REAL TIME FLOOD AND INUNDATION FORECAST IN TRANS-BOUNDARY RIVER BASIN USING MULTI-MODEL HIGH RESOLUTION PRECIPITATION FORECAST

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ABSTRACT

An attempt has been made to predict river discharge and inundation depth in a transboundary sparsely gauged Chenab River Basin (CRB), eastern tributary of Indus River system, using high resolution multi-model precipitation forecast coupled with hydrological models IFAS and RRI. This study analyzed the catastrophic exceptionally high flood of Sept. 2014 in CRB. Quantitative Precipitation Forecast (QPF) from global models and their high resolution downscaled rainfall using Weather Research and Forecasting (WRF) model were used to predict flood discharge. Calibration of IFAS model was carried out using bias corrected Global Satellite Mapping and Precipitation (GSMaP-Gauged) data. Results conclude that peak discharge in large river basin through downscaled QPF from multi-model deterministic forecast could be predicted as early as six days prior to the observed peak with varying degree of accuracy. A confident forecast at rim station also produced reliable inundation by RRI at downstream catchment and was validated through MODIS data. Based upon study outcome, "strengthening of existing flood early warning system in Pakistan using high resolution multi-model precipitation forecast" has also been proposed.

Keywords: Numerical Weather Prediction, Hydrological Models, High resolution rainfall, Flood and Inundation forecast

INTRODUCTION

Heavy rainfalls during monsoon season (Jun 15 – Oct 15) have been the major cause of flood disasters in Indus River system, specifically in the Eastern tributaries which are under the active belt of monsoon. Presence of Himalaya Mountain ranges located at the upstream of Eastern Rivers provide suitable conditions for orographic lifting to monsoon currents penetrating from Bay of Bengal and Arabian sea, resulting into heavy rainfalls on the windward side (Awan 2003; Ray *et al*. 2015), that can produce huge streamflow and can transform into disastrous floods. Severe flooding in Chenab and Jhelum River catchments occur when tropical storm originating at Bay of Bengal approaching upstream of Indus River system, comes under the influence of Eastward moving Westerly trough along the Northern latitudes of Pakistan (Majid and Nazia, 2010). Similar meteorological condition during catastrophic exceptionally high flood of September 2014 appeared when two low pressure areas

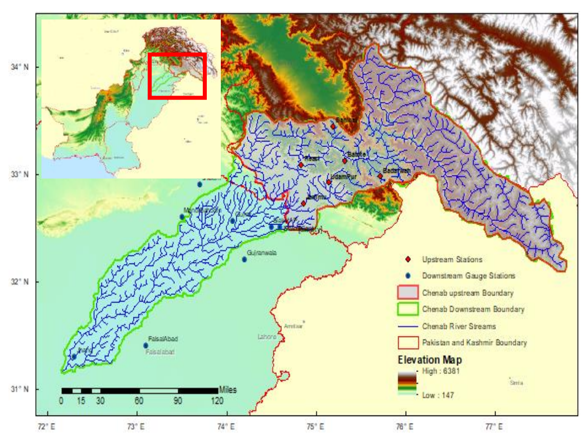

Figure 1. Location and elevation map of Chenab River Basin.

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** International Center for Water Hazard and Risk Management, Public Works Research Institute, Tsukuba, Japan located over central India and Gujrat merged together and system moved northwest of India under the presence of mid tropospheric trough as explained by Ray et al. (2015).

Prolonged high rain spell of four days contributed into water level rise in the CRB above danger levels. Water overtopped/breached river embankments and several hundred villages in many districts of Punjab were badly affected. A few villages were completely submerged and many people were killed. Catastrophic flooding also posed huge infrastructural and economic losses.

Table 1. Flood criteria at Marala in CRB

Flood State		Threshold(m^3/s)	Description of water flow
Low		2800	Flow in main channel may spill over Sandbars/Islands
Medium		4200	Partly inundating Sandbars/Islands
High		5600	Fully submerged Islands/Sandbars, flow in flood plain.
Very High		11300	Flow between embankments/bands, advancing to unprotected lands
Exceptionally High		17000	Danger of over topping/Breaching or breaching has already occurred.

