Proc Indian Natn Sci Acad **82** No. 3 July Spl Issue 2016 pp. 817-832

DOI: 10.16943/ptinsa/2016/48487

Review Article

Hydrologic Modelling

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(Received on 10 April 2016; Accepted on 10 June 2016)

Advances in computational tools and modelling techniques combined with enhanced process knowledge have, in recent decades, facilitated a rapid progress in hydrologic modelling. From the use of traditional lumped models, the hydrologic science has moved to the much more complex, fully distributed models that exude an enhanced knowledge of hydrologic processes. Despite this progress, uncertainties in hydrologic predictions remain. The Indian contribution to hydrologic science literature in the recent years has been significant, covering areas of surface water, groundwater, climate change impacts and quantification of uncertainties. Future scientific efforts in hydrologic science in India are expected to involve better, more robust observation techniques and datasets, deeper process-knowledge at a range of spatio-temporal scales, understanding links between hydrologic and other natural and human systems, and integrated solutions using multi-disciplinary approaches.

Keywords: Hydrologic Modelling; Surface Water; Groundwater; Climate Change; Uncertainties

Introduction

This report presents the progress achieved in India in hydrologic modelling, over the last five years. Indian hydrology, characterized as it is by significant heterogeneities at spatial and temporal scales, offers a fertile ground for useful research contributions. Notable contributions have been made by the hydrologic community in areas covering surface water models, groundwater models, hydrologic impacts of climate change, non-stationarity in hydrologic processes and uncertainty quantification. Large river basins such as the Ganga, Brahmaputra, Mahanadi and Krishna basins have been studied, among others. The following sections provide an overview of recent hydrologic studies carried out in India or with applications pertaining to the Indian region.

Surface Water Modelling

In India, surface water is a major resource to meet different demands and accounts for about 61.5% of total estimated utilizable water available within the country (CWC, 2015). In spite of this,many of the river basins in India, except for the main stem of major rivers, remain ungauged or minimally gauged for measuring streamflow and other relevant hydrologic variables. Internationally, the decade of 2003-2012 was declared as a decade of research dedicated toward prediction in ungauged basins by the International Association of Hydrological Sciences (IAHS) (Sivapalan, 2003). During the past decade, therefore, several hydrologic modelling studies have been taken up in India towards prediction of streamflow in ungauged basins. In this regard, geomorphologic instantaneous unit hydrograph (GIUH) are still being researched and widely used (Sahoo *et al*., 2006; Kumar, 2014) for estimating floods from ungauged basins in India with scant data. Singh *et al*. (2013) reviewed recent advances in flood hydrograph modelling by synthetic unit hydrograph approaches and found that the approach based on geomorphology is perhaps the most useful for

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ungauged basins.

During the last decade, thanks to advances in satellite remote sensing, more and more geo-spatial datasets related to hydrology such as topography, land use and soil are becoming widely available through several open sources at free of cost or at a nominal cost. Such datasets aid distributed hydrologic modelling greatly. For example, through an online portal called Bhuvan (http://bhuvan.nrsc.gov.in/), National Remote Sensing Center (NRSC), of the Indian Space Research Organization (ISRO) has made the 10m Digital Elevation Model (DEM) available for the entire country free of cost. Similarly, landuse / landcover datasets are available from NRSC or they may be generated from satellite imagery. Central Water Commission (CWC) of the Ministry of Water Resources (MoWR), Govt. of India and ISRO have developed a web enabled Water Resources Information System in the Country (http://www.india-wris.nrsc.gov.in/). The aim of India-WRIS is to serve as a "single window" for providing comprehensive and consistent data related to water resources at different spatial and time scales. Similarly, international data portals such as USGSearth explorer, Food and Agricultural Organization (FAO), International Water Management Institute (IWMI), World Data Center for Soils (ISRIC) and several other organizations have made a wealth of geo-spatial datasets, though some of them at a coarser spatial resolution, needed for distributed hydrologic modelling for almost free of cost. Access to these open source geo-spatial datasets has stimulated several studies on the development and application of distributed hydrologic model for several river basins across India. However, as a country we still have a long way to go to have an open data policy governing academic research, so that good quality data, especially river discharge and diversion/extraction data,becomes available from government bodies, for increasing the impact of ongoing research by rooting it on measured field data (Mujumdar, 2015).

Due to rapid urbanization and the associated impact of land use change on the hydrology, and with the availability of geo-spatial datasets, there has been increasing interest among the hydrology community in India to use distributed hydrologic models for assessing the impacts due to land use change. The hydrologic model Soil and Water Assessment Tool (SWAT) has been used in several studies to understand the impact of landuse/landcover change on the stream flow response (Babar and Ramesh, 2015; Sajikumar and Remya, 2015). The impact specifically due to urbanization on flooding of urban catchment have been investigated by several studies (Zope *et al*., 2015) using HEC-HMS. Most of the studies related to land use change studied the impacts by simply treating the land use as static between two time periods. This assumption could lead to bias in model parameters during calibration. Wagner *et al*. (2016) attempted to incorporate the dynamic changes in land use (modelled with SLEUTH)using SWAT to make hydrologic assessment of a rapidly developing catchment near Pune, and found such an approach to be more favorable for assessing seasonal and gradual changes in water balance (Fig. 1). Future studies in landuse/landcover change and its impact on hydrology can further explore incorporation of dynamic changes within the framework of distributed hydrologic model so that uncertainty in model parameters arising out of static landuse/landcover assumption could be investigated in detail.

