Hydrology & Water Resources Symposium
12-15 November | Sydney

ENGINEERS AUSTRALIA
National Committee on Water Engineering

ISBN number for HWRS 2023 is 978-1-925627-81-7

Extreme Flooding in the Kimberley and the Loss of WA's Fitzroy River Bridge

Krey Price

Surface Water Solutions

krey.price@surfacewater.biz

ABSTRACT

In December 2022 and January 2023, Ex-Tropical Cyclone Ellie brought extreme rainfall and flooding to the Kimberley region of Western Australia, leading to the overtopping and failure of the Great Northern Highway's Fitzroy River Bridge at Fitzroy Crossing. The loss of the bridge severed a key regional transportation artery, isolating communities from critical services.

This paper examines the meteorological events that led to the flooding, with an assessment of gauge records across the contributing catchment. The 2023 flood peak is presented alongside historical gauge records, with high water marks collected during previous events shown for comparison.

Rating curves for the Fitzroy Crossing gauge have required frequent re-adjustment as a result of changing river bed conditions. Due to several gauge failures during the 2023 flood events, hydraulic modelling has been applied to estimate flow rates and recompute rating curves. Previous flood peaks had been estimated using rating curves derived from 1D flood models; updated rating curves using 2D techniques show some improvements over the previous reliance on inherent 1D assumptions.

The Fitzroy River is highly dynamic in the Fitzroy Crossing reach. An analysis of historical satellite imagery is applied to show flow paths and bank migration over time. Implications of impinging flows on armoured bank revetments are discussed, with a comparison to post-flood photographs showing extreme lateral bank migration.

The 2023 Fitzroy River flooding exceeded all previously recorded events by a substantial margin; other Australian river systems may be similarly tested in the face of climate change. The survey and demolition of the previous bridge and the modelling, design, and construction of a replacement bridge are providing additional lessons learnt from the event. The Fitzroy River flooding and bridge collapse provide a case study of extreme event hydrology and extreme forces on hydraulic structures.

INTRODUCTION

Western Australia's Mardoowarra (Martuwarra or Fitzroy River) drains approximately 46,000 km^2 upstream of Fitzroy Crossing, approximately half of the total catchment area at the river mouth in King Sound. Tropical cyclone Ellie reached the coast of the Northern Territory in December 2022, then hovered over the Northern Territory and the Kimberley as a tropical low for two weeks, which resulted in extreme rainfall and flooding impacts along the Fitzroy River.

Flood levels at Fitzroy Crossing exceeded all historical records, and the extreme conditions led to the overtopping and failure of the Great Northern Highway's Fitzroy River Bridge, severing National Highway 1 and isolating communities from critical services.

METHODOLOGY

This paper provides background on the meteorological events, an assessment of the unique elements of the Fitzroy Crossing flooding and bridge failure, and a discussion regarding future implications of the record events for other major river systems in Australia.

Cyclone Ellie

Tropical Cyclone Ellie made landfall on 22 December 2022. Figure 1 shows the 18-day best track of the cyclone and tropical low from 21 December 2022 to 8 January 2023. Ellie was relatively small in size and weakened to below tropical cyclone intensity after landfall; however, as the ex-tropical cyclone tracked west across the inland Kimberley after reversing its path over the Northern Territory, a loop formed in the path. The circulation was invigorated by a ridge to the east and strong inflow of warm, moist monsoon flow to the north (Courtney and Patterson 2023), resulting in several days of intense rainfall within the Fitzroy River catchment area.

