25th International Congress on Modelling and Simulation, Darwin, NT, Australia, 9 to 14 July 2023
mssanz.org.au/modsim2023

Data-driven risk mitigation: Water quality forecasting during extreme events

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Abstract: As part the operation of the state's rivers and water supply systems, WaterNSW regularly undertakes reservoir modelling of several reservoirs across Greater Sydney. In March 2022, Greater Sydney received three to five times of it monthly average rainfall; and consequently, recorded as the wettest March on record for some areas (source: BoM monthly rainfall statistics). This was followed by the July 2022 event during when an East Coast Low brought several days of heavy rain around Sydney that resulted in major flooding of the Hawkesbury-Nepean River and extended along the NSW coast (source: BoM monthly rainfall statistics). Weather events of such a magnitude can significantly impact drinking water quality by affecting water catchments, storage reservoirs, the performance of water treatment processes or the integrity of distribution systems.

The effect of large amount of rainfall inflow on the reservoir was investigated using WaterNSW's real-time reservoir management system (SCARMS) for the March 2022 and July 2022 events. SCARMS integrates observational data and coupled hydrodynamic and aquatic ecosystem models into a decision support system Results reinforced that the runoff into the reservoir played a dominant role in the water quality of Lake Burragorang. Subsequently, operational decisions were made to optimise raw water supply and prevent unwarranted stress on the water filtration plants during events of such magnitudes. Improvements to the modelling have been identified and further work continues to build on the existing success of the implementation of these hydrodynamic-aquatic ecosystem models.

Keywords: *Water quality modelling, forecast, analytics, hindcast*

1. INTRODUCTION

Lake Burragorang (Figure 1), a dendritic, y-shaped reservoir, is supplied by 7 major inflows: Coxs, Kedumba, Kowmung, Little, Nattai, Werriberri and Wollondilly rivers, with most of the river confluences farther than 30 km from the dam wall. The bulk inflows entering the lake are contributed by the two major river systems of Coxs–Kowmung in the west and Wollondilly in the south of the main reservoir. The water extracted from Warragamba Dam goes into 3 water filtration plants: Prospect, Orchard Hills and Warragamba. The dam has height adjustable vertical outlet screens, through which water can be selected from different depth of the highly stratified lake. Spill over the dam wall enter the Hawkesbury Nepean River at Warragamba River confluence and therefore can affect the flood levels in the Hawkesbury-Nepean River.

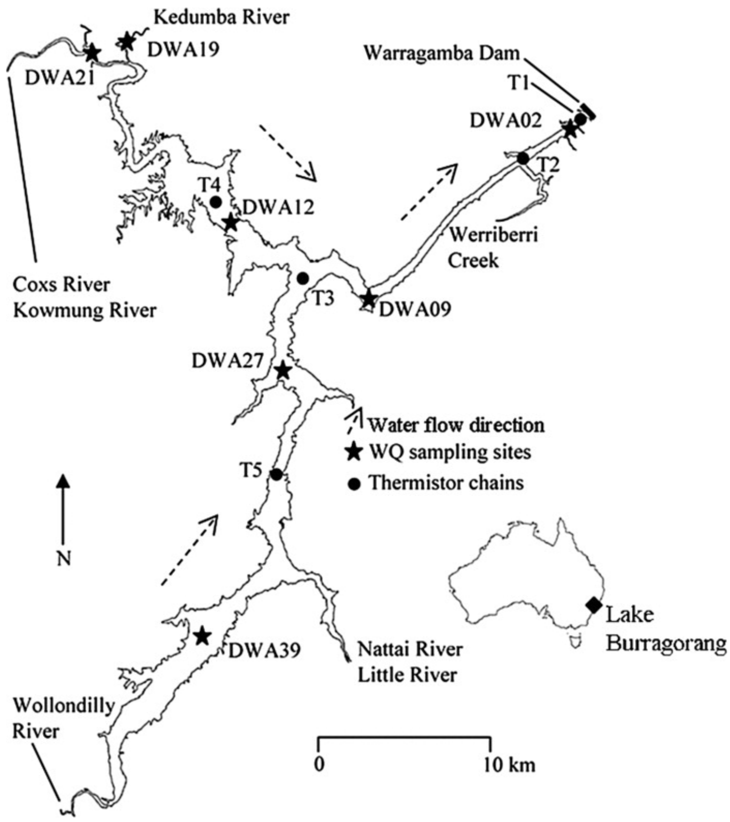


Figure 1. Lake Burragorang key infrastructure and inflow locations (water flow directions) towards the dam wall