Precipitation is one of the hydrologic variables with the highest amount of uncertainty. This is because precipitation is highly variable in both space and time. Although, Indian Meteorological Department (IMD) has a wide network of rain gage(~1289 automatic rain gages and ~675 automatic weather stations, in addition to several hundred non-recording rain gages), there are still regions with sparse rain gage data. In order to overcome this lacuna, few studies have explored using rainfall data from satellite data such as Tropical Rainfall Measurement Mission (TRMM). Indu and Nagesh Kumar (2014) developed a bootstrap approach for assessing sampling errors in satellite derived rainfall products such as TRMM over ungauged basins lacking in situ validation data. Based on the sampling errors, such products may be used for hydrologic modelling. Shah and Mishra (2016a) used rain gauge adjusted TRMM rainfall data with Variable Infiltration Capacity (VIC) model to develop an experimental real-time drought monitor for India.

One of the research areas that need larger attention within India is radar hydrology. The great deluge of Mumbai in 2005 and Chennai in 2015 reiterate the need to have a real-time flood forecast system. Radar hydrology (Krajewski, 2002) focuses

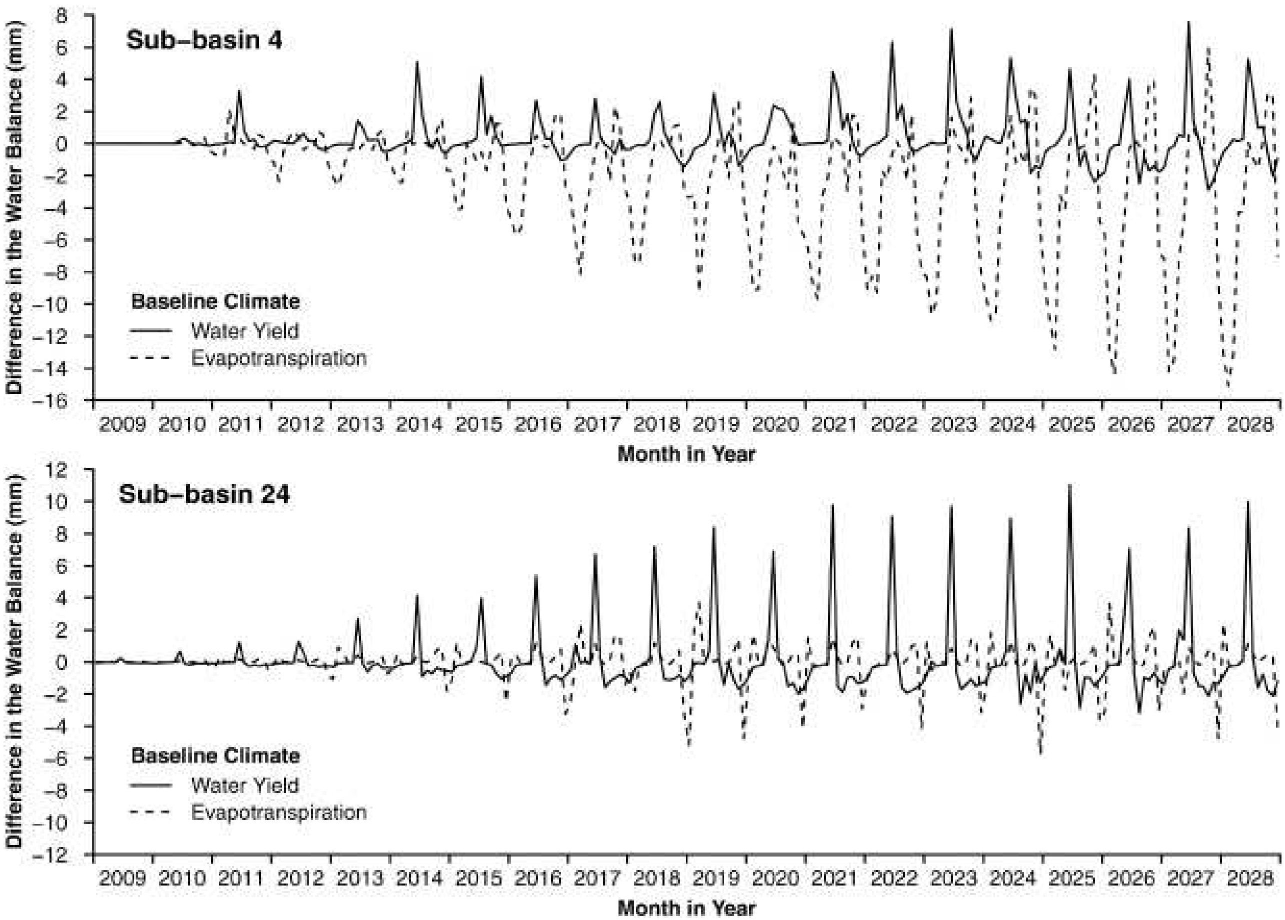


Fig. 1: Difference in water yield due to continuous (dynamic) land use representation when compared to the static land use representation in SWAT model (Source: Wagner *et al.*, 2016)

on development and use of hydrologic models based on radar-rainfall products on real-time suitable for flood prediction, monitoring and management. While there is lot of active research on this topic in North-America and Europe towards development of real-time systems, this is still in its infancy in India. In one of the of the only study till date in India, Josephine *et al*. (2014) used Doppler Weather Radar data for modelling flood hydrograph caused due to Cyclone *"Jal"* in the Adyar watershed near Chennai city. However, many more studies are needed within the country to advance the research in this field. Although radar data effectively captures the spatial and temporal pattern of rainfall, much better than the rain gage network, still it suffers from several systematic errors. These errors have to be corrected by developing improved bias adjustment methods (Vieux *et al*., 2008) specifically for monsoonal climate such as ours.

