Flood forecasting and warning for Muar River: Non-structural measures for flood mitigation

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Abstract

The Muar River catchment has repeatedly suffered prolonged, significant flood events which have caused widespread disruption and impacts to residents, businesses and infrastructure; the impacts have been exacerbated by considerable rapid development over the past decade, which has modified the flow regimes and flooding mechanisms. To help prepare for, and mitigate, the effects of future floods, the Malaysian government is implementing a range of flood management projects, which will provide an integrated approach based on structural and non-structural measures.

The integrated Flood Forecasting and River Monitoring system (iFFRM) for the river Muar is a key non-structural measure that has been recently implemented. The government's Department of Irrigation and Drainage (DID) is responsible for providing a flood forecasting and warning service to the public; the iFFRM is a tool designed to enable effective decision support by DID.

The iFFRM is a fully automated system that is driven by a combination of live, telemetered gauged data from DID's own InfoBanjir database, spatial rainfall radar data, and Numerical Weather Prediction (NWP) rainfall forecasts from the Malaysian Meteorological Department. Hourly simulations are carried out automatically, to forecast water levels and flows in the river channels, and to map the flood inundation process within the flood plains. Simulation results are used to warn DID staff so that immediate action can be taken to provide an effective and proactive emergency response. Results are also passed to the project website, and dedicated smartphone application, enabling forecasts to be disseminated more widely. A parallel analytical modelling network can take over the forecasting role should the primary iFFRM system fail.

Ongoing structural measures for flood mitigation are captured through a flexible modelling approach that can incorporate model updates to reflect real changes in the catchment, complementing the structural measures being implemented by DID and ensuring a sustainable solution.

Keywords
Flood forecasting, warning, decision support

1. Introduction

Hydrological extremes, droughts and flooding, affect every generation and cause suffering, death and material losses (Kundzewicz and Kaczmarek, 2009). The latest data on natural disasters puts the size of historical flood disasters into context, illustrated through information on the impacts of the top ten flood disasters since 1900, through the numbers of people killed and the numbers affected (CRED, 2014). Strikingly, in the first half of the twentieth century, hundreds of thousands of people lost their lives to flood disasters; on the other hand, in the latter half of the period, hundreds of millions of people have been affected. This would imply that whilst the situation has improved in terms of reducing the numbers of people killed through flood disasters, there is still an enormous role for effective flood forecasting and warning to reduce the wider impacts of flood disasters. Significantly, the people affected in the greatest numbers, and the countries suffering the largest economic damages, are primarily found in east and south-east Asia. Flood records for peninsular Malaysia, as far back as 1886 and 1926, report severe floods affecting large parts of the country and causing extensive damage to road systems, property, agricultural lands and crops (Wing, 2004). In recent decades, flooding has become more frequent; the main reasons include loss of flood storage due to development in floodplains, increased runoff due to urbanisation, inadequate drainage systems, flow constriction in river channels due to bridges, culverts and blockages, and siltation due to land clearing (Wing, 2004). In addition, climate change is expected to cause an increase in flood frequency in Malaysia towards the second half of the 21st century (Amin et al., 2017).

Hydrological forecasting is a non-structural measure which has proven to be efficient and cost effective in minimising the negative impacts of flooding and increasing drought preparedness and mitigation (WMO and GWP, 2013; Mishra and Singh, 2011). Effective flood forecasting has the potential to save significant numbers of human lives, as well as saving disruption to many times that figure, and has the ability to save enormous sums of money. A global survey of early warning systems carried out by the UN and the International Strategy for Disaster Reduction, (UN/ISDR, 2006), resulting from the assessment of progress towards Millennium Achievement Goals, concluded that to be effective, early warning systems must be people-centred and must integrate four elements:

- Risk knowledge;
- Monitoring and warning service;
- Dissemination and communication;
- Response capability.

The global survey notes that "a weakness or failure in any one part could result in failure of the whole system" (UN/ISDR, 2006). Kundzewicz (2013) takes this description of the 'Achilles heel' of effective flood forecasting and warning systems one step further by pointing out that " the observation system may fail, the forecast may be grossly in error, the warning message may be wrong, the communication of a warning may be deficient and the response may be inadequate. A single weak point in a system, which otherwise contains many excellent components, may render the overall system performance unsatisfactory". Furthermore, to be successful, such a system requires sufficient integration of components and collaboration and coordination between multiple institutions. Flood forecasting and warning systems sit at the interface of meteorology, hydrology, hydraulics, information technology, and social science. Therefore, each component must be able to perform its role, and the links between them, their integration, must be working effectively too.