In 2022 across the east coast of New South Wales (NSW), a series of troughs and east coast lows occurred during a La Niña weather cycle. This resulted in the region receiving rainfall events of significant magnitude and was primarily in the first 7 months of 2022. During the March 2022 rainfall event, the automated weather station at Warragamba dam, the main water supply reservoir of Greater Sydney forming the Lake Burragorang, recorded 475 mm rainfall received by the system from March 1 to March 8. The Hawkesbury River at Windsor rose to 13.8 meters, which at the time was at its highest level in more than 40 years (Infrastructure NSW, July 2022). Warragamba dam started spilling at a rate in excess of 70 GL/d on March 2, after torrential rainfall over its catchment exceeded earlier predictions. Continued heavy rainfall on March 3, 8 and 9 resulted in significant flash flooding across Sydney, along with major flooding in the Hawkesbury-Nepean catchment (source: BoM monthly rainfall statistics for March 2023).

For the July 2022 event, the forecast indicated, ~240 mm and the system received another ~275 mm over a period of 10 days until the east coast low in early July 2022 (July 1 to July 10). Warragamba dam started spilling again on July 3 peaking at ~450 GL/d.

When significant rainfalls such as that of March 2022 and July 2022 occur, operators and managers require information on projected inflows and its impacts on storage level and possible spills impacting the downstream area of the dam. This information is then used to assess issues that are likely to arise and possible solutions, such as dam gate operational preparation and operation, possible water quality supply issues as well as coordinated communication to emergency services, the community and government. Being the largest dam in Greater Sydney (approx. 2,065 GL), Warragamba dam supplies nearly 80% of Sydney's drinking water supply. The water balance of the reservoir is primarily governed by inflow coming into the Wollondilly and Coxs River arms of the catchments and relatively constant outflows used for drinking water supply.

Like any water supply reservoir, a major concern that WaterNSW often deals with during a large rainfall event is potential contamination (suspended solids, pathogens, nutrients) brought into the Warragamba dam carried by the flood runoff from the catchment. Such inflows can enter as dense underflows that can disrupt the storage operation in several ways, e.g., turbidity intrusion carried by the inflow near the offtake thus creating pressure on the water filtration plants, and inflow of nutrients, providing suitable environment for algal bloom. To minimise the impact of such intrusion on the drinking water supply scheme, the offtake gates operating at variable depths are adjusted in order to avoid a deteriorated water quality due to intrusion. Consequently, the ability to simulate the water quality impact of a pending flood event is critical for maintaining offtake water quality, especially during events of such magnitude.

During the March 2022 rainfall event, large amounts of runoff entered Lake Burragorang representing one of the largest monthly runoffs entering the lake resulting in spill from the dam. During the July 2022 event, additional runoff entered the Lake Burragorang with the water levels at ~8 m below the full supply level prior to the event, resulting in another spill event peaking at 450 GL/d. The hydrodynamic behaviour of the flood underflow and its impact on the reservoir was carried out during both events to aid in operational decision making using WaterNSW's reservoir management system SCARMS. SCARMS integrates observational data and coupled hydrodynamic and aquatic ecosystem models into a decision support system (DSS). SCARMS DSS outputs, since launched in 2004 and upgraded a number of times with new and improved functionalities, have been used to create a number of scenarios across a few reservoirs in Greater Sydney – for example, predicting the impact on lake Burragorang for June 2007 major inflow event (Martin and Maheswaran, 2012a) or predicting winter turnover in lake Burragorang (Martin and Maheswaran, 2012b). The DSS allows the ability to generate several scenarios to predict the impact on water quality as an event progress. Scenario modelling results such as, intrusion depth and intensity to lake Burragorang allows in operational decision making a few days ahead in time to minimise impacts of intrusions of such magnitude on the water filtration plants. This paper aims to present some of the results modelled during the events and its impact on the operational decision making during the events.

