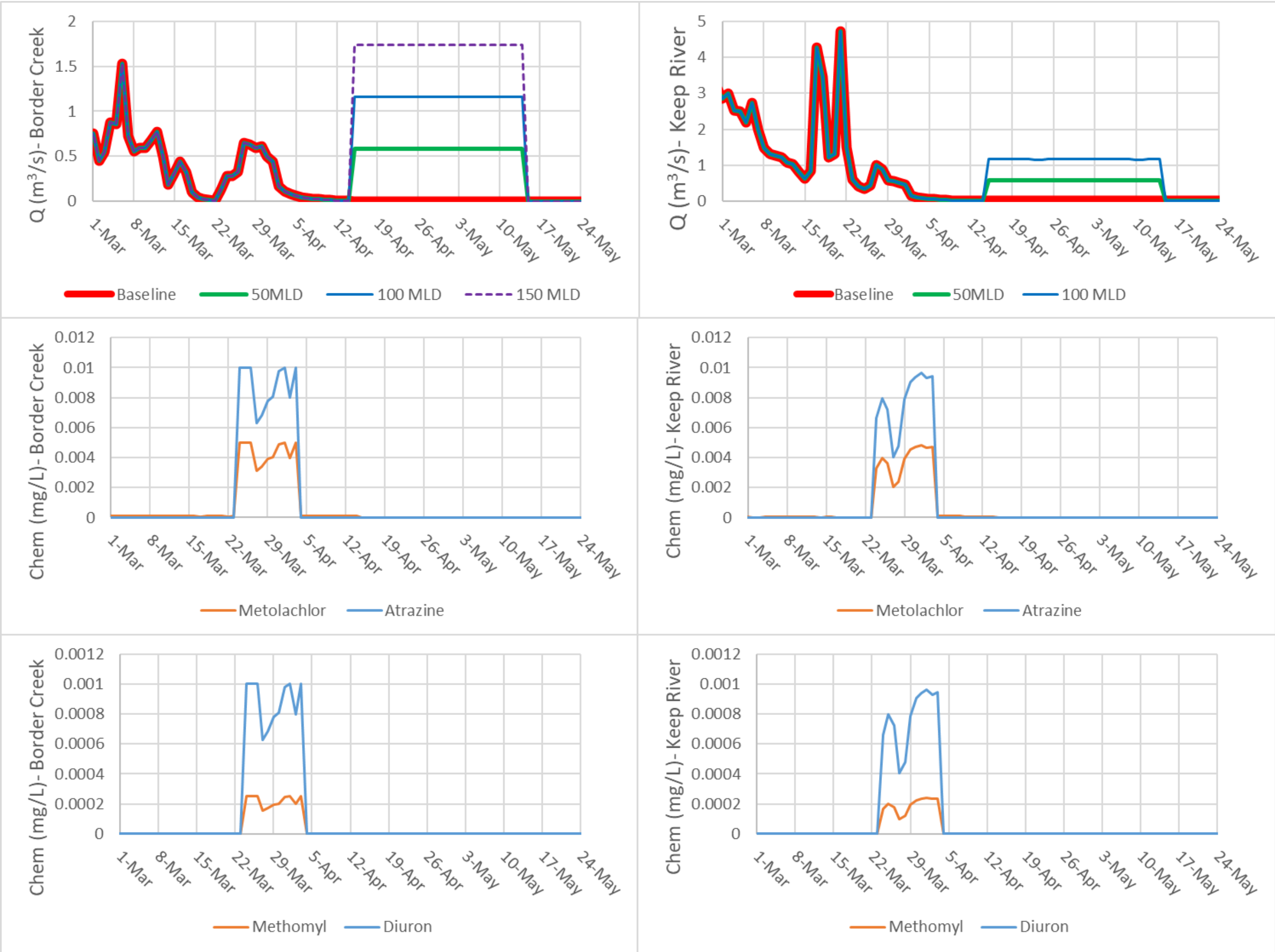

Figure 3.12 ***End of wet season scenario range of model inputs for discharge (Q) from Border Creek (upper left) and Keep River (upper right) into pools K4 and K3, respectively, and concentrations of the four (4) chemicals from the Goomig farmlands into Border Creek and the Knox Plain farmlands into Keep River during the 23 March-3 April high risk event. M2 flushing flows begin 10 days later on 14 April for a period of 30 days.***

3.5.3 Overview of scenarios

A summary of the scenarios that were evaluated in this investigation is provided in Table 3.4.

Table 3.4 Summary of scenarios

Scenario ID	Simulation Period and Primary Hydrology Driver	M2 Flush Goomig	Knox Plains Farmlands	M2 Flush Knox Plains	Scenario Description and Objective
Dry Season Infrastructure Failure Scenarios					
Verify	Simulation Period: 22 July-1 December 2019 Hydrology Driver: Infrastructure failure incident with direct release of tailwater into Border Creek above confluence with DW1 from 19 July-17 October 2019	Yes	No	No	2019 Goomig verification scenario to evaluation high risk infrastructure failure event from 19 July-17 October 2019 with M2 irrigation water releases implemented as management action. *Objective: Verify atrazine measurements in the pools over the incident period that accounts for M2 flushing flows released into Border Creek. Evaluate effect of half-life degradation rates on resultant chemical levels in pools assuming same loading.*
No Flushing		No	No	No	2019 Goomig baseline scenario to evaluate high risk infrastructure failure event from 19 July-17 October 2019 if there was no management action (i.e. no M2 irrigation water flushing flows). *Objective: Predict chemical levels in the lower Keep River pools with no M2 irrigation water flushing flows.*
50% Less Flushing		Yes	No	No	2019 Goomig flushing scenario to evaluate of high risk infrastructure event from 19 July-17 October 2019 with a 50% decrease M2 irrigation water flushing flows. *Objective: Predicted chemical levels in the lower Keep River pools with 50% decrease in the duration of M2 irrigation water flushing flows.*
Reduce TW (tailwater) Conc (concentration)		Yes	No	No	2019 Goomig verification scenario with release of alternative tailwaters with lower chemical levels. *Objective: Predicted chemical levels in the lower Keep River pools with M2 flushing flows and a reduction in tailwater release chemical levels.*
End of Wet Season Scenarios					
Goomig Baseline	Simulation Period: 20 Febuary-1 October 2019 Hydrology Driver: 23 March-3 April 2019 elevated drain water primary source to lower Keep River	No	No	No	2019 Goomig baseline scenario to evaluate high risk discharge event from 22 March-3 April 2019 with no management action. *Objective: Establish baseline worst case condition in the absence of any management actions (i.e. flushing) from a high risk farmland release event with very high chemical levels for existing operation.*
Goomig 50 MLD Goomig 100 MLD Goomig 150 MLD		Yes	No	No	2019 Goomig M2 flushing scenarios with releases via DW1GS from 15 April–14 May 2019 (~1 month) of 50, 100 and 150 MLD. *Objective: Evaluate benefit of a range of M2 irrigation water flushing discharge rates over 1 month immediately after high risk event to meet acceptable environmental criteria in lower Keep River pools.*
Goomig+Knox Baseline		No	Yes	No	2019 Goomig and Knox Plains baseline scenario to evaluate high risk release event from 22 March-3 April 2019 with no management action. *Objective: Establish baseline worst case condition in the absence of any management actions (i.e. flushing) from a high risk event with very high chemical levels for existing and future farmlands in operations.*
Goomig+Knox 50+50 MLD Goomig+Knox 100+100 MLD		Yes	Yes	No	2019 Goomig and Knox Plains M2 flushing scenarios with releases into Border Creek and Keep River, respectively, from 15 April–14 May 2019 of 50 and 100 MLD from each development. *Objective: Determine volume of M2 irrigation water flushing flows over a 1 month duration after high risk event that occurs in both the existing and future farmlands to meet acceptable environmental criteria in the lower Keep River pools.*

3.5.4 Scenario exposure evaluation

Comparisons of chemical monitoring data to relevant PC99s served as initial evaluation criteria of these substances on the potential toxicity risk to the lower Keep River system environment in this investigation. However, the use of PC99 exceedance as a toxicity risk criterion does not account for the duration and cumulative exposure of sensitive environmental receptors to such chemicals.

An improved toxicity risk criterion was also used to evaluate potential toxicity risks for the scenarios of the three (3) cases (i.e. dry season infrastructure failure, end of wet season Goomig farmland, end of wet season Goomig and Knox Plains farmlands), namely the simulated chemical exposure when above the relevant PC99. This exposure criterion (E, ppb hr) is calculated as follows:

$$E = \sum_{i=1}^{i=N} \frac{1}{48} C_i$$

where N is the number of half hourly model output concentrations when the chemical (C_i, µg/L) is greater than the PC99, and 1/48 represents the half hourly interval portion of a day. It is assumed that if the simulated concentration at a time step is less than PC99, then toxicity is negligible.

E is calculated for each of the four (4) sites of the lower Keep River pools (K4, K3, K2, K1) and the two (2) further down-river estuarine sites (G8100111, E3). E at the end of each simulation for each chemical is tabulated and used as a second metric of potential toxicity risks to the lower Keep River system.

4. Model verification

Model verification of the 3D hydrodynamic model was based on adequately reproducing observations of the water levels, water temperatures and salinities of the lower Keep River pools. Additionally, verification of the chemical model was carried out through comparisons of atrazine measurements in pools K3, K2 and K1 during the 2019 infrastructure failure incident (Section 2.4.1).

All simulations were carried out over the period between 20 February 2019 (end of the 2018-19 wet season) and 1 December 2019 (end of 2019 dry season). There were no measurements of water levels, temperatures and salinities in the lower Keep River pools over this period, so the 2013 dry season hourly measurements (see Section 2.3) were used to quasi-validate the model as the annual (July-June) Keep River discharge of 100 GL/y (rank 23 of 24 from 1998-2022) was similar the year that was 2018-19 with 77 GL/y (rank 24). Hence, model verification was based on comparisons between the 1 April-1 October 2013 measurements and the 2019 simulation in pools K3, K2 and K1 of water level, temperature (T) and salinity (S). Electrical conductivity (EC, mS/m) was converted to salinity (S, PSU) with the relation $S = 0.465\ (EC/100)^{1.0878}$. Simulated and measured atrazine concentrations in pools K1, K2 and K3 from July-October 2019 were used to verify the chemical model.

4.1 Water levels

A comparison of the 2013 hourly measured and 2019 half hourly simulated water levels is illustrated in Figure 4.1. Generally, the range in water level variations of the measurements and the simulation in each of the pools are similar. In both cases peak water level variations occurred during large spring tides. This indicates that the hydrodynamic model adequately simulates water level variations of the lower Keep River pools.

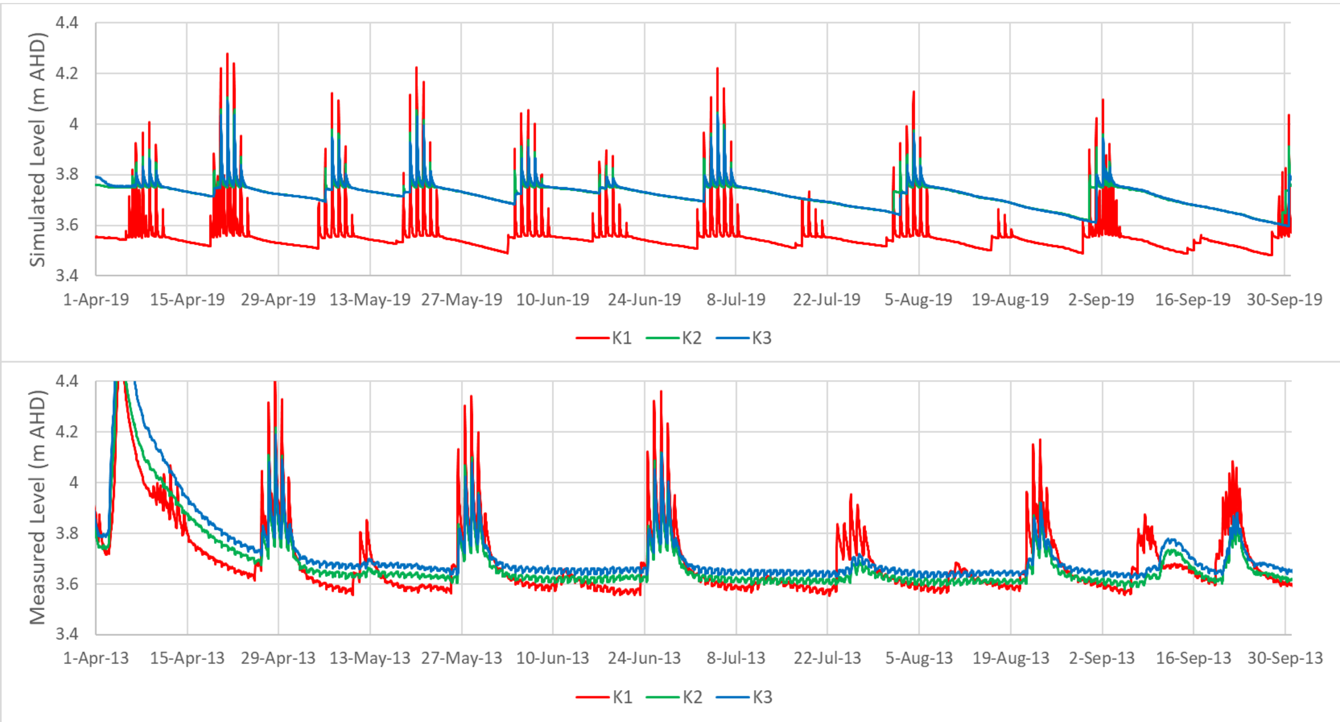

Figure 4.1 ***Comparison of the 2019 half hourly simulated and 2013 hourly measured water levels in pools K1, K2 and K3 from April-October.***

4.2 Temperature

A comparison of the 2013 hourly measured and 2019 half hourly simulated water temperatures is illustrated in Figure 4.1. The measured and simulated water temperatures both spanned a range of ~20-32°C. Diel (24 hour) temperature variations were typically ~2°C in the simulations and somewhat larger (~3°C) in the measurements. Generally, the simulated seasonal and diel water temperatures are reproduced well by the model, which indicates that the surface heat fluxes (insolation, incoming longwave radiation, sensible and latent heat), offshore open ocean boundary water temperatures and river inflow temperatures are adequately simulated.

