04 - Development of a National-scale Hydrological Model utilising remote sensing

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Abstract

Remote sensing datasets have become increasingly useful in hydrology. Today, many satellite missions provide timely delivery of data with spatial coverage not achievable with terrestrial systems. These advantages make remote sensing datasets suitable for forcing a national hydrological model.

In this paper, we present the initial results of the first national hydrological model forced with remote sensing dataset. We use the Variable Infiltration Capacity (VIC) model incorporated into 'The Regional Hydrologic Extremes Assessment System (RHEAS)' and precipitation estimates from CMORPH and meteorology data from NCEP to generate discharge estimates across Ireland from 2005 to 2013 at the spatial resolution of 0.2 degrees (~20 km). These discharge estimates are then routed through a national scale inundation model. The outputs from the inundation model are compared to a subset of the national hydrometric data.

This national-scale coupled hydrological and hydraulic model will provide the starting point for future research in developing a national flood inundation model and to investigate the impact of climate change on Ireland's water resources.

1. INTRODUCTION

In hydrology, there has been a move away from local hydrologic and hydraulic modelling to regional, national and global scale. As we move to these larger spatial scales, remote sensing becomes increasingly more beneficial than in-situ measurements. At the global scale, the current in-situ based hydrological and meteorological datasets are not sufficient for many water resources applications, especially in developing nations. However, this is an issue in developed nations too. For example, while Ireland's hydrometric collection programme provides good coverage, our meteorological collection programme is currently only able to provide sub-daily data at twenty-five locations and has only two weather radar that cannot provide full coverage over Ireland and have associated issues with quality.

For regional and large-scale hydrology remote sensing is becoming more prevalent, especially in data-scarce regions. Sheffield et al. (2014) utilised remote sensing datasets and the Variable Infiltration Capacity (VIC) model in the creation of a drought monitoring and forecasting system for Africa that runs near real-time. Schumann et al. (2013) presented a flood inundation forecasting model for the Zambezi River using the VIC model forced by remotely sensed derived datasets.

In this paper, we present the framework for developing a national-scale hydrological model. We use 'The Regional Hydrologic Extremes Assessment System (RHEAS)' (Andreadis et al. 2017) framework which includes the VIC model to generate gridded runoff from remotely sensed estimates for precipitation and other meteorological parameters. These uncalibrated gridded runoff are then routed using the LISFLOOD-FP model and the discharge is compared to in-situ measurements. Finally, we present the future work needed to transform this framework into a near real-time flooding forecasting and inundation model for Ireland.

2. METHODOLOGY

2.1. Models

2.1.1. RHEAS

To generate the runoff to be routed using LISFLOOD-FP, we use the Variable Infiltration Capacity (VIC) model (Liang et. al., 1994) which has been incorporated into the RHEAS framework (Andreadis et al. 2017). RHEAS is a software framework developed by the NASA Jet Propulsion Laboratory (JPL) for the assimilation of remote sensing observations into water resources simulations. Both nowcast and forecast runs can be produce by RHEAS. VIC is a core component of RHEAS which on a grid system balances the energy and water budget including a soil-vegetation-atmosphere scheme that models how moisture and energy fluxes between land and atmosphere are controlled by vegetation and soil. Each grid cell is independently modelled producing a time-series of runoff which must then be routed.

The input requirements for VIC include meteorological data that force the model, information on soil properties, elevation, and land cover. VIC as implemented in RHEAS uses the GTOPO30 global digital elevation model to partition each model grid cell into elevation zones, soil properties which are adapted from global and regional implementations of the VIC model (Xia et al., 2012). For this study the meteorological data was obtained from CMORPH and NCEP (described below).

