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Flood inundation modelling summary report – a review of existing methods and data and description of proposed method

Murray–Darling Water and Environment Research Program

Project RQ7 Enhancing floodplain inundation and volume prediction to support environmental watering and water resources planning

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Foreword

The Murray–Darling Water and Environment Research Program is an Australian Government initiative to strengthen scientific knowledge of the Murray–Darling Basin. It is designed to help inform water and environment management decisions which will improve outcomes for the Basin and its communities. Four priority themes have been identified as the focus of the strategic research: Climate Adaptation, Hydrology, Environmental Outcomes, and Social, Economic and Cultural Outcomes. Research Question 7 (RQ7) – Enhancing floodplain inundation and volume prediction to support environmental watering and water resources planning – is one of the research projects in the Hydrology theme. This report is a summary of the findings from the first 6 months of RQ7 research. It consists of 2 parts: Part I is a review of related literature, existing models, and past projects; and Part II describes details of the proposed method, prerequisites, and outputs.

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The authors pay respect to the Traditional Owners and their Nations of the Murray−Darling Basin. We acknowledge their deep cultural, social, environmental, spiritual and economic connection to their lands and waters.

Executive summary

Flood inundation models are useful tools to support decision making in environmental watering and water resources planning. Since the 1970s, systematic efforts in the research community have greatly improved the capability of the models. Different models of varying complexity, data requirements and computational demands have been developed to apply to a range of applications. Hydrodynamic models are often used to inform water resources management. However, even with advances in computing power, the high computational cost and data requirement associated with hydrodynamic models prevent their use in systematic management and scenario planning, which requires modelling across large areas.

The RQ7 research aims to build on the capacity and models from previous research and develop a model that is tailored for this purpose. The proposed model is a hybrid between RiM-FIM and the TVD model: it builds a database from remote sensing imagery like RiM-FIM does and uses a model to simulate water balance on the floodplain like the TVD model does. The RQ7 research will improve the prediction of flood inundation extent, depth and duration, and floodplain volumes.

The first part of this report reviews the commonly used flood inundation models and previous key modelling efforts in the Murray—Darling Basin. The second part of the report describes the proposed innovative method that combines multiple datasets and predictive modelling. The method will be developed and tested in key locations. Approaches will also be developed for upscaling the method to other parts of the Basin. The report also describes the collation, development and synthesis of multiple datasets required for developing, constraining and validating flood inundation models (e.g. spatial water extent, water depth, DEM, hydrodynamic model outputs, river stage heights, flow hydrographs).

The main users of the project outputs will be the MDBA, Basin States, CEWO and hydrological and environmental consultants. The knowledge and tools developed in this project will enhance floodplain inundation and volume prediction and modelling under current and future climates and under different management options to inform environmental watering and water resources planning and adaptation.

Part I Review of methods and projects

1 Introduction

Flooding is a phenomenon that causes casualties and property loss nearly everywhere in the world. It is the most frequent weather-related disaster with the highest impact in the number of people affected (International Disaster Database https://www.emdat.be). Multiple lines of evidence show that the socioeconomic impact of flooding is increasing, and that poor countries are disproportionally more affected (Di Baldassarre et al., 2010; Blöschl et al., 2017; Hallegatte et al., 2016). It is also the most expensive natural disaster in Australia.

The most costly summer for floods in Australia was 2010-11, with extensive flooding in the Lockyer Valley, Ipswich and Brisbane in January 2011. This flooding resulted in a cost of A$6.64 billion (2013 Australian dollars, including deaths and injuries but excluding most indirect losses). There were 35 deaths and 20,000 people were made homeless. Between 1967 and 2013, the average direct annual cost of flooding has been estimated at A$943 million (excluding the cost of deaths and injuries).

– Geoscience Australia

Floods can have positive impacts as well (Poff, 2002). They can bring welcome relief for people and ecosystems suffering from prolonged drought. Being part of a natural cycle, periodic scouring floods are essential for maintaining the health of wetlands and riparian ecosystems. The recognition of both positive and negative impacts of flooding has enabled enormous effort to be committed to the study of rivers and their inundation.

Human activities are known to change the flow regime and bring devastating consequences to the freshwater ecosystems and biodiversity (Poff & Matthews, 2013). Water diversion and extraction for human use can cause loss of connectivity between rivers and their floodplains, destruction of wetlands and extinction of flora and fauna – and eventually, have extensive effects on human welfare, including jeopardised water security, declining water quality, reduction in riverine productivity and degradation of river basins. Many countries have realised these adverse effects and are using environmental flows to restore the health of ecosystems (Arthington et al., 2006; Patten et al., 2001). Australia is one of the first countries to acknowledge the environment as a legitimate water user. Since 2004, the Australian government has been undertaking a globally unprecedented water recovery process that involves investment in water-saving infrastructure and strategic water purchasing. The delivery of the acquired water to the environment is, however, extremely challenging both technically and politically. How to best balance among cost, safety and benefit is a research question that Australian scientists have been striving to answer in the last decades and are the interest of the entire world with the rising global awareness of riverine systems in crisis.

Flood inundation models are useful tools to support such decision making. Systematic efforts within the research community since the 1970s have greatly improved the capability of the models. The models are widely used in flood risk mapping, flood damage assessment, real-time flood forecasting, hydraulic engineering, and water resources planning, as well as having served as an important prerequisite for investigating riverbank erosion and floodplain sediment transport, contaminant transport, floodplain ecology, river system hydrology and catchment hydrology. Different models with varying complexity, data requirement and computational demand have been developed to apply to a range of above-mentioned applications (Teng et al., 2017). Learning from the existing models, we are proposing to develop a quantitative, objective method to provide information at an appropriate spatial scale that is relevant to basin wide water management decision making, and at a temporal scale that low frequency temporal variations can be considered.

In this report, we first review the most widely used flood inundation models and previous key modelling efforts in the Murray—Darling Basin (MDB) (Sections 2 – 3); we then describe the innovative method under development that has the potential to be scaled up for systematic water management (Sections 4 – 6).

2 Commonly used flood inundation models

In the last century we have witnessed rapid advancement in the way we undertake flood inundation modelling. Two categories of approaches have attracted the most attention in the research community, with a third type gaining popularity in recent years. The 2 most commonly used approaches are empirical methods and hydrodynamic models, and the third type is conceptual models.

2.1 Empirical methods

The empirical methods include geological evidence, on-ground measurements, surveys, interviews, photographs and most recently, remote sensing data. Most of the time, the results from these methods are regarded as "observations" and used as truth to validate other model results. But in fact, they are a limited representation of reality and there are uncertainties associated with each of them. However, they are still powerful tools to provide insights to the behaviour of flooding.

One of these methods that is particularly useful is remote sensing. It has been proven to be a valuable source of water observation at synoptic scale, complementing the declining network of on-ground measurements, and is most beneficial for data sparce remote regions and developing countries (Schumann & Domeneghetti, 2016). It has been routinely incorporated in flood inundation model calibration, validation, and to a lesser extent, model assimilation, as well as providing real-time flood mapping and monitoring. The proliferation of airborne (including drone based) and spaceborne missions in recent years has rapidly increased the spatial and temporal coverage of remote sensing data. Better sensors, faster data transmission and processing and more advanced data mining techniques using Artificial Intelligence/Machine Learning (AI/ML) offering new opportunities to advance our understanding of flood dynamics and enhance our ability to monitor floods at local and global scales. Two special issues published by Remote Sensing (Domeneghetti et al., 2019; Schumann, 2015) have been dedicated to the advances in remote sensing techniques and applications in flood modelling and monitoring. Most of the latest research focusses on extraction of flood extent using multispectral or hyperspectral sensors (Ticehurst et al., 2021a; Kordelas et al., 2018; De Vries et al., 2017), with an increasing number of studies making use of synthetic aperture radar (SAR) to detect flood water in complex environments (Chaabani et al., 2018; Chini et al., 2019; Huang et al., 2018).

The above-mentioned studies are only a demonstration of a rich literature on approaches that detect the spatial extent of floodwaters from satellite imagery. The maturity of these approaches has reached the point that government agencies are providing the spatial extent of floodwaters as standard analysis ready data products. There are some good examples such as the Water Observations from Space (WOfS), a web service provided by Geoscience Australia (GA), displaying historical surface water observations derived from Landsat imagery for all of Australia from 1987 to present day (https://www.ga.gov.au/scientific-topics/community-safety/flood/wofs); and the NRT global flood mapping using MODIS imagery funded by NASA (https://floodmap.modaps.eosdis.nasa.gov); and the European Space Agency Grid Processing on Demand (G-POD) tool (https://gpod.eo.esa.int/) that provides datasets from ENVISAT as well as a high-performance data processing service. This, and the growing availability of high-resolution Digital Elevation Model (DEM), such as Space Shuttle Radar Topography Mission (SRTM), ASTER Global Digital Elevation Model (GDEM), Copernicus DEM, and Light Detection and Ranging (LiDAR), freely available at many data service providers, such as U.S. Interagency Elevation Inventory, Elvis Elevation and Depth, Open DEM Europe, have made it possible for us to gain more information on flood behaviour historically. Soil moisture and land use data derived from remote sensing are also widely used to inform flood inundation models.

Nonetheless, remote sensing imagery is typically affected by cloud cover, vegetation cover, wind, view angle and other factors depending on the sensor used. It is also worth noting that they are snapshots of the past and therefore cannot reflect the future.

2.2 Hydrodynamic models

The second category of the approaches is hydrodynamic models. They can be used in a predictive way. They are the most thoroughly researched and are undergoing the fastest development. There is one thing in common among these models: they all model the water movement by solving some forms of equations.

The **Navier-Stokes Equations** were first devised in the 18th century. This set of equations can describe the flow of any fluid we can encounter in life: air, gas, smoke, cloud, water, blood, honey, glass, glacier, sand, galaxy and so on. It is widely used in weather forecasting, design and testing aeroplanes, ships and vehicles, modelling water in pipes, rivers and oceans, design of harbors, dams and dykes, investigating the flow of blood in the circulatory system, and studying the formation of nebulas and galaxies in astrophysics.

Conservation of momentum $$\frac{\partial u}{\partial t} + u \cdot \nabla u + \frac{1}{\rho}\nabla p = g + \mu \nabla \cdot \nabla u \quad (1)$$

Incompressibility condition $$\nabla \cdot u = 0 \quad (2)$$

where u is the velocity; ρ is the fluid density; p is pressure; g is gravitational acceleration; μ is kinematic viscosity; ∇u is the tensor gradient and $\nabla \cdot$ is the divergence. The first equation is the momentum equation. It is derived from Newton's Second Law: the sum of forces is equal to mass times acceleration. The second equation is a simplification of continuity equation, which enforces conservation of mass in a Eulerian analysis. The solution of this equation is a velocity field by time. As there is no analytical solution to these equations, various simplification and assumptions have been made for approximation.

The **Saint-Venant Equations** were formulated in the 19th century by 2 French mathematicians. They are also known as the two-dimensional shallow water equations, which represent mass and momentum conservation in a plane, and can be obtained by depth-averaging the Navier-Stokes equations. They are very similar to the Navier-Stokes equations in form: both contain the equations to enforce conservation of momentum and conservation of mass. Except the unknown variables are no longer velocity in 3 directions, but only in 2 directions plus the depth of the water.

Conservation of mass $$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \quad (3)$$

Conservation of momentum $$\frac{\partial(hu)}{\partial t}+\frac{\partial}{\partial x}\left(hu^2+\frac{1}{2}gh^2\right)+\frac{\partial(huv)}{\partial y}=0 \qquad (4)$$

$$\frac{\partial(hv)}{\partial t}+\frac{\partial(huv)}{\partial x}+\frac{\partial}{\partial y}\left(hv^2+\frac{1}{2}gh^2\right)=0 \qquad (5)$$

where *x* and *y* are the 2 spatial dimensions, and the 2D vector (u, v) is the horizontal velocity averaged across the vertical column. The solution of these equations comprises estimates of *u, v,* and *h* over space and time. The Saint-Venant Equations have no analytical solutions. Many numerical schemes are therefore developed for algebraic approximation.