2. MODEL SETUP

SCARMS uses 3D hydrodynamic Estuary, Lake and Coastal Ocean Models (ELCOM) coupled with the ecological Computational Aquatic Ecosystem Dynamics Model (CAEDYM) to carry out the reservoir scenario modelling. The models are described in detail in Hodges et al. (2000), Romero and Imberger (2003) and Dallimore et al. (2003), respectively.

The forecast model uses predicted inflows and default values for events for the contaminants and a warm-up period of 40-day hindcast built on measured data. Several scenarios for each event were modelled for a period of 30 days from the start of the rain events and input boundary conditions were updated as the events progressed. Measurements of inflow rate entering the lake estimated from the forecasted rainfall, inflow temperatures provided by the operators for each scenario, outflow volumes as well as measured dissolved oxygen and suspended solids (turbidity) in the 7 major inflows were provided as model inputs. Models used meteorological parameters e.g., the wind speed, wind direction and solar radiation measured from the automated weather station in Lake Burragorang (Figure 2). A set of inflows for the tributaries to Lake Burragorang is modelled from daily Sacramento estimate blended with the hourly catchment response from a predefined RORB pattern using the daily 25% forecast calculated from gridded Australian Digital Forecast Database (ADFD) from midnight-to-midnight. Input files for each tributary are created using the modelled inputs for the ELCOM-CAEDYM model and are used as the boundary conditions for the scenario modelling.

Figure 2 shows the inflow (in ML/day) to Lake Burragorang used as model input.

3. MODELLING RESULTS

3.1. March event

The largest rainfall and consequently largest inflow were observed on March 2 and a peak inflow at around 700 GL/d and peak discharge 650 GL/d was predicted by March 3. A scenario was run with observed inflow until 8 PM of March 2. Modelling results were able to predict inflow from Werriberri creek, southwest of the dam, passing over the dam wall (Figure 3a, top pane). Results also showed inflow with suspended solids of ~20 mg/l entering from Wollondilly and Coxs arms reaching roughly 5 km u/s of the dam wall.

As the event unfolded, intrusion from upstream Wollondilly and Coxs River were evident at the junction by March 5 while Warragamba dam continued to spill. BoM forecast was also upgraded to about 150 mm. During this period, the outlet screen (outlet 3) of the dam was at 40 – 50 m depth from the surface (-40 to -50 m from FSL). The modelled inflows peaked at 470 GL/d with an inflow volume of 1,400 GL (until March 11, 6:00 PM) as per the measured flows and the upgraded forecast.