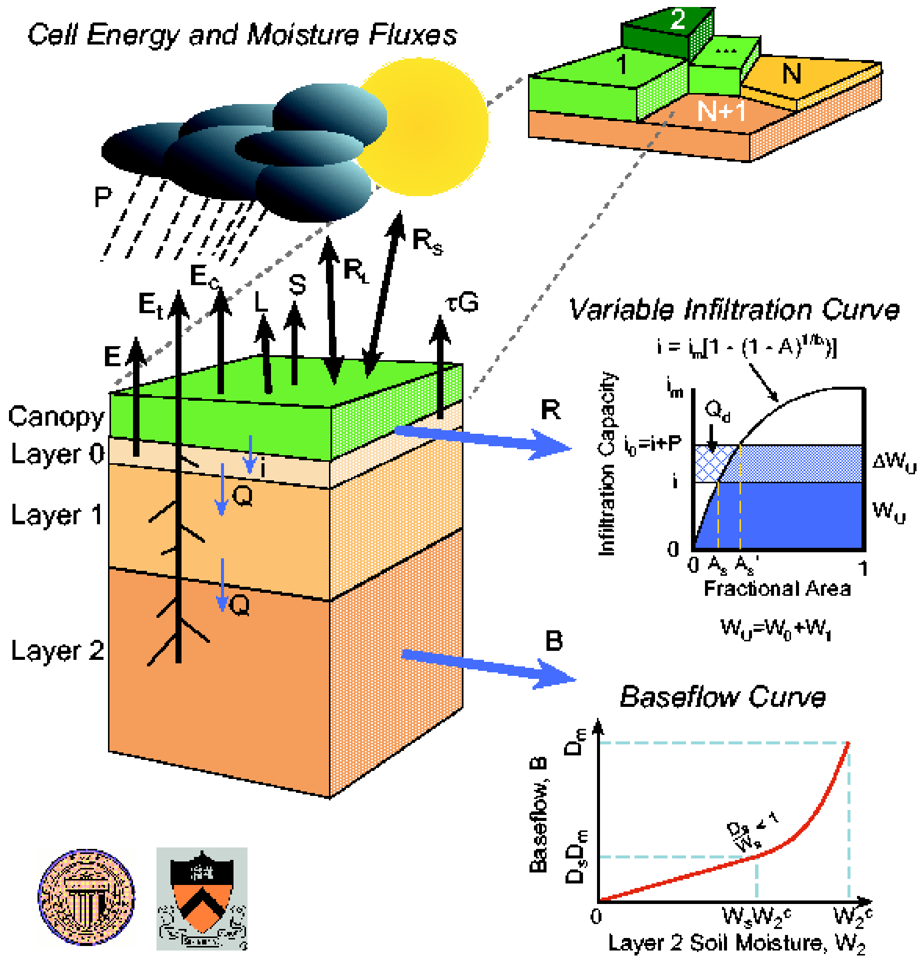


***Figure 1**: Schematic of the VIC model (Gao et al., 2010)*

2.1.2. Lisflood-FP

We use the LISFLOOD-FP hydraulic model with the subgrid formulation of Neal et al. (2012) to route the runoffs generate by RHEAS. LISFLOOD-FP (Bates and De Roo, 2000) is a 2-D hydraulic model that solves the local inertial form of the shallow water equations omitting only the advection force term (Bates et al 2010). As input, the model requires ground elevation data describing the floodplain topography, channel bathymetry information (river width, depth and shape), boundary condition data consisting of discharge time series at all inflow points to the domain, water surface elevation time series at all outflow points and friction parameters which typically distinguish different values for the channel and floodplain. For this study river widths are estimates based on each river cells upstream catchment area and the corresponding depth is estimated using the Manning's equation and the assumption the bankfull discharge corresponds to the two-year return period (Andreadis et al., 2013, Sampson et al., 2015). Rivers and upstream accumulation area were obtained from the hydrosheds database (Lehner et al., 2008).