The Malaysian government's Department of Irrigation and Drainage (DID) is responsible for providing a flood forecasting and warning service to the public. It is developing a programme based upon the phased implementation of systems for key river basins; the integrated Flood Forecasting and River Monitoring system (iFFRM) for the river Muar is one of the first flood forecasting systems to have become operational. The objectives of this system were to develop and maintain an effective and efficient integrated flood forecasting and river monitoring system, with flood warning dissemination, using national network data, telemetry data, radar data and rainfall forecasts; the iFFRM is a tool designed to enable effective decision support by DID.

The development of the iFFRM is described in this paper, from a description of the nature of flooding in the catchment, through the dataflow and modelling methodologies used, and the operational implementation of the end-to-end forecasting system. Lessons learnt are discussed, with suggestions for how these lessons will be integrated into the total framework of flood forecasting systems in Malaysia.

2. Background

2.1. Catchment description

The river Muar lies on the west coast of peninsular Malaysia, straddling Negeri Sembilan and Pahang states (Figure 1). Its catchment has repeatedly suffered prolonged, significant flood events which have caused widespread disruption and impacts to residents, businesses and infrastructure (Asmara and Ludin, 2014); the impacts have been exacerbated by considerable rapid development over the past decade, which has modified the flow regimes and flooding mechanisms (Wing, 2004). Significant recent flood events occurred in 2006, 2007, 2011, and 2015; these events led to the evacuation of tens of thousands of local residents in the Muar catchment alone. Across Malaysia, an estimated fifth of the population is at risk of flooding (DID, 2009).