The **One-dimensional Saint-Venant Equations** are simplification of the two-dimensional Saint-Venant Equations.

Conservation of mass $$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=0 \qquad (6)$$

Conservation of momentum $$\frac{1}{A}\frac{\partial Q}{\partial t}+\frac{1}{A}\frac{\partial(\frac{Q^2}{A})}{\partial x}+g\frac{\partial h}{\partial x}-g\left(S_0-S_f\right)=0 \qquad (7)$$

where *Q* is the flow discharge (*Q = uA*, where u is the cross-sectional averaged velocity and *A* is the flow cross-section area), *t* represents time, *h* is the water depth, *g* is the gravitational acceleration, S_f is the friction slope and S_o is the channel bed slope. These equations are very difficult to solve analytically but can be solved using numerical techniques. The solution of these equations comprises estimates of *Q* and *h* for every cross-section at each time step.

The hydrodynamic models can be generally divided into 1D, 2D, and 3D depending on their spatial representation and equations they solve. 1D models represent a floodplain with a series of cross-sections. They simulate a single value for each cross-section by solving one-dimensional Saint-Venant equations. These types of models are particularly useful when the flow is markedly 1D, such as in a channel or a pipe. They are not suitable for free surface flow spreading to a floodplain. Some examples of 1D models that are widely used in Australia are: TUFLOW 1D, SOBEK, MIKE 11, HEC-RES 1D.

2D models represent the floodplain in a two-dimensional mesh with the assumption that the water depth is shallow in comparison to the area. The 2D models are probably the most well-developed, widely used models in flood risk assessment. The 2D models normally solve two-dimensional Saint-Venant Equations or Diffusive Wave equations. Many techniques have been developed to simulate water movement accurately and rapidly as well as to overcome numeric instability. The 2D models commonly seen in Australia are: TUFLOW 2D, MIKE 21, MIKE Flexible Mesh, TELEMAC 2D, Cama-Flood, LISFLOOD-FP, ANUGA, HEC-RES 2D etc.

Another research hotspot is the combination of 1D and 2D models which use a 1D model to simulate flow in the channel and a 2D model to simulate water movement on the floodplain. By doing so we benefit from both 1D and 2D models. MIKE FLOOD is one such model.

3D models come into the picture to address the representation of vertical features like turbulence and vortices, which might not be very important for a gradually swelling river but becomes important for storm surge and flooding caused by dam break. 3D models solve the Naiver-Stokes Equations. They were once thought to be prohibitively expensive to run and were rarely used in flood modelling. But with fast hardware and development of smoothed particle hydrodynamics (SPH) models, their use in flood modelling is increasing (Prakash et al., 2014). The SPH was first developed to solve astrophysics problems and its use in flood simulation is relatively recent. As 3D fluid simulators are used in many fields, such as astrophysics, engineering, atmospheric science and entertainment industry, there have been a lot of research in developing fluid solvers, to list a few, there are Marker and Cell, Particle in Cell, and most recently, Fluid Implicit Particle (FLIP), which is a hybrid between grid based and particle based models. Some well-known 3D flood inundation models are: TUFLOW FV, SPM, DELFT3D, MIKE3, TELEMAC 3D.

With proper set-up, the hydrodynamic models can be quite accurate (Néelz et al., 2013). However, these models typically have high computational cost and input data requirements. The most common input data include high resolution DEM, flow hydrographs, spatial surface roughness coefficients and validation data. High resolution and accurate DEM such as LiDAR (1m) is not available across large regions and roughness coefficients and validation data are not always reliable and easily obtainable and reliable, which can affect the performance of these models.

2.3 Conceptual models

With all the advances, hydrodynamic models are becoming faster and cheaper to run. However, they are still computationally expensive and not suitable for very large floodplains and probabilistic flood risk estimates which require many modelling runs (Néelz et al., 2013). This is where the conceptual models becoming appealing. These models are based on simplified physical processes and once the pre-processing is done, it is orders of magnitude faster to run than the hydrodynamic models when simulating a flood event. The flood extent, water level and volume simulated by these models have been shown to be comparable to 2D hydrodynamic models. However, they have no representation of inertia terms and are therefore not suitable for dam break, tsunami and erosion studies.

One of such models is the Height Above Nearest Drainage (HAND) model (Garousi-Nejad et al., 2019; Nobre et al., 2011), which generates a drainage network, then normalises topography by finding local relative heights along the drainage network. The flood inundation is then derived from displaying the cells with the same relative height.

There is also the rapid flood spreading method (RFSM) (L'homme et al., 2008), which divides the floodplain into impact zones in the pre-processing and then use a series of spill and merge rules to spread water into adjacent impact zones.

Another 2 models described in detail below were both developed at CSIRO Land and Water. They laid the foundation of the newly proposed model and built the capacity of the flood inundation modelling team within CSIRO.

2.3.1 RiM-FIM/MDB-FIM

The River Murray Floodplain Inundation Model (RiM-FIM) (Overton et al., 2006) was developed at CSIRO as a research and decision support tool for environmental flow management in the River Murray. The model development started from 1997. RiM-FIM was initially developed to cover the River Murray from the South Australian border to the Lower Lakes. It was later expanded to include the entire length of regulated section of the Murray River and was enhanced further by incorporating a DEM to provide water depths during flooding events (Penton & Overton, 2007).

Similar methods were subsequently applied in the Edward-Wakool, Lower Murrumbidgee and Lower Darling systems (Sims et al., 2014). An attempt to expand this technique across the Basin was undertaken in MDB-FIM with the inclusion of MODIS imagery and Open Water Likelihood (OWL) index (Doody et al., 2009; Chen et al., 2011; Overton et al., 2009).

The model was developed using remote sensing, spatial analysis functions (ArcPy or NumPy/SciPy) and hydrological modelling. Satellite images of individual flood events were captured and classified to map the extent of inundation. The extent of flooding was then interpolated between observations using a DEM to model flood growth patterns. The model was then linked to river flow gauges to provide a predictive tool for flood extent for a range of river flows. The model was also able to predict the depth of flooding and could be used to determine wetting and drying cycles when linked to river flow regimes.

The RiM-FIM predicts the extent of flooding on the River Murray floodplain from a range of river flows and weir levels. It is useful for predicting the extent of inundation on the River Murray floodplain (~606,000 ha) including the flow regimes of wetlands and floodplain vegetation. It allows for spatial and quantitative analysis of the flood extents to be used as an input into the management decision process. The modelling approach was quite labour intensive, and results varied from site to site. The accuracy of the RiM-FIM methods were not formally established; however, water resource managers report that these methods provided a cost-effective dataset that was useful in supporting their decision-making.

2.3.2 TVD model

The Teng Vaze Dutta (TVD) model (Teng et al., 2015) was first developed to close floodplain water balance for a river system model. The model works like a bathtub method except it adjusts the DEM first to remove the general slope in the terrain along the length of the river channel. It then derives the flood extent by intersecting a series of planes at fine intervals with a high-resolution DEM then eliminating the depressions that are not connected to the river channel. A database is built to link water level, overbank volume, flood extent and depth. This pre-processing is done only once, and the result can be used to model any flood events by linking the water level or streamflow with flood extent. The remote sensing data are used to adjust the outputs. An improved version of the model (Teng et al., 2018) supports modelling of a river reach with a changing flow direction. It has also incorporated a module to capture the process of changing soil moisture, taking into account rainfall, evapotranspiration and infiltration. The model works particularly well in floodplains with even slope and confined channels.

2.4 Advantages and limitations

Table 1 compares the 3 approaches described above. They all have their own strengths and limitations and are suitable for different applications. In summary, the empirical method is most suitable for flood monitoring and post disaster assessment; the hydrodynamic models are good with impact of dam break, flooding caused by tsunami, and riverbank erosion studies; and the conceptual models are most suitable for probabilistic flood risk assessment, multi-scenario modelling, and water resources management on large floodplains.

Table 1 Comparative summary of the relative merits and weaknesses of different modelling approaches

METHOD	STRENGTHS	LIMITATIONS	SUITABILITY
Empirical models	• Relatively quick and easy to implement • Based on observation • Derived inundation estimate is independent • Technology is rapidly improving	• Non-predictive • No/indirect linkage to hydrology (difficult to use in scenario modelling) • Coarse spatial and temporal resolution (although improving) • Engineering limitations (sensors, carriers, transmission devices) • Environmental impacts (clouds, wind, damaging weather conditions, other natural constrains) • Processing errors (algorithm, artificial errors…)	• Flood monitoring • Flood damage assessment • Serve as observations to support calibration, validation and data assimilation for other methods
Hydrodynamic models	• Direct linkage to hydrology • Detailed flood risk mapping • Can account for hydraulic features/structures • Quantifies timing and duration of inundation with high accuracy	• High data requirements • Computationally intensive • Input errors can propagate in time	• Flood risk assessment • Flood damage assessment • Real-time flood forecasting • Flood related engineering • Water resources planning • River bank erosion • Floodplain sediment transport • Contaminant transport • Floodplain ecology • River system hydrology • Catchment hydrology
Conceptual models	• Computationally efficient	• No inertia terms (not suitable for rapid varying flow) • No/little flow dynamics representation	• Flood risk assessment • Water resources planning • Floodplain ecology • River system hydrology • Catchment hydrology • Scenario modelling

Source: adapted from Table 3 in Teng et al. (2017)

2.5 Volumetric analysis

All 3 flood inundation modelling approaches can provide information for volumetric analysis on the floodplain. The depth of floodwater is the key input when the volume of water is required. Hydrodynamic models that characterise flows in one, 2 or 3-dimensional domains can be used to estimate flood water depth. However, these models, which typically solve differential equations of conservations of mass and momentum, quickly become inefficient, time consuming and expensive with increasing scale (Hosseiny et al., 2020). In cases, where large scale hydrologic-hydraulic modelling is implemented, as in the case of the National Water Model (Cohen, Praskievicz, et al., 2018), a number of simplifications/assumptions are applied, such as a trapezoidal channel geometry and quasi-normal flow conditions, resulting in increased uncertainty and errors (Zarzar et al., 2018). Theoretically, if the extent and elevation of the flooded area's terrain are given, the water depth is also known. Simple approaches have been developed inferring the depth from a priori information on the elevation of terrain, such as the Floodwater Depth Estimation Tool

(FwDET) (Cohen et al., 2019; Cohen, Brakenridge, et al., 2018) that we will discuss further in Section 5.3.

When the flood extent and water depth are known, the floodplain volume can be defined as follows:

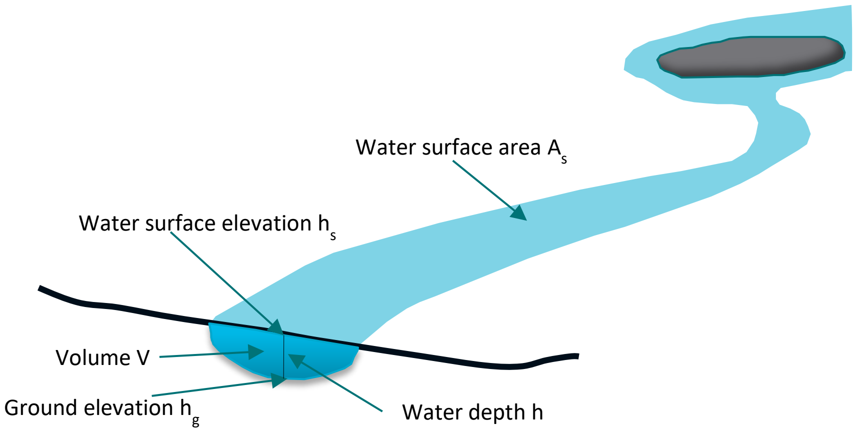

Figure 1 Volumetric analysis

where
Single cell area $\boldsymbol{A_c = dxdy}$ (8)
Single cell water depth $\boldsymbol{h = h_s - h_g}$ (9)
Surface area $\boldsymbol{A_s = \sum A_c}$ (10)
Volume $\boldsymbol{V = \sum A_c h}$ (11)

The accuracy of the volume estimation depends on the accuracy of water extent, water surface elevation and ground elevation (including floodplain bathymetry).