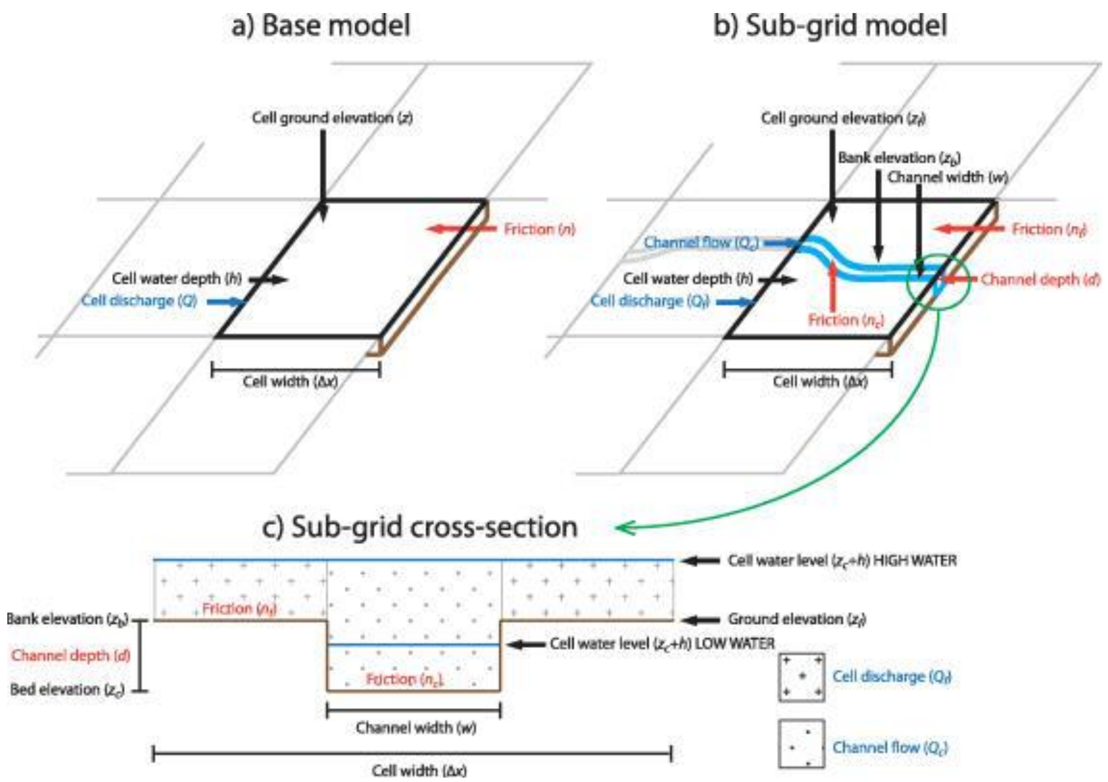


__Figure 2__: Conceptual diagram of a) LISFLOOD-FP base model, b) subgrid channels model, and c) subgrid section. (Neal et. al., 2012.)

2.1.3. Coupling models

A simple coupling methodology was applied to couple the runoff generated from RHEAS to the hydraulic model, LISFLOOD-FP. RHEAS generated runoff at a spatial scale of 0.2 degrees (~20 km at the Equator); however, the spatial resolution of the LISFLOOD-FP model is 30 arc-seconds (~1 km at the Equator). For this study, we assigned the runoff from RHEAS to the LISFLOOD-FP river cell nearest to the centre of the RHEAS grid. Figure 3, shows the river modelled in the LISFLOOD-FP model with the RHEAS grid overlaid and locations where runoff is inputted into the LISFLOOD-FP model.