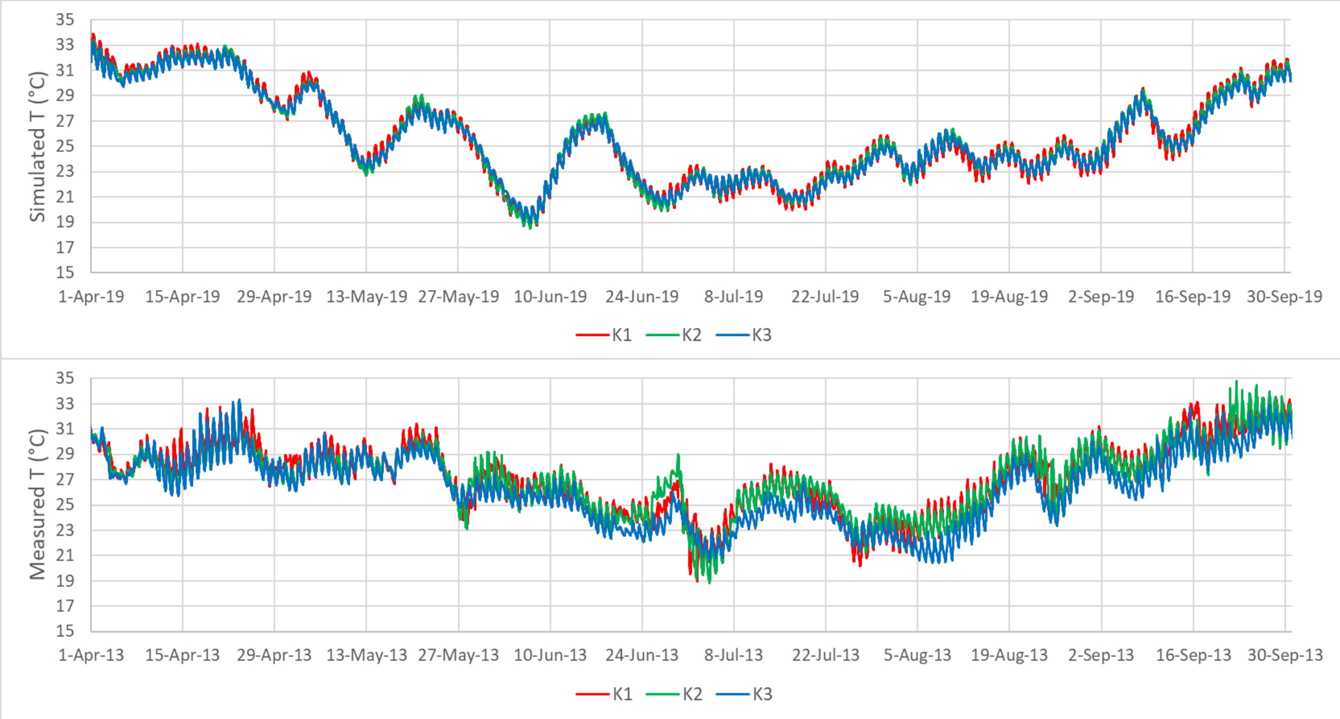

Figure 4.2 ***Comparison of the 2019 half hourly simulated and 2013 hourly measured water temperatures (T) in pools K1, K2 and K3 from April-October.***

4.3 Salinity

A comparison of the 2013 hourly measured and 2019 half hourly simulated water salinities is illustrated in Figure 4.3. The 2013 electrical conductivity measurements were considered adequate through early to mid-July, which are shown here. Generally, the pattern of increasing salinity in each of the lower Keep River pools was similar between the measurements and simulation from tidal transport of Joseph Bonaparte Gulf marine waters up the Keep River. For example, measured and simulated rates of salinity increases in pool K1 were similar at ~5 PSU per month. Similarly, measured and simulated rates of salinity increases at sites K2 and K3 were similar. Generally, the simulated rate of salinity increases in the lower Keep River pools are reproduced well by the model, which indicates that the offshore open ocean boundary salinities, river inflow salinities and tidal transport dynamics are adequately simulated.

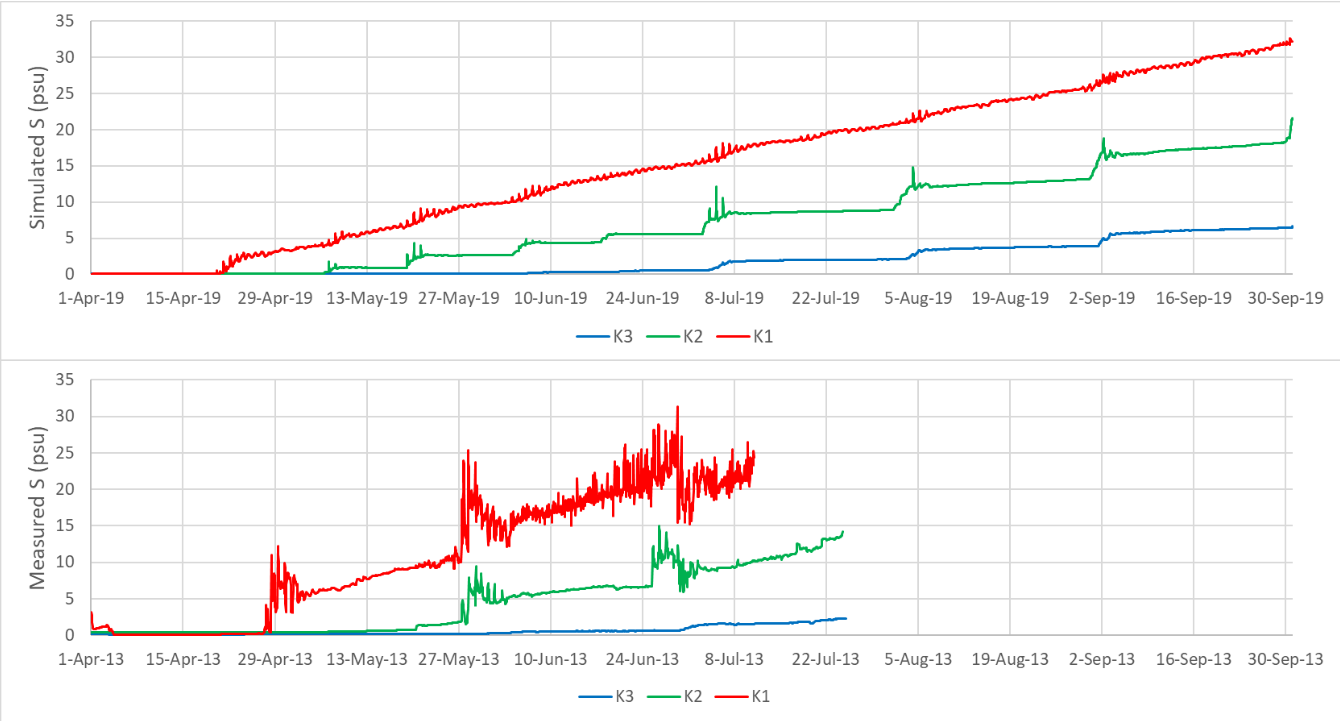

Figure 4.3 ***Comparison of the 2019 half hourly simulated and 2013 hourly salinity (S) estimates from electrical conductivity (EC) measurements in pools K1, K2 and K3 from April-October.***

4.4 Water quality

The simulated atrazine levels in the lower Keep River pools during the 2019 dry season tailwater release incident with the idealised hydrology and estimates of tailwater release concentrations reasonably reproduced the spatial and temporal measurements of the lower Keep River pools at sites K1, K2 and K3 (Figure 4.4). The simulation predicts atrazine was above PC99 for ~13 and ~10 days in pools K3 and K2, respectively (no PC99 exceedance simulated in pool K1). Generally, the measured atrazine concentrations are reproduced well by the model, which indicates that:

– The estimates of Border Creek model inputs of atrazine levels are adequate.
– The Border Creek hydrologic inputs (i.e. M2 flushing rates and tailwater releases) are estimated properly.
– The transport and dispersion dynamics of the lower Keep River pools are simulated well.

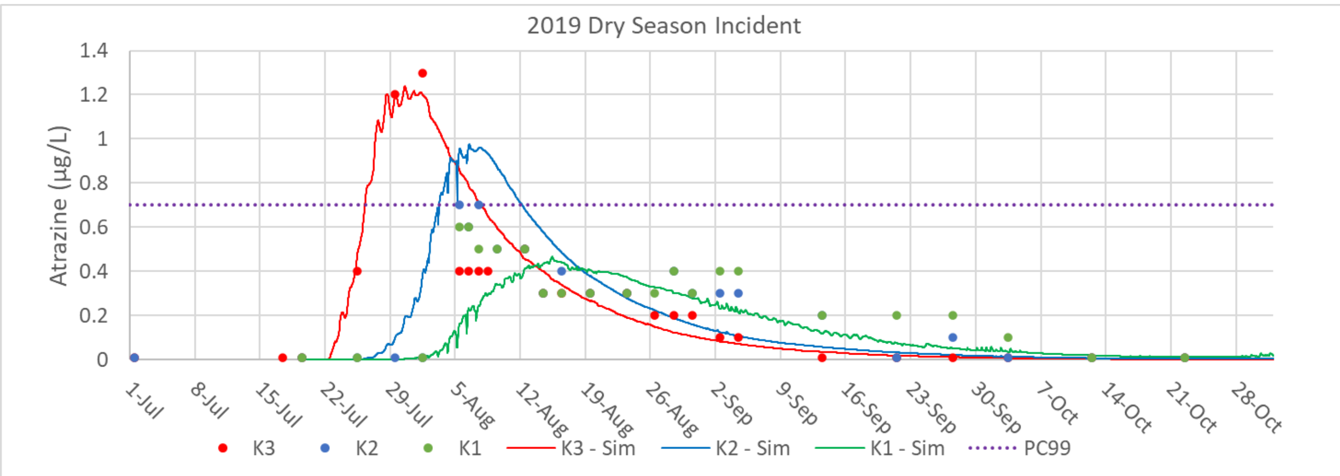

Figure 4.4 ***Comparison of simulated (lines) and measured (symbols) atrazine concentrations in the lower Keep River pools at sites K3, K2 and K1 during the 2019 dry season tailwater release incident. Purple dashed line represents the PC99 for atrazine of 0.7 µg/L.***

5. Scenarios

5.1 Dry season infrastructure failure scenarios

In addition to the simulation of atrazine for the dry season infrastructure failure verification scenario (scenario 'Verify') presented in Section 4.4, it is informative to consider the other three (3) chemicals (metolachlor, diuron, methomyl) assuming they had the same Border Creek concentrations as atrazine (note atrazine was the only chemical that was regularly sampled over the 2019 dry season tailwater release [infrastructure failure] incident). This allows an assessment of the effect of the range of degradation half-life values of these four (4) chemicals (~3 to ~90 days, see Section 3.4.1) on chemistry levels in the lower Keep River system as loads and subsequent transport and dispersion are equivalent between the four (4) pesticides for each of the four (4) dry season infrastructure failure scenarios. The atrazine and diuron PC99 values of 0.7 µg/L (relatively high criterion with relatively low toxicity) and 0.08 µg/L (relatively low criterion with relatively high toxicity), respectively, were adopted for the dry season infrastructure failure scenarios to demonstrate the effect of a range of chemical degradation rates (i.e. half-lives) and toxicity (i.e. PC99s) on potential risks to the lower Keep River system environment.

5.1.1 PC99 exceedance assessment

Figure 5.1 and Figure 5.2 illustrate the simulated concentrations of the four (4) chemicals at the selected sites in the lower Keep River system for the four (4) dry season tailwater release (infrastructure failure) scenarios (see Section 3.5.3).

A summary of the 'No Flushing' scenario simulation includes:

– Simulated concentrations of diuron and methomyl (with relatively rapid degradation rates and shorter half-life values) decreased rapidly to low levels relative to metolachlor and atrazine (with relatively slow degradation rates and longer half-life values). This pattern was common to the other three (3) scenarios as well.

– For the relatively high atrazine PC99 indictive of relatively low toxicity:
  - The exceedance duration of atrazine and metolachlor in pool K3 was ~1 month for both chemicals. In pool K2 the exceedance duration was ~3.5 and ~8 weeks for atrazine and metolachlor, respectively. The lower exceedance duration of atrazine was due to its faster degradation rate (half-life 30 days) than that of metolachlor (half-life 90 days).
  - Diuron exceeded the atrazine PC99 for ~3 weeks in pool K3, but because of this chemical's relatively rapid degradation rate (half-life 10 days) it was not predicted to exceed the toxicity criterion value in pool K2.
  - There were no atrazine PC99 exceedances for any of the chemicals in pool K1, and sites G8100111 and E3, primarily due to insufficient tidal exchange between the pools to increase concentrations of the slowly degrading metolachlor to this toxicity criterion value (i.e. atrazine PC99).

– For the relatively low diuron PC99 indicative of relatively high toxicity:
  - The slowly degrading (half-life 90 days) metolachlor exceeded the diuron PC99 in pools K3, K2 and K1 from the first several weeks to the end of the simulation on 1 December, but there was insufficient tidally induced exchange below pool K1 to lead to exceedances at sites G8100111 and E3.
  - Atrazine, with a moderate degradation rate (half-life 30 days), exceeded the diuron PC99 in pools K3, K2 and K1 from the first several weeks to nearly the end of the simulation, but degradation was sufficient to decrease concentrations below the toxicity criterion by 1 December (end of simulation).
  - Due to the rapid degradation rate (half-life 10 days) of diuron, this chemical exceeded the diuron PC99 in pools K3 and K2 for ~8 weeks and ~6 weeks, respectively. However, there were no exceedances in pool K1, and sites G8100111 or E3.
  - Due to the very rapid degradation rate (half-life 3 days) of methomyl, this chemical only exceeded the diuron PC99 in pool K3 for ~5 weeks with no exceedances at any of the other sites in the lower Keep River system.

- In summary, if no flushing was implemented during the 2019 tailwater release incident, the low tidally induced exchange between the pools was predicted to primarily restrict elevated chemical levels to the upper three (3) pools. If the chemical of concern has rapid to very rapid degradation rates similar to diuron (half-life 10 days) and methomyl (half-life 3 days), then the management option to not release M2 irrigation water to flush the pools ought to be considered for a similar future dry season incident. If the chemical of concern has moderate to slow degradation rate similar to atrazine (half-life 30 days) and metolachlor (half-life 90 days), then flushing of the pools with M2 releases is necessary to reduce the PC99 exceedance duration of these chemicals for such a dry season incident.