The MDB has numerous floodplain reaches where river flows can overtop the river bank and spread across the floodplain during high flows (from natural flood events or from controlled storage and/or environmental flow releases). To support and enhance water resources management, it is important to know how much of the flow goes to the floodplain under different flow regimes and for how long, how much of it fills up wetlands, evaporates and infiltrates, and how much of it eventually returns to the river. The estimation of floodplain flows from water balance components can be conceptualised as follows:

$$\boldsymbol{V_i + V_o + P = V_h + E + I + V_r} \quad (12)$$

Where V_i *is* in-channel flow volume; V_o is overbank flow volume; P is floodplain rainfall; V_h is harvested volume; E is floodplain evaporation; I is floodplain infiltration; and V_r is return flow volume.

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3 Previous flood studies in MDB

The MDB extends across 4 States: New South Wales, Victoria, Queensland, and South Australia and covers an area of 1.061 million km^2. It is subject to multi-year droughts and intense wet periods. Mean annual precipitation across the Basin varies from around 200mm/year in the west to more than 1,500 mm/year in headwaters the east. The basin has large interannual variability of precipitation and streamflow (Potter et al., 2010), and the basin has seen statistically significant reductions in precipitation and streamflow in recent decades. The river system is also highly modified. River operators manage the river flows through a series of dams and weirs to provide water to irrigators and environmental assets along the length of the system. It is no surprise then, that there have been numerous flood studies by government agencies.

Government agencies ranging from the Commonwealth government organisations, State governments, CMAs, local councils, research institutes including universities and private organisations such as insurers, utility companies and consulting firms have carried out many flood modelling activities in the Basin throughout the years for various purposes. Since a high-resolution DEM is a foundation dataset for almost any modelling work related to flooding, a DEM coverage map gives us a good indication on the coverage of flood modelling work across the basin. Figure 2 is a map from https://elevation.fsdf.org.au showing the coverage of the high-resolution DEM. It is almost certain that wherever DEM <=5 m is available, there are flood/tsunami inundation modelling activities carried out for that region.

The New South Wales Flood Data Portal (https://flooddata.ses.nsw.gov.au) has recorded 1375 flood projects that were conducted by 157 organisations. There are 2501 datasets archived, in which 579 are public (based on the last visit on 10 Nov 2021). The majority of them are floodplain risk management studies and plans commissioned by local city councils. Similarly, Geoscience Australia has a nationwide Australian Flood Risk Information Portal (https://afrip.ga.gov.au/flood-study-web). Queensland Department of Resources has Flood Check Queensland (https://floodcheck.information.qld.gov.au), which provide the spatial extent and information of the flood study carried out within Queensland. Some flood modelling related datasets can be found in the Queensland Government Open Data Portal (https://www.data.qld.gov.au). The Government of South Australia has Flood Awareness Map (https://www.waterconnect.sa.gov.au/Systems/FAM) and provide coastal flood mapping viewer (http://spatialwebapps.environment.sa.gov.au/CoastalFloodMappingViewer/?viewer=CoastalFloodMappingViewer). Major South Australian flood modelling related datasets can be found in the Data SA (https://data.sa.gov.au) archive. The Victorian Department of Department of Environment, Land, Water and Planning is also providing state-wide flood warning and mapping service (https://www.water.vic.gov.au/managing-floodplains/flood-warning-and-mapping) and the Victorian Flood Database can be downloaded from the Victorian Government Data Directory (https://discover.data.vic.gov.au/dataset/victoria-flood-database).

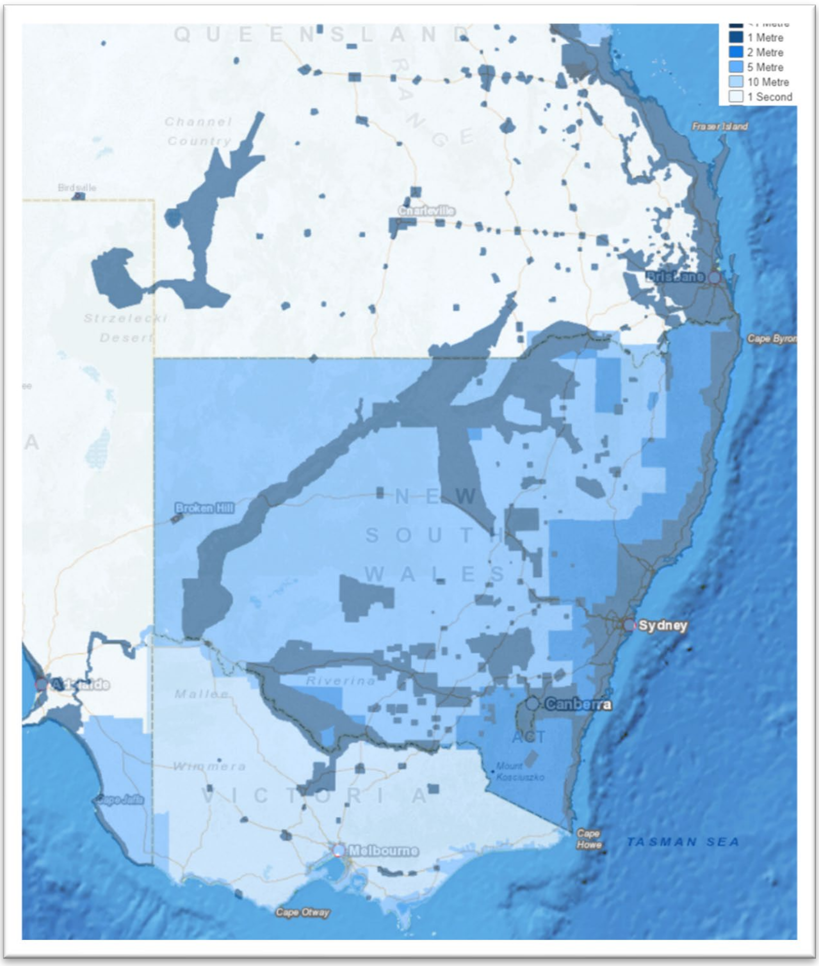

Figure 2 Map from Elvis - Elevation and Depth - Foundation Spatial Data (GA) showing the coverage of high-resolution DEMs

There are thousands of flood related modelling studies that have been carried out previously in the MDB. On one hand, this highlights the importance of the work; on the other hand, it is difficult to review all the previous work in details. The team reviewed reports and outputs for fifteen key flood inundation modelling in different parts of the Murray—Darling Basin:

SA:

- 1956 flood model (Renmark Paringa - https://www.waterconnect.sa.gov.au/Content/Publications/DEW/DEWNR-TR-2015-56.pdf)
- Riverine Recovery Weir Pool Hydraulic Modelling Hydraulic Modelling (2012) - first database of flows (https://www.waterconnect.sa.gov.au/Content/Publications/DEW/Weir%20Pool%20Hydraulic%20Modelling_FINAL.pdf)
- 2020 Model (DHI) - updated database from SA
- Production of 80 000 ML/day flood inundation map for the South Australian section of River Murray (Montazeri & Gibbs, 2020)

(Some of the MIKE models are described separately – e.g. for Katarapko wetlands - https://www.waterconnect.sa.gov.au/Content/Publications/DEW/DEWNR-TN-2016-06.pdf)

NSW:

- Barwon Darling Reach 3 - Background document to the Floodplain Management Plan for the Barwon-Darling Valley Floodplain 2017 (https://www.industry.nsw.gov.au/__data/assets/pdf_file/0006/146085/Background-document-FMP-Barwon-Darling-Valley-Floodplain-2017.pdf)
- Mollee - Background document to the Floodplain Management Plan for the Lower Namoi Valley (2020) (https://www.industry.nsw.gov.au/__data/assets/pdf_file/0011/321131/Background-document-to-the-Floodplain-Management-Plan-for-the-Lower-Namoi-Valley-Floodplain-2020.pdf)
- Lower Gingham (report not publicly available)
- Murrumbidgee
- Macquarie Marshes

CSIRO:

- Darling system (Dutta et al., 2016)
- Edward-Wakool system (Vaze et al., 2018a)
- RiM-FIM (Penton et al. 2007, Sims et al., 2014)
- MDB-FIM (Chen et al., 2011)

MDBA:

- Lindsay hydraulic model (Water Technology 2006)
- Edward Wakool Model (currently under development)

After examining the above-mentioned models and reports, we have selected 5 large-scale high impact projects that have modelling results accessible to us and listed them in Table 2. Their spatial locations are shown in Figure 3.

Table 2 Selected flood modelling projects in MDB

LOCATION	ORGANISATION	PURPOSE	MODEL	MORE INFORMATION
The South Australian section of River Murray	SA Department for Environment and Water	Environmental flow	• MIKE FLOOD	Montazeri & Gibbs (2020)
Lower Balonne and Middle Darling System	• CSIRO • MDBA	Water management Environmental flow	• MIKE 21	Dutta et al. (2016)
Lower Murrumbidgee River	• CSIRO • NSW Office of Environment and Heritage	Environmental flow Flood risk management	• RiM-FIM • TUFLOW (upstream of Balranald)	• Sims et al. (2014) • https://www.wmawater.com.au/projects/murrumbidgee-floodplain-risk-management-study
Namoi River	NSW Office of Environment and Heritage	Healthy floodplains and general flood studies and investigations	• MIKE 11 • MIKE 21 Flexible Mesh (FM) • MIKE FLOOD FM	• (NSW OEH, 2017)
Edward-Wakool System	• CSIRO • MDBA	Water management Environmental flow	• RiM-FIM • MIKE 11 • MIKE 21	• Sims et al. (2014) • Vaze et al. (2018a)

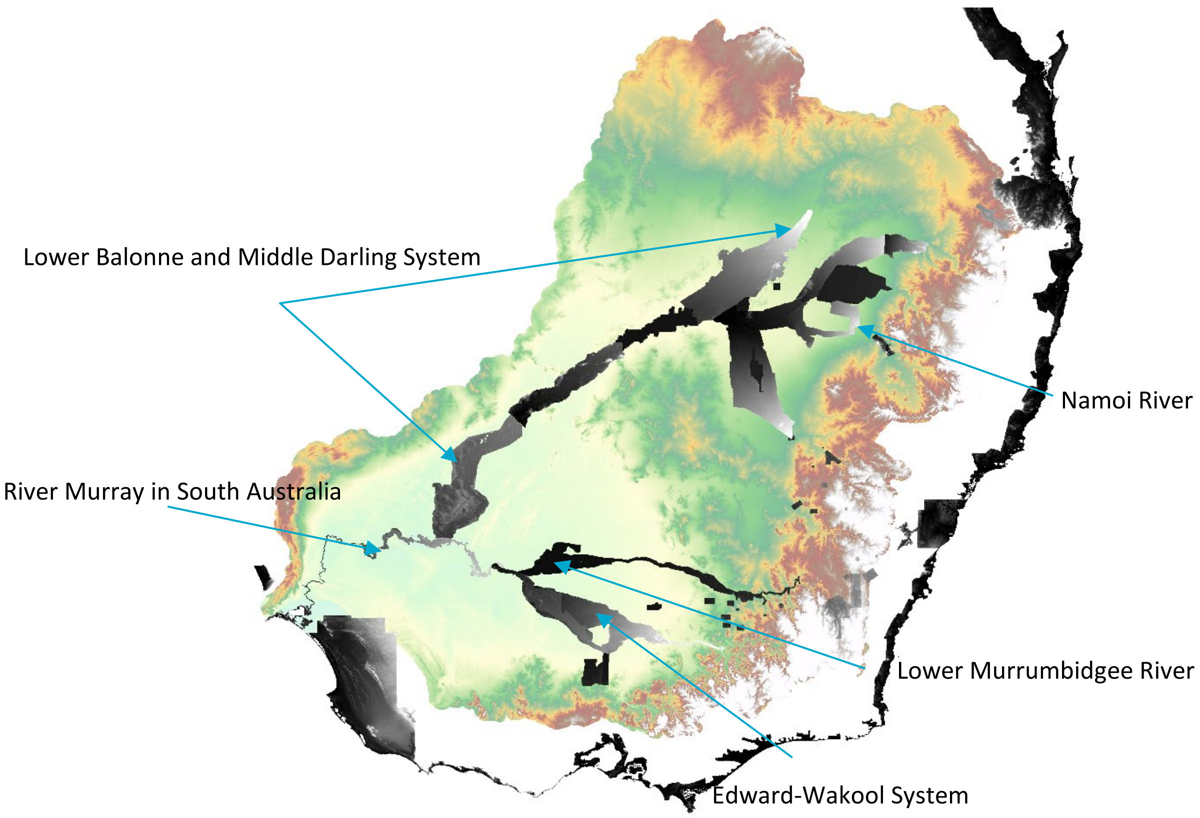

Figure 3 Spatial location of a number of selected flood modelling projects

Part II Description of the proposed method

4 Design concept

The high computational cost and data requirements associated with hydrodynamic models prevent their use in systematic management and scenario planning, which always involve large scale (basin-wide to nation-wide) modelling at high spatial and temporal resolution (Néelz et al., 2013). Benchmarking the latest generation of 2D hydraulic modelling packages. Environment Agency, UK.. The RQ7 research aims to build on the capacity and models from previous research and develop a model that is tailored for this purpose. The proposed model is a hybrid between RiM-FIM and the TVD model: it builds a database from remote sensing imagery like RiM-FIM does and uses a model to simulate the water balance on the floodplain like the TVD model does. This project has 2 research activities that address knowledge gaps in (i) predicting flood inundation extent, depth and duration and (ii) predicting floodplain volumes.