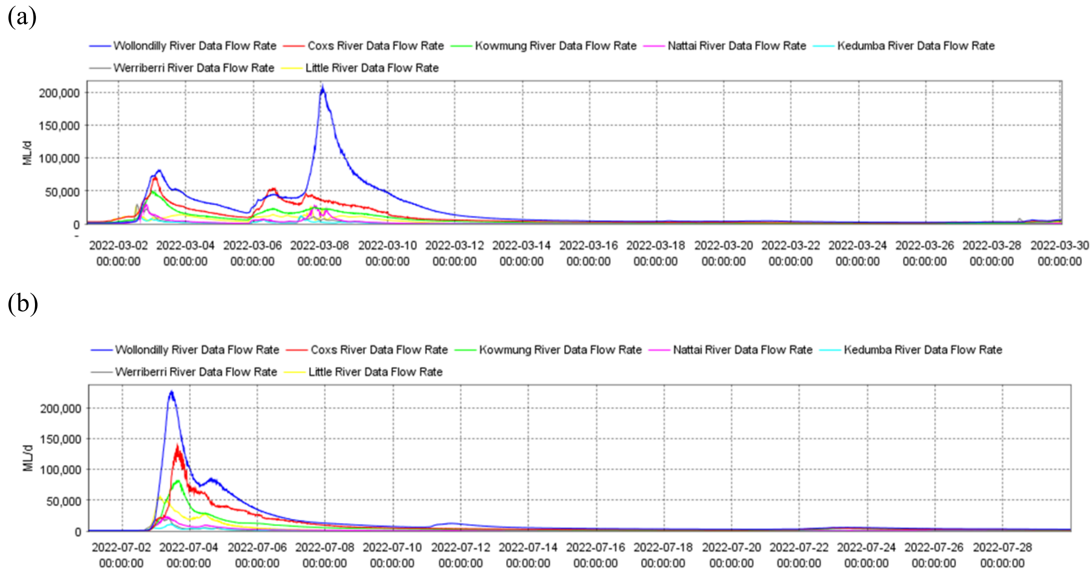


Figure 2. Measured inflow used as model input (a) March 2022 and (b) July 2022 events

Further intrusion of the suspended solids at the DWA2 was also predicted by the model from March 9 to March 10 consequently impacting the outlet screen levels and openings by late afternoon on March 9.

On March 8, the largest inflow from Wollondilly arm was observed and ongoing monitoring of quality indicated turbidity spikes. Modelling for this scenario also considered the high wind values peaking at 50 km/hour on March 8 at 6:00 PM. Intrusion of suspended solids driven by the large inflow volumes and high wind continued to predict to impact the screen openings at -40 m but a time lag of about 24 hours was predicted compared to the March 7 due to downgraded forecast for the next 72 hours. Based on the prediction, a change from outlet screen 3 to the lower outlet 1 (-54m to -62m FSL) was recommended and implemented.

