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Complications of multi-channel hydraulic modelling

A case study: the proposed upgrading of bridges across the Orange River near Keimoes by SANRAL

BACKGROUND

SANRAL (South African National Road Agency Limited) awarded a tender to BKS (Pty) Ltd for the design and implementation of the widening of the R27 bridges crossing the Orange and Sout Rivers (near Keimoes, as shown in Figure 1). Prof Fanie van Vuuren and Marco van Dijk from the University of Pretoria were commissioned to undertake a detailed hydrological and hydraulic assessment of the Orange River at the sites where the bridges near Keimoes had to be improved. The project involved the widening and possible raising of four single-lane structures near Keimoes to handle a design flood based on a specific recurrence interval.

The Orange River is South Africa's largest river and, through various transfer schemes, is used for irrigation, and domestic and industrial needs along the river and in adjacent catchments. The impoundments also contribute to hydropower generation and create the ability to manage the flood attenuation requirements by controlled releases.

The stretch of the Orange River in the vicinity of the town of Keimoes in the Northern Cape Province can be described as an extensive braided river channel. Kanoneiland, the largest island system in the Orange River, is located roughly 20 km upstream of Keimoes, and the Neusberg Weir is situated approximately 25 km downstream of Keimoes. Just downstream of Kanoneiland the main river channels divide into an even more heavily complex

Table 1 Characteristics of the gauging stations up- and downstream of Keimoes

Hydro no	Place	Effective catchment area* (km²)	Period of usable data
D7H002	Bridge at Prieska	274 396 (336 348)	1971-07 to present
D7R001	Boegoeberg Dam	279 088 (341 693)	No DT
D7H008	Weir just downstream of Boegoeberg Dam	279 090 (341 695)	1932-10 to present
D7H005	River section (Upington)	288 776 (363 031)	1974-07 to present (low flow DTs for 1942-10 to 1974-07)
D7H014	Neusberg 'weir'	293 126 (367 381)	1993-07 to present
D7H003	Bridge at Kakamas	293 406 (367 661)	1965-10 to present

Note: * The total catchment area is given in brackets as obtained from WRSM2005 and braided river reach. Upstream of the R27 road crossing, the Orange River is less braided, creating four main river channels. Dense bank vegetation (trees and reed beds) protect and stabilise the banks during flood events. At Neusberg the Orange River drains a total catchment area of nearly 370 000 km², i.e. nearly 30% of the total surface area of South Africa.

The creation of various storage facilities in the Orange and Vaal River Systems (Gariep, Van der Kloof, Vaal, Katse, Bloemhof, Mohale, Grootdraai, Kalkfontein, Erfenis, Allemanskraal and Sterkfontein Dams) has changed the flood characteristics at the project site. The historical flow records at Neusberg (D7H014), Kakamas (D7H003), Boegoeberg Dam (D7H008) and Upington (H7H005) were reviewed and relationships were established to correlate the flow at the different gauging stations, and to obtain a flow record for the sites at Keimoes.

ASSESSMENT OF THE HISTORICAL FLOOD DATA

The hydrological review required a quantification of the probability of inundation and determining of the flood peaks for the design recurrence intervals.

It is common knowledge that the confidence of flood frequency is influenced by the length of the reliable data record and hence 'as long as possible' flow records are needed to improve the reliability of any flood prediction. In the Orange River downstream of the Vaal river confluence a number of flow gauging stations exist. Table 1 indicates some characteristics of the gauging stations.

The low incremental flow contribution between selected consecutive gauging stations in the Orange River, as well as the flow magnitude and time-based flow variation in the Orange River, facilitate the inter-changeability of the flow data of such gauging stations. Neusberg Weir (D7H014) and Kakamas Bridge (D7H003) just downstream of Neusberg, are two such gauging stations. It can therefore be assumed with a high degree of confidence that the flood peak record of the one can be used for the other, because the flow records are for practical purposes similar (Van der Spuy 2008).

Review of the discharge rating curves to be used in the assessment of the flow at the Keimoes bridges

The various flow records for the different gauging stations, as listed in Table 1, were compared and correlations obtained to enable the compiling of a representative flood record at Upington and Kakamas Bridge. The procedure for this process was to use correlations between gauging stations, filling in gaps in the data sets and overall improvement of the discharge tables at the stations in this river section to compile annual flood peak records.