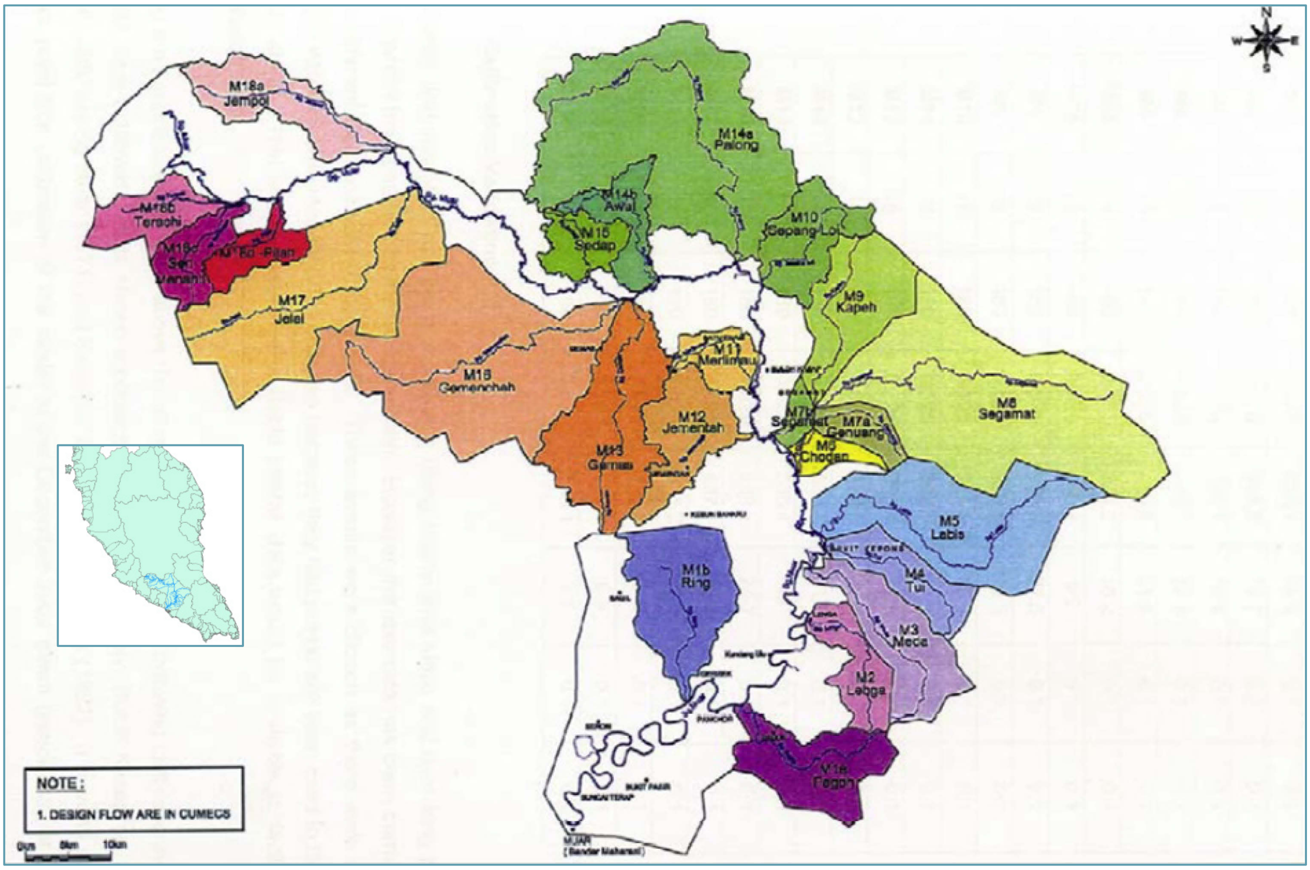

Figure 1: Map of the River Muar catchment, showing the location of the catchment in Peninsular Malaysia (insert).

The topography of the catchment is a mix of steep mountainous, hilly country and undulating low terrain (Hong and Hong, 2016). The climate in the Muar catchment is tropical, with the southwest monsoon occurring in April and May, and the northeast monsoon occurring in October to December. Dry periods dominate in January to March and June to September (Hong and Hong, 2016). The annual average rainfall in peninsular Malaysia is 2500 mm, with as much as 600 mm falling in 24 hours in extreme storm events (DID, 2009b).

The Muar catchment area is approximately 6600 km^2 and subdivides into 21 subcatchments. The total length of the main channel is 310 km, with an average annual discharge at the river mouth of approximately 140 m^3/s. High flows are recorded during the monsoon seasons, with the north-east monsoon (October to December) resulting in the highest flow conditions. The lowest flows are recorded during the dry period of July and August.

Land use in the Muar catchment is a combination of urban, primary rainforest, and agricultural plantations including rubber, oil palm, paddy, maize and vegetable cultivation. Land use has changed rapidly in recent decades. From the 1950s, increasing agricultural production has led to the loss of forested land to become agricultural land to rubber plantations and then palm oil (Abdullah and Nakagoshi, 2008). Malaysia has also seen a growth in manufacturing since the 1980s, which has led to rapid industrialisation and associated increases in urbanisation (Abdullah, 2003) and decreases in agricultural land (Erickson, 1995). Levels of urbanisation are expected to increase further due to allocated housing, commercial and industrial activities. The precise impacts of land use change on hydrology are difficult to predict accurately, but deforestation is generally associated with an increase in runoff (Siriwardena et al., 2006) and increased urbanisation is associated with increases in peak flows (Hundecha and Bardossy, 2004). In summary, the rapid urbanisation and associated land use change in the catchment has led to reduced permeability of runoff surfaces and thus higher, faster, rates of runoff, as well as reduced conveyance capacity in the river channels. These factors have led to increased flood risk, notably of flash flooding, in the catchment (DID, 2007).

3. Approach to system development

The main goals of the iFFRM are to forecast river levels up to three days into the future and to issue warnings if threshold levels have been crossed, and to provide an indication of the likely flood extents on the floodplain.

The iFFRM is a fully automated system that is driven by a combination of live, telemetered gauged data from DID's own InfoBanjir database, spatial rainfall radar data, and Numerical Weather Prediction (NWP) rainfall forecasts from the Malaysian Meteorological Department. Hourly simulations are carried out automatically, to forecast water levels and flows in the river channels, and to map the flood inundation process within the flood plains.

The catchment is represented by a series of models driven by live, observed and forecast, data feeds. These models broadly represent the processes of runoff generation from upstream subcatchments (rainfall-runoff models), feeding the boundaries of detailed hydrodynamic models of the main river channels.

3.1. Hydrological and hydrodynamic modelling

In selecting appropriate models to for flood forecasting, the approach of Booij (2005) is sensibly taken: "find a model that is sufficiently detailed to capture the dominant process and natural variability, but not unnecessarily refined that computation time is wasted or data availability is limited."