Hydro-meteorological forecasting and early warning with sufficient lead time has become critical in managing risk in order to initiate adequate measures to save lives and reduce economical losses. In recent years several studies have been conducted in area of flood forecasting through coupling of hydrological and meteorological models (Davolio *et al.*, 2008; Yu *et al.*, 2016). With improved computational power and addressing observational data quality issues, QPF by NWP models has substantially improved (Yan and Gallus, 2016) and coupling of skillful QPF with hydrological model can greatly improve lead time of flood forecast for hazardous events. Ushiyama *et al*. (2014) argued that river flow and inundation in Kabul River basin (Western tributary of Indus River basin) could be predicted with the use of NCEP-GFS lagged ensemble precipitation forecast; downscaled at regional scale with ample lead time.

To minimize the losses and make relief and evacuation process effective it is required to implement a flood forecasting and early warning system to predict flood peak with ample lead time. In this study high resolution QPF from Numerical Weather Prediction (NWP) models have been analyzed to select the suitable deterministic and ensemble precipitation forecast to predict flood and inundation in River basin several days before the arrival of peak discharge.

THEORY AND METHODOLOGY

Original and downscaled rainfall forecast of global models was supplied to the hydrological model to simulate river flow, targeting the storm rainfall duration from Sept. 03, 2014 to Sept. 07, 2014 to discuss the possibility of flood and inundation forecasting in Chenab River Basin. Integrated Flood Analysis System (IFAS) was calibrated using bias corrected GSMaP-Gauged rainfall covering the upstream area with outlet at Marala headworks. At downstream catchment of mild slope, RRI model was calibrated using observed boundary discharge at Marala headworks along with observed ground rainfall. Outlet was taken above Trimmu headworks before the confluence of Jhelum River with Chenab River.

Initially the global models deterministic rainfall forecast, initialized every 12 hour from Sept 01, 2014 to Sept 03, 2014, was coupled with IFAS in upstream catchment; however inconsistencies were seen in the forecasted discharges. Later forecast from three different Global atmospheric models namely NCEP-GFS, Integrated Forecast System of European Centre for Medium-Range Weather Forecasts (ECMWF-IFS), and Global Spectral Model of Japan Meteorological Agency (JMA-GSM) were downscaled at regional domain through WRF model using Kain-Fritsch convective scheme (Fritsch and Kain 1993;Kain 2004) every 12 hours from Sept.

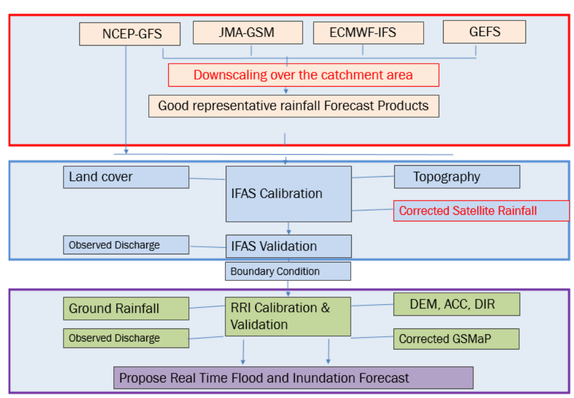

Figure 2. Study methodology.

01, 2014 to Sept. 03, 2014. In WRF two-way nested domain with 1:4 ratio was defined keeping CRB in the center as shown in figure 3. Outer domain (4400km x 3300km) covers whole Pakistan and extends up to Bay of Bengal in the East, Arabian Sea at South and Caspian Sea on its West with grid cell resolution of 20km. Inner domain (1105km x 845km) is defined at 5km grid spacing and covers CRB in center. For land surface process, thermal diffusion with four layer soil temperature was used.

Downscaling improved rainfall intensity and location significantly and coupling of downscaled rainfall with hydrological model improved consistency in flood peak estimation. Downscaled version of rainfall from 21 Ensemble members of NCEP-GEFS were also coupled with hydrological model to see uncertainty in flood prediction. Forecasted discharge produced by IFAS was later fed to calibrated RRI model along with forecasted rainfall. Flood forecast by RRI at Qadir Abad headworks. Inundation provided at downstream of Qadir Abad was compared with water extent extracted through MNDWI from eight day composite MODIS reflectance image. Finally a real time flood forecasting and early warning system has been proposed. Study methodology is also shown in Figure 2.

