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River system modelling to support water sharing plan evaluation: A case study in the Clarence River Valley

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Abstract: In New South Wales, Water Sharing Plans (WSPs) govern how water is shared between the environmental needs of a river or aquifer and consumptive water users, which could include town water supply, rural domestic supply, stock watering, industry, and irrigation.

WSPs are a statutory obligation under the Water Management Act 2000. Once a plan is developed and enacted, it has effect for 10 years. Each WSP is evaluated by the Natural Resource Commission every five years. These evaluations consider whether the plan has materially contributed to the achievement of identified environmental, social, and economic outcomes. They also determine where changes to the plan may be warranted. River system modelling is key in informing the development, review and evaluation of WSPs.

This paper presents a case study of how river system modelling informed the evaluation of the *Water Sharing Plan for the Clarence River Unregulated and Alluvial Water Sources 2016* (the Clarence River WSP). It describes the model's key components, how it performed during calibration, and the scenarios modelled around key changes made to water sharing rules. It presents the results of these scenarios, showing impacts on flows and environmental metrics at key gauges of five important water sources.

We modelled scenarios to allow comparison of long- and short-term flows prior to the implementation of the WSP to flows occurring after WSP rules were applied. The model also helps us identify changes in baseflow patterns during the first five years of the plan, when the 2018-19 drought likely caused lower river flows and triggered the application of cease-to-pump rules. The model outputs also helped us identify how baseflow and very low flow patterns changed in the first five years of the WSP, when cease-to-pump rules were applied. No cease-to-flow days occurred in four of the five system water sources during the first five years of the WSP, likely due in combination to the relatively frequent application of cease-to-pump rules and periodic rainfall events in the Clarence catchment during this time.

The model also provides information on the environmental flow rules designed to support the endangered Eastern freshwater cod, an important objective of the Clarence River WSP.

Keywords: *Water sharing plan, Clarence River System modelling, evaluation of water sharing plan*

1. INTRODUCTION

Balancing the competing needs of the environment and consumptive water users is critical to preserving long-term river water resources. Economic gains may result in substantial environmental losses (Flavel, Bari et al., 2010). Several research studies have been conducted to promote coordinated WSP in pursuit of goals for the multiple-objective development and management of water resource systems (Lv, Wang et al. 2021). A participatory approach was used to monitor changes in economic and social indicators within the WSP (Bari, Singh et al. 2008). A modelling framework was employed to undertake a socio-economic assessment of the impacts of water sharing rules (Flavel, Bari et al. 2010). Despite recent advances in environmental flow science, water governance, and management, there is still no universal systematic approach for determining environmental flow requirements for all regions worldwide, including both the natural and social science fronts and, in particular, the interaction between social/political and environmental systems.

In NSW, how water in a river basin is shared between the environmental needs of the river or aquifer and water users is regulated by WSPs (DPE 2016). WSPs also regulate how water is shared between different types of consumptive water users such as town supply, rural domestic supply, stock watering, industry and irrigation.

WSPs are a statutory obligation under the *Water Management Act 2000*. Once a plan is developed and enacted, it has effect for 10 years. Each WSP is evaluated by the Natural Resource Commission every five years. These evaluations consider whether the plan has materially contributed to the achievement of environmental, social, and economic outcomes. They also determine where changes to the plan may be warranted.

This paper presents a case study of how river system modeling has informed the evaluation of the Clarence River Water Sharing Plan (WSP) and its environmental impacts. The research is closely linked to on-the-ground implementation initiatives. The specific case study analyzes the environmental flow to support the endangered Eastern freshwater, which is an important objective of the WSP. The modeling system was developed for four scenarios, including no water extraction for uses, current water extraction without limits, current water extraction under WSP year 1-5, and current water extraction under WSP year 6-10.

The first section of the paper provides background information on the catchment, including water use and the water sharing plan. The second section describes how the baseline Clarence River system model was built. The third section details the scenarios that were modeled to evaluate the WSP for the Clarence Unregulated and Alluvial Water Sources in 2016. The results of the modeled scenarios are presented in the Results and Discussion section. The Conclusion section summarizes the outcomes of the modeling system

2. CATCHMENT DESCRIPTION

The Clarence River catchment is located on the north coast of NSW, around the city of Grafton. With a catchment area of 22,716km^2, it is the largest river on the North Coast of NSW (DPE 2016).

