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Advantages of two-dimensional hydraulic modelling for quantifying flood risk in complex urban drainage systems

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ABSTRACT

In South Africa, floods can be considered one of the most catastrophic natural hazards impacting on built-up areas. Even though flood risk associated with a specific urban area is assessed and quantified prior to the development, the frequency and magnitude of floods may increase over time as a result of changes in the natural flow patterns caused by urbanisation, encroachment of development on floodplains and climate change. Quantifying flood risks associated with an urban environment should be a priority for local authorities in terms of disaster management.

Two-dimensional hydraulic modelling is particularly suitable to provide a realistic representation of the complex flow conditions associated with urban drainage systems, braided river systems, off-channel flows and defining flood risk in flood prone areas. The results from these models can also be used to inform and optimise flood disaster risk management programmes. Two-dimensional hydraulic modelling has considerable advantages over conventional one-dimensional hydraulic modelling in quantifying flood risk in complex urban drainage systems.

As a case study, a two-dimensional hydraulic model of the lower reaches of the Kuils River in Cape Town was compiled to quantify the flood risk associated with a development along this section of the river. Quantifying flood risk in the lower Kuils River has posed a significant challenge as a result of the nature of the river in this area, the impact of major developments along the major drainage systems, bridge structures, as well as the flat topography resulting in off-channel flow. The hydraulic analysis extent included three major drainage systems, i.e. the Kuils River, Eerste River and Kleinvlei Canal, encompassing a total modelled area of approximately 36 km^2.

Two-dimensional hydraulic modelling allowed for a clear understanding of the flow regime, associated flow dynamics and flood risk at the confluence of the Kleinvlei Canal, Kuils River and Eerste River systems.

INTRODUCTION

Flooding in urban areas is a significant challenge faced by municipal engineers in South Africa. Major urban flood events often result in loss of life and significant damage to infrastructure and property. Furthermore, smaller, more frequent flooding events can cause direct and indirect economic impacts that are unacceptably high given the current challenges facing South Africa such as poverty and lack of economic growth.

Local municipalities are mandated in Schedule 4 Part B of the South African Constitution (Republic of South Africa, 1996) to manage stormwater systems in built up areas. In addition, the National Water Act (Republic of South Africa, 1998) states that those people who may be affected by flood hazard are made aware of the risks by indicating the extent of 100-year floodplains on development layouts. Identifying flood risk is also critical for disaster management, a key competency of municipalities in terms of the Disaster Management Act (Republic of South Africa, 2002).

Many of the impacts of flooding could be avoided with a better understanding of flood risk, and measures put in place to mitigate these risks. A key step to achieving this is the development of stormwater management models which represent the real-life characteristics of runoff and corresponding floodwaters occurring given certain input conditions (e.g. rainfall, imperviousness of catchment, infiltration parameters, etc.) (Pinos & Timbe, 2019). The hydraulic component of such models simulate the flow characteristics of floodwaters via watercourse channels, stormwater systems and overland routes within the floodplain. Key outputs of the model include the extent of flooding and the depth and velocity of flow (Robinson, 2018).

ONE-DIMENSIONAL VS TWO-DIMENSIONAL HYDRAULIC MODELS

In the past, South African municipalities and consulting engineers mostly had to rely on one-dimensional (1D) hydraulic models such as the United States Army Corps of Engineers' (USACE) Hydraulic Engineering Centre River Analysis System (HEC-RAS) to assess flood risk along watercourses. A 1D modelling approach is based on the fundamental assumption that water flows perpendicular to a predetermined cross section and that all flow at a given cross section is flowing uniformly in the same direction (USACE, 2016a). This implies that the modeller needs to decide on the flow direction. Flow conditions where the fundamental assumptions of a 1D modelling approach would be violated (e.g. branched flow or splitting of flow) require assumptions and modelling judgement.

Although two-dimensional (2D) hydraulic modelling has been used for over 25 years, the requirements for survey data, computing capability, software licensing, and an experienced modeller, made the use of 2D hydraulic models too expensive and time consuming in most cases (Robinson, 2018). However, with the availability of Light Detection and Ranging (LiDAR) survey data increasing, and advances in hardware and software technology, 2D hydraulic modelling, or 2D modelling coupled with 1D components, has been growing in popularity in the last decade (Teng et al, 2017). In complex flow conditions within built up areas, 2D hydraulic modelling has significant advantages over conventional 1D hydraulic modelling.