1 Location of bridges
2 Natural river cross section used as gauging section (Upington, D7H005)
3 Visual depiction of flood frequency distributions at Upington (D7H005)

Table 2 Proposed design floods based on data from D7H005 (Upington)

RI (years)	1:2	1:5	1:10	1:20	1:50	1:100	1:200
Q (m3/s)	1437	2994	4212	5508	7369	8899	10542

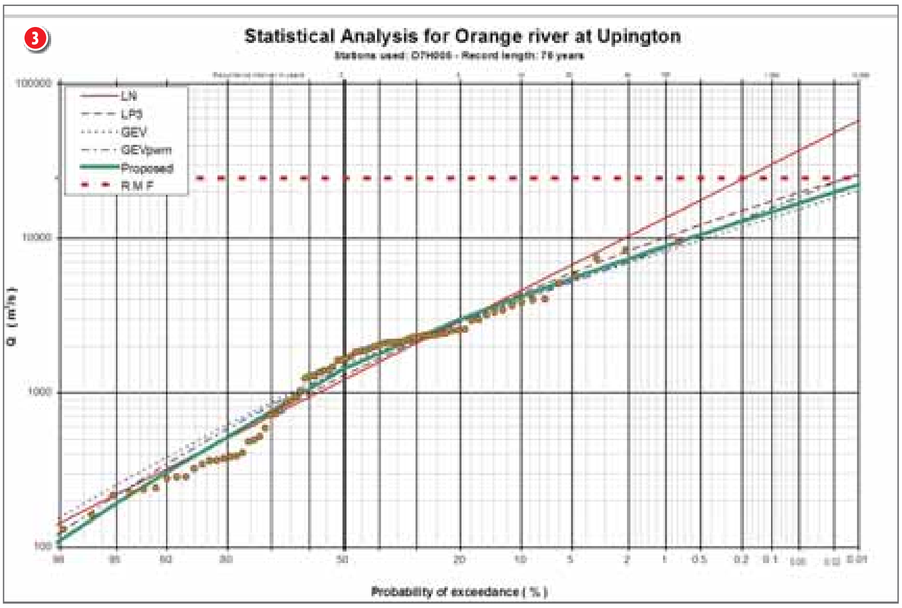


Figure 2 provides a pictorial view of the natural section at Upington (D7H005), which is used as the gauging section.