A summary of the 'Verify' scenario simulation includes:

- Peak levels of atrazine and metolachlor were lower than the 'No Flushing' scenario in pools K3 (1.8 and 1.6 µg/L to 1.3 and 1.2 µg/L for metolachlor and atrazine, respectively) and K2 (1.8 and 1.6 µg/L to 1.3 and 1.2 µg/L for metolachlor and atrazine, respectively). However, flushing increased peak levels of diuron and methomyl in pools K2 and K1 relative to the 'No Flush' scenario because the induced down-river transport of these chemicals was more rapid than the degradation time scales. The down-river transport induced by the flushing also substantially increased metolachlor, atrazine and diuron (only at site G8100111 for diuron) at sites G8100111 and E3 relative to the 'No Flush' scenario.
- For the relatively high atrazine PC99 indicative of relatively low toxicity:
  - The exceedance durations of atrazine and metolachlor were ~2 and ~1.5 weeks in pools K3 and K2, respectively, which were clearly much shorter than the 'No Flushing' scenario. However, though M2 releases were effective in flushing the persistent chemicals of metolachlor and atrazine almost entirely from the lower Keep River pools, with the cessation of M2 releases in October, the elevated metolachlor (and to a lesser degree atrazine) concentrations down-river of pool K1 (i.e. site G8100111) were tidally transported up-river over the last month of the simulation. This led to increased concentrations in pool K1 over the final ~1 month of the simulation. This increase late in the dry season for metolachlor was well below the relatively low toxicity atrazine PC99 (0.7 µg/L), but increased sufficiently to exceed the relatively high toxicity diuron PC99 (0.08 µg/L).
  - The exceedance duration of diuron in pool K3 was greatly reduced to ~1.5 weeks relative to the ~4 weeks of the 'No Flush' scenario. Further, though flushing increased peak levels in the three (3) pools, it was not sufficient to exceed the atrazine PC99.
  - Similarly, flushing increased methomyl peak concentrations in all three (3) pools relative to the 'No Flush' scenario, but not sufficiently to exceed the atrazine PC99.
- For the relatively low diuron PC99 indicative of relatively high toxicity:
  - Slowly degrading metolachlor exceeded the diuron PC99 in pools K3, K2 and K1, and site G8100111 for ~5, ~6, ~8 (for initial period of exceedance) and ~11 weeks, respectively. Relative to the 'No Flushing' scenario, there was a predicted decrease in the exceedance duration in pools K1 and K2, but flushing also led to exceedances at sites G8100111 and E3. As described previously, in pool K1 after metolachlor levels decreased below the diuron PC99 at the end of September, subsequent tidal exchange with the down-river estuarine waters increased concentrations to just above the toxicity criterion value after ~1 month. Substantially higher concentrations were simulated at site E3 than the 'No Flushing' scenario, albeit below the diuron PC99.
  - Moderately degrading atrazine exceeded the diuron PC99 in pools K3, K2 and K1, and site G8100111 for ~5, ~6, ~7 and ~7 weeks, respectively. Relative to the 'No Flushing' scenario, there was a large decrease in the exceedance duration of pools K3, K2 and K1, but flushing also led to a substantive exceedance at site G8100111 that did not occur with no flushing. Further, substantially higher concentrations were simulated at site E3 than the 'No Flushing' scenario, albeit below the diuron PC99.
  - Rapidly degrading diuron exceeded the PC99 in pools K3, K2 and K1 for ~5, ~5 and ~4 weeks, respectively. Relative to the 'No Flushing' scenario, there was a predicted decrease in the exceedance duration in pools K3 and K2, but flushing also led to a substantive exceedance in pool K1 that was not modelled with no flushing. However, there were no exceedances at sites G8100111 or E3 as sufficient degradation had occurred prior to transport by the M2 flushing flows that concentrations were very low at these locations.

- Due to the very rapid degradation rate of methomyl, this chemical only exceeded the diuron PC99 in pools K3 and K2 for ~5 and ~2 weeks, respectively. Relative to the 'No Flushing' scenario, there was a predicted decrease in the exceedance duration in pool K3, but flushing also led to an exceedance at pool K2 that was not modelled with no flushing. There were no exceedances of the diuron PC99 by methomyl at any of the other lower Keep River system sites due to the rapid simulated degradation of this chemical.

– In summary, the effect of the ~2 months of M2 releases was to flush and dilute chemical levels in pools K2 and K3 so that peak levels and exceedance durations were markedly decreased in these water bodies. However, flushing also transported greater chemical loads (and associated concentrations) to pool K1 and site G8100111 that increased the toxicity risk to these water bodies, particularly for chemicals with lower degradation rates, relative to the simulation with no flushing. In fact, up-river tidally induced transport after the cessation of M2 flushing releases was predicted for metolachlor in pool K1 over the final month of the simulation due to sufficiently elevated levels at site G8100111. In short, flushing to manage toxicity from a dry season incident similar to that of 2019 is an effective mitigation measure for slowly to moderately degrading chemicals (metolachlor, atrazine), but less so for rapidly degrading substances (diuron, methomyl) where *in situ* degradation without flushing may be preferable.

A summary of the '50% Less Flushing' scenario simulation includes:

– Peak levels of all four (4) chemicals were similar to the 'Verify' scenario at all five (5) sites. However, higher metolachlor and atrazine levels in pool K1 relative to the 'Verify' scenario after the cessation of M2 releases at the beginning of September (see Figure 3.11) resulted from insufficient flushing of this pool. Consequently, this led to simulated increases in metolachlor (and atrazine) in pool K2 from up-river tidally induced transport.

– For the relatively high atrazine PC99 indicative of relatively low toxicity:
  - The exceedance durations of atrazine and metolachlor of ~2 and ~1.5 weeks in pools K3 and K2, respectively, were as the 'Verify' scenario.
  - The exceedance duration of diuron in pool K3 of ~1.5 weeks was as the 'Verify' scenario.
  - As the 'Verify' scenario, methomyl did not exceed the atrazine PC99 at any of the sites.

– For the relatively low diuron PC99 indicative of relatively high toxicity:
  - Slowly degrading metolachlor exceeded the diuron PC99 in pools K3 and K2 until the end of the simulation on 1 December, albeit very near to the toxicity criterion value. The concentration in pool K1 remained at least twice as high as the PC99 until the end of the simulation due to insufficient releases of M2 irrigation water to properly flush this pool. Site G8100111 had a similar exceedance duration as the 'Verify' scenario simulation of ~10 weeks. Relative to the 'Verify' scenario, there were generally large predicted increases in the exceedance durations of pools K1, K2 and K3 due to insufficient flushing.
  - Moderately degrading atrazine exceeded the diuron PC99 in pools K3, K2 and K1, and site G8100111 for ~6, ~10, ~12 and ~5 weeks, respectively. Relative to the 'Verify' scenario, there was a modest predicted increase in the exceedance duration of pools K3, K2 and K1, and a substantive reduction at site G8100111 due to less chemical loads transported via flushing to this location.
  - Rapidly degrading diuron exceeded the diuron PC99 in pools K3, K2 and K1 for ~6, ~5 and ~3 weeks, respectively. Relative to the 'Verify' scenario, there were only modest changes in the exceedance durations of these three (3) pools as the reduction in M2 releases did not materially affect diuron concentrations due to substantial degradation.
  - Very rapidly degrading methomyl exceeded the diuron PC99 in pools K3 and K2 for ~5 and ~2 weeks, respectively, the same as the 'Verify' scenario. Because of the very high degradation rates, the shortened duration of M2 releases had a negligible effect on this chemical's concentrations in the pools.

– In summary, the effect of reducing M2 releases to flush and dilute chemical levels in the lower Keep River system from ~2 to ~1 months had greater effect on the slowly to moderately (metolachlor, atrazine) than rapidly (diuron, methomyl) degrading substances. A shortened period of flushing should not be considered for slowly degrading substances (metolachlor) because elevated levels are predicted to remain in pool K1 that can then be tidally transported up-river and increase toxicity risks to pool K2. In short, a reduced dry season flushing period from ~2 to ~ 1 months may be an effective mitigation measure for rapidly degrading substances (diuron, methomyl), but should not be considered for slowly degrading chemicals (metolachlor, atrazine).

A summary of the 'Reduce TW Conc' scenario simulation includes:

– Peak levels of all four (4) chemicals were similar to the 'Verify' scenario at all five (5) sites. However, lower metolachlor and atrazine levels were predicted after peak concentrations in the three (3) pools relative to the 'Verify' scenario. This scenario's reduction in chemical input loads from the tailwater releases during August (see Figure 3.11) predicted much more effective dilution over this period because of the lower concentrations in the Border Creek model inputs, which led to very low chemical levels over the final three (3) months of the simulation relative to the 'Verify' scenario.
– For the relatively high atrazine PC99 indicative of relatively low toxicity:
  - The exceedance durations of atrazine and metolachlor of ~1 week in pools K3 and K2 were shorter than the 'Verify' scenario (~1.5-2 weeks).
  - The exceedance duration of diuron in pool K3 of ~1 week was shorter than the 'Verify' scenario (~1.5 weeks).
  - As the 'Verify' scenario, methomyl did not exceed the atrazine PC99 at any of the sites.
– For the relatively low diuron PC99 indicative of relatively high toxicity:
  - Slowly degrading metolachlor exceeded the diuron PC99 in pools K3, K2 and K1, and site G8100111 for ~4, ~4, ~6 and ~9 weeks, respectively, which were less than the 'Verify' scenario (~5, ~6, ~8 and ~11 weeks, respectively).
  - Moderately degrading atrazine exceeded the diuron PC99 in pools K3, K2 and K1, and site G8100111 for ~4, ~4, ~5 and ~3 weeks, respectively, which were less than the 'Verify' scenario (~5, ~6, ~7 and ~7 weeks, respectively).
  - Rapidly degrading diuron exceeded the diuron PC99 in pools K3, K2 and K1 for ~4, ~3 and ~2 weeks, respectively, which were less than the 'Verify' scenario (~5, ~5 and ~4 weeks, respectively).
  - Very rapidly degrading methomyl exceeded the diuron PC99 in pools K3 and K2 for ~3 and ~1 weeks, respectively, which were less than the 'Verify' scenario (~5 and ~2 weeks, respectively).
– In summary, the combined effect of reducing tailwater chemical loads into Border Creek along with the ~2 months of M2 flushing flows was to materially reduce the exceedance durations of PC99s in the lower Keep River system. Implementation of this strategy would rely upon the availability of several tailwater systems of varying water quality that could be preferentially released (e.g. release tailwater from system with lower concentrations and internally transfer (or store) within the farmlands poor quality waters), which may not be possible to implement if such a dry season incident occurs. In short, when and where possible, selection of tailwater releases of higher quality (i.e. lower chemical concentrations) to decrease chemical loads to the lower Keep River system will provide a reduction in toxicity risks.

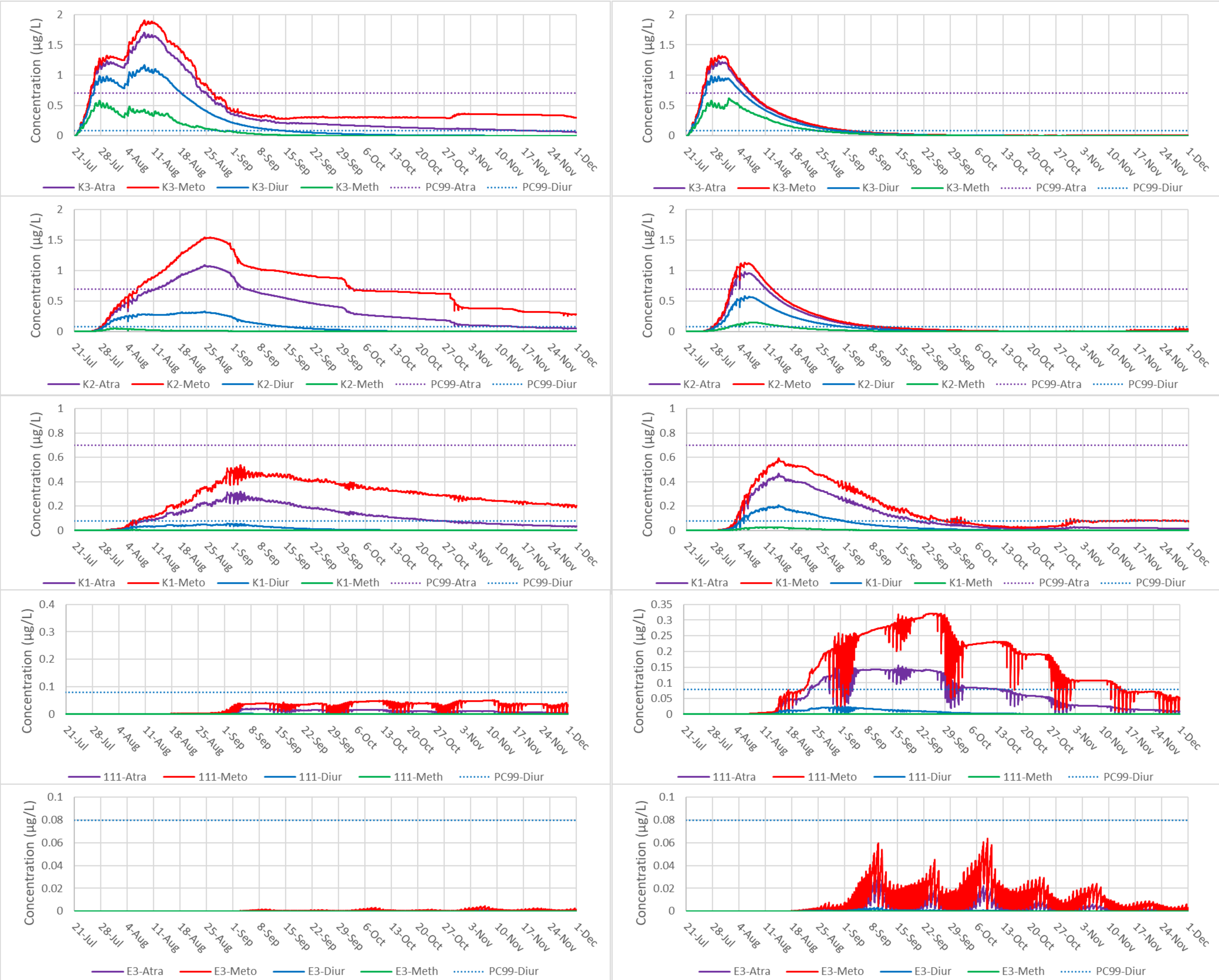

Figure 5.1 ***Comparison of the concentrations in the lower Keep River system at pools K3 (top), K2 (upper middle) and K1 (middle), and sites G8100111 (lower middle) and E3 (bottom), of four (4) chemicals with differing degradation half-life values supposing all had the same tailwater release loads during the 2019 dry season tailwater release incident for scenarios 'No Flushing' (left) and 'Verify' (right).[3]***

[3] Only the adopted atrazine and diuron PC99s for this dry season infrastructure failure case are plotted and evaluated.

