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Department of **Water and Environmental Regulation**

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Assessing the 2021 Gascoyne River flood at Carnarvon

Preliminary report

June 2021

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Department of Water and Environmental Regulation

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Summary

Heavy rainfall in the Gascoyne River catchment in the first week of February 2021 resulted in flooding of some plantations in the Carnarvon horticultural district.

Carnarvon has a history of regular flooding. In 2015, the Government of Western Australia constructed flood levees to reduce the impacts of large flooding events (such as in March 2000 and December 2010) to the horticultural district adjacent to the town. The 2015 levees, designed by modelling, complement the network of levees constructed over the past 60 years.

The February 2021 flood at Carnarvon was the largest flow event since 2011 and the first since the construction of the 2015 levee system. The 2021 flood was smaller (~1 in 10 annual exceedance probability [AEP]) than the levees were designed to mitigate, and was similar in size to the 1995 event. The 2021 event is the first opportunity to assess flood behaviour and the effectiveness of the levees in reducing flooding and damages in the Carnarvon horticultural area.

Our assessment included:

- analysing the gauged rainfall and streamflow data
- collecting field measurements and observations from the 2021 event
- comparing the 2021 flood event information to the flood behaviour predicted from modelling and observations from past flood events
- reviewing existing measures for managing flood risk.

We focused on the observed flooding from upstream of the Nine Mile Bridge on North West Coastal Highway (NWCH) to Sheridans Gully at the western end (Figure S1).

Our review shows that the levees and peak flood levels of the 2021 event behaved as predicted by modelling of the 1995 event. Field observations between the 2021 and 1995 events were also similar in extent and peak levels.

During the 2021 event, flooding was mitigated at the eastern end of the McGlades Road area and between South River Road and the NWCH. We could not fully assess how the levees would perform during a large event (1 in 100 AEP).

Our assessment concluded that the modelling adequately represents observed flood behaviour at a regional scale, but in local areas – such as upstream of the Nine Mile Bridge, and in the breakouts between Burnt Gully and Boundary Road – there were some small differences in the modelling (and observations) from the 1995 event.

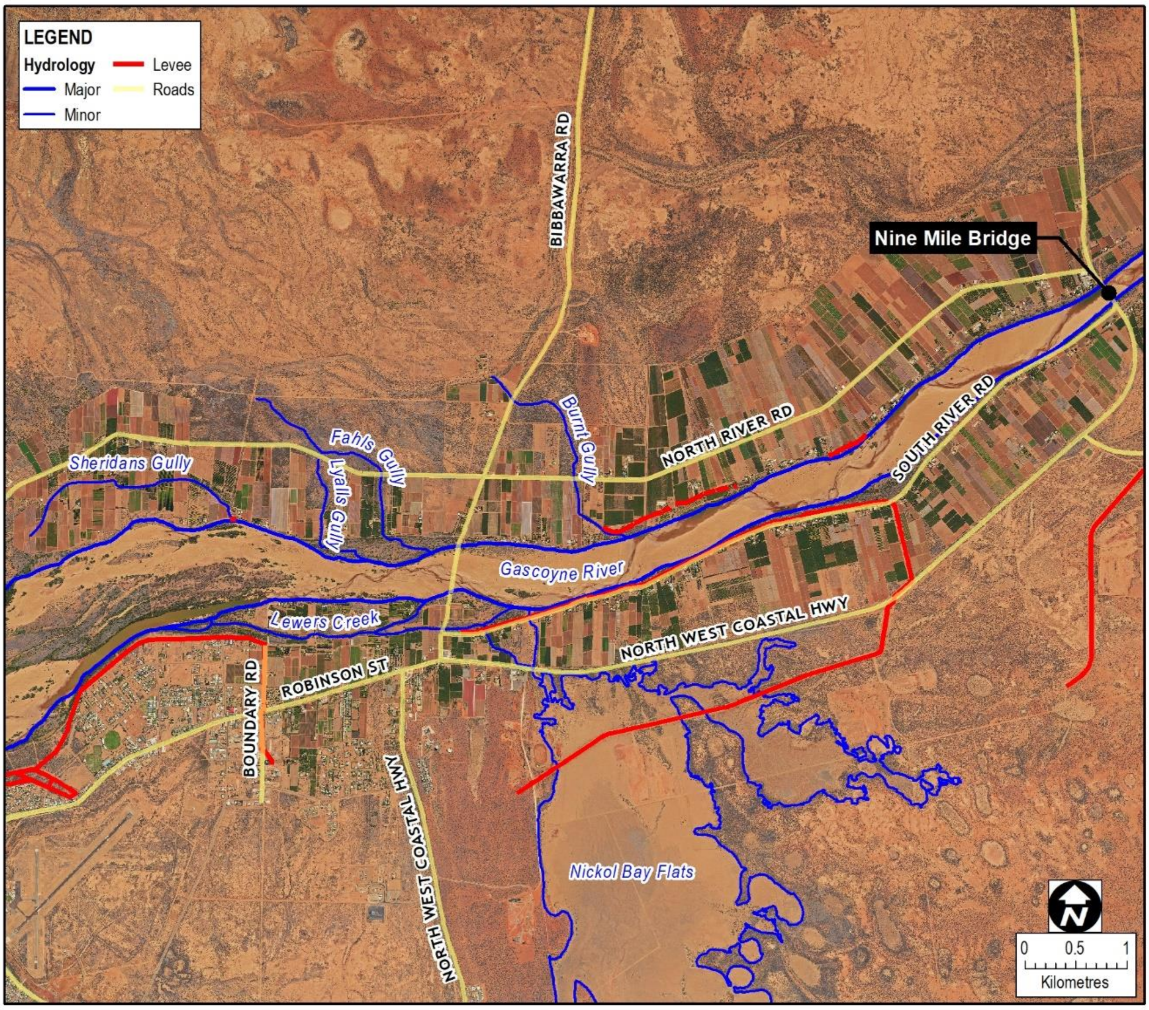


Figure S1. Gascoyne River and waterways within the Carnarvon horticultural district

Peak flood levels were lower upstream of the Nine Mile Bridge because the bridge was replaced by a larger structure in 2002. The newer, replacement bridge obstructs flow less than the previous bridge, so flood levels upstream of the bridge were lower than those observed in 1995. Water levels recorded at our gauging station during the 2021 event were also lower than earlier events of the same size because of the new bridge.

There are many other factors that could have potentially contributed to these modelled vs observed differences. At the local scale, flood levels and flow velocities are affected by structural features, including fencing/wind breaks, filling and/or vegetation of drainage lines, and horticultural practice (such as cropping in flow paths/floodplains and the location of bare paddocks).

Surveying additional peak water levels in the Lewers Island and northern breakout channels would assist in provision of a more accurate modelling and assessment. Similarly, a more detailed survey of the river and plantation areas would better define the hydraulic conditions at the entrance to gullies and on the floodplain. From this information, we could assess how local factors and the levees contributed to the difference between the 2021 flooding and the flood levels observed in 1995. More detailed surveys could also support future flood modelling and the impact of land management activities on flood behaviour.

This report also looked at existing flood mitigation measures and highlighted a range of potential other measures that might improve flood mitigation in the future. The intention was not to provide an exhaustive list of future mitigation measures, nor was it to provide a detailed analysis of the relative values of these measures to mitigate future flooding impacts in Carnarvon; these actions remain the subject of future work.

Some of this future work has already commenced. Community concerns discussed with the department during this assessment have been raised at the June 2021 Flood Warning Consultative Committee meeting. As a result of this, the department is now working across government to examine issues around the communication of water level information provided during (and after) the event, and the adequacy of the existing streamflow and rainfall gauging station network. A committee is also currently being formed to consider land management arrangements of the drainage channels within the plantation area.

The Department of Water and Environmental Regulation stands ready to provide further input into future Gascoyne River flood mitigation work, as appropriate.

1 Background

The Gascoyne River is the longest river in Western Australia (WA). Its catchment covers an area of about 79,000 km^2, extending from 550 km inland (east) near Three Rivers Homestead to the coast at Carnarvon. A detailed description of physical and social setting of the Gascoyne River catchment and the Carnarvon township is provided in Sinclair Knight Merz (2002).

Major flood events were observed in 1960, 1961, 1980, 1995, 2000 and 2010 (Figure 1). In the first week of February 2021, heavy rainfall in the Gascoyne River catchment resulted in flooding of many plantations in the Carnarvon horticultural district.

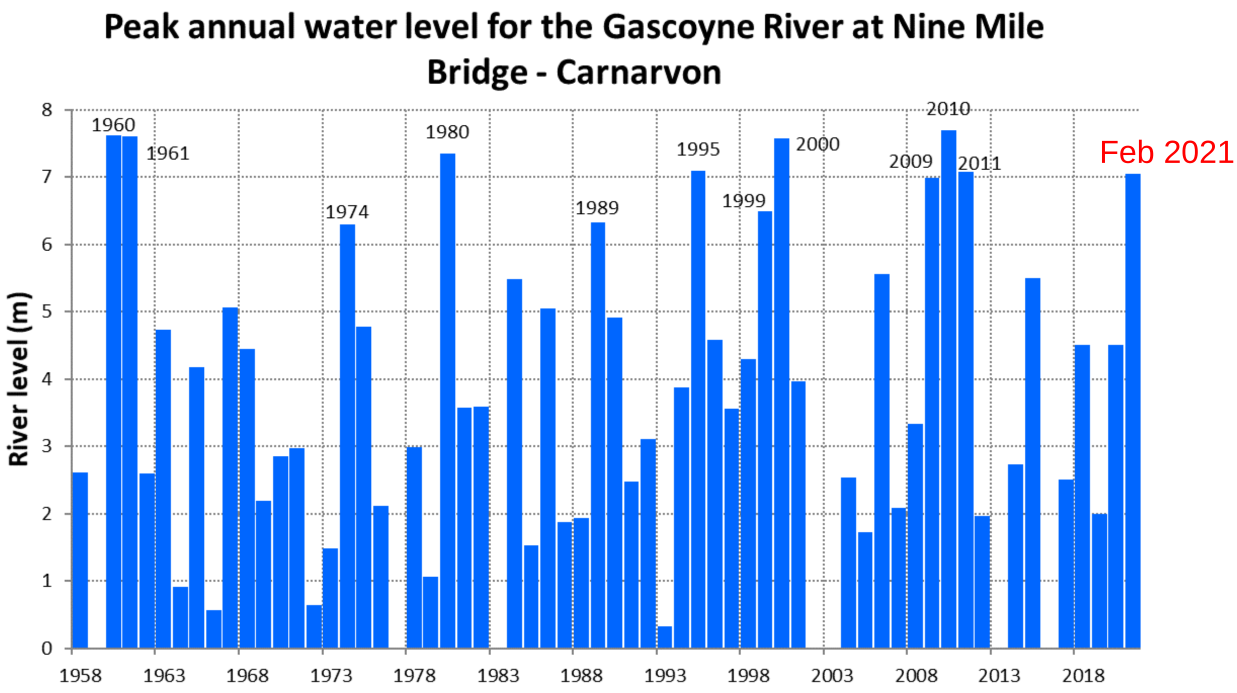


Figure 1 Peak annual river level at the Department of Water and Environmental Regulation's (DWER's) streamflow gauge on the Gascoyne River at Nine Mile Bridge

The Carnarvon townsite is protected from river flooding by a network of levees which are maintained by the Shire of Carnarvon. In 2015, the Government of Western Australia constructed additional flood levees to mitigate flooding within the horticultural district adjacent to the town. Figure 2 illustrates the layout of the local government townsite levee system (shown in blue) and the State Government levee system (shown in red). There are also privately owned levees that protect individual properties and infrastructure.

The 2021 flow at Carnarvon was the largest flow event since 2011, and the first where all the breakouts along the river flowed since the construction of the 2015 levee system.

Purpose

This report has been prepared to assess the effectiveness of the 2015 levee system in reducing flooding and damages in the Carnarvon horticultural area and identify a range of potential other measures that might improve flood mitigation in the future.

Approach

This event provided the opportunity to assess the performance of the levee network in Carnarvon by:

- analysing the gauged rainfall and streamflow data
- collecting field measurements and observations from the 2021 event
- comparing the 2021 flood event information to the flood behaviour predicted from modelling and observations from past flood events
- reviewing existing measures for managing flood risk.

Figure 2 Location of Carnarvon levees

2 Catchment rainfall and streamflow

To determine how rainfall patterns (timing and spatial distribution) influence flooding in Carnarvon, we analysed observed rainfall and streamflow data from the 2021 event and previous events. We also compared published estimates of the likelihood of such events in the future with data from the 2021 and past years' events. This improved our understanding of the relationship between rainfall patterns and floods and will help future flood warning and response planning and actions.

We used data from a network of rain and streamflow gauges in the Gascoyne River catchment (Figure 3). The Bureau of Meteorology (BoM) operates a network of 51 rainfall gauges in the catchment, including 13 rainfall intensity sites installed since the flooding in 2010/11. We operate six streamflow gauging stations in the catchment, four of which also include rainfall intensity gauges.

We also used a gridded rainfall dataset (BoM, 2021) to assess rainfall spatial and temporal distribution, and BoM's intensity-frequency-duration (IFD) curves for locations across Australia (BoM 2016). IFD curves provide a basis for comparing the rainfall intensity observed during a storm to the expected likelihood of observing a storm of that intensity. The curves use annual exceedance probability (AEP) to express the expected likelihood of events. For example, a 10 per cent AEP rainfall intensity of 100 mm in 24 hours means there is a 10 per cent (1 in 10) chance of recording more than 100 mm (in a 24-hour period) each year.

2.1 February 2021 rainfall

Rainfall spatial and temporal distribution

Within the Gascoyne River catchment, the highest total rainfall between 2 and 6 February 2021 was near Gascoyne Junction (the confluence of the Gascoyne and Lyons rivers). Higher totals were observed outside of the Gascoyne River catchment, in the neighbouring Lyndon and Minilya River catchments (Figure 4).

Rainfall patterns varied within five daily periods (9am to 9am) over 2–6 February 2021 (Figure 5).

The highest daily rainfall totals within the catchment were recorded in the 24 hours to 9am on 4 February 2021.

The highest rainfall over the event was near Gascoyne Junction and the highest daily rainfall (137 mm) was recorded at Carnarvon Airport (No. 006011) on 5 February 2021.

Rainfall intensity

Rainfall intensity for a given storm is reflected by the cumulative amount of rain that falls over the duration of a storm, at a given location. It is relevant because higher intensity rainfall increases the likelihood and severity of flooding.

Figure 6 compares maximum rainfall intensity for the February 2021 storm event at the Fishy Pool rainfall gauge with BoM IFD curves. The IFD values became increasingly unlikely (or rare) the longer the storm continued. For example:

- for one-day duration (1440 mins), the rainfall at Fishy Pool corresponded to a BoM 20 per cent (1 in 5) AEP IFD.
- For three-day duration (4320 mins), the rainfall at Fishy Pool corresponded to a BoM five per cent (1 in 20) AEP IFD.

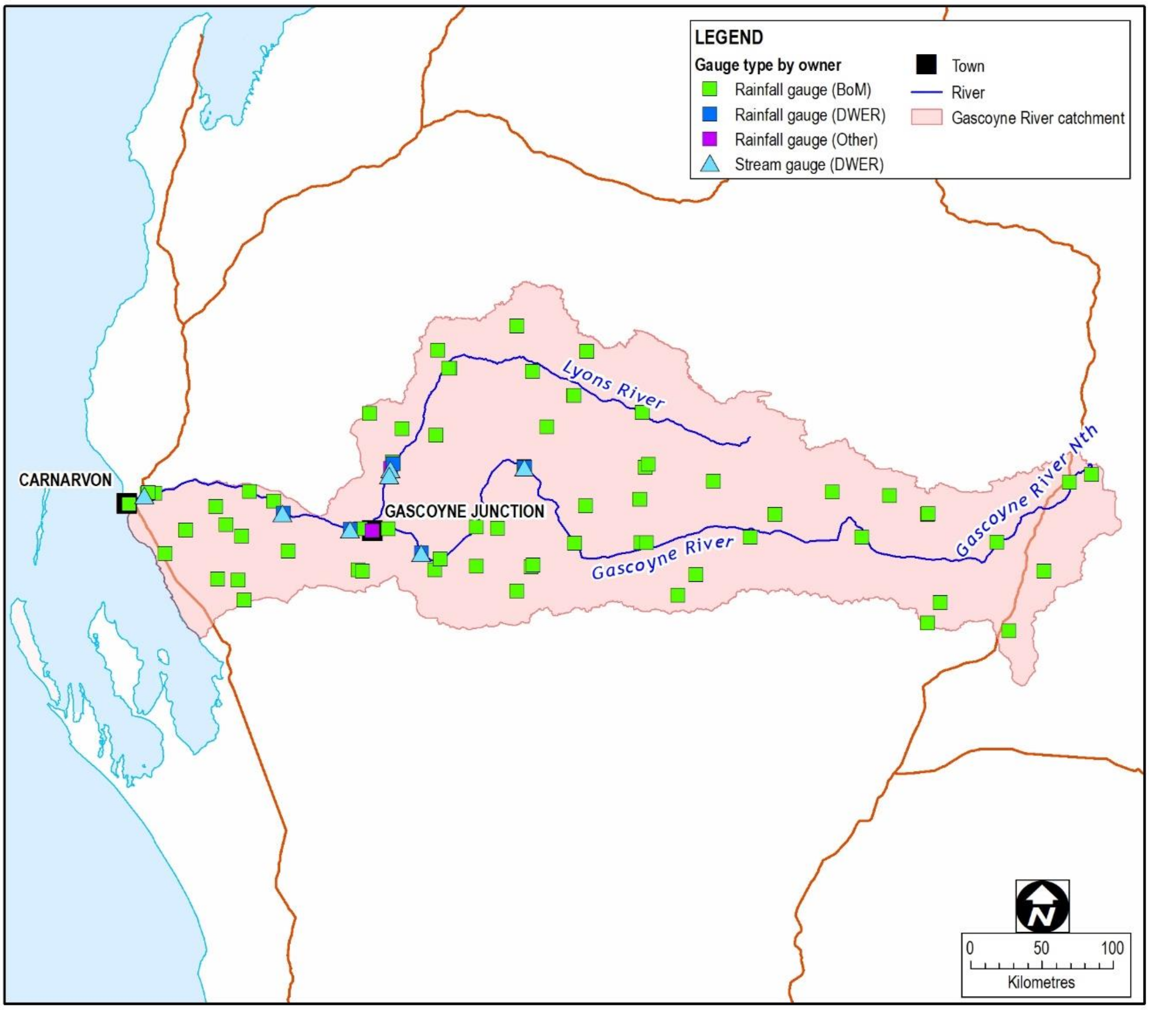


Figure 3 DWER and BoM rainfall gauges within the Gascoyne River catchment

2.2 Comparison of February 2021 rainfall to previous events

Rainfall spatial and temporal distribution

Figure 7 compares the spatial distribution of rainfall for four events which resulted in major flooding in Carnarvon over the last 30 years. It shows that although the rainfall totals vary between events, their rainfall spatial distribution is quite similar. The area of highest rainfall for each event was recorded in the central portion of the catchment, within 150 kilometres of Gascoyne Junction. In contrast, a high rainfall event in the eastern part of the catchment in February 2020 did not lead to major flooding in Carnarvon.