Activity 7.1 will build on the research in the MDB Ecosystem Function (MDB-EF) project and co-develop a hybrid model based on remote sensing imagery and conceptualisation of physical processes to predict flood inundation extent, depth and volume from a given flow hydrograph at a daily time step. The model will be developed for key locations with demonstrated applications informing environmental watering and water resources planning.

Activity 7.2 will improve the estimation of floodplain flows from water balance components of in-channel flow volume + overbank flow volume + floodplain rainfall = harvested volume + floodplain evaporation + floodplain infiltration + return flow volume. The research will seek to relate most of the above terms to floodplain soil physical properties, antecedent soil moisture conditions, flood inundation extent and water depth. The model will establish the stage height - inundation area - volume (H-A-V) relationship for major river reaches, which can then be a direct input to river system models to account for floodplain losses and return flows.

4.1 Building a database

Remote sensing has been proven to be a valuable source of water observation at synoptic scale, complementing the declining network of on-ground measurements. Advanced technologies have been developed to detect the flood extent using multispectral sensors (Ticehurst et al., 2021a). The depth of floodwater is more difficult to estimate but equally important as flood extent, especially when the volume of water is required. Teng et al. (2021, in prep.) reviewed 3 popular methods: Height Above Nearest Drainage (HAND), TVD and Floodwater Depth Estimation Tool (FwDET) for estimating water depth from remotely sensed water extent and a DEM, evaluated the accuracy of these methods for estimating depth against the industry's benchmark hydrodynamic models, and assessed their applicability, advantages, and limitations. It was found that FwDET provides the most accurate water depth out of all 3 methods.

With the rich historical archive of remote sensing data, matured techniques to map water extent enhanced by water depth estimated using DEM, it is possible to build a database linking flow to flood extent and water depth. However, as shown in

Figure 4, with the same flow condition, the flood extent on the falling phase of a hydrograph can be much larger than that on the rising phase, as it can be contaminated by previous flooding. This has reduced the number of remote sensing images that can truly reflect the relationship between flow and inundation by about a half.

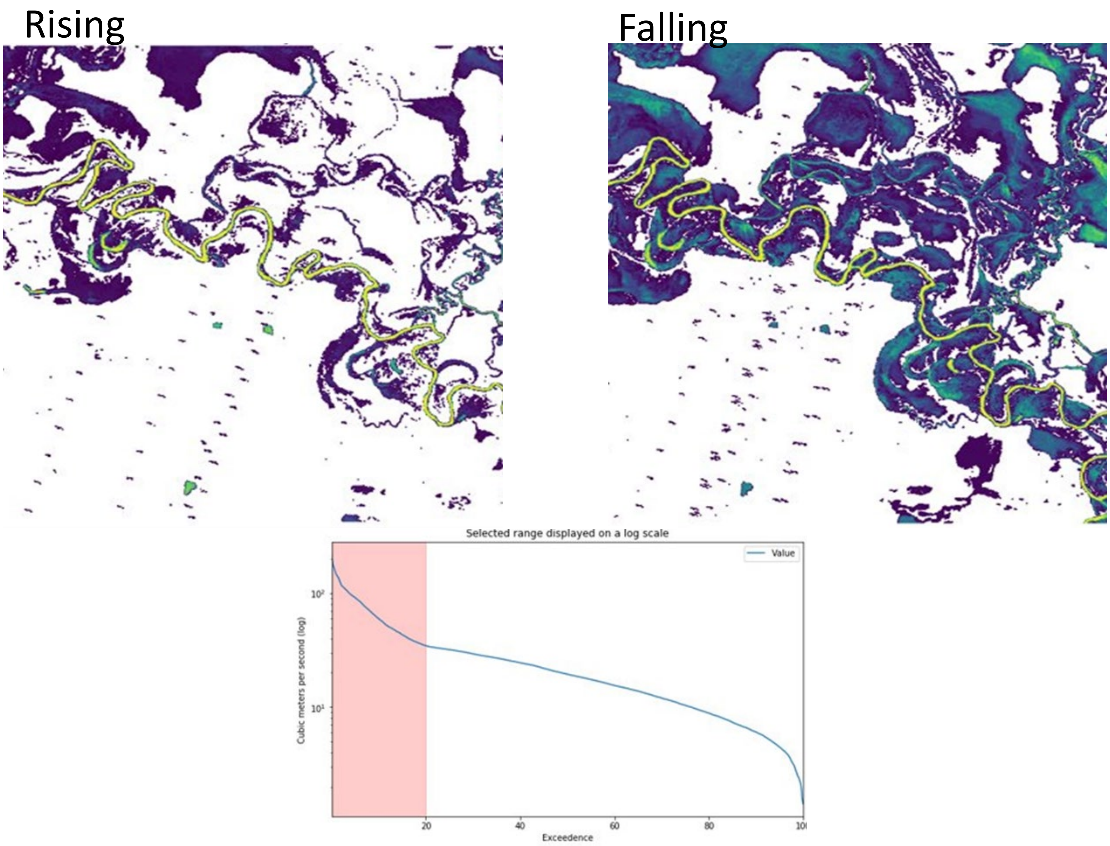

Figure 4 Different flood extents from WOfS for the same flow on the rising and falling phase of the hydrograph

Inspired by RiM-FIM and the GA tool to link flow with inundation data, we propose to build a database of the flow required to inundate areas and water depth on the floodplain. The inundation information will be derived from the multi-index water extents (Ticehurst et al., 2021a) using Landsat (and possibly Sentinel 2) imagery, enhanced with FwDET estimated water depth, on the rising phases of historical hydrographs. Intermediate flood extent and water depth will be interpolated between these extents using a combination of a water balance model and a mathematical model to produce a mapping for the entire spectrum of flow and its inundation, as illustrated in Figure 5.

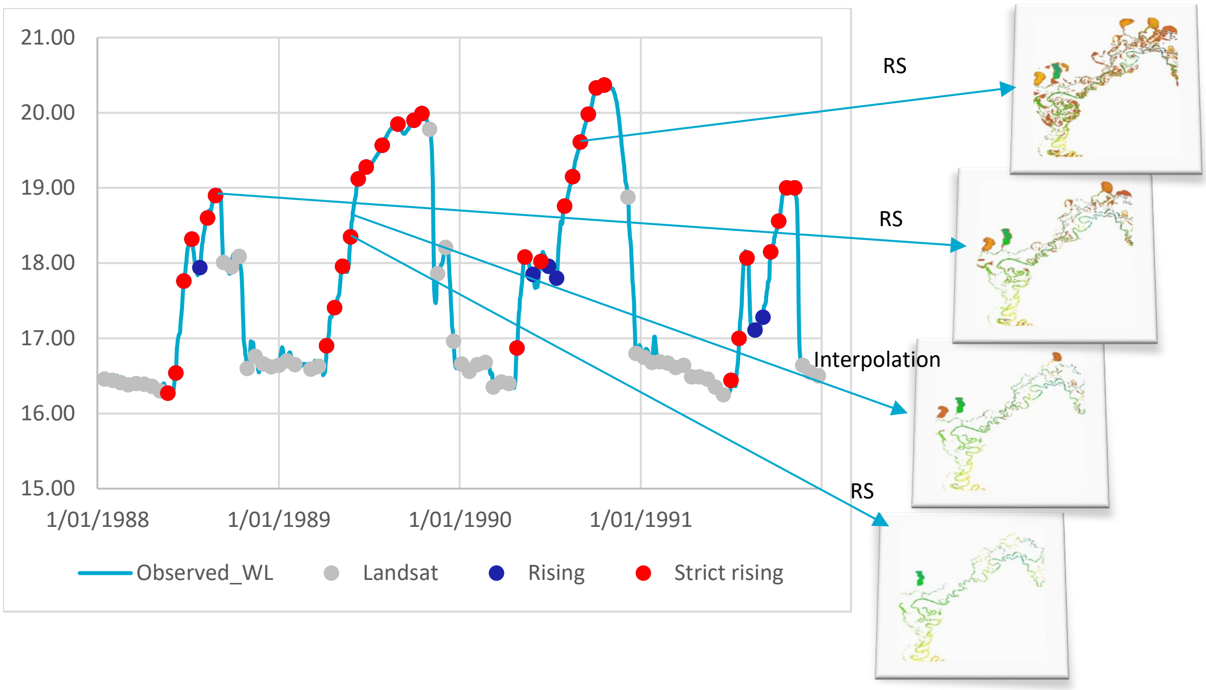

Figure 5 Building a database mapping flow to corresponding inundation using remote sensing and interpolation

4.2 Model simulation

Building on the research carried out in the MDB Ecosystem Function (MDB-EF) project, we will develop a model that is a hybrid between an empirical model (Rim-FIM) and a conceptual model (TVD), which can be applied to major floodplain reaches in the MDB. The hybrid model will predict flood inundation extent and depth for any given hydrograph by linking flow with inundation based on the database described in the last section (Section 4.1). On the rising phase of any hydrograph, the model will look up the corresponding inundation from the database for each time step. On the falling phase, the model will simulate inundation dynamics based on the water balance on the floodplain. Local rainfall, evapotranspiration and infiltration all have substantial impacts on the spreading of the flood, and the wetting and drying of the floodplain depressions that are disconnected to the main channel. We will use the module implemented in the TVD model to capture these processes. The soil moisture content will be continuously updated throughout the model simulation. An empirical method – the Horton model (Horton, 1941) – will be used to relate infiltration rate to elapsed time modified by certain soil properties. The infiltration capacity f_p to time t relationship may be expressed as

$$f_p = f_c + (f_0 - f_c)e^{-\beta t} \quad (14)$$

where f_0 is the maximum infiltration rate at the beginning of an event and reduces to a low and approximately constant rate of f_c as the infiltration process continues and the soil becomes saturated. The parameter β controls the rate of decrease in the infiltration capacity. Horton's equation is applicable only when effective rainfall intensity is greater than f_c and parameters f_0, f_c and β must be evaluated using observed infiltration data (Maidment, 1993). To satisfy these conditions in the model, the infiltration equation will be set to be effective only when the rainfall intensity is greater than f_c or when the grid cell is covered by flood water. The soil moisture is only affected by evaporation if none of the criteria are met.