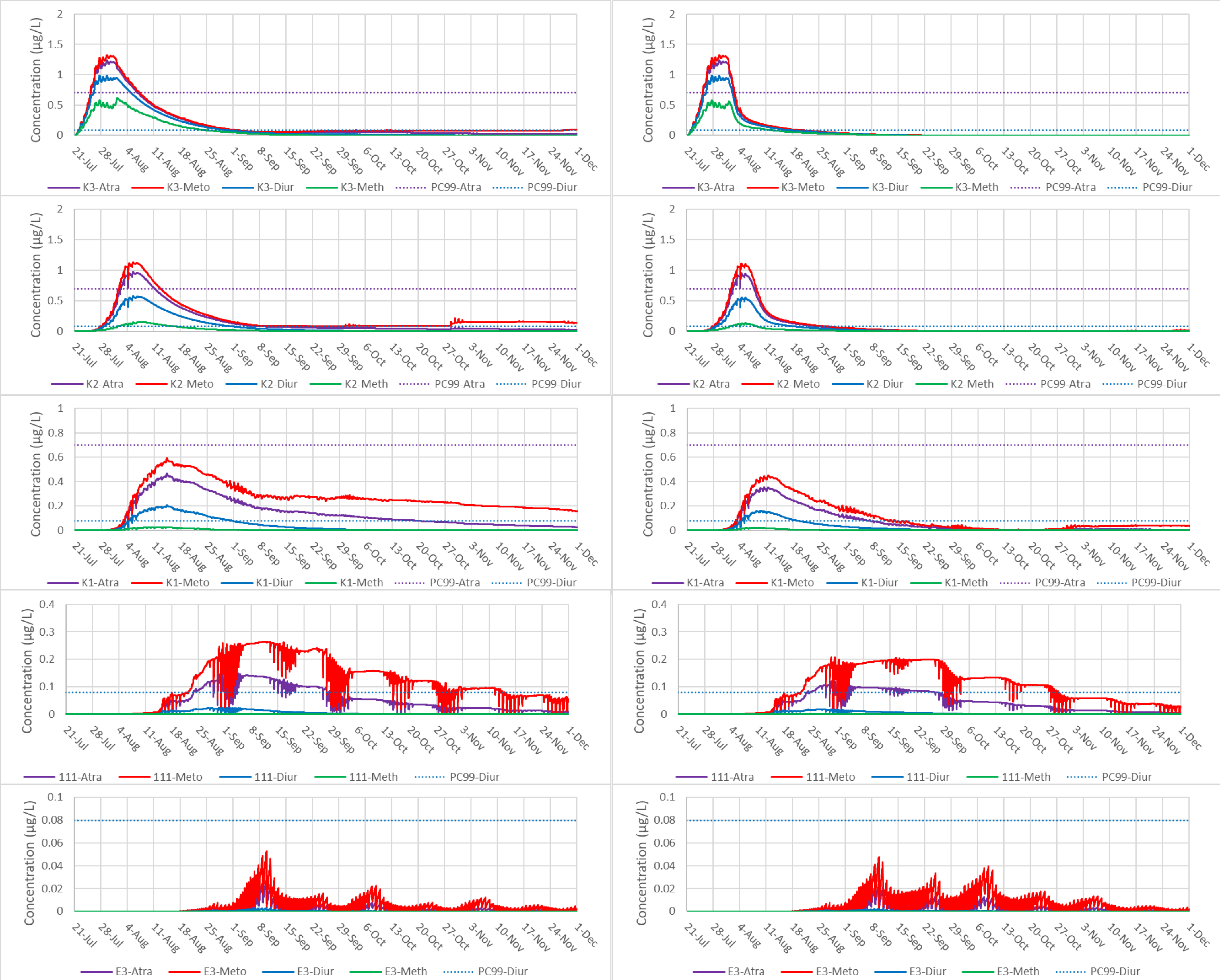

Figure 5.2 ***As Figure 5.1 for scenarios '50% Less Flushing' (left) and 'Reduce TW Conc' (right).***

5.1.2 Exposure evaluation

As an illustrative example of cumulative exposure (see Section 0), the simulated chemical concentrations (reproduced from Figure 5.1) and cumulative exposure (when concentrations were greater than the atrazine and diuron PC99s) of the dry season 'Verify' scenario at the five (5) sites in the lower Keep River system are shown in Figure 5.3. Recall that all four (4) chemicals for this scenario had the same input concentrations via Border Creek into pool K3, so differences in simulated levels at each location are solely due to variations in degradation rates. Additionally, the assessments have focussed on only two PC99 values for atrazine (relatively high PC99 with relatively low toxicity) and diuron (relatively low PC99 with relatively high toxicity) to clearly demonstrate the effect of differing chemical toxicities on the risks to the lower Keep River system. Generally, most of the cumulative exposure in the pools (K3, K2 and K1) occurs during the presence of the pulse of high chemical waters when it is greater than the relevant PC99 over the first ~1-2 months of the simulation. In contrast, at site G8100111, the long duration of exceedance of the diuron PC99 by metolachlor (and to a lesser extent atrazine) during the middle of the simulation results in a gradual increase in the cumulative exposure. As no chemicals were above either PC99 at site E3, the cumulative exposure at the end of the simulation was 0 ppb hr. For this investigation the cumulative exposure at the end of simulations is used as an additional integrative measure of potentially toxicity risks across all scenarios.

The cumulative exposures of the four (4) chemicals for each of the two (2) PC99s (atrazine, diuron) at the end of the simulation at each of the five (5) locations of the dry season infrastructure failure incident scenarios are summarised in Table 5.1, which indicate the following:

– For the relatively high atrazine PC99 the 'Reduce TW Conc' scenario always yielded the lowest exposure in pool K3 for metolachlor (229 ppb hr), atrazine (213 ppb hr) and diuron (150 ppb hr), and pool K2 for metolachlor (154 ppb hr) and atrazine (115 ppb hr). There was no difference in the exposures between the 'Verify' and '50% Reduce Flush' scenarios in pool K3 for metolachlor (332 ppb hr), atrazine (303 ppb hr) and diuron (208 ppb hr), and pool K2 for metolachlor (253 ppb hr) and atrazine (185 ppb hr), which are the likely actionable management actions. In other words, if the PC99 is relatively high (e.g. relatively low toxicity such as atrazine PC99), then consideration of ~1 month of flushing rather than ~2 months for a dry season incident of similar magnitude to that of July-October 2019 could be considered, even if the chemical(s) of concern have slow (metolachlor) to moderate (atrazine) degradation rates (i.e. high to moderate half-lives). Clearly, all three (3) evaluated mitigation strategies substantially decreased metolachlor (slow degradation) and atrazine (moderate degradation) exposure in pools K3 and K2, and diuron (rapid degradation) exposure in pool K3. There was no exposure above the relatively high atrazine PC99 for the four (4) scenarios at:

  - Any of the five (5) locations for methomyl due to its very rapid degradation.
  - Diuron at four (4) of the five (5) locations except pool K3 due to its rapid degradation.
  - Atrazine and metolachlor at three (3) of the five (5) locations except pools K3 and K2 as sufficient dilution occurred to decrease concentrations below this relatively high environmental criterion.

  Using the sum of end of simulation exposures across all sites as an integrative measure, it was lower for the 'Reduce TW Conc' scenario for the three (3) chemicals (383 ppb hr metolachlor, 328 ppb hr atrazine, 150 ppb hr diuron) than the two (2) flushing scenarios (585 ppb hr metolachlor, 488 ppb hr atrazine, 208 ppb hr diuron). Further, the sum of exposures for the three (3) chemicals of the two (2) flushing scenarios was substantially lower than the 'No Flush' scenario (2,548 ppb hr metolachlor, 1,445 ppb hr atrazine, 526 ppb hr diuron), which demonstrates that M2 releases are a beneficial management action to reduce overall toxicity of the lower Keep River system for chemicals with a relatively high PC99 and slow (metolachlor) to rapid (diuron) degradation rates (assuming equivalent loadings into pool K3).

– Not surprisingly, for the relatively low diuron PC99 (relatively high toxicity) the predicted exposures were much greater than for the relatively high atrazine PC99 (relatively low toxicity). The 'Reduce TW Conc' scenario always yielded the lowest exposure in pool K3 for metolachlor (341 ppb hr), atrazine (321 ppb hr), diuron (258 ppb hr) and methomyl (145 ppb hr), in pool K2 for metolachlor (279 ppb hr), atrazine (236 ppb hr) and diuron (129 ppb hr), and in pool K1 for metolachlor (243 ppb hr) and atrazine (169 ppb hr). However, the 'No Flush' scenario yielded the lowest exposure in pool K2 for methomyl (0 ppb hr), in pool K1 for diuron (0 ppb hr) and at site G8100111 for metolachlor (0 ppb hr) and atrazine (0 ppb hr). No exposure above the relatively low diuron PC99 for the 'No Flush' scenario was due to the lack of flushing-induced down-river transport of the tailwater chemical loads as described in Section 5.1.1. In contrast to the relatively high atrazine PC99, there was generally lower exposure of the ‘Verify’ scenario than the ‘50% Reduce Flush’ scenario for the relatively low diuron PC99 because of greater dilution (lower concentrations) and down-river transport (shorter high concentration pulse duration) of the chemical loads due to the increased duration of flushing (also see Section 5.1.1). In other words, if the PC99 is relatively low (e.g. diuron PC99), then flushing for at least ~2 months for a dry season incident of similar magnitude to that of July-October 2019 should be carried out with no reduction in the flushing duration if the chemical(s) of concern have a slow to moderate degradation rate (high to moderate half-lives). However, for chemicals with high (diuron) to very high (methomyl) degradation rates, consideration of no or reduced duration flushing should be considered. There was no exposure above the relatively low diuron PC99 (relatively high toxicity) for the four (4) scenarios at:

- Site E3 for all four (4) chemicals.
- Site G8100111 for methomyl and diuron due to rapid degradation.
- Pool K1 for methomyl due to rapid degradation.

As for the relatively high atrazine PC99, the sum of exposures across all sites for the relatively low diuron PC99 was lower for the ‘Reduce TW Conc’ scenario for the four (4) chemicals (1,107 ppb hr metolachlor, 796 ppb hr atrazine, 430 ppb hr diuron, 164 pp hr methomyl) than the ‘Verify’ flushing scenario (1,873 ppb hr metolachlor, 1,352 ppb hr atrazine, 747 ppb hr diuron, 294 ppb hr methomyl). However, the sum of exposures for three (3) chemicals of the ‘Verify’ flushing scenario were substantially lower than the ‘No Flush’ scenario (4,997 ppb hr metolachlor, 2,870 ppb hr atrazine, 1,005 ppb hr diuron) except for methomyl which were similar (294 ppb hr ‘Verify’ scenario, 270 ppb hr ‘No Flush’ scenario), which demonstrates an overall toxicity reduction of M2 releases for chemicals with a relatively low PC99 and slow (metolachlor) to rapid (diuron) degradation rates (assuming equivalent loadings into pool K3). For a chemical with a very rapid degradation rate (methomyl) and relatively low PC99 then consideration of no or reduced flushing is plausible for a similar type of dry season incident as considered here.

Table 5.1 ***Cumulative exposure of each chemical for atrazine (relatively low toxicity) and diuron (relatively high toxicity) PC99s at the completion of the dry season infrastructure failure incident scenario simulations.***

Chemical	Scenario	K3	K2	K1	G8100111	E3	Sum
Atrazine PC99							
Metolachlor (ppb hr)	Verify	332	253	0	0	0	585
	No Flush	1,064	1,484	0	0	0	2,548
	50% Reduce Flush	332	253	0	0	0	585
	Reduce Concentration	229	154	0	0	0	383
Atrazine (ppb hr)	Verify	303	185	0	0	0	488
	No Flush	923	522	0	0	0	1445
	50% Reduce Flush	303	185	0	0	0	488
	Reduce Concentration	213	115	0	0	0	328
Diuron (ppb hr)	Verify	208	0	0	0	0	208
	No Flush	526	0	0	0	0	526
	50% Reduce Flush	208	0	0	0	0	208
	Reduce Concentration	150	0	0	0	0	150
Methomyl (ppb hr)	Verify	0	0	0	0	0	0
	No Flush	0	0	0	0	0	0
	50% Reduce Flush	0	0	0	0	0	0
	Reduce Concentration	0	0	0	0	0	0
Diuron PC99							
Metolachlor (ppb hr)	Verify	536	475	452	410	0	1,873
	No Flush	1,865	2,263	869	0	0	4,997
	50% Reduce Flush	545	700	824	314	0	2,383
	Reduce Concentration	341	279	243	244	0	1,107
Atrazine (ppb hr)	Verify	508	406	301	137	0	1,352
	No Flush	1,343	1,212	315	0	0	2,870
	50% Reduce Flush	508	407	390	95	0	1,400
	Reduce Concentration	321	236	169	70	0	796
Diuron (ppb hr)	Verify	420	236	91	0	0	747
	No Flush	741	264	0	0	0	1,005
	50% Reduce Flush	420	236	91	0	0	747
	Reduce Concentration	258	129	43	0	0	430
Methomyl (ppb hr)	Verify	251	43	0	0	0	294
	No Flush	270	0	0	0	0	270
	50% Reduce Flush	251	43	0	0	0	294
	Reduce Concentration	145	19	0	0	0	164

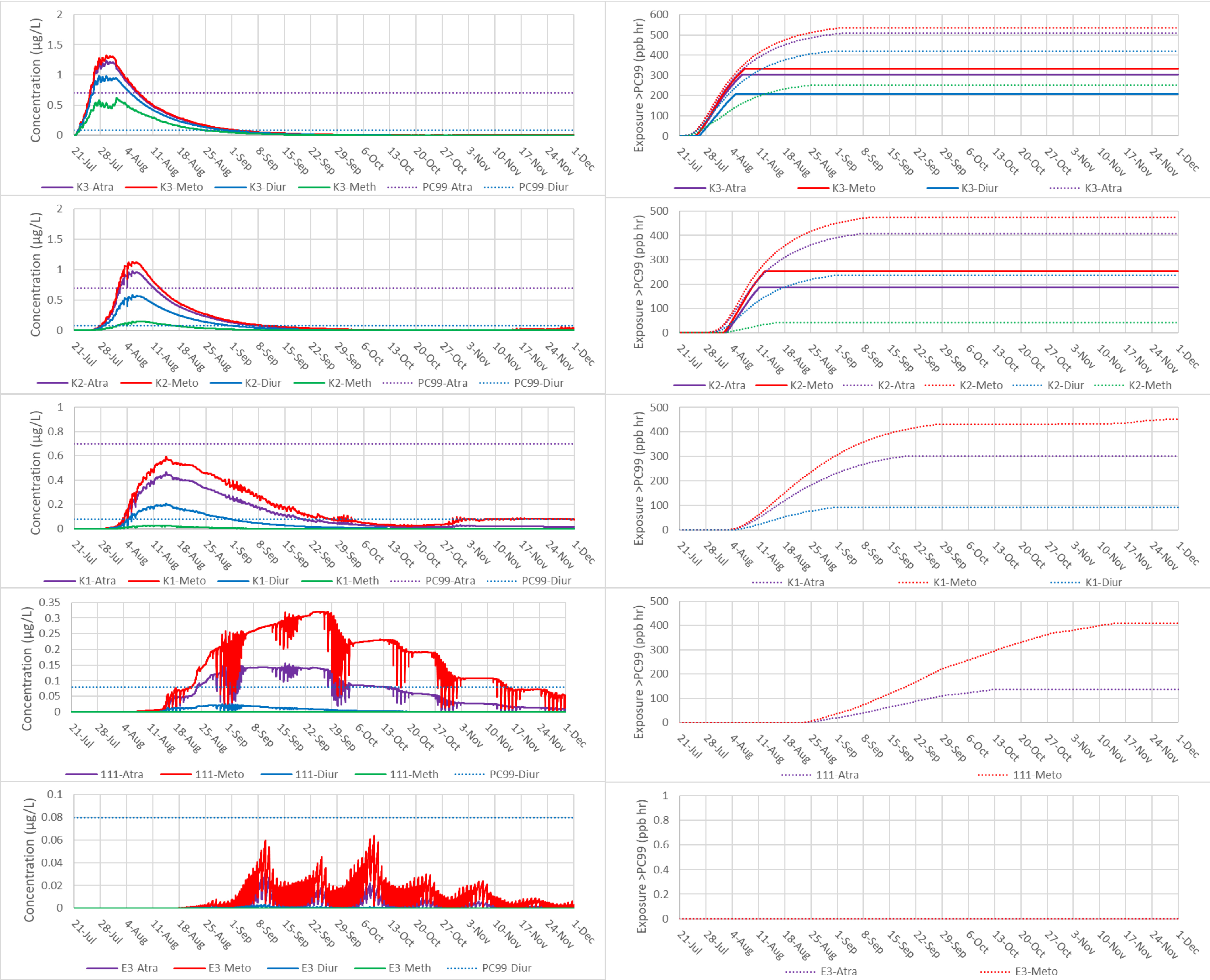

Figure 5.3 *Simulated chemical concentrations (left, also illustrated in Figure 5.1) and cumulative exposure of each chemical (right) when chemical concentrations above the atrazine (solid lines) and diuron (dashed lines) PC99s for dry season scenario 'Verify' in pools K3 (top), K2 (upper middle and K1 (middle), and sites G8100111 (lower middle) and E2 (bottom) .*

5.2 End of wet season scenarios

The end of wet season scenarios served to characterise the potential toxicity risks from the existing Goomig farmlands to the three (3) lower Keep River pools and two (2) down-river sites (G1100111 and E3) from the four (4) chemicals (atrazine, metolachlor, diuron, methomyl) for the high risk end of wet season hydrology case (see Section 2.2.2.1). Maximum credible chemical concentrations from farmland discharge during such an event served as inputs (see Sections 3.4.2 and 3.5.2). Farmland discharge was assumed to occur over ~10 days (23 March-3 April 2019) when a very high proportion of Border Creek discharge was from the Goomig farmlands (see Figure 2.8 of Section 2.2.2.2). Assessment of potential toxicity risks for each chemical was based on their respective PC99s.