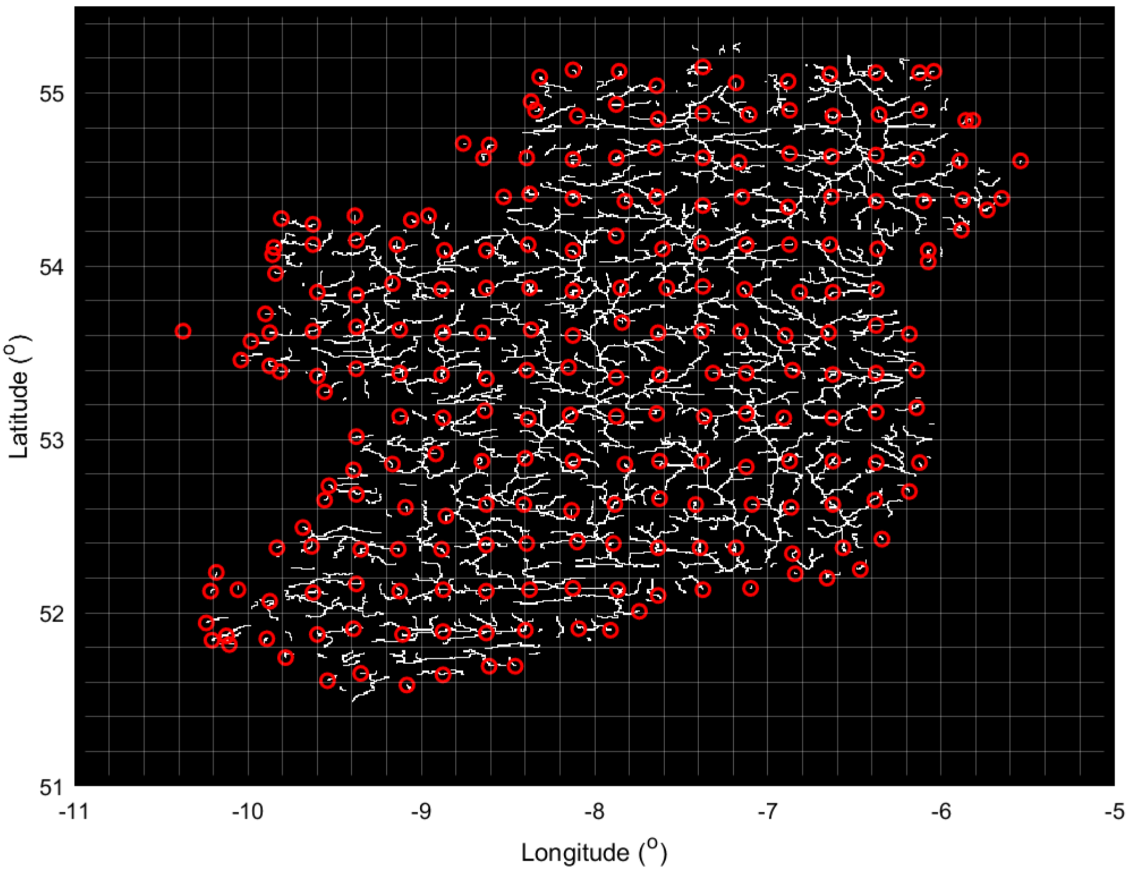


Figure 3*: LISFLOOD-FP model domain showing rivers modelled (white) and RHEAS runoff input locations (red). Grid lines represent the RHEAS grids.*

2.2. Data

2.2.1. Digital Elevation Model

In hydraulic modelling, the DEM is one of the most critical inputs (Sanders, 2007). In many areas of the global, including Ireland, LiDAR DEMs are not freely available; therefore, space based DEMs are invaluable. The Shuttle Radar Topography Mission (SRTM) is the most popular; however, suffer from vegetation biases. These biases must be accounted for to ensure the DEM is representing the bare earth. In this study, we use the recent vegetated corrected SRTM dataset from O'Loughlin et al. (2016) as the digital elevation model (DEM) to build the hydraulic model. This dataset is the first global attempt at correcting vegetation errors in SRTM and uses a non-linear correction function based on vegetation density and climatic zone. The final product results in the errors in vegetated areas close to non-vegetated areas. We then applied a 2-D adaptive smoothing algorithm to this dataset followed by a median filter, as suggested by O'Loughlin et al. (2016), to remove noise and small artefacts.

2.2.2. Precipitation Data

CMORPH precipitation was the chosen precipitation dataset to be used in this study,
based on spatial coverage and temporal range (Joyce et al., 2004). The Climate Prediction Center morphing method (CMORPH) produces global precipitation estimates from passive