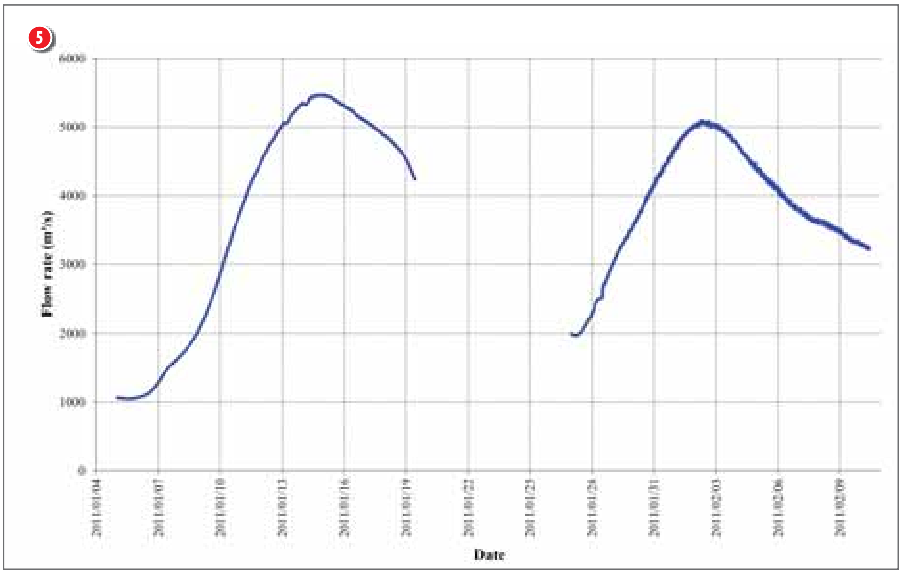
Flood frequency analyses

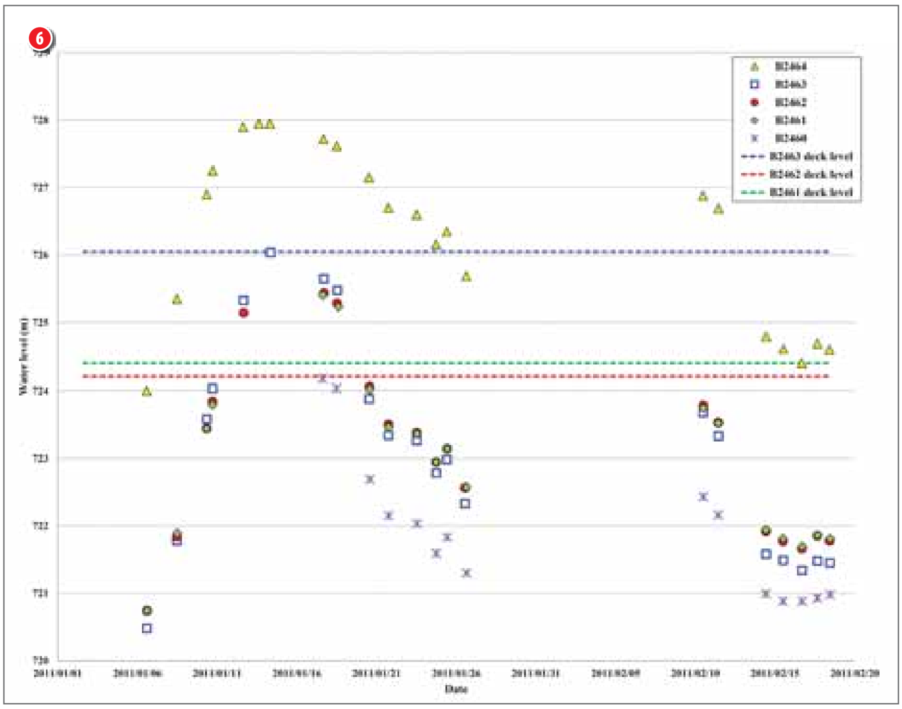
Table 2 reflects the proposed design floods based on the flood frequency distribution functions for the data at Upington (D7H005). Figure 3 reflects the statistical flood peak assessment for the data at Upington (D7H005).

4 Position of measuring plates

5 Flow hydrograph January and Feburary 2011 (D7H005)

6 Water levels at bridges during the January and February 2011 floods





Flood management by DWA in the Orange–Vaal River System

Real time recordings of rainfall and runoff provide valuable input into the effective operations of the dams to reduce the flood peaks. Vaal Dam, with multiple crest gates, provides for flood management, while the Gariep and Van der Kloof Dams in the Orange River have uncontrolled spillway sections. The Regional Offices of the DWA (Department of Water Affairs) are responsible for the management of local floods in their administrative regions, while the Directorate Hydrological Services of the Department's Head Office is responsible for flood management in the Vaal and Orange River System. The emphasis is on the optimisation of yield from the dams and minimising the flood peaks.

In the lower Orange River there is enough time between the storm event and the arrival of the flood for early flood warning, which is also of importance during the construction phase of the project.

