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A near real-time early flood warning system for dam safety in Western Australia

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Abstract

This paper presents an early warning and flood intelligence system developed for Ophthalmia Dam, which is a BHP-operated water storage facility in Western Australia. The system was originally developed to support flood preparedness and overtopping risk management at Jimblebar Wye and Ophthalmia Dam. However, the system is adaptable to a range of asset life cycle stages, in particular operated assets undergoing progressive closure, final closure readiness, and post-closure monitoring and maintenance. Regular monitoring and flood modelling validation during the operational period of an asset can inform closure planning and frame decision-making around flood protection design criteria.

The system enhances asset awareness by integrating a live hydrometeorological monitoring network with an adaptive catchment response model. By automatically processing rainfall and water level sensor data into the model, the system provides continuous oversight that reduces the need for frequent physical site inspections.

The system includes probabilistic risk modes that can be used to evaluate a range of upstream catchment responses. This is essential for defining and continuously refining the magnitude of events associated with closure design criteria (e.g. the flows resulting from a specific rainfall event). Hydrographs in the model are user tuneable and can evolve as more storm data is gathered. A decision support interface within the model also provides an intuitive visual output of predicted water level trajectories and alert threshold envelopes. This enables remote teams to manage flood preparedness and safety risks from a centralised location. Adaptive learning features also provide event-based adjustments to rainfall loss parameters. This allows the predictive model to refine accuracy of estimated flood hydrographs as post-closure data are observed over time.

This paper outlines the system architecture and the operational outcomes of deploying data-enabled infrastructure to manage residual risk. The work demonstrates how data automation and predictive analytics can strengthen the resilience of closed mine sites.

Keywords: *remote monitoring, decision support interface, adaptive flood intelligence, predictive analytics, post-closure monitoring*

1 Introduction

Near real-time flood warning systems must balance 3 requirements: (i) timeliness during rapidly evolving storms, (ii) usability for operators under time pressure, and (iii) defensibility under uncertainty, including transparent communication of data quality limitations and model assumptions.

The purpose of this paper is to document a telemetry-enabled flood intelligence system for Ophthalmia Dam, a water reservoir located in the Pilbara region of Western Australia, and describe how the system could be

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adapted and applied to assets approaching their closure life cycle stages, with a particular focus on remote, low-intervention monitoring.

2 Site context

The flood warning system provides coverage for the Ophthalmia Dam and Jimblebar Wye (a rail junction and crossing) catchments, which span an area of approximately 4,953 km^2. The Wye is a key infrastructure asset in the Pilbara, with significant iron ore passing through the corridor daily; further supporting the need for timely flood intelligence in case of extreme weather events in the upstream catchments. Ophthalmia Dam is a BHP-operated water storage facility. The dam was constructed in 1981 to support groundwater recharge using the ephemeral Fortescue River. The dam is comprised of a reservoir, 3 earth-filled embankments and 3 spillways. The spillways have staggered activation levels, meaning each begins discharging water when the invert level (base of the spillway) is reached, which may occur at different times depending on the reservoir water level. At Ophthalmia, the service spillway (1) releases first, then the auxiliary spillway (2) and then the fuse plug (3). Figure 1 provides a summary of the key infrastructure components governing the operation of the dam in relation to Jimblebar Wye.