Hydrodynamic modelling for the Muar catchment was carried out using InfoWorks RS. This tool is able to model river reaches using full hydrodynamic solution techniques, based upon the Saint Venant equations for shallow water waves in open channels. It can be used to model open channel and overbank flows in any network of channels. Any sensible looped or branched network can be modelled along with a wide range of hydraulic structures. It can be used to solve systems under both steady and unsteady flow conditions. For unsteady solutions, InfoWorks RS uses the governing hydraulic equations for each network object. These equations are a combination of empirical and theoretical equations many of which are non-linear. The non-linear equations are first linearised and the solution to the linear version of the problem is then found via matrix inversion. An iterative procedure is used to account for the non-linearities. (Innovyze, 2014). InfoWorks RS also includes flow routing methods. Flow routing determines the change in shape of a flow hydrograph as it moves along a channel without necessarily calculating water levels; it is a useful technique where detailed cross-section data are not available and a smaller range of results is required. The Muskingum method is a commonly used hydrologic routing method in situations requiring a variable storage-discharge relationship. The network object is based on the continuity equation and the Muskingum storage relationship. The representation of the main river channels of the Muar catchment is shown in Figure 2.

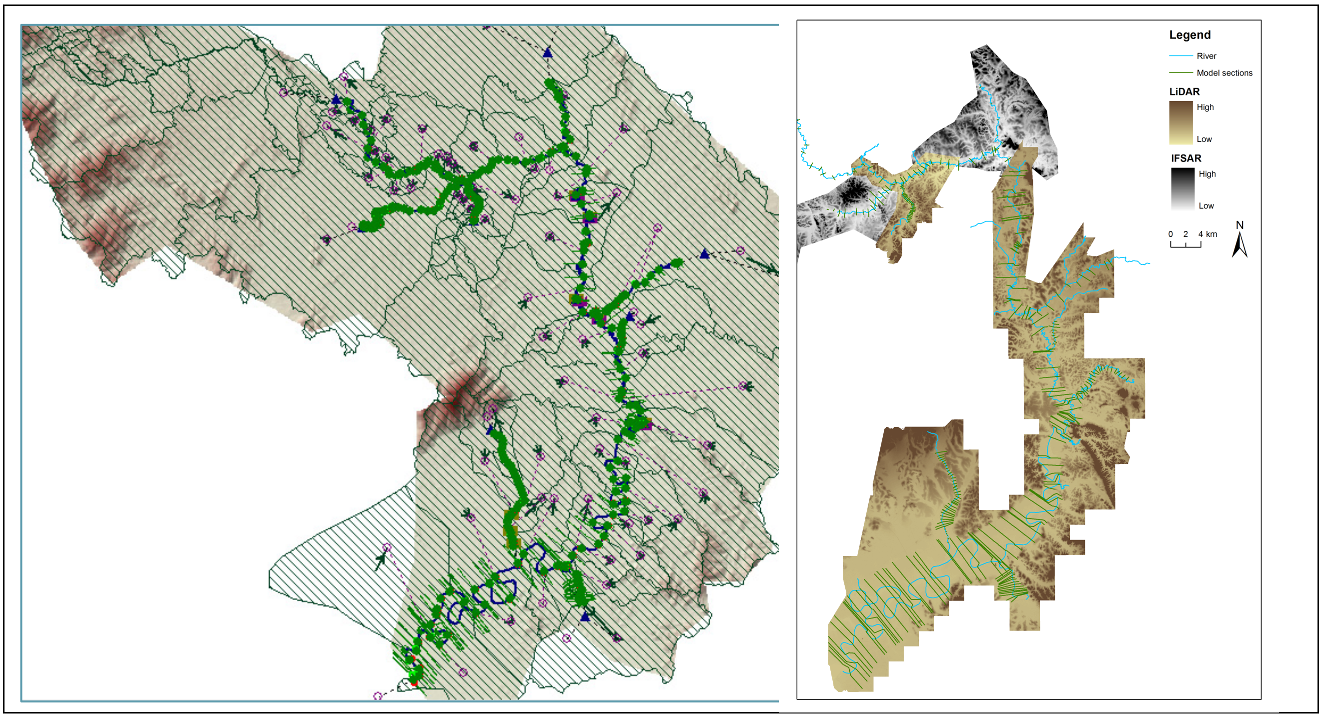

Figure 2: Map of the River Muar catchment, showing the modelled representation of the subcatchments (left), the main and flood plains as covered by the DTM (right).

