PAPER 13

REVOLUTION ON ROUTE 319 (MR261): UNCONVENTIONAL METHODS PAVE THE WAY FOR FLOOD SAFETY

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ABSTRACT

South Africa has faced significant challenges in recent years owing to devastating floods, impacting both communities and infrastructure. During these events, emergency responses have been strained, leaving communities isolated. One such community resides in the globally renowned tourist destination of Struisbaai and L'Agulhas at the most southern tip of Africa, which has been particularly severely affected. The Regional Route 319 (R319), also known as Main Road 261 (MR261) connecting Bredasdorp to L'Agulhas, has consistently faced flood-related issues. Not only is the road prone to flooding during extreme storm events, but the long periods of inundation and slow subsiding of flood waters exacerbates the impacts of flooding.

In the context of road upgrades, an unconventional and revolutionary approach to drainage design and flood immunity of the road infrastructure was adopted. The assessment employed a holistic two-dimensional modelling framework of the approximately 340 square kilometre area, extending beyond the typical scope for road upgrade projects. It considered not only the topographically flat network of braided watercourses and environmentally sensitive wetlands, but also the steeper mountainous areas within the Heuningnes River catchment. The innovative rain-on-grid hydrological modelling approach enhanced our understanding of the intricate responses of various catchment segments to rainfall events, and the consequential flooding of the area. The flood study served multiple purposes. Firstly, it provided insights into the existing flood risk and levels associated with the R319. Secondly, mitigation strategies, such as the raising of the road levels, increasing cross drainage capacity and proposed canals, were explored to reduce this risk, ensuring the safety of surrounding communities during extreme weather events. Additionally, the impact of these mitigation interventions on environmentally sensitive areas were explored, emphasising sustainable practices. Importantly, the findings of the study justified deviations from standard guidelines, aligning the project with the specific site, community needs, and environmental considerations.

This groundbreaking approach not only enhances road resilience but also sets a precedent for future infrastructure projects. By integrating unconventional hydrological and hydraulic modelling techniques, and considering the broader context, we can revolutionise flood risk management and create more resilient road networks.

INTRODUCTION

South Africa grapples with the growing challenge of severe flooding events that devastate communities and cripple infrastructure. Traditional flood risk management approaches in South Africa have often focused on localised solutions, failing to account for the complex interplay between geography, extreme weather events, and infrastructure vulnerability. Recent extreme weather events underscore the need for a more comprehensive flood risk management approach when designing for infrastructure.

This paper presents a case study – the upgrade project of Main Road 261 (MR261), also known as Regional Route 319 (R319), a vital 37,5km transportation artery connecting Bredasdorp to the southernmost tip of Africa and encompassing the popular tourist destination of Struisbaai and L'Agulhas, illustrated in Figure 1. During this study, an innovative approach that prioritises both flood resilience and sustainable solutions is implemented. The road has consistently faced flooding issues in recent years, jeopardising not only emergency response and disaster management capabilities, but also isolating communities during flood events for prolonged periods of time.

The study conducted for the upgrading of the MR261 developed an understanding of the hydrological setting and flood regime associated with the braided river systems and wetlands located in the L'Agulhas Plain, as shown in Figures 2, in order to optimise the drainage design. Recognising the limitations of standard practices, the project adopted a comprehensive approach that included utilising advanced hydrological and hydraulic modelling techniques based on the extensive datasets outlined in the IMESA Best Practice Guideline for Design Flood Estimation in Municipal Areas in South Africa (Brooker *et al.*, 2023).

The investment by the Western Cape Government Department of Infrastructure to conduct a flood level assessment of this extent is unconventional, but this approach improved the sustainability of the drainage design and quantified the impact of mitigation interventions on

FIGURE 1: *Locality plan*

FIGURE 2: *Aerial view of flooding along the MR261*

the surrounding flood levels, public safety, potential damage to property and the impact to the sensitive environment.