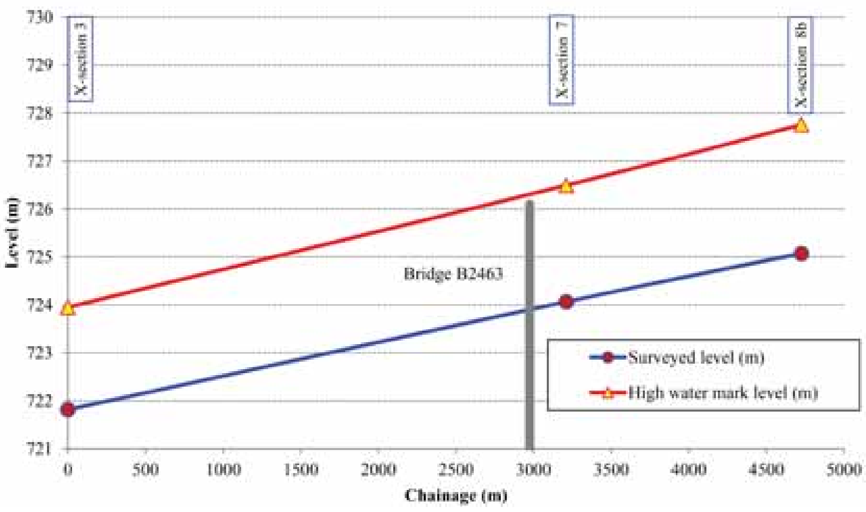
REVIEW OF THE STAGE–DISCHARGE RELATIONSHIP NEAR KEIMOES

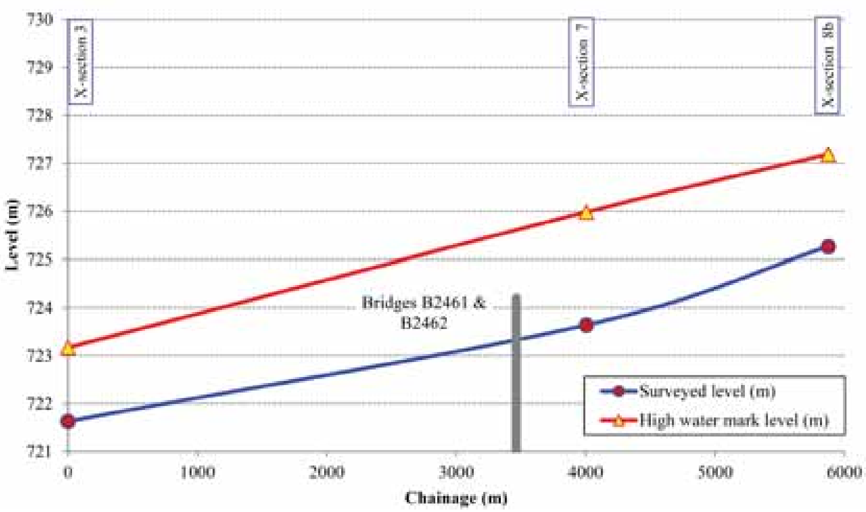
Flow measurement

Low flow gauging was performed (± 21 to 70 m^3/s) at two gauging sites in the main stream (northern stream) and in the southern stream. A 1,5 MHz Sontek Acoustic Doppler Profiler was used to perform the velocity measurements along a suspension tagline across the canals. The flow measurements indicated that the flow distribution between the main and southern channel is an approximately 75:25 split.

Stage flow gauging

Seven measuring plates were installed up and downstream of the bridges at Keimoes. The positions of these measuring plates are shown in Figure 4. Readings were taken twice weekly for four months (December 2008 until April 2009). The flow data from the Upington and Neusberg gauging stations were used, as well as the estimated travelling times to determine the flow rate associated with the recorded water levels at the gauge plates. The flow during this period varied between 44 and 1 026 m^3/s.





These water level recordings reflected the flow characteristics of the river system, indicating that for similar flow rates, the water levels obtained on the rising limb of the flood hydrograph, and the falling limb, were different. This confirmed the intuitive understanding of the variation of roughness in river sections overgrown with reed beds and thick bank vegetation. It was found that the water level in the southern channel is usually higher than the flow in the main stream by between 0,4 to 0,7 m for the low flows. The opposite, however, occurs during the higher flows that were measured where the main stream water level was between 0,8 and 1,0 m higher than the southern channel.

The recent floods of February 2010 and January/February 2011 resulted in some of the bridges at Keimoes being overtopped. This flood data was used to re-calibrate the numerical model for the following flood peaks:

- A peak discharge of 3 288 m^3/s on 8 February 2010
- A peak flood of 5 470 m^3/s on 14 January 2011 (Figure 5)
- A flood of 5 079 m^3/s on 2 February 2011

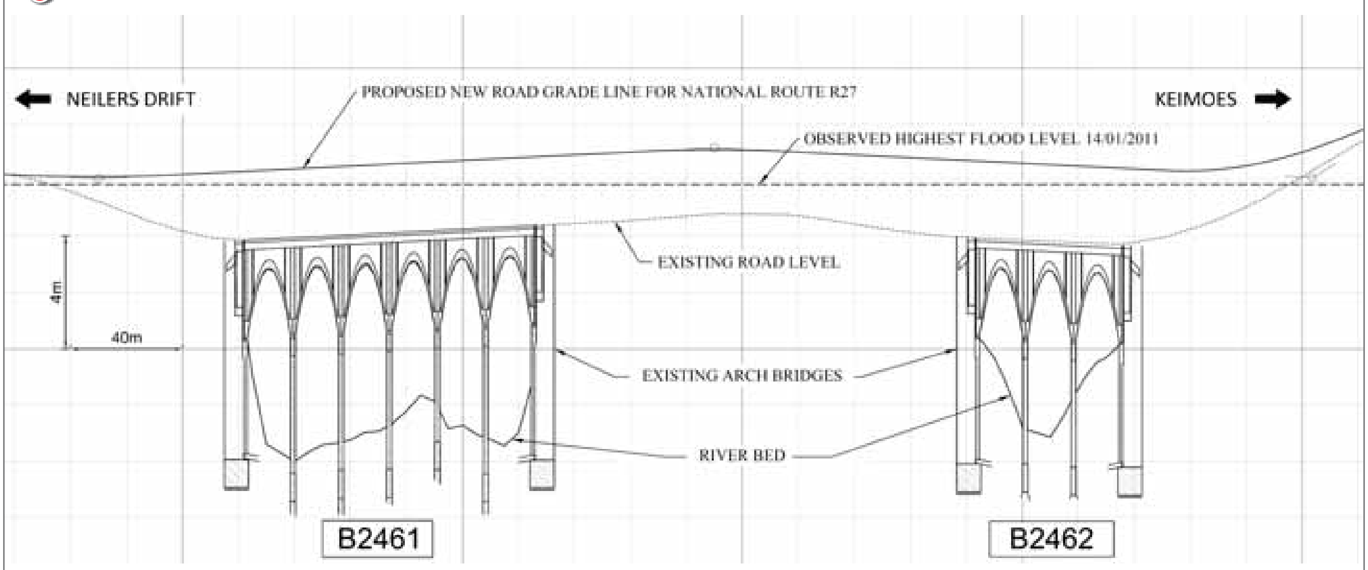
A visual recording was made, and the date, time and water levels were recorded at