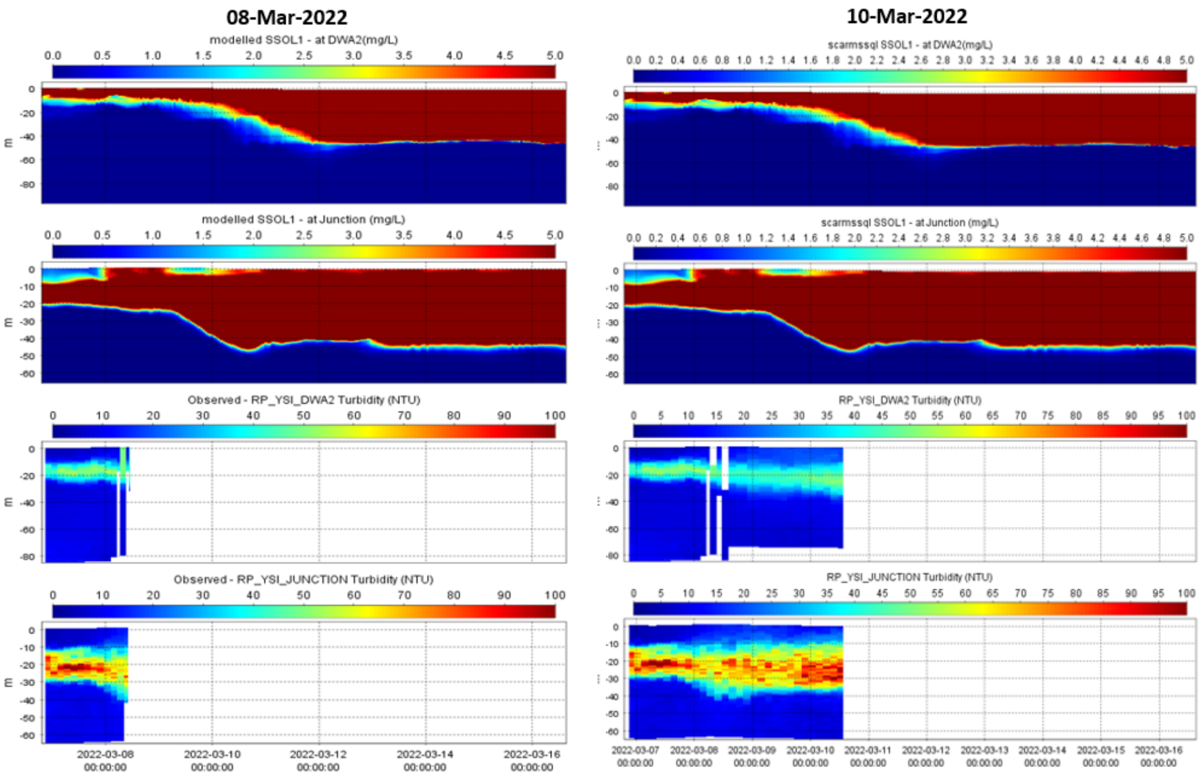


Figure 3. Modelled and observed suspended solids at DWA2 and Junction (a) Scenario 08-Mar-2022 and (b) Scenario 10-Mar-2022

By March 10, the rainfall forecast was significantly downgraded. Warragamba dam continued to spill and the intrusion to the dam wall remained between at 0 to -40 m range. Modelling results predicted a further 5-8 m expansion down into the water column over the next few days (Figure 3b).

Field sampling data were available in March from the water quality monitoring at the dam wall. The input suspended solids data for the March 8 scenario was updated with the field suspended solids data i.e., lighter suspended solids (SSOL1) of 2.75 µm (50th percentile value) and heavier suspended solids (SSOL2) of 5.21 µm (70th percentile value) from the measured data at DWA2 at 12 m sampled 12-14 March 2022) was applied to the model. Results predicted that the intrusion of suspended solids 1 (lighter particles) would likely stay within ~-40 m for the forecasted period consistent with the previous forecast. Results also indicated that as the inflow comes in, the heavier particles were being pushed further to the lower depths. Both results were consistent with the observed turbidity sampled at the DWA2 profiler.

3.2. July event

A scenario model on July 2 was created with total forecast inflows of 1050 GL and peak of 380 GL/day, outflow peak of 350 GL/day and inflow temperature of between 8.5 - 9°C was created and further modifications were made to magnitude and timing of flows with a more certain forecast and observations, especially Werriberri creek as available. Results predicted Werriberri inflows to arrive at the dam wall ~ 18 hours after significant rainfall, followed by the remainder of the inflow arriving around Wednesday evening on July 6 (Figure 4). The modelled suspended solids profiles below at DWA2 predicted water quality to be impacted at the outlet positions at -25m to -32 m below FSL triggering a move up to the outlet screen at -12m to -19m. Further modelling on the July 3 identified high change of supply problems to the largest Water Filtration Plant servicing Sydney for a prolonged period of time. The decision was made to divert all water to Prospect reservoir. Subsequently the Prospect Reservoir model was used throughout July and August to assist in managing the water supply quality for Sydney. Prospect reservoir model, in addition to the lake Burragorang model, have been extensively used or event management during this event assisting the incident team and the management of the water supply in Sydney.