HYDROLOGICAL SETTING

The upgrading of MR261 encountered a complex hydrological setting due to its location within the low-lying and topographically flat L'Agulhas Plain. This vast area is characterised by a network of braided rivers and extensive wetlands that receive drainage from four primary catchments: the Droë, Poort, Kars, and Nuwejaars Rivers, delineated in Figure 3. The total area draining into these wetlands is approximately 1 640km^2, with the potential to significantly impact floodwaters affecting the MR261, especially between kilometre marker (KM) 4 and KM 18. These catchments play a significant role in contributing floodwaters to the L'Agulhas Plain, particularly during periods of heavy rainfall. The catchments are predominantly covered by commercial rain-fed crops and natural low fynbos shrubs, as identified by the South African National Land Cover data 2020 (SANLC20 data). The Droë River catchment also encompasses the town of Bredasdorp. Notably, the Nuwejaars and Poort River catchments include the Nuwejaars River Special Management Area (SMA). Over the past fifteen years, clearing efforts have removed invasive alien vegetation from the Nuwejaars Wetlands SMA. While the removal of alien vegetation may benefit biodiversity restoration in critically endangered biomes and wetlands, it could also impact the

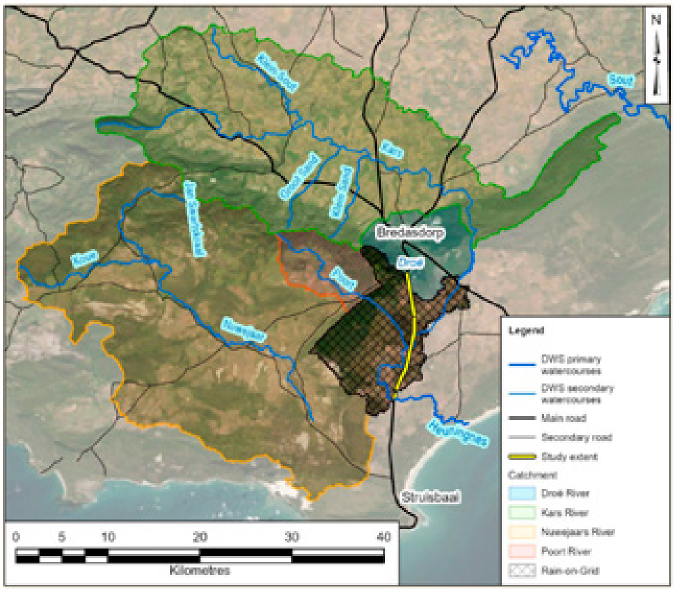

FIGURE 3: *Catchment delineation*

stormflow potential of the catchment by altering factors such as vegetation interception, roughness, and infiltration characteristics. This, in turn, could influence flood immunity for downstream infrastructure like the MR261.

During recent extreme flooding events, water depths of between 300 and 500mm were recorded along the MR261 according to Overberg District Municipality. Furthermore, floodwater would subside very slowly, typically over several days, exacerbating the impact and consequences of these flood events.

TRADITIONAL HYDRAULIC ANALYSIS CHALLENGES AND LIMITATIONS

Given the complex hydrological setting of the L'Agulhas Plain, traditional hydraulic analysis approaches presented some limitations for the MR261 upgrade project. These approaches often rely on limited-scope assessments based on standardised design guidelines. A design return period would typically be determined for each structure, based on the road functional classification and the magnitude of the 1 in 20-year peak runoff rate at that specific drainage structure, as illustrated in Figure 4. In the case of the MR261, the traditional standard design approach may not adequately address the complexities of specific landscapes, and climatic and catchment conditions, potentially oversimplifying the design approach and underestimating peak runoff rates at structures, leading to associated localised flooding.

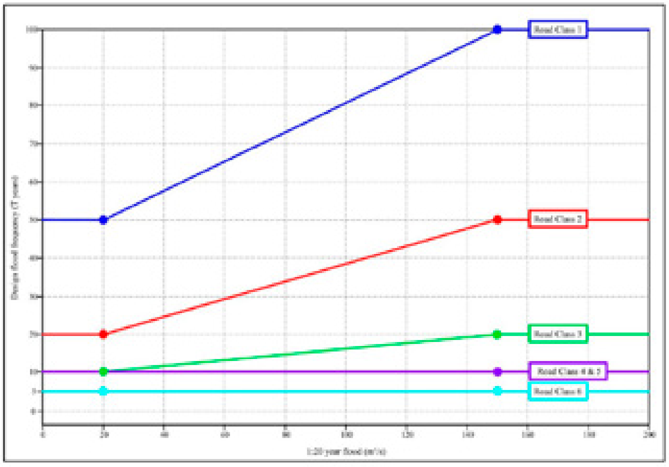

FIGURE 4: *Design flood frequency estimate (SANRAL, 2013)*

For the upgrading of MR261, traditional approaches could have overlooked crucial factors such as the flat topography and complex drainage network. The L'Agulhas Plain features a flat terrain with a network of braided watercourses and environmentally sensitive wetlands. Standard drainage designs might not be suitable for such intricate hydrological systems. For instance, inadequate consideration to the design of cross drainage structures could inadvertently starve the wetlands from their natural water sources, negatively impacting sensitive wetland ecosystems. Similarly, it could result in an increase in flood levels, resulting in flooding of properties in the area, which pose a safety risk.