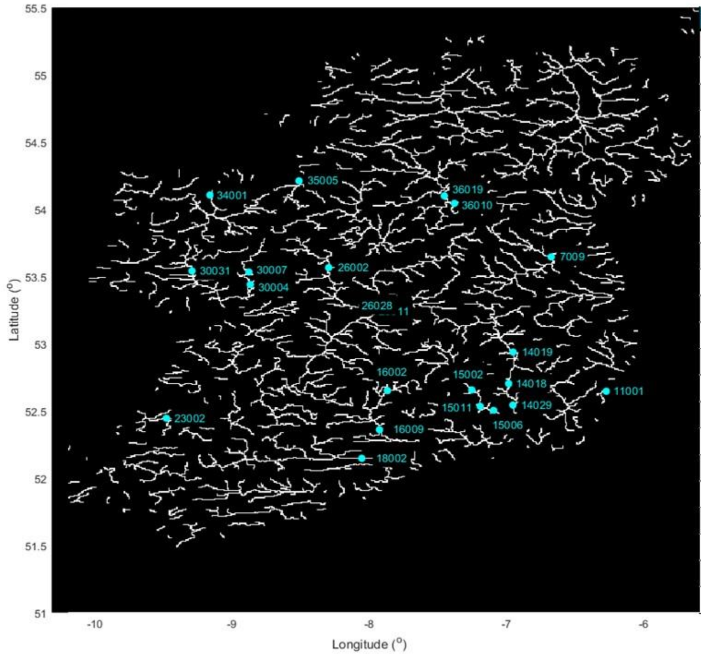
microwave observations. Currently, the estimates are derived from ten different geostationary satellites. Data are available from 1998 to the present day at a three-hourly timestep. However, in this study, we have only used data from April 2005 at a daily timestep. CMORPH data has previously been used in an Irish context by Sampson et al. 2014 who investigated the impact of different precipitation sources on insurance loss estimate from a flood catastrophe model.

2.2.3. Meteorology Data

While precipitation is obtained from the CMORPH dataset, VIC also requires information on temperature and wind speed. This meteorology data required by RHEAS was obtained from the NCEP-DOE AMIP-II Renalysis Project (Kanamitsu et al., 2002). This reanalysis project covered the period 1948 to present day and utilise satellite remote sensing and is based on the previous NCEP/NCAR Reanalysis.

3. RESULTS & DISCUSSION

The discharge from the uncalibrated coupled RHEAS and LISFLOOD-FP model were compared with the discharges recorded from twenty-two locations gauged by the OPW. Figure 4 shows the locations, station number and name and the river the gauge is located on.



Station number	Station name	River name
7009	Navan Weir	BOYNE
11001	Boleany	OWENAVORRAGH
14018	Royal Oak	BARROW
14019	Levitstown	BARROW
14029	Graiguenamanagh U/S	BARROW
15002	Johns Bridge (Nore)	NORE
15006	Brownsbarn	NORE
15011	Mount Julliet	NORE
16002	Beakstown	SUIR
16009	Cahir Park	SUIR
18002	Ballyduff	BLACKWATER
23002	Listowel	FEALE
25011	Moystown	BROSNA
26002	Rookwood	SUCK
26028	Shannonbridge	SHANNON
30004	Corrofin (Clare)	CLARE
30007	Ballygaddy	CLARE
30031	Cong Weir	CONG
34001	Rahans (Moy)	MOY
35005	Ballysadare	BALLYSADARE
36010	Butlers Bridge	ANNALEE
36019	Belturbet	ERNE

Figure 4: Left Panel: Location of in-situ locations used for comparison. Right Panel: Meta-table of in-situ sites

Figure 5 shows the modelled discharge versus the in-situ discharge for the selected locations, with the exception for Navan Weir and Shannonbridge were only the modelled discharge is shown. From visual inspection of the results, it's clear the modelled discharges do not match the in-situ. However, this is expected as the runoff from the RHEAS framework are uncalibrated. The results also show that the models are not producing the correct runoff and do not represent the baseflows correctly.