Typically, at the end of the wet season, farmland irrigation needs are low, so there are no limitations per se on the M2 flow rate available to flush the lower Keep River pools. This contrasts with the dry season infrastructure failure incident scenarios of Section 5.1 where an upper M2 release discharge limit of ~50 MLD was set so as to maintain surface levels in the irrigation channels that are suitable for farmland use. The dry season infrastructure failure (tailwater release) scenarios of Section 5.1 and 'actual' event of Section 2.4.1 demonstrate that ~2 months of M2 releases at ~50 MLD is sufficient to flush the pools (Section 5.1).

The objective of the end of wet season scenarios was to determine the M2 release flow rate(s) over 30 days that adequately flush the lower Keep River pools (K4 [only for future Knox Plains farmlands scenarios], K3, K2 and K1) if high chemical concentrations occur. In addition to the baseline scenario (no M2 releases), simulations of M2 releases of 50, 100 and 150 MLD for 30 days starting on 15 April 2019 (~10 days after the end of high risk event on 3 April 2019) are described for the existing Goomig farmlands in Section 5.2.1. Section 5.2.2 describes three (3) scenarios for such a high risk hydrological event that occurs simultaneously for both the existing Goomig and future Knox Plains farmlands, namely the baseline (no flushing), and M2 releases of 50 MLD and 100 MLD from each farmland (total of 100 MLD and 200 MLD) for 30 days initiated on 15 April 2019.

5.2.1 Existing Goomig farmlands

5.2.1.1 PC99 exceedance assessment

Figure 5.4 to Figure 5.7 illustrate the simulated four (4) chemical concentrations in the three (3) pools (K3, K2 and K1) and two (2) down-river sites (G8100111 and E3) that are potentially affected by the end of wet season releases from the existing Goomig farmlands over the four (4) end of wet season scenarios (see Section 3.5.3).

The 'Goomig Baseline' scenario with no M2 releases predicted exceedance of the atrazine and diuron PC99s for ~12 and ~4 weeks in pool K3, respectively. However, the PC99s were not predicted to be exceeded for these two (2) chemicals in pools K2 and K1. In other words, the end of wet season farmland releases of these two (2) chemicals were largely retained in pool K3 for the remainder of dry season, albeit with unacceptably high atrazine and diuron levels. Metolachlor always exceeded its very low PC99 (0.0084 µg/L) once the farmland waters reached each of the three (3) pools with exceedance also occurring at site G8100111 (albeit near the PC99 concentration). Metolachlor was below the PC99 at site E3 due to insufficient tidally induced transport over the course of the simulation at this location from the up-river sites with high concentrations. Maximum credible methomyl concentrations from the farmland releases were less than its PC99, and hence it does not pose a risk to the lower Keep River pools on the basis of the database of available measurements to date. Nonetheless, due to methomyl's rapid degradation rate (half-life ~3 days) rapid decreases were simulated from its peak of ~0.1 µg/L in pool K3 within several weeks.

Scenario 'Goomig 50 MLD' with M2 releases of 50 MLD for 30 days effectively flushed pool K3 of all chemicals. The predicted duration that atrazine and diuron concentrations were above their PC99s decreased from ~12 and ~4 weeks for the baseline scenario, respectively, to ~3.5 weeks with the 50 MLD release. However, these high chemical concentration waters were displaced (flushed) into pool K2 with a resultant atrazine PC99 exceedance for ~2 weeks. Recall that atrazine PC99 exceedance in pool K2 was not simulated for the 'Goomig Baseline' scenario because the high chemical waters were largely retained in pool K3 over the dry season. For several days the peak diuron concentration in pool K2 was predicted to nearly reach its PC99. The M2 releases were sufficient to mostly displace (flush) and dilute the high chemical waters from pool K2 to pool K1 where atrazine levels were predicted to exceed the PC99 for ~2 weeks, albeit at a lower peak level of 1.2 µg/L than in pools K2 (3 µg/L) and

K3 (6 µg/L). Over the ~1 month during the transport and dilution of high chemical concentration waters from pool K3 to pool K1, atrazine decreased from ~2-fold higher than metolachlor in pool K3 to nearly equivalent in pool K1 due to its higher degradation rate (half-life of 30 days versus 90 days for metolachlor). The 50 MLD M2 release rate for 30 days was insufficient to decrease metolachlor levels below 0.1 µg/L at the end of the simulation in pool K1. Metolachlor also exceeded the PC99 at site G8100111 for most of the simulation, albeit at relatively low levels <0.1 µg/L. However, metolachlor did not exceed the PC99 at site E3.

As with the 'Goomig 50 MLD' scenario, the 'Goomig 100 MLD' and 'Goomig 150 MLD' scenarios effectively displaced (flushed) the high chemical concentration waters from pool K3. The predicted duration that atrazine and diuron concentrations were above their PC99s decreased from ~3.5 weeks for the 50 MLD scenario to ~3 weeks for both the 100 and 150 MLD scenarios. As with the 50 MLD scenario, the high chemical concentration waters were displaced (flushed) into pool K2 where exceedance of the atrazine PC99 was simulated for ~1.5 and ~1 weeks for the 100 and 150 MLD scenarios, respectively. These shorter durations of atrazine PC99 exceedance than the 50 MLD scenario (~2 weeks) were primarily driven by more rapid flushing of the pools as the M2 release rates increased. The simulated peak diuron levels in pool K2 for the 100 MLD and 150 MLD scenarios both exceeded the PC99 for ~3-4 days (recall that the peak diuron concentration in pool K2 was predicted to nearly reach its PC99 for the 50 MLD scenario). The high chemical concentration waters were then displaced (flushed) into pool K1 where simulated atrazine levels were greater than the PC99 for ~1.5 and ~1 weeks for the 100 MLD and 150 MLD scenarios, respectively. Peak diuron levels in pool K1 for the 100 MLD and 150 MLD scenarios were not predicted to exceed the PC99 in part due to dilution of the high chemical concentration waters over the one (1) week of transport time from pool K2 to pool K1, as well as substantive chemical degradation (half-life 10 days). Peak atrazine concentrations in pools K2 and K1 for the 100 MLD and 150 MLD scenarios remained greater than metolachlor because of the short transport time (via flushing) from site K3 to K1 (~1 and ~2 weeks for 100 MLD and 150 MLD scenarios, respectively), which was more rapid than the simulated degradation half-life of atrazine (30 days). Recall for the 50 MLD scenario that the ~1 month duration for the peak concentrations to transit from sites K3 to K2 was similar to atrazine's degradation half-life so that concentrations of these two (2) chemicals concentrations were nearly equivalent even though atrazine was initially twice as high in pool K3. Though the 100 MLD M2 release scenario greatly improved the residual levels of metolachlor in pool K1 after 30 days relative to the 50 MLD scenario, the 150 MLD scenario flushed even a greater proportion of the chemicals (metolachlor in particular) down-river of pool K1 so that metolachlor increases in this pool were markedly lower due to subsequent up-river tidal transport during the remainder of the dry season. As with the 50 MLD scenario, metolachlor also exceeded the PC99 at site G8100111 from the end of April onwards for the 100 MLD and 150 MLD scenarios with higher peak values as the flushing rate increased (~0.08 µg/L 50 MLD, ~0.3 µg/L 100 MLD, ~0.5 µg/L 150 MLD). In contrast to the 50 MLD scenario, metolachlor during the 100 MLD and 150 MLD scenarios exceeded the PC99 at site E3 for ~7 weeks with peak values of ~0.03 µg/L and 0.12 µg/L, respectively.

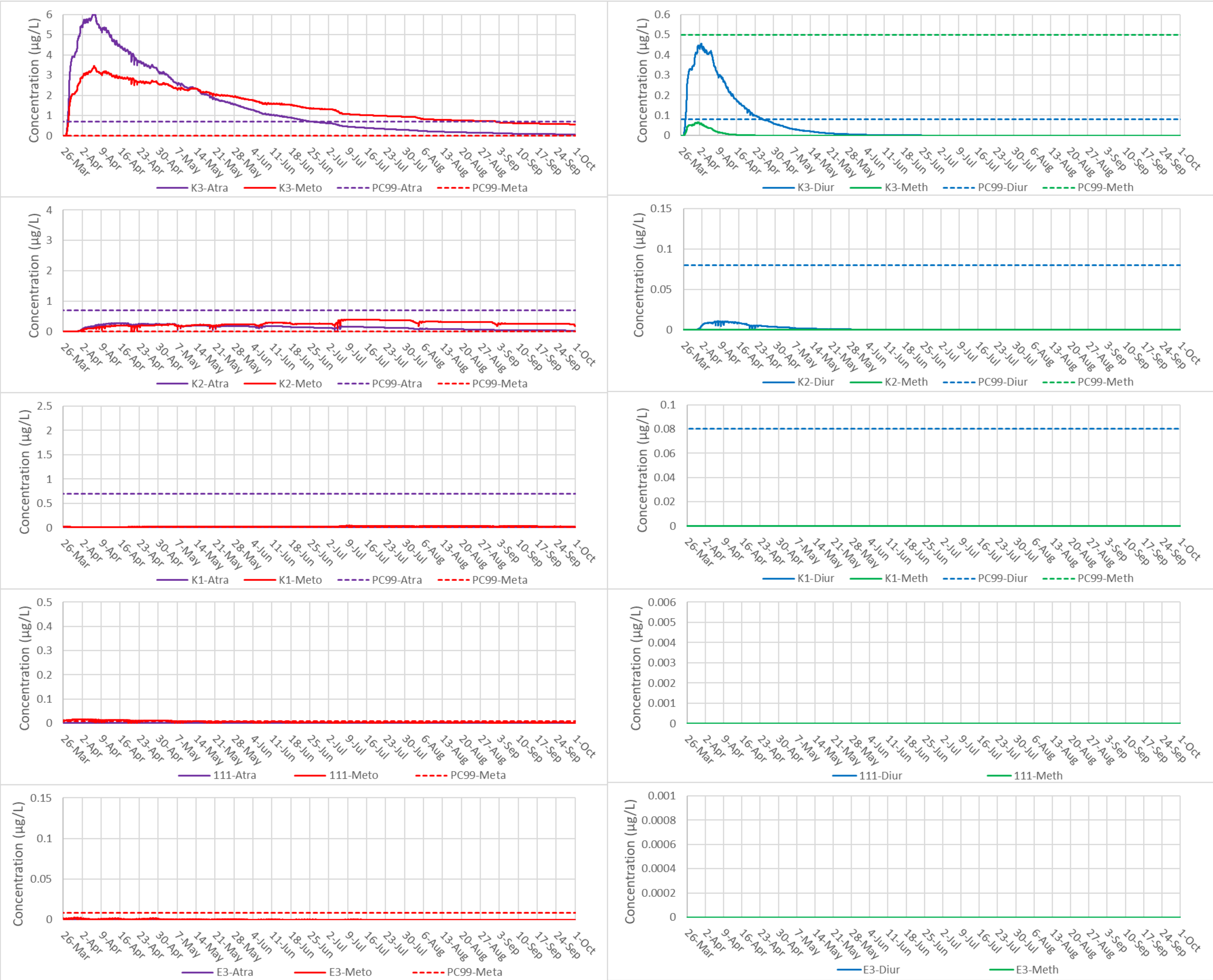

Figure 5.4 ***Comparison of the concentrations in the lower Keep River pools K3 (top), K2 (upper middle) and K1 (middle), and sites G8100111 (lower middle) and E3 (bottom) of metolachlor and atrazine (right), and diuron and methomyl (left) during the 2019 end of wet season event for scenario 'Goomig – Baseline'.***