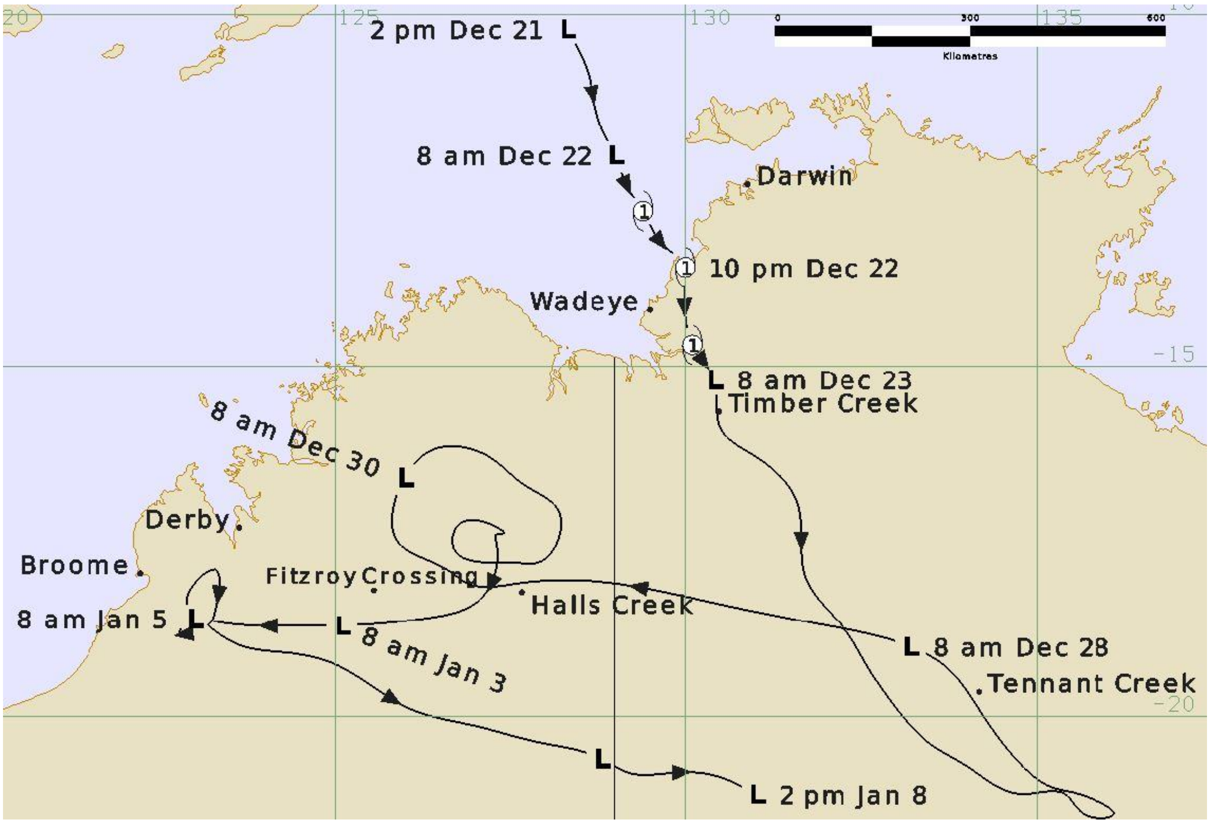

Figure 1. Track of Tropical Cyclone Ellie (Courtney and Patterson 2023).

The Dimond Gorge precipitation gauge (Site ID 502139), located approximately 90 km upstream of Fitzroy Crossing, recorded a 24-hour rainfall depth of 402 mm on 1 Jan 2023, and a 1-week total rainfall depth of 824 mm to 2 Jan 2023. Based on Bureau of Meterology (BoM) Intensity-Frequency-Duration (IFD) data, the 24-hour total corresponded to the 1 in 2,000 Annual Exceedance Probability (AEP) event, and the 4-, 5-, 6-, and 7-day totals substantially exceeded the 1 in 2,000 AEP event (Figure 2). Over a 30-year period of record, all totals from 1 to 7 days more than doubled the previously recorded maximum precipitation depths.