The river rises in the Macpherson Ranges on the NSW–Queensland state border and flows south through an extensive coastal floodplain to Yamba, where it meets the Pacific Ocean. Its major tributaries include the Mann, Nymboida, and Orara rivers (Figure 1).

The river mouth is situated between the towns of Yamba and Iluka, and the estuary extends 108 km inland to Copmanhurst. The main population centres along the estuary are Grafton, Maclean, Yamba, and Iluka. Other towns in the catchment include Tenterfield and Dorrigo.

Most rivers and creeks in the catchment are unregulated (DPE 2016), with no major storages to capture and control flows. Water users rely on natural flows or small storages such as weirs for water extraction. As with most unregulated rivers, flows are impacted during relatively dry periods when water is scarce, and demand is high.

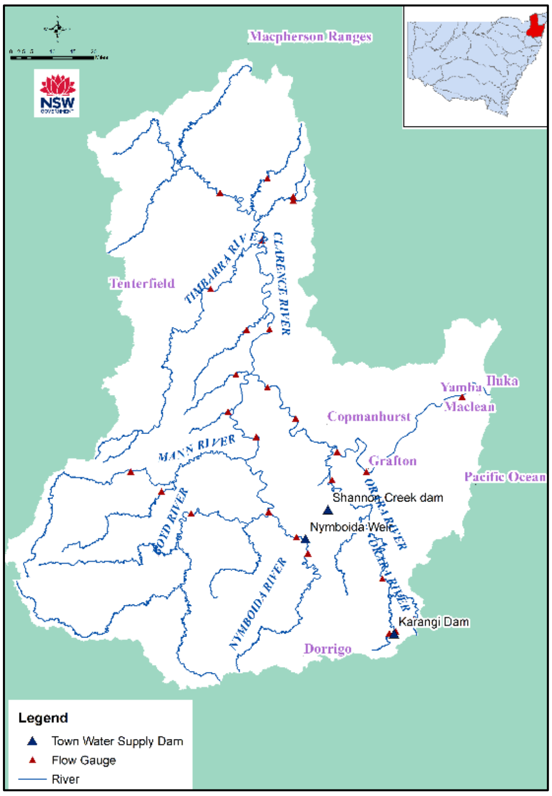

Figure 1. Main rivers, streamflow gauges and storages in the Clarence River basin

2.1. Water users

The catchment's main water users include town water utilities, irrigators, landholders, and water for stock and domestic purposes (DPE 2016). The greatest water demands are irrigated farming in floodplain areas where pasture and crops (such as sugarcane, blueberries, bananas, vegetables and herbs, pecans, and citrus) are grown (Hope 2003). The most significant town water user in the Clarence River Basin, is the Clarence Valley and Coffs Harbour Regional Water Supply Scheme, or RWSS (DPE 2016). The RWSS provides bulk raw water to the NSW North Coast from Iluka in the north to Sawtell in the south. Using the Karangi Dam and Shannon Creek Dam, the RWSS delivers a secure, safe, and reliable water supply to residents regardless of rainfall (GHD 2017). Karangi Dam and Shannon Creek Dam are off-stream dams. Water is harvested from the Nymboida River at the Nymboida Hydro-Electric Power Station intake weir to fill Shannon Creek Dam. Karangi Dam is typically fed by water from the Orara River; the RWSS also delivers water from the Nymboida River and Shannon Creek to Karangi Dam.

2.2. Water sharing plan

At the commencement of the Clarence River WSP (NSW 2017), there were approximately 2,189 water licences in the Clarence River WSP area totaling 86,140ML in entitlement. This entitlement is divided between surface water (81,864ML) and alluvial groundwater (2,019 ML). The surface water entitlements are categorised into four types: irrigated (unregulated river); domestic and stock; local water utility and basic landholder right. Table 1 shows total entitlements for each type.

Table 1. Total entitlements for different types of licenses (NSW 2017)

Licence type	Entitlements (ML)
Domestic and Stock	541
Local water utility	41,213
Unregulated river (irrigation)	36,734
Basic landholder right	5,633

The WSP limits the amount of surface water that can be extracted. Water sharing is managed annually through long-term average annual extraction limits, and daily through cease-to-take rules and special environmental rules. These vary for different licence classes and water sources.