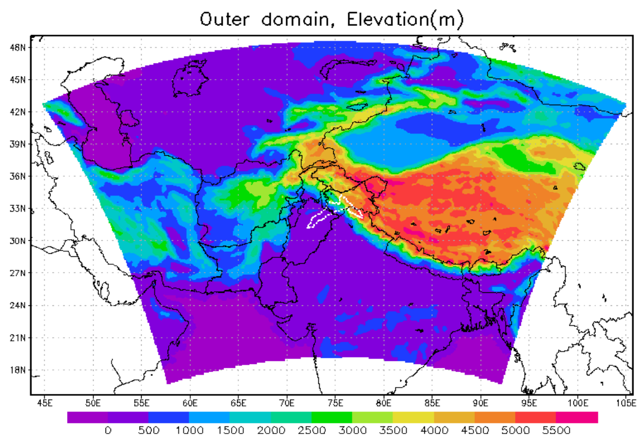

Figure 3. Domain setup in WRF model

DATA

In the downstream catchment, storm rainfall data of eight observation stations was collected from Pakistan Meteorological Department (PMD) and rainfall in upstream was used from Ray *et al.* (2015). Total storm rainfall of 2014 flood in upstream and downstream catchment is given in figure 4. Flood hydrographs at Marala and Qadir Abad Headworks are shown in figure 5. Since upstream of CRB is trans-national and ground observations are not available in real time, satellite rainfall was the ultimate option to rely on. Apart from its very high applicability in the sparsely gauged basin, there are some limitations in satellite rain predictions especially during convective storms and in mountainous regions (Shrestha et al, 2011; Kubota et al, 2009). GSMaP-Gauged product provides more realistic rainfall however it does not resolve data issues in the areas where ground stations have not been used in correction of GSMAP-MVK. Accumulated storm rainfall from original GSMaP-Gauged is shown in figure 6. Maximum total rainfall provided by GSMaP-Gauged in CRB was much less as compared to total observed rainfall, and

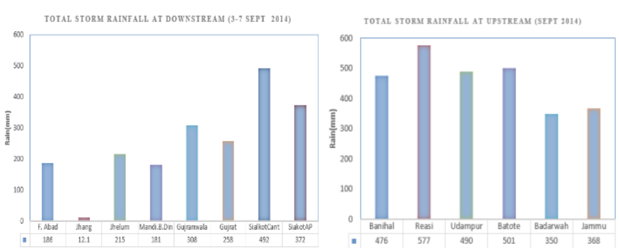

Figure 4. Accumulated storm rainfall at downstream (left) and upstream (right) rain gauge stations

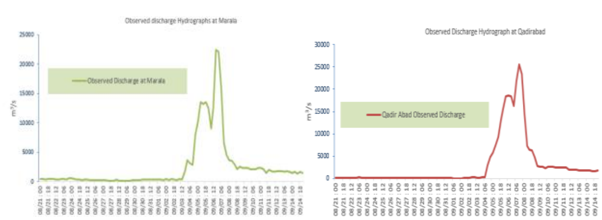
Figure 5. Observed discharge hydrographs at Marala (left) and Qadir Abad (Right) headworks during flood event of Sept. 2014, in CRB

concentration was also not rightly placed. Therefore ground stations outside the upstream of CRB boundary; were considered to identify the bias, and acquired scale factors were applied in upstream of CRB to make GSMaP-Gauged rainfall equivalent to the ground observations. This bias corrected rainfall was later used in IFAS model calibration.

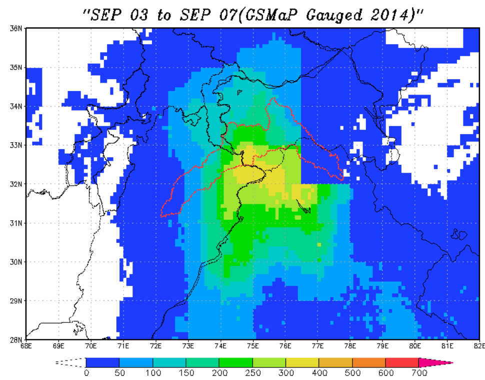

Figure 6. GSMaP-Gauged accumulated storm rainfall from Sept. 03, 2014 00UTC to Sept. 07, 2014 00UTC

NCEP-GFS eight day forecast with three hour interval was obtained at resolution of 0.5° and with 28 vertical levels, from Sept 01, 2014 to Sept 03, 2014 every 12 hour. Control forecast of ECMWF-IFS and JMA-GSM at 0.5° resolution were taken from TIGGE datasets twice a day with six hour interval. GEPS ensemble forecast was also taken from TIGGE. GCMs data sets were provided as initial and boundary conditions to WRF for dynamic downscaling at finer regional scale resolution.