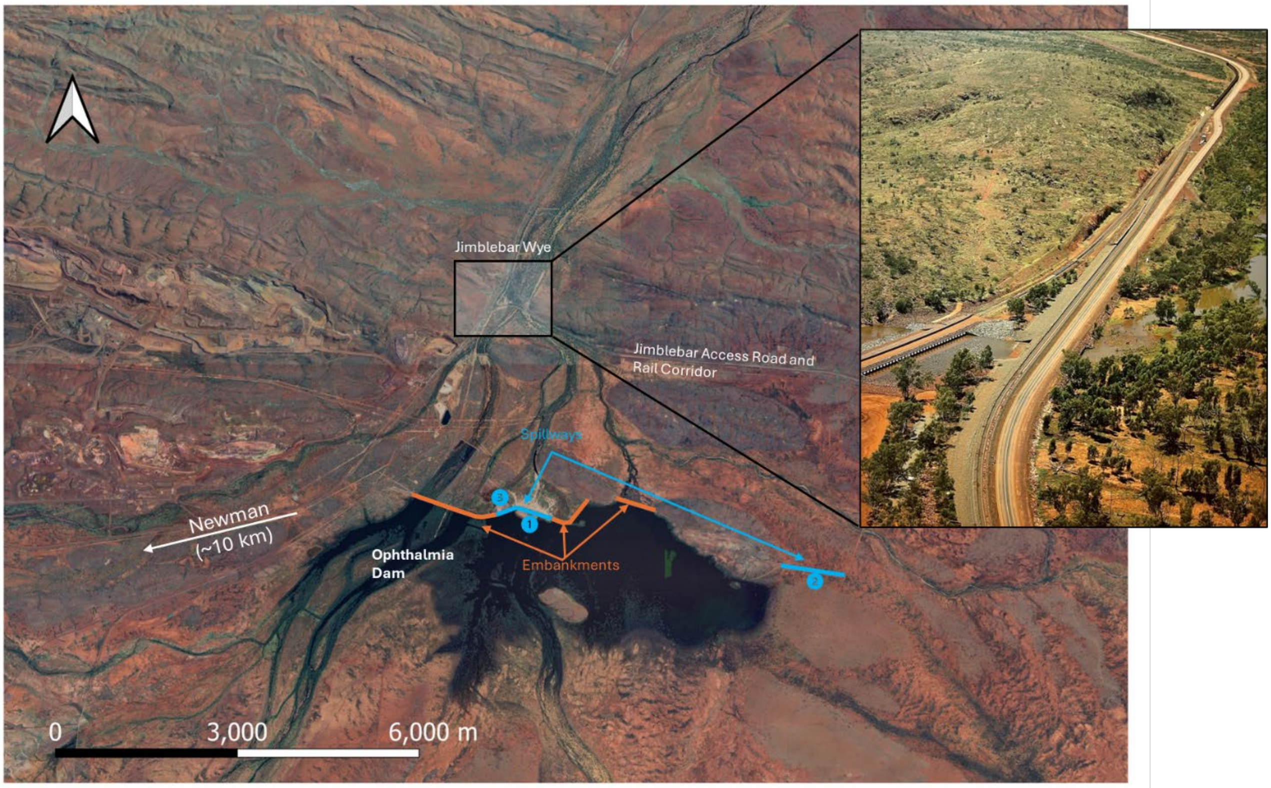

Figure 1 Ophthalmia Dam and Jimblebar Wye key components

3 Climate setting and catchment hydrology

The Pilbara region of northwestern Western Australia is characterised by an arid to semi-arid climate with very high summer temperatures and low and highly variable annual rainfalls, influenced predominantly by tropical weather systems over the summer period. The regional climate exerts a dominant control on surface water behaviour, flood generation mechanisms and the operational reliability of flood warning systems in both operational and closure phases. Tropical cyclones and decaying tropical lows contribute approximately 25–34% of mean annual rainfall along the Pilbara coast, with a measurable influence extending several hundred kilometres inland (Sudmeyer 2016). However, the cyclone contribution to annual rainfall is highly variable.

Fortescue River, Warrawandu Creek and Whaleback Creek contribute inflows to Ophthalmia Dam (shaded in dark orange in Figure 2), while Homestead and Shovelanna Creeks (shaded in light orange in Figure 2) contribute downstream of the dam towards the Jimblebar Wye crossing. Figure 2 provides a conceptual catchment flow logic schematic and the relationship between key contributing catchments, the reservoir and the crossing.

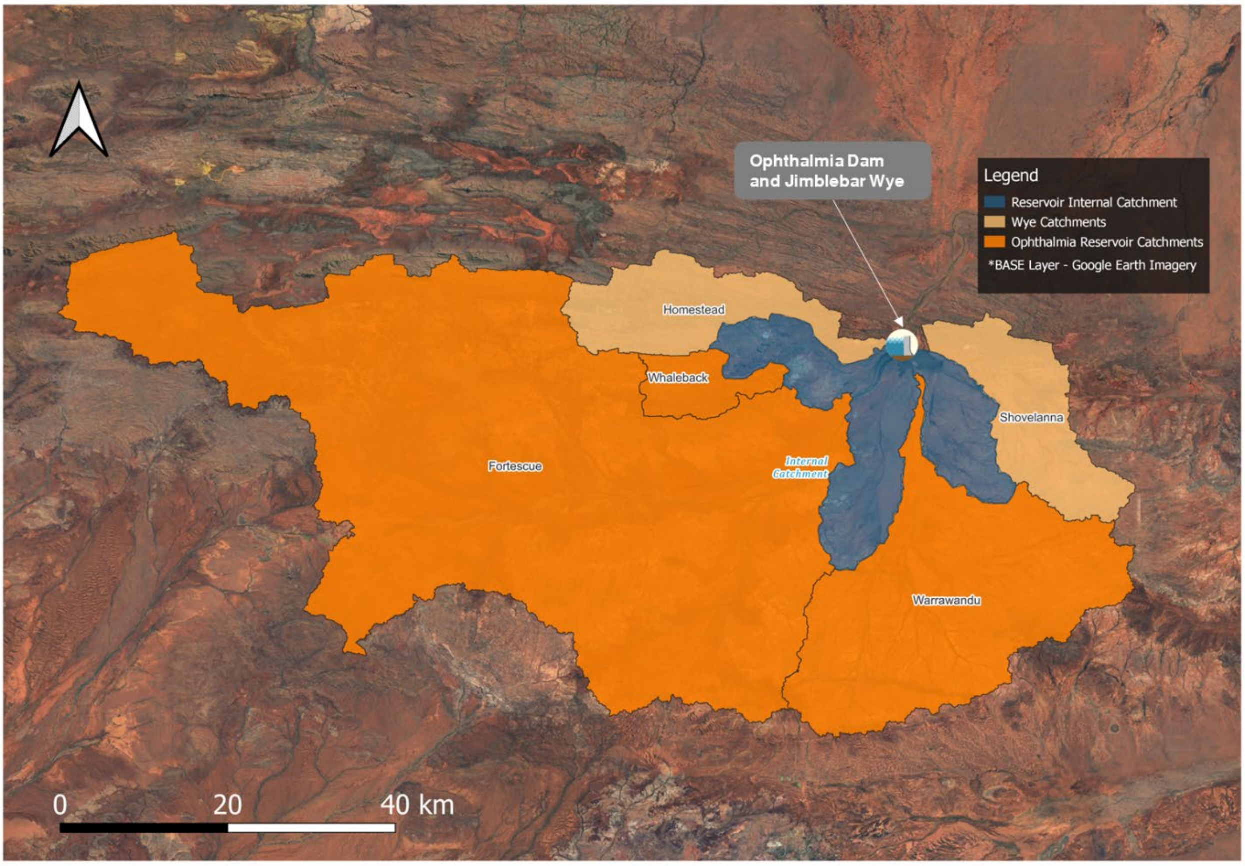

Figure 2 Conceptual catchment flow logic schematic

4 Flood warning system overview

The flood warning system is designed as a modular, telemetry-enabled architecture to support decision-making during extreme weather events. System components are loosely coupled to allow operation under partial connectivity (e.g. redundancy of gauge data sources within the telemetry system if stations are down) while maintaining a consistent modelling workflow.

The system integrates the following core elements:

- hydrometeorological monitoring network – upstream rainfall gauges and water level sensors distributed across upstream catchments, the reservoir and the downstream Wye crossing
- telemetry and central data platforms – near real-time transmission and centralised storage of observations from the monitoring network, reducing reliance on physical site access during events
- data extraction workflows – automated or operator-triggered routines that convert raw telemetry data into a model-ready time series, with basic quality checks and gauge substitution capability in the event one or more gauges are unavailable

- hydrological and flood routing model – a unit hydrograph rainfall–run-off framework implemented in GoldSim (GoldSim Technology Group Ltd 2025), coupled with rainfall loss modelling and routing logic
- decision support interface – a fast dashboard presenting forecast hydrographs, water levels, and the timing and duration of threshold exceedance aligned with facility-level trigger action response plans (TARPs) in Ophthalmia Dam and at the Wye. The user is empowered to rapidly simulate multiple rainfall projections as required while new data is refreshed by the minute.