Instead of using a constant parameter f_0, we can make a modification to Horton's model by varying f_0 at each time step based on the soil moisture content. Considering that the grid cell may have been flooded on the earlier time steps other than the immediately previous one, the maximum infiltration rate f_0 becomes a function of the soil moisture content:

$$f_0 = C(S_0 - S_t)e^{-\beta t} \quad (15)$$

where C is a constant, S_0 is the maximum soil moisture capacity and S_t is the modelled soil moisture content at the time step. This requires the soil moisture content S_t to be kept in memory throughout the computation. As the Horton model usually runs at an hourly time step, but our model will run at a larger interval, typically at a daily time step, the infiltration needs to be accumulated for the actual time step using iterations or a cumulative summary function.

4.3 Consideration of volume

The research activity 7.2 will first explore the possibility of using existing models (e.g. Source, as used by MDBA and Basin States) and data (e.g. in situ measurements, remote sensing derived ET and water extent) to approximate floodplain volume for water accounting purposes and evaluate how reliable these estimates are. The model under development in Activity 7.1 (Section 4.2) will then be used to establish the stage height - inundation area - volume (H-A-V) relationship for the major floodplain river reaches, which can be a direct input to any river system model to account for losses and return flows. The method will be tested in key areas that have most community concerns and have good input and validation datasets available. The research will attempt to reduce the uncertainty in the floodplain volume prediction by incorporating information on floodplain soil physical properties, antecedent soil moisture conditions, flood inundation extent and water depth.

The model will be used to estimate the amount of water gained from rainfall, lost to infiltration (input to groundwater as recharge), lost to evaporation, harvested by floodplain storages and returned to the river (see Section 2.5). This activity is essential to close the water balance on the floodplain for accurate water accounting. We anticipate challenges during the development of the new model allowing for volumetric analysis. The greatest challenge in this research is probably the estimation of floodplain harvesting volume, which requires inputs from RQ8-H, MDBA and Basin States.

4.4 Challenges and mitigations

Robust prediction of floodplain inundation and volume is a long standing and complex problem. This project will improve floodplain inundation predictions using innovative methods that combine multiple datasets and developing predictive models that are fit-for-purpose for the applications. Major challenges include accounting for changes in floodplain infrastructure over time and floodplain harvesting. Other risks include promising too much and losing key expertise. To overcome these risks, the project has attempted to set realistic goals and expectation management through jointly working with partners across MDBA and WERP.

Some other challenges that we can anticipate include:

- Change of river morphology, terrain, or infrastructure

To mitigate this, we are looking into the option of weighing towards later acquisitions of remote sensing images, including the Sentinel 2 imagery.

- Accounting for river operation and extraction

  This would require operational data and rules, and technical and modelling knowledge, from MDBA and Basin States, which are not always readily available.

4.5 Initial testing sites and planning for model upscaling

The initial testing sites will be chosen to reflect the diversity of riverine environments found in the MDB while aligning with the best available models and datasets. The available hydrodynamic modelling datasets described in Section 5.4.1 will be used as 'truth' to validate the model under development. The initial testing sites will encompass 3 locations, and 11 river reaches in the MDB (Figure 11**Error! Reference source not found.Error! Reference source not found.**). In total, 7 calibration events will be used in the validation of the model (Table 5**Error! Reference source not found.**). Once the hydrodynamic modelling results for the Edward-Wakool system and Lower Murrumbidgee River become available, the plan is to include these 2 locations as the additional testing sites.

We will also develop methods to expand the model to other parts of the MDB. This requires the division of the Basin into appropriately sized regions through which water can travel in around one day (to be consistent with the daily time step of the river system model). We are currently exploring options between Thiessen polygon and residual catchment for the Australian Water Resource Assessment – River System Model (AWRA-R) gauges (Figure 6). The 3D lengths for main channels within each region are also being calculated. We are also collecting data that are required to estimate average velocity, along with the 3D length, so the appropriate size of each region can be determined. Some gauges will be eliminated, and some dummy gauges will be included so that the density of the gauges is even across the Basin.

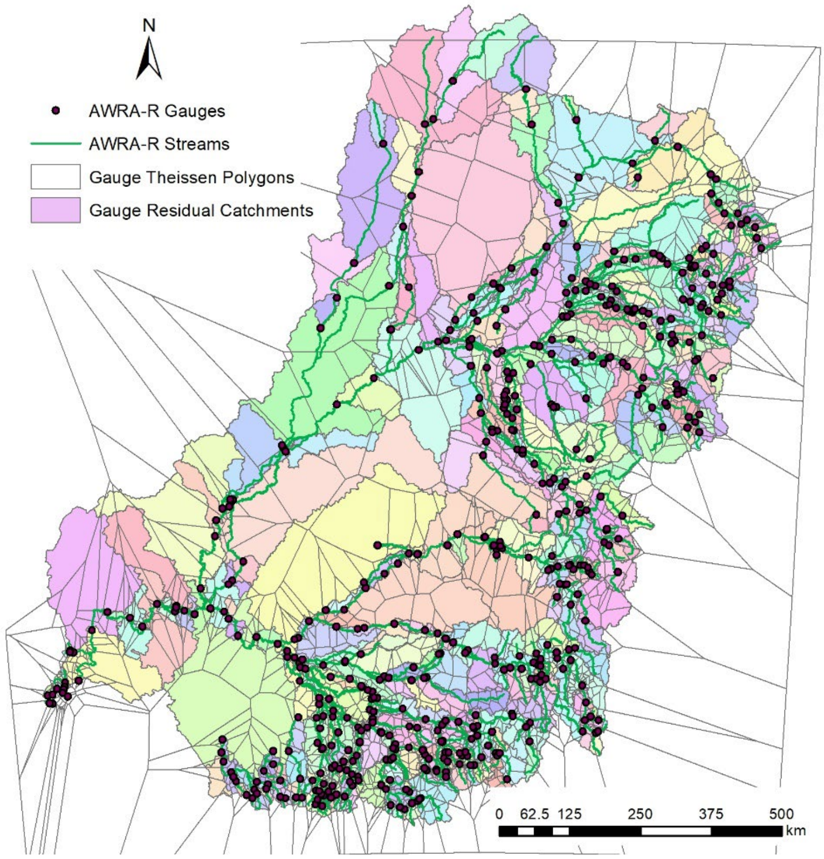

Figure 6 AWRA-R gauges, streams, and their corresponding residual catchments and Theissen polygons

Once the zoning is finalised and the model is developed, users would be able to create the database and set up the model for each of the regions and expand the modelling to other parts of the Basin. The modelling results from individual regions at the end of each time step can then be integrated for a particular river system or a region to reflect the dynamics of the inundation at a larger scale. This will be a useful tool to support decision making for systematic and integrated management.

5 Pre-requisites

The proposed model development builds on previous research carried out in CSIRO including development of conceptual flood modelling through projects such as RiM-FIM and TVD model. In particular, the project builds on outputs of the lateral connectivity research component in the MDB Ecosystem Function (MDB-EF) project. In particular, the proposed model development will use the following research products and outcomes from MDB-EF to build the database described in Section 4.1:

- Improved Floodwater Depth Estimation Tool (FwDET);
- Multi-index surface water mapping product;
- DEM fusion data from LiDAR and SRTM; and
- Data products from hydrological monitoring stations and soil moisture estimates.

The following section provides details about each of these.

5.1 Multi-index water surface detection

This section is adapted from the Ticehurst et al. (2021a), a journal paper currently under review and Ticehurst et al. (2021b) MODSIM 2021 paper.

Mapping surface water extent is an important step in estimating water volume. Ground observations of surface water extent can provide valuable information but are not always available. It is also difficult to obtain large scale synopsis of current and historical water extents through gauging stations and high water marks. Remote sensing technologies provide an affordable means of capturing surface water extent with reasonable spatial and temporal coverage suited to the purpose of water monitoring. The spatial resolution of the Landsat satellite series (30m) makes it suitable for capturing much of the fine spatial detail of a large river basin (e.g. Pekel et al., 2016), at a temporal scale of 16 days (subject to cloud cover). It also has a rich archive of data dating back to 1987 for the thematic mapper series.

There are many methods available for mapping surface water using the Landsat series of remote sensing data. Some of the more commonly used methods within Australia are the modified Normalised Difference Water Index by Xu (NDWI), Geoscience Australia's Water Observations from Space (WOfS), and the Fisher's Water Index (FWI). These methods are designed to map open surface water, leaving flooded vegetation underestimated. To help overcome this gap, Geoscience Australia has invested time and effort into incorporating the Tasselled Cap Wetness Index (TCW) into a wetland mapping tool. Each of these will now be discussed in more detail.

mNDWI –The modified Normalised Difference Water Index (NDWI) uses the green and SWIR surface reflectance bands (Xu, 2006). According to Xu (2006), pixels with values > 0 are water, which also agrees with the work of Fisher et al. (2016). However, Sims et al. (2014) found a threshold value > –0.3 for water was more successful at capturing water extent at a range of sites along the Murrumbidgee River. This threshold (–0.3) has been subsequently used for mapping flooding and persistent waterholes in Northern Australia, as well as flood events in the Fitzroy River WA and the northern MDB. However, it has been found to overestimate surface water extent along the dark floodplains in central Australia (the Cooper basin), where a threshold of 0 was found to be more suitable.

WOfS – The Water Observations from Space dataset is generated by Geoscience Australia and available through Digital Earth Australia (Mueller et al., 2016). WOfS uses a decision tree approach based on a selection of spectral bands and indices from the entire Landsat archive for Australia. Individual images of surface water extent, along with summary statistics (from 1980's to present) are available. The WOfS data was designed to provide a conservative estimate of surface water extent, making it a robust product, but it is more likely to underestimate rather than overestimate water extent. Ticehurst et al. (2017) found an mNDWI with > –0.3 water performed better than WOfS for a selection of flood events in the MDB. The WOfs data are already available for Australia for the whole Landsat archive, making it a valuable source of surface water extent.

FWI – Fisher et al. (2016) developed a new index suitable for mapping surface water with Landsat data across eastern Australia, and uses the green, red, SWIR-1 and SWIR-2 surface reflectance bands. In their analysis, Fisher et al. (2016) compared 7 water index methods (the modified NDWI, and the Tasselled Cap Wetness index), as well as their new water index, for a range of water and non-water types. The results showed the Fisher Water Index (now referred to as FWI) performed best at correctly identifying pure water pixels with a threshold of >0.63, although most indices performed well.

TCW – The Tasselled Cap Wetness (TCW) index uses the blue, green, red, NIR, SWIR1 and SWIR-2 surface reflectance bands (Crist 1985). Fisher et al. (2016) found a threshold of –0.01 was best for mapping pure water pixels. Geoscience Australia has utilised this index to map flooded vegetation as part of their Wetland Insite Tool (Dunn et al., 2019) based on a TCW index threshold of > –0.035 (based on surface reflectance).

These indices have their strengths and weaknesses, as well as different thresholds used for various applications. In particular, our experience has found different methods (both index and threshold value) perform better depending on the vegetation cover, soil colour, soil moisture and water colour. For example, the FWI can miss parts of a major perennial river, while the modified NDWI (with a threshold of –0.3) can detect the river but over-map water along floodplains on dark soil. The TCW can detect more water under flooded vegetation compared to the other indices. While the investigation of Fisher et al. (2016) was extensive in comparing Landsat-derived water indices over eastern Australia, it did not include WOfS data, or some of the thresholds mentioned earlier.

The MDB Ecosystem Function project tested these indices within different environments across the MDB, to assess where they perform best, and compiled a rule set to apply across the whole MDB for achieving the best estimate of surface water. A multi-index method (MIM) was developed for mapping surface water extent within the Murray–Darling Basin (Ticehurst et al. 2021a). It is based on existing indices already used for mapping surface water extent, where each index is applied in the area where it performs at its best. The resulting rule set uses the NDWI>–0.3 to map water in major perennial rivers, TCW>-0.035 to map water in wetlands, and the maximum of NDWI>0 and FWI>0.63 for mapping water in the remaining areas (Figure 7).