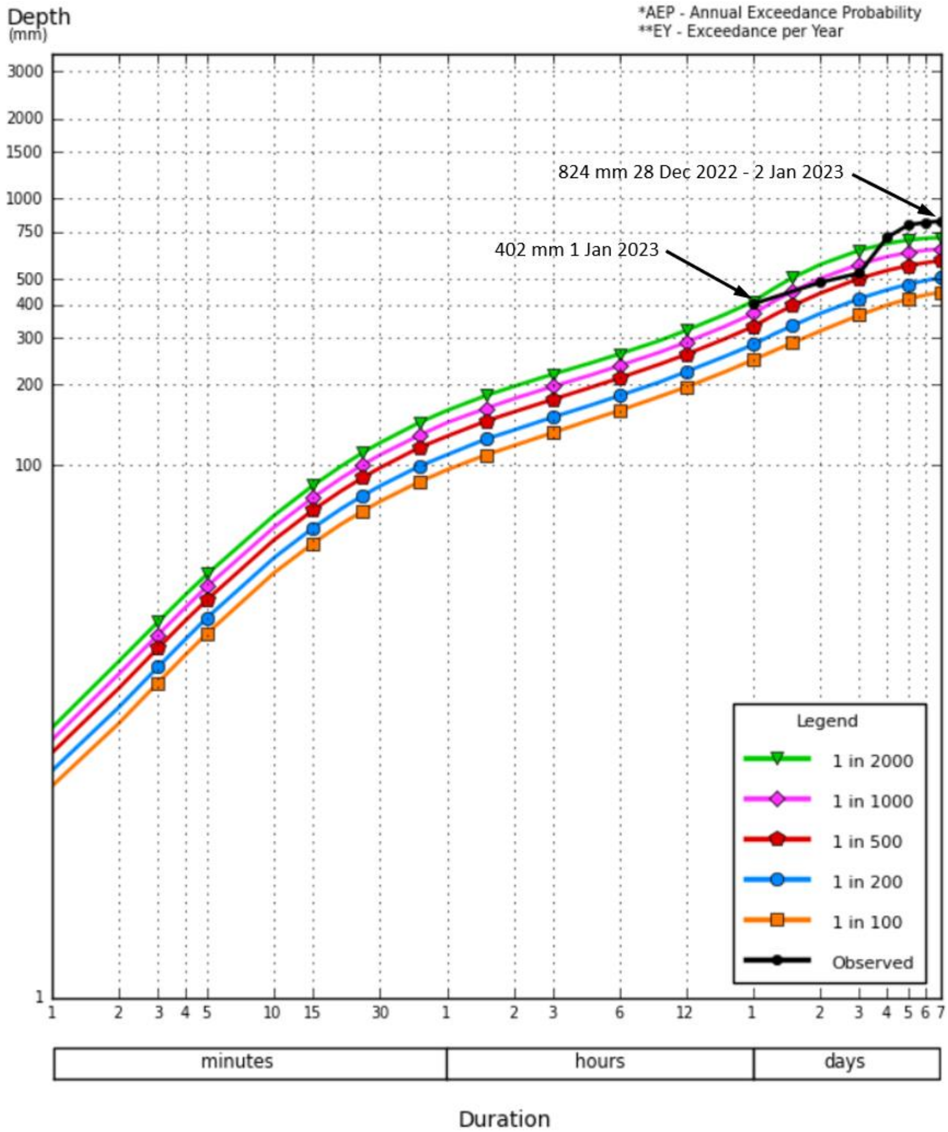

Figure 2. Dimond Gorge precipitation from 28 Dec 2022 – 2 Jan 2023 against BoM IFD.

Fitzroy River Flooding

Figure 3 shows the WA Department of Water and Environmental Regulation (DWER) flow gauge network in the Fitzroy River catchment. Fitzroy Crossing is located just downstream of the Fitzroy River confluence with the Margaret River tributary, with the two contributing catchment areas being nearly equal in size. The estimated January 2023 peak flow rate from the downstream-most gauge on the Margaret River (Mt Krauss) is just over 15,000 m^3/s (DWER 2023).

The Dimond Gorge river gauge on the Fitzroy River was destroyed before the peak flood level could be measured; however, calibrated hydraulic modelling using high water marks yielded a peak flow rate of nearly 20,000 m^3/s for the January 2023 event at Dimond Gorge. The destroyed river gauge is shown in Figure 4. Observed flood levels were 4 m higher than the previous record, and estimated flow rates were almost double the previous maximum peak flow since readings began in 1961.

Although the river gauge at Fitzroy Crossing was also destroyed during the 2023 flood event event, the peak flood level of 15.81 metres was captured on 4 January prior to the gauge going off line during the recession of flow. Flow records for the Fitzroy Crossing gauge began in 1956, and the measured 15.81 m peak flood stage at Fitzroy Crossing exceeded the previous record (set in February

2002) by nearly 2 m. Subsequent survey results indicate that the gauge reading may have overestimated the peak flood level by approximately 0.5 m; however, all previous flood records were clearly exceeded. BoM initially estimated the corresponding Fitzroy River peak flow rate at 60,000 m^3/s, which far exceeds the previous record peak flow of just over 25,000 m^3/s (Lawry 2023). The peak discharge rate is subject to further confirmation; if substantiated, it would represent the highest observed flow rate for an Australian river.