The 2D modelling approach is based on a mesh or grid, comprising of depth averaged cells, to represent the topography of the channels and floodplains. This approach allows flow to move in various directions and flowpaths and to change at various depths without being predetermined, resulting in a more accurate distribution of flow volumes, velocities and depths across a floodplain and ultimately significantly reduced assumptions and modelling judgement required regarding flow direction. The

FIGURE 1: Flow regime of the Kuils River

2D modelling approach also accounts for the effect of cross-momentum at flow splits, which occur at road intersections and confluences of watercourses, and losses due to secondary 2D flow directions, e.g. at bends or diverging flow (Engineers Australia, 2012).

The visual representation of complex hydraulic conditions and flowpaths emanating from a 2D hydraulic modelling approach enhances communication with stakeholders.

Even though 2D modelling has significant advantages over the 1D modelling approach, 2D modelling does require more survey data, more computational time and the possibility of a trade-off between computational time and model detail (or cell size) (Engineers Australia, 2012). It should also be noted that 2D modelling does not take into consideration any vertical distribution of flow but rather assumes depth-averaged hydraulic conditions.

DEFINING FLOOD RISK IN URBAN AREAS

It is widely accepted that risk can be defined as the product of hazard and consequences. Kron (2005) expands this definition to include three variables, as shown in the following formula:

Flood Risk = Hazard x Exposure x Vulnerability

- **Hazard** is the threatening natural event including its probability of occurrence. For example, during a storm with a 50-year recurrence interval, flood waters inundate an area to a depth of 1m. An accurate determination of the flood hazard is the essential first step in defining flood risk in a given area. It is therefore crucial that a suitable stormwater management model, backed up by adequate data, is developed by a competent person to get a good understanding of the flood hazard.

The model should firstly determine the extent of flooding for a range of probabilities. This would typically be in the form of "floodlines", and defined by a recurrence interval (or return period), e.g. 100-year floodlines. 100-year floodlines would be the estimated extent of flooding that might occur, on average, once every 100 years. Put differently, there is a 1% chance of this event taking place in any given year.

In addition to floodlines, factors that need to be determined using the model include depth, velocity and direction of flow, rate of floodwater rise, and duration of inundation.

- **Exposure** relates to the people, property and assets that are present at the location of the hazard. The higher the number of people and value of the property and assets, the higher the exposure.
- **Vulnerability** relates to the lack of resistance to damaging/destructive forces. For example, some informal settlements are extremely vulnerable since people living there are often unaware of the risk of flooding and do not know how to react in the event of a flood. Furthermore, informal dwellings typically cannot withstand the effects of a flood event, and it's often difficult for emergency vehicles to access areas affecting by flooding.

Based on the above flood risk definition, it is noted that an improvement in the modelling approach would ensure a more accurate quantification of the flood hazard.

CASE STUDY: ASSESSMENT OF FLOOD RISK ALONG THE LOWER KUILS RIVER, CAPE TOWN

Project Background and Flow Regime of the Lower Reaches of the Kuils River

A flood level assessment was undertaken for a development located in close proximity to the Kuils River and Kleinvlei Canal, indicated in Figure 1.

The historical natural flow regime of the lower reaches of the Kuils River was a seasonal, braided river which dried up during the dry season resulting in a series of small ponds or "kuils". During the winter months, surface water flowed in torrents over windblown sands (The Environmental Partnership, 2005). This system comprised of extensive seasonal braided channels and wetlands, which are still features of the lower reaches. Most of the above-mentioned seasonal wetlands have been lost due to large-scale manipulation of ground levels associated with developments. Nutrient-enriched water and an elevated water table have further resulted in the degradation of the complex diversity of habitats that used to occur, which have since been replaced by extensive stands of bulrush that also impacts on the hydraulics conveyance capacity of the river system.

The historical understanding of the flow regime of the lower Kuils River was based on the results from previous studies commissioned by the City of Cape Town, which mainly included 1D hydraulic modelling. The 1D modelling approach required extensive modelling assumptions to simplify the complex flow regime associated with the lower sections of the Kuils River.

Flow discharged into the lower section of the Kuils River is controlled by the Driftsands Dam, a flood detention dam located to the northwest of the National Route 2 (N2) and Regional Route 300 (R300) interchange, with a catchment area of approximately 177km^2. The Dam Safety report compiled during 2011 (City of Cape Town, 2011) highlighted the risk of extreme floods bypassing the embankment along the eastern edge of the dam.