Figure 3 provides an overview of data flow in the flood warning system. The top-line guidance provides general timing bands when rainfall is projected, noting that timing can be highly variable depending on the intensity of the event and where it occurs in the catchment.

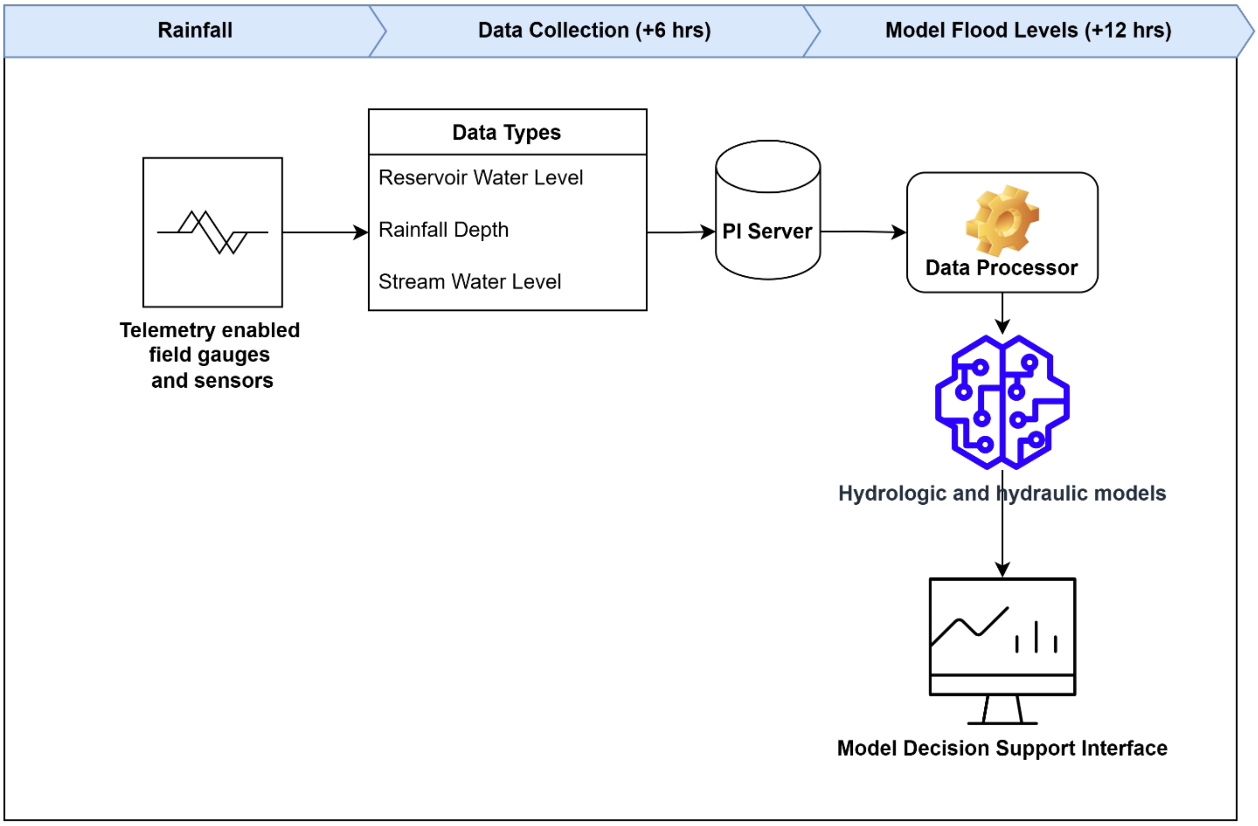

Figure 3 Flood warning system overview

5 Hydrometeorological monitoring network and telemetry

The system uses a network of rainfall gauges and water level sensors distributed across the contributing catchments. The network covers most of the contributing catchments with at least one rainfall station in each catchment. Most gauges were installed and telemetry enabled after 2017. The Bureau of Meteorology (BoM)-operated Newman Aero gauge, located near Ophthalmia Dam, has the most complete historical record of storm events. Since 2020 BHP has installed and upgraded water level gauges in Shovelanna, Whaleback and Homestead Creeks. Water level gauges at the Wye and reservoir provide downstream coverage to validate catchment-specific hydrological responses and projected water levels. Storm events post-2020, for which rainfall and water level gauges were available, were used to validate model outputs. Table 1 provides a summary of the catchment rainfall gauges and captured storm events.

Table 1 Summary of catchment rainfall gauges and captured historical storm events

Storm date in columns and station name in rows	1999 14–16 Dec	2003 25–27 Jan	2009 1–3 Mar	2017 22–25 Mar	2021 1–3 Feb	2024 23–25 Jan	2024 10–13 Dec
Newman Aero (007176)	**222**	**197**	**122**	**131**	**81**	**175**	**115**
Sylvania Downs				128	**112**	83	No data
Wops Bare				124	**76**	**188**	**81**
Prairie Downs		No data		24	**56**	**195**	**16**
Cappy				77	**112**	**265**	**137**
Dingos				85	**73**	**193**	**55**
Lightning Ridge				106	**70**	**203**	**29**

Bold = full temporal coverage with sub-daily intervals; rainfall depth is expressed in mm

5.1 Telemetry and near real-time acquisition

Telemetry enables passive monitoring by transmitting rainfall and water level data to central platforms with typical latencies in the order of minutes to tens of minutes. This reduces reliance on physical site access during storms and supports remote teams during low-staffing closure phases. Most sensors in the BHP hydrometeorological network have a 15-minute latency, which is typical of most hydrometric monitoring systems.

5.2 Data quality and failure modes

Operational forecasting is sensitive to raw data availability and quality. Common issues observed for the available datasets include negative or drifting water levels, missing data gaps, inconsistent cumulative rainfall sequences and applied offsets. The system therefore includes simple quality checks and operational guidance to reject unreliable inputs and substitute alternative gauges. The operator can also override the data processor engine and provide custom time series rainfalls as required.