A significant limitation of traditional approaches is their focus on isolated drainage structures. Typically, the design is done for individual culverts or bridges based on localised peak flow rates. In the case of the MR261 upgrade project, this approach would have failed to account for the cumulative impact of multiple drainage structures on the overall flow regime across the flat L'Agulhas Plain. Excess flow draining from one culvert to the next, with limited consideration for the entire system, could have resulted in unintended consequences such as increased water levels at specific locations or even localised flooding.

To address these limitations, a more comprehensive system-wide analysis was required for the MR261 upgrade project. This approach considers the entire drainage network as a holistic system, enabling the design of drainage structures that function effectively within the broader hydrological context of the L'Agulhas Plain. By moving away from isolated assessments and toward a system-wide perspective, this approach ensures that the cumulative impacts of the drainage infrastructure are considered, minimising negative environmental consequences and optimising floodwater management for the entire region.

It was recommended that MR261 be adopted as a Class 2 in terms of flood risk, considering the consequences of flooding of the road. Additionally, the highest return period presented in Figure 4 for a Class 2 road be adopted for the road drainage design.

HYDROLOGICAL AND HYDRAULIC ANALYSIS APPROACH

In order to assess the complex drainage system of the L'Agulhas Plain for the MR261 upgrade project, a hydrological and hydraulic modelling approach was adopted. This type of modelling provides a representation of reality to understand of how the drainage system functions and how changes to the system might impact floodwaters.

Traditionally, a catchment averaged approach, also known as a 'lumped' model, is used for design flood estimation. This approach treats the entire catchment as a single unit, as illustrated in Figure 5. Distributed approaches, enabled by increased computing power, subdivide catchments into smaller areas and simulate flow routing between these catchments. The distributed modelling structures provides a more realistic representation of the catchment parameters, but can become computationally expensive for very large areas. Distributed models can further be sub-divided into two types: semi-distributed models which use delineated sub-catchments, and fully-distributed models which employ a grid or mesh-based approach.

The four catchments draining towards the L'Agulhas Plain are well-defined with minimal variation in characteristics. Applying a lumped modelling approach for design flood estimation was deemed sufficient for these upstream areas. However, the flat topography of the L'Agulhas Plain itself presented a challenge for catchment delineation. To address this, a two-dimensional (2D) hydraulic modelling approach was employed for the hydraulic analysis of the L'Agulhas Plain using the United Sates Army Corps of Engineers (USACE) Hydraulic Engineering Centre River Analysis System (HEC-RAS) (version 6.5), alongside the lumped modelling of the upstream catchments. The 2D hydraulic modelling approach is based on a depth averaged computational solution, which is better represents the depth, velocity and momentum distribution across a floodplain. Furthermore, the section of the catchments within the L'Agulhas Plain was simulated as part of the hydraulic model using an advanced hydrological and hydraulic modelling approach known as "Rain-on-Grid."

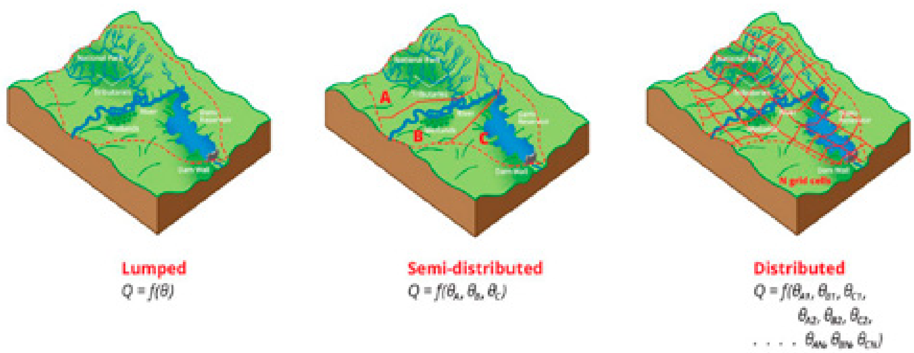

FIGURE 5: *Spatial representation of physical processes in hydrological models (Ball et al., 2019)*

RAIN-ON-GRID MODELLING

Traditionally, flood assessment involved separate stages for design flood estimation and hydraulic analysis of flow through the drainage system. Recent advances in computational capabilities have led to the development of Rain-on-Grid, or direct rainfall, modelling. This approach simulates rainfall directly onto a 2D modelling domain, as illustrated in Figure 6, eliminating the need for separate hydrological and hydraulic modelling stages. Rain-on-Grid modelling, with its distributed spatial structure, has become widely adopted and is now included in many mainstream 2D modelling software packages (Zeiger and Hubbart, 2021; David and Schmalz, 2020; Broich et al., 2019).