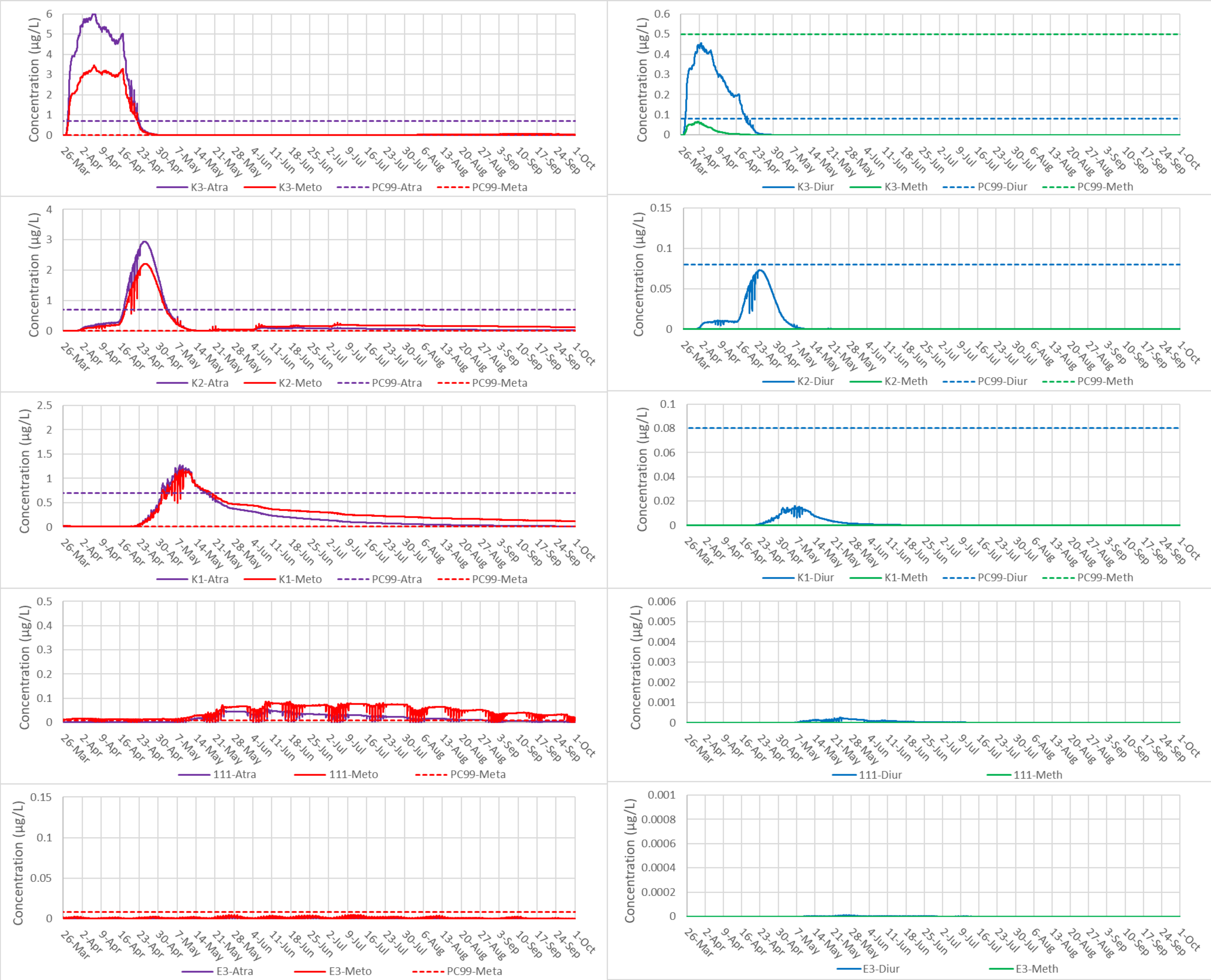

Figure 5.5 ***As Figure 5.4 for scenario 'Goomig – 50 MLD'.***

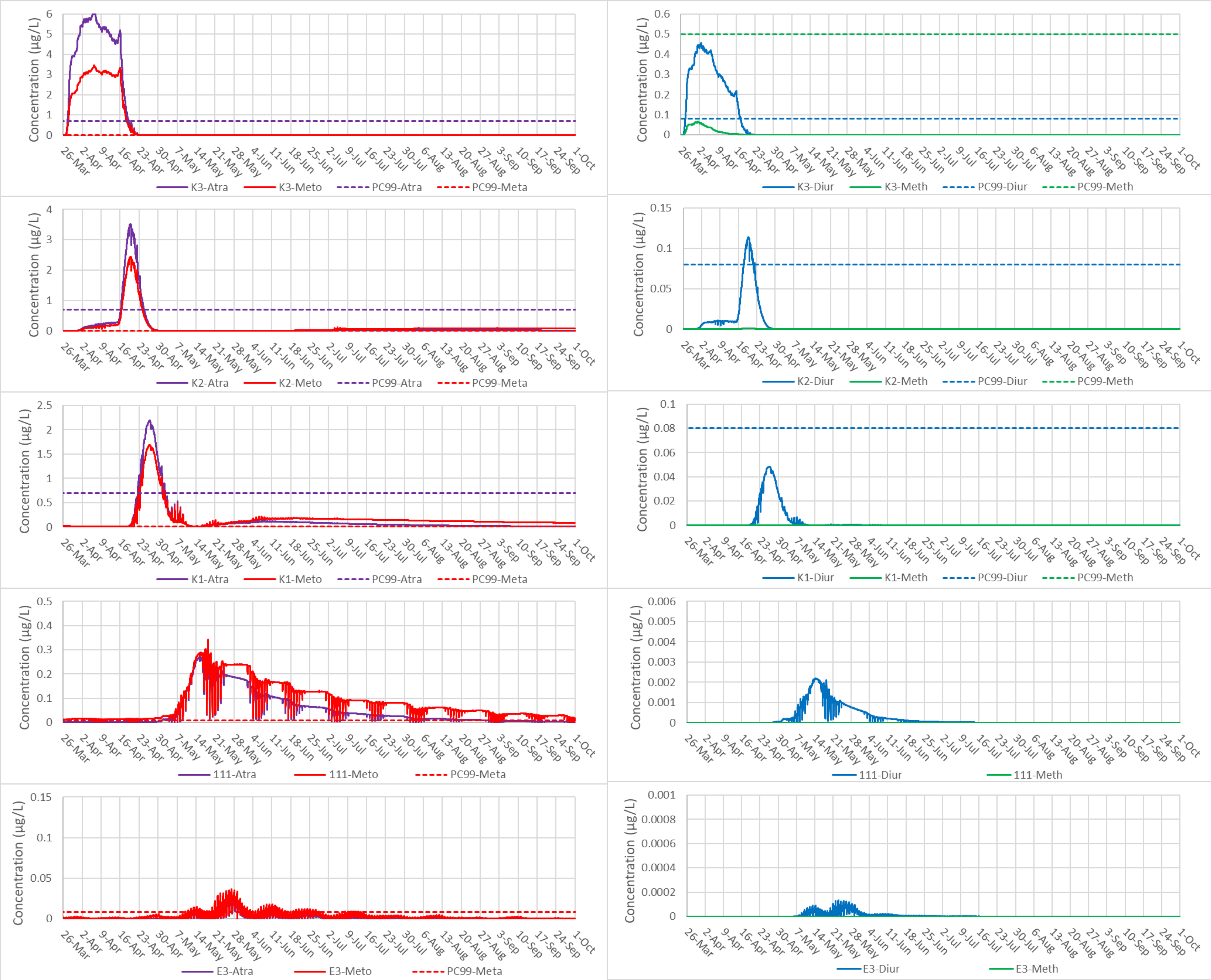

Figure 5.6 ***As Figure 5.4 for scenario 'Goomig – 100 MLD'.***

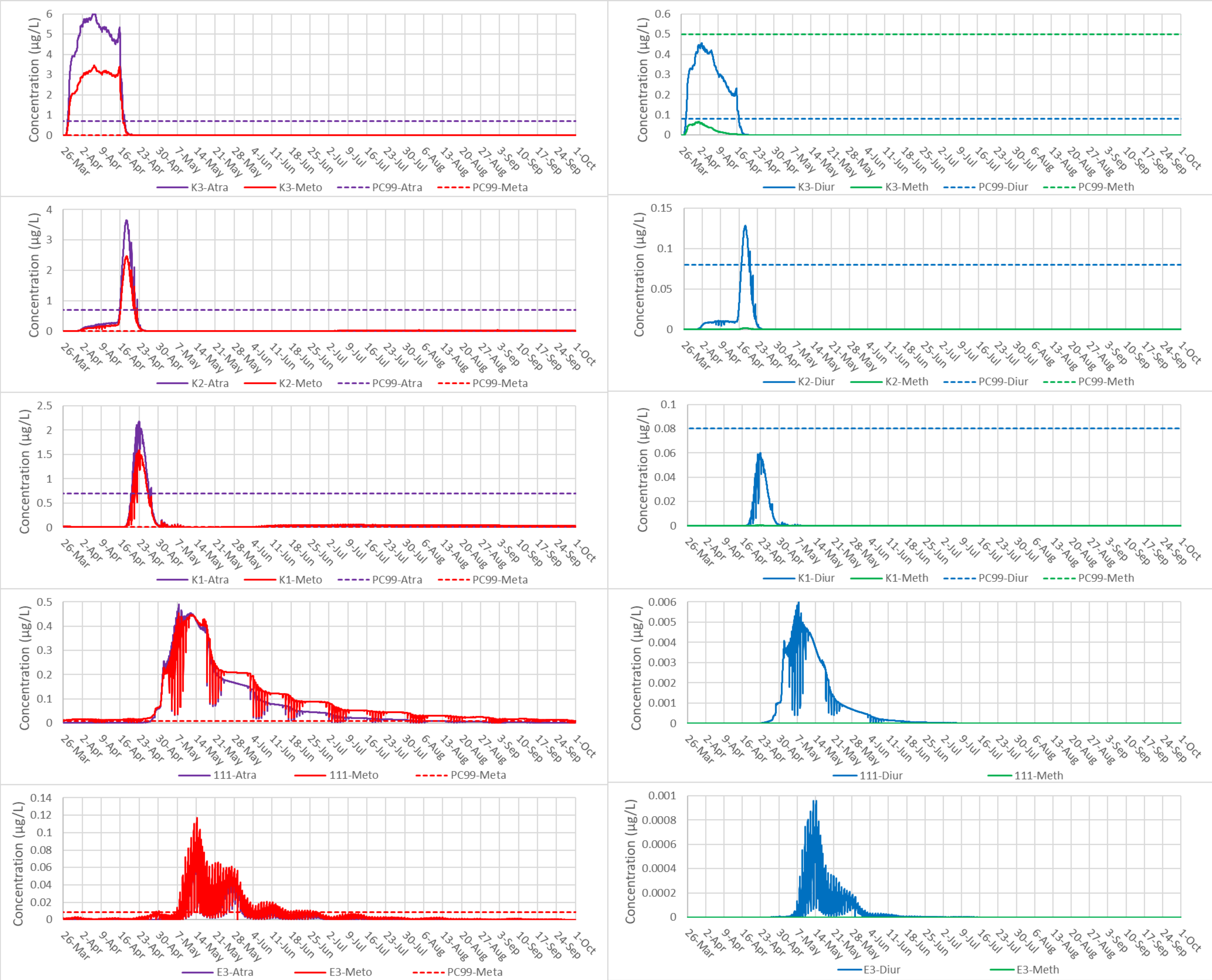

Figure 5.7 ***As Figure 5.4 for scenario 'Goomig – 150 MLD'.***

5.2.1.2 Exposure evaluation

The cumulative exposure of the four (4) chemicals for each of their respective PC99s at the end of the simulations at each of the five (5) locations of the end of wet season event scenarios for the existing Goomig farmlands case is summarised in Table 5.2, which indicates the following:

– For the slowly degrading metolachlor with a very low PC99 (very high toxicity), at pool K3 all three (3) flushing rates (50, 100, 150 MLD) yielded similar exposures that were ~20-25% (1,392-1,719 ppb hr) of the baseline scenario (6,835 ppb hr). However, at pool K2 the 150 MLD flushing rate exposure (345 ppb hr) was markedly lower than the 100 MLD (568 ppb hr), 50 MLD (1,165 ppb hr) and baseline (1,150 ppb hr) scenarios. At pool K1 the baseline scenario with no flushing had the lowest exposure (124 ppb hr) relative to the 50 MLD (1,272 ppb hr), 100 MLD (774 ppb hr) and 150 MLD (345 ppb hr) flushing rates. Recall that tidally induced transport for the baseline scenario with no M2 flushing releases retained the waters with high chemical levels in the uppermost two (2) pools of K3 and K2, hence the lowest simulated exposure at pool K1 for this scenario. Similarly, exposure was lowest at site G8100111 for the baseline scenario (12 ppb hr) relative to the flushing scenarios. In fact, the 100 MLD (368 ppb hr) and 150 MLD (378 ppb hr) flushing scenarios had the highest exposure at these sites because a greater proportion of the waters with high concentrations were transported (via flushing) to this location relative to the 50 MLD scenario (193 ppb hr). Exposure at site E3 was very low for the 100 MLD (8 ppb hr) and 150 MLD (24 ppb hr) flushing rates with no exposure (0 ppb hr) for either the baseline or 50 MLD scenarios. In summary, on balance the 150 MLD flushing scenario reduces the exposure of a slowly degrading chemical with a very low PC99 such as metolachlor in the three (3) pools most effectively, though moderate exposure of the estuarine reach immediately below pool K1 (site G8100111) occurs. The sum of predicted exposures across all sites is much lower for the 150 MLD scenario (2,484 ppb hr) than the other two (2) flushing scenarios (4,349 ppb hr 50 MLD, 3,188 ppb hr 100 MLD) and the baseline scenario (8,121 ppb hr).
– For atrazine with a moderate degradation rate and a relatively high PC99, at pool K3 all three (3) flushing rates (50, 100, 150 MLD) yielded similar exposures that were ~50% (2,385-2,749 ppb hr) of the baseline scenario (5,830 ppb hr). However, there was no simulated exposure of atrazine at the remaining four (4) sites below pool K3 for the baseline scenario (no flushing) because the combination of low tidally induced exchange with pool K2 and sufficient degradation within pool K3. Of the flushing scenarios the 150 MLD flushing rate exposure in pool K2 (331 ppb hr) was lower than the 100 MLD (464 ppb hr) and 50 MLD (780 ppb hr) scenarios. Similarly in pool K1 the 150 MLD flushing rate exposure (233 ppb hr) was lower than the 100 MLD (369 ppb hr) and 50 MLD (363 ppb hr) scenarios. The combination of the moderate degradation rate of atrazine and relatively high PC99 (relatively low toxicity) led to no exposure (0 ppb hr) at sites G8100111 and E3 for any of the flushing scenarios in contrast to metolachlor with a low degradation rate and very low PC99 (high toxicity). In summary, on balance the 150 MLD flushing scenario reduces the exposure of a moderately degrading chemical with a relatively high PC99 (relatively low toxicity) such as atrazine in the three (3) pools most effectively, though moderate exposure of pools K2 and K1 occurs (unlike the baseline scenario). However, the high sum of exposures across all sites of the baseline scenario (5,830 ppb hr) is much greater by ~2-fold than the 150 MLD scenario (2,949 ppb hr).
– For diuron with relatively low input concentrations, a rapid degradation rate and relatively low PC99, at pool K3 all three (3) flushing rates (50, 100, 150 MLD) and the baseline scenario had very similar simulated exposures (153-179 ppb hr) because degradation prior to the onset of flushing was sufficient to reduce concentrations in the pool. There was no simulated exposure of diuron at the remaining four (4) sites below pool K3 for any of the scenarios because of the combination of relatively low input concentrations, low tidally induced exchange with pool K2 and sufficient degradation within pool K3. In summary, there is no benefit from flushing in terms of exposure of a rapidly degrading chemical with a low PC99 and relatively low inputs concentrations such as diuron because low rates of tidally induced exchange with pool K2 and sufficient degradation occurs to contain elevated levels in pool K3. However, there may be some benefit if the lag in the onset of M2 flushing flows is shortened from the ~10 days considered here (see Figure 3.12).
– For methomyl with relatively low Border Creek input concentrations, a very rapid degradation rate and high PC99, there was no simulated exposure (0 ppb hr) at any of the three (3) pools and two (2) sites (G8100111 and E3).

Table 5.2 Cumulative exposure of each chemical for respective PC99s at the completion of the end of wet season event simulations for the existing Goomig farmland scenarios.