As illustrated in Figure 1, the Kuils River immediately downstream of the Driftsands Dam flows in a south easterly direction, conveyed through the

Old Faure Road bridge towards the N2 bridge. Flow conveyed through the N2 bridge meanders in a general south-easterly to easterly direction along the northern edge of Khayelitsha and flow in excess of the N2 bridge's capacity is conveyed along the north of the N2 in a general south easterly direction through a wetland area.

The Kleinvlei Canal, conveying flow in a southerly direction converge with the Kuils River at appoint close to the N2 / Baden Powell Drive intersection.

The flow in the Kuils River main channel is conveyed across Baden Powell Drive south of the N2 and further in a south-easterly direction where it converges with the Eerste River and flows in a general south-easterly direction.

Hydraulic modelling approach

The hydraulic model included an approximately 15km section of the Kuils River from the Driftsands Dam to the Macassar Road Bridge, an approximately 3.5 km section of the Kleinvlei Canal and a 2.5km section of the Eerste River. Major drainage structures along the flow paths included six bridge and major culvert structures along the Kuils River, four along the Kleinvlei Canal and one along the Eerste River. The catchment areas and peak runoff rates for the 1 in 50 (2% annual probability) and 1 in 100 year (1% annual probability) storm events are provided in Table 1.

TABLE 1: Peak runoff rates

Location	Catchment area (km^2)	Peak runoff rate (m^3/s)	
		1 in 50 year	1 in 100 year
Driftsands Dam	177	236	275
Eerste River at the confluence with the Kuils River	345	506	630
Kleinvlei canal at confluence with the Kuils River	30	72	86

Modelling Software

The introduction of the freely available HEC-RAS 2D software in 2016 made 2D hydraulic modelling more accessible and affordable to simulate complex open surface flow conditions and was used for the hydraulic analysis (Version 5.0.3). HEC-RAS is widely used in South Africa, and the 2D component of the software is intuitive to use and compares very well to other well-known software packages in terms of performance (Lintott, CM, 2017; USACE, 2018). The software is also fully capable of running models in steady and unsteady flow conditions.

The 2D component of HEC-RAS expanded the software's abilities to model 1D, 2D, and integrated 1D-2D conditions, and is designed to use a uniform, structured grid, as well as non-uniform, unstructured meshes to define the 2D domain of the hydraulic model. The software uses an implicit finite volume algorithm for 2D unsteady flow equations, which allows for larger computational time steps, and supports multiple processors on a computer (USACE, 2016b). It should be noted that HEC-RAS's functionality does not take into account any morphological changes in the river system due to sediment transport.