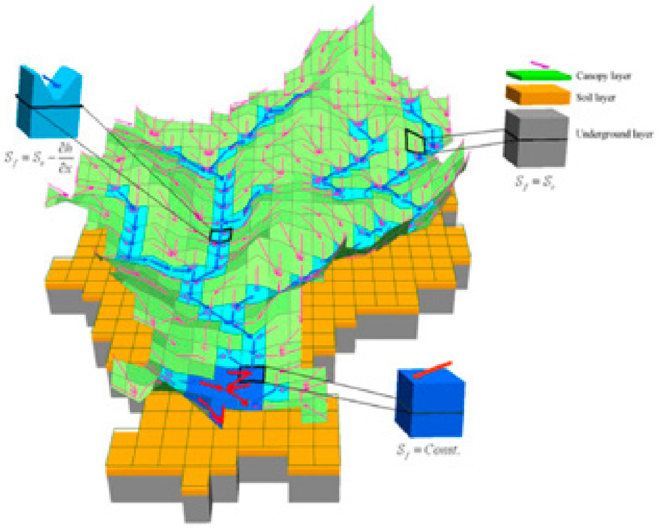

FIGURE 6: *Schematic representation of modelling approach (Li et al., 2019)*

One advantage of Rain-on-Grid modelling is the ability to incorporate more complex loss models compared to the simpler assumptions often used in lumped modelling approaches (Caddis et al., 2008). However, several cautions are important to consider when using this method:

- Parameter Transfer: Care is needed when transferring model parameters developed for either lumped hydrological models or even hydraulic modelling parameters to a distributed Rain-on-Grid approach. This transfer requires caution, and research is ongoing to determine appropriate surface roughness coefficients for various land covers within a Rain-on-Grid modelling framework (Caddis et al., 2008). For the MR261 model, rainfall losses were simulated using a Curve Number approach. These has been significant research into the development of the Curve Number approach in South Africa, as part of the South African Soil Conservation Services (SCS-SA) method, which was correlated with the SANLC20 dataset and the SCS-SA hydrological soil groups (Schütte et al., 2023) for the purpose of the MR261 model.
- Model Sensitivity: Studies by Clark (2008) highlight the sensitivity of 2D Rain-on-Grid models to parameters such as roughness coefficients, grid cell size, and timestep. Further testing is recommended on gauged catchments with observed data to gain a better understanding of parameter interactions.
- Calibration and Verification: Hall (2015) emphasises the importance of proper guidance and quality assurance when using Rain-on-Grid modelling. Without these measures, the results can be inaccurate.

In the MR261 project, since limited recorded data was available within the simulated area for calibrating and verifying the Rain-on-Grid model results, the Droë River catchment was included in the modelling extent. The Rain-on-Grid simulated results for the Droë River catchment were compared to established hydrological methods for South Africa, encompassing various deterministic and empirical methods for different return periods, in order to increase the confidence in the results emanating from the modelling approach.

HYDROLOGICAL MODELLING RESULTS

The hydrological model included Rain-on-Grid modelling of the Droë River catchment, which was used to increase the confidence in the results for the L'Agulhas Plain. A variety of established hydrological methods were also employed, including the Rational Method Alternative 3 (RM3), South African Soil Conservation Services (SCS-SA), Synthetic Unit Hydrograph (SUH), Standard Design Flood (SDF), SDF method with adjustment factors (Van Bladeren, 2005) (Adj. SDF)), Midgley and Pitman (MIPI), Hydrological Research Unit 1/71 (HRU 1/71) and the Catchment Parameter (CAPA) methods. The results from the Rain-on-Grid modelling are compared to these established methods in Figure 7.