7 Hydraulic gradeline of surveyed water level and high-water mark (main channel)

8 Hydraulic gradeline of surveyed water level and high-water mark (southern channels)

9 Schematic longitudinal section of bridges across the southern channel

10 Existing Bridge B2461 (southern channel)



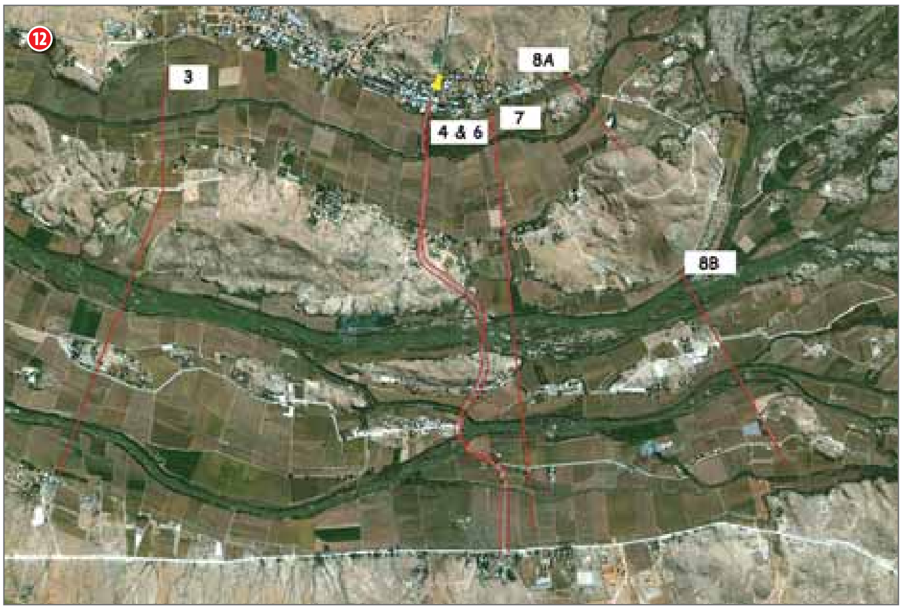
the bridges during the floods of January and February 2011, which overtopped the bridges across the southern and main channels (B2461, B2462 and B2463). Figure 6 illustrates the recorded water levels at the bridges during these high floods.

Surveyed hydraulic gradelines

A hydraulic gradeline was plotted based on the surveyed water levels up and downstream of the site. This was compared with the natural bed slope of the river. Graphical representations of the hydraulic gradelines representing the water surface level for a ± 5–6 km river section is shown in Figures 7 and 8 for the main channel and southern channels respectively. This is shown for the maximum observed flow of 5 470 m^3/s (high-water mark) and the water levels during the day of the survey (21 January 2011) when the flow was equal to 3 340 m^3/s.