Groundwater Modelling

In India, groundwater has emerged as the main source of both drinking water and irrigation with an estimated 30 million wells (Shah, 2013). Groundwater is being exploited beyond sustainable levels, which is resulting in loss of functioning wells threatening drinking water supplies and irrigated crops in addition to water quality deterioration. Further, depleted aquifers cause higher greenhouse gas (GHG) emissions (Nayak *et al.*, 2015).

During the last decade an important regional assessment of groundwater depletion was carried using terrestrial water storage-change observations from the NASA Gravity Recovery and Climate Experiment (Rodell *et al.*, 2009) to show that groundwater is being depleted at a mean rate of 17.7 $\pm$ 4.5 km^3 yr^{-1} over the Indian states of Rajasthan, Punjab and Haryana. Recently, Papa *et al.* (2015)

used a multi-satellite approach to estimate surface freshwater storage (SWS) and subsurface water storage (SSWS) variations over Ganges and Brahmaputra (GB). The monthly SWS variations for the period 2003–2007 at the GB basin-scale showed a mean annual amplitude of <410 km^3 and SSWS mean annual amplitude was estimated to be <550 km^3.

Groundwater modelling efforts were made using popular models in various river basins to assess groundwater budgets and ways to improve groundwater resource sustainability. A case study on the semi-arid Musi sub-basin (11,000 Km^2) of Krishna basin was performed using three dimensional MODFLOW model (Massuel *et al*., 2013) and two water allocation scenarios were assessed and compared. Perrin *et al*. (2012) applied SWAT model in an 84 km^2 semi-arid crystalline watershed of southern India with no perennial surface water source. The model was found to reproduce the recharge rate estimates derived independently by a groundwater balance computation, runoff and surface water storage occurring in tanks that spread along the drainage system, and groundwater table fluctuations monitored at a monthly time step. Results showed that evapotranspiration was by far the largest water flux and the role of percolation tanks was significant as they provide about 23% of the annual aquifer recharge.

Relatively little is known about climate change impacts on groundwater (Green *et al*., 2011). Changes in land cover, land use and water resource management affect groundwater resources, and these environmental change signals often mask the relatively small climate change signals in groundwater systems there by attribution to climate change quite challenging (Green *et al*., 2011). The general and the simple approach used to investigate the potential impact of climate change on groundwater fluxes is by forcing the future projections of precipitation and temperature from the global climate models (GCM) into an established groundwater model for a watershed or region (Cambi and Dragoni 2000; Ferrant *et al*., 2014) illustrated the effects of potential projected climate change on the Kudaliar crystalline aquifer catchment (983 Km^2) in Krishna basin and under tropical semi-arid conditions through downscaled GCM forcing the spatially distributed agro-hydrological model, SWAT. The simulated seasonal groundwater storage for the historical and future periods averaged over the whole Kudaliar catchment were compared. Nayak *et al*. (2015) evaluated the impact of climate change on groundwater storage using WEAP model for Joga distributary of Sirhind command area which falls under Satluj basin in India. It was shown that sustainable groundwater use may require a reduction in rice area (by 25%), or the reduction of crop consumptive use through the use of mulches, and improved irrigation technologies for some crops.

Urbanization often modifies the groundwater cycle and induced changes to the groundwater system may be sharp decline or rise of groundwater levels, reduced well yields and deterioration in quality of groundwater. Investigations were made to analyze the groundwater system in urban areas (Srinivasan *et al*., 2010). The climate change impacts on urban groundwater systems have not received the desired attention. Furthermore, there is yet limited information on addressing impacts from a combination of climate change and management scenarios. Sekhar *et al*. (2013) investigated the behavior of the groundwater system in a small urban town in a semi-arid hard rock aquifer in south India, wherein the water utility solely depends on groundwater for drinking and other uses and analyzed the impact of combined climate and management scenarios on the hydrogeological system, in particular on the future groundwater declines and vulnerability of the municipal pumping well network.

To get a comprehensive understanding of the impact of climate change on vegetation and soil on to the groundwater system the complex coupled models are run in a distributed framework for a catchment (Mileham, 2009) which requires a series of parameters to be estimated. Instead alternate approaches are being projected wherein the region/catchment is delineated into zones called the recharge response units (RRUs) or groundwater management units (GMUs) based on climate, land cover, rainfall and soil, a few pivotal locations are selected or identified for each of the zones and the impacts of climate change on the groundwater system were analyzed by using coupled models in a lumped or 1-D approach (Crosbie *et al*., 2013). An alternative framework that was proposed by Subash *et al.* (2016) was to study the impact of climate change on groundwater system by using a gridded (e.g. 0.5^o x 0.5^o) groundwater level data. The advantage of such an approach is that gridded data products for meteorological variables like rainfall, temperature already exist globally with long temporal records ideally suited for climate change studies (e.g. gridded rainfall and temperature products of India's Meteorological Department (IMD) covering entire India at different resolutions 0.5^o or 0.25^o, availability of satellite products such as Tropical Rainfall Measuring Mission, TRMM). Further, a number of large international projects are setup to produce large ensemble of regional based climate models (RCM) for use in impact studies NARCCAP (North American Regional Climate Change Assessment Program) inter-comparison project, ENSEMBLES and CORDEX. Generating a robust gridded groundwater level time series is more likely feasible option, when the groundwater monitoring networks are evolving and sparse. Further, the benefit of zonal groundwaterlevels is that they provide a better representation of the specific yield and pumping for the region or the grid. Since the GCM simulated variables are available for a grid, having grid based groundwater data would also eliminate downscaling of rainfall from GCM to a point or a pivot. In addition, the simulations of groundwater storage time series performed over grids of 0.5^o or 0.25^o using this approach would be of great utility to downscale or debias the storage dynamics obtained from GRACE products.