6 Unit hydrograph method for flood intelligence

6.1 Rationale for unit hydrograph approach

The unit hydrograph (UH) method (US Army Corps of Engineers 2025) provides a computationally efficient and interpretable relationship between rainfall excess and run-off at a catchment outlet. The UH approach was selected over more complex hydraulic models due to its computational efficiency, transparency and suitability for near real-time decision support. For closure-phase decision support, the ability to perform rapid scenario sweeps and to explain why a forecast changes (e.g. gauge selection, antecedent losses) can be more valuable than a higher complexity model that is difficult to calibrate with limited data. More complex models utilising linked flood forecasting and hydraulic applications such as TUFLOW or HEC-RAS can be computationally infeasible during real-time model simulations where data is being processed concurrent with the occurrence of a storm event. The unit hydrograph-based model runs in seconds and can provide answers to a range of rainfall scenarios quickly.

The UH is implemented using a discrete convolution relationship between rainfall excess and discharge (Equation 1):

$$Q_n = \sum_{m=1}^{n\leq M} R_m U_{n-m+1} \tag{1}$$

where:

Q = discharge (m3/s)

R = rainfall excess (mm)

U = unit hydrograph ordinates (m^3/s)

m = number of periods of rainfall excess

n = number of periods of unit hydrograph.

6.2 Assumptions and implications

The UH framework adopted in this study relies on a small number of simplifying assumptions that are appropriate for event-based, operational forecasting but which should be interpreted as approximations rather than exact representations of catchment behaviour. These assumptions are explicitly acknowledged to frame model uncertainty while guiding post-event review and refinement.

The key assumptions and implications are:

- approximate linearity. Increases in rainfall excess are assumed to proportionally scale with run-off, whereas nonlinear responses may arise during very high rainfall intensities or under strongly varying antecedent moisture conditions
- approximate time invariance. Catchment response shape is assumed stable for events of similar duration; however, surface conditions and landform geometry may evolve in some catchments during closure, particularly in disturbed areas (e.g. due to mining or agriculture), noting that these represent relatively small footprints relative to the undisturbed upstream catchment
- rainfall spatial representativeness**.** Point rainfall gauges are used as proxies for areal rainfall, introducing uncertainty where networks are sparse, storm patterns are highly localised and areal rainfall distribution is substantial.

6.3 Derivation of catchment-specific unit hydrographs

Catchment-specific unit hydrographs are derived where adequate concurrent rainfall and discharge data exist for large historical events. Where observational records are limited or where discharge is derived from unvalidated rating curves, design-event hydrographs may be used as proxies to define initial UH shapes. Subsequent refinement can be made as additional storms are observed in the future, enabling the UHs to be re-evaluated.

Figure 4 provides an overview of the unit hydrographs used in the model. The Fortescue River hydrograph is derived from 2 large storm events that occurred in 1999 and 2009, whereas other catchments are derived from 24-hr duration design hydrographs.