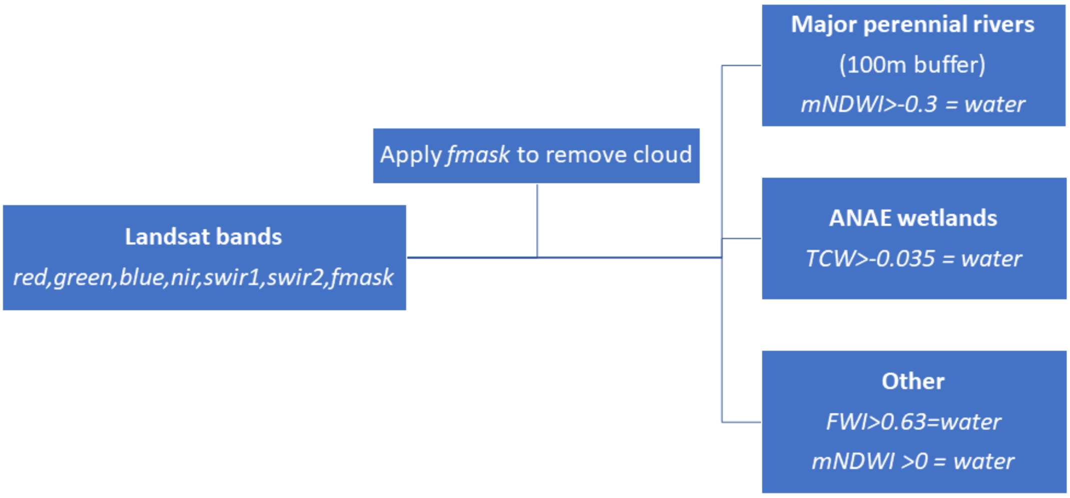

Figure 7 The rule set of the multi-index method (MIM)

An extensive validation dataset is available from Fisher et al. (2016) for eastern Australia. In total 440 plots, of 300m x 300m in size, were used that coincided with the MDB and where Digital Earth Australia Landsat data were available. Based on the 440 validation plots in the Murray–Darling Basin, this resulted in an overall balanced accuracy of 92.7%. Table 3 compares the validation results for MIM and other methods and confirms the advantage of using MIM.

Table 3 Validation results from over 450 plots for different water indices

WATER INDEX	BALANCED ACCURACY
MIM	93%
Fisher WI	91%
mNDWI>0	91%
mNDWI>-0.3	90%
TCW >-0.035	92%
TCW >-0.01	90%
WOFS	86%

Based on these preferred water indices for the different environments within the MDB, the MIM was used for mapping surface water across the basin. Images of two-monthly maximum water extent were created for January-February 2019 for the whole MDB. As this was a relatively dry period, this assessment was about comparing the ability of the water indices for detecting the more permanent water bodies. From these basin-wide mosaics, 5 subsets of the Basin were extracted, and visually assessed (Figure 8**Error! Reference source not found.**). We concluded that the MIM is capable of successfully detecting dams, river channels, permanent wetlands and small water bodies.

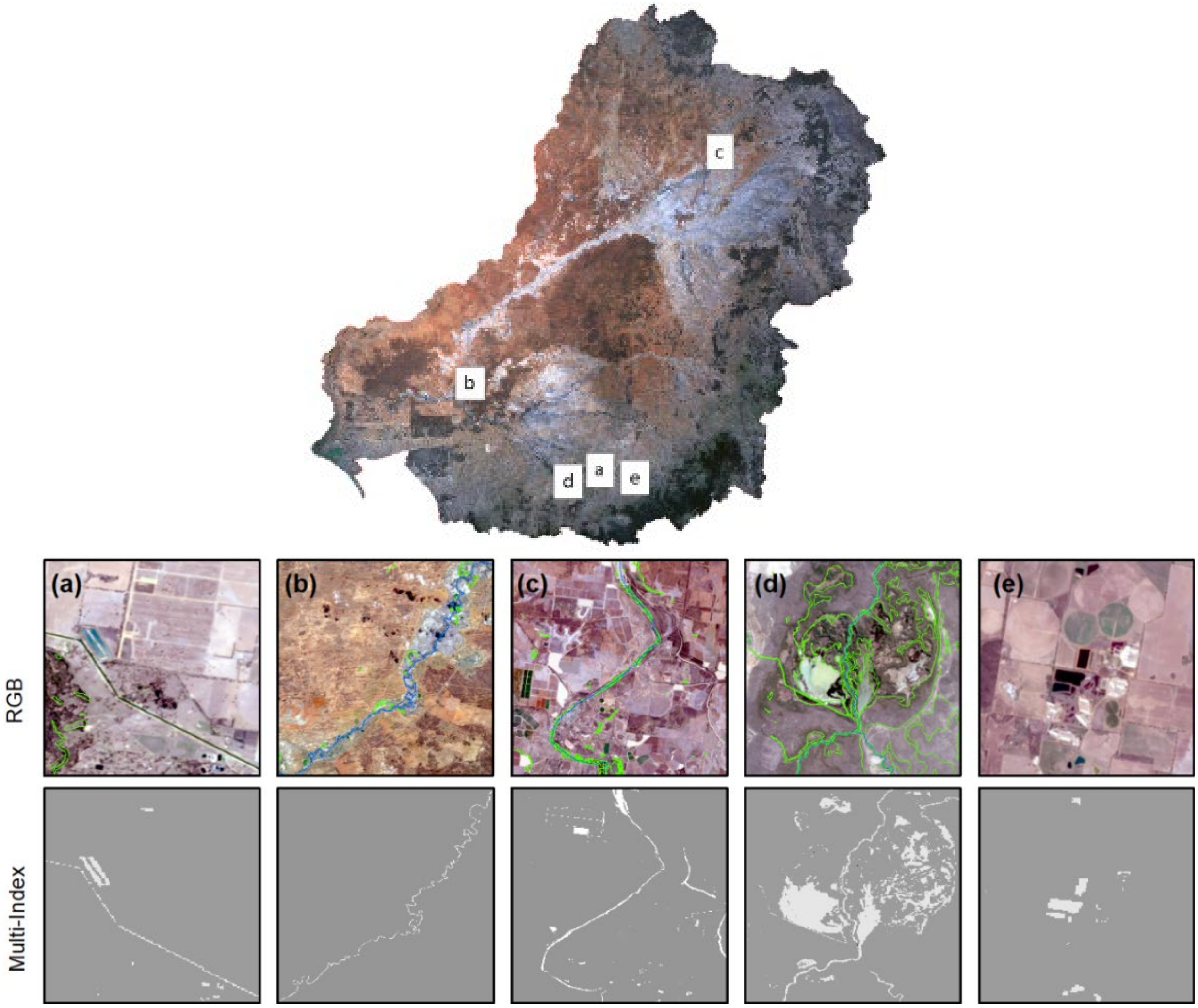

Figure 8 Performance of MIM in identifying water in various environments

In summary, the MIM is relatively simple and fast to process across the whole basin, making it suitable for regional-scale multi-temporal analysis. It captures the maximum of small water bodies where possible, without compromising commission errors for water pixels. It utilises the advantages, as well as minimises the disadvantages, of existing surface water indices commonly used within an Australian environment.

5.2 DEM fusion

This section is adapted from Gallant (2019).

Modelling of flood inundation requires accurate topographic data, which in most cases means high resolution LiDAR or photogrammetric DEM with removal of non-ground features like vegetation. The entire modelling domain must be represented but the area prone to flooding is often a small part of the entire domain, therefore it is often cost-effective to use expensive and detailed elevation data in the focus area and cheaper, less detailed data elsewhere. This leads to the need for combining the 2 DEMs seamlessly so that there are no abrupt changes in height or slope at the transition.

In MDB, LiDAR data was collected in the floodplain area covering most part of floodplains along the main river channels (Figure 9) and the remaining area was covered by SRTM-derived DEM-H at

1 arcsecond resolution. We have adopted a method first developed by Gallant (2019) for adjusting the DEM-H to match the LiDAR data to remove abrupt steps at the boundary to ensure the combined data are suitable for flood modelling. Two main steps in the process are (1) removal of systematic vertical errors and (2) adjusting the less reliable DEM-H to match the LiDAR at the boundary. We have improved the method by fine-tuning the buffer size at the boundary of the 2 DEMs. The method successfully removed local steps and produced a satisfactory result as shown in Figure 9.

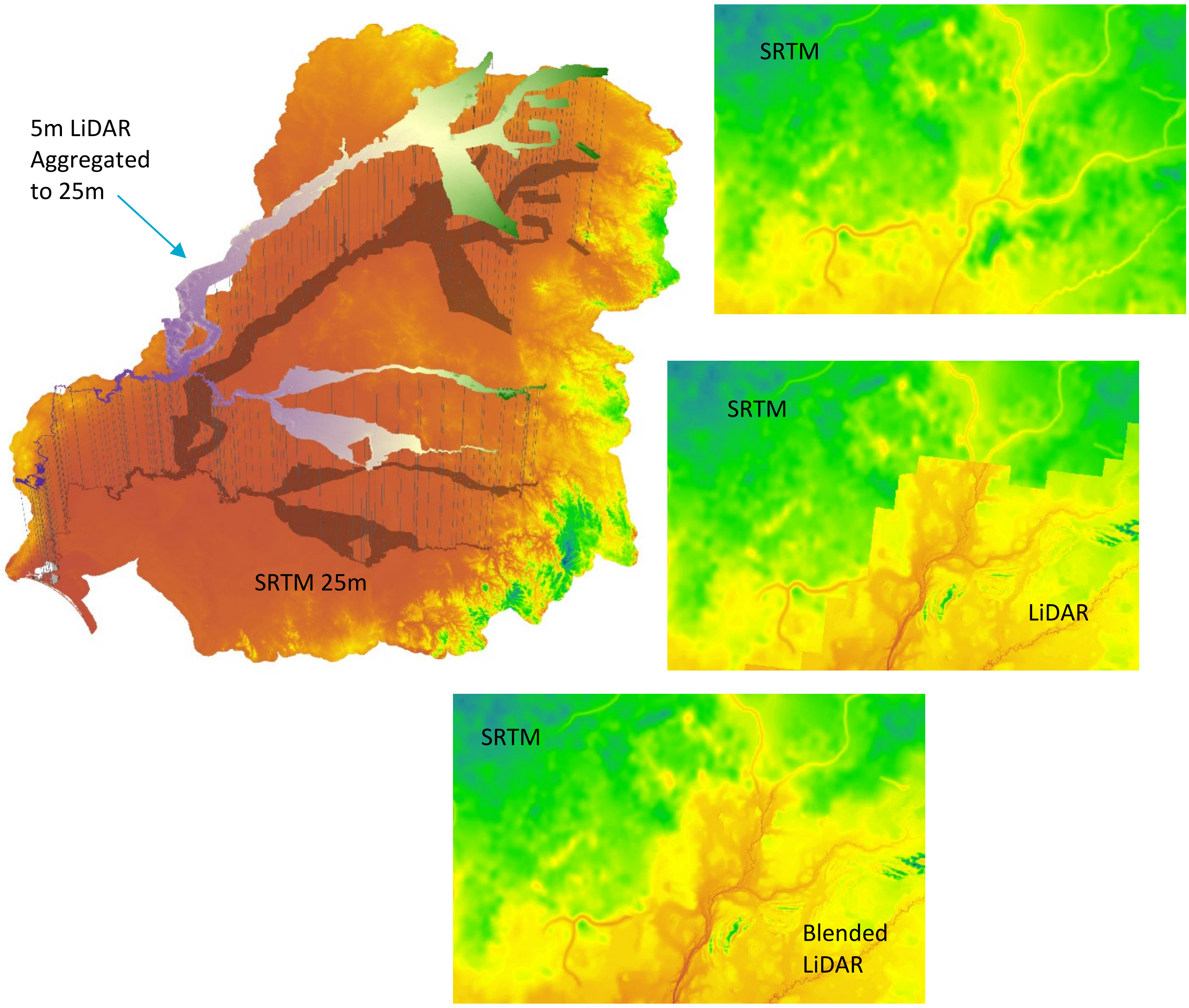

Figure 9 Merging LiDAR DEM and SRTM: the original SRTM and LiDAR DEM are shown in the large map on the left; the top right insert shows a zoomed in view of SRTM; the middle insert shows the abrupt change (local steps) at the boundary of the 2 datasets; the bottom insert shows the merged data with the abrupt change removed.