3. BASELINE MODEL

When building the Clarence River system model, we divided the catchment into 24 sub-catchments comprised of 14 headwater sub-catchments and 10 residual reaches. We delineated sub-catchments using a 30-second SRTM digital elevation model, WSP boundaries, and streamflow gauge locations. We used a rainfall-runoff model for headwater catchments. Residual catchments consist of five main components: rainfall-runoff model; flow routing and in-stream transmission loss; crop demand model; Local Water Utilities (LWU) demand model and WSP rules. We incorporated two off-stream storages, Karangi Dam and Shannon Creek, into the model to simulate the town water supply system for the RWSS.

3.1. Modelling components

We simulated runoff from headwater and residual catchments using the Sacramento rainfall-runoff model. We used the Muskingum method to estimate reach flow routing. In-stream transmission loss was estimated as a proportion of the river flows. Water demand from irrigated crops was estimated using the Irrigator module of the Source software. It uses the FAO56 daily water balance method to estimate evapotranspiration, which is then used to predict irrigation requirements(Allen 2000). Each irrigator node represents an irrigation district and can be configured for multiple crop types and cropping areas. Cropping areas can be configured to represent the impact of crop characteristics and planting decisions on crop water use. The number and size of cropped areas can be changed over time in response to available water resources. The LWU demand model consists of three components (Bethune 2015): critical human water needs; seasonal use variations in response to climate drivers and use variations in response to water restrictions.

WSPs restrict access by implementing cease-to-pump rules that require users to stop taking water on days when stream flows fall below a set level. The flows at water sources in the Clarence River WSP area have been classified as having high, medium, or low flows. When flows at reference gauges fall within the Very Low Flow Class, cease-to-pump rules are applied.

Extraction is restricted by special environmental flow rules. For example: *'water must not be taken for more than twelve hours/day when the flow at the gauge is less than or equal to 225 ML/day or for a period of 24 hours after flows at the gauge first exceed 764 ML/day following any period during which flows in the Copmanhurst-Lower Mid Clarence Water Source were in the Very Low Flow Class'* (DPE 2016).

Water extraction in the modelled system is also limited by the entitlements. WSP restrictions in the Clarence River system include 100% allocation every year, 200% maximum carryover, and maximum uses of 300% within every two consecutive years.

3.2. Data description

To build and calibrate the model, we used climate data, including rainfall, evaporation, and streamflow. Observed data of crop types, irrigated crop area, and water diversion for irrigation and town water supplies were also used We obtained daily rainfall and evaporation data for 1889 to 2020 from SILO. Daily flow data were extracted from the HYDSTRA database of WaterNSW. We determined irrigated area and crop type using satellite images and land use maps. The Clarence Valley Council (CVC) provided data on water extraction from Karangi Dam and Shannon Creek Dam.

3.3. Model performance

We developed the Clarence River system model using the eWater SOURCE Modelling platform (eWater 2021). The modelling system consists of 14 headwater sub-catchments, 10 residual sub-catchments and 70 supply point nodes. The 70 supply point nodes include 36 unregulated irrigation nodes, 4 water utility nodes and 30 basic landholder right nodes. Figure 2a shows an example of reach nodes and links. Figure 2b shows the node-link schematic of the CVC and Coffs Harbour City Council (CHCC) RWSS.

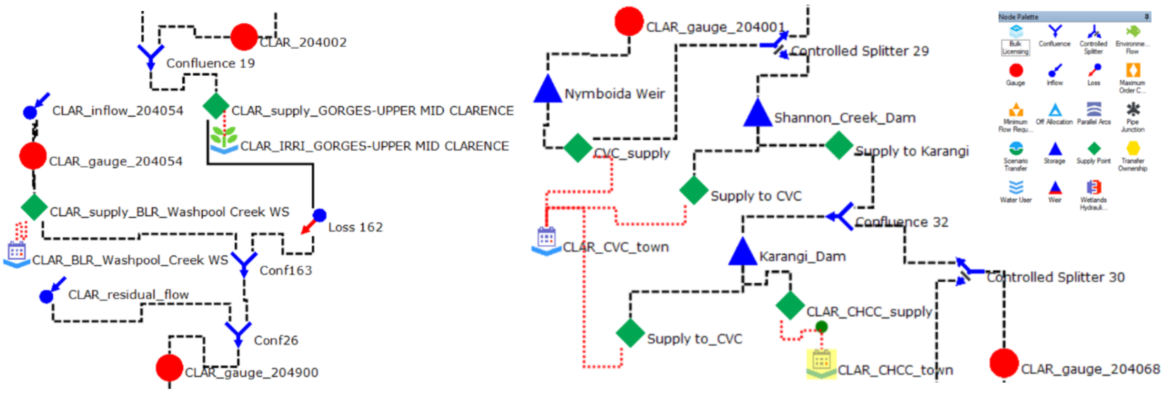

Figure 2. Nodes and links schematics for a river reach (a) and for RWSS (b)