An example of modelling the impacts of climate change on a gridded groundwater system is presented here. Fig. 2 presents the 0.5^o x 0.5^o grids for the

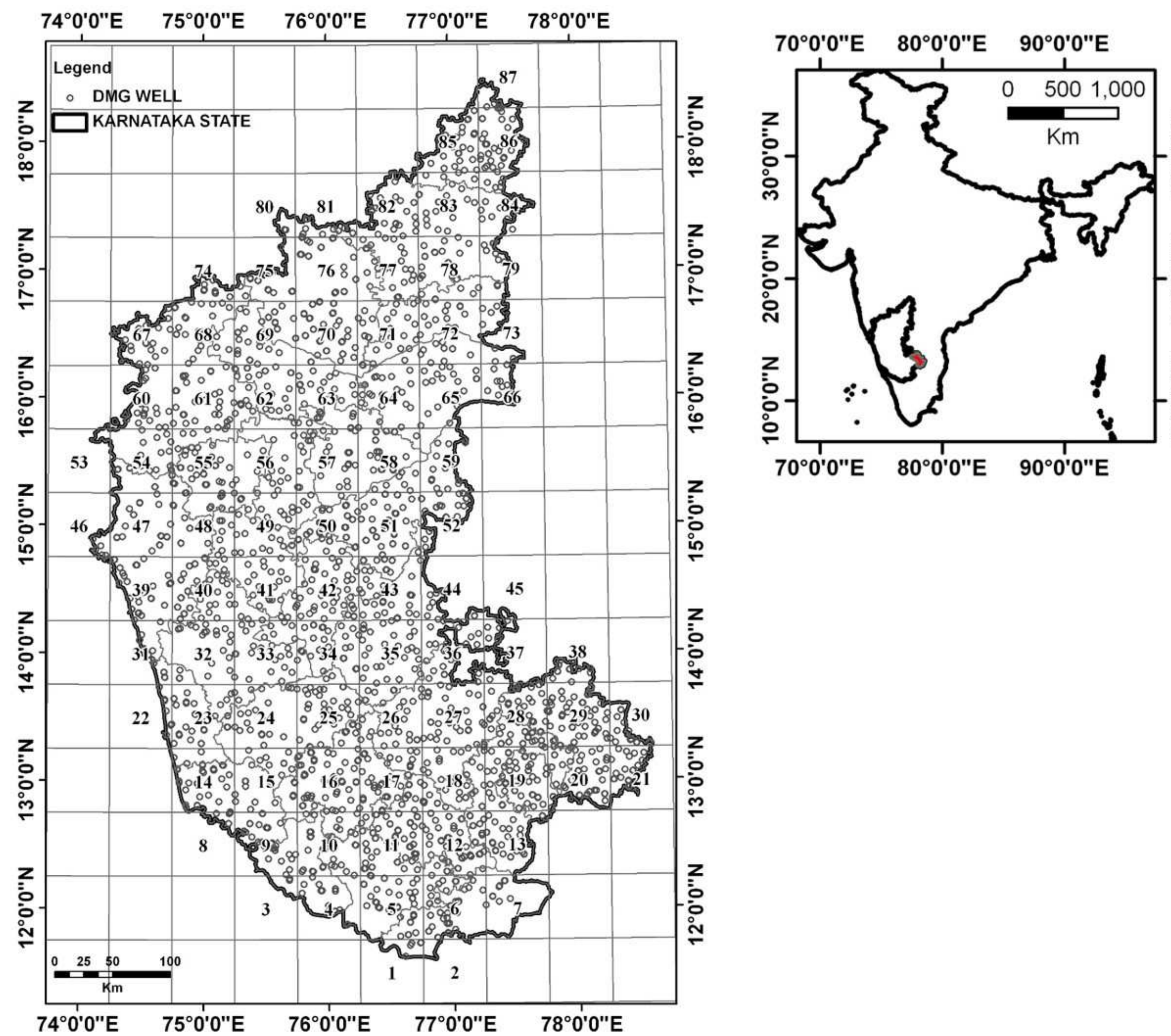


Fig. 2: Groundwater level station data in Karnataka with 0.5^0 x 0.5^0 grids

Karnataka state along with groundwater level monitoring network of Department of Mines and Geology, Government of Karnataka. For illustration the grid numbered 6 was chosen here. The gridded groundwater level time series is shown in Fig. 3 for grid 6 along with monthly rainfall. The block Kriged monthly rainfall is generated using the 0.25º x 0.25º resolution rainfall of APHRODITE (1976-2005) and TRMM_3B43 (2006-2012). The AMBHAS-1D model (Subash *et al*. 2016) was used to simulate the groundwater levels and its performance is shown in Fig. 3. Correlation coefficient and RMSE with the observed rainfall for the period 1976-2005 is shown in Fig. 4 using 19 GCMs and 3 RCMs for the grid 6. Future groundwater levels were simulated using the GCMs and RCMs, which resulted in correlation coefficient of 0.4 and the mean and standard deviation of groundwater levels are shown Fig. 4. This demonstrates an approach of analyzing climate change impacts on stressed groundwater regions using aggregated groundwater data. Going forward, studies must focus on approaches to arrive at scenarios of future pumping based on land cover changes and irrigation amounts taking into account newer technologies and improved land management practices.