3.1.1. Probability Distributed Hydrological Model (PDM)

There are broadly two types of hydrological model to choose from: physically-based models and data-driven models. Both types of model have advantages and disadvantages, the reader is referred to (Todini, 2007) for a comprehensive overview. In the case of the Muar catchment there is limited historical data available which would limit the training sets that could be created for a data-driven approach. Using a physically-based model allows all *a priori* knowledge of the hydrological processes to be used in setting up the model, with the aim of reducing the uncertainty of the *a posteriori* forecasts (Todini, 2007).

For gauged subcatchments, the Probability Distributed Model (PDM) provides a pragmatic approach between inherently complex, physically-based approaches, and simplified lumped modelling approaches; this probability-distributed approach considers the frequency of occurrence of certain hydrological variables used to derive algebraic expressions for the integrated flow response from the basin (Moore, 1985). The PDM is a fairly general conceptual rainfall-runoff model which transforms rainfall and evaporation data to flow at the catchment outlet and was developed with operational applications in mind (Moore, 1985). The PDM model essentially distributes rainfall between runoff and recharge according to a soil moisture store. The runoff and recharge is routed via stores to the catchment outflow. One of the main advantages of the model is the use of a probability distribution rather than a single value for the soil moisture store. This represents the spatial variability in soil storage across the catchment and prevents threshold type behaviour. The model's short computational run time and continuous soil moisture accounting model makes it suited to continuous simulation using incoming telemetry data for flood forecasting. The model can also use observed flow data from telemetry to update its internal soil moisture values in a process known as state correction, which is important for maximising the accuracy of the model results.

3.1.2. Simple Runoff Model (SRM)

In the Muar catchment, not all of the subcatchments for which the rainfall-runoff process needs to be modelled are gauged. Setting up hydrological models for ungauged catchments remains a challenge (Bloschl, 2006). When no runoff data are available, keeping it simple is often the best solution. The Simple Runoff model (SRM) is useful for deployment in catchments without any calibration data, or in urban areas if the runoff response is thought not to follow a soil moisture response. Eq. [1] presents the SRM equation.

$$P_{eff} = P_c * RC * (1 - SMD) \qquad [1]$$

where,

$$P_{eff} = Effective\ Precipitation$$
$$P_c = Catchment\ Precipitation$$
$$RC = Constant\ Runoff\ Coefficient\ (0-1)$$
$$SMD = Soil\ Moisture\ Deficit\ Fraction\ (0-1)$$

In this approach, catchment rainfall is multiplied by a runoff fraction which is determined by the user and by a soil moisture deficit (SMD) fraction. The SMD fraction may be fixed, but for rural catchments more accurate results are achieved if a time series of values is supplied. Observed soil moisture data are not available in this catchment. However, using the concept of hydrological similarity, it is assumed that catchments close to each other will behave hydrologically in a similar manner, this assumption is known as spatial proximity (Bloschl, 2006). Using these concepts the soil moisture deficit time series from the PDM models in the gauged catchments can applied to the ungauged catchments. Although this method will increase the uncertainty of the forecasts, using calibration parameters from similar catchments in the same region is preferable to for example using parameters from donor catchments (Bloschl, 2006).

3.2. Representation of the flood plain

An important feature of effective flood warning dissemination, particularly to the general public, is the use of flood inundation maps, ideally generated in real time from the hydrodynamic model rather than as offline look up tables. Offline, event-based hydrodynamic models typically use a linked 2D model of the floodplain to generate flood inundation maps. However, for operational purposes, the simulation time required for 2D flood inundation mapping can be prohibitive, so a 1D approach must be used. For the flood prone areas of the Muar catchment, the topography of the flood plain was represented by a Digital Terrain Model (DTM); a combination of Light Detection and Ranging (LiDAR) data at 10 metres spatial resolution, along with an Interferometric synthetic aperture radar (IFSAR) data set with a spatial resolution of 5 metres. A 1D flood inundation modelling approach was used, to generate flood compartments, at the nodes of which the model calculates water levels, then subtracts the ground elevation to obtain flood depths, and interpolates between them to achieve contoured flood inundation maps. An example of the operational flood map output from the Muar iFFRM is given in Figure 3.