As new DEM datasets are gradually becoming available, we have set up a strategic project in CSIRO to investigate better methods (including methods using AI/ML) to merge different datasets, including SRTM, LiDAR, and Photogrammetry data. We will be using the outcome from the strategic project to update the DEM whenever a new dataset becomes available.

5.3 FwDET

This section is adapted from Teng et al. (2021), a journal paper in preparation.

The Floodwater Depth Estimation Tool known as FwDET (Cohen et al., 2018) uses an inundation extent raster and a DEM to calculate depth by extrapolating between surface water levels identified along the perimeter of an inundation (Figure 10). The FwDET model estimates the water surface elevation of points along the perimeter of flooded areas. Once this boundary polyline is defined, the water elevation for each inundated cell is interpolated based on the nearest flood-boundary grid-cell. This interpolated surface can also be smoothed using a 3x3 focal averaging technique. Cohen et al. (2018) reported that in comparison with a hydraulic model, the RMSE for FwDET with 10 m Sentinel-1 input was 0.37 m for the Branzos River in Texas, USA and 0.38 m for the St. Vrain Creek, Colorado, USA. The greatest differences (>5 m) were underestimations of flood extent near the flood channel. Cohen et al. (2019) introduced FwDET version 2.0 to improve handling of coastlines and model runtime efficiency using a slightly different interpolation technique. They found that the revised model slightly underestimated flood extent (0.18 m) for a coastal case study in Norfolk-Portsmouth, Virginia, USA. With FwDET version 2.0, the MAE for the Branzos River case study was 0.18 m with a standard deviation of 0.28 m. In our comparison, we did not apply any smoothing and instead, we applied a linear interpolation scheme across Delaunay Triangles.

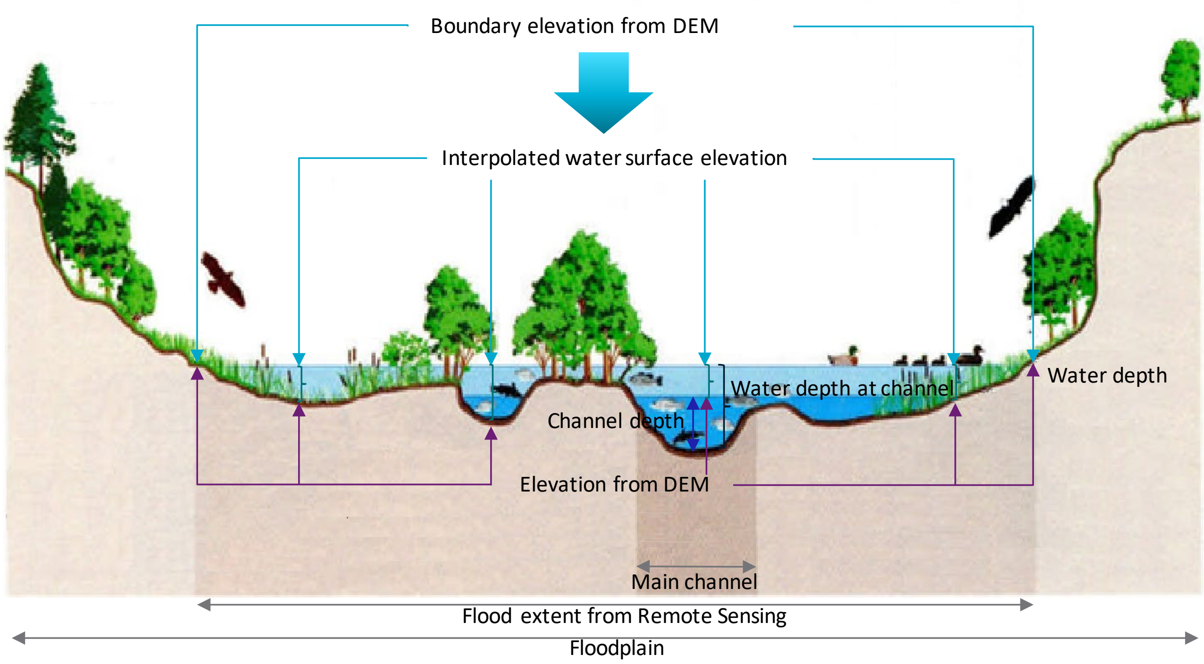

Figure 10 Concept illustration of FwDET

We conducted a study to review 3 popular methods for estimating depth from remotely sensed water extent and DEM, to evaluate the accuracy of these methods for estimating depth against the industry's benchmark hydrodynamic models, and to assess their applicability, advantages, and limitations. The 3 simple models were designed for continental or regional assessment of flood patterns: Height Above Nearest Drainage known as HAND (Nobre et al., 2011), Teng Vaze Dutta known as TVD (Teng et al., 2015) and FwDET.

Each of these models have been compared with hydrodynamic models in the past, usually with an emphasis on the spatial extent of predicted inundation or just with limited case studies. Of the 3 models examined, FwDET provided the best depth estimates with a median RMSE of 0.85 m and a median MAE of 0.67 m across the 26 floods examined as shown in Table 4, although it underpredicted flooding in almost all images - on average by 0.42 m. It was most accurate on the floodplain edge with median RMSE of 0.68 m for floodwaters below 2 m, but the median RMSE for deep inundation (>4 m) was 2.10 m. The distribution of FwDET errors for a combined analysis of 26 flood reaches was reasonably consistent and comparable with a Cauchy distribution. By quantifying the error characteristics, it becomes possible to design and develop methods for using these flood models that are statistically robust. Model accuracy is dependent on the quality of inputs including the resolution of flood extent and DEM. Using higher resolution satellite imagery (e.g. Sentinel 2) and more accurate LiDAR DEM would improve the accuracy. It should be noted that although here we used the hydrodynamic modelling results as 'true' water depth due to lack of water depth observations on the floodplain, there are uncertainties associated with these models too. The fact that FwDET is able to produce water depth in a similar magnitude as the hydrodynamic models is encouraging. Being a simple method that requires less input data and is suitable for processing across large regions, FwDET is therefore chosen to be used to build the database described in Section 4.1.

Table 4 The median estimated from the 26 combinations of modelled flood/reach for HAND, TVD and FwDET. The bracketed numbers are 5th and 95th percentile confidence intervals from 10,000 samples using statistical bootstrapping

	RMSE (M)	MAE (M)	25^{TH} PERC (M)	50^{TH} PERC (M)	75^{TH} PERC (M)	RANGE (25^{TH} TO 75^{TH} PERC) (M)
HAND	1.70 (1.23, 2.37)	1.46 (0.98, 2.15)	-2.36 (-2.87, -2.08)	-1.32 (-2.24, -0.65)	-0.55 (-0.80, -0.17)	1.80 (1.27, 2.27)
TVD	1.53 (1.36, 1.78)	1.28 (1.20, 1.40)	-1.56 (-1.97, -1.25)	-1.09 (-1.43, -0.72)	-0.66 (-0.76, -0.31)	0.88 (0.58, 1.27)
FwDET	0.85 (0.69, 1.09)	0.67 (0.51, 0.76)	0.28 (0.21, 0.38)	0.42 (0.32, 0.48)	0.59 (0.45, 0.80)	0.35 (0.18, 0.77)

5.4 Data preparation

5.4.1 Hydrodynamic modelling results

The RQ7 newly proposed model's predicted water depth will need to be validated with 'true' water depth across the floodplain. As the water depth observations on floodplain are rare and difficult to obtain, for the purposes of the validation, we will be limited by mainly using the depth predicted by a hydrodynamic model as 'true' water depth. Although there are many previous hydrodynamic modelling experiments carried out in MDB, only a few of them have the datasets available in the format and quality that can be used for the purpose of the RQ7 research. For the comparison to be meaningful, it was essential for the hydrodynamic model to be of the highest standard. The RQ7 project evaluated hydrodynamic models based on:

- whether they were peer reviewed, especially whether they had been revised and improved based on experience or feedback.
- whether they were calibrated to dynamic conditions (as distinct from steady-state models).
- the quality of DEM and channel bathymetry – only those based on high resolution LIDAR digital terrain models were considered.
- the resolution of the floodplain in the modelling, with preference to flexible meshes.
- consistency with other information such as gauged levels and spot heights.

The project identified models that best met these criteria – 3 of which would be used in an initial assessment of model accuracy and an additional 2 that would be acquired for later analysis. For the initial 3 models, we extracted outputs of model depth for calibration events to use as validation datasets. This dataset encompassed 3 locations in MDB, 11 river reaches and 7 calibration events.

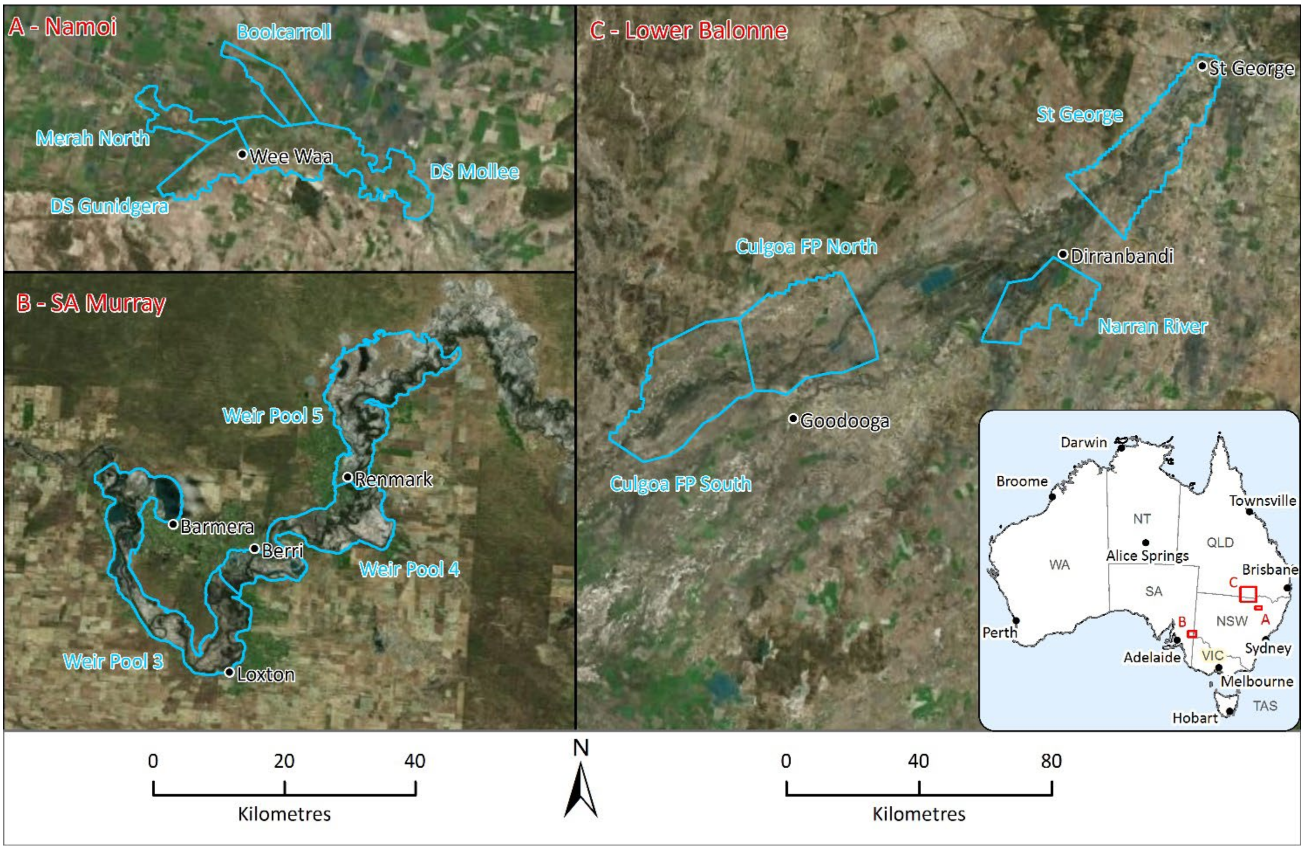

Figure 11 The locations for the available validation datasets including 4 reaches of the Balonne River (right), 4 reaches of the Namoi River (upper left) and 3 reaches of the River Murray (lower left).