Climate Change Impacts and Hydrologic Extremes

Long-term changes in the climate system due to natural or forced variability is expected to alter the hydrologic cycle. For a rapidly developing country such as India where natural resources such as water might already be in a state of stress, climate change in conjunction with concurrent confounding factors like urbanization and industrial growth can have a significant impact on the society. While natural climate variability is known to drive the hydrological cycle in a steady manner over time, hydrologic impact of anthropogenic climate change due to greenhouse gas emissions remain of particular concern to the scientific community and the water managers. Large-scale changes in the earth's climate system have been attributed to human-induced climate change (Bindoff *et al*., 2013). Starting from the early days of linking increases in only global average temperature with greenhouse gas emissions, climate scientists have come a long way in establishing the anthropogenic effects on several aspects of the earth system as part of a coherent story.

Hydrologists, however, are typically interested in smaller spatio-temporal scales, such as discharge in a watershed, where it is increasingly difficult to attribute historically observed changes to human-induced climate change because of the interplay of several causal factors including large natural variability noise and local human interventions and regulations. In addition to investigating long-term changes through detection and attribution (D&A) studies (Hegerl *et al*., 1996), recent research efforts also attempt to quantify human effects on individual hydroclimatic extreme events to evaluate how much more likely the event became because of anthropogenic climate change through a probabilistic event attribution (PEA) framework (Stott *et al*., 2004). The global climate model simulations play a central role in attribution studies as they can be used to obtain patterns of the earth's climate system with or without particular forcings. These patterns are thereafter searched in the actual observations to conclude whether signals of such forcings are detectable.

However, the GCMs operate at coarser resolutions; therefore, they cannot represent fine-resolution processes and cannot provide at-site estimates of hydrologic variables. This scale and physical-process mismatch can be addressed to facilitate comparisons between coarse scale model simulations and fine-scale observations by *downscaling* methods. While dynamic downscaling involves running regional climate models (RCMs) nested within the GCMs, to capture local features, statistical downscaling constitutes fitting a relationship between large scale climate predictors and small-scale hydrologic predictands. Physically-based hydrologic models or other impact models can be further used in conjunction with climate model simulations to obtain regional variables of interest.

Once the signals of human emissions are detected in regional hydrologic variables, future projections of such variables can be obtained based on projected scenarios of emissions for impact assessment. The impact assessment studies also use GCM simulations for obtaining projections of large-scale climate predictors that can be further downscaled to a regional variable of interest. In addition to assessing impact of climate change on precipitation

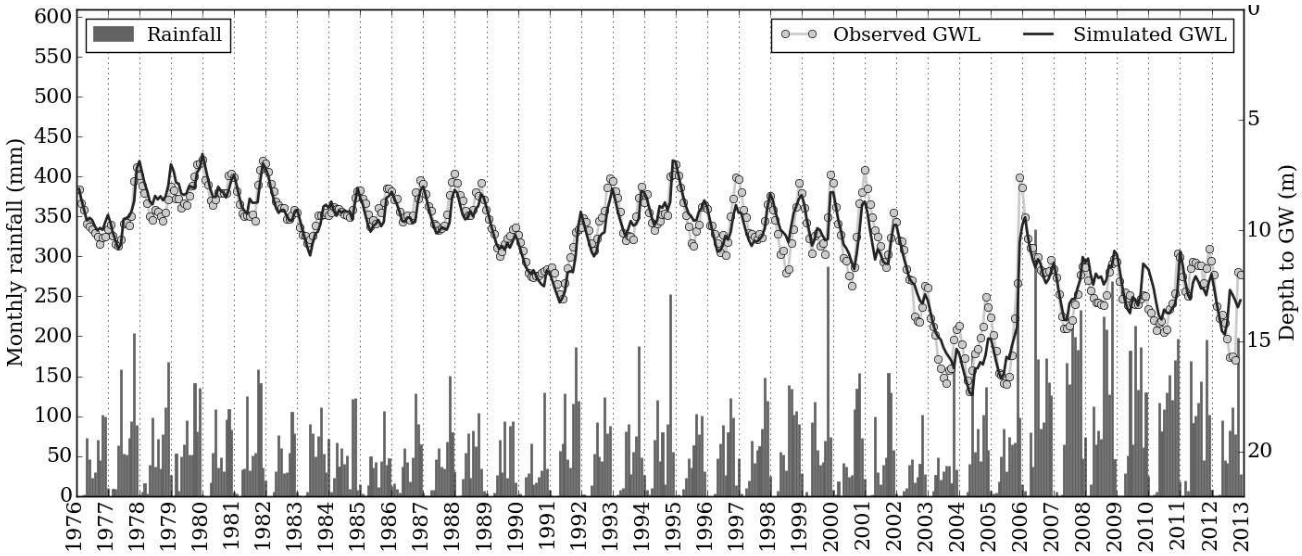
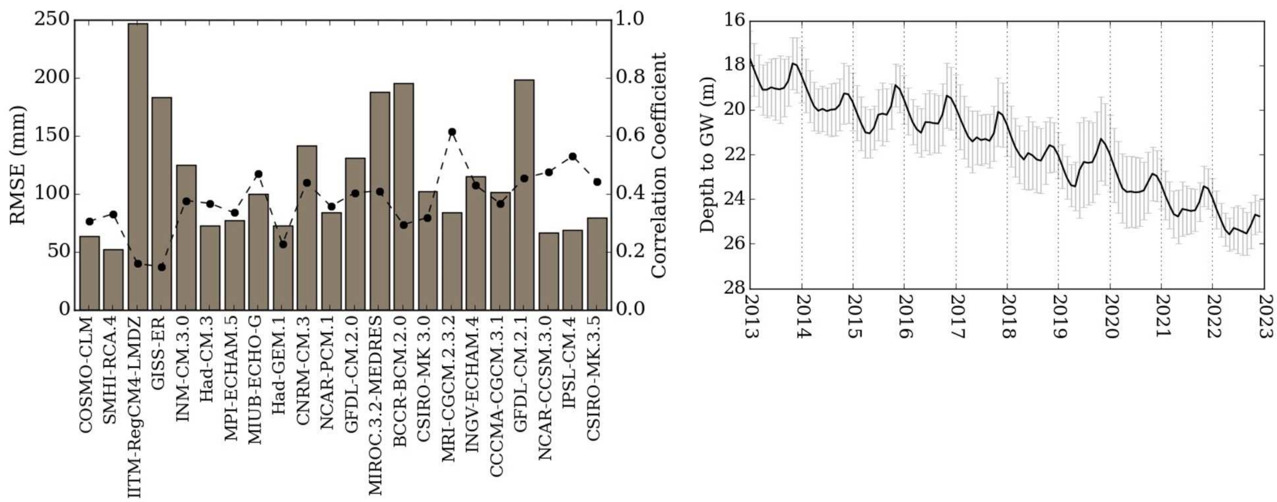