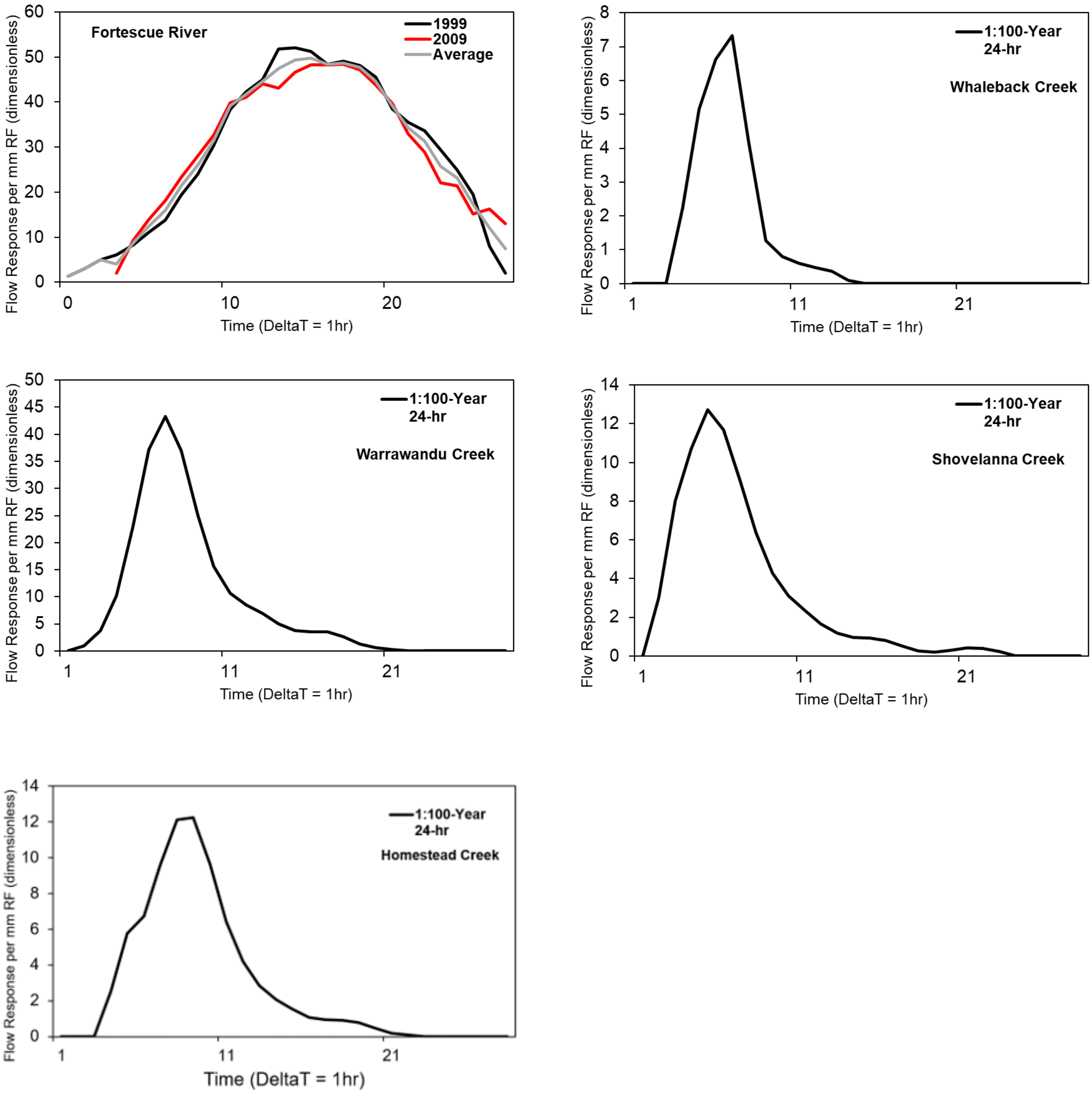

Figure 4 Unit hydrographs for each catchment. RF = rainfall

6.4 Validation of Fortescue River flow response using unit hydrograph

Fortescue River has a catchment area of approximately 2,944 km^2, which represents over 60% of the total catchment area in the system. A calibrated Fortescue River flow response is therefore critical for model accuracy and reliability. Concurrent rainfall and flow gauge data were used to estimate the flood hydrographs for 2 large storm events in 2003 (Jan) and 2024 (Jan). Both events are estimated to exceed 100 mm of rainfall over the modelled Fortescue River catchment area. The storm is estimated to have around a 1:70 to 1:80 annual exceedance probability (AEP) for a 24 to 36-hr duration. The comparison of observed and simulated flood hydrographs is shown in Figure 5. There is general agreement in the shape of the flood hydrographs, with some minor offsets in the timing of between 2 and 6 hours for peak flows in both storm events.

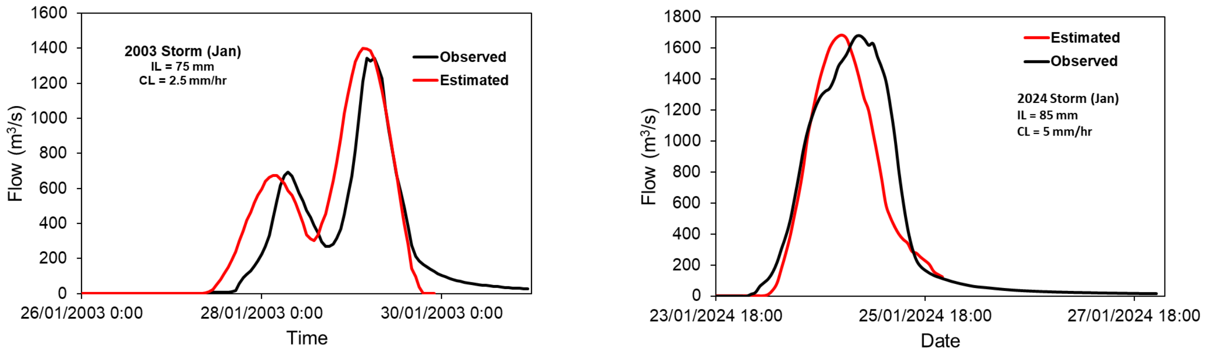

Figure 5 Fortescue River catchment hydrograph validation using large storm events. IL = initial loss, CL = continuing loss

6.5 Rainfall loss modelling as the calibration lever

In the modelling approach, initial loss (IL) and continuing loss (CL) are applied to rainfall to estimate rainfall excess. IL primarily controls the onset timing of run-off by delaying excess rainfall initiation, while CL controls the continuing conversion of rainfall to run-off during an event. In the operational workflow, IL and CL provide transparent adjustment levers to bracket plausible antecedent conditions for a specific storm rather than to force or adopt a single, unique best fit. Figure 6 provides an overview of the concept.

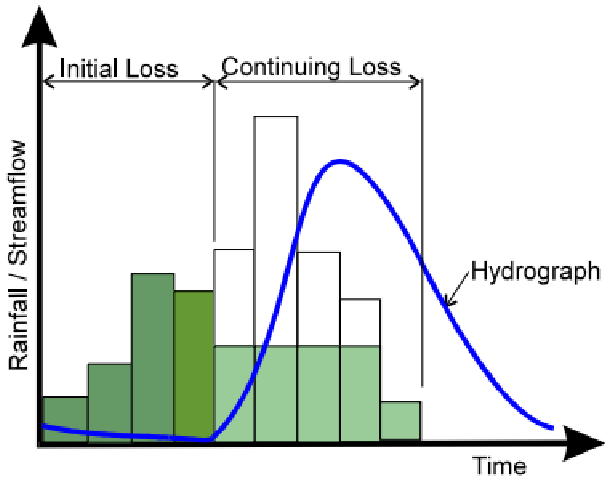

Figure 6 Loss parameter concepts (Geoscience Australia 2019)

Adopted CL and IL parameter ranges used Australian Rainfall and Runoff (ARR) guidance (Geoscience Australia 2019) for the Pilbara to constrain the maximum and minimum ranges that the user could adopt in the model. Table 2 lists the adopted CL and IL ranges.

Table 2 Adopted continuing loss and initial loss parameters for the Pilbara (Australian Rainfall and Runoff Region 2)

Parameter	Minimum	Median	Maximum
Initial loss (mm)	17.5	37.2	85.5
Continuing loss (mm/hr)	0.5	3.2	10.7

6.6 Rainfall gauge selection and substitution

Given point rainfall estimates are being adopted over large catchments, the model enables gauge substitution by catchment if required. This supports resilience against sensor malfunction and allows rapid exploration of alternative (and possibly more likely) spatial rainfall patterns during a storm.

6.7 Observational constraints and rating curve uncertainty

For several catchments in which water level sensors are installed, discharge can currently only be derived from theoretical stage-discharge relationships that have not yet been validated by stage-discharge measurements. In braided or shifting channels, rating curves may drift over time. Consequently, agreement between modelled and derived discharge should be interpreted cautiously and cross-checked against downstream observations (e.g. considering the Ophthalmia Dam water level response) where possible.

6.8 Reservoir routing

Catchment inflows are translated into water surface elevations through the reservoir using a stage-storage relationship and spillway rating curves with staggered activation levels for the service, auxiliary and fuse plug spillways. Forecast outputs are expressed primarily as a water surface elevation time series relative to spillway inverts and operational trigger levels. The largest water level driver for the reservoir water level is the Fortescue River, which is the largest contributing catchment.