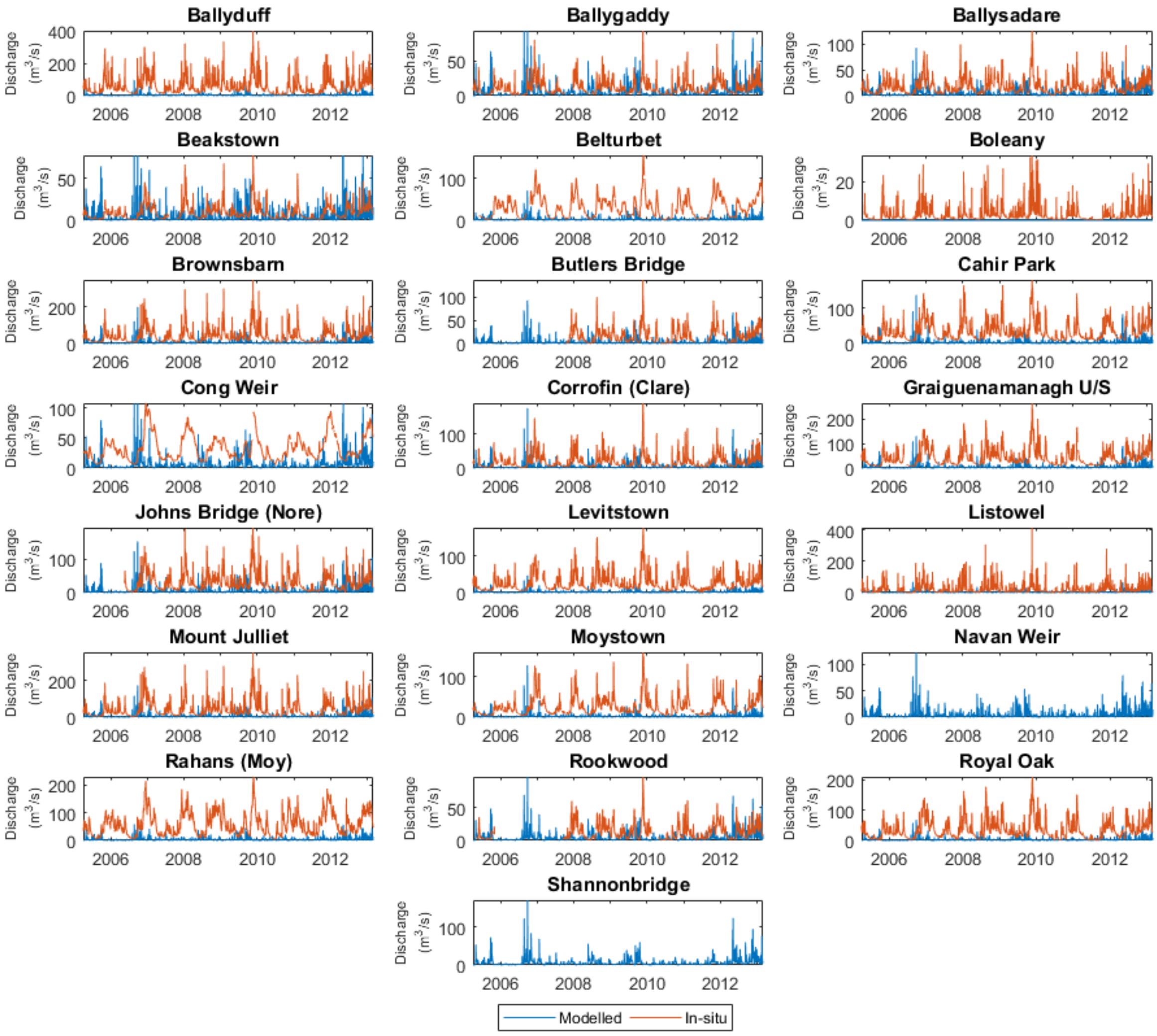


Figure 5*: Modelled and In-situ discharges at selected locations highlighted in Figure 4.*

While this study uses uncalibrated models whose input datasets may not have represented all the river networks correctly, we are able to produce inundation extents and depths. Figure 6 show the maximum depth of water produced during the simulation. While it was out of scope of this study to investigate the accuracies of these extents and depths, it's clear the LISFLOOD-FP model can produce inundation where expected. Such as along the Shannon upstream of Maleek Weir, along the Suir, Barrow and in the upper catchment of the Boyne.