The model runs on a daily time step. We used monthly and annual biases to calibrate modelled extraction for irrigation or town water supply and square-root daily, exceedance, and bias (SDEB) as the objective function for headwater runoff and streamflow calibration. This included three components: the bias term, the daily term, and the exceedance term (Coron et al, 2012).

$$\text{SDEB}=\left[1+\frac{|\sum Q_{sim}-\sum Q_{obs}|}{Q_{sim}}\right]*[0.1\sum(Q_{sim}^{1/2}-Q_{obs}^{1/2})^2+0.9\sum(R_{sim}^{1/2}-R_{obs}^{1/2})^2]$$

where: Q_{sim} is simulated flow; Q_{obs} is observed flow; R_{obs} is observed quantile flow and R_{sim} is simulated quantile flow.

SDEB values at 22 calibrated gauges across the river basin were between 0.63 to 0.93 (Table 2). These results indicate the model performs well in simulating long term daily flows.

Irrigation extraction data was only available for two water years, 2017-2018 and 2018-2019. Figure 3 compares observed and simulated irrigation extraction for irrigation. For water years 2018-2019, the difference between annual observed and simulated extraction was 3.4%.

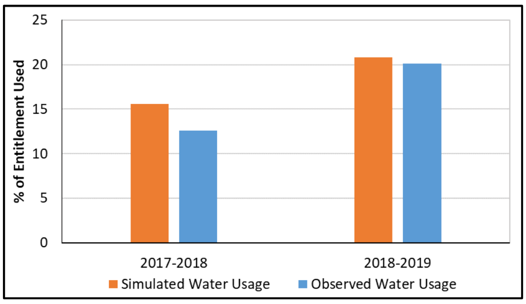

Figure 3. Annual water extraction for irrigation

We calibrated the town water model at a monthly step using CVC and CHCC water extraction data, provided by the CVC, for 2013-2020. Figures 4 and 5 illustrate good agreement between the observed and modelled values, with average annual volume differences of 3% for CHCC and CVC towns.

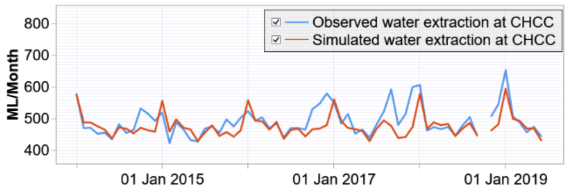

Figure 4. Observed and modelled extraction by CHCC towns

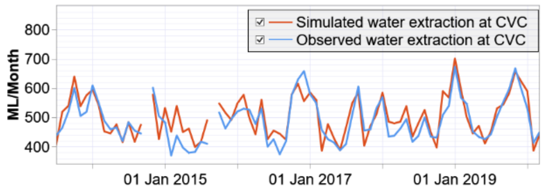

Figure 5. Observed and modelled extraction by CVC towns

Table 2. Calibration key results at gauges

Gauge	Volume bias (%)	SDEB	Calibration period	Gauge	Volume bias (%)	SDEB	Calibration period
204001	0	0.83	06/1956-04/2019	204046	-0.1	0.83	07/1969 – 04/2019
204014	-0.3	0.73	07/1971-02/2019	204048	-4.1	0.73	06/1974- 11/1985
204015	0	0.8	05/1970-4/2019	204049	0	0.63	09/1970-11/1985
204034	-0.1	0.79	08/1971-04/2019	204051	0	0.83	03/1976-04/2019
204043	-0.1	0.69	03/1960-04/2019	204054	5.4	0.72	09/1972-06/1985
204044	0	0.73	05/1969-06-1985	204056	-0.9	0.79	05/1975-04/2019
204002	0.9	0.4	03/1976- 02/2019	204004	0.87	-3.8	09/1997-02/2019
204025	0.84	10.3	12/1988-02/2019	204041	0.81	3.8	11/1972-02/2019
204060	0.9	0.84	05/1975-04/1990	204007	0.92	1.8	10/1970-02/2019
204068	0	0.89	08/1995-01/2019	204906	0.88	-0.1	11/1972-02/2019
204069	0.82	0.1	09/1997-02/2019	204900	0.93	-1.5	09/1972-02/2019