Rainfall intensity

Figure 8 compares the rainfall intensities recorded during the February 2021, March 2000 and December 2010 events with the BoM IFDs. It illustrates that the 2000 and 2010 events were significantly more intense than the 2021 event. No rainfall intensity data is available for the February 1995 event in the catchment.

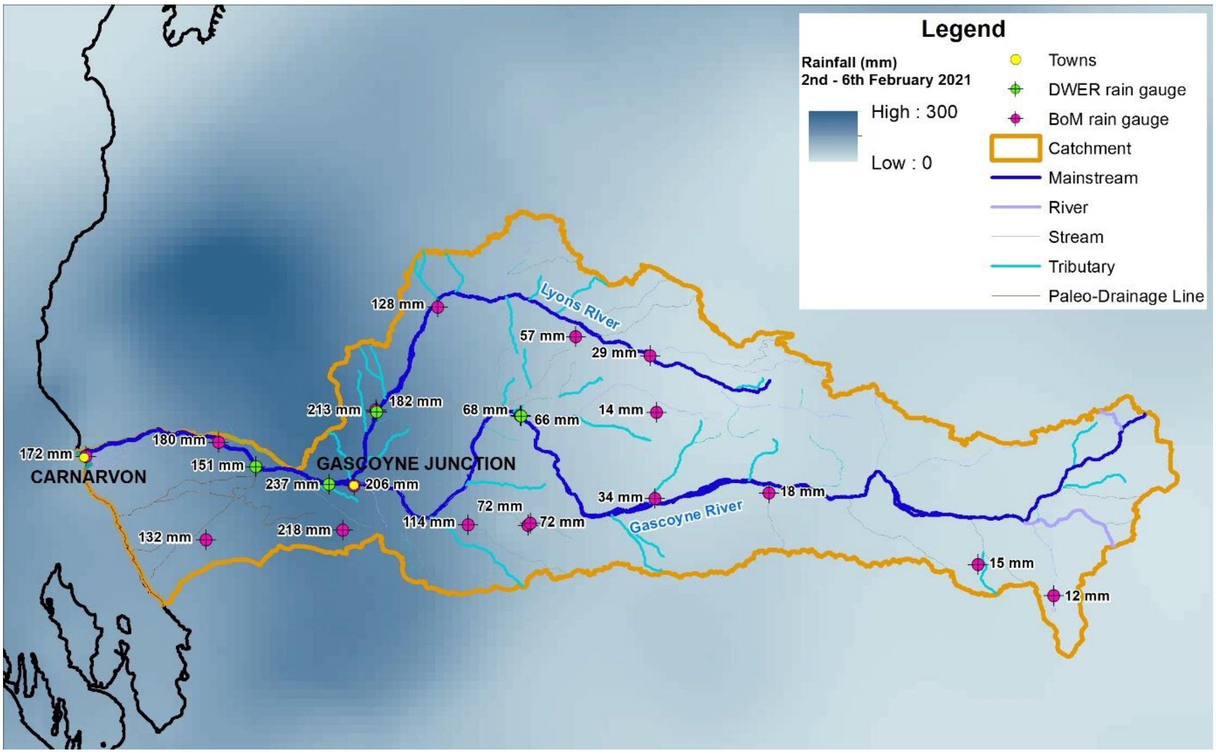


Figure 4 Total rainfall (mm) 2– 6 February 2021

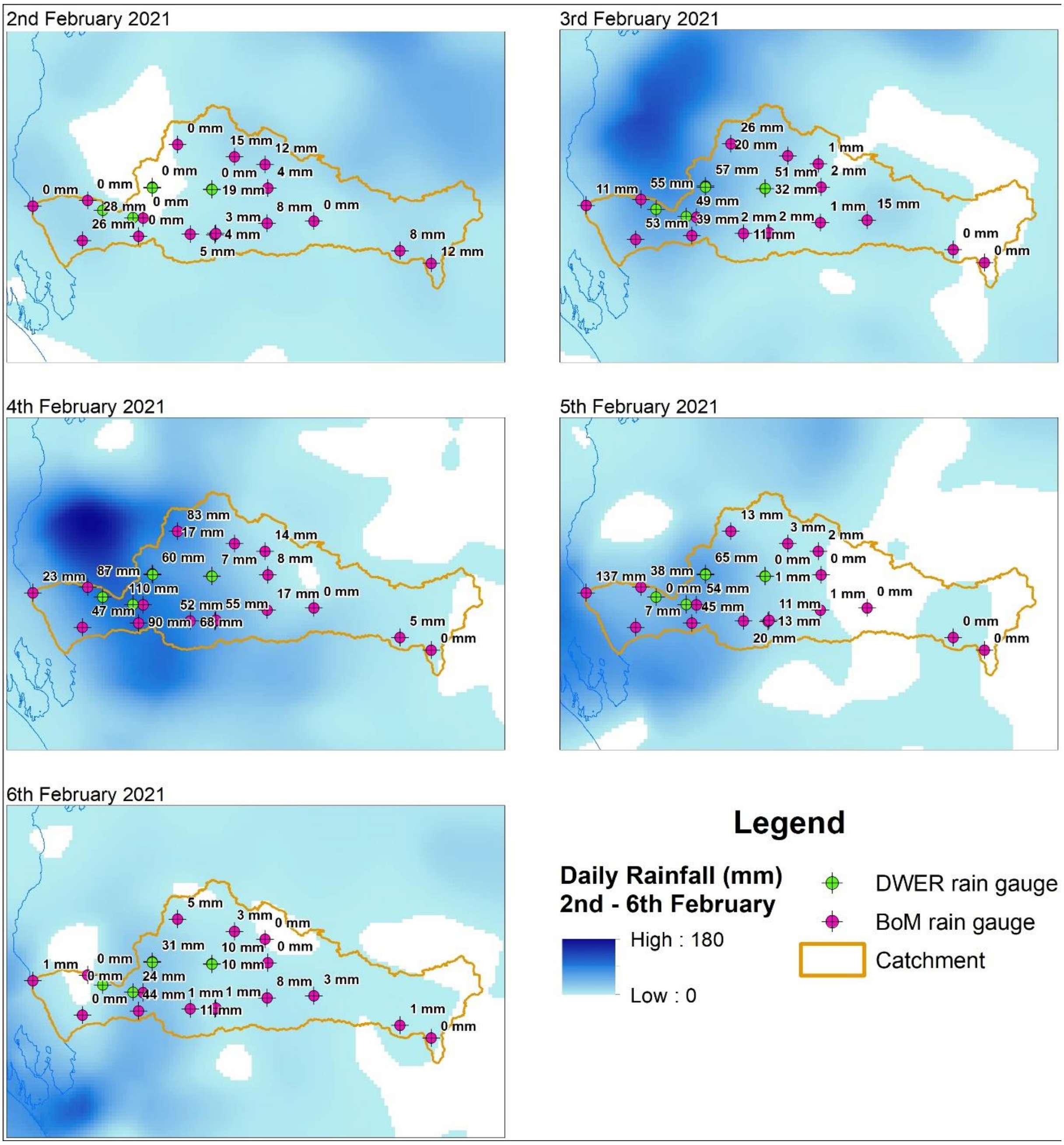


Figure 5 Daily rainfall (mm) 2–6 February 2021

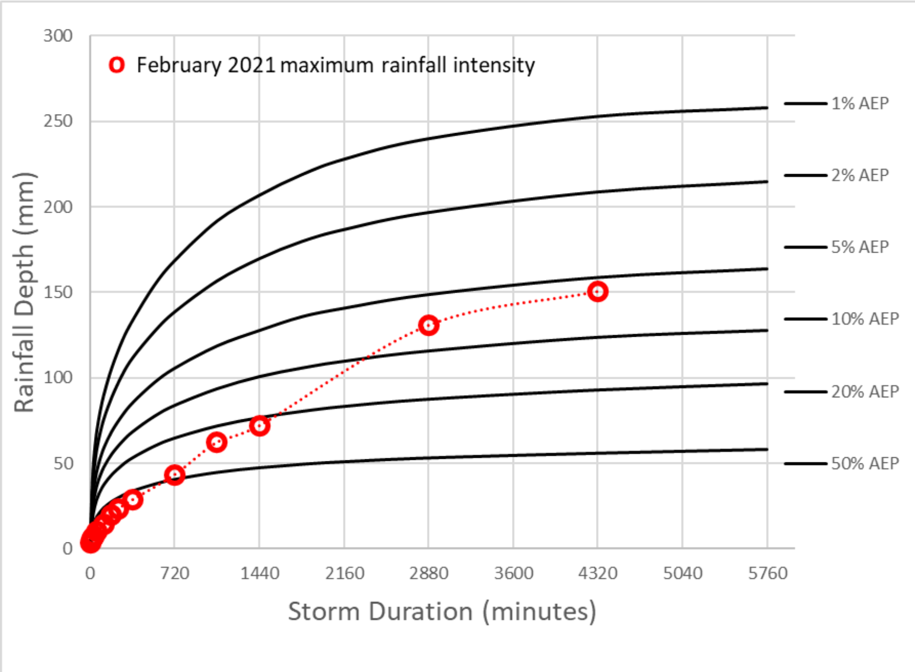


Figure 6 Comparison of February 2021 rainfall intensity at DWER's Fishy Pool rainfall gauge with BoM (2016) design intensity-frequency-duration values

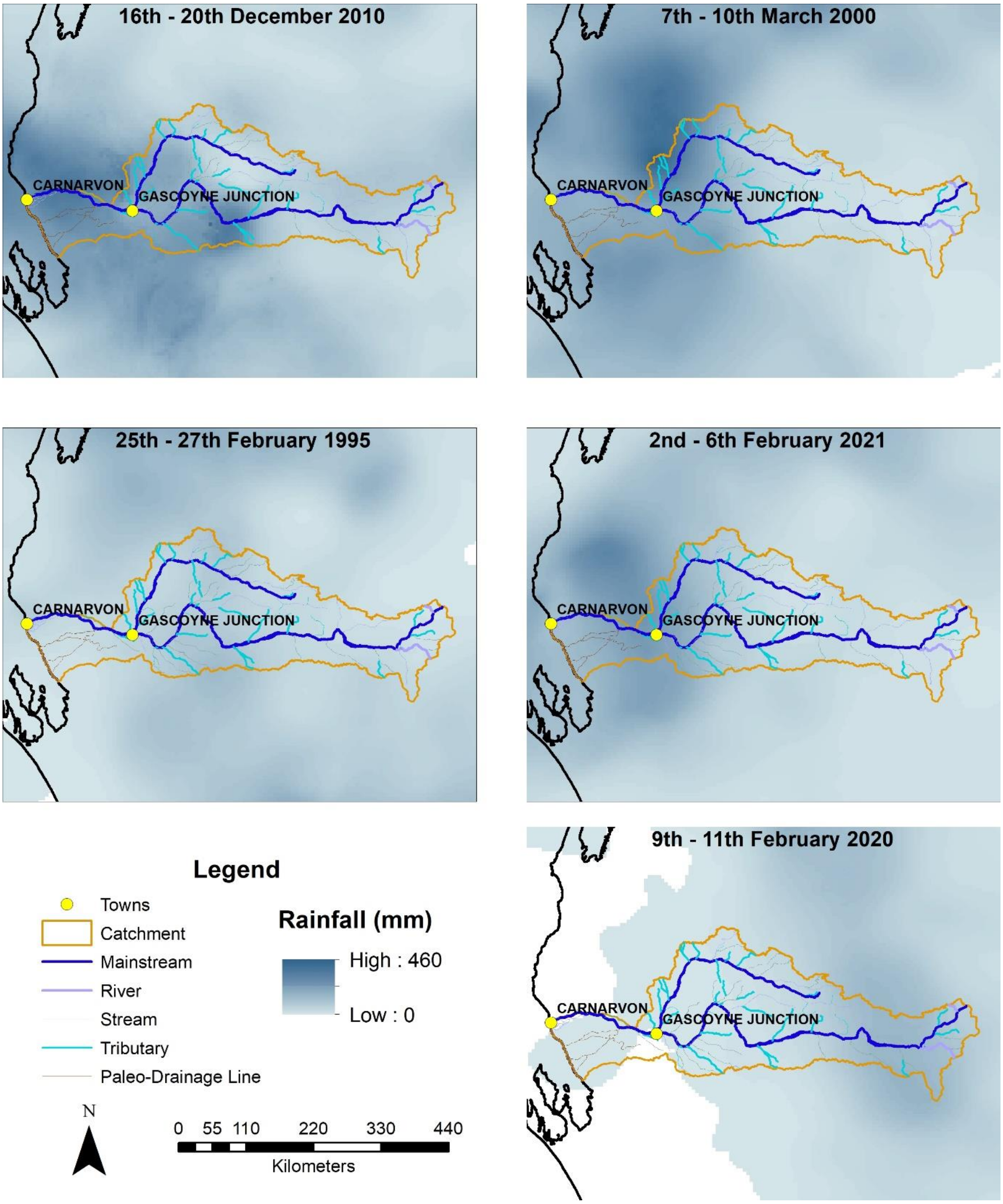


Figure 7 Spatial distribution of rainfall which resulted in major flood events at Carnarvon

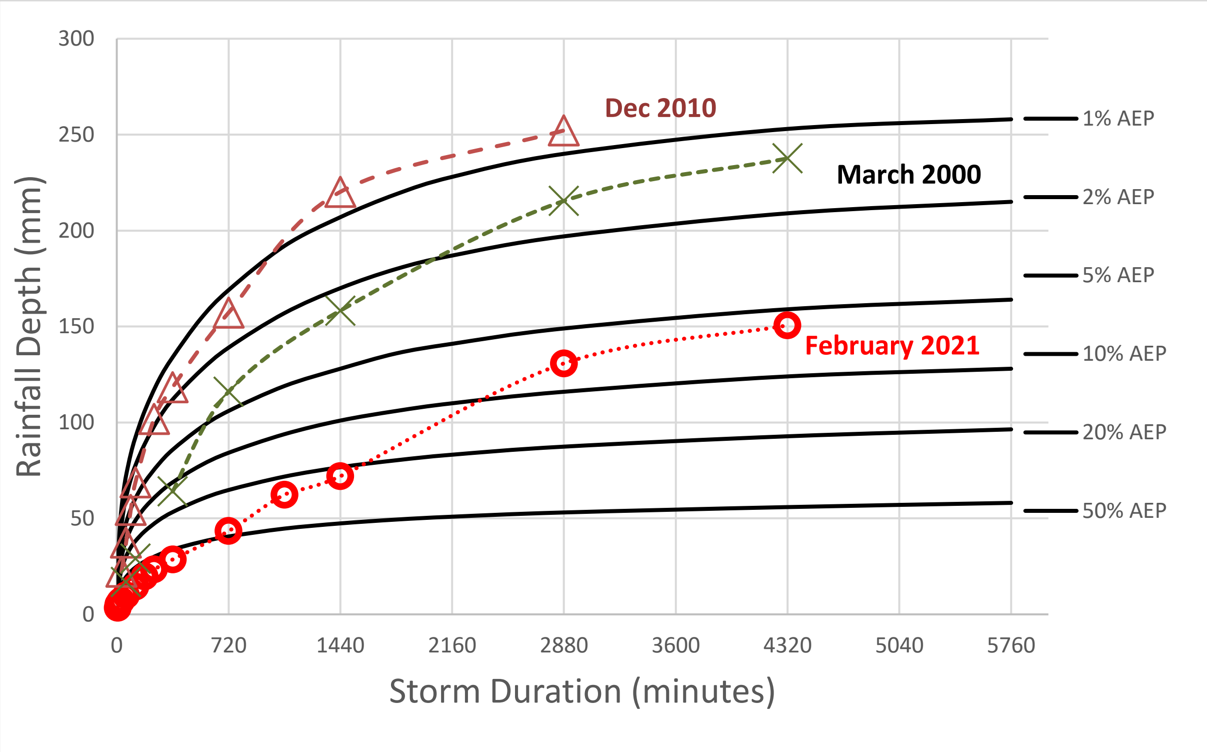


Figure 8 Comparison of the recorded rainfall intensities at DWER's Fishy Pool rain gauge for events in March 2000, December 2010 and February 2021 with BoM (2016) IFD estimates

2.3 February 2021 streamflow

We operate six telemetered streamflow gauging stations in the Gascoyne River catchment (Figure 9). From upstream to downstream:

- three sites record streamflow upstream of Gascoyne Junction: Yinnethara Crossing; Pells Island on the Gascoyne River; and Lyons River Xing on the Lyons River
- two streamflow gauges, Jimba and Fishy Pool, are located on the Gascoyne River between Gascoyne Junction and Carnarvon
- the Nine Mile Bridge streamflow gauge, which is located at the North West Coastal Highway (NWCH) bridge crossing of the Gascoyne River near Carnarvon.