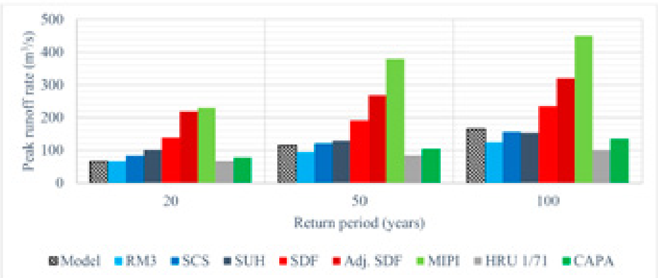

FIGURE 7: *Rain-on-Grid results comparison to lumped methods for the Droë River catchment*

From Figure 7, it can be concluded that the Rain-on-Grid modelling results correlated well with established deterministic hydrological methods, with good agreement observed for the SCS-SA and RM3 methods. These methods are based on catchment-specific parameters and tend to provide more accurate results typically for smaller catchments. For the lower return period event, the Rain-on-Grid model results were slightly lower than these two methods, likely attributed to the detailed modelling of flow routing through the catchment and a more accurate representation of the attenuation associated with the flatter topography near the L'Agulhas Plain. For the larger return periods, the model results were similar to the SCS-SA and SUH results. The catchment area for the Droë River is approximately 76km^2, which does exceed the catchment size application guidelines for the SCS-SA and RM3 methods. However, these methods have been used for catchments exceeding the recommended maximum area, with the SANRAL Drainage Manual (6th edition) stating that the size limitation depends on the method of calculating rainfall intensity, and Gericke and Du Plessis (2013) referring to an aerial limitation for the SCS-SA method of less than 80km^2. The confidence in these results is also supported by the results from the SUH method, which is based on regionalised catchment parameters, but provides similar results to the Rain-on-Grid model and the SCS-SA methods.

Van Bladeren's (2005) analysis of Region 18 for the SDF method was based on catchments not part of the L'Agulhas Plain catchment area. Additionally, the catchment characteristics used to develop the SDF and Adj. SDF parameters are likely significantly different due to the flat topography of the L'Agulhas Plain.

Results from the empirical methods are typically used for comparative purposes and not design purposes. The results from the MIPI method were the highest of all the methods. However, this method is typically used for return periods less than 100-years and has an aerial limitation of a minimum of 100km^2, although it could be applied with caution to smaller catchments. The results from the CAPA and HRU 1/71 methods were similar to that of the RM3 and SCS-SA methods, and correlated generally well with the Rain-on-Grid model results.

The application of the Rain-on-Grid model and associated modelling parameters were considered adequate for the flood level assessment and simulating rainfall onto the L'Agulhas Plain. Furthermore, considering the flat topography of the Droë River and associated complex hydraulic conditions where the Droë River discharge into the L'Agulhas Plain, is was recommended that the Rain-on-Grid model also be used for design flood estimation of the Droë River catchment. For the remaining catchments, i.e. the Poort, Kars, and Nuwejaars River catchments, the SCS-SA method and the SUH method were selected based on catchment size and applicability. The peak runoff rates for various return periods are presented in Table 53.

TABLE 1: *Summary of the hydrological assessment results*

Description	Droë	Poort	Kars	Nuwejaars
Catchment area (km²)	76	60	635	735
Longest watercourse (km)	20.7	17.3	71.0	68.5
Longest watercourse slope (%)	0.63	1.27	0.27	0.14
Catchment slope (%)	5.9	11.8	10.1	6.8
Peak runoff rates (m³/s)				
1 in 20 year	65	95	405	445
1 in 50 year	115	140	520	570
1 in 100 year	165	180	620	680
Hydrological method	Rain-on-Grid modelling	SCS-SA	SUH	SUH

HYDRAULIC MODELLING RESULTS

The hydraulic model was used to gain a better understanding of the interaction between the runoff hydrographs from the various catchments. By gaining an understanding into the runoff dynamics and flow regime through the L'Agulhas Plain, impacts of the proposed mitigation strategies could be quantified. The models developed were divided into:

- Baseline models: Model representing the existing flood regime and to quantify the existing flooding impacts for different return periods.
- Mitigation models: Various models representing different mitigation measures, to quantify the change in flood properties and impacts of the interventions.