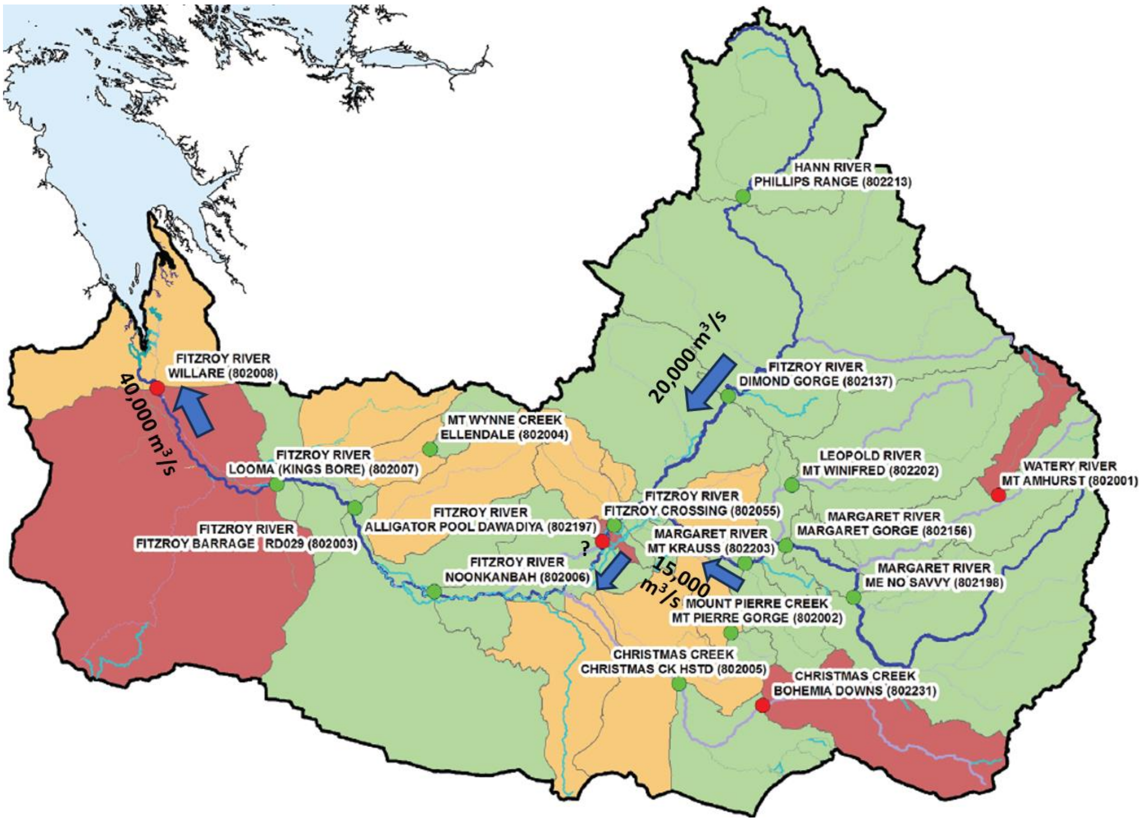

Figure 3. Gauges in the Fitzroy River catchment (Greening et al. 2019).

Figure 4. Destroyed river gauge at Dimond Gorge (Lawry 2023).

Two additional Fitzroy River gauges (Looma and Fitzroy Barrage) were also destroyed during the event without capturing the peak conditions, which complicated efforts to reliably estimate maximum flood rates and forecast downstream flood levels. All Fitzroy River gauges that captured the peak flood levels recorded their highest levels on record. DWER regional hydrographers completed a gauging across the 10 kilometre wide floodplain of the Fitzroy River at Willare at approximately 0.5 metre below the peak level. The measured discharge near the river mouth was almost 25,000 m^3/s, with an estimated peak flow of almost 40,000 m^3/s on 9 Jan 2023 (Lawry 2023). Hydraulic modelling indicates significant flow attenuation between Fitzroy Crossing and Willare, substantiating the estimates of larger flow rates at Fitzroy Crossing.

Following the event, satellite imagery and flood photographs from helicopter and drone surveys confirmed the flood extents captured by the river gauges and reflected in model simulations. Figure 5 shows the Moderate Resolution Spectroradiometer (MODIS) images from NASA's Aqua satellite on 17 December 2022 and on 9 January 2023, indicating floodplain widths of up to 25 km (NASA, 2023).

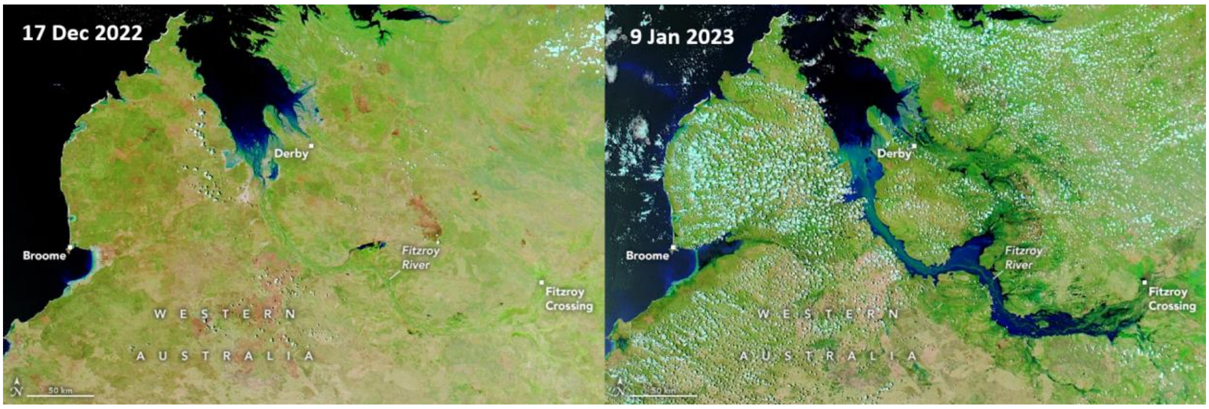

Figure 5. False colour images of Fitzroy River (NASA 2023).

Rating Curves

DWER have undertaken recent efforts to update previous rating curves, including two Fitzroy River rating curves (Looma and Fitzroy Barrage) that were updated to allow extrapolations above measured discharge rates based on 2D hydraulic analyses rather than the previous 1D assessments (Greening et al. 2019). As shown in Figure 6, differences between modelling approaches were apparent at Looma but were not significant at Fitzroy Barrage.