Figure 7 provides the model performance against the storm that occurred in January 2024. The projections generally show strong agreement with the hydrograph shape but a slight underestimation of the peak outflow discharge and associated timing. Considering the size of the catchments in the model, some level of deviation is expected. The differences in spatial-temporal rainfall patterns in each catchment can have a considerable influence on the amount of inflow projected at the reservoir and these may not be captured fully by point rainfall gauges (i.e. 1–2 gauges per catchment). In addition, the stage-storage relationships of the reservoir can be subject to change due to vegetation growth and sediment transport from upstream catchments. These factors may influence ponding characteristics, the overall storage capacity and when the spillways activate (the primary source of outflow from the reservoir). The model itself is built to allow flexibility with stage-storage relationships as the user can enter new curves based on updated surveys collected over time.

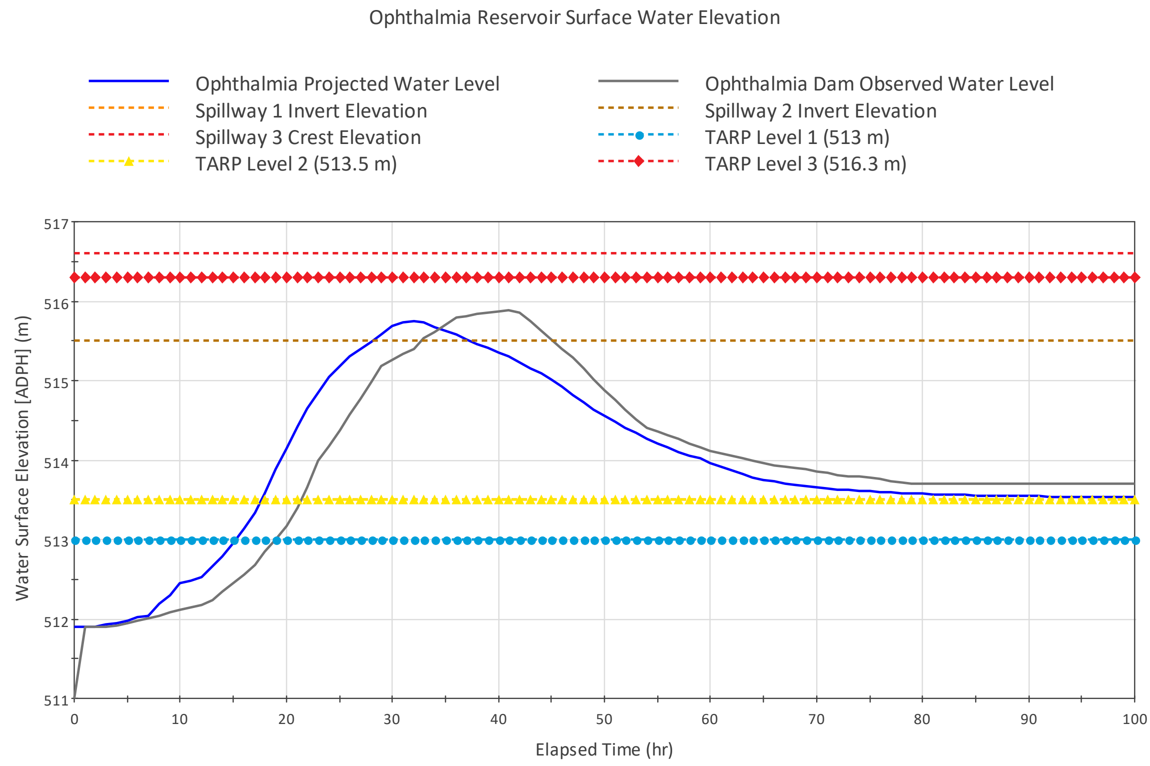

Figure 7 Reservoir projected versus observed surface water elevations and trigger action response plan (TARP) levels during a large storm event in January 2024 [water elevations in Admiralty Datum Port Hedland (ADPH)]

6.9 Wye crossing routing and decision outputs

At the Jimblebar Wye crossing, the tool forecasts water surface elevation, time to peak, peak level and duration above critical thresholds. Figure 8 shows the projected water levels at the Wye during the January 2024 storm event.

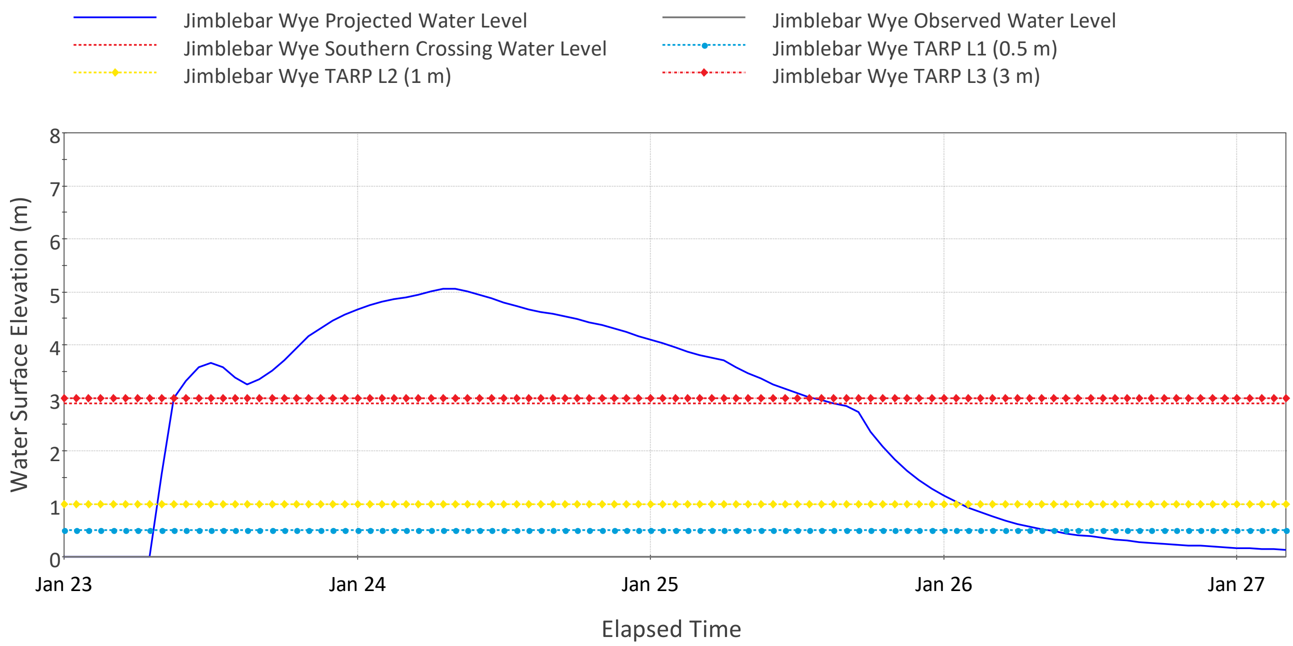

Figure 8 Jimblebar Wye projected surface water elevations during a large storm event in January 2024 [water elevations in Admiralty Datum Port Hedland (ADPH)]