From the baseline model results, it was concluded that the flooding of the road surface occurred during the design return period (Q_T) of 50-years between KM 5.7 and KM 6 with flood depths on the road surface of up to approximately 300mm, and between KM 7 to KM 13 with flood depths on the road surface of up to approximately 500mm. This correlated well with the flooding reports received from the Overberg District Municipality, as well as the flooding extent captured on photographs. Furthermore, the levels for twice the design return period (Q_{2T}), i.e. the 100-year event, were on average approximately 0.07m higher than the design return period, with a similar maximum depth difference between KM 5.7 and KM 6, and on average approximately 0.09m higher than the design return period, with maximum depth differences of up to 0.15m between KM 7 and KM 13.

From the baseline model results, a low hydraulic gradient was observed at KM 6, KM 9, KM 12 and KM 15 along the MR261, indicated in Figure 8a. With the exception of the latter, there correlated well with the location where flooding has been reported. A profile of the existing MR261 road surface and associated 50 and 100-year flood level are presented in Figure 9. Furthermore, the time to peak flood level indicated in Figure 8b, indicated the complexity of the drainage system, and how the delayed peaks downstream would impact on hydraulic capacities of the culverts, as well as provide an understanding for the subsiding of floodwater over several days. This understanding is crucial for assessing the effectiveness of the mitigation measures. The upcoming sections will present the results of the mitigation models, which evaluate the impact of various interventions such as raising of the road level, culvert enlargement and channel improvements, on these flood properties.

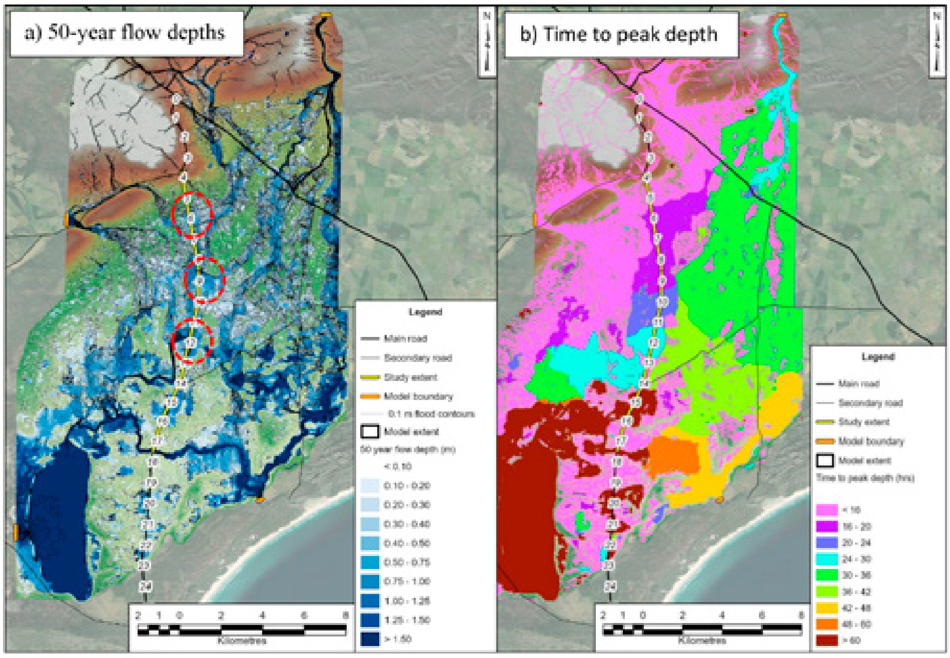

FIGURE 8: *Baseline modelling results, a) 50-year flow depths, and b) time to peak depth*