BRIDGE STRUCTURES

The overall objective of the proposed construction project is to increase the capacity and improve the safety of



11 Existing Bridge B2463 (main channel)
12 Surveyed cross sections (at project site)

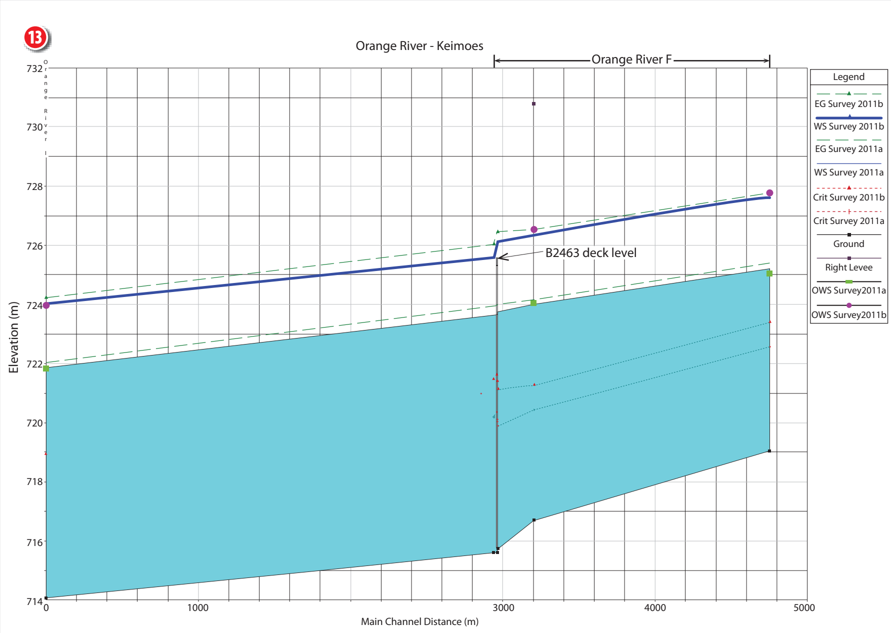
Sections 10 and 11 of the R27 National Route between Kenhardt and Keimoes in the Northern Cape, for the following main reasons:

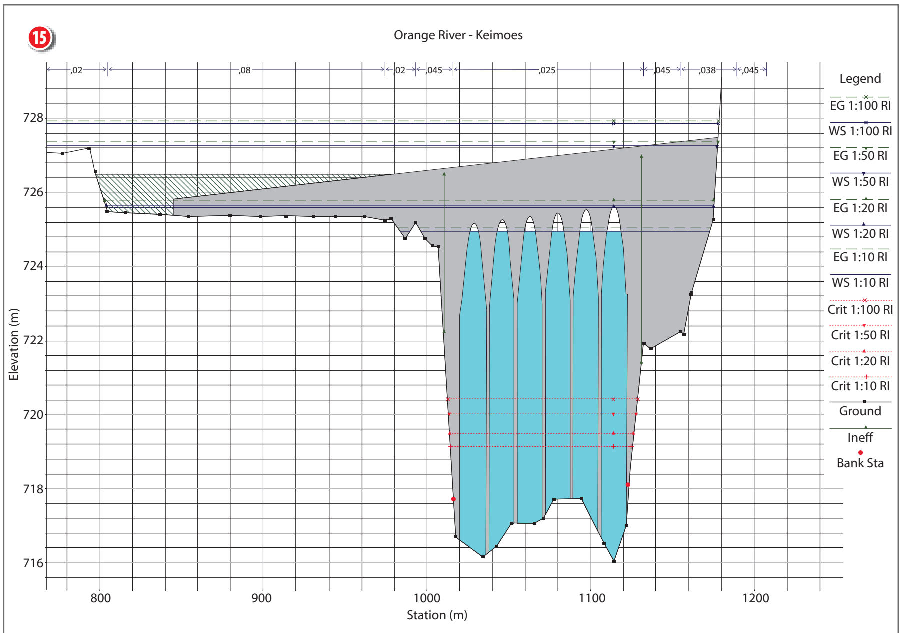
- To accommodate existing and future traffic volumes without the current delays, which are being caused by having to wait for approaching traffic at the four single-lane bridges across the Orange River and nearby tributary.
- To increase the flood capacity of two of the bridges to an acceptable level, thereby improving safety for the travelling public and reducing the time that landowners and communities are isolated during major flood events.
- To address safety concerns for cycle and pedestrian traffic.

Lifting the two southern bridges will not only provide a supply and escape route during flood events, but the widening of the bridges will streamline traffic across the bridges, particularly during the grape harvesting season when many heavy vehicles use these (currently single-lane) bridges. SANRAL undertook, in consultation with the local farming community, to widen the bridges to two lanes with road shoulders. Sidewalks will also be provided for the many pedestrians.