In large events, a proportion of the flow breaks away from the river to the floodplain between the Fishy Pool and Nine Mile Bridge gauging stations. These flows are not measured by the Nine Mile Bridge gauge. Therefore, many of the streamflow assessments on catchment flows are based on the recorded information at Fishy Pool, which is not affected by these breakaway flows. Fishy Pool monitors flow from over 90 per cent of the catchment.

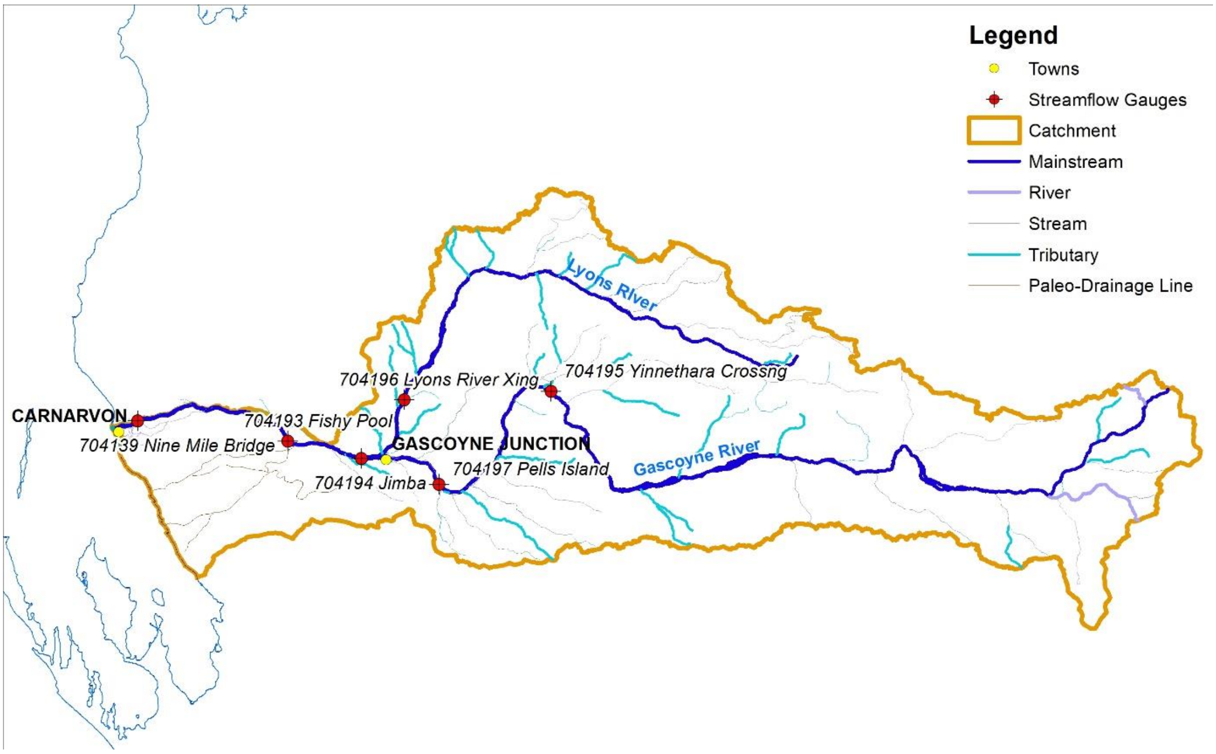


Figure 9 Location of DWER's streamflow gauging stations in the Gascoyne River catchment

Figure 10 shows the recorded streamflow at each of the gauging stations during the February 2021 event. The peak flow at Jimba was substantially higher than the peak flows at the upstream gauges on the Gascoyne River (Pells Island and Yinnietharra Crossing) and Lyons River (Lyons River Xing). Their timing was similar. These observations suggest that a large proportion of the flow was generated in the central part of the catchment (between these upstream gauges and Jimba), and not from further east. This is also consistent with the distribution of rainfall across the catchment (Figure 4).

Table 1 shows that the flood peak travel time between Jimba and Fishy Pool was about nine hours. The flood peak travel time between Fishy Pool and Nine Mile Bridge was 12 hours, slightly quicker than previous flood events (such as 2000 and 2010) which showed travel times between 14 and 16 hours. Localised high rainfall (measured at Carnarvon Airport in the 24 hours to 9am on 5 February) and resulting local inflows may have interacted with the flood-wave from the upper catchment, contributing to the faster travel time to flood peak at the Nine Mile Bridge streamflow gauge.

There is relatively little additional catchment area between Jimba, Fishy Pool and Nine Mile Bridge and the slight reduction and broadening of the hydrograph as the flood travels downstream from Jimba is consistent with observed flows in past events.

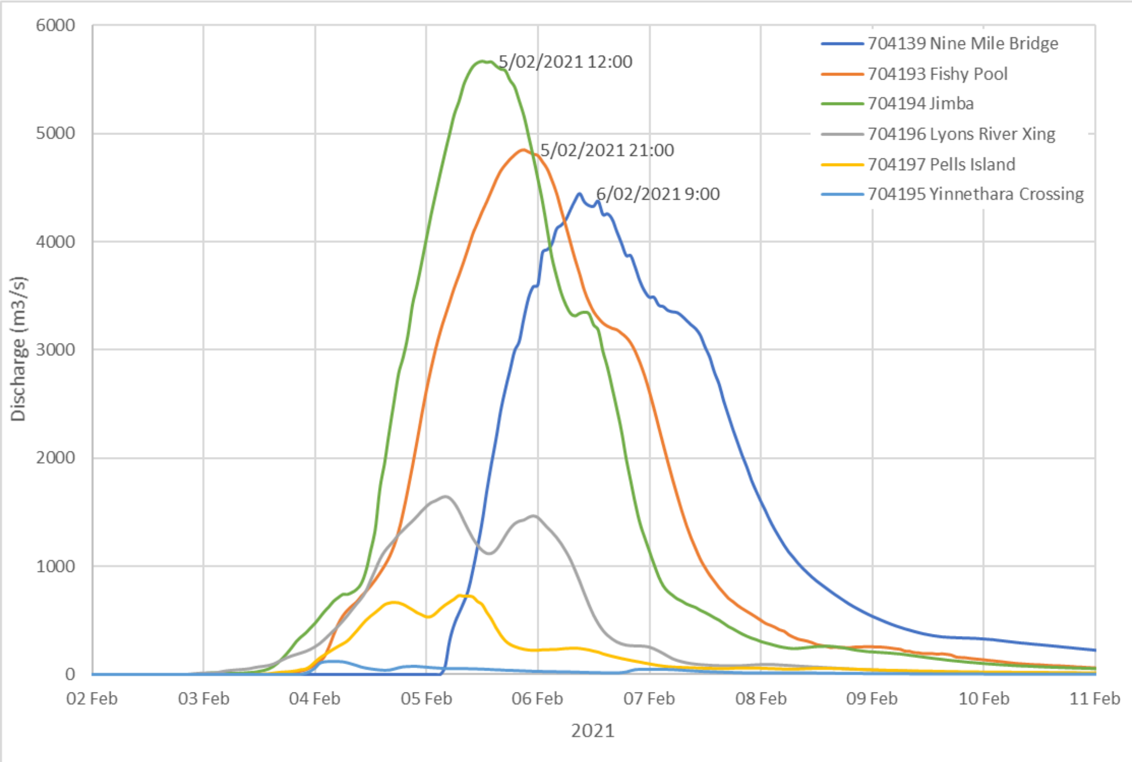


Figure 10 Streamflow at DWER's streamflow gauges in the Gascoyne River catchment during the February 2021 event

Table 1 Summary of flow travel time between DWER's streamflow gauges downstream of Gascoyne Junction for the February 2021 event

Gauging station		Lead waters			Peak		
	Distance from mouth (km)	**Time arrived**	**Time between (hrs)**	**Speed (km/h)**	**Time arrived**	**Time between (hrs)**	**Speed (km/h)**
Jimba	169	00:00 3/2/21			12:40 5/2/21		
Fishy Pool	122	14:00 3/2/21	14	3.4	21:05 5/2/21	8.4	5.6
Nine Mile Bridge	17	04:30 5/2/21	38.5	2.7	09:25 6/2/21	12.3	8.4

2.4 Comparison of February 2021 streamflow to previous flood events

Streamflow measured at Fishy Pool during the February 2021 event was lower than previous flooding events (Figure 11).

In contrast to Fishy Pool, data from further downstream at Nine Mile Bridge, close to the Carnarvon townsite, shows that river levels during the February 2021 event were close to those for the 1995 event. This is due to the gauge measuring only the flow in the main channel and not the flows in the floodplain, which break out from the river channel between Fishy Pool and Nine Mile Bridge. Both the 1995 and 2021 events exceeded the capacity of the main river channel, with the additional flows overtopping the riverbanks and surging onto the floodplain north and south of the river. Consistent with the measured flows at the upstream gauges in the catchment, larger floodplain flows upstream of Nine Mile Bridge were observed in the 1995 event compared with the recent 2021 event.

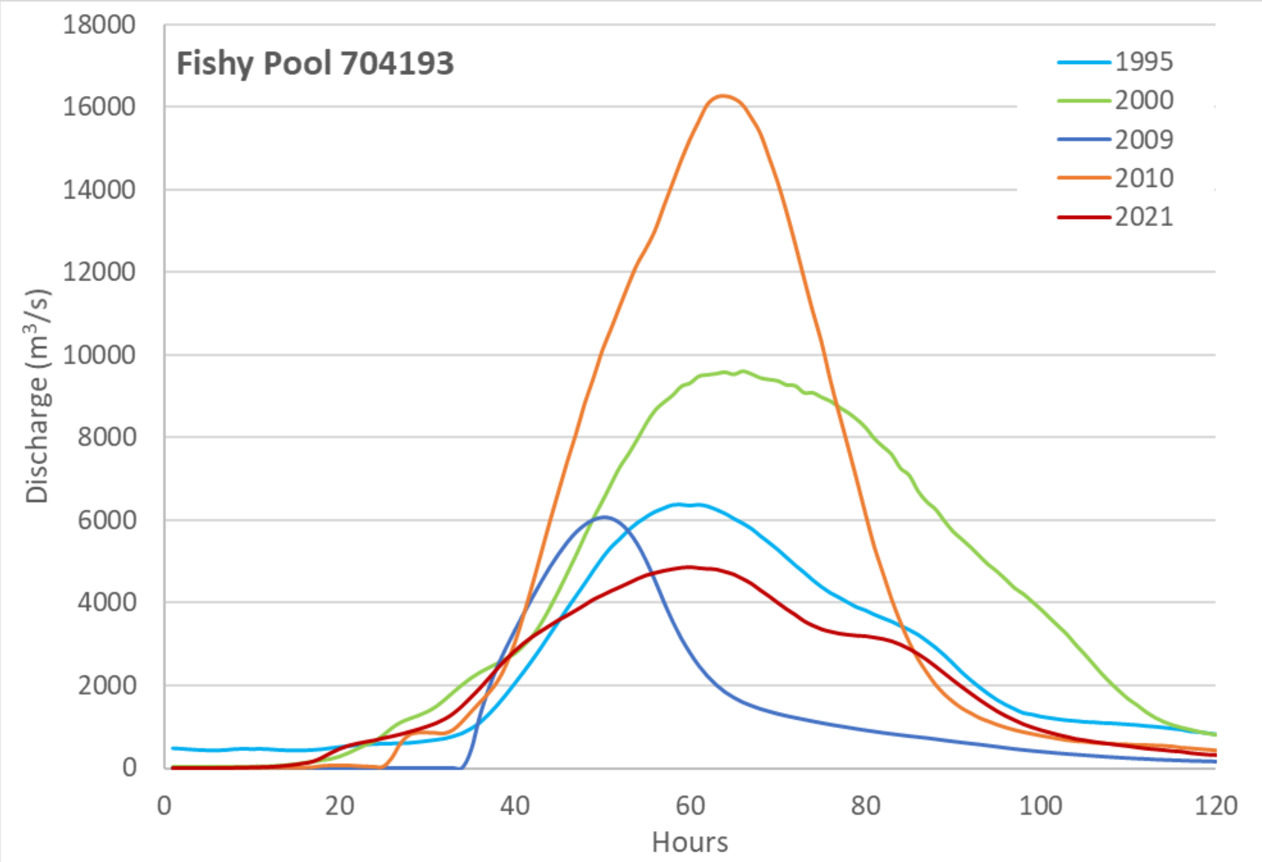


Figure 11 Comparison of the February 2021 streamflow to other major events at DWER's streamflow gauge on the Gascoyne River at Fishy Pool

Issues with water level comparisons at Nine Mile Bridge

The department and BoM report on river depth at Nine Mile Bridge. At this site, river depth is not an accurate measure for comparing water levels between flood events. At Nine Mile Bridge, the riverbed is sandy and easily modified by flow events, so the riverbed's height (e.g. in relation to sea level) changes frequently. This means that the level from which river depth is reported also typically changes between flood events.

To compare river levels between events accurately, we recommend measuring the water surface (rather than the depth above the sandy riverbed), referenced to either a local datum or a standard datum, such as the Australian Height Datum (AHD).

For this report, water levels at Nine Mile Bridge were converted to metres AHD. Figure 12 shows that the recorded water levels at Nine Mile Bridge for the February 2021 event most closely resemble the peak (and shape) recorded in February/March 1995.

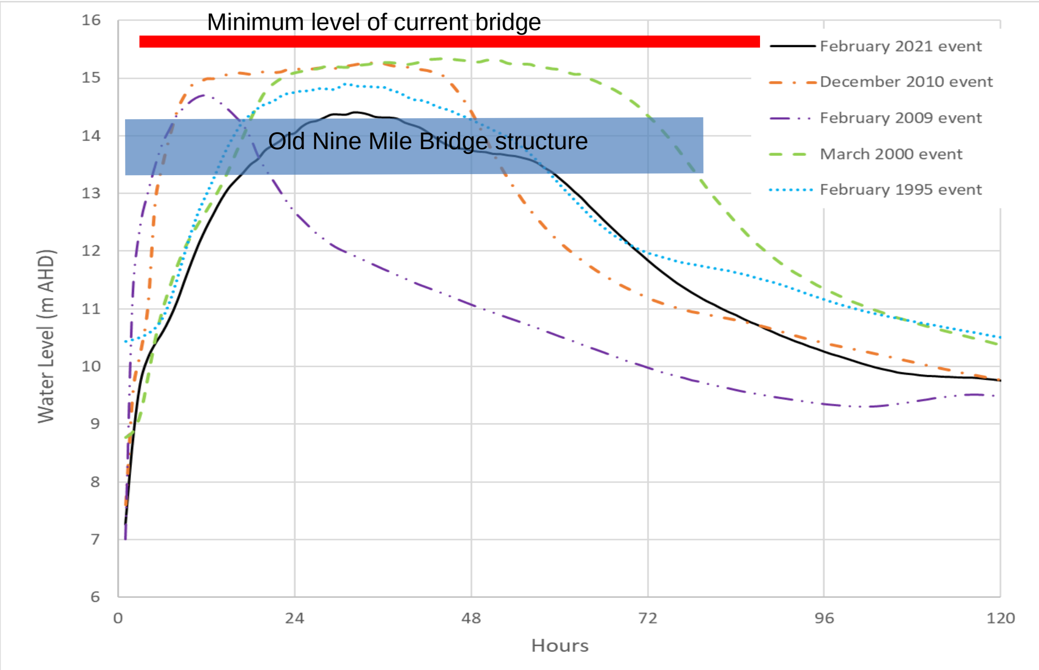


*Figure 12 Comparison of recorded water levels at DWER's streamflow gauging station at Nine Mile Bridge**

*The pre-2002 bridge structure (Old Nine Mile Bridge) soffit 13.45 m AHD and deck 14.3 m AHD levels were taken from MRWA (1999).

Comparisons of water level data between events at Nine Mile Bridge was further complicated by the replacement of the NWCH bridge in 2002, which changed hydraulic conditions. Prior to the bridge replacement, the streamflow gauge was located immediately upstream of the old bridge. Due to its design, water levels during floods banked-up at the old bridge. The new bridge is higher and has much less impact on upstream flood levels.

Figure 13 compares the water building upstream of the old bridge during the 1995 event to the flatter conditions during the February 2021 flow event. The replacement of the bridge resulted in lower water levels recorded at the Nine Mile Bridge streamflow gauge for the same downstream flow.

Due to these changed hydraulic conditions, despite the difference in water levels recorded at Nine Mile Bridge streamflow gauge (Figure 12), the peak flow downstream of the bridge for the February 2021 event was similar to that in 1995.

The impact of the replacement bridge on the relationship between the recorded water levels at the department's streamflow gauge and the expected impacts downstream is discussed further in Section 5.