RESULTS AND DISCUSSIONS

Precipitation forecasts of global models initialized at Sept. 01, 2014, Sept. 02, 2014 and Sept. 03, 2014 at 00UTC and 12UTC was converted into a readable format for hydrological model and then supplied to calibrated IFAS to see global models forecast ability to predict flood. Simulated peak discharges obtained at Marala headworks along with observed discharge are shown in Figure 7. Forecasted hydrographs showed significant inconsistencies. For instance peak discharge (slightly above 20000m^3/s) obtained from NCEP-GFS precipitation forecast of Sept 01, 00UTC is a good indication of huge flood peak with lead time of six days. But the subsequent QPFs of 12UTC and 00UTC of next day were shifted eastward outside the catchment boundary, producing less rain inside CRB and failed to produce any significant discharge. However later forecasts produced good intensity rainfall within catchment and were successful in predicting exceptionally high flood discharge (Figure 7a). In general only three forecasts of NCEP-GFS out of six were able to produce very high flood as per the criteria given in Table 1. ECMWF-IFS model forecasts were able to give consistent discharges however intensity of flood did not reach upto exceptionally high flood (Figure 7b). In case of JMA-GSM all the forecasts even remained below the high flood mark since rain distribution was mostly outside the catchment (Figure 7c). Inconsistencies in time variant discharge prediction is highly uncertain and is a big hindrance to build confidence of the forecaster on original global model's forecast in terms of explaining hydrological phenomena. NWP models should predict heavy rainfall events consistently in order to be considered for flood forecasting. Most of the upstream area of CRB is mountainous (Figure 3) and provides suitable conditions for the orographic lifting of moist current coming from Arabian Sea and Bay of Bengal producing heavy rainfall during monsoon period. Coarse resolution precipitation forecast of global models could not consistently predict good representative rainfall both in intensity and space. In order to improve the reliability and consistency of the time variant forecast, GCMs output (NCEP-GFS, ECMWF-IFS and JMA-GSM) from Sept. 01, 2014 to

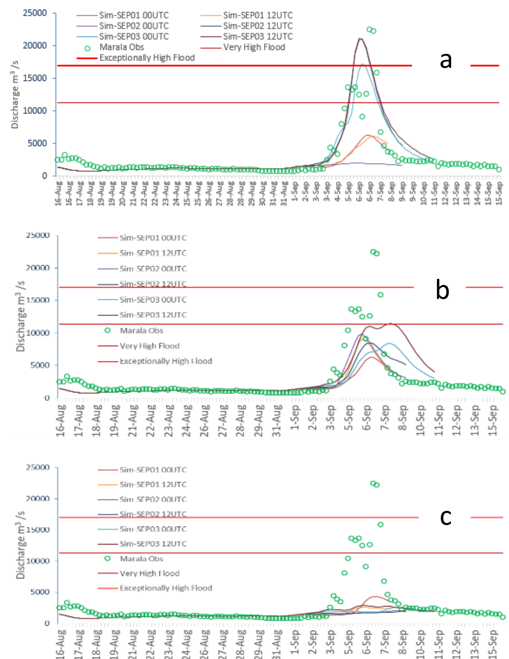

Figure 7. Simulated hydrographs by IFAS from original (a) NCEP-GFS, (b) ECMWF-IFS and (c) JMA-GSM forecast

Sept. 03, 2014 with 12 hour lag were downscaled under regional geographic features covering Chenab River basin at fine resolution of 5km grid cell using WRF.

Downscaling improved rainfall intensity and distribution significantly over the catchment. Resulted hydrographs produced by the downscaled rainfall from all three GCMs are more consistent, probability of exceptionally high flood prediction has also improved significantly and most of the forecasts are in good coordination with the observed peak. In 13 out of 18 cases, predicted discharge remained above very high flood mark as indicated by flood level criteria given in Table 2, whereas nine cases predicted the exceptionally high flood with varying lead time of four to six days prior to the arrival of flood peak at Marala headworks. However the peak discharge predicted by JMA-GSM rainfall was relatively less in comparison with other two models.