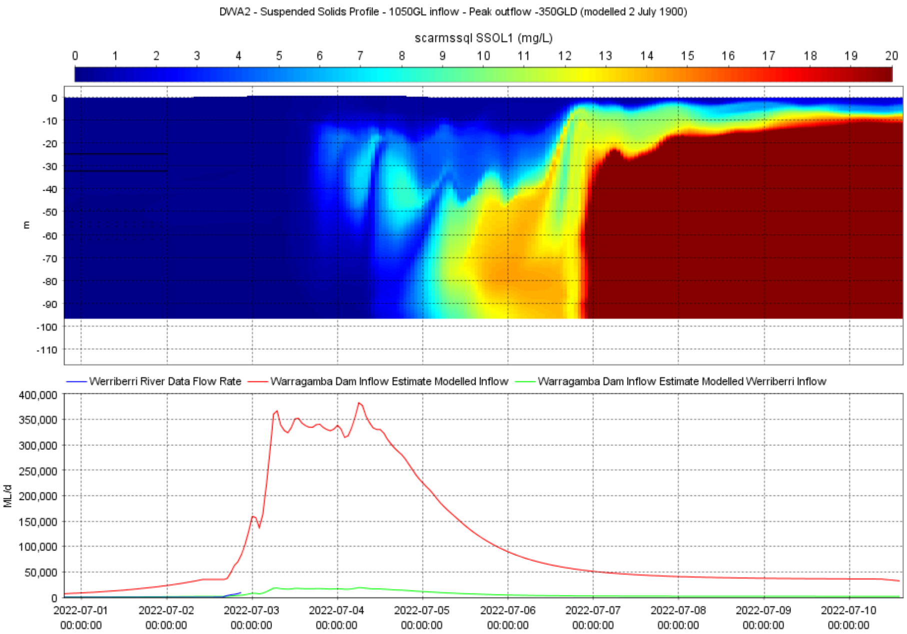


Figure 4. Modelled suspended solids at the dam wall and inflow to the lake on July 2, 2022

4. THE BENEFIT OF HINDSIGHT

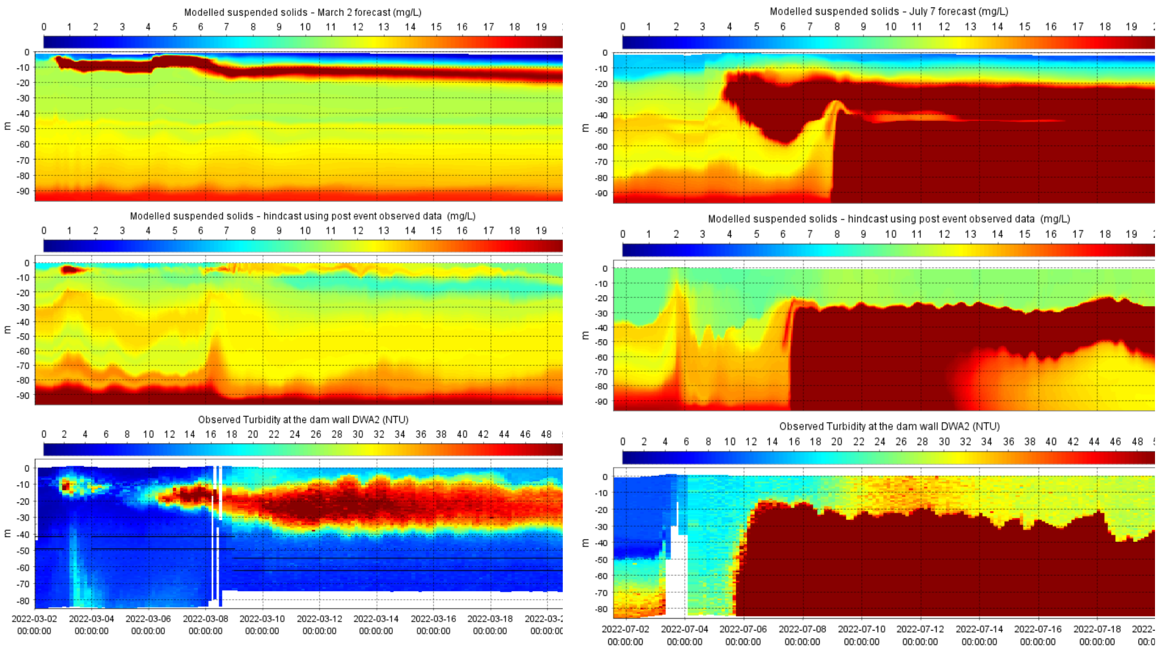
The model was able to predict some of the key impacts of the inflow event in the lake and consequently aided in the operational decision-making process during this large inflow event of March 2022 and July 2022. For example, it was able to capture the inflow passing over the dam wall (and consequently, it's impact on the water quality) from the Werriberri creek early during the event (from observed turbidity and inflow for the March 2022 event, Figure 3). Figure 3 also showed that the model prediction of suspended solids likely staying within the 0 to – 40 m also was consistent with the observed turbidity at the dam wall and resulted in subsequent changes of the outlet screens to the deeper outlet.