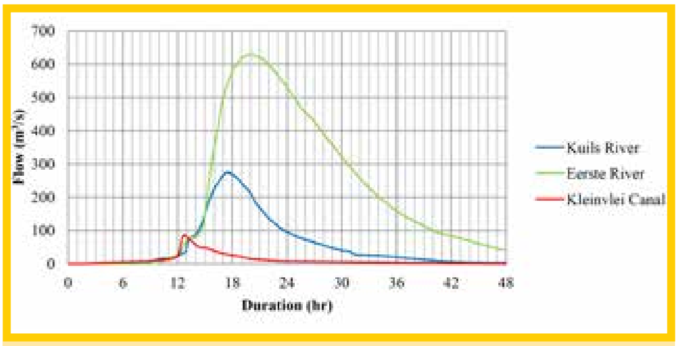


FIGURE 2: 1 in 100 year storm hydrographs for the various drainage systems

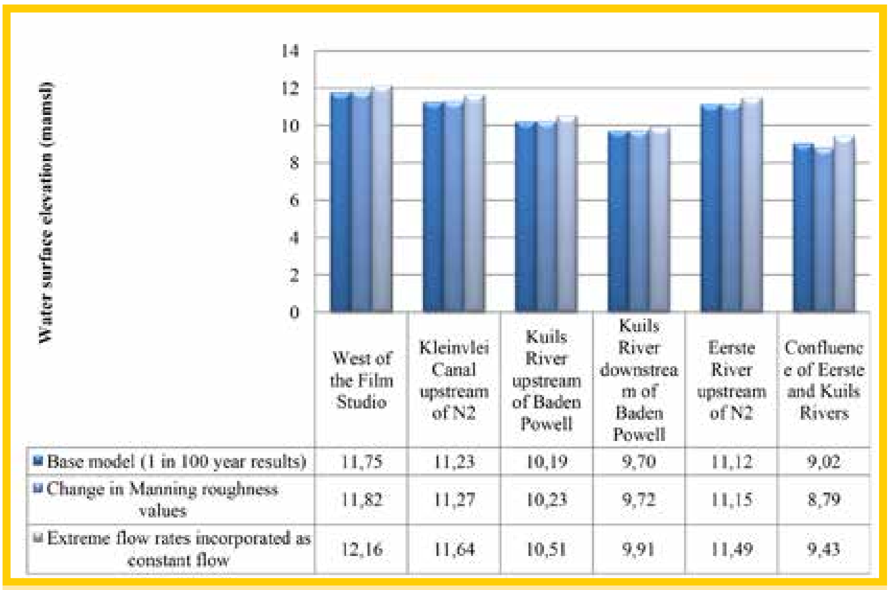
Modelling Geometry Configuration

The availability of accurate, high-resolution survey data for the areas being modelled is an essential component in reducing model uncertainties (Anees et al, 2017). Digital terrain data used to generate the ground and river bed surface in the model were based on the City of Cape Town's available LiDAR survey information, surveyed during January 2014. The digital terrain model (DTM) generated from the LiDAR survey were verified with a detailed survey of the proposed development site, which correlated very well.

One of the limitations of the LiDAR survey information is the ability to penetrate water surfaces and densely vegetated areas, such as the wetlands associated with the Kuils River. These errors in the survey were deemed acceptable considering the insignificant effective conveyance of flow through areas of permanent ponding and high density vegetation.

For a large study area such as this using a relatively coarse mesh to determine flood extent and peak flood levels is considered acceptable best practiced. Channels, flow paths, storage areas, controls and major topographical changes were refined with a finer grid to accurately model the flow routing through the study area.

Hydraulic structures, which includes bridges, culverts, and roadways (modelled as weirs), were included in the model as 1D components. Data on these hydraulic structures and other features which might impact on the hydrodynamics of the flood conditions were obtained from previous hydraulic analyses and site investigations.



	West of the Film Studio	Kleinvlei Canal upstream of N2	Kuils River upstream of Baden Powell	Kuils River downstream of Baden Powell	Eerste River upstream of N2	Confluence of Eerste and Kuils Rivers
■ Base model (1 in 100 year results)	11,75	11,23	10,19	9,70	11,12	9,02
■ Change in Manning roughness values	11,82	11,27	10,23	9,72	11,15	8,79
■ Extreme flow rates incorporated as constant flow	12,16	11,64	10,51	9,91	11,49	9,43

