Using remotely sensed precipitation in large-scale distributed hydrological modelling

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Abstract

The combination of satellite-based remote sensing and distributed hydrological modelling provides a powerful tool for hydrological prediction and forecasting. Remote sensing (RS) data can be incorporated in distributed models in a number of ways including; static input data (e.g. land use classification) calibration and validation (e.g. soil moisture, vegetation status, surface temperature, evapotranspiration), data assimilation (i.e. update model variables to match currently observed conditions, e.g. LAI) and as dynamic input data (i.e. model driven by RS data time series, e.g. satellite-based rainfall). Meteorological information is of great importance for any hydrological model and in particular for flood forecasting. In many areas with sparse coverage by conventional rain gauges and high spatial and temporal variability in rainfall, spatially distributed rainfall information from satellites, weather radar and meteorological models provide promising new sources of precipitation information.

For small-scale applications, detailed data from either weather radar or high-density rain gauges networks are the most appropriate. For large-scale models where high spatial resolution of rainfall information is less important, time scales are larger and results less sensitive to uncertainty then remote sensing-based precipitation is a feasible alternative source rainfall information. Despite the potential benefits of remote sensing data for water resources and hydrological modelling there are relatively few case studies that show practical benefits. In this paper a case study using satellite-based precipitation nowcasting and large-scale hydrological modelling is presented. An evaluation of the benefits and limitations of remote sensing for this type of application is presented. The case study investigates the feasibility of such an approach for flood forecasting in Bangladesh.

Introduction

With the increasing availability and rapid technological development within satellite remote sensing hydrologists have recognised the potential benefits of employing satellite data in hydrology and water resources. In particular satellite remote sensing provides much sought after spatially distributed information for distributed hydrological modelling.

Application of RS data in hydrological modelling

Satellite remote sensing (RS) data is of interest in hydrological modelling for several reasons. Firstly it is possible to obtain direct measurements of the state of the catchment, including flooding conditions, surface temperature for monitoring evapotranspiration, soil moisture conditions, snow coverage and snow water content, etc. Perhaps the most scientifically interesting benefit of RS data is that it provides data integrated over an area rather than point data as in usually the case for traditional monitoring networks. Since many distributed hydrological models both use hydrological parameters integrated over a numerical grid and make predictions on the same grid (Refsgaard and Butts, 1999), satellite remote sensing can provide data directly at the modelling scale. RS data can also be expected to improve our understanding of scale effects in hydrological modelling as information is captured as
an integrated measurement, which can be performed at different scales. The particular strength of RS data is that it is often the only source of information, in remote areas such as deserts and areas with low network density. Satellite remote sensing can even provide historical data where no traditional measurements have been made. The increasing availability of RS data opposes the global trend in the reduction of traditional monitoring networks. (UN/WWAP, 2003). Finally, RS data is available in near real-time, which is one of the reasons it has been a normal part of weather forecasting systems for many years.

RS data that is relevant in hydrological applications include basin characteristics such as land-use, topography, vegetation cover, etc and key hydrological variables such as precipitation, evapotranspiration, snow cover and water content and surface water extent and depth including flood extent and depth. To a lesser extent it is possible to derive information concerning soil moisture and groundwater however there are severe limitations associated with these data. While RS data provides spatially distributed data for distributed modelling, modification is required to explicitly use or simulate RS data. This is essentially because the relationship between the satellite signal and the hydrological quantities of interest are often indirect. This is discussed in more detail in the next section.

The incorporation of RS data into distributed hydrological modelling can be classified into four categories:

1. Static Input data. Data such as land use classification, irrigated areas, inundation areas, is used to define the model set-up, i.e. the value and distribution of model parameters (Bøgh et al. 2004).
2. Calibration and Validation data. Data such as flood extent, soil moisture, vegetation status, surface temperature, evapotranspiration are used to determine model parameters via manual or automatic calibration or to test the predictive ability of the model. (Andersen et al. 2002, Jørgensen and Høst-Madsen 1997)
3. Data Assimilation. To update model variables or states, such as Leaf Area Index LAI soil moisture using the satellite observations to improve hydrological predictions or forecasts using a feedback process, (Bøgh et al. 2004, Pauwels et al. 2001)
4. Dynamic Input Data. A time sequence of RS data (e.g. satellite-based rainfall, snow cover, LAI, irrigation status) to either to drive the model. (Andersen et al 2002, Dybkjær 2003)

In the remote sensing literature the term “assimilation” is often used in a more general sense to the combination of RS data with models. This usage encompasses all of the four categories described above. In this classification, data assimilation is used more specifically to the application of RS data in a feedback or updating process.

**Limitations of Satellite Remote Sensing Data in Hydrology**

Despite it’s potential there are a number of limitations that must be addressed in the application of remote sensing data for hydrological simulation.