Chemical	Scenario	K3	K2	K1	G8100111	E3	Sum
Metolachlor (ppb hr)	Baseline	6,835	1,150	124	12	0	8,121
	50 MLD Flush	1,719	1,165	1,272	193	0	4,349
	100 MLD Flush	1,470	568	774	368	8	3,188
	150 MLD Flush	1,392	345	345	378	24	2,484
Atrazine (ppb hr)	Baseline	5,830	0	0	0	0	5,830
	50 MLD Flush	2,749	780	363	0	0	3,892
	100 MLD Flush	2,475	464	369	0	0	3,308
	150 MLD Flush	2,385	331	233	0	0	2,949
Diuron (ppb hr)	Baseline	179	0	0	0	0	179
	50 MLD Flush	163	0	0	0	0	163
	100 MLD Flush	155	9	0	0	0	164
	150 MLD Flush	153	8	0	0	0	161
Methomyl (ppb hr)	Baseline	0	0	0	0	0	0
	50 MLD Flush	0	0	0	0	0	0
	100 MLD Flush	0	0	0	0	0	0
	150 MLD Flush	0	0	0	0	0	0

5.2.2 Existing Goomig and future Knox Plains farmlands

5.2.2.1 PC99 exceedance assessment

Figure 5.8 to Figure 5.10 illustrate the simulated four (4) chemical concentrations in the four (4) pools (K4, K3, K2 and K1) if an end of wet season high risk event occurred simultaneously from both the existing Goomig farmlands and the future Knox Plains farmlands during the three (3) scenarios (see Section 3.5.3).

The ‘Goomig+Knox Baseline’ scenario had twice the chemical loading as the ‘Goomig Baseline’, albeit with half the loading into pool K4. Because pool K4 has no tidally induced exchange with pool K3, the low dry season Keep River flows are insufficient to materially dilute and flush this pool, hence the primary mechanism to decrease chemical concentrations over time is via degradation. The chemical concentrations at pool K3 were very similar between the Goomig and Goomig+Knox baseline scenarios. Though chemical levels in pool K2 remained low for the Goomig baseline scenario (i.e. no M2 releases), the additional Knox Plain farmland drainage filled both pools K4 and K3 (atrazine ~6 µg/L), and partially filled pool K2 (atrazine ~2 µg/L). Again, metolachlor levels in the pools were well above its very low PC99 (0.0084 µg/L). Atrazine and diuron concentrations in pool K4 decreased through chemical degradation, but were above their PC99s for ~4 and ~1 months, respectively. Due to the effect of tidal exchange the atrazine and diuron PC99 exceedance durations were lower in pool K3 (~3 weeks) than pool K4 (~3 months). Atrazine and diuron PC99 exceedance durations were ~1 month and ~1 week in pool K2, respectively, where the influence of tidal exchange during spring tides is evident. Pool K1 was simulated to remain relatively unimpacted by the Goomig+Knox baseline scenario in the absence of flushing flows as the chemical loads were retained to the upper three (3) pools of K4, K3 and K2. However, given the very low PC99 of metolachlor, there was sufficient tidally induced down-river transport from pool K2 to exceed this toxicity criterion value in pool K1. Similarly, tidally induced down-river transport was also sufficient for metolachlor concentrations at site G8100111 to just exceed the PC99.

The ‘Goomig+Knox 50+50 MLD’ scenario simulated effective flushing of pools K4 and K3 for all four (4) chemicals. The predicted duration of atrazine concentrations above its PC99 decreased markedly (~3-4 weeks) relative to the baseline scenario (~4 [K4] and ~1 [K3] months). Further, flushing caused much higher peaks in metolachlor, atrazine and diuron in pool K1 and sites G8100111 and E3 than the ‘No Flushing’ scenario. Clearly, this scenario did not have sufficient M2 releases to adequately decrease metolachlor levels in proximity of its PC99 by the end of the simulation, which indicates that a greater volume of M2 releases is required for such a persistent and high toxicity substance.

The ‘Goomig+Knox 100+100 MLD’ scenario simulated very effective flushing of chemicals from the four (4) pools and two (2) down-river sites. However, this resulted in diuron briefly exceeding the PC99 in pool K1 (~0.5 weeks) and a short duration PC99 exceedance of atrazine at site G8100111 that was not predicted for the ‘Goomig+Knox 50+50 MLD’ scenario. Additionally, there was a substantive increase in the peaks of metolachlor, atrazine and diuron at both down-river sites of the pools (G8110111 and E3) relative to the ‘Goomig+Knox 50+50 MLD’ scenario, though of short duration. Nonetheless, metolachlor and atrazine levels achieved very low concentrations by the end of the simulation in the four (4) pools and two (2) down-river sites, which indicates sufficient M2 irrigation water was released to ameliorate the risk of high toxicity and persistent chemicals (e.g. metolachlor) from subsequent tidally induced up-river transport.

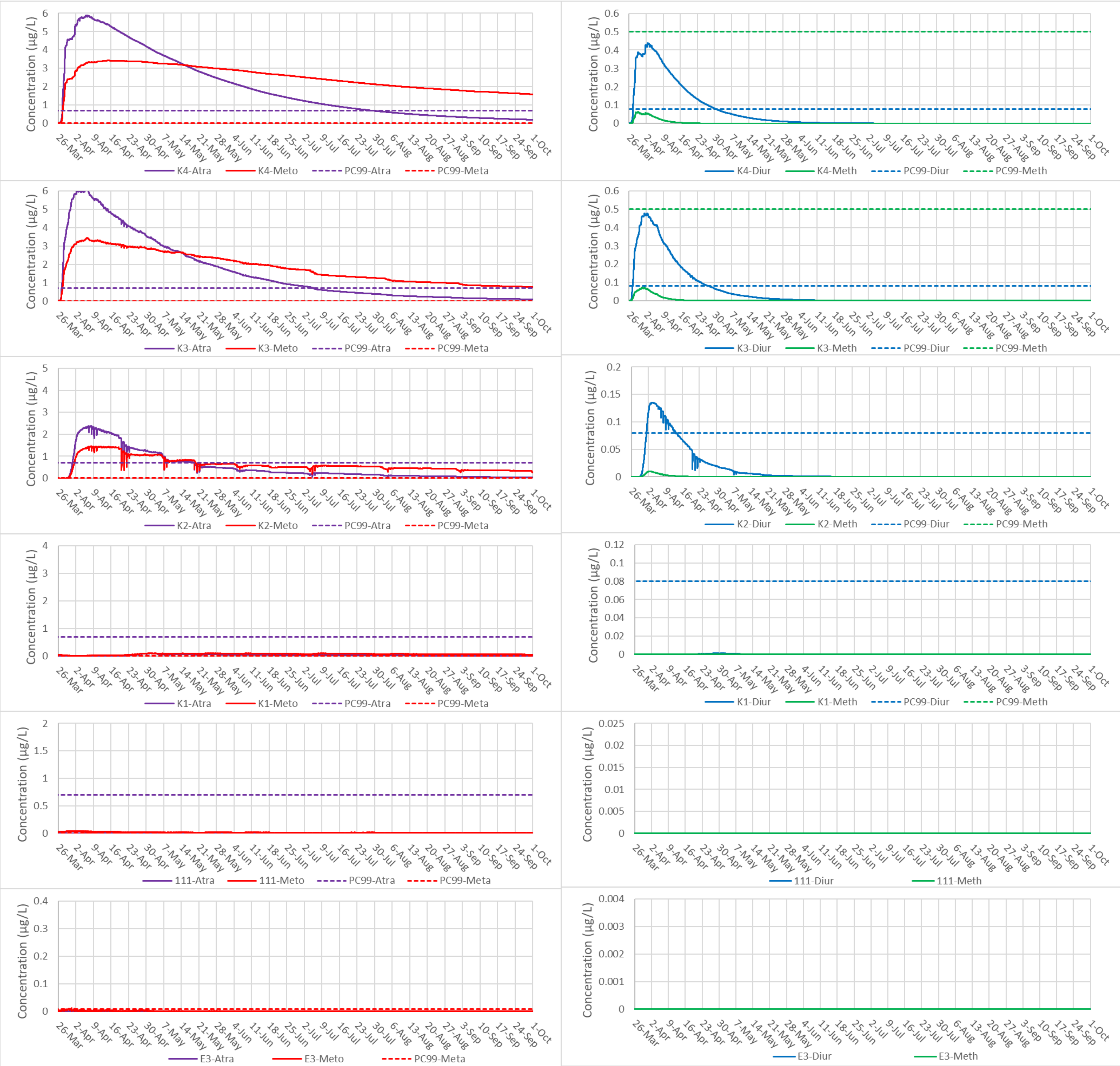

Figure 5.8 ***Comparison of the concentrations in the lower Keep River pools K4 (top), K3 (2nd row), K2 (3rd row) and K1 (4th row), and sites G8100111 (5th row) and E3 (bottom) of metolachlor and atrazine (right), and diuron and methomyl (left) during the 2019 end of wet season event for scenario 'Goomig + Knox – Baseline'.***

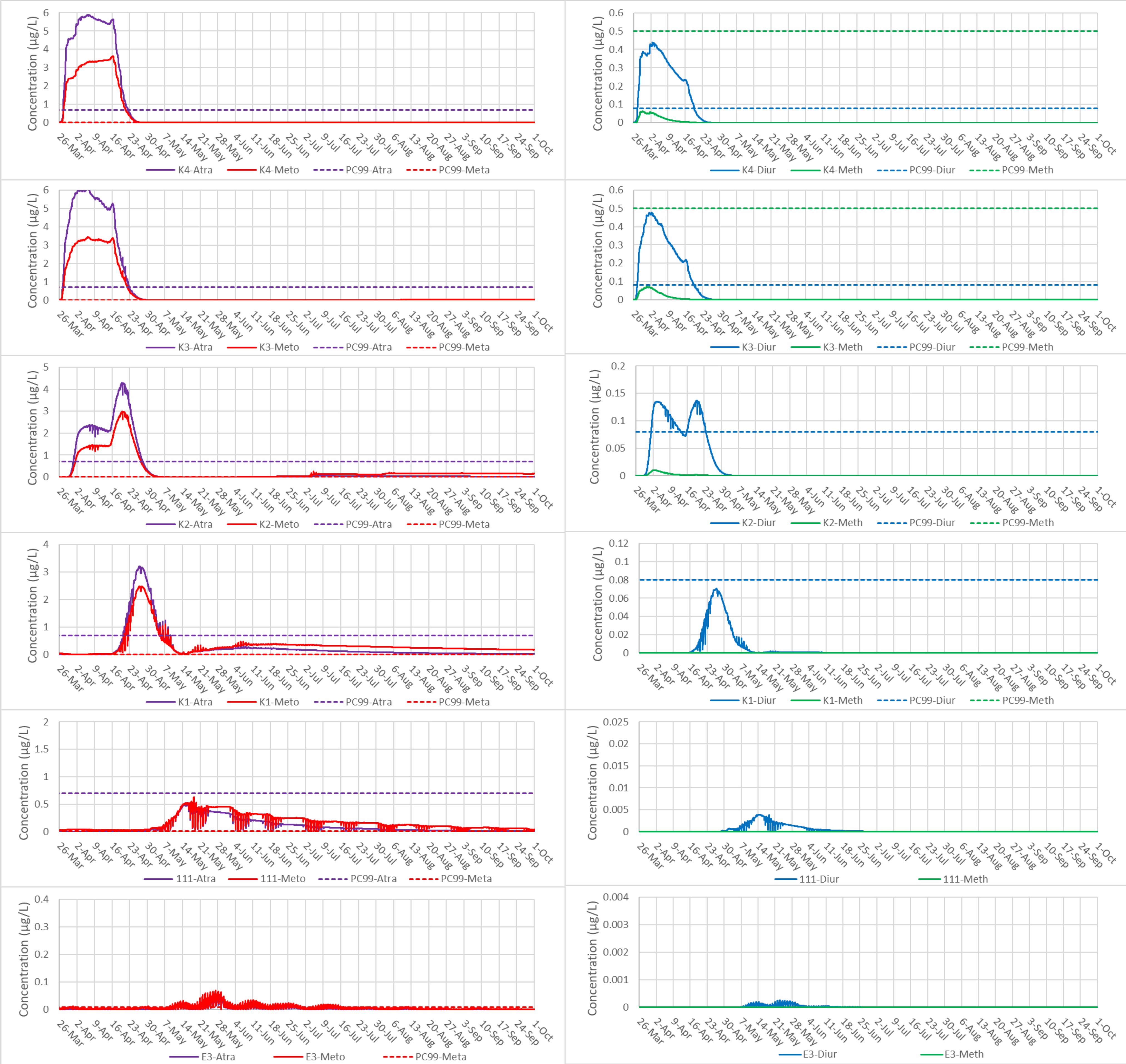

Figure 5.9 ***As Figure 5.8 for scenario 'Goomig + Knox – 50 + 50 MLD'.***

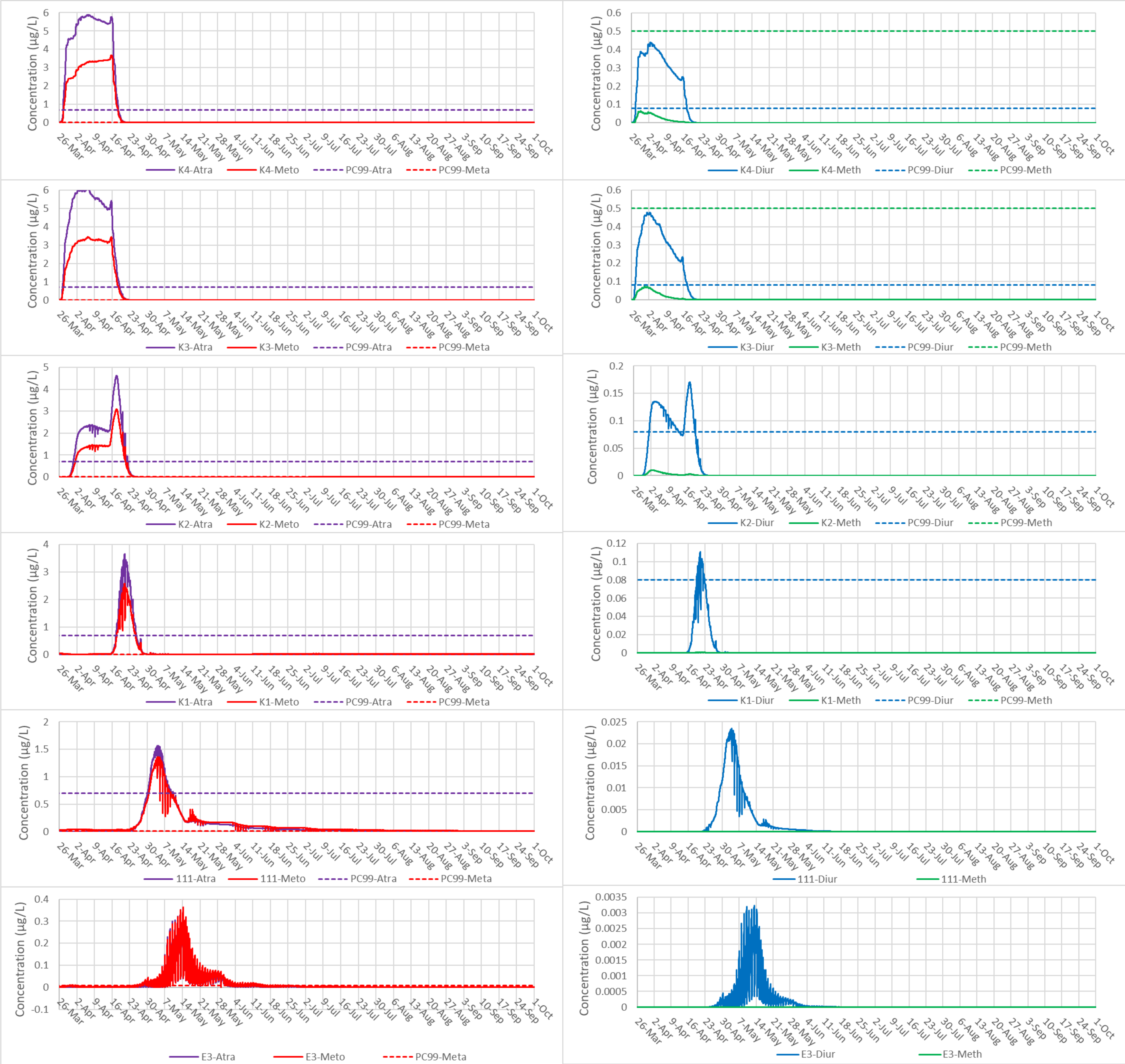

Figure 5.10 ***As Figure 5.8 for scenario 'Goomig + Knox – 100 + 100 MLD'.***

5.2.2.2 Exposure evaluation

The cumulative exposures of the four (4) chemicals when above their respective PC99s at the end of the simulations at each of the five (5) locations for the end of wet season event of the existing Goomig and future Knox Plains farmlands scenarios are summarised in Table 5.2, which indicate the following:

– For slowly degrading metolachlor with a very low PC99, at pool K4 both flushing rates (50+50 MLD and 100+100 MLD) yielded similar exposures that were ~15% (1,535-1,724 ppb hr) of the baseline scenario (11,307 ppb hr). Similarly at pool K3 both flushing rates (50+50 MLD and 100+100 MLD) yielded similar exposures as pool K3 (1,553-1,777 ppb hr) that were ~20% of the baseline scenario (8,214 ppb hr). However, at pool K2 the 100+100 MLD flushing rate exposure (845 ppb hr) was markedly lower than the 50+50 MLD (1,479 ppb hr) and baseline (2,887 ppb hr) scenarios. At pool K1 the baseline scenario with no flushing had the lowest exposure (325 ppb hr) relative to the 50+50 MLD (1,583 ppb hr) and 100+100 MLD (435 ppb hr) flushing rates. Recall that relatively low tidally induced transport during the baseline scenario with no M2 flushing releases retained high chemical levels in the uppermost three (3) pools of K4, K3 and K2, hence the lowest simulated exposure at pool K1 for this scenario. Similarly, exposure was lowest at site G8100111 for the baseline scenario (64 ppb hr) relative to the two (2) flushing scenarios (719 ppb hr for 50+50 MLD, 535 ppb hr for 100+100 MLD) because waters with high concentrations were not transported via flushing to this location, but rather were only transported by low rates of tidally induced exchange. Exposure at site E3 was very low for the 50+50 MLD (21 ppb hr) and 100+100 MLD (65 ppb hr) flushing rates with no simulated exposure (0 ppb hr) for the baseline scenario. In summary, on balance the 100+100 MLD flushing scenario reduces the exposure of a slowly degrading chemical with a very low PC99 such a metolachlor in the uppermost three (3) pools (K4, K3 and K2) most effectively, though relatively modest increases are predicted in pool K1, and sites G8100111 and E3 relative to the baseline scenario. The sum of exposures across all sites is much lower for the 100+100 MLD scenario (4,968 ppb hr) than the 50+50 MLD flushing scenarios (7,303 ppb hr) and the baseline scenario (22,797 ppb hr).
– For atrazine with a moderate degradation rate and a relatively high PC99, at pools K4 and K3 both flushing rates (50+50 MLD, 100+100 MLD) yielded similar exposures that were ~30-35% (2,609-2,898 ppb hr) of the baseline scenario (8,304 ppb hr). At pool K2 the simulated exposure at pool K2 was similar between the baseline and 50+50 MLD scenarios (1,634-1,699 ppb hr), but it was lower for the 100+100 MLD scenario (1,219 ppb hr). There was no simulated exposure (0 ppb hr) of atrazine in pool K1 and at the two (2) sites below the pools (G8100111 and E3) for the baseline scenario (no flushing) because of the combination of low tidally induced exchange between pools K2 and K1, and sufficient degradation in the uppermost three (3) pools. In pool K1 the 100+100 MLD flushing rate exposure (424 ppb hr) was lower than the 50+50 MLD flushing rate (764 ppb hr). There was no simulated exposure at sites G8100111 and E3 for the 50+50 MLD flushing rate, though for the 100+100 MLD scenario there was a low simulated exposure of 257 ppb hr at site G8100111. In summary, on balance the 100+100 MLD flushing scenario reduces the exposure of a moderately degrading chemical with a relatively high PC99 such as atrazine in the three (3) uppermost pools most effectively, though the occurrence of moderate exposure at pool K1 and site G8100111 is not predicted for the baseline (no flushing) scenario. The sum of the exposures across all sites for the baseline scenario (16,732 ppb hr) is much greater by ~2-fold than the 100+100 MLD (7,139 ppb hr) and 50+50 MLD (8,174 ppb hr) flushing rates.
– For diuron with relatively low input concentrations, a rapid degradation rate and relatively low PC99, at pools K4 and K3 both flushing rates (50+50 MLD, 100+100 MLD) and the baseline scenario had very similar simulated exposures (162-203 ppb hr) because degradation prior to the onset of flushing was sufficient to reduce elevated levels in the pools. The baseline scenario exposure in pool K2 (32 ppb hr) was similar to those of the two flushing scenarios (47-54 ppb hr). In summary, there is no (limited) benefit from flushing in terms of exposure of a rapidly degrading chemical with a low PC99 such as diuron for the magnitude of event considered here. However, there may be some benefit if the lag in the onset of M2 flushing flows is shortened from the ~10 days considered here (see Figure 3.12).
– For methomyl with low input concentrations, a very rapid degradation rate and high PC99, there was no simulated exposure at any of the four (4) pools and two (2) sites (G8100111 and E3).

Table 5.3 Cumulative exposure of each chemical for respective PC99s at the completion of the end of wet season event simulations for the existing Goomig and future Knox Plains farmland scenarios.

Chemical	Scenario	K4	K3	K2	K1	G8100111	E3	Sum
Metolachlor (ppb hr)	Baseline	11,307	8,214	2,887	325	64	0	22,797
	50+50 MLD Flush	1,724	1,777	1,479	1,583	719	21	7,303
	100+100 MLD Flush	1,535	1,553	845	435	535	65	4,968
Atrazine (ppb hr)	Baseline	8,304	6,729	1,699	0	0	0	16,732
	50+50 MLD Flush	2,878	2,898	1,634	764	0	0	8,174
	100+100 MLD Flush	2,609	2,630	1,219	424	257	0	7,139
Diuron (ppb hr)	Baseline	203	196	32	0	0	0	431
	50+50 MLD Flush	170	173	54	0	0	0	397
	100+100 MLD Flush	162	166	47	6	0	0	381
Methomyl (ppb hr)	Baseline	0	0	0	0	0	0	0
	50+50 MLD Flush	0	0	0	0	0	0	0
	100+100 MLD Flush	0	0	0	0	0	0	0

6. Recommendations

There have been challenges in the implementation of the existing Surface and Groundwater Discharge Management Plan for the Goomig farmlands. This has been due to both the complexity of the hydrology, and gaps in data and systems required to drive the original Operational Surface Water Model that underpinned the plan. The Operational Surface Water Model required flow and chemical concentrations to be known at key locations within the Goomig farmlands (i.e. DW1 drain) and downstream (i.e. Border Creek, Keep River at pool K4, pool K3). It also required a method of predictive chemical modelling to forecast potential PC99 exceedances in the lower Keep River system.

In an effort to develop a simpler management rule, Bennett (2020) evaluated a proposal whereby farmland water releases of up to 1.5% of the total flow at pool K3 were used as a surrogate. This proved ineffective for highly persistent (long half-lives) and highly toxic (very low PC99s) chemicals such a metolachlor.

Planning to manage risks to the lower Keep River system needs to also include developments underway in the Knox Plains and additional proposed areas in the Northern Territory. To manage these future risks, an understanding of the hydrodynamics of the lower Keep River, tailwater releases from farmlands and potential aquatic toxicity effects to species are required. This investigation has shown that it is possible to use the updated hydrodynamic-chemical model to forecast the fate and transport of pesticides that are released from the existing Goomig and future Knox Plains farmlands. In particular, the updated modelling framework has shown that a reduction in potential toxicity risks to acceptable levels can be achieved through various mitigation measures (e.g. timing of pesticide application on-farm, selection of pesticides with lower toxicity and/or degradation half-times) and management actions (e.g. M2 releases to flush lower Keep River pools).

An objective of this investigation was to provide some key management, mitigation and monitoring recommendations on the basis of the scenario modelling. Recommendations and guidance for consideration in the management of farmland chemical risks to the lower Keep River system include:

– All else being equal (e.g. chemical loads, concentrations, farm application effectiveness, mobility), chemicals with higher degradation rates (short half-life) and/or higher PC99 (lower toxicity) substantially decrease the ecological risks to the lower Keep River system. Potential pesticide substitutes with lower toxicity and/or degradation rates can be evaluated with available tools such as the Pesticide Decision Support Tool (PDST) (Warne et al 2023). The benefits in the preferential use of farmland chemicals with higher degradation rates (short half-lives) is demonstrated in this report with the dry season scenarios.

– Reynolds and Morgan (2023) also provide guidance on chemical selection criteria to be considered to reduce the toxicity risks to the lower Keep River ecosystem. In fact, Reynolds and Morgan (2023) recommend that the use of metolachlor as a pesticide be discontinued because of its slow degradation rate (half-life ~90 days) and very high toxicity (0.0084 µg/L PC99). This investigation's modelling supports this recommendation as credible releases of M2 irrigation water to flush and dilute metolachlor in the lower Keep River system does not predict decreases in concentrations below its PC99 over large reaches and for long durations. It is recommended that very persistent (slow degradation rate) **<u>'and'</u>** high toxicity (very low PC99) chemicals are substituted for alternative pesticides.

– For rapidly degrading chemicals (<~10 days half-life) if the volume from a dry season incident or end of wet season event is sufficiently small to be largely contained in pools K3 and/or K4 then consider natural degradation as a management option (i.e. do nothing but monitor). A condition for the not flushing option is that chemical concentrations in pools K3 and/or K4 are not substantially greater than the PC99 (e.g. <~2-5 fold of the PC99 depending on the degradation rate). This strategy reduces the risk of exposure of relatively rapidly degrading chemicals to the down-river K2 and K1 pools. This is illustrated by the baseline scenario simulations of this report for the chemicals diuron and methomyl.

– During a dry season incident of similar magnitude to that of July-October 2019 for chemicals with moderate (~30 days half-life) to long (~90 days half-life) degradation rates and relatively low toxicity (e.g. atrazine PC99 of 0.7 µg/L), then consider reducing the duration of M2 flushing releases at ~50 MLD from ~2 months to ~1 month. However, for chemicals with a relatively high toxicity (e.g. diuron PC99 of 0.08 µg/L), then flushing for at least ~2 months should be carried out. This is illustrated by the dry season incident scenarios for the chemicals metolachlor and atrazine.

- For persistent chemicals (>~30 days half-life) with a relatively high toxicity (e.g. diuron PC99 of 0.08 µg/L) and high concentrations in the lower Keep River system greater than PC99s, implement sufficient M2 releases to flush high chemical concentration waters well down-river of pool K1 to prevent subsequent up-river tidally induced transport that may pose a toxicity risk to the pools later in the dry season. This is illustrated by the end of wet season flushing scenarios of this report for metolachlor (slow degradation with ~90 days half-life, recommendation that this chemical be discontinued on the basis of the very low PC99) and to a lesser extent atrazine (moderate degradation with a ~30 days half-life). On the basis of the scenario simulations the following M2 releases to flush the pools for persistent and relatively high toxicity chemicals are provided as a guide:
  - For an end of wet season event that is only from the existing Goomig farmland (i.e. while Knox Plains farmland under development) release ~150 MLD over ~30 days.
  - For an end of wet season event that occurs at both the existing Goomig and future Knox Plains farmlands release a total of ~200 MLD over ~30 days (~100 MLD from each farmland).
  - For a dry season infrastructure failure incident, release ~50 MLD (dry season limit to allow irrigation use on farmlands) for at least ~2 months into the Keep River (future Knox Plains farmlands) or Border Creek (Goomig farmland incident).
- In the event of an infrastructure failure incident, and tailwater releases are required to Border Creek (Goomig) and/or Keep River (Knox Plains), if and where possible, identify alternative tailwater ponds with lower concentrations to preferentially release and internally transfer poor quality tailwaters to alternate locations to degrade over time prior to their later release (if needed). A reduction in chemical loads markedly decreases the toxicity risk to the lower Keep River system as illustrated in the 'Reduce TW Conc' scenarios of this report for the slow and moderate degradation rate chemicals of metolachlor and atrazine, respectively.
- As pool K4 has no tidally induced flushing, it is particularly at risk from an end of wet season event or dry season infrastructure failure incident at the future Knox Plain farmlands. The 'Goomig+Knox Baseline' scenario in this report demonstrates that persistent chemicals will maintain elevated levels in pool K4 throughout the dry season following such an incident. Hence, periodic monitoring of pool K4 from the end of the wet season throughout the dry season is recommended to identify such events/incidents and to timely manage such risks in the event of an occurrence. As pool K3 is weakly tidally flushed and could be impacted by events/incidents from the existing Goomig farmland, it would also be prudent to monitor this water body simultaneously with pool K4.
- There was a lag of ~10 days after the onset of dry season incident in which M2 flushing releases were implemented for the dry season incident (and simulations in this report). Similarly, for the end of west season simulations, a lag of ~10 days to implement M2 releases from the end of the high chemical loading event was assumed. Clearly, prompt M2 flushing releases immediately after (or ideally during) such events/incidents will reduce toxicity risks markedly to the lower Keep River system. Alternatively, an increase in this flushing response lag time would increase the toxicity risks, which clearly is undesirable. It is recommended that an adaptive monitoring strategy is implemented for rainfall events that occur at the end of the wet season whereby real-time discharge measurements are monitored to determine if a high risk event (i.e. large proportion of flows into pool K4 from the future Knox Plains farmland and pool K3 from the existing Goomig farmland) occurs. If so, monitoring of the farmland releases, Border Creek, Keep River above pool K4, and pools K4 and K3 are recommended during and immediately after the event.
- In addition to the simplistic toxicity assessment metric of exceedance of a chemical's PC99, this investigation used cumulative exposure (when simulated concentrations were greater than a chemical's PC99) as an additional metric to differentiate relative toxicity risks of the various scenarios. It is recommended, if possible, that numeric exposure criteria are developed to improve predictions of the 'actual' toxicity risks to ecological receptors during incidents/events.
- This investigation has updated and refined the lower Keep River modelling framework that can serve as a decision support tool to assist with understanding and management of farmland chemical risk events/incidents to the lower Keep River system. For example, quasi-real-time predictions of the spatial and temporal concentrations of a chemical of concern during and following an incident could be readily simulated to inform targeted monitoring, to evaluate the effectiveness of ongoing and planned mitigation measures, and to support close-out post-incident reporting of the potential ecological impacts from such events.

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