Fig. 3: Groundwater level time series (circle markers) for grid 6 along with monthly rainfall. Also shown is the modeled groundwater levels (thick line)



A B

Fig. 4: (A) Correlation and RMSE of RCMs and GCMs with the observed rainfall for the period 1976-2005, (B) Simulated future groundwater levels (mean and standard deviation) using GCMs and RCMs whose correlation coefficient was above 0.4

and streamflow, hydrologists are also interested in studying water quality, groundwater levels, and hydroclimatic extremes such as short duration high intensity rainfall, floods or droughts, under climate change.

Finally, for effective water management taking all these factors into consideration, robust measures of hydrologic risk are required for designs under climate change. The traditional assumption of stationarity on which hydrologic designs are based, implies that the past can be a guide to the future. However, this assumption needs to be re-evaluated under changing climate conditions and therefore, newer, more robust methods need to be formulated for defining hydrologic design levels.

Here we discuss recent research efforts with specific applications in the Indian region, towards addressing the scientific aspects described above. Uncertainties related to the use of climate models, downscaling, emission scenarios or hydrologic models are dealt separately subsequently.

Climate Change Detection and Attribution

Several studies in the recent times examined changes in hydroclimatologic variables in different parts of the country and possible links with climate change: while some investigated long term trends in rainfall or temperature over relatively larger spatial scales (Kumar *et al*., 2010; Jain and Kumar, 2012; Sonali and Nagesh Kumar, 2013; Kothawale *et al*., 2010; Mondal *et al*., 2015, etc.), others focused on specific regions (Kumar and Jain, 2010; Singh and Mal, 2014; Jain *et al*., 2013; Adarsh and Janga Reddy, 2015; Thomas and Prasannakumar, 2016, etc.) or particular aspects of the monsoon system (Sahana *et al*., 2015; Turner and Annamalai, 2012; Dash *et al*., 2015; Bollasina *et al*., 2013) or hydroclimatic extremes (Goswami *et al*., 2006; Rajeevan *et al*., 2008; Ghosh *et al*., 2012; Guhathakurta *et al*., 2011; Krishnaswamy *et al*., 2015; Mondal and Mujumdar, 2015a; Vinnarasi and Dhanya, 2016; Deshpande *et al*., 2016 etc.). However, only a handful of studies attempt a formal fingerprint-based attribution analysis to categorically link anthropogenic climate change with observed changes in hydrologic variables in India. While Lau and Kim (2010) attribute trends in Indian monsoon to anthropogenic aerosols, Mondal and Mujumdar (2012) concluded, through a detection and attribution analysis on monsoon precipitation and streamflow in the Mahanadi River Basin, that at local scales human-induced climate change signals may not be unequivocally identified in hydrologic observations. Sonali and Nagesh Kumar (2015) inferred that changes in extreme temperatures over India lie outside the range of natural climate variability, while Mondal and Mujumdar (2015b) highlight the difficulties in uniquely attributing changes in extreme rainfall over India to anthropogenic greenhouse gas emissions.