FIGURE 3: Sensitivity analysis results

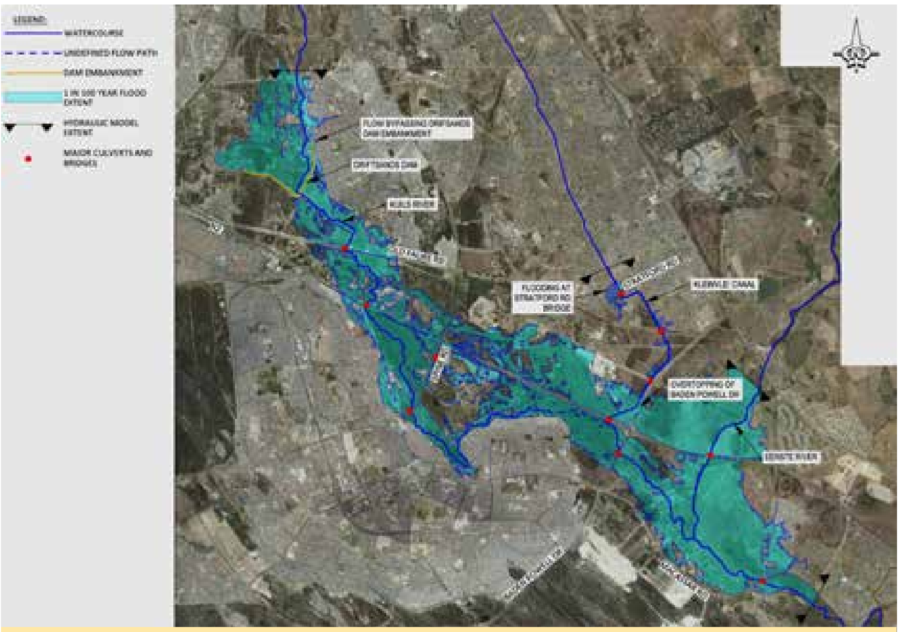


FIGURE 4: Flood hazard map

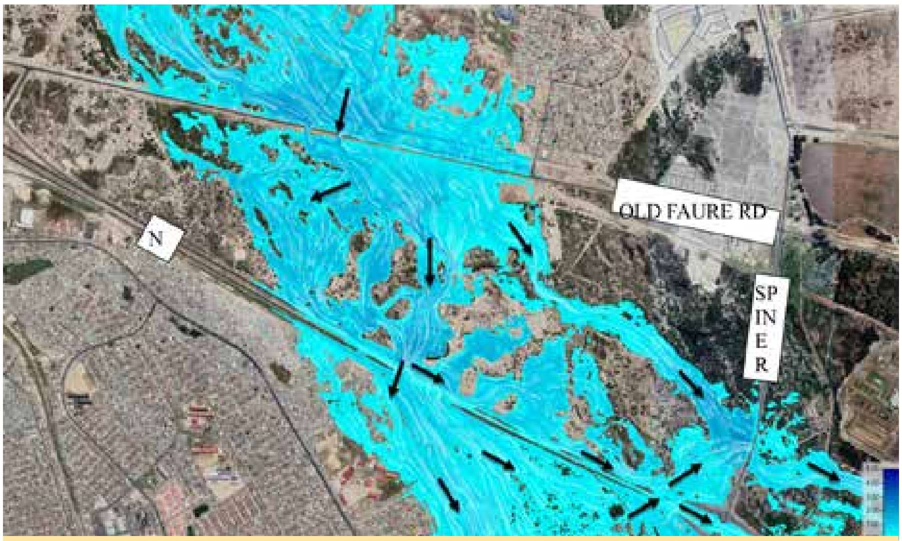


FIGURE 5: Braided flow conditions upstream of the N2 bridge

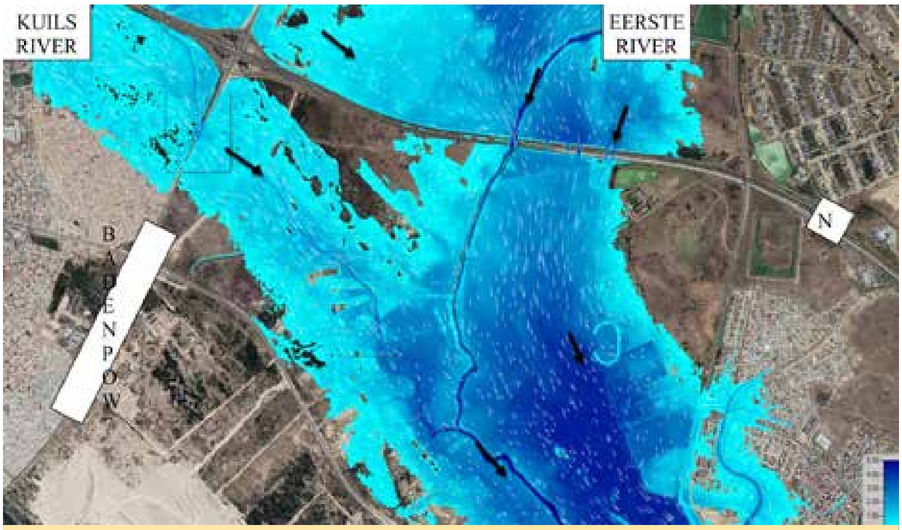


FIGURE 6: Confluence of the Kuils and Eerste Rivers

Land use data and aerial imagery obtained from the City of Cape Town were used to ascribe hydraulic roughness categories to the model surface. Roughness values assumed in the model were based on the recommended Manning 'n' values sourced from the HEC-RAS Hydraulic Reference Manual (USACE, 2016c).

Modelling Boundary Conditions

As a result of the complex nature of the stormwater system associated with the developed catchments, flood hydrographs for the Kuils and Eerste Rivers were obtained from the City of Cape Town's stormwater management models. Flood hydrographs for the Kleinvlei Canal were obtained from the rainfall runoff model compiled specifically as part of this assessment. The inflow hydrographs are provided in Figure 2. Downstream boundary conditions were based on normal flow depths in the main river channel.