The large storm event was estimated to have a 1:77 annual exceedance probability (1.3%) over a 24-hr duration, which exceeded the crossing's capacity and caused temporary overtopping. The peak projected water level was 503.79 m Admiralty Datum Port Hedland (ADPH), reached at the 31-hr mark of the model simulation (23 hrs after excess rainfall); corresponding to 1:00 on 25 January 2024. The peak aligns closely to the timing of peak water levels observed in the Ophthalmia reservoir, which also resulted in maximum outflows from the spillways. The total duration of overtopping at Jimblebar Wye was estimated to be 55 hrs. A water level gauge with telemetry is located upstream of the crossing, however, this sensor malfunctioned and recorded zero water level increases during the event. The rail junction was reopened after repairs were conducted and flood levels receded.

To validate the model output, several alternative sources were reviewed:

- flood warning memos issued by BHP during the event
- camera footage screenshots
- footage of the post-event site (via drone)
- qualitative observations from reports commenting on the duration of overtopping.

The above review of alternative sources revealed the duration of overtopping at the Wye was estimated to last approximately 2.3 days or ~55 hrs. The duration of overtopping predicted by the model suggests that the model is reflecting observed results. However, peak water levels were not recorded manually so comparisons could not be drawn on the estimated peak water levels or exact timing.

7 Interface design and operator workflow

7.1 User interface

The user interface is treated as a risk control. A dashboard-based design supports consistent execution under time pressure and decreases reliance on specialist modelling expertise. The interface groups inputs (rainfall series, initial levels), adjustment levers (IL/CL per catchment) and outputs (forecast plots, threshold markers, summary metrics) into a small number of dashboard screens established within the GoldSim platform.

Figure 9 demonstrates the intuitive user interface. Left side represents the user tuneable parameters, whereas the bottom dashboard denotes the main decision support interface with TARP-linked threshold envelopes and time-based projections of flood levels.

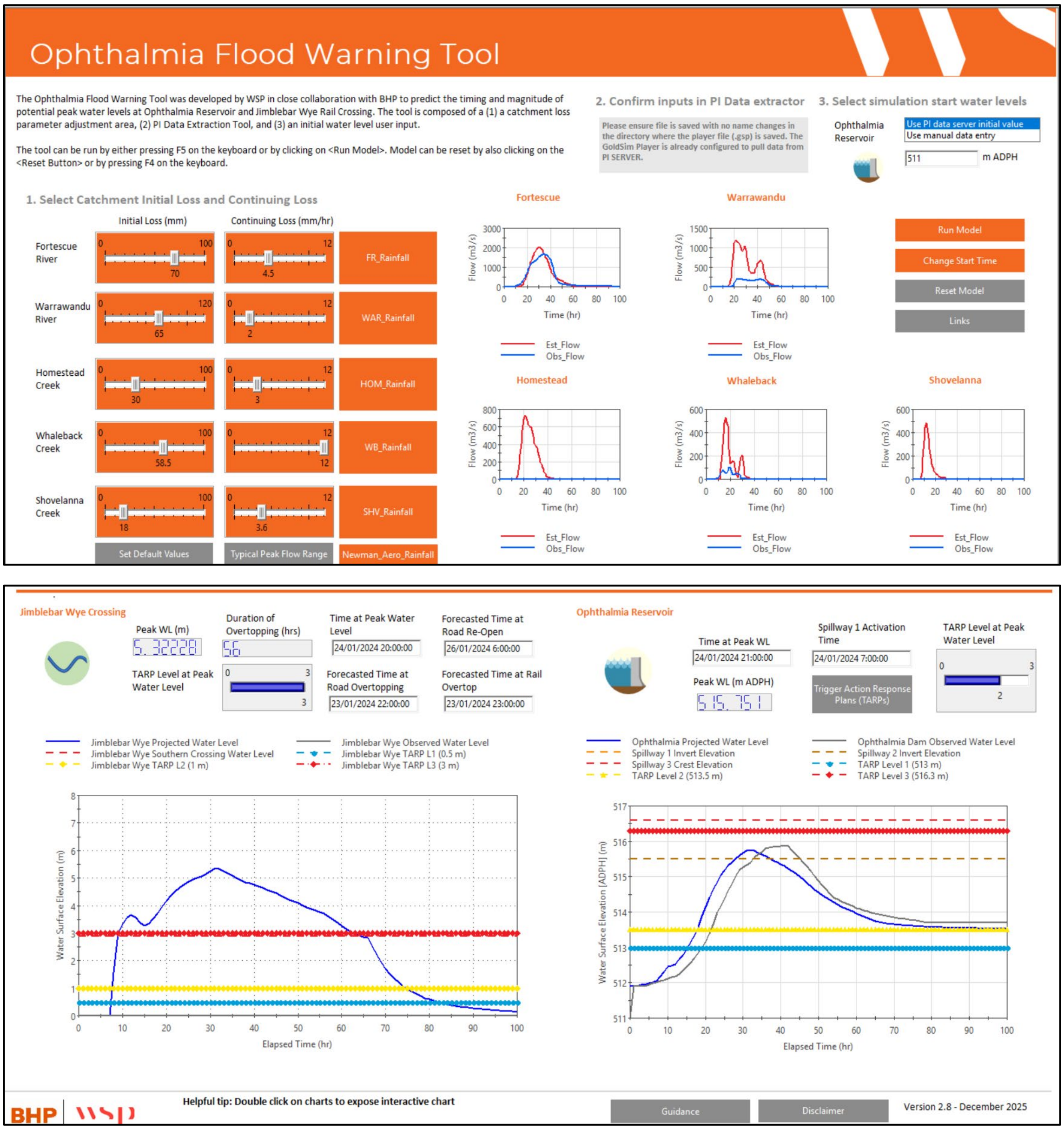

Figure 9 Model user interface and decision support outputs. TARP = trigger action response plan, WL = water level