As shown in Figure 11 the first location covered the area of the Balonne River downstream of the St George township in Queensland to Weilmoringle in New South Wales. The Culgoa River is an upper tributary of the Darling River in the far north-west of the MDB. The second location was the Namoi River from Keepit Dam to the junction of the Barwon River near Walgett in New South

Wales (one of the upper tributaries of the River Murray). The third location was between Lyrup and Lock 3 on the River Murray in South Australia. The locations were broken down into reaches based upon the location of streamflow gauges and water infrastructure, location of major confluences or distributaries, and location of major irrigation districts. As a result, the Balonne study location was broken into 4 reaches, the Namoi study area was broken into 4 reaches and the SA study location was broken into 3 reaches.

Table 5**.** shows the selected hydrodynamic models. In total there were 7 flood events spread across the 3 study locations with peak discharges of around 25 GL/d to 300 GL/d.

Table 5 Hydrodynamic model properties

	BALONNE RIVER	NAMOI RIVER	RIVER MURRAY
Shortened form in graphs	LBS (Lower Balonne System)	Namoi	SA (South Australia)
Jurisdiction	Queensland, New South Wales	New South Wales	South Australia
Model Type	MIKE 21 – 90m Grid	MIKE 21 Flexible Mesh (FM)	MIKE HYDRO River for channel, MIKE 21 Flexible Mesh for floodplain
Dynamic/steady	Dynamic	Dynamic	Dynamic for 25 GL/d, steady state for 90 GL/d
Flood discharge (nominal)	150 GL/d, 50 GL/d, 250 GL/d, 300 GL/d	185 GL/d	25 GL/d, 90 GL/d
Dates modelled	1995-12-27 to 1996-01-30 2008-01-19 to 2008-02-23 2010-12-28 to 2011-01-28 2012-01-28 to 2012-03-02	1998-07-20 to 1998-07-31	2013-09-06 to 2013-11-03 2016-12-09
Gauging station used for measurement	Balonne at St George (422201),	Namoi River at Molle (419039)	Lock 1 U/S (A4260902) and Calculate for to South Australia (A4261001)
Dates of imagery used	1996-01-28, 2008-02-05* (filled with imagery from: 02-22, 01-29, 02-06), 2011-01-21, 2012-02-17	1998-07-24 (Aerial photography)	2013-10-30, 2016-12-09 (filled with imagery from 2016-12-25)
Publications	Dutta et al, 2016	(NSW OEH, 2017)	Montazeri and Gibbs, 2020
Notes	There are significant irrigation districts in the area (e.g. Cubbie station). We have defined the reaches to avoid these areas.	LandSat imagery was not available for this flood. The channel was defined using cross-sections.	The bathymetry of some small permanent lakes were not fully incorporated in model.

Source: Teng et al. (2021, in prep.)

The hydrodynamic modelling results for Edward-Wakool system and Lower Murrumbidgee River are gradually becoming available. We will convert the results to suitable format and review the quality of the data in due course.

5.4.2 Gauged flow, water level and cross section

The gauged flow and water level data are needed to relate flow and water level for interpolation and model simulation. The velocity data are required to estimate the travel time for each modelling reach, which is essential to determine the size of modelling regions. Velocity u can be derived from

$$u = \frac{Q}{A} \qquad (16)$$

where Q is flow (in m^3/sec or ML/day), A is cross section area, which is a function of water level.

Table 6 lists the online data portals that can be used to extract MDB gauged water data observations and gauge information. However, the data QA is a significant issue. In particular, it is difficult to determine whether the gauged water levels are in local level datum or AHD elevations. Therefore, we are requesting the operational data from MDBA wherever available. We are also requesting data along with metadata directly from the State governments. We have also obtained snapshot of datasets from previous projects where license was granted, such as AWRA and MDB-EF projects. This will be an ongoing process with the change of requirement and new data becoming available, which will involve contacting the data custodians, manual extracting, digitising and other manipulation of the data.

Table 6 Online water data portals

NAME	WEB SITE	PROVIDER	DATA COVERAGE
Water Data Online	http://www.bom.gov.au/waterdata/	Bureau of Meteorology (BoM)	Nation-wide
The River Murray system Live river data	https://riverdata.mdba.gov.au/system-view/	MDBA	The River Murray System
WaterNSW	https://realtimedata.waternsw.com.au/	NSW government	NSW
Water Data SA	https://water.data.sa.gov.au/	SA Department for environment and water	SA
Water Measurement Information System VIC	https://data.water.vic.gov.au/	VIC Department of environment, land, water & planning	VIC
Water monitoring information portal	https://water-monitoring.information.qld.gov.au/	QLD government	QLD
ALS client data portal	https://hydportal.alsglobal.com/web.htm	ACT Icon Water/ACT gov	ACT

5.4.3 Soil property data

The soil property data are required for estimating infiltration in the model simulation as described in Section 4.2. We have obtained the soil property data, namely, saturated hydraulic conductivity for the top soil layer (0 – 10 cm), shallow soil layer (10 – 100 cm) and deep soil layer (100 – 600 cm), available water holding capacity for the top soil layer (0 – 10 cm), shallow soil layer (10 – 100 cm) and deep soil layer (100 – 600 cm) from the Australian Water Resource Assessment Landscape Model (AWRA-L). The nation-wide data layers at 90 m resolution, which was aggregated to 1 km and 5 km resolutions to support AWRA-L, will be extracted for modelling regions to estimate amount of water lost to infiltration for each grid cell at each time step. The methodology for estimating soil hydraulic properties grids using pedotransfer functions and digital soil mapping is described in Appendix A in Vaze et al. (2018b). Vaze et al. (2018b) also provides a brief description of each of the spatial layers (including the source data used to derive the layers) that are used in the continental AWRA-L implementation.

6 Outputs of the project

6.1 Association with the MDB-EF project

The research in RQ7 has strong synergies with the MDB-EF project. Many outputs from the MDB-EF project are used for the RQ7 research. The concept of the RQ7 model was conceived during the MDB-EF project, initially to address the floodplain lateral connectivity for flood durations shorter than 2 months. Most members in the RQ7 research team are also working on the MDB-EF project. The team consists of highly skilful and experienced researchers who have collaborated for many years and are accustomed to work with mutual respect, common and aligned goals, open communication, and patience.

There are clear distinctions between the 2 projects. The research in MDB-EF mainly focused on providing historical information on the floodplain connectivity so that the ecologists can develop relevant metrics for bio-chemical connectivity, productivity, habitat, movements and dispersal for multiple species. In contrast, RQ7 aims to develop a predictive model to enhance floodplain inundation and volume prediction to support environmental watering and water resources planning.

In addition, in RQ7, we plan to:

- Increase the testing sites (from one location and 4-5 reaches initially planned for the MDB-EF project to 3-5 locations and 11-20 reaches, and upscaling the method for application to other parts of the MDB)
- Conduct more in-depth research (for example, we are currently developing an algorithm to better identify rising phases in gauged flow time series, an interpolation method based on water level rather than linear interpolation for the flow between available images, and adding volumetric component in the model, including Santinel-2 data)
- Help build capacity in the MDBA (a MDBA modeller has joined the RQ7 research team and is activity involved in the research)
- Invest in better quality data (apart from WERP, CSIRO has invested in a strategic project for the fusion of multi-resolution DEM data in collaboration with DATA61)
- Develop better visualisation and data distribution method.

Furthermore, most of the composite datasets used in the MDB-EF project need to be updated. The current DEM we are using in the MDB-EF project was combined from SRTM and LiDAR DEM available to us at the time the dataset was generated. As new datasets are gradually becoming available, we will be using the outcome from the CSIRO strategic project to update the DEM. For the next step, we are planning to replace the SRTM data in the NSW domain with the 5m photogrammetry data. Remote sensing derived water extent needs to be derived for each scene on the rising phase (currently we have two-monthly maximum water extent and depth for MDB). The gauged flow and water level data are being updated with new acquisitions and quality control information is becoming available. We are also collecting additional hydrodynamic modelling results for more testing sites, such as the Edward-Wakool modelling results that the MDBA modelling team is finalising, and the Lower Murrumbidgee data from NSW DPIE.

6.2 List of outputs

By the end of the project, we aim to deliver:

6.2.1 Reports and publications

- This report, which (i) reviews existing models and datasets, (ii) conceptualises flood inundation models, (iii) describes data availability (including hydrodynamic model outputs) and modelling requirements in the Basin, (iv) identifies stakeholder needs and key locations, and (v) describes modelling products and datasets for the Basin
- A technical report and/or research paper on development and testing of the prototype hybrid floodplain inundation model
- A technical report and/or research paper on application of the hybrid floodplain inundation model to several key locations (3-5 sites with 11-20 reaches)
- A technical report and/or research paper on the floodplain volume prediction model applied to several key locations.

6.2.2 Datasets

Composite spatial datasets (and short technical note describing them) of:

- 5 m and 25 m DEM for the MDB, seamlessly merged from LiDAR, SRTM, photogrammetry and other sources;
- remote sensing derived water extent (WOfS, multi-index) for key locations
- gauged streamflow and water level for key locations
- hydrodynamic model outputs for validation sites.

6.2.3 Database and model

For key locations, we will build a database for each modelling region linking flow with the flood extent and water depth derived from the remote sensing imagery captured on the rising phases of historical hydrograph. We will also develop a hybrid model for predicting floodplain inundation extent and water depth from any given hydrograph.

6.2.4 H-V-A relationships

For the key locations, we will run model simulations to predict floodplain volume (evaporation, infiltration/recharge and return flows) and provide H-A-V relationships that can be directly used with the Source model, and applied and tested on selected applications.

6.2.5 Use cases

For the key locations, we will develop use cases with MDBA and stakeholders to demonstrate the application of the model in:

- balancing environmental benefit and risks to human society
- estimating efficiency and opportunities of piggy-backing events
- scenario modelling for long-term water resources planning.

6.2.6 Enhanced capability

Through collaboration and training, we aim to enhance the modelling capability within our stakeholder organisations so that the modelling work can be expanded to large parts of the MDB, and the development and application can continue after the project is concluded. We will build stronger hydrology-ecology-management link, collaborations between technical experts in research and MDBA and Basin States, and stronger consensus enhancing trust and progress in water resources management and planning to achieve floodplain outcomes. The RQ7 research will make progress in floodplain inundation and flow prediction science, communicated through direct collaboration across the many related projects that WERP researchers are part of, through research papers from WERP, and through leadership in scientific and modelling forums. Stronger engagement with practitioners and communities will also be formed through WERP communications and engagement strategy and plan (developed by MDBA with consortia partners).

Acronyms

AI/ML: Artificial Intelligence/Machine Learning

AWRA: Australian Water Resource Assessment

BoM: Bureau of Meteorology

DEM: Digital Elevation Model

DTM: Digital Terrain Model

FwDET: Floodwater Depth Estimation Tool

GA: Geoscience Australia

GDEM: Global Digital Elevation Model

GIS: Geographical Information System

HAND: Height Above Nearest Drainage

LiDAR: Light Detection and Ranging

MDB: Murray—Darling Basin

MDB-EF: MDB Ecosystem Function Project

MIM: Multi-index Method

WOfS: Water Observations from Space

RiM-FIM: River Murray Floodplain Inundation Model

RQ7: Research Question 7 – Enhancing Floodplain Inundation and Volume Prediction to Support Environmental Watering and Water Resources Planning

SPH: Smoothed Particle Hydrodynamics

SRTM: Shuttle Radar Topography Mission

TVD: Teng Vaze Dutta

MDWERP: Murray—Darling Water and Environment Research Program

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