Modelling Verification

Adequately recorded rainfall and associated flood level information of the Kuils River was not available for calibration purposes; however, various previous flood records were used to assist with the verification of the model results, which included photographs of flooding in the vicinity of the confluence of the Kleinvlei Canal, Eerste and Kuils Rivers during 2013. In addition, information was obtained from the Driftsands Dam Safety Report (City of Cape Town, 2011), stating that surface water would bypass the dam in the case of extreme floods.

Furthermore, sensitivity analyses were conducted which included a significant increase in the roughness parameters for the wetland areas, and routing an extreme, constant flow through the hydraulic model. The results from these sensitivity analyses are provided in Figure 3. The model compiled for the flood level assessment was used as a base model.

As illustrated in Figure 3, an increase in the roughness coefficients of the wetlands and increased peak flows had very little impact on the flood levels in the vicinity of the site as a result of the flat topography and large areas inundated during extreme flood events.

Modelling Results

From the results of the hydraulic analysis, illustrated in Figure 4, it is evident that the flow dynamics in the study area can be characterised by braided flows, off-channel flows, and extensive ponding in various areas. The results further confirmed the findings of the Driftsands Dam Safety Report that floodwater attenuated in the Driftsands Dam will bypass the embankment along the eastern edge of the dam during extreme flood events.

Figure 5 illustrates the braided flow conditions associated with flow in excess of the main river channel immediately upstream of the N2 bridge, and Figure 6 illustrates the flow regime associated with the confluence of the Kuils and Eerste Rivers. The modelling results clearly indicate the advantages of using a 2D hydraulic model to develop a good understanding of the complex flow conditions prevalent in the study area, and underscores the limitations of 1D models in such instances.

CONSIDERATIONS FOR ADOPTING A 2D MODELLING APPROACH

Important considerations for adopting a 2D modelling approach are as follows:

Topographical information

The resolution and accuracy of the DTM used for the compilation of a 2D model could have a significant impact on the detail and accuracy of the hydraulic model. Inaccuracies in the geometric data of the 2D model could result in modelling errors.

Modelling software

A clear understanding of a specific software's modelling approach, assumptions, limitations and capabilities is required to select the most appropriate software package.

Modification of input data

Modifications to the topographical survey information and DTM might be required to ensure model stability and accurate simulation of the stormwater system, which could be time consuming.

Cell size vs computational time

As mentioned previously, one of the disadvantages of 2D models are the computational time required to run a simulation. Typically, to analyse a specific area in a higher level of detail, a smaller mesh resolution is required; however, a decrease in mesh resolution would typically require an increase in computational time to ensure model stability. In addition, with the modelling of larger areas, the simulation time step is dependent on the smallest cell size in the 2D mesh. Applying a time step which is too large could result in model instabilities.

Hardware requirements

When reference is made to 2D models and hardware requirement to process these models, the focus is mainly on the processing capabilities. However, input files required, such as the DTM and output files from the simulation is quite large in comparison to that of 1D models. Sufficient storage capacity is required to store model results.

Third party peer review

For the review and approval of 2D models, it is recommended that a third party peer review be conducted, similar to the best practices associated with other hydraulic models.

CONCLUSIONS AND RECOMMENDATIONS

The availability and affordability of 2D modelling software has created the opportunity to quantify flood risk more accurately. 1D models are ideally applied for in-channel flows, whereas 2D hydraulic modelling is preferred for complex flow conditions such as braided river systems, off-channel flows and defining flood risk in flood prone areas by significantly reducing the assumptions and modelling judgement required. Furthermore, the 2D modelling approach results in an accurate visual representation of complex hydraulic conditions and flowpaths which is a significant advantage when engaging with interested and affected parties.

It is recommended that the following be taken into consideration when adopting a 2D hydraulic modelling approach:

- Detailed topographical survey of the entire 2D domain of the model extent, typically a LiDAR survey, is required.
- A clear understanding of a specific software's modelling approach, assumptions, limitations and capabilities is required to select the most appropriate software package.
- Allowing sufficient computational time for the level of detail required in the hydraulic model.
- Sufficient processing and data storage availability.
- Making provision for a third party peer review, in line with international best practice for hydraulic modelling.

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