The establishment of a consistent rating curve at Fitzroy Crossing is complicated by the braided nature of the floodplain flow in the area (Taylor 2000). Figure 7 shows flow measurements estimated from high water marks collected along the Great Northern Highway following flood events in 1983, 1984, and 1986 (Goh 1990). The calculations indicate that approximately one fourth to one third of the total Fitzroy River flow crossed the Great Northern Highway at the Fitzroy River Bridge location, with the remainder crossing a number of additional bridges and floodways across a floodplain width of approximately 13 km.

Figure 8 shows all peak daily flood levels and flow rates acquired at Fitzroy Crossing since 1957. As indicated by the plotted points, the rating curves that serve as a basis for converting flood level to discharge have been frequently revised to reflect changing conditions; 18 separate rating curves have been developed by DWER and Main Roads Western Australia (MRWA) since records began (Greening et al. 2019), with a series of adopted curves subsequently consolidated into the current flood records (DWER 2023). As indicated by the points on the rating curve and validated by flow measurements, a single elevation point measured at the Fitzroy Crossing gauge location may reflect a relatively wide range of total flow rates across the floodplain; these results have subsequently been confirmed by 2D hydraulic modelling.

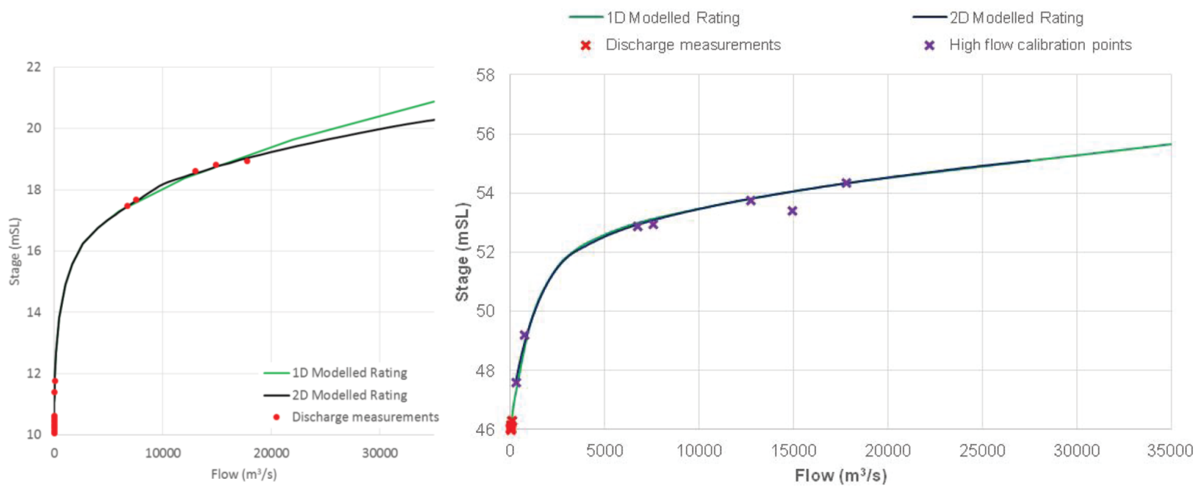

Figure 6. Flow measurements vs 1D and 2D model rating curves for Looma (left) and Fitzroy Barrage (right) gauging stations (Greening et al. 2019).