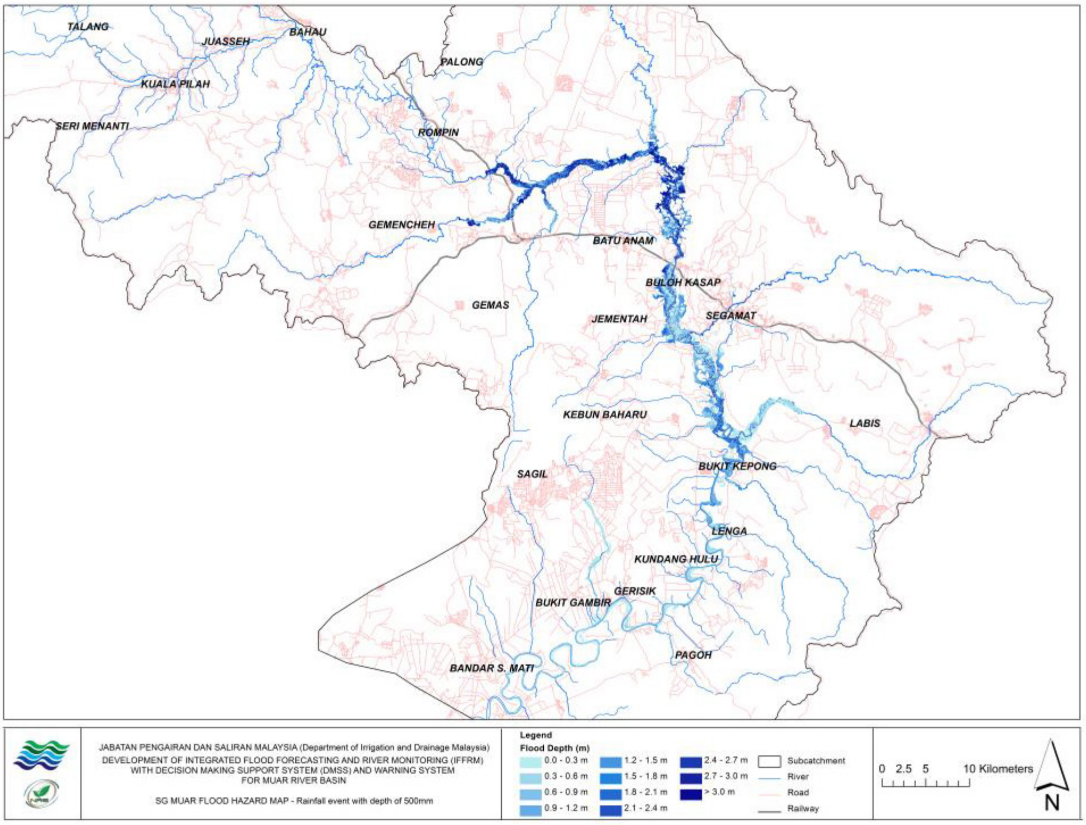

Figure 3: Example of the operational flood map output from the Muar iFFRM.

3.3. Observed data

As with any operational system, the availability of high quality input data of suitable coverage were required for calibration of the underlying models and for driving the operational models in real time. DID operates its own network of telemetered gauges, whose data are stored in the InfoBanjir telemetry database. InfoBanjir was first developed in 1999 as a centralised database system for the telemetry stations and was commissioned in the year 2000. The system receives real time rainfall and water level data from almost 200 telemetry stations throughout the country. Hydrological data from the stations is sent to the state server and further transmitted to InfoBanjir. Initially, InfoBanjir was developed to assist DID officers in monitoring current river water level and rainfall status remotely. More recently, a public portal for InfoBanjir has been developed, with a special focus on flood warning to the general public; a new initiative aims to update InfoBanjir, combining information from the two portals, improving the interface to ease public understanding, and to process the raw data more quickly.

DID operates 19 rain gauges (Figure 4) and 11 water level gauges (Figure 5) throughout the Muar catchment; DID plans to install further gauges to increase the network density. The data are made available through a live feed from InfoBanjir direct to the iFFRM server located at DID headquarters. In addition, rating equations for two of the water level data streams enable conversion to pseudo real time flow data for those locations. Telemetered water level (and flow) data were used in calibration of the underlying models, and are used operationally to raise warnings and for validation of the model results.