4. MODELLING SCENARIOS

We used the baseline model to build four scenario models to support evaluation of the WSP:

- scenario 1 (Sc 1): pre-development or without development. This scenario returns the natural river flows when no extraction and no storages regulate river them. We removed the demand models and water sharing rules of the baseline model to build this scenario model.
- scenario 2 (Sc 2): current development with unlimited extraction rules. This scenario includes current water demand for irrigation, basic landholder rights and urban demands. Storages are included, and there are no restrictions on extraction to meet these demands.
- scenario 3 (Sc 3): Current development with limited extraction under years 1-5 of the WSP (NSW 2017). This scenario differs from scenario 2 in that extraction is limited by cease-to-pump and other environmental rules applied during this time.
- scenario 4 (Sc 4): Current development with limited extraction in years 6-10 of the WSP. The WSP applies greater restrictions on extraction in years 6-10. For example, the Very Low Flow Class threshold (below which water cannot be extracted) increases from 86ML per day at the Copmanhurst-Lower Mid Clarence source in years 1-5, to 125ML per day in years 6-10 (NSW 2017).

5. RESULTS AND DISCUSSION

The model allows for a relative comparison of flow regime under different scenarios. We evaluated the results across four metrics (Table 3): cease-to-pump rule; cease to flow; flows at the 80th and 95th percentiles and flows to support Cod habitant (Cod flows). The Eastern freshwater cod is a threatened fish species that is thought to now only be found only in the Clarence River catchment and potentially in the Richmond River catchment. During the development of the Clarence River WSP, the Regional Panel considered that special environmental low flow rules and CtP rules were required in seven water sources where the cod occurs. Research afterwards in the Nymboida River in 2009 found that during low flows of 260 ML/d and 360 ML/d or greater, promoted most upstream movement of 6.79 and 7.85 km by cod near the Nymboida weir (Reinfields and Butler 2014). Table 4 presents summaries of the key output metrics at five main gauges located at five key water sources within the Clarence WSP area. Results include statistics for the long-term period of record (1893-2020 (P-all)). We also considered the 10-year period before the plan was implemented (2006-2015 (P2)) and the first five years of the WSP (2016-2020 (P3)) to assess recent changes to flow.

Table 3. Metrics used in model outputs

Metrics		Metric acronym	Metrics		Metric acronym
Cease to pump (CtP) rule	Number of years each of the CtP occurred	CtP1	**80th and 95th percentiles**	80th%ile in ML/d	P80
	Total number of CtP days in each year (avg of period)	CtP2		95th%ile in ML/d	P95
	Longest duration of CtP rule per year (avg of period)	CtP3		number of days per year ≤ 80th%ile	DP80
	Longest duration of a CtP rule in this period (days)	CtP4		number of days per year ≤ 95th%ile	DP95
Cease to flow	Average number of cease to flow days per year	CtF1	**Cod flows**	Average number of days that flows above 260 ML/d	C260
	Average number of cease to flow events per year	CtF2		Average number of days that flows above 360 ML/d	CF360
	Average duration (days) of a CTF event per year (avg of period)	CtF3		Special environmental rule (a) listed in the Clarence Unregulated River WSP	EVR1
	Longest duration of a cease flow spell in this period (days)	CtF4		Special environmental rule (b) listed in the Clarence Unregulated River WSP	EVR2

In terms of long-term analysis (period P-all):

- The model results show that in scenario 4, CtP rules would have been activated more frequently at all key water sources compared to scenario 3. At gauge 204007, scenario 3 resulted in an average of two CtP days per year, while scenario 4 increased the number of CtP days to three per year. At gauge 204900, the number of CtP days increased from 11.4 days in scenario 3 to 23.6 days in scenario 4. Scenario 4 also showed an increase in the longest duration from 37 days to 63 days at gauge 204007 and from 53 days to 102 days at gauge 204900.
- CtF events occurred at some gauges under scenario 2, but only at gauge 204900 under scenarios 3 and 4, with an average of 1.7 days per year. The longest duration was 22 days in water year 2019-2020.
- Baseflows (80th percentile) and very low flows (95th percentile) were modelled based on pre-development conditions (scenario 1). We used this threshold for other scenarios to calculate the number of days river flow fell below the baseflows and very low flows. Outputs showed that the number of days the flows were below the baseflows ranged from 75 days at gauge 204900 to 126 days at 204004. The number of days when the flows were below very low flows were 18 days and 42 days at gauge 204001 and gauge 204007, respectively.