Firstly the cost of obtaining the data is still relatively high when large quantities are needed, limiting it widespread use particularly in developing countries. There is therefore a corresponding lack of technical skills in the same countries as the collection and processing of remote sensing data is still a specialist task. At present many of the existing platforms are focussed on geophysical applications within oceanography, climatology, and meteorology, so hydrological uses are generally only a secondary product. This means that limitations in the frequencies and frequency ranges actually measured limit the hydrological quantities that can be derived. The most challenging aspect of the application of remote sensing is that the relationships between the satellite measurement and the physical quantity of interest are often indirect. To derive the physical quantities requires either the introduction of interpretative models or local ground measurements or both. The type of satellite used (geostationary or orbiting) and the height determine the spatial and temporal resolution of the RS data. In general many hydrological applications require both higher resolution and more frequent measurements than are currently available. As well as these more general limitations there are a
number of more specific limitations depending on data of interest. For example cloud cover may prevent the use of satellite imagery for crop water requirements and plant development. Similarly soil moisture estimation is limited to the upper few centimetres of soil where the soil moisture signal is highly dynamic and which are not necessarily representative of the underlying soil profile, Engman 2000.

While we have identified several of the current limitations this situation is by no means static. There are a number of planned and proposed sensors and platforms with generally improved spatial resolutions, narrower and more specific spectral bands and more in the microwave spectrum. Several global projects have been initiated where data is free and easily accessible on the web. New sensors have been designed to provide products that are geo-coded, calibrated and atmosphere-corrected. Examples include MODIS, (USA) with 250, 500 and 1000 m pixels, and daily values of LAI, Vegetation Index, Surface temperature, Net Primary Production, tree cover, land cover and Meris from ENVISAT (Europe/ESA) provides an increase in the spatial resolution down to 300 meters for all bands and generally improved radiometric quantities. New Internet services are being developed focusing on tailoring products to users needs and near-real time access through the net, e.g. TRMM. Finally very high-resolution data such as Ikonos (1 m panchromatic / 4 m multispectral) and QuickBird (0,61 m / 2,4 m). are now available on-line.

In summary RS data offers a number of opportunities for improved hydrological modelling. The application of remote sensing data requires a critical evaluation of their limitations. Nevertheless, further exploitation of both routine satellite remote sensing data and emerging developments are required to demonstrate their practical application. The remainder of this paper will focus on the application of satellite-based precipitation estimation for large-scale hydrological modelling.

**Flooding in Bangladesh.**

Bangladesh is subject to frequently flooding and often catastrophic flooding with recent extreme floods in 1987, 1988 (Brammer, 1990), 1998 (Chowdury 2000) and 2000. Bangladesh is a low-lying country on the delta formed at the confluence of the three major rivers the Ganges, the Brahmaputra and the Meghna, Figure 1. The Ganges and the Brahmaputra both have their origins in the Himalayas. After entering Bangladesh from the west and the north, and renamed to be Padma and Jamuna, respectively, the two rivers merge into the Padma River in the middle of Bangladesh. The Meghna River drains the northeastern part of Bangladesh. The Padma and the Meghna River merge to be simply the Meghna River and it ultimately discharges into the Meghna Estuary (e.g. Jakobsen et al., 2002) in the northern Bay of Bengal. The catchment area of the Ganges, Brahmaputra and Meghna Rivers are 907,103 km2, 583,103 km2 and 65,103 km2, respectively, of which only 8% lie in Bangladesh.

Flooding is an annual recurring event during the monsoon in Bangladesh, Hofer and Messerli, (1997). Normal floods (barsha) may be considered as natural assets as they maintain the high fertility of cultivated land, whereas extreme floods (bonna) may be considered as natural hazards. Extreme floods are characterized by either unusual high water levels and/or long-duration of flood or by unusual early or late arrival of flood. An important contributing factor to the flood hazard is the synchronisation of high flows through the Ganges and the Brahmaputra. For example, during the 1998-flood the water level reached its maximum level at Hardinge Bridge in the Padma River (Ganges) on 8 September 1998 at 03.00 hrs, while at Bahadurabad in the Jamuna River (Brahmaputra) on 7 September 1998 at 13.00 hrs. The time difference between the peaks was only 14 hours. However several other mechanisms also lead to flooding in Bangladesh. Local flooding occurs because of heavy rainfall events within Bangladesh. Flash flooding occurs in the north-eastern part of Bangladesh as a result of heavy rainfall in the Meghalaya Hills. This is the first orographic barrier that the humid SW monsoon wind meets coming from the Bay of Bengal. Finally, storm surges produce flooding along the coast as a result of cyclones hitting the southern coastline of Bangladesh and the generally extremely flat topography of this delta area.
Figure 1 Bangladesh in relation to the Ganges, Brahmaputra and Meghna River basins

Flood forecasting system

One response to the frequent and often catastrophic flooding in Bangladesh is the application of flood forecasting. Since the early nineties a flood forecasting and warning system based on hydrodynamic modelling of the river system and hydrological modelling of the rainfall-runoff processes has been applied in Bangladesh, (Jørgensen and Høst-Madsen 1997). Operational forecasts are made on a daily basis in the monsoon season through the Flood Forecasting and Warning Centre (FFWC). FFWC operates "Flood information Centre" as focal point in connection with Disaster Management both for cyclones and floods, (http://www.ffwc.net/).

The core of the forecasting system is a GIS based flood management system MIKE FLOODWATCH, http://www.dhisoftware.com/mike11/Description/MIKE_11_FW.htm. The flood forecasting hydrometric network consists of more than 60 water level and rainfall stations. Data is collected both manually and via telemetry systems. This data is acquired by the MIKE FLOODWATCH real-time databases for display and monitoring, for real-time flood forecasting of both water levels and discharge within the river network and flood extent in the surrounding floodplains. The flood forecasting is carried out using the MIKE 11 model (Havnø et al. 