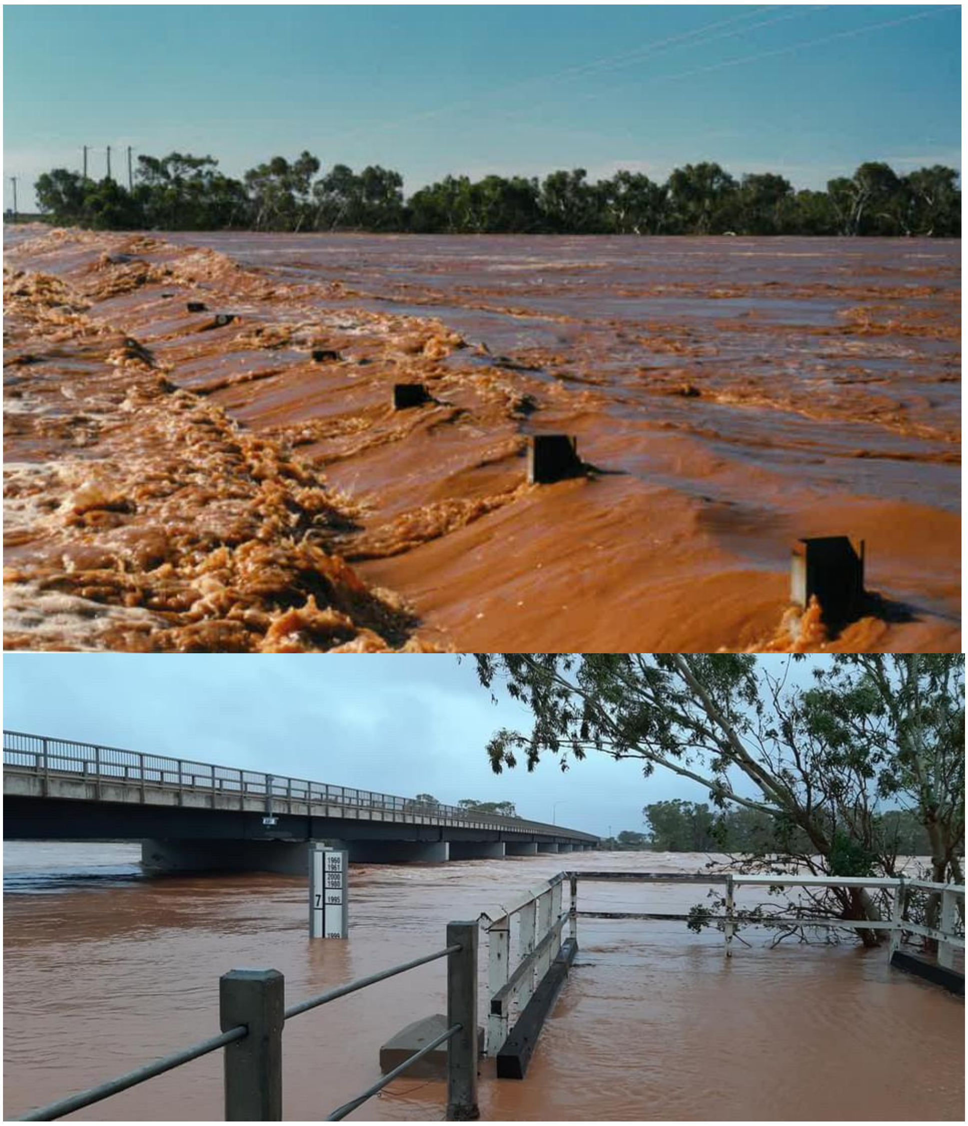


Figure 13 Comparison of river flows at Nine Mile Bridge in February/March 1995 (above: old bridge) and February 2021 (below: replacement bridge with section of old bridge in foreground)

2.5 Flood frequency analyses

Flood frequency analysis (FFA) involves fitting a statistical distribution to historical records of peak flows. We can then assess the likelihood of past floods and determine the likelihood of floods in the future. The analysis can also be applied to other characteristics of flood behaviour, such as volumes. The peak flows (and levels) from FFAs are used in land use planning and infrastructure design to provide a prescribed level of flood protection.

The most recent flood hydrology study for the Gascoyne River was prepared by Sinclair Knight Merz (SKM) in 2007. The study included a detailed FFA to quantify the likelihood of various peak discharge and flood volumes at the Fishy Pool stream gauge on the Gascoyne River. By comparing a given flood event with the curves produced, we can assess how likely it is to observe a flood of that magnitude.

The expected likelihood of the peak flow and volume of major flood events recorded over the last 30 years is summarised in Table 2.

Figure 14 and Figure 15 compare five flood events including the February 2021 event (for peak flow and 10-day flow volume), using the FFA by SKM (2010). Of the five events, the 2021 flood was the most likely (at 1 in 9 AEP for peak flow and 1 in 8 for 10-day flow volume). For comparison, the 10-day flow volume of the 2000 and 2010 events were 1 in 50 and 1 in 60 respectively (Figure 14, Figure 15 and Table 2).

Table 2 Comparison of the likelihood of historic flood peaks and streamflow volumes (based on results in SKM 2007)

Flood event	**Likelihood of exceeding (AEP*)**	
	Peak flow	**10-day flow volume**
1995	7% (1 in 15)	7% (1 in 15)
2000	3% (1 in 30)	2% (1 in 50)
2009	8% (1 in 13)	20% (1 in 5)
2010	1.1% (1 in 95)	1.8% (1 in 60)
2021	11% (1 in 9)	12% (1in 8)

*AEP denotes the likelihood of an event of a certain size being equalled or exceeded in any given year.

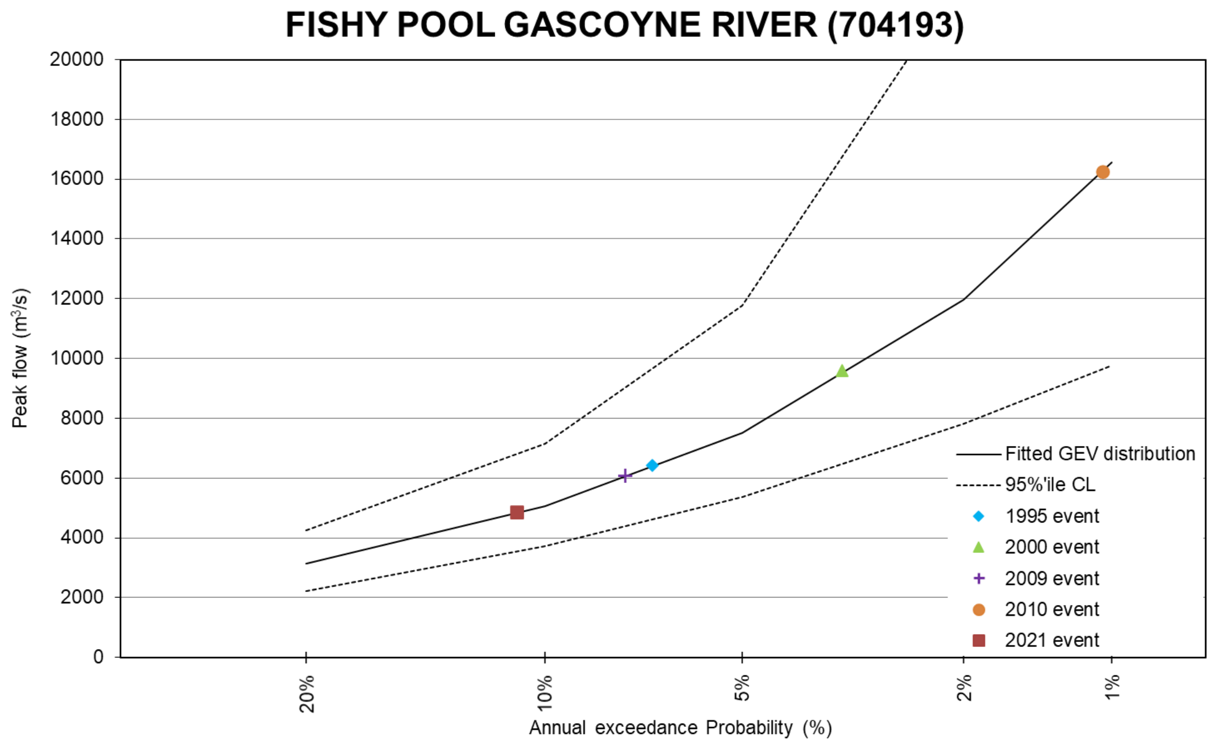


Figure 14 Expected likelihood of the February 2021 event and other recent notable events by peak flow at DWER's Fishy Pool streamflow gauge

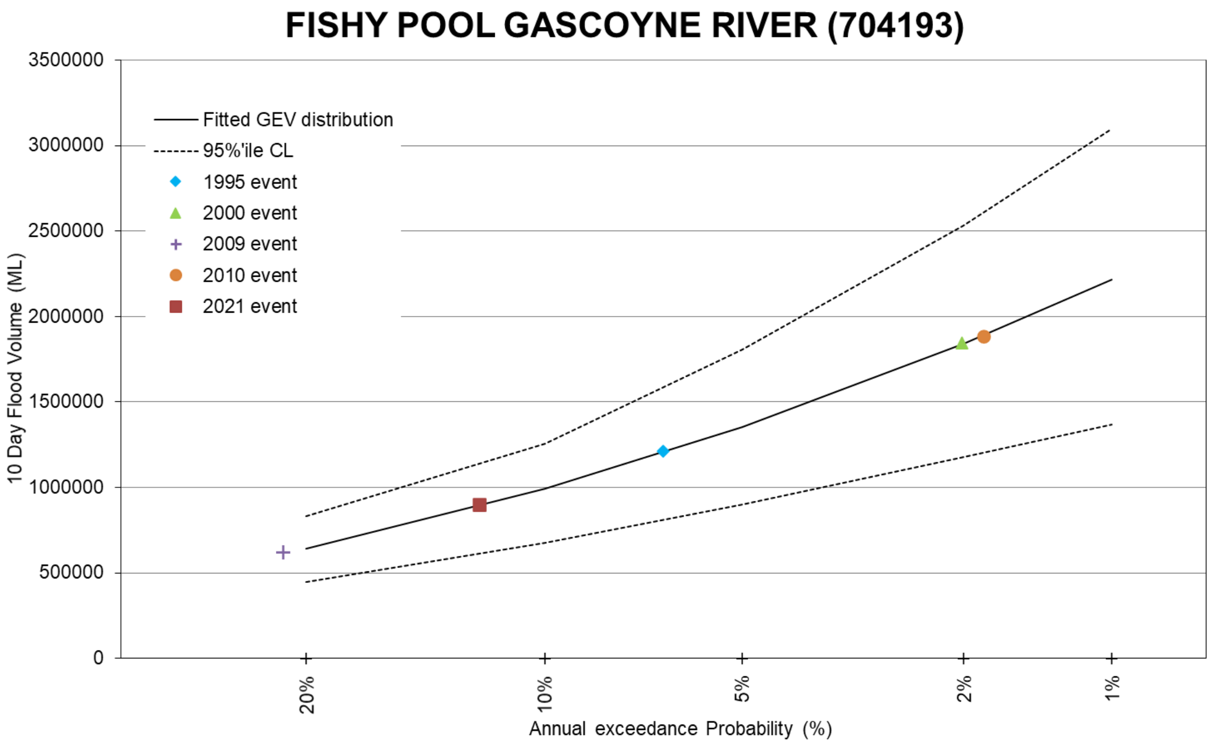


Figure 15 Expected likelihood of the February 2021 flood event and other recent notable events based on flow volume over a ten-day period at our Fishy Pool streamflow gauge

3 Observed flood behaviour and comparison to previous events

After the February 2021 flood event, we identified and surveyed peak flood levels along the river and floodplain to compare with data from previous events. We also used historical photos and videos as part of our assessment, and drew on satellite imagery to help us map flood extent. We met with staff from other agencies and discussed the flooding with local government and plantation owners on both the north and south banks of the river.

3.1 Real-time kinematic survey

One hundred and forty-five reliable peak flood levels were surveyed along the riverbank and floodplain using Real-Time Kinematic (RTK) positioning technology. It was not possible to survey the Lewers Island area as it was flooded at the time of the survey. Instead, anecdotal evidence was collected from local residents (see Section 3.5).

Regular checks at Landgate benchmarks and standard survey marks were taken throughout each day. The average horizontal and vertical errors in these checks were less than 10 mm.

To determine flood level for flood marks on fences, power-poles, signs, trees, etc., we measured the height above ground using a tape (Figure 17). The measured height was added to the RTK survey of the ground level to determine the flood level in metres AHD. Manually reading the tape means there is the possibility for a small margin of error.

To indicate peak flood level, we surveyed the highest location of the debris left behind on the floodplain. The actual peak flood level may have been slightly different as debris is sometimes pushed above the average peak water level by waves on the water surface or can float down as the flood recedes. The flood marks evident on some power-poles and trees showed a marked difference on the upstream side compared with the downstream side (Figure 18). Where this was identified, the average between upstream and downstream levels was surveyed. Some of the surveyed peak levels were located at marks left behind on fences and buildings. These marks may be slightly higher than true peak levels observed for similar reasons to the difference in upstream levels observed on poles.

Considering all potential sources of errors, the surveyed flood levels are likely to be within +/- 100 mm (10 cm).

Figure 16 RTK survey (left: base station set up at Landgate survey benchmark, right: rover unit and flood debris mark)

Figure 17 Measuring up from ground to flood mark (downstream side of culverts at Six Mile Creek crossing of North West Coastal Highway)

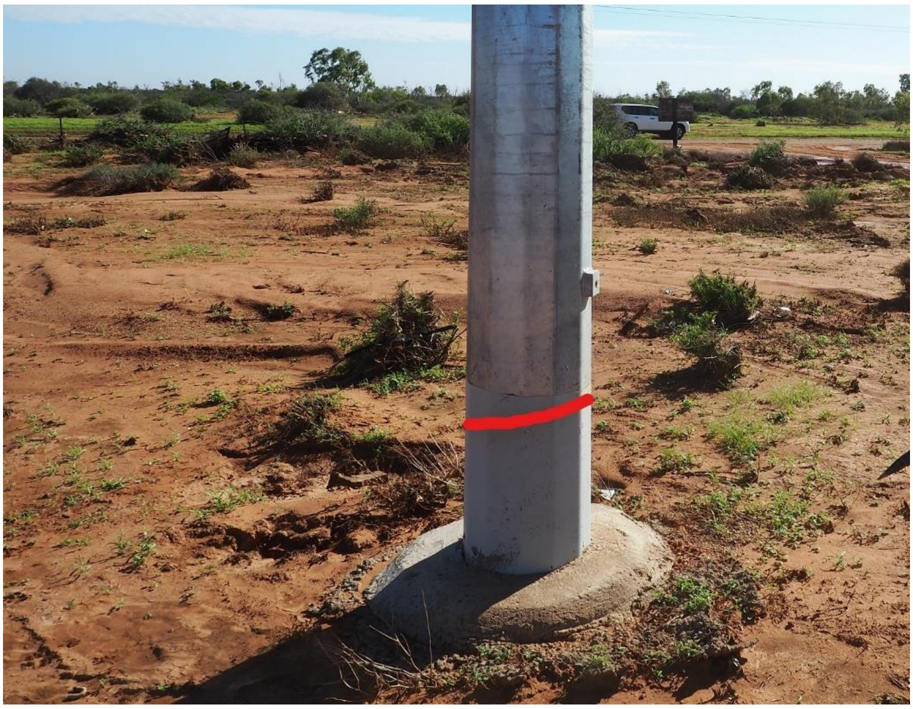


Figure 18 Flood mark on power-pole (difference in upstream [right] and downstream level [left] has been highlighted)

3.2 Photographs/video

Photography and video were collated from the community and online sources. This information helped us understand the observed extent of inundation during the event, and identify local factors that may not be represented well in modelling. Videos taken by a local helicopter operator and posted to the internet were useful to confirm flooded areas.

Photographs of the flood have also been used to assess the existing flood modelling and mapping qualitatively.

Aerial photography and videos taken during the event indicated that the levee system was effective in protecting the plantations between South River Road and the NWCH from river flooding. Figure 19 shows flooding in January 2009 at the intersection of Giles Road and South River Road, before the levees were built. By comparison, Figure 20 shows that this location and all land behind the South River Road levee remained dry during the February 2021 event. Based on limited survey data, peak levels during the 2009 flood were similar to (within 200 mm of) the peak levels observed in 2021.

Figure 19 Flooding in January 2009 on the south bank of the Gascoyne River at Giles Road and South River Road intersection

Figure 20 Plantations protected from flooding in February 2021 by levee network

3.3 Satellite imagery

Satellite imagery from close to the flood peak covering the entire floodplain confirmed that breakouts from the river upstream of Nine Mile Bridge flowed over the floodplain to pond behind the Nickol Bay levee (despite cloud cover obscuring part of the images). The Lawson Street levee performed as expected by diverting these floodwaters south rather than allowing them to flow into the rear of the plantations east of the Nickol Bay/South River Road levee (Figure 21).