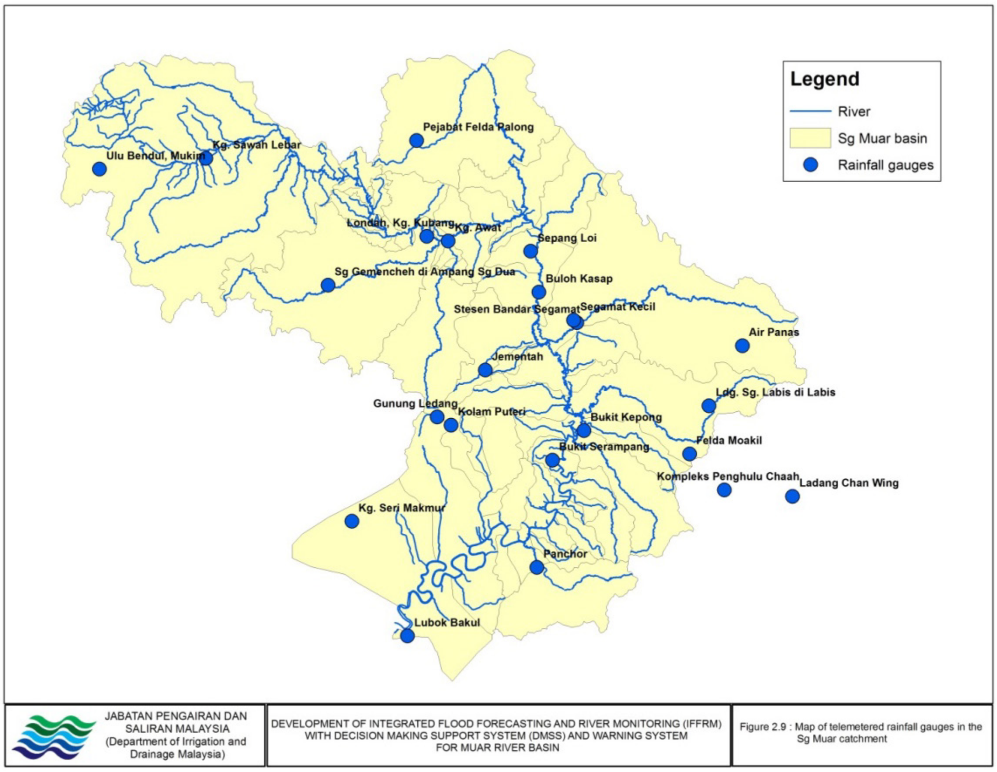

Figure 4: Map of the River Muar catchment, showing the location of the telemetered rain gauges.

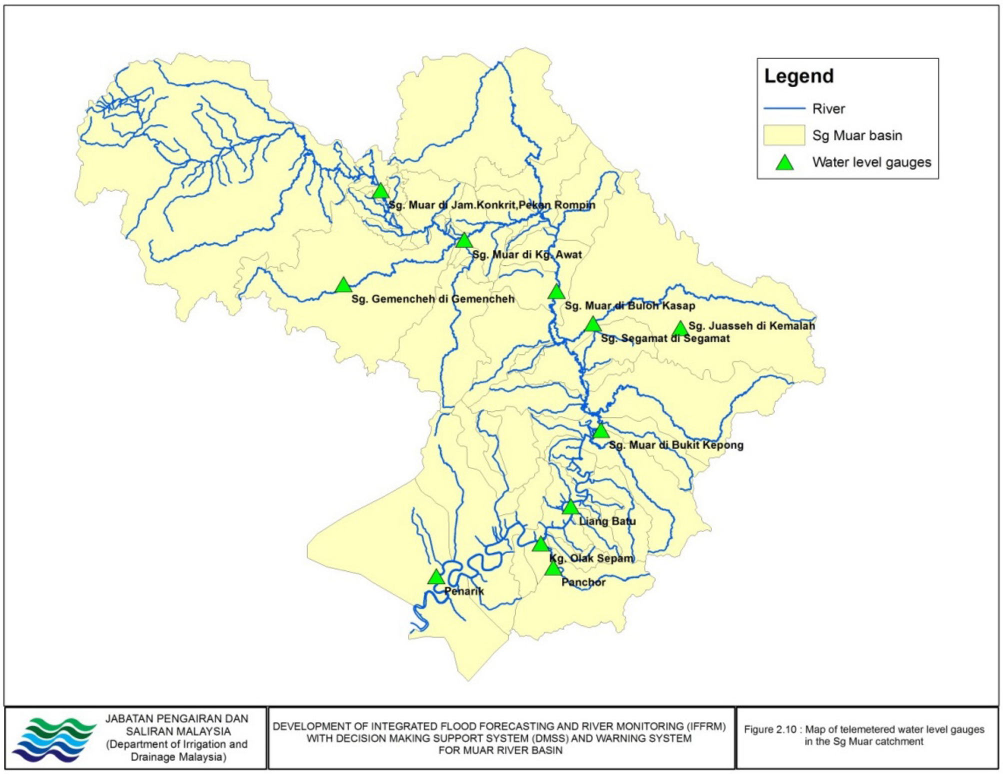

Figure 5: Map of the River Muar catchment, showing the location of the telemetered water level gauges.