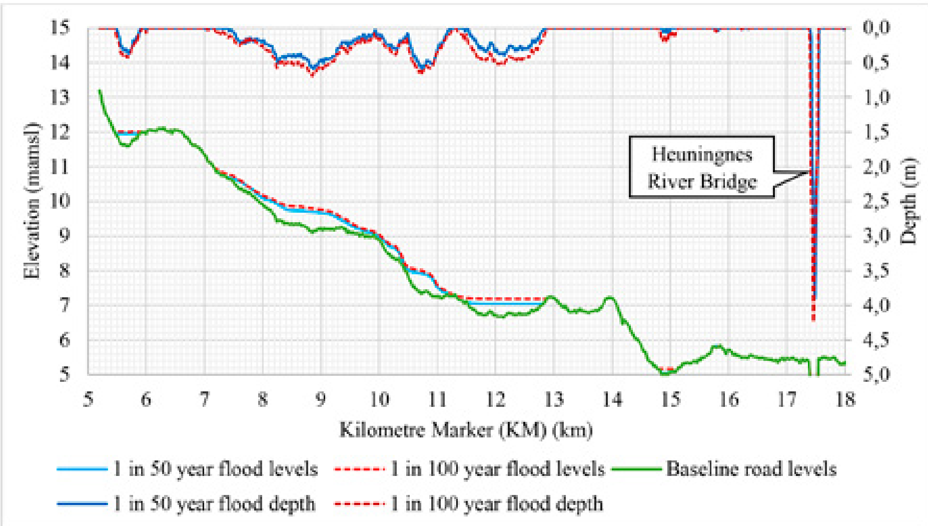

FIGURE 9: *Existing flood levels along the MR261 road surface*

FLOOD MITIGATION STRATEGIES

The comprehensive flood study facilitated the development of targeted mitigation strategies aimed at reducing flood risk along the MR261 corridor. These strategies included the following main interventions:

- Increase the road elevation: Raising the road level was a key strategy to create a buffer zone, protecting the road surface from inundation during flood events. This can potentially cause upstream flooding or divert flow, leading to higher flood levels elsewhere along the road. The initially proposed increase in flood level was 400mm, but additional raising of the road was required to address consequential flooding as part of Option 4.
- Enhanced cross-drainage capacity: Upgrading existing culverts and potentially constructing new ones aimed to increase the overall flow capacity of the drainage system, allowing floodwater to drain more efficiently. Sediment deposition and blockage of the culverts are a concern, as a result of the low velocities associated with the flow topography. The mitigation intervention included upgrading of all culverts to a minimum size of 600mm diameter, and also increasing cross drainage capacity for Options 2, 3 and 4.
- Proposed Canals: The feasibility of constructing canals along the MR261 road was explored to further improve drainage efficiency and reduce the risk of flooding along the road corridor. This would also improve the conveyance of floodwater between the culverts to drain across the road. While canals offer potential benefits, their environmental impact and long-term maintenance requirements need to be considered.

A schematic representation of the four mitigation strategy options is presented in Figure 10a. Flood depths along the road surface for the baselines, as well as the four options, are presented in Figure 11. From Figure 11 it can be concluded that Options 1 to 3 significantly reduced the flood levels along the road, however, there was still significant flooding further downstream between KM 8 and KM 12. Option 4 indicated minor flooding along the road, demonstrating its effectiveness in mitigating flood risk. The change in flood levels between the baseline model results and Option 4, the recommended intervention, is presented in Figure 10b.

From Figure 10b, it can be concluded that significant changes in water level are primarily limited to the immediate vicinity of the road. The mitigation measures resulted in a reduction of flood levels on the western side of the road, primarily due to the raised road elevation, and increased flood levels along the eastern side of the road. The model results indicated a change in water level of less than 0.2m, and negligible change in the inundated area.

REVOLUTIONISING FLOOD RISK MANAGEMENT FOR INFRASTRUCTURE

This study has explored the application of advanced hydrological and hydraulic modelling techniques to assess flood risk along the MR261 corridor. The findings demonstrate how these techniques can play a crucial role in revolutionising traditional approaches to flood risk management.

- Rain-on-Grid Modelling: The application of Rain-on-Grid modelling for the L'Agulhas Plain represents a significant advancement over conventional methods that may not account for the complexities of flat topography. This highlights the potential of high-resolution, distributed modelling approaches for flood risk assessments in similar environments.
- Targeted Mitigation Strategies: The modelling results facilitated the development of targeted mitigation strategies that address the specific challenges of the MR261 corridor. This data-driven approach contrasts with traditional flood risk management, which may rely on generic solutions without a comprehensive understanding of the local hydrology and hydraulics.

While this study focused on a specific case, it exemplifies the transformative potential of engineering advancements in flood risk management. By leveraging advanced modelling techniques and fostering a data-driven approach, engineers can develop more effective and sustainable solutions for mitigating flood risk and protecting infrastructure in a changing climate.