In order to make flood forecast more understandable, a simplified color coded box representation is given in Figure 9, similar to the one used by Thielen et al. (2008), showing the high, very high and exceptionally high flood threshold exceedances in the number of cases from the downscaled forecast of all three global models. Diagram indicates that NCEP-GFS predicted the exceptionally high flood on Sept. 01, 2014; however in the subsequent forecasts, signal disappeared, whereas ECMWF-IFS forecast remained consistent in all the cases, indicating exceptionally high flood signal. JMA-GSM could only predict up to very high flood signals. In general, all the 18 cases predicted high flood in River Chenab at Marala with lead time of four to six days.

This shows that downscaled rainfall is more consistent in time and space, producing more realistic flood forecast, when hydrological models are coupled with such rainfall and multi-model approach can improve confidence in decision making. Finally flood forecast from IFAS at boundary station was input to RRI along with downscaled forecasted rainfall. Predicted discharge was validated with observed data at Qadir Abad headworks about 85km downstream of Marala headworks as shown in figure 10. Inundation extent provided by RRI downstream of Qadir Abad till Jhang was validated

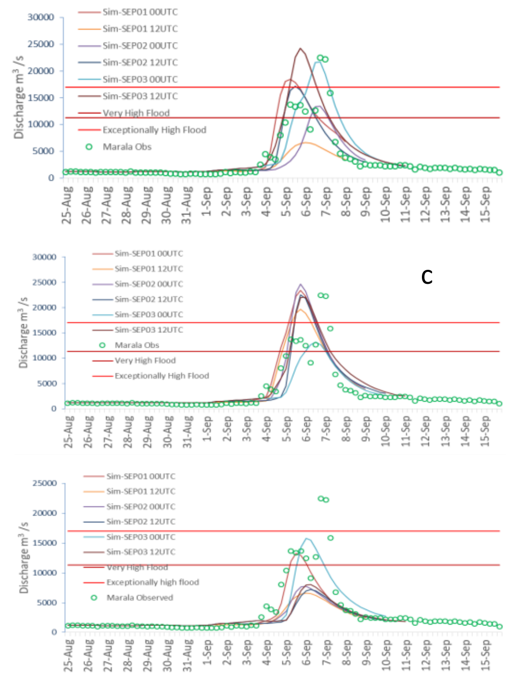

Figure 8. Simulated hydrographs at Marala from downscaled QPF of (a) NCEP-GFS, (b) ECMWF-IFS and (c) JMA-GSM

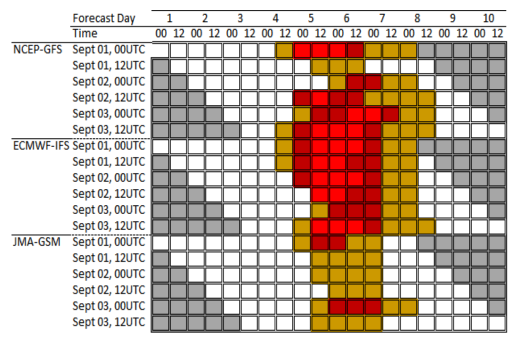

Figure 9. Simulated flood threshold exceedances by the downscaled rainfall of global models

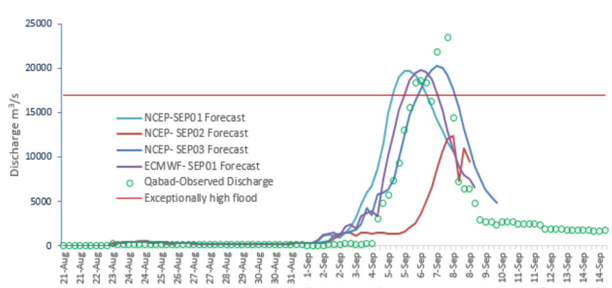

Figure 10. Forecasted discharge by RRI at Qadir Abad using downscaled rainfall and IFAS forecast.