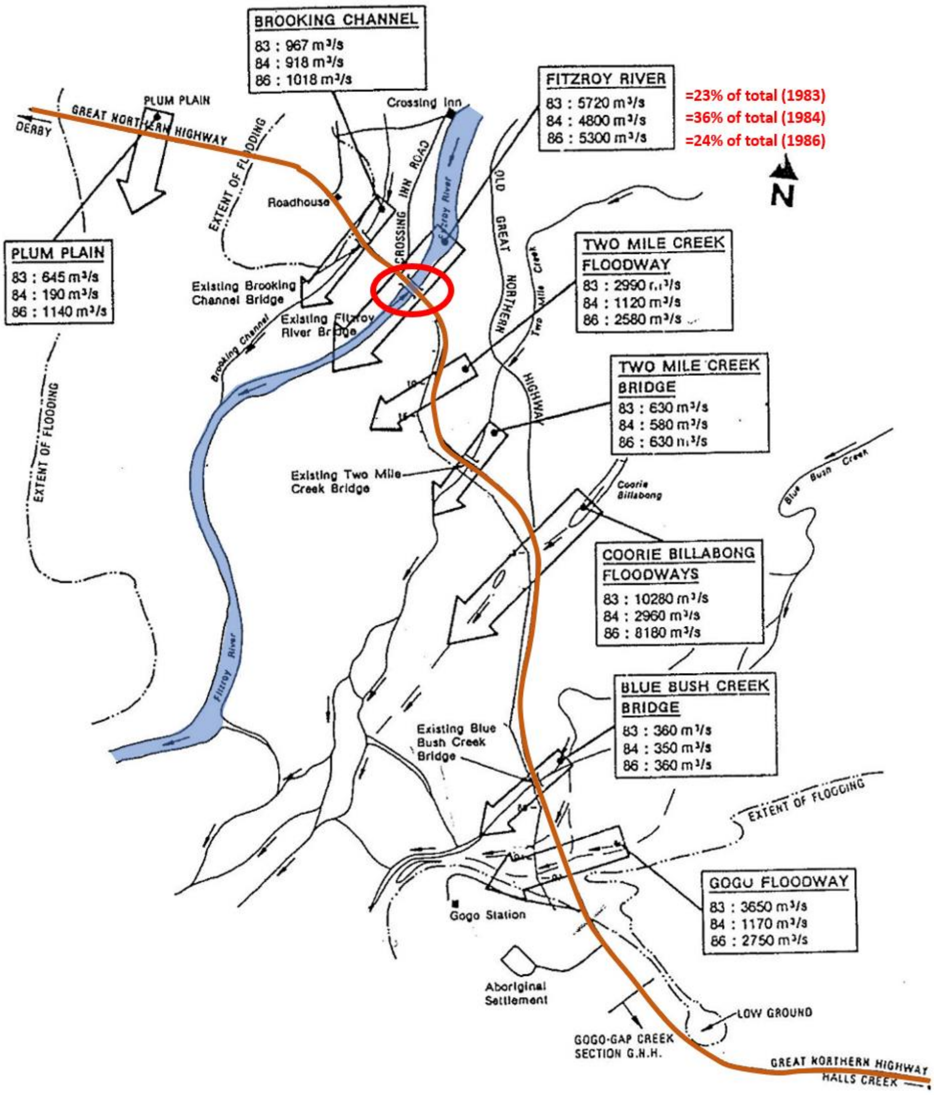

Figure 7. Great Northern Highway flow measurements in 1983, 1984, and 1986 (Goh 1990).

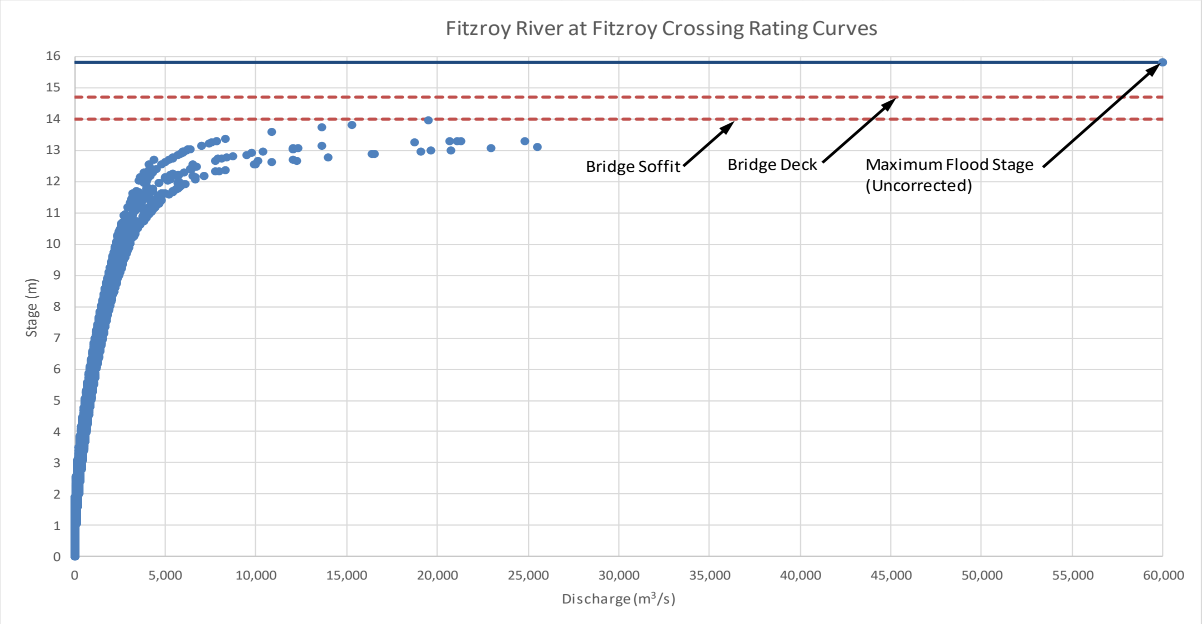

Figure 8. Fitzroy Crossing rating curve (DWER 2023).

FITZROY CROSSING BRIDGE

Original Bridge

A 270-m span bridge was constructed along the current alignment of the Great Northern Highway in 1974, replacing an original bridge located 3 km upstream that was periodically inundated by floodwaters. The 1974 bridge was designed by the Main Roads Department of WA to accomoodate a total flow of 5,100 m^3/s (DMR 1972) and was constructed by Hercules Construction. The bridge served as the only all-weather roadway corridor connecting the west and east Kimberley. During its nearly 50-year life of operation, the bridge had not been subject to overtopping; however, erosion threatened at times to undermine the eastern bridge abutment. In response to approximately 50 metres of lateral bank erosion between 2002 and 2011, MRWA placed rip rap bank protection along the eastern abutment. Figure 9 shows the bridge structure and armour rock with a directional arrow showing the flow direction toward the revetment that was constructed in 2011.