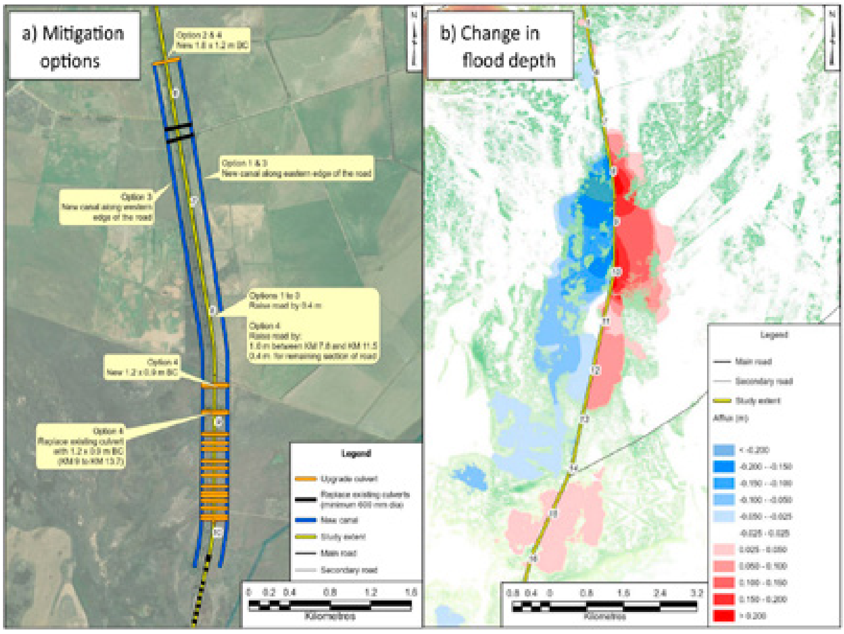

FIGURE 10: *Proposed mitigation modelling results, a) schematic layout of mitigation options, and b) change in flood depth for the preferred Option 4*

CONCLUSION

This study explored the application of unconventional hydrological and hydraulic modelling techniques to assess flood risk. The key conclusions regarding the modelling approach are as follows:

- Rain-on-Grid modelling: This approach demonstrated its effectiveness as an alternative to traditional methods for catchments with complex topography. This approach provides a high-resolution and distributed representation of rainfall-runoff processes, potentially leading to more accurate flood risk assessments in non-standard environments.
- Focus on data-driven approach: The study highlighted the importance of employing modelling techniques that can be informed by detailed catchment data. This data-driven approach can lead to more reliable and targeted mitigation strategies compared to generic solutions based on limited information.

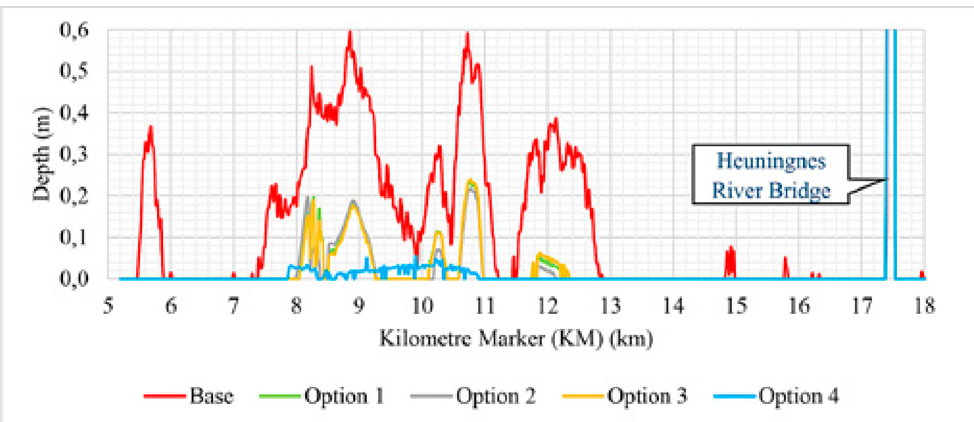

FIGURE 11: *Comparison of various mitigation interventions modelling results*

RECOMMENDATIONS

Based on the successful application of unconventional modelling techniques in this study, the following recommendations are made for future flood risk assessments:

- Explore the wider application of Rain-on-Grid modelling: This study suggests that Rain-on-Grid modelling has the potential to be valuable for flood risk assessments in various regions with complex terrain that may not be well-suited for traditional methods. Further research is recommended to explore its applicability in diverse geographical settings.
- Integration of unconventional data sources: Consider incorporating non-traditional data sources, such as high-resolution LiDAR (Light Detection and Ranging) or the 2m Digital Elevation Model of South Africa (DEMSA2) for detailed terrain mapping, into the modelling process. This can enhance the accuracy of flood simulations, particularly in areas with complex topography.
- Continuous development and adoption of advanced modelling techniques: The field of flood risk management should continue to embrace advancements in modelling techniques. Studies like this showcase the potential of unconventional approaches to improve flood risk assessments and inform the development of more effective and sustainable mitigation strategies.

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