An in depth heritage study, which formed part of the Environmental Authorisation process, was performed on these structures. This study established that the three arch bridges collectively known as Grobler's Bridges were built between 1931 and 1933. The following is a brief summary of pertinent information provided in the comprehensive Basic Heritage Impact Assessment:

During the early 1920s farming activity in the area was well established and grapes, along with other fruit and vegetables, were produced in enormous quantities. While the river was the life





blood for these activities, it was also a huge economic impediment as there were no bridges across the river able to carry the large loads. The farmers relied on fording the river during low-flow conditions or using pontoons, but it did happen that for several months a year entire island communities were marooned due to floodwaters. The need for adequate bridges was pressing and, after petitioning the government over a number of years, a bank loan was eventually raised by the Divisional Council in 1931 to construct the bridges. A tender call was advertised in February 1932, and some 14 companies responded, of which the new Cape Town company, Murray & Stewart (Pty) Ltd, offered the most competitive bid. These were the years of the great depression and construction methods adopted were labour-intensive, using local materials as far as possible, to enhance employment opportunities in the local community. A huge flood that took place in 1925 largely informed the design, and it would appear that the design engineer was fully aware that the bridges would overtop and built them accordingly with light removable railings. The completed bridges have withstood the test of time, but improvements are now necessitated by vehicle and pedestrian capacity requirements, as well as by the limited flood capacity of Bridges B2461 and B2462.

The study concluded that the improvement of the bridges has distinct economic advantages, but that concerns exist with respect to retaining the heritage qualities. However, the following approach, adopted in the design of the improvements, was considered acceptable:

- Retain as much of the original fabric of the bridges as possible, which includes the widening of B2463, instead of demolishing it, which would be more economical. The other two bridges have to be replaced at a higher elevation, as noted above, to ensure acceptable flood capacity for crossing.

13 Recalibrated model results (Analysis D) – water surface levels in main channel – cross section 8b to 3 (Bridge B2463)

14 Overtopping of B2463 (14 January 2011, 5 470 m^3/s)

15 Cross sectional view of Bridge B2461 (southern canal)

- Ensure that the form of the original bridges is acknowledged by using a similar arch configuration and similar detailing.
- Provide a stopping area, with information boards describing the historical significance of the bridges, on the northern (Keimoes) side of B2463.

HYDRAULIC ANALYSES

The hydraulic modelling of a complex river stretch, consisting of a number of channels and subdivisions, has to be based on a good understanding of the hydraulic behaviour under different flow rates in the system. Detailed cross-sectional surveying at a number of positions (some shown in Figure 12) in the study area was also undertaken to allow for the setting up of a hydraulic model.

Calibration of roughness parameters

In order to calibrate the model the roughness parameters were varied along each cross section. The model roughness was adjusted to reflect similar water levels as those observed. A complication was that in the Orange River the roughness decreases with an increase in flow and depth, typical for large river systems. The modelling software allowed the changing of the roughness factor with change in flow, i.e. flow depth.

Numerical modelling

The public domain and internationally accepted software package HEC-RAS (version 4.1.0) developed by the US Army Corps of Engineers was used to hydraulically model the river system.

Six different analyses were conducted:

- *Analysis A* represents the hydraulic modelling of the system without and with the existing bridges at Keimoes.
- *Analysis B* represents the system after it had been calibrated (initially only based on flow measurements and a four-month flow gauging period in 2008/09).
- *Analysis C* represents the hydraulic modelling of the upgraded bridges crossing the southern streams, raising Bridge B2461 by ± 1,8 m and Bridge B2462 by ± 2,0 m.
- *Analysis D* was conducted containing the existing bridge structures, and the model was recalibrated using the additional 2010 and 2011 flood data, as well as hydraulic gradeline surveys performed in 2011.
- *Analysis E* utilised the recalibrated model constructed in *Analysis D* and investigated the impact of the upgrading of the bridges as originally planned in *Analysis C*.
- *Analysis F* utilised the recalibrated model constructed in *Analysis D* and investigated the impact of the upgrading of the bridges to a revised design level (raising Bridge B2461 by ± 2,3 m and Bridge B2462 by ± 2,5 m).