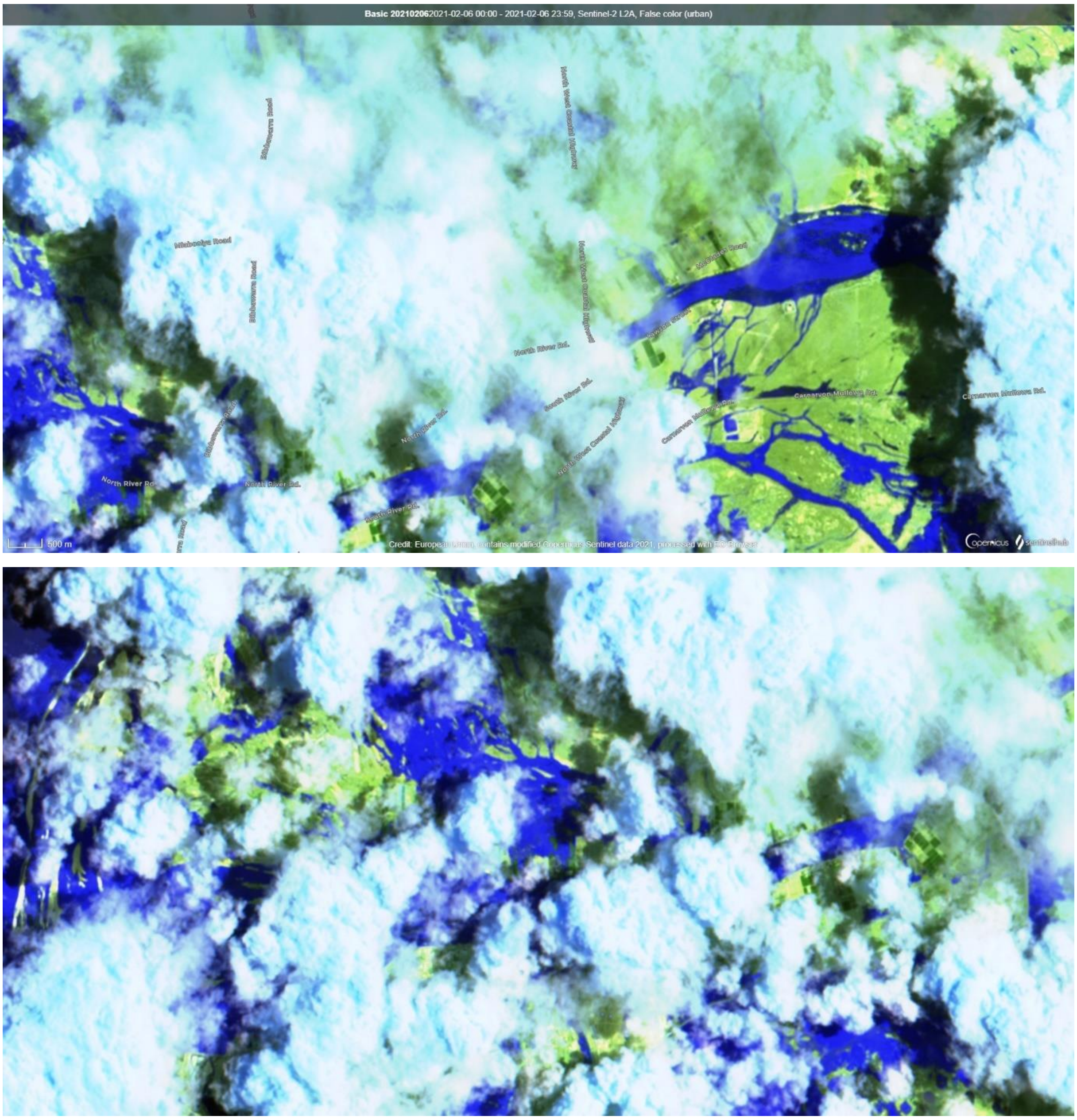


Figure 21 Sentinel-2 satellite imagery of Carnarvon – Bibbawarra Road to McGlades Road (top), Coast to Santa Rosa Plantation levee (bottom) (based on false colour using bands 12, 11 and 4 from Sentinel Hub EO Browser)

Satellite imagery from 7 February (after the event) shows areas of water ponding and provides some indication of flow paths within the floodplain. The imagery does not show the extent of inundation observed on 6 February (Figure 22, Figure 23).

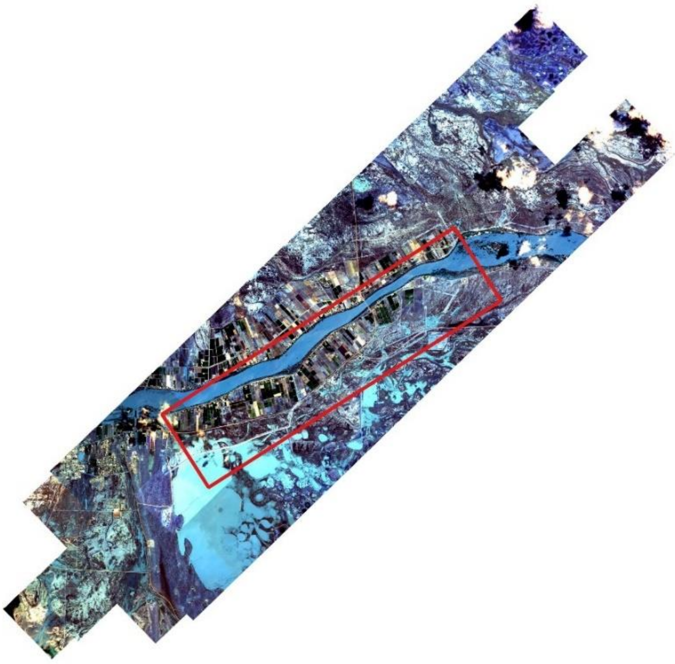


Figure 22 Satellite image of Carnarvon – Bibbawarra Road to Brickhouse Station (source: Planet)

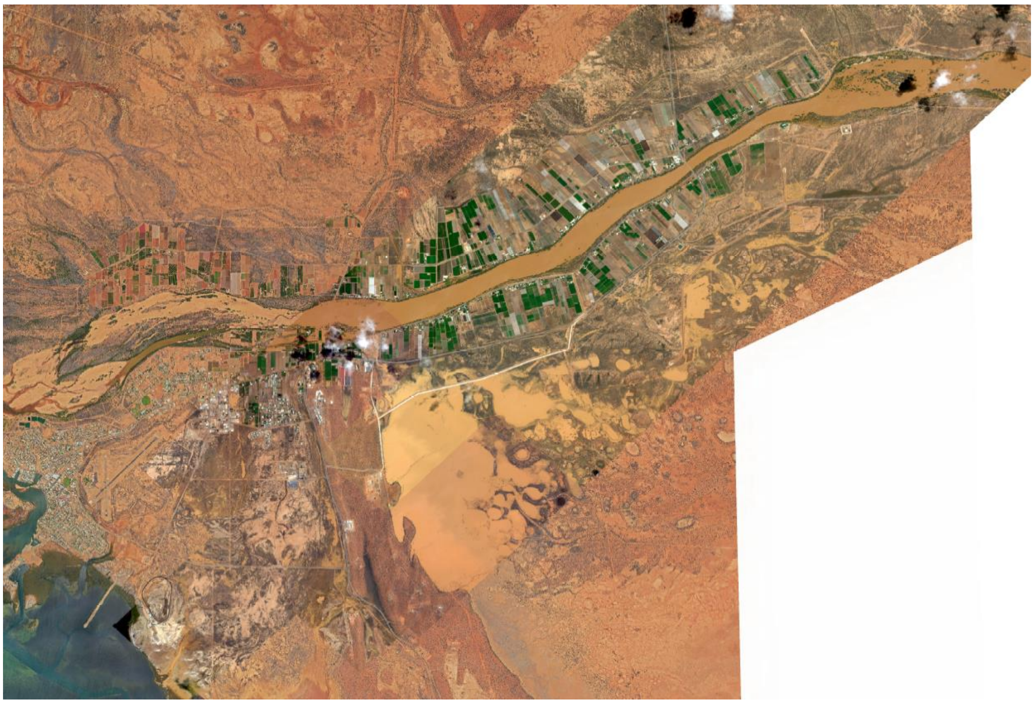


Figure 23 Skysat satellite imagery from Planet overlaid on aerial photography for Carnarvon

Soil and productivity loss assessment

There are about 170 commercial horticultural properties in Carnarvon. Sixty-four of these reported damages from the February 2021 event and were assessed by DPIRD. Findings from the damage assessment are consistent with the extent of flood inundation interpreted by this review.

Figure 24 compares the plantations that reported soil loss following the 2021 flood (yellow triangles) with similar surveys from 1995 (pink shading, taken from WAWA, 1995). Most reported soil erosion was located in the western end of the horticultural district and downstream of the new levee system (marked in red in Figure 24).

In 2021, there were fewer plantations reporting soil erosion on McGlades Road, east of Nine Mile Bridge and along South River Road. One property on South River Road reported soil erosion but this is not related to river flooding.

Three properties located between Burnt Gully and Bibbawarra Road, on the northern riverbank, reported soil erosion following the recent 2021 event but were not surveyed in 1995.

Two plantations immediately east of Burnt Gully were surveyed in 1995 but not in 2021. This suggests that the private levee bank may have been extended to protect these properties after the 1995 event.

Further details on the soil and productivity losses for the February 2021 event is available in DPIRD (2021).

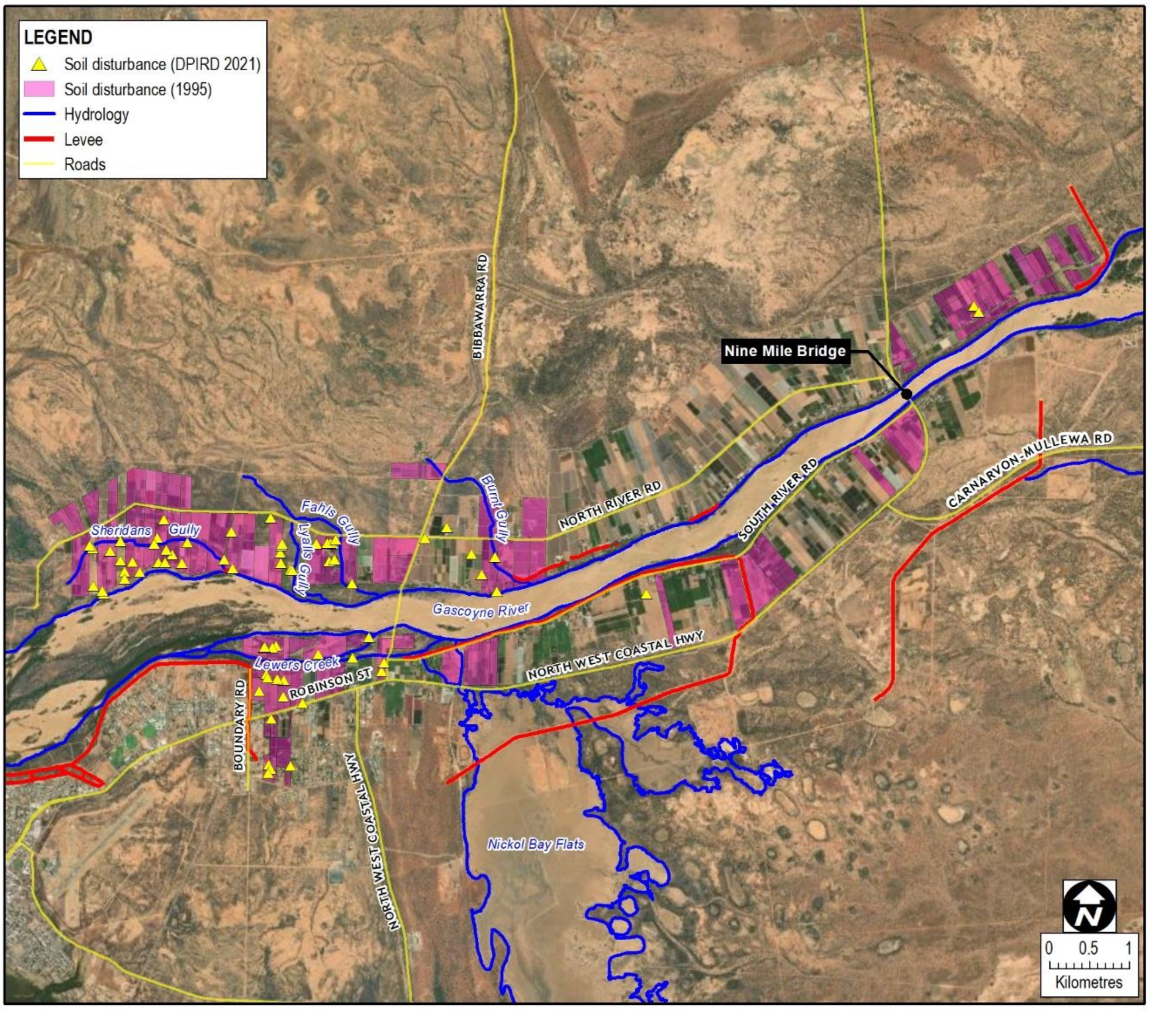


Figure 24 Location of damage caused by flooding in the Carnarvon horticultural area (reproduced from WAWA, 1995 and DPIRD, 2021)

3.4 Anecdotal information

Collecting anecdotal evidence provides supplementary information which can be used to complement surveyed field data and provide an insight into local observations to help analyse previous modelling.

Residents commonly reported that the February 2021 event had higher velocity on the floodplain than previous flood events. Some residents stated that the peak levels in the December 2010 were higher, yet it was possible to wade through floodwaters on their property. By comparison, it was not possible to wade through floodwaters in the February 2021 event because of the water's high speed.

Some community members also identified local factors which may have impacted floodplain flows, citing the location and extent of filling, dense vegetation, and infrastructure (buildings, fences, etc.). They considered that these factors could obstruct flood flows and contribute to localised changes in flood behaviour, causing erosion or damage to property.

Many plantation owners offered suggestions to mitigate flood impacts, including better management of the channels, such as Sheridans Gully and Lewers Creek, as they drain floodwaters away from the river during major events. They observed that vegetation (both native and weeds) combined with debris ‘choked up’ gullies which are not under cropping, and reduced their capacity to convey floodwaters away from the river.

Community members also suggested options for reducing flood risk, such as diverting the river upstream of Nine Mile Bridge and building levees connecting the existing townsite levees to the South River Road levee.

We discuss these suggestions further and identify additional flood mitigation options in Section 5.6.

Flooding prevented the survey of peak levels on Lewers Island. However, observations from residents were that levels for the February 2021 event were similar to the 2009 event, and up to 0.5 metres lower than the 2010 event. We have used this information to help validate the flood modelling.

3.5 Comparing peak levels in the February 2021 event with previous events

Compared with the March 2000 and December 2010 events, the February 2021 event had lower peak flood levels throughout the entire floodplain.

Compared with the 1995 event, the 2021 event had lower flood levels upstream of Nine Mile Bridge. This finding is consistent with the expected impact of replacing the old bridge. Downstream of Nine Mile Bridge, peak flood levels were mostly similar between the two events (Figure 25), with the following exceptions.

Through Kingsford, south of the river, flood levels were ~0.2 m higher in 2021 than in the 1995 event (Figure 26). Through Lyalls, Fahls and Burnt Gullies on the northern riverbank, the limited data suggest flood levels were also slightly higher than in 1995. This possibility is supported by anecdotal observations which described the flow uncharacteriscally ‘exploding’ out of Lyalls Gully. Further surveys in these areas are needed to confirm peak water levels in the gullies.