Although extreme hydroclimatic events are often encountered in India - some examples include flooding in Mumbai and Chennai in 2005 and 2015 respectively or the heat wave in Northern and Eastern India in 2015 that resulted in huge societal losses, PEA, for investigating how these individual events were influenced by human-induced climate change, is relatively unexplored in this country. Across the globe,a handful of extreme events are deemed to be made more likely by anthropogenic climate change: they include the 2003 European heat wave (Stott *et al*., 2004), 2000 European floods (Pall *et al*., 2011), 2010 Russian heat wave (Otto *et al*., 2012) 2011 East African drought (Lott *et al*., 2013) and 2014 England winter floods (Schaller *et al*., 2016). In the Indian context, Cho *et al*. (2015) could establish a link between anthropogenic greenhouse emissions and aerosols and the June 2013 heavy rainfall and flooding in Northern India, while Singh *et al*. (2014) conclude that the same event was at least a century time-scale event and the evidence for increased probability of such an event in the recent times because of increased human influence is equivocal. Relatively short good quality observational records and computation-exhaustive modelling exercise and related uncertainties pose challenge for PEA analysis for extreme events in India.

Hydrologic Impacts of Climate Change

Over the last decade or so, several research articles have carried out climate change impact assessment analyses. Recent examples include studies on extreme temperatures (Srinivas *et al*., 2014), rainfall (Menon *et al*., 2013; Salvi and Ghosh, 2013etc.), water availability and streamflow (Gosain*et al*., 2011; Islam *et al*., 2012; Raje *et al*., 2014; Uniyal *et al*., 2015a; Whitehead *et al*., 2015, Singh and Kumar, 2015 etc.), soil erosion (Mondal *et al*., 2014), water quality (Rehana and Mujumdar, 2012) irrigation demands (Rehana and Mujumdar, 2013), and groundwater availability and recharge (Shah, 2009; Panwar and Chakrapani, 2013etc.). Most of these studies use climate model simulations along with downscaling approaches and physically-based hydrologic/impact models. Though these studies present plausible future projections of impact variables of interest, uncertainties and caveats at each modelling step must be duly recognized. Indeed, some recent studies evaluate model performances for hydroclimatic variables over India. While Sonali *et al*. (2016) compare model skills for extreme temperatures, Shashikanth *et al*. (2014) and Saha *et al*. (2014) report inabilities of the most recent climate models to simulate Indian monsoon rainfall. Mishra *et al*. (2014) also reported poor regional and global model performances for extreme precipitation over India.

Impact of Climate Change: Hydroclimatic Extremes and Non-stationarity

Extreme events such as very heavy rainfall, floods, droughts or heat waves are overly important as they can have devastating effects on lives and property; yet, at the same time, their behavior is difficult to be understood as they are rare by their very definition. Moreover, traditional hydrologic designs are based on the assumptions of stationarity which can be questionable under changing climate conditions. For example, the definition of a 100-year flood changes if the probability of its exceedance changes with time. Two interpretations of return period based on expected waiting time and expected number of events respectively, can be extended to the non-stationary conditions. Moreover, some recent studies also propose the probability of failure (Rootzen and Katz, 2013; Serinaldi, 2015) as a more robust measure of hydrologic risk as compared to return period and return level. Mondal and Mujumdar (2016) present a comparison of these novel risk measures for non-stationary conditions for extreme rainfall at a location in South-Western India and conclude that under confounding uncertainties, further investigation is required to arrive at the 'best' estimate of hydrologic risk under climate change. Indeed, statistical parameter uncertainty (or sampling variability) is an important aspect for hydrologic designs and constitutes an additional source of uncertainty along with other uncertainties discussed in the next section. For precipitation intensity-duration-frequency relationships that have implications for urban infrastructure designs, Chandra *et al*. (2015) in fact show that statistical parameter uncertainty can indeed be higher than GCM uncertainties for short duration high intensity precipitation.

Uncertainty Modelling

Uncertainties at all stages of hydrologic modelling, from state estimation to parameter estimation and system identification pose a major challenge to hydrologists in communicating the predictions with confidence. In the Indian context, missing data, small samples of data and unacceptable quality of data pose another – and a significant – source of uncertainty as model calibration and validation are based on such datasets. Use of GCMs, scenarios and downscaling methods in obtaining hydrologic projections under climate change introduces a significant uncertainty in the projections. This section describes the work carried out in India over the last about five years on quantification of uncertainties in hydrologic impacts of climate change and in modelling hydrologic processes.

Uncertainties in Climate Change Impacts

Uncertainties in projections of hydrologic responses to climate change arise from various sources including limitations in scientific knowledge (for example, effect of aerosols) and human actions (such as future greenhouse gas emissions). These two forms of uncertainties are classified generally as model uncertainty and scenario uncertainty respectively. Downscaling of GCM outputs to station-scale hydrologic variables using statistical relationships introduces an additional source uncertainty. Another source of uncertainty arises from the hydrological modelling itself.

Over the last five years, a number of studies have been conducted in India to quantify uncertainty in projections of large scale climate change impacts on hydrology at river basin scales. The studies have generally used a spread of results from a number of GCMs/RCMs, scenarios and downscaling methods (e.g., Raje and Mujumdar, 2011; Ghosh and Katkar, 2012; Singh *et al*., 2015; Dimri *et al*., 2013). Mujumdar and Nagesh Kumar (2012) provide an extensive discussion of these methods. Shashikanth *et al.* (2014) used linear regression based statistical downscaling with outputs from 19 GCMs for projecting the Indian Summer Monsoon Rainfall (ISMR) at different spatial resolutions. They argue that merely increasing the resolution of statistical downscaling does not necessarily increase the effectiveness of downscaling. When projections are obtained from a single GCM, the intra-model uncertainty is addressed with a large number of model runs. For example, Salvi and Ghosh (2013) have used this approach to obtain projections of the All India Summer Monsoon Rainfall. Uncertainty in the projections resulting from the GCMs is estimated by developing probability distributions of key variables such as the precipitation and streamflow.