Figure 13 shows the modelled water levels compared to the surveyed water levels on 21 January 2011, as well as the high-water mark levels. The reference to *WS Survey 2011a* in Figure 13 refers to the modelled water levels for a flow of 3 340 m³/s for 21 January 2011, and *WS Survey 2011b* refers to the modelled water surface of the peak flood (5 470 m³/s). The reference to

A huge flood that took place in 1925 largely informed the design, and it would appear that the design engineer was fully aware that the bridges would overtop and built them accordingly with light removable railings. The completed bridges have withstood the test of time, but improvements are now necessitated by vehicle and pedestrian capacity requirements, as well as by the limited flood capacity of Bridges B2461 and B2462

Table 3 Summary of modelled water surface levels

Channel	Bridge	Water levels (m) upstream of bridges for different RI				
		1:5	1:10	1:20	1:50	1:100
Main*	B2463	723,44	724,67	726,09	727,18	727,95
Southern	Existing – B2461 & B2462	723,87	725,06	725,67	727,04	727,65
	Upgraded to current design proposal –B2461 & B2462	723,14	724,94	725,85	727,17	727,76
	Upgraded to current design proposal plus 0,5 m – B2461 & B2462	723,14	724,94	725,62	727,25	727,87

Note: * No change due to fixed flow distribution utilised in the model (± 25:75 for southern and main channels)

The proposed upgraded bridges across the southern canal, as per the current design proposal, which is to raise Bridge B2461 and Bridge B2462 by approximately 1,8 m and 2,0 m respectively, will provide sufficient hydraulic capacity to prevent overtopping of the structure for the 1:20 year flood. However, the lowest shoulder breakpoint level on the bridge is 725,4 m, whilst the highest is 725,9 m and thus, although not overtopping, the 1:20 year flood will inundate a section of the road. The raising of the bridges in the southern channel reduces the upstream water levels for the lesser recurrence interval floods. The raising of the bridges, as well as the bigger approaches, results in a small increase in damming levels upstream thereof for the 1:20 RI flows and higher floods

OWS Survey 2011a (green blocks) in Figure 13 indicates the observed water levels on 21 January 2011, which was surveyed, while *OWS Survey 2011b* (pink dots) refers to the observed water surface where the high-water mark level was surveyed. A similar analysis was conducted for the southern channel.

As can be seen in the model results (Figure 13), the main stream bridge is just overtopped, as depicted in Figure 14. The analyses indicated that the bridge arches create a large obstruction in the flow path, and consequently higher water levels upstream. A small increase in flow rate when at this level would result in a sharp change in flow depth and overtopping of the bridge structures. Hydraulically speaking these structures are not very efficient.

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In *Analysis F* above the two bridges across the southern channel were raised a further 0,5 m.

Comparing the results of *Analyses E* and *F* it was clear that the raising of the bridge by a further 0,5 m reduces the 1:20 year RI flood level upstream of the bridges, but results in slightly higher damming levels for the higher recurrence interval floods. The total impact of these two bridges on the 1:50 and 1:100 year RI water levels would result in an increase of the upstream water levels in the southern channel with respect to the current conditions of approximately 0,2 m. This is substantially less than the generally accepted norm of 0,6 m. The impact on the upstream water surface levels at the bridges is summarised in Table 3.

REMARKS / CONCLUSION

The hydrological and hydraulic analyses included the:

- Review of historical flow records to generate a flood frequency distribution at Keimoes (Table 3).
- The determination of the flood peaks in the Orange River which will overtop the existing bridges at Keimoes (± 3 150 m^3/s for B2461 and B2462, ± 5 350 m^3/s for B2463).
- Use of stage-discharge data, as well as a survey of the hydraulic gradeline of the river to calibrate the numerical model by varying the roughness parameters, for the flow ranges 40 to 5 500 m^3/s.
- Quantifying of the roughness parameter, which decreases with an increase in flow rate and depth in this part of the braided river section. It was also found that this river system's roughness and flow distribution between the different braided channels are sensitive to antecedent higher flows.

It was also established that:

- There could be a hydraulic control in the river system between two selected cross sections which, depending on the roughness parameter and river geometry, could only start functioning as a control once a certain flow rate is achieved.
- Flow measurements are required to obtain the flow distribution in the various channels in a braided system when performing one-dimensional hydraulic modelling.
- The selection of the cross section positions in a braided river system for one-dimensional modelling can be disconnected for each river stream, for example cross section 8b (Figure 12) spilt into two separate cross sections at suitable locations for the main and southern channels. This complicates the calibration of one-dimensional hydraulic modelling.
- The hydraulic gradelines should preferably be determined from level recordings at different cross sections for different flow rates to enable accurate calibration of the hydraulic model.
- The flow data provided valuable information for construction and design related decision-making processes.

REFERENCES

The list of references is available from the editor. ◻

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