7.2 Linking outputs to trigger action response plans

Forecast outputs are intended to map directly to TARPs. The system enables proactive decisions such as early road/rail closure, active spillway monitoring and escalation of TARPs based on forecast conditions. The most common use of the tool is threshold focused: identify when key water elevations may be exceeded and for how long (for the Wye), and trigger pre-defined actions with documented assumptions and notes linked to data completeness (e.g. sensor down, data replaced with different sensor). The model is therefore designed with redundancy in mind, with backup station linkages to provide resolution on catchments where sensor density is higher or data for a specific station is unavailable or potentially unreliable.

7.3 Post-event review and adaptive calibration

A post-event review is intended to be conducted for all significant events. Review provides a forum to discuss how to improve timing, peak and duration between observed and simulated flood hydrographs and flood levels in the Ophthalmia reservoir and at the Wye, where observed benchmarks are credible. Attribution should explicitly consider rainfall representativeness, rating curve uncertainty (e.g. stage-storage drift) and spillway rating sensitivity where possible. The model is built in a highly graphical GoldSim environment that enables rapid changes to the interface and updates of unit hydrographs on the back end. A library of past events can be used to further refine model performance as more new concurrent gauge data (rainfall and water level) are collected over time, particularly for larger flood events.

8 Role of flood intelligence in mine closure

During progressive closure and post-closure monitoring and maintenance phases, flood risk increasingly becomes a function of designed landforms (typically more vulnerable when the landform is first constructed), active surface-water controls and downstream receptors, while site access and staffing numbers typically reduce. In this context, flood intelligence systems must transition from being active operational support tools (high intervention) to remote monitoring (low-intervention) systems that continue to provide valuable oversight while demonstrating a site's compliance to long-term closure objectives. These low-intervention systems are expected to achieve the same or a better level of risk management without reliance on active surveillance that you would otherwise have within an operating asset.

The flood warning system supports an asset's closure outcomes through the following mechanisms:

- low-intervention monitoring and operational continuity. Telemetry-based rainfall and water level monitoring enables continuous oversight of hydrological conditions without reliance on frequent site attendance, supporting low-staffing closure phases and remote decision-making. The key requirement is maintenance of the facilities and data collection interfaces
- direct linkage to TARPs. Forecast outputs are aligned with operational trigger levels and TARPs, allowing consistent, auditable escalation of controls for infrastructure protection, access management and downstream risk
- consistency of data collection. Long-term, standardised monitoring creates defensible datasets for assessing performance of landforms, surface-water controls and erosion mitigation measures across closure and post-closure timeframes. This is particularly important where any downstream infrastructure (such as the Wye) may remain in place and operational into the post-closure future
- scenario-based decision support. Highly tuneable modelling modes support risk-based decision-making rather than reliance on single deterministic forecasts, aligning with the uncertainty inherent in closure landscapes
- legacy and relinquishment planning. Archived event libraries and reproducible forecasts provide evidence of ongoing performance, support statutory compliance and stakeholder confidence, and improve planning around residual water-related risks .

9 Future enhancements and emerging technologies

While the current system is intentionally pragmatic and specific to the Ophthalmia context, future iterations could incorporate additional technologies to improve scalability, resilience and transferability to other sites and operational contexts using comparable approaches. These enhancements are not prerequisites for effective operation. Instead, they represent opportunities to strengthen flood intelligence as data availability and digital maturity increase, especially in the advent of agentic capabilities in artificial intelligence models.

Potential future developments include these benefits:

- Satellite-derived information, including post-event flood extent mapping and surface condition indicators, will support the validation of flow pathways and refinement of channel and floodplain geometry. High-resolution InSAR datasets generated directly before and after events can provide redundancy if sensors are down or malfunctioning.
- Event library analytics will enable rapid comparison of new events against historical events to inform starting parameter ranges and plausibility checks.

- Custom Monte Carlo simulations will use different probabilistic inputs to model complex flood scenarios.
- AI agents can be used to reduce operator reliance on lower-value processing tasks that are not directly related to decision-making and interpretation.
- Improved data integration pathways, such as application programming interface (API)-based ingestion and cloud-hosted workflows, will improve data extraction and portability across site portfolios.

These enhancements would support broader deployment while retaining the model's emphasis on defensibility and operator judgement.

10 Conclusion

This paper presents a flood intelligence system tailored to an operational site in the Pilbara, Western Australia, that is designed to support operational flood risk management and real-time decision-making (e.g. flood preparedness, trigger action response plans (TARPs) activation and infrastructure protection). This model is highly portable to the closure life cycle stages of an operated asset where flood risk can be driven by intense storm events, high uncertainty and limited opportunities for direct verification in remote areas. By integrating telemetry-based monitoring, a transparent unit hydrograph framework and an operator-focused decision interface, the system converts episodic and potentially imperfect data into actionable and auditable decision support aligned with TARPs. Key modelling assumptions are treated explicitly as approximations and are addressed through a formal adaptive calibration and event process, allowing model behaviour and parameters to be reviewed as data is accumulated during the event. While effective in its current form, the system architecture is extensible and can incorporate emerging technologies to support broader application across other operating assets and provide key insights for assets approaching their closure life cycle stages, all while retaining an emphasis on engineering judgement and defensibility.

Acknowledgement

The authors acknowledge BHP for supporting the development and application of this novel flood warning system as part of ongoing mine operations and water risk management. The contribution of EWS Consulting is also acknowledged for its role in the design, configuration and ongoing operation of the remote monitoring and telemetry systems that underpin real-time hydrometeorological data acquisition. The system also utilises datasets and reference information provided by the Australian Bureau of Meteorology, with long-term climate statistics, rainfall observations and guidance forming an essential foundation for regional hydrological characterisation and event interpretation within the Pilbara and more generally across Australia. The views expressed in this paper are those of the authors and do not necessarily represent the positions of the contributing organisations.

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