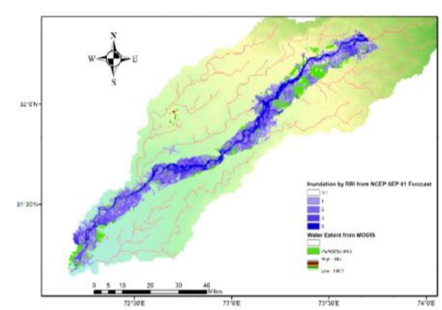

Figure 11. Inundation depth by RRI overlaying with extent from MODIS

with the water extent extracted from the MODIS eight day composite surface reflectance 500m resolution image. Inundation area given by RRI is slightly greater than the inundation extent provided by MODIS since depletion of flood water had already occurred by Sept 14, 2014. Timely inundation forecast can be issued if upstream discharge is predicted well which is highly dependent on forecasted rainfall.

CONCLUSION and RECOMMENDATIONS

Study concludes that multi-model high resolution rainfall forecast coupled with combination of hydrological models (IFAS and RRI) can be used to predict exceptionally high floods and to identify inundation area with lead time of four to six days in CRB with varying degree of accuracy. Early warning from such forecast can help in timely emergency operation and evacuation before catastrophic flood events.

Since study area is transboundary and real time data at the upstream catchment is either not available or not timely communicated, detailed study is required to develop more reliable bias correction technique that is essential to make correction in the NRT satellite rainfall products for use in hydrological models for flood forecasting. Based upon the study results, a project has been proposed to implement High Performance Computing Cluster to perform downscaling from multiple GCMs and provide reliable high resolution rainfall forecast to hydrological models in order to improve the existing flood early warning system. Implementation of such system in real time can provide more insight into benefits of high resolution forecasted rainfall in flood prediction. Regional model WRF results are sensitive to domain size and model resolution, further studies should be conducted to find optimal WRF settings to get better forecast results. Further studies on different events with various catchment size may give more confidence over the implementation of such system in other river basins where ground observations are sparse and flood forecast is desired with adequate lead time. River dimensions play important role for the calibration of Rainfall Runoff Inundation model and use of observed cross sectional data can represent more realistic river geometry in improving model performance.

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REFERENCES

Awan, S. A. (2003) 'Associated Programme on Flood Management Integrated Flood Management Case Study1'.

Davolio, S. Miglietta, M., Diomede, T., Marsigli, C., Morgillo, A. and Moscatello, A. (2008) 'A meteo-hydrological prediction system based on a multi-model approach for precipitation forecasting', *Natural Hazards and Earth System Science*, 8(1), pp. 143–159. doi: 10.5194/nhess-8-143-2008.

Kain, J. S. (2004) 'The Kain–Fritsch Convective Parameterization: An Update', *Journal of Applied Meteorology*, 43(1), pp. 170–181.

Majid, A. and Nazia, A. (2010) 'Mangla Cat-III Flood Forecasting Procedure', pp. 1–13.

Ray, K., Bhan, S. C. and Bandopadhyay, B. K. (2015) 'The catastrophe over Jammu and Kashmir in September 2014: A meteorological observational analysis', *Current Science*, 109(3), pp. 580–591.

Thielen, J., Bartholmes, J., Ramos, M.-H. and de Roo, A. (2008) 'The European Flood Alert System Part 1: Concept and development', *Hydrology and Earth System Sciences Discussions*, 5(1), pp. 257–287.

Ushiyama, T., Sayama, T., Tatabe, Y., Fujioka, S. and Fukami, K. (2014) 'Numerical Simulation of 2010 Pakistan Flood in the Kabul River Basin by Using Lagged Ensemble Rainfall Forecasting', *Journal of Hydrometeorology*, 15(1), pp. 193–211. doi: 10.1175/JHM-D-13-011.1.

Yan, H. and Gallus, W. A. (2016) 'An Evaluation of QPF from the WRF, NAM, and GFS Models Using Multiple Verification Methods over a Small Domain', *Weather and Forecasting*, 31(4), pp. 1363–1379.

Yu, W., Nakakita, E., Kim, S. and Yamaguchi, K. (2016) 'Impact Assessment of Uncertainty Propagation of Ensemble NWP Rainfall to Flood Forecasting with Catchment Scale', *Advances in Meteorology*, 2016. doi: 10.1155/2016/1384302.