Table 4. Results of modelled scenarios for 5 key water sources

Metrics	Clarence River gauge @ Lilydale (204007)			Mann River gauge @ Jackadgery (204004)			Orara River gauge @ Glenreagh (204906)			Nymboida River gauge @ Nymboida (204001)			Clarence River gauge @ Baryulgil (204900)		
	Sc 3 (Sc 4)	Sc 2	Sc 3	Sc 3 (Sc 4)	Sc 2	Sc 3	Sc 3 (Sc 4)	Sc 2	Sc 3	Sc 3 (Sc 4)	Sc 2	Sc 3	Sc 3 (Sc 4)	Sc 2	Sc 3
	P-all	P2	P3	P-all	P2	P3	P-all	P2	P3	P-all	P2	P3	P-all	P2	P3
CtP1	9 (15)			8 (15)			21 (21)			26 (38)			37(63)		
CtP2	2 (3)		3.2	1.6 (3.4)		0	7.0 (7.0)		4.8	12.2 (19.4)		10.2	11.4 (23.6)		34.4
CtP3	0.4 (1.0)		1.1	0.3 (0.8)		0	1.1 (1.1)		0.6	2.2 (4.5)		3.1	2(5.4)		4.8
CtP4	37 (63)		6	37 (78)		0	97 (97)		15	224 (226)		16	53 (102)		53
CtF1	0		0	0		0	0		0	0		0	1.7(1.7)	0	13.4
CtF2	0		0	0		0	0		0	0		0	0.4(0.4)	0	2.2
CtF3	0		0	0		0	0		0	0		0	0.37(0.37)	0	1.2
CtF4	0		0	0		0	0		0	0		0	22(22)	0	22
P80	957			500.7			61.8			388.0			258.5		
P95	379			208.6			23.5			180.1			71.8		
DP80	77.5(77.5)	38.3	126	80.3(80.3)	38.3	122	88.2(88.2)	34.8	97.8	73.4(73.4)	47.9	98.6	75.6(75.6)	38.6	123.8
DP95	21.4(21.4)	1.8	42.4	23.5(23.5)	4.1	37.6	23.5(23.5)	0	17.2	18.5(18.5)	7.3	20.8	20.2(20.2)	0.3	50.6
C260	356	365	340	339	355	309	122	164	75	329	354	320	292	326	241
C360	349	364	325	320	345	278	92	128	53	301	334	275	259	295	207
EVR1		0	20		0	0		0	12		7	32		12	78
EVR2		0	0					0	1		0	0		0	0

In terms of short-term analysis (periods P2 and P3), the statistics were calculated for scenario 2 during the period P2 and for scenario 3 during the period P3.

- The average number of CtP days under scenario 3 ranged from 3.2 days at gauge 204007 to 34.4 days at gauge 204900. CtF events occurred only at gauge 204900 during scenario 3, with an average of 13.4 days per year. Baseflows and very low flows occurred less often at all selected gauges. However, in scenario 3, these events occurred more frequently. This increase is likely due to a decrease in stream flows in 2018-2019 during the drought.

Regarding flows to support eastern freshwater cod, the average number of days where flows exceeded 260ML per day and 360ML per day found to be widespread across the system. This information is especially useful for identifying Cod habitat and breeding environments. Special environmental flow rules were applied more frequently in the first five years of the WSP than in the 10 years before the plan was implemented.

6. CONCLUSIONS

In presenting this paper, we have described the model's key components and its performance during calibration. We have outlined the four scenario models built with key changes to water sharing rules, and presented the results of this scenario modelling at five key gauges using environmental metrics.

The Clarence River System model was able to provide outcomes to inform the Clarence WSP evaluation process. The modelled outputs of the scenario models enable comparisons of the flow regime before and after the WSP rules being in place. In addition, the outputs describe how baseflow and very low flow patterns have changed in the first five years of the WSP, when cease-to-pump rules were triggered. It also provides insight into very low flows over different time periods: pre-development; before the plan's implementation; the first five years of the plan and the second five years of the plan. The influence of the 2018-2019 drought was also have been simulated and is likely driver for the decrease in river flows and CtP rule occurring. Importantly, the model provides outputs related to the application of the (often-multilevel) special environmental flow rules designed to support the endangered eastern freshwater cod. This support is a key objective of the Clarence River WSP.

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