Uncertainty Combination: GCM, Scenario and Downscaling Uncertainty

Assessing regional hydrologic impacts of climate change through downscaling adds another source of uncertainty, through the choice of downscaling method. Combination of model, scenario and downscaling uncertainties has been studied using the Dempster-Shafer theory and natural variability linkages have been used for constraining uncertainty in regional impacts (Raje and Mujumdar, 2010a, b). The Dempster-Shafer (D-S) theory or the theory of belief functions is a mathematical theory of evidence which can be interpreted as a generalization of probability theory. The D-S theory provides methods to represent and combine weights of evidence. A case study for the uncertainty quantification methodology is presented for projecting streamflow of Mahanadi River at the Hirakud reservoir (Raje and Mujumdar, 2010b). A conditional Random Field (CRF) based downscaling is used to account for downscaling uncertainty. The Standardized Streamflow Index (SSFI), which is similar to the more commonly used Standardized Precipitation Index (SPI) is adopted to describe the hydrologic droughts. Each scenario-GCM gives a projected range of future CDFs for SSFI-4 classifications. The DSSs obtained from all scenarios for a particular GCM are first combined by assigning equal weights to each scenario, and then a combination across all models is carried out to provide a band of uncertainty in the projections.

In addition to GCM and scenario uncertainty, uncertainty in the downscaling relationship itself is explored by linkages to changes in frequencies of modes of natural variability. Raje and Mujumdar (2010a) demonstrated that incorporating changes in projected frequencies of natural regimes, and applying a novel constraint of GCM performance with respect to natural variability, results in a large reduction in uncertainty in regional hydrologic prediction, in the Mahanadi basin. Kannan *et al.* (2014) recognized another source of uncertainty resulting from use of multiple data sets and reanalysis products in impact assessment, in simulating the 21st century Indian Summer Monsoon Rainfall (ISMR). They observed that the uncertainty resulting from use of different data sets and reanalysis data sets is comparable to that resulting from multiple GCMs, and thus should not be ignored in impact studies.

The Coordinated Regional Climate Downscaling Experiment (CORDEX) South Asian Experiment provides downscaled projections on temperature and precipitation useful in hydrologic impact assessment. The simulations from CORDEX over the historical period have been shown to differ significantly from the observed data in several regions (e.g., Chawla and Mujumdar, 2015; Mishra, 2015). Mishra (2015) showed that the CORDEX-RCMs overestimate observed warming by threefold in Ganges and Brahmaputra basins. The CORDEX-RCMs showed larger uncertainty at the lower elevations in both precipitation as well as temperature, while the observed data sets showed larger uncertainty with increase in elevation, perhaps because of the sparse data in the higher elevations. An interesting observation of Mishra (2015) is that the parent GCMs from which the CORDEX RCMs are derived show a better performance in simulating winter climate than the CORDEX-RCMs, which suggest that an improved representation of elevation may not necessarily improve the model's performance.

An important recent work on uncertainty quantification in climate change impacts is by Singh and Kumar (2015) who presented a probabilistic Budyko framework to derive estimates of water availability across India with quantification of associated uncertainty. They conclude that southern India is most susceptible to changing climate with less than 10% decrease in precipitation causing a 25% decrease in water availability.

Hydrologic Model Uncertainties

Uncertainties in the hydrological models result from parameter estimation with limited data, and the process approximation in the models.Uncertainty resulting from the commonly used hydrologic model, Soil and Water Assessment Tool (SWAT) has been studied by Narasimlu (2013), Singh *et al*., (2013), Singh *et al*., (2014), Uniyal *et al*., 2015b and Kumar Raju and Nandagiri (2015). Raje and Krishnan (2012) addressed the parameter uncertainty in the Variable Infiltration Capacity (VIC) model, a macroscale hydrologic model, using the Bayesian inference theory. The VIC model was employed in the climate change impact assessment of streamflow at four discharge stations in India, namely, Farakka, Jamtara, Garudeshwar, and Vijayawada. While emphasizing the parameter uncertainty in the hydrologic models, they observed that uncertainty introduced due to choice of GCM, is larger than that due to parameter uncertainty for the VIC model, when it is used for climate change impact assessment. Dhanya and Kumar (2011) have used a novel approach of ensemble wavelet networks to quantify the predictive uncertainty of daily streamflow in the Mahanadi Riverbasin, displaying a chaotic behavior. They observed that the total predictive uncertainty in the streamflow is reduced when modeled with ensemble wavelet networks with different lead times. Other recent studies addressing uncertainty in modelling hydrologic variables include those by Barua *et al*. (2010), Panda *et al*., (2013) and Shah and Mishra (2016b).

Concluding Remarks

While a significant progress has been achieved in hydrologic modelling of Indian river and aquifer systems, the models may be constrained by sparse observation networks. A commensurate effort is needed on developing well instrumented watersheds to measure surface and groundwater fluxes to enhance the growth of hydrologic science. The knowledge generated through such controlled watersheds could then be exploited to upscale the processes with suitable parameterization to larger scales. Advances achieved in addressing non-stationarity and quantification of uncertainties should facilitate such multiscale hydrologic modelling. Finally, an end-to-end analysis can be achieved by integrating advances in hydrologic modelling with those in closely related disciplines such as ecology, atmospheric science, geomorphology, and mathematical and social sciences.

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