Bridge Failure

As shown in Figure 9, the bridge deck was overtopped on 3 January 2023, and floodwater circumvented the armour rock at the eastern abutment. Additional lengths of Great Northern Highway floodways were significantly damaged within the Fitzroy River floodplain, and sewer and power lines were also destroyed. Evacuation efforts were required from various Fitzroy Valley communities, and a temporary barge and low-level floodway solution was implemented following recession of flows.

Replacement Bridge

The Fitzroy Bridge Alliance was formed with Georgiou Group Pty Ltd, BMD Constructions Pty Ltd, and BG&E Pty Ltd to design and construct a replacement bridge in coordination with MRWA and local Traditional Owners. The replacement bridge (Figure 9) was constructed in-situ on a concrete casting bed and incrementally launched across the river from the west bank. The bridge is supported by seven piers, each with four piles sunk to a depth of 40 m, approximately twice the pile depth of the previous bridge (DMR 1972). The piles are topped with concrete-infilled casings and pile caps supporting the bridge. Roadway repairs are nearly complete, and the bridge is scheduled to open in late 2023. The Fitzroy Crossing river gauge and other destroyed gauges are also being rebuilt to be more robust.

Figure 9. Fitzroy Crossing bridge photographs before, during, and after the 2023 event.

RESULTS

Eight sets of historical aerial photographs of the Fitzroy River were compiled from 2002 to 2023. The results indicate approximately 50 m of lateral bank migration upstream of the Fitzroy River bridge between 2002 and 2022, a recession rate of approximately 2.5 m/year. Approximately 30 m of additional bank recession occurred during the single event in January 2023 (Figure 10).

Similar bank migration rates were observed along the eastern bank of the channel where it coincides with the outside of a major channel bend for approximately 700 m upstream of the Great Northern Highway crossing. No observable bank migration occurred on the inside of the bend (western bank) over the same period of time. Approximately 1500 m upstream of the crossing, the river bends in the opposite direction, and the western bank experienced approximately 10 m of bank migration between 2002 and 2022, and up to 50 m of bank migration during the January 2023 event. The eastern bank of the river on the inside of the bend experienced no significant migration during the same time periods.

The revetment along the eastern bridge abutment appears to have largely remained in place during the 2023 flood event; however, the extreme flood flow eroded a channel east of the abutment, with a width of approximately 100 m downstream of the crossing (Figure 9 and Figure 10). A depositional sand bar formed where the side channel re-joined the main channel. The replacement bridge will be approximately 100 m longer than the original bridge, accommodating the additional channel width and reducing hydraulic impacts associated with the constriction and redirection of flow.

Although the peak flood stage was recorded during the 2023 event, estimates of the corresponding peak Fitzroy River flow rate at Fitzroy Crossing vary widely (ranging from approximately 40,000-60,000 m^3/s). The uncertainty is related to complexities in adopting an accurate rating curve for the event that accounts for flow across the bridge as well as each of the additional bridges and floodways within the floodplain. Based on 65 years of record, preliminary flood frequency analyses of the annual maxima place the estimated discharge rates between the 1 in 500 and 1 in 10,000 AEP event.

DISCUSSION

Detailed assessments of the flood event and bridge failure mechanism are still forthcoming; however, some conclusions and recommendations can be drawn from observations of the events. Although some Fitzroy River rating curves have been updated to reflect 2D modelling results, extrapolation of results above measured discharge rates is based on fixed-bed hydraulic models at all gauging locations. In reality, extreme floods such as the Janary 2023 event in the Fitzroy River result in highly dynamic bed conditions. Accurately converting stage measurements to discharge rates would require modifications to the channel cross section over time. Establishing an accurate rating curve for the replacement river gauge in this locations will require detailed as-constructed survey of the channel and reconstructed bridge along with calibration efforts to aid estimates of head losses.

According to BoM, meteorological models failed to indicate the formation of Ellie, and Tropical Cyclone Outlooks in the days preceding the event indicated a low risk of a tropical cyclone developing (Courtney and Patterson 2023). In general, severe weather warnings accurately portrayed the rainfall distribution as the circulation moved over the Northern Territory and Western Australia; however, during the period that impacted the Fitzroy River catchment most severely, the localised rainfalls were heavier than predicted. Severe weather warnings were issued for the Northern Territory and Western Australia when Ellie weakened below tropical cyclone intensity over land.