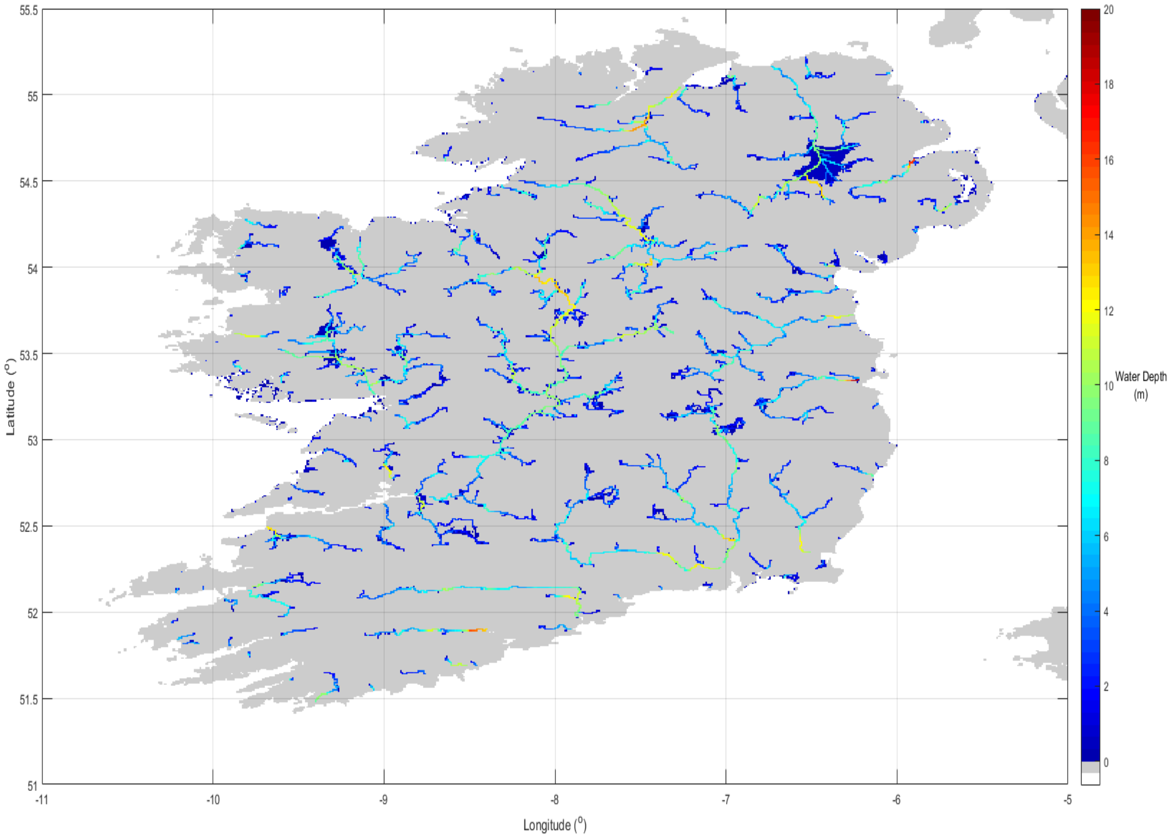


Figure 6: Maximum Water Depths (m) from LISFLOOD-FP run.

Future improvements this framework to create a nation-scale coupled hydrological and hydraulic models will focus on both the hydrological model and the hydraulic model. The first step will be to investigate the accuracies of the input datasets used by RHEAS to generate runoff. Secondly, we will investigate the impact that assimilating soil moisture and water storage will have on the generated runoffs. Finally, the impact of spatial resolution of the hydrological model will be investigated. For the hydraulic model, we will look to improve the accuracies of the input data required by LISFLOOD-FP. Future work will utilise the EPA's River Network (available to download from gis.epa.ie) instead of the coarser hydroshed dataset and develop a river width to upstream catchment area calibrated for Ireland or use in-situ cross-sections if available. By these two steps will can be confident that the Irish river network is being accurately represented. Finally, inundation maps produced from the coupled model will be compared to flooding extents that occurred during the simulation period.

4. CONCLUSIONS

We have presented a framework to create the first coupled hydrologic and hydraulic model forced by remotely sensed datasets for Ireland. The runoff was generated on a 0.2 degree grid by the VIC model incorporated into the RHEAS framework. These runoffs were then routed using the LISFLOOD-FP hydraulic model, which runs at an one kilometre spatial resolution.

The framework created is flexible so that different components can be replaced if needed, i.e. the VIC model could be exchanged with a different hydrological model or the models could be forced with in-situ rather than remotely sensed data.

The modelled discharge from the uncalibrated models were visual compared to in-situ measurement at twenty-two locations across Ireland. It clear that the modelled discharge does not compare well with the in-situ measurements and future research is needed to address the differences, including calibration of the models and investigating uncertainties in the forcing data.

Once the current known short-comings of the framework have been addressed, the framework presented here will be able to: be used in flood forecasting and inundation modelling; look at the impact of climate change on inundation across the entire island; and investigate impacts droughts may have.

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