The field sampling greatly assisted in the suspended solids modelling by providing event based observed TSS data sampled at DWA2 at 9-12 March 2022. This was deemed to be important, due to the recovering nature of the catchment from the 2019/2020 bushfire season. Caccamo et al (2015) discusses a methodology to use NDVI (a “greenness” index which represents vegetation) measured from remote sensing in the years after fires in the Greater Sydney area to estimate the time it takes for vegetation to recover. The paper suggests that significant recovery of vegetation is observed in the first 1 to 3 years with almost 100% recovery within 5 to 6 years. To get a more accurate picture, the observed TSS data as available were added to the model. Results from the modelling suggested that the finer nature of the sediments changed the turbidity and influenced the settling of the sediment through the water column.

High winds can disrupt the surfaces of the lakes thereby exacerbating the mixing of runoff during an event. During the events, scenarios were constructed using high ‘historical’ wind profiles in addition to forecasted wind profiles as an update (see measured wind profiles for March and July – Figure 2) improving the accuracy of the forecast models. However, a challenge that was identified was the generation of wind direction and velocity forecasts suitable for the modelling. Several methods were discussed to refine the wind direction and velocity forecasts going forward from the BoM to be used as input boundary condition for the forecast modelling.

Figure 5 provides a comparison of the forecast during the event for suspended solids, versus a post-event suspended solids hindcast validated using the measured data, versus observed turbidity at the dam wall during both events. As evident from the figures, the forecast models have predicted the timing of intrusion of the runoff from the flood towards the dam wall in both events reasonably well. The depth at which the inflow entered as well as how far it spread vertically across the left was also reasonably well forecasted compared to the turbidity profile measured at the dam wall. During the July event, efforts have been made to make the pre-modelling warm-up period more accurate using available observed data resulting in a more accurate prediction of the intrusion during the July event, compared to March event.

With the benefit of hindsight, it could be concluded that the models allowed us to identify possible situations and act accordingly. Looking back, the decisions made were the most appropriate for the time and can also be considered the right decision if we had the benefit of hindsight on the day of the event. There is always room for improvement of the models; however, they are fit for purpose.



(a) March event

(b) July event

Figure 5. Modelled suspended solids event forecast (top pane), hindcast using post event data (mid pane) and observed turbidity at the dam wall (bottom pane) for (a) March event and (b) July event

Extreme events, such as a high rainfall episode can lead to fast deterioration of water quality even in a large reservoir. Increased alertness and more rapid response to prevent such challenges can be achieved by using combined hydrodynamic-aquatic ecosystem models to minimise impacts of such events on the reservoir operations, ensuring that impacts are managed without significantly compromising the raw water quality.

The scenario models review identified improvements in the handling of the input data, including the generation of constituent throughout the event. WaterNSW is developing catchment water quality model to generate constituent inflow for the reservoir to enable better representation. Enhancement and inclusion of forecasted wind direction and velocity into the boundary conditions was also identified as a potential improvement.

Overall, the forecast scenario models worked well in terms of predicting the timing and depth of runoff intrusion in the lake during the larger than average floods in 2022. Modelling results aided in quick and complex decision making which is extremely critical during events like this and justified operational decisions such as vertical placement of the outlet screens, temporarily shutting Warragamba pipelines and diversion to Prospect reservoir to manage sediment loads. This, therefore, helped in protecting the quality of water supplied to the majority of Sydney during an event of such magnitude. Continued forecasting as the event progressed also enabled regular communication between the decision makes and the operators and allowed feedback to be incorporated in every step of the decision making as well as provided directions where further investigations were required.

The scenario modelling also highlighted that the operational models need to be continuously maintained and improved as more data and information become available. Maintenance of these models will greatly reduce the spin-up time that was required evaluating the warm-up periods during a major event such as the March/July event where providing a forecast is extremely time-critical and vital for rapid response. Additional staff training on the use of the models was also identified to expand the capacity and available resources within WaterNSW to use the scenario modelling during incidents and to ensure employees are comfortable using the system.

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