The Fitzroy River is a highly dynamic, sand-bed river system that was subject to constriction and redirection of flow in the vicinity of the bridge crossing. Although no fatalities were recorded during the flood events, the collapse of any major bridge should be assessed in detail and published publicly to help reduce risks associated with similar failures in the future. In particular, real-time assessment of scour may aid in the assessment of structural integrity for other bridges subject to greater-than-design flows that are becoming more prevalent in the face of climate change. Following a flood event, scour measurements may be misleading as the scour hole may have re-filled with deposited material.

Ground-penetrating radar (GPR) and other techniques can provide a profile of the streambed and sub-streambed characteristics and can be effective, post-event scour-monitoring tools. Pulse or radar devices, buried or driven rod systems, sound-wave devices, fiber-Bragg grating devices and electrical conductivity devices can provide real-time scour monitoring that can guide roadway closure decisions and improve public safety during a flood event (Prendergast and Gavin, 2014).

As an additional safety measure, image-based, AI-assisted streamflow monitoring equipment may be located on high ground for critical gauge locations in catchment areas with vulnerable properties and infrastructure, allowing the continued transmittal of real-time data for downstream flood prediction when gauges within the floodplain are compromised (Pena-Haro 2021).

Figure 10. Top of bank migration during the 2023 event.

CONCLUSIONS

Ex-Tropical Cyclone Ellie hovered over the Fitzroy River catchment in January 2023, resulting in record flooding and the collapse of the Fitzroy River bridge at Fitzroy Crossing. The bridge collapse and damage to additional Great Northern Highway floodways severed vital transportation links between communities in the Kimberley region. The flooding was a result of a unique combination of events that caused greater-than-design flow conditions at the crossings.

If the initial estimates by DWER and BoM are substantiated, the peak discharge rate at Fitzroy Crossing may be the largest flow recorded for an Australian river. Additional assessment of the flood event is recommended, including the acquisition of detailed post-flood terrain data, the development of comprehensive hydraulic modelling, and the calibration of predicted results against high water marks observed during the event. Hydraulic modelling should account for the extreme changes in bed and bank conditions during the flood, and rating curves subsequently applied to the replacement river gauge should account for calibrated flow conditions at the structure upon completion of construction.

Australia's rivers will be subject to greater-than-design flows more frequently in the face of climate change. Scour assessment and analyses of the impacts of extreme hydraulic forces for major arterials in particular should take advantage of the latest available technology for real-time scour monitoring and image-based backup systems to allow prediction of flow conditions when physical gauges fail.

[Author's note: WA's Fitzroy River (Martuwarra) and the 2022-2023 Cyclone Ellie are not to be confused with Queensland's Fitzroy River (Toonooba) and a 2009 Cyclone Ellie that made landfall between Townsville and Cairns.]

REFERENCES

Bureau of Meteorology. Design Rainfall Data System. http://www.bom.gov.au/water/designRainfalls/revised-ifd/, 2016.

Courtney, J. and Patterson, L. Tropical Cyclone Environmental Prediction Services, Tropical Cyclone Ellie 21 December 2022 – 8 January 2023, Bureau of Meteorology, 2023.

Department of Main Roads. Great Northern Highway No 1037, Fitzroy Crossing Bridge Deviation. Plan and Profile Drawings, 1972.

Department of Water and Environmental Regulation. Water Information Reporting. https://wir.water.wa.gov.au/Pages/Water-Information-Reporting.aspx, 2023.

Goh, J. and Joyce, M. Flood Investigations Report, Fitzroy River Flooding: March 1983, March 1984, and January 1986. Department of Main Roads, Kimberley Division. Internal Report, 1990.

Greening, L. et al. "Modelling Rating Curves to Manage Uncertainty in the Fitzroy River Catchment in North West Western Australia." *Australasian Hydrographer*, July 2019.

Lawry, R. "Beyond the Rating – Fitzroy Martuwarra River Floods 2023." *Australasian Hydrographer*, July 2023, Australian Hydrographers Association, 2023.

Main Roads Western Australia. Kimberley Flood Response https://www.mainroads.wa.gov.au/travel-information/driving-in-wa/kimberley-flood-response/, 2023.

NASA Earth Observatory. Flooding along Australia's Fitzroy River, 2023.

Pena-Haro, et al. Image-Based Streamflow Measurements for Real-time Continuous Monitoring, 2021.

Prendergast, L. and Gavin, K. "A review of bridge scour monitoring techniques." *Journal of Rock Mechanics and Geotechnical Engineering*. Volume 6, Issue 2, Pages 138-149, April 2014.

Taylor, C.F.H. "The flood geomorphology of the Fitzroy River, Northwestern Australia: controls and implications for paleoclimate reconstruction." University of Western Australia, Centre for Water Research. ED 1346 CT, 2000.

BIOGRAPHY

Krey Price is a civil engineer with a 25-year career specialising in hydraulic design. He has a masters degree in civil engineering from the University of California at Berkeley and is the director of Surface Water Solutions, a Perth-based consultancy.