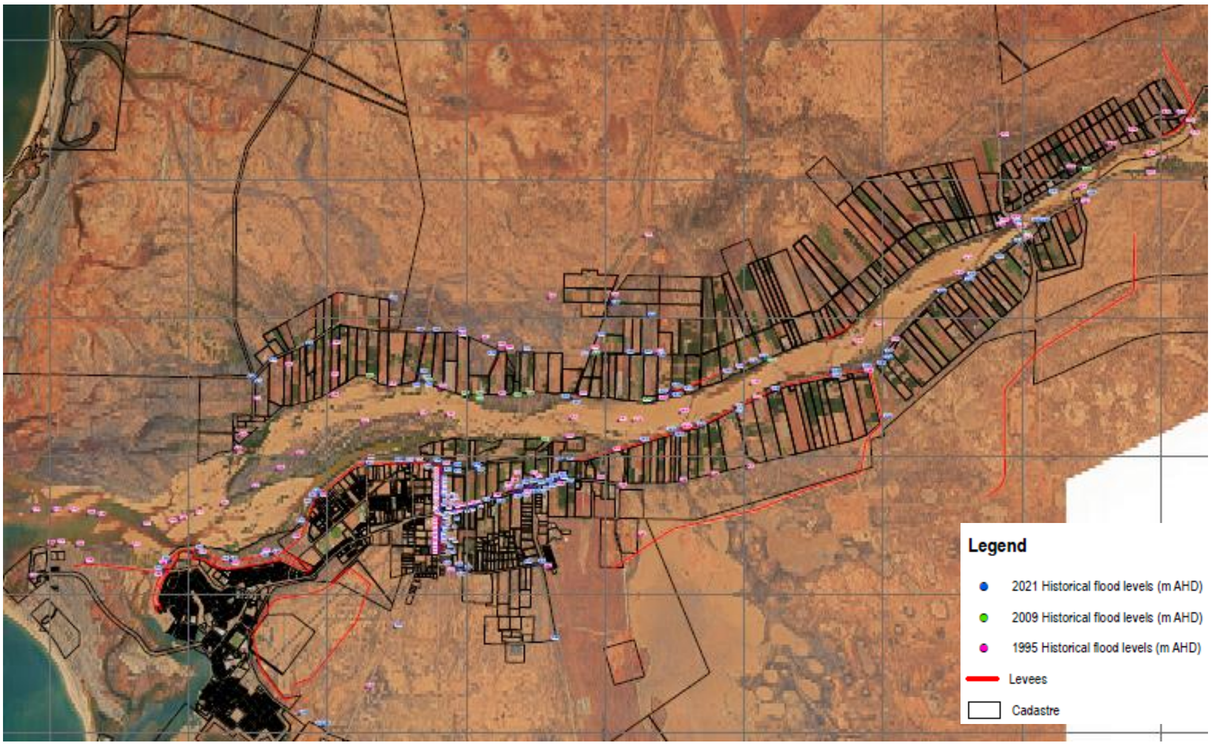


*Figure 25 Surveyed peak flood levels for February 2021 and 1995 flood events**

*A larger plan is provided as an addendum to this report

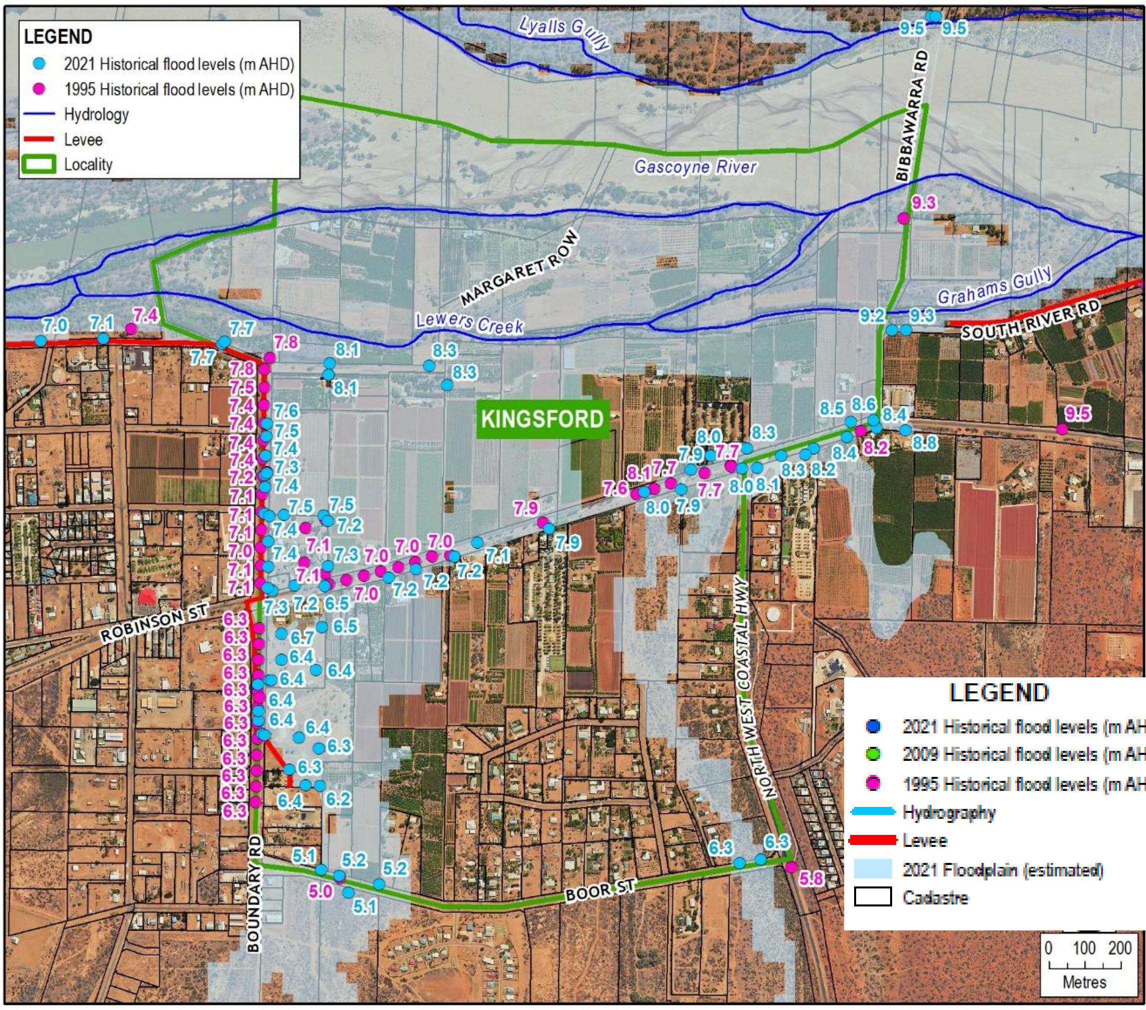


Figure 26 Comparison of 1995 and 2021 surveyed peak water levels in the Kingsford area of Carnarvon

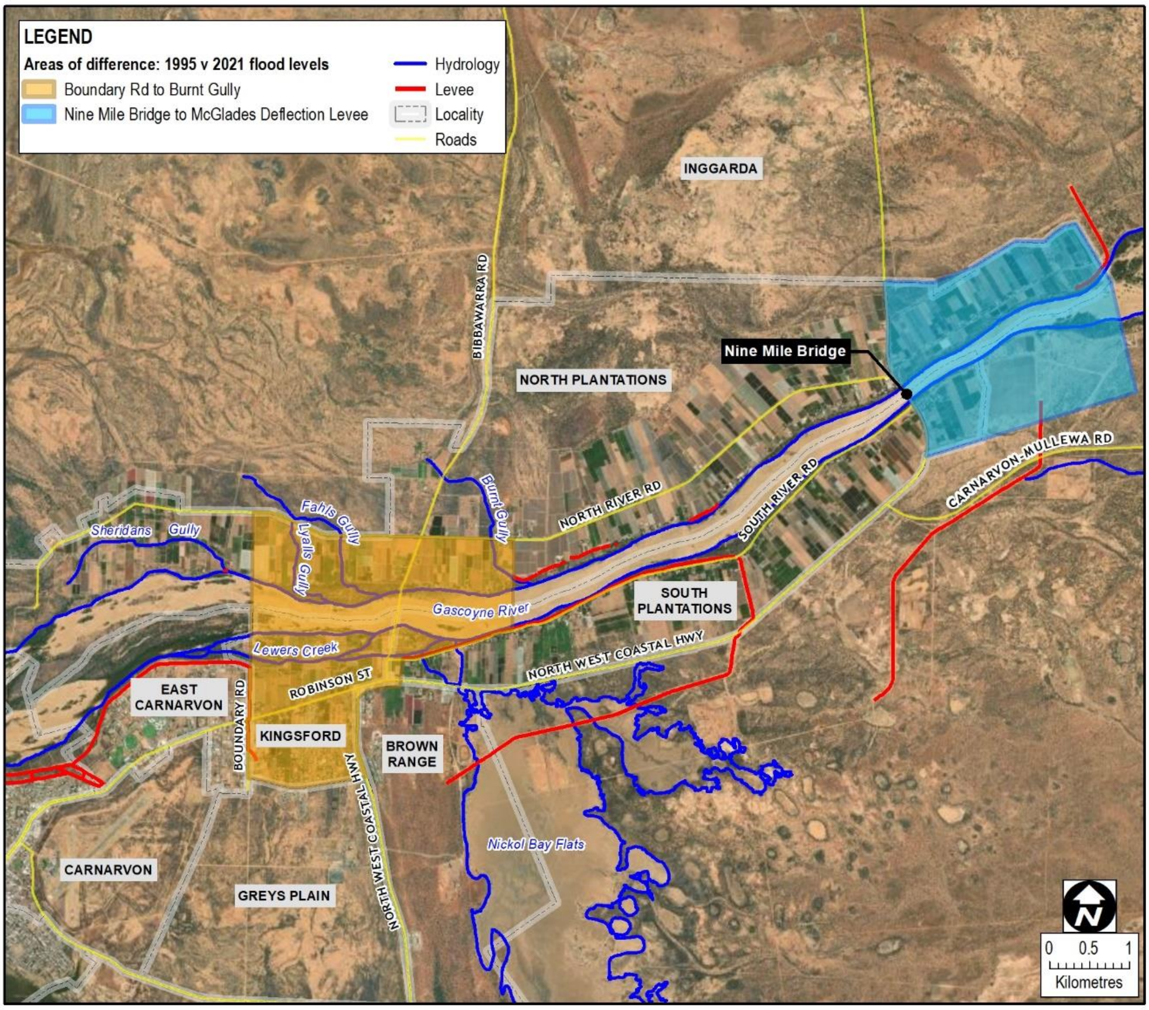


*Figure 27 Areas where 2021 flood levels differ from peak levels observed in 1995**

*Yellow shading identifies an area between Burnt Gully and Boundary Road; blue shading denotes the area upstream of the Nine Mile Bridge.

Given that the 1995 and 2021 flood levels were otherwise similar, several factors may have contributed to higher levels in specfic locations on the floodplain during the 2021 event:

- Local features such as fences (both solid and shadecloth), buildings and filling of low areas (and gullies) can obstruct flows, and may have contributed to the slight increase in flooding above the 1995 levels in the area between Burnt Gully and Boundary Road (yellow-shaded area in Figure 27).
- Changes in the areas of dense cropping and bare paddocks can alter the flow paths, water levels and flow velocities between events of similar size.
- Cropping type and dense planting close to the river channel, as observed in some areas between Burnt Gully and Boundary Road, can also obstruct flow. In these circumstances, water finds a prefered pathway of least resistance around the obstruction, increasing velocities and therefore erosion.

Conversely, bare paddocks provide an ‘easy’ path for floodwaters compared with vegetated areas, which can make the former more susceptible to erosion.

- The South River Road levee may have also contributed to increased flooding in this area. The 2010 modelling predicted the levee would increase peak levels in the main Gascoyne River channel and Lewers Island area by almost 50 mm for the 1995 scenario.

The comparison between observed levels and model results is discussed further in Section 4.2.

4 Validation of flood modelling and mappings

This section compares the data and information collected from the February 2021 event to the levee design modelling (MRWA 2010).

The objective of the 2010 levee design was to improve flood protection within the plantation areas in Carnarvon. The modelling assessed three different-sized flood events:

- the February/March 1995 flood, a seven per cent (1 in 15) AEP event
- the March 2000 flood, a three per cent (1 in 30) AEP event
- a hypothetical scenario of a one per cent (1 in 100) AEP event.

The post-levee scenario and the existing landscape (as it was prior to the construction of the levees) were both modelled, for each of the three events.

The 2010 modelling used an earlier model which was calibrated to the observed flooding for the March 2000 event, and validated against the 1995 event observations (SKM 2002). SKM (2002) noted that although the calibration of the model was reasonable, some local areas are not well represented. For example, the model significantly underestimated flows near the Boundary Road and Robinson Street intersection. Finer scale details may need to be incorporated into the model to capture the local-scale processes occuring in this area (SKM 2002).

Additional modelling using more refined elevation data than in the current modelling (e.g. from Lidar or ground survey) would provide greater confidence in expected flooding for the localised areas where the current modelling does not adequately capture the observed flood behaviour.

4.1 Comparison between modelled scenarios with and without levees

We used the design modelling to compare the impact of the 2015 levees on flood behaviour. The modelling found that benefits of the levees are much greater for larger events (similar to the 2000 and 2010 floods or larger) than for events like the 1995 and February 2021 floods.

Modelling indicates that the 2015 levees will substantially reduce flooding broadly across the plantation area in a 1 in 100 AEP event. However, in an event like the 1995 flood, most plantations will experience similar flooding with, or without, the 2015 levees. Figure 28 shows the predicted change in peak flood levels due to the 2015 levees for the 1995 event. Flood levels were predicted to reduce in the blue and purple areas (negative numbers); increase in the green and orange areas (positive numbers); and change by less than 50 mm in the unshaded areas. Figure 29 shows the predicted change in peak flood levels due to the 2015 levees, for the 1 in 100

AEP event, with the same colour scheme. The significant increase in blue and purple shading show that the levees provide a broader reduction in flooding throughout the plantation areas.

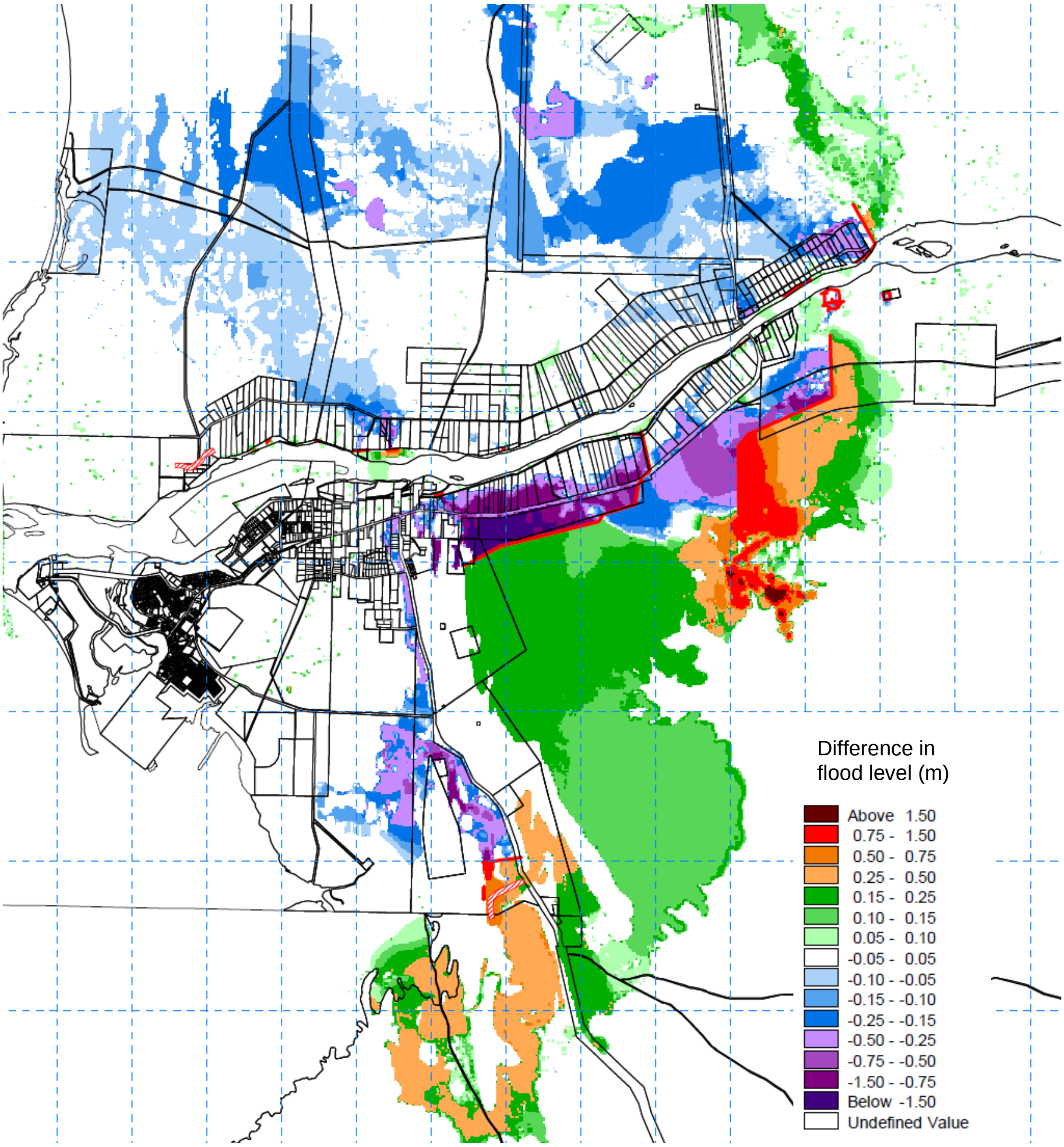


Figure 28 Modelled impact of levees constructed in 2015 on peak flood levels for the 1995 flood

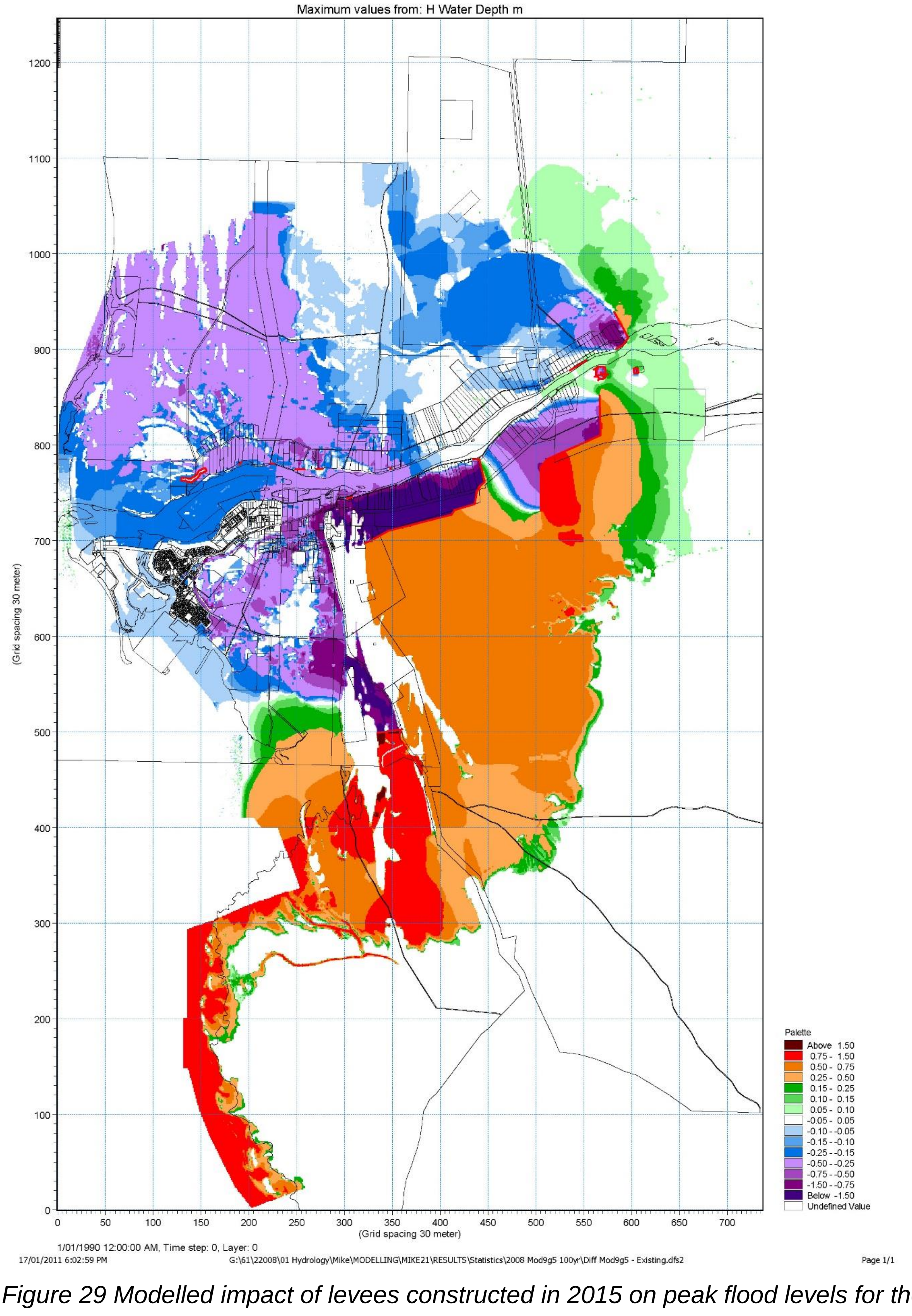


Figure 29 Modelled impact of levees constructed in 2015 on peak flood levels for the one per cent (1 in 100) AEP flood

4.2 Comparison of modelling to February 2021 event

Based on the rainfall and streamflow analysis, field data and anecdotal observations, the 1995 event is the closest modelled event (MRWA 2010) to the February 2021 event. Since the magnitude of the 2021 flood was similar to that in 1995, it was too small to assess the effectiveness of the levee system for the large events they were designed for (discussed above). However, it was still possible to compare the 2021 event to the modelled results.