3.4. Radar rainfall data

Spatial variability of rainfall is known to be high in peninsular Malaysia. Given the relatively low density of the telemetered rain gauge network in the Muar catchment, the use of radar rainfall observations, of a suitably high spatial and temporal resolution, was required. Through better understanding the localised nature of the rainfall events, a better representation of the runoff generation process could be achieved through rainfall-runoff modelling. Radar rainfall data were available as in the grib file format. FloodWorks automatically finds and loads the radar rainfall data when it becomes available. Prioritisation can be given to either the gauged or the radar rainfall, as appropriate. The model will then use the prioritised rainfall to calculate the runoff. The iFFRM uses both telemetered rainfall data and radar rainfall images as inputs.

3.5. Forecast data

In addition to observed rainfall data, rainfall forecasts were required to provide a Quantitative Precipitation Forecast (QPF) to drive the iFFRM into the forecast period. The Malaysian Meteorological Department (MMD) makes available rainfall forecasts from its Numerical Weather Prediction (NWP) model twice a day. Gridded ASCII files are made available twice per day at 00 hours and 12 hours. FloodWork checks for new files and loads the new forecast data. The first three days of the precipitation forecast are used for the flood predictions.

The Malaysian Meteorological Department (MMD) operationally runs the Weather Research and Forecasting model (WRF) (NCAR et al., 2017). The WRF model was first released in 2004 with one of its main objectives being to advance the understanding and prediction of mesoscale weather systems including precipitation systems. The wide user community and dissemination of the WRF model has been successfully advanced since the release date. Currently the user group has over 30,000 registered users in 150 countries (NCAR et al., 2017). The MMD has extensively tested the forecast performance of the WRF model for precipitation forecasts in Malaysia, for more information the reader is referred to Ibadullah et al. (2013). Currently MMD are running WRF model version 2.2, a hydrostatic model at a horizontal resolution of 3km over a forecast time period of 5 days. The WRF model will be updated to a later version corresponding with the upgrade of the high performance computer (HPC). In preparation for this, extensive tests of the WRF model version and ensembles have been conducted (Subramaniam et al., 2010).

3.6. Flood warning dissemination and communication

The Office of U.S. Foreign Disaster Assistance (OFDA) experience in communication of forecasts supports the need to strengthen the links between the early-warning systems (often managed by government institutions) and their intended beneficiaries at the local level, “thereby encouraging the development of truly end-to-end early warning systems that result in timely, well-understood warnings and effective response actions based on preparedness of the local communities. This link, often called the “last mile” of the system, has consistently been seen as both the most essential and the weakest aspect of early warning systems in developed and developing countries, alike” (USAID, 2013). The forecasting and warning strategy, including raising awareness of flood risk, and appropriate communication strategies, has a range of features that can be enhanced by effective system development.

Simulation results from iFFRM Muar are used to warn DID staff directly so that immediate action can be taken to provide an effective and proactive emergency response. A total of 137 Points of Interest have been configured to provide fast access to results for locations prone to flooding. Results are also passed to the project website, and to a dedicated smartphone application, enabling forecasted flooding to be disseminated more widely, to the public at large.

This system has been designed so that a parallel analytical modelling network can take over the forecasting role should the primary iFFRM system fail.

4. Discussion

The paper presents the work undertaken to develop an end-to-end flood forecasting and warning system for the river Muar in Malaysia. Efforts have been made towards developing the system so that it is resilient to missing or poor quality input data, and a pragmatic approach has been taken towards system development for subcatchments with sparse data observation networks. Ongoing structural measures aimed at flood mitigation are captured through the use of a flexible modelling approach that can incorporate model updates to reflect real changes in the catchment. Continuous simulation maintains catchment states to ensure that the models at the core of the iFFRM form a realistic representation of catchment conditions. Updating applied algorithms at key locations around the catchment enable real time data to be used to correct model results and so improve model forecasts. In these ways, the iFFRM complements the structural measures being implemented by DID and ensures a sustainable solution.

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