Another way to compare the modelling with the 2021 event was by assessing the modelled flow information. We used modelled flow at a cross-section across the Gascoyne River, just upstream of the entrance to Burnt Gully, to compare with measured flows for the 2021 event. The estimated peak of the 2021 flow at the Nine Mile Bridge streamflow gauge is comparable with these modelled flows (Figure 30). This verifies that the 1995 modelling results are suitable for comparing with observations from the 2021 flood event.

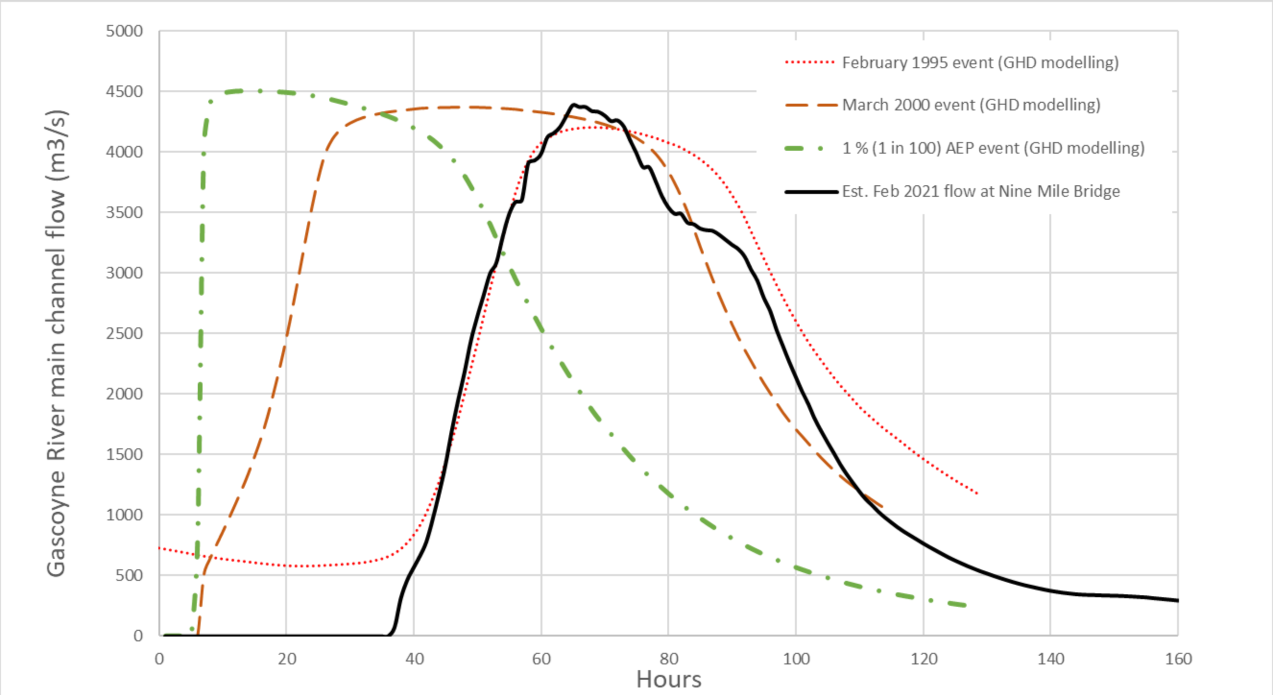


Figure 30 Comparison of recorded 2021# flow with modelled Gascoyne River main channel flows in a cross-section at Research Road

#The February 2021 discharge is the raw data at Nine Mile Bridge streamflow gauge and is yet to be verified.

Anecdotal evidence from residents on Lewers Island observed that the peak water levels were higher during the 2021 event than in 1995, and similar to the peak levels in 2009. However, there is only one surveyed flood level on Lewers Island from the 2009 event. Modelling predicted increased flood levels of about 50 mm for the 1995 scenarios in the Lewers Island area, as a result of the 2015 levees (MRWA 2010).

Further analysis of February 2021 flood levels would support a more rigourous comparison to the modelling in this area.

The comparison between observations and modelling for Burnt Gully and Boundary Road area (SKM 2002) found that the model also underpredicted the 1995 flood levels in this area. This is likely due to the model's representation of the river bank levels, drainage channels, hydraulic controls (such as roads) and the vegetation on Lewers Island. Additional survey (such as Lidar) of the river and plantation areas would enable further assessment of the existing modelling.

Modelling using this updated survey would help us better understand the potential contributions of the South River Road levee and the other local factors (vegetation, buildings, fencing, etc.) to the observed difference in flood levels between the 1995 and 2021 flood events.

Comparison between the 1995 event modelling and the 2021 information confirmed the predicted reduction in flooding on the plantations between South River Road and NWCH.

The observations from the 2021 event also confirmed that no flooding was observed in the areas behind two privately owned levees, within the red circles marked on Figure 31. MRWA (2010) carried out modelling with and without these private levees to account for their unknown structural integrity.

The combined impact of the State Government levee system and the largest of the private levees was modelled for the 1 in 100 AEP event (MRWA 2010). This private levee is located just upstream of the entrance to Burnt Gully (marked as red line on northern riverbank in Figure 31). In the modelling, adding the private levee to the model raised flood levels by ~50 mm within the river and the eastern portion of Lewers Island and Kingsford, compared with the scenario showing only the government levees (Figure 32). Despite this slight increase, the modelling demonstrated one per cent (1 in 100) AEP flood levels in these areas were 0.25 to 0.75 metres lower than the AEP levels without the levees, and lower than those experienced in 2010.

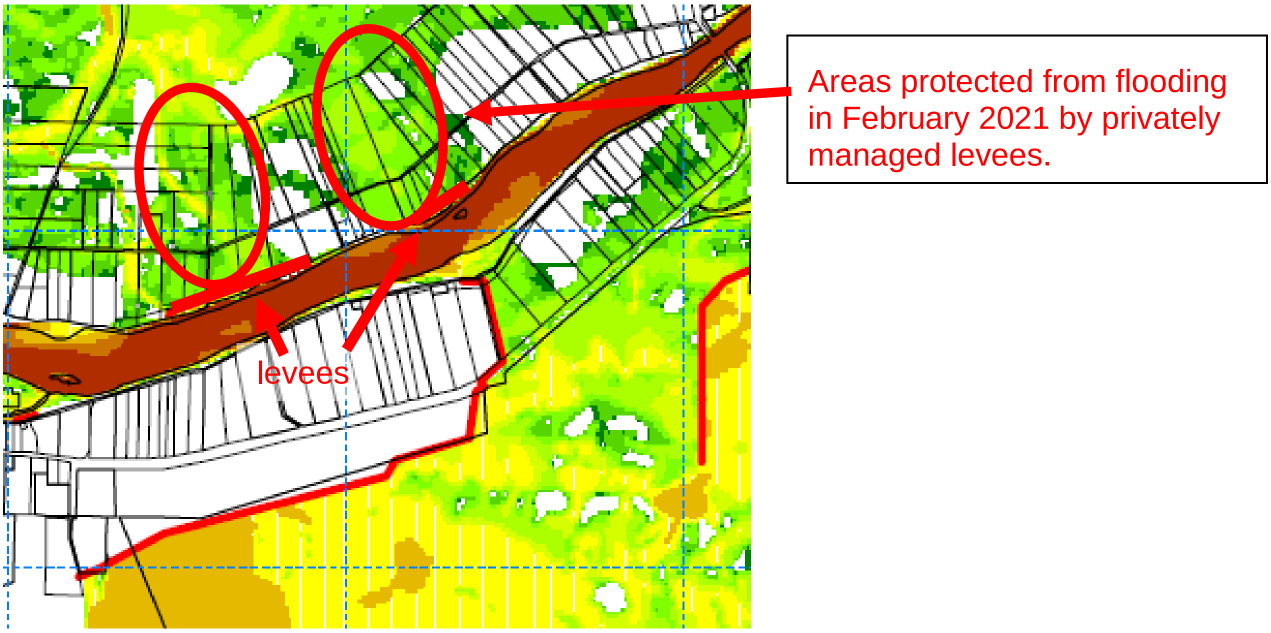
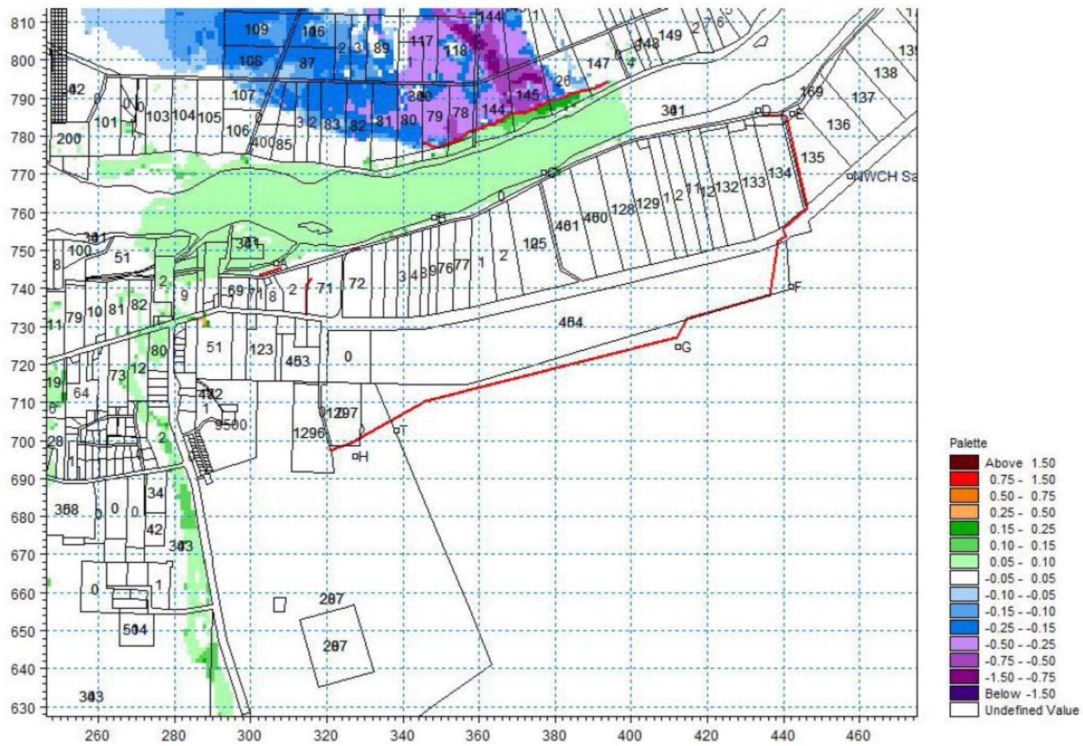


Figure 31 Location of private levees on the north riverbank between Bibawarra Crossing and Nine Mile Bridge providing flood protection to plantations on North River Road



With the private levee incorporated within the hydraulic model, water levels adjacent to SRR are estimated to rise approximately 50 mm compared to modelling without the northern private levee.

Figure 32 Modelled impact of the private levee on one in 100 AEP flood levels compared to the scenario with only State Government-managed levees

5 Review of existing flood mitigation measures

This section looks at existing flood mitigation measures and highlights a range of potential other measures that might improve flood mitigation in the future. The intention is not to provide an exhaustive list of future mitigation measures, nor is it to provide a detailed analysis of the relative values of these measures to mitigate future flooding impacts in Carnarvon; these actions remain the subject of future work. The Department of Water and Environmental Regulation stands ready to provide input into such work, as appropriate.

Previous studies discuss existing flood mitigation measures and recommend additional options to further reduce flood risk (PWD 1974; Sinclair Knight & Partners 1981; Water and Rivers Commission 1999; SKM 2002).

Flood mitigation measures can be non-structural or structural. Non-structural measures include flood forecasting and warning, land use planning, education and awareness programs, and effective land management activities. Structural measures include levees, diversions, river channel enlargements, and detention basins.

There are several state and local agencies which have various responsibilities for flood mitigation measures. The roles and responsibilities of the key organisations are summarised in Table 3.

Table 3 Roles and responsibilities for flood mitigation measures in Carnarvon

Organisation	Role and responsibilities
BoM	• Prepare and issue flood watches and warnings. • Operate rainfall monitoring sites to help flood forecasting.
DWER	• Assist with preparing floodplain mapping. • Provide advice on land use planning measures to reduce potential flood risk and damage. • Support and assist implementation of flood mitigation measures which reduce the risk of flooding. • Collect, analyse and store flood data. • Support community flood risk awareness and education. • Operate streamflow and rainfall monitoring sites that can assist flood forecasting.
Department of Planning, Lands and Heritage/ Western Australian Planning Commission	• Develop, review and implement the land use planning system, planning policies. • Review local government town planning schemes. • Manage and maintain flood mitigation infrastructure.

Department of Fire and Emergency Services	• Lead hazard management for flooding. • Develop and maintain response and risk treatment plans for floods (flood emergency management plans). • Support community flood risk awareness and education. • Recommend adopting risk treatment strategies to state, regional and local emergency management committees. • Help disseminate flood watch and warning information and flood advice to the community. • Assist in recovery process.
DPIRD	• Provide guidance and advice on horticultural practice to reduce erosion and damages. • Provide guidance and advice to individual property management plans. • Support community recovery process.
Shire of Carnarvon	• Incorporate floodplain management into town planning scheme and control development and works on the floodplain. • Manage and maintain local flood mitigation and drainage infrastructure. • Help develop and implement flood emergency management plans. • Support community flood risk awareness and education. • Lead the community recovery process.
Landowners and community groups	• Be aware of local flood hazards and emergency management plans. • Be responsible for personal safety and property during a flood. • Adhere to local land use planning policy and farm management guidance.

5.1 Flood forecasting and warning

BoM uses the network of streamflow and rainfall gauges (Section 2, Figure 3) to forecast flooding at our streamflow gauges at Jimba, Fishy Pool and Nine Mile Bridge (BoM 2020). BoM uses these forecasts to provide flood watches and warnings for the Gascoyne River catchment.

After the 2021 flood event, the community questioned whether the coverage of the rainfall and streamflow gauge network, particularly in the upper Gascoyne area, is adequate to provide sufficient time to take appropriate actions to reduce flood risk and damages during flood events.

There was also significant community concern about information provided for the Nine Mile Bridge streamflow gauge. Specific queries related to:

1. the inconsistency of the quoted peak water levels for the 2021 flood event
2. the differences in observed flooding compared with previous events of similar flood levels.

Section 2.4 outlines the complexities in interpreting water levels between events at this gauge. The community concern, in part, reflects the challenges government authorities have in communicating the intricacies of the data and modelling. In contrast, the staff gauge (Figure 33) and community members' lived experience of multiple events provide simpler and more tangible observations.

Developing consistent communication about peak flood levels to enable comparison between events is important to help emergency personnel and the community to take appropriate actions to reduce the risks and impacts of flooding. Future work on the appropriateness and mechanisms for this communication could provide greater clarity around these matters.

Figure 33 Staff gauge installed downstream of the Nine Mile Bridge

As discussed in Section 2.4, using river depth for reporting makes comparing recorded levels between events complicated. It means that the department's and BoM's reported levels from the Nine Mile Bridge streamflow gauge, which have been corrected/adjusted to account for changes in the riverbed and impacts of the old bridge, cannot be compared to the levels marked on the staff gauge.

The department has previously published information which relates observations of the impacts from past flood events to water levels at the Nine Mile Bridge (DWER 2016). Many of these observations are for events in 1980, 1995, 1999 and 2000 and before the replacement of Nine Mile Bridge. We have therefore updated the relationship between river levels at the Nine Mile Bridge streamflow gauge and flood impacts upstream of the bridge (Table 4).

Table 4 Preliminary update of relationship between Nine Mile Bridge water levels and flood impacts

River level			**Flood effects**
Existing[1]	**Updated[2]**	**Updated**	
(m)	(m)	(m AHD)	
7.0 to 7.6	6.6 to 7.2	14.4 to 15.0	Properties along South River Road (outside of levee) flooded.
6.9	6.5	14.2	Water severs NWCH at Geraldton turnoff. The old Nine Mile Bridge would have been overtopped.
6.7	6.3	14.0	All breakouts flowing.
6.5	6.1	13.8	Gascoyne Junction Road is closed due to flow of Coburn Creek.
6.0	5.8	13.5	Overflow to McGlades Road area.
5.0 to 5.5	4.8 to 5.3	12.5 to 13.0	Sheridans Gully starts to flow and North River Road overtopped (~1km west of Bibbawarra Rd).
4.5	4.5	12.2	Grahams Gully and Fahls Gully start to flow.
3.5 to 4.0	3.5-4.0	11.2 to 11.7	Lewers Island cut off.
2.8	2.8 m	10.5	Water flowing in Lewers Creek.
2.3	2.3 m	10	Low-level crossing at Bibbawarra Road crossing becomes unpassable.

1. existing levels based on observations when the old Nine Mile Bridge was in place
2. updated river levels use the same datum as the previous documented flood effects table

We have updated the information, based on earlier design work for the replacement bridge (MRWA 1999), to correct river levels. We have also converted the levels to AHD to account for the riverbed changes.

The estimated equivalent water level at the Nine Mile Bridge staff gauge for the 2021 event, assuming the old bridge was in place, is seven metres. This is comparable to the level for the 1995 event (about 7.1 m).

5.2 Land use planning

The Shire of Carnarvon is responsible for ensuring land use and development is suitable for the level of flood risk. All new developments require an appropriate level of flood protection. Best practice has new buildings (and contents) raised above flood levels to protect them and their occupants from flood damage. New developments should not increase the risks of flooding and flood damage to existing properties.

Observations from 2021, and the larger 2010 event, illustrate that flood damages were reduced by raising new developments above flood levels. No new dwellings were flooded above floor level when constructed to meet our minimum habitable floor level advice. However, some older buildings were impacted in the recent 2021 event and there was significant flood damage to older properties in 2010.

Fencing and fill should also be considered as ‘new development’ as these can obstruct major flows and contribute to higher localised flood levels. The shire’s town planning scheme provides a mechanism for achieving these outcomes. The scheme could be reviewed to verify its effectiveness in reducing flood risk to and from new developments, and ensure that it remains consistent with latest guidance on flood risk management.

The department currently provides floodplain development advice for proposals located within the floodplain when referred by the Shire.

5.3 Land management

Managing the relief drainage channels that convey floodwaters away from the river can lessen flood impacts. Appropriately spaced trees and full ground cover vegetation will stabilise soils while not impeding flood flows. However, dense shrubby vegetation (both natural and introduced weeds) and debris can ‘choke up’ gullies that are not under cropping, reducing their capacity to drain floodwaters away from the river. Some channels are also impacted by horticultural practices, such as filling and high-density cropping (e.g. bananas). These practices can obstruct flow and increase inundation, velocity and erosion in adjacent areas.

Appropriate land management in drainage channels downstream of Bibbawarra Road is critical to any attempts to reduce erosion and flood damage to the channels and adjacent plantation areas. Past studies (WRC 1999, SKM 2002 and Parr 2003) recognised the importance of managing drainage channels to reduce the impact of floods, particularly the smaller more frequent events like that in early 2021. Parr

(2003) provides guidance on appropriate management and horticultural practices to manage the soil erosion risk in these areas.

While much of the emphasis of previous reports and comments from the residents have focused on the management of drainage channels, maintaining vegetated ground cover and avoiding creating obstructions to flow are equally important for the entire floodplain.

Observations following the 2021 flood suggest that further actions could improve the management of drainage channels and the broader floodplain to reduce damage from flooding. Filling of drainage channels and other flow paths, fencing, cropping type and other horticultural practices have diverted or channelised flow and were significant contributors to some of the observed damage.

The Shire of Carnarvon’s local laws and town planning scheme, together with soil conservation notices, are existing mechanisms which could be appropriate for managing drainage channels. However, future detailed consideration of legislation, policy, governance arrangements, funding opportunities and options for restricting horticultural use in these areas may improve flood mitigation outcomes.

5.4 Education and awareness

Public awareness and education are important elements which support flood warning and emergency planning and can influence land management practices within the horticultural area.

Previous public awareness and education campaigns have been undertaken in Carnarvon. However, apart from BoM’s pre-cyclone season presentations each year, there is no ongoing program to inform the community about flooding and appropriate actions they can take to mitigate their individual risks.

The Department of Fire and Emergency Services (DFES) publishes fact sheets and guidance documents on their website to help residents prepare for and respond to cyclones and floods. Our Mid West Gascoyne regional office provides public information on expected local effects along the river for a range of gauged river levels at the Nine Mile Bridge gauge.

DPIRD has prepared guidance on farm management measures which can reduce the risk of erosion and damage on plantations in the Carnarvon horticultural district (Department of Agriculture 2003). The report describes the factors contributing to soil erosion and provides guidelines for soil management to help farmers, local government planners and government with the responsibility for resource protection and conservation.

5.5 Structural measures

A timeline of major flooding in the Gascoyne River and the flood mitigation works to protect Carnarvon is included in Appendix A.

The government-owned levee systems have evolved over the last 60 years. These levees are designed to protect the Carnarvon townsite and mitigate flooding to the horticultural area. A ‘fusible levee’ at the entrance to Sheridan’s Gully East provides a level of protection against relatively small (smaller than that in early 2021) flood events. The risk with this form of levee is that, if not managed appropriately, a rapid failure can send a high velocity flood wave down the gully. Mitigation of any unintended consequences of this fusible levee could be the subject of future work examining flood mitigation options.

Further, several privately owned ‘permanent’ levees have been constructed by landowners on both banks of the river to protect land and property from flooding during major flows. The construction material and current condition of the private levees are unknown. Consequently, we recommend that reliance is not placed on these levees to provide flood protection when planning land use.

Solid permanent fencing and temporary bunds have also been constructed to protect buildings and other infrastructure. The impacts of these have not been assessed but they may have localised impacts on flood levels and velocities experienced on neighbouring properties.

5.6 Additional options for floodplain management

Our assessment as well as limited discussion with the community have highlighted two main areas which could benefit from additional flood protection:

- the Kingsford area, between Bibbawarra Road and Boundary Road to the south of the river
- the Sheridan Gully area and other breakouts on the northern riverbank, west of Bibbawarra crossing.

These areas are consistent with most of the impacts identified in DPIRD’s assessment of soil and productivity loss.

The existing non-structural measures (land use planning, flood warning, land management and education and awareness) are critical to future flood risk management in these areas. The observations following the 2021 flood and the discussion above (in sections 5.1 to 5.4) highlight areas for future ongoing improvement in flood mitigation measures. In addition to these existing measures, previous studies have identified several measures that could provide further flood protection. These are summarised and a preliminary evaluation is provided below.

Land purchase/exchange

Removing land with a high flood risk from horticultural use and managing it to reduce potential flood damage to neighbouring properties could reduce flood damage without significant engineering effort. This could involve purchasing the land at market cost, or exchanging the land for property suitable for horticultural production with a lower flood risk.

To be acceptable to the community affected property owners must be supportive of such a scheme and participate voluntarily.

River channel enlargement

The sandy riverbed is mobile and the changes to river morphology are not well documented. Local anecdotal information shows that river sand builds up in the river channel, which is expected of river delta dynamics (SKM 2002). SKM (2002) considered an option to dredge the river channel to increase the waterway area of the river and lower flood levels. Such a measure could impact social and heritage values attached to the river channel and would be costly as it involves significant excavation (and disposal) of sand. An ongoing program to maintain the channel would be required, as redistribution of sand in the river channel would take place after each flow event.

River diversions

Another possible option for reducing flooding in the Carnarvon horticultural area is diverting floodwaters away from the river upstream of Nine Mile Bridge (Figure 34). Options to divert additional floodwaters south by enhancing existing breakouts at Coburn Creek, Nyrinde and Boodalia Creek were discussed in SKM (2002). The options require significant excavation to divert enough flow from the river to have appreciable difference on flooding in the plantation areas. The cost and potential environmental disturbance are likely to be high. This option could increase floodwaters over the NWCH, increasing inundation periods and potential flood damage, and closing roads between Perth and Carnarvon for longer. Additional upgrade works could mitigate these impacts.

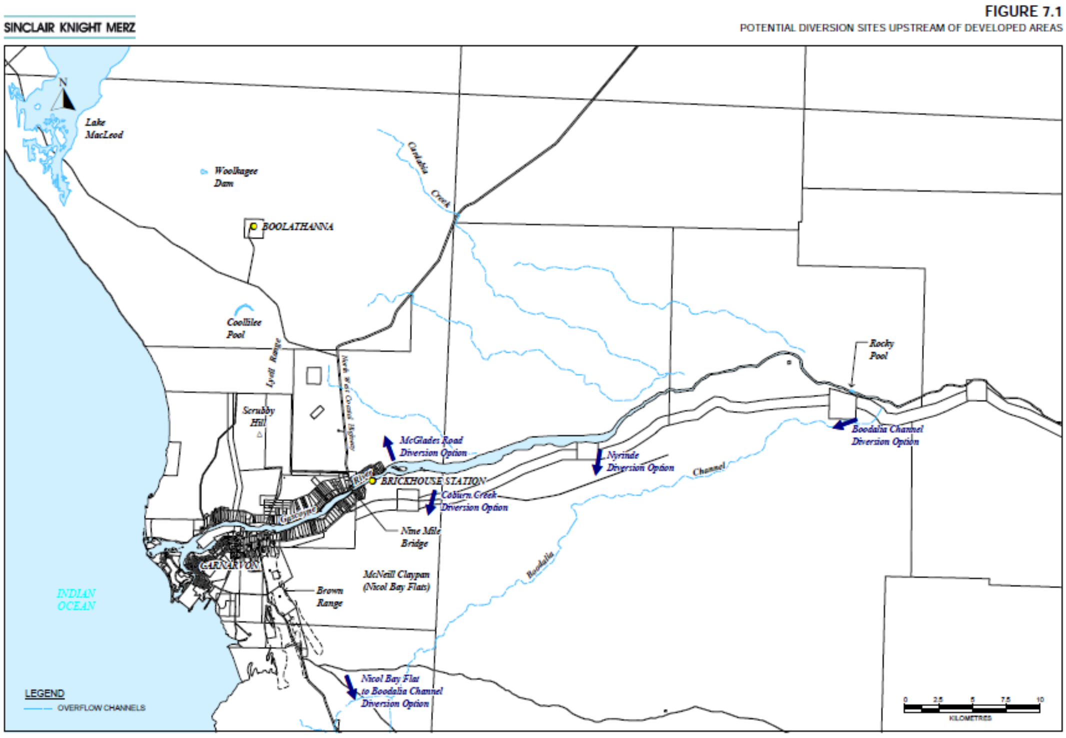


Figure 34 Possible flood diversion options upstream of Carnarvon (from SKM 2002)

Levees

MRWA (2010) investigated potential options for improving the flood mitigation provided at Sheridan Gully East and other current breakouts at Burnt Gully, Lyall's Gully and Fahls Gully. One idea was to construct works of up to one metre high in the entrance to these gullies.

The study used anecdotal information which suggested the proposed levee at Lyall's Gully may have been able to stop flows down the gully for eight of the 16 significant flood events over the past 50 years. Based on the same assumptions adopted in this study, a levee at the entrance to the Lyall's Gully may have been able to prevent breakout flows in three of the six largest flood events observed in the 11 years since the 2010 study.

If mitigation options are considered further at these locations to provide some level of flood protection in relatively minor events (i.e. up to 5–5.5 metre river levels at Nine Mile Bridge, or about 1.5 metres lower than the February 2021), then either a 'deliberately fusible' or 'gully fill' form of 'non-permanent' levee is recommended (MRWA 2010). Indicative designs for these types of levees are provided in MRWA 2010. Such levees would still be overtopped, and flooding experienced, in large events like that early in 2021.

The MRWA 2010 study concluded that the relatively minor benefit gained by construction of these levees would be outweighed by the financial liabilities their ongoing maintenance/reconstruction would require. However, a review of this decision could be incorporated into considerations of a committee formed to investigate the management of the drainage channels (Section 5.3).

One resident suggested constructing a levee by raising Margaret Row to join the South River Road levee to prevent floodwaters entering the Kingsford area. This proposal requires further investigation to ensure that it would not result in increased flooding on the northern floodplain areas, including overtopping the existing private levee near the entrance to Burnt Gully.

6 Conclusion and recommendations

The February 2021 flood event was similar to that in 1995, and smaller than the 2000 and 2010 floods. It was about a 1 in 10 (10%) AEP event.

Our assessment shows that modelling used to design the 2015 levees adequately represents observed flood behaviour at a regional scale, but some differences were observed in localised areas.

This study confirms that the levees successfully diverted floodwaters away from plantations between South River Road and the NWCH, which previously would have flooded in an event of this size. Flooding at Nine Mile Bridge (and upstream) was reduced because it was replaced with one having a higher and slightly wider structure in 2002. Water levels recorded at our gauge at Nine Mile Bride are also lower than for the same flow for events prior to 2002 because the of the new bridge.

Flood levels in an area between Burnt Gully and Boundary Road were slightly higher than during the 1995 event. While modelling predicted that the construction of the South River Road levee could contribute to a small (< 50 mm) increase in flood levels in this area, the levee alone is unlikely to be responsible for the increased water levels, or damage observed. Local factors including fencing, wind breaks, filling and/or vegetation of drainage lines, and horticultural practices (such as dense cropping in flow paths/floodplain and the location of bare paddocks) also affect local flood levels and velocities.

The 2015 levees were designed based on modelling to mitigate damage from events larger than that of early 2021 (such as March 2000 and December 2010). We could not fully assess the levee performance against the design for events akin to this year’s magnitude.

To better understand the contribution of the levee and other local factors to the difference between the 2021 flooding and the flood levels observed in 1995, a detailed survey of the river and floodplain (plantation areas) and additional peak water level survey in the Lewers Island and northern breakout channel are proposed for future work. These surveys would support future flood modelling and land management activities.

Recent actions

Community concerns discussed with the department during this assessment have been raised at the June 2021 Flood Warning Consultative Committee meeting. As a result of this, the department is currently working across government to examine issues around the communication of water level information provided during (and after) the event, and the adequacy of the existing streamflow and rainfall gauging station network. A committee is also currently being formed to consider land management arrangements of the drainage channels within the plantation area.

Future Work

As outlined above, this report examined existing flood mitigation measures and highlighted a range of potential other measures that might improve flood mitigation in the future. The intention is not to provide an exhaustive list of future mitigation measures, nor is it to provide a detailed analysis of the relative values of these measures to mitigate future flooding impacts in Carnarvon; these actions remain the subject of future work. The department stands ready to provide input into such work, as appropriate.

Appendices

Appendix A — Major flooding history in the Gascoyne River and mitigation works to protect Carnarvon

1960 Major flooding in Gascoyne River (1 in 60 AEP flow).

Carnarvon flooded.

1961 Major flooding in Gascoyne River (1 in 60 AEP flow).

Carnarvon flooded; Morgantown single levee built.

1967 Morgantown levee duplicated.

1970 Cyclone Ingrid causes extensive tidal storm surge flooding in Carnarvon.

1972 Scale model of Gascoyne River floodplain used to simulate flooding and assess various flood mitigation options. Concept of fusible levees across breakouts developed and constructed.

1975 Dual levee system proposed for East Carnarvon.

1976 Plateau levee concept proposed for East Carnarvon as a cheaper and more acceptable alternative to dual levee system.

1980 June: major flooding in Gascoyne River (1 in 25 AEP flow). Extensive flood damage to property and plantation areas.

September: consultant Sinclair Knight & Partners commissioned to develop a floodplain management strategy for Carnarvon.

1981 Sinclair Knight's report *Gascoyne floodplain management strategy* completed and endorsed.

1982 Sinclair Knight completes detailed working drawings.

1984 The Shire of Carnarvon's new council reconfirmed endorsement of the proposed flood mitigation strategy (i.e. East Carnarvon and Boundary Road levees, South Arm closure and Brown Range Spur levee).

1987 Sinclair Knight & Partners Gascoyne River flood mitigation project: Brown Range Spur Levee review.

1988 Construction of East Carnarvon levee and South Arm closure completed.

1990 Construction of Boundary Road levee.

1995 March: major flooding in Gascoyne River (1 in 15 AEP flow).

2000 March: major flooding in Gascoyne River (1 in 30 AEP flow).

2002 October: Sinclair Knight Merz's report *Lower Gascoyne River – Carnarvon floodplain management study* completed. Concept design of flood mitigation works produced to minimise flood damages in horticultural district.

2007 Completion of Stage 1 of the Carnarvon flood mitigation project including the upgrade of two major floodways on the North West Coastal Highway just south of Brown Range.

2010 December: major flooding in Gascoyne River (1 in 80 AEP flow). Town of Carnarvon was not impacted by flooding due to the existing town levee system, but the horticultural district was badly affected, with at least $90M flood damages.

2015 Completion of Stage 2 of the Carnarvon flood mitigation project, which involved the construction of four major levees totalling 16 kilometres in length and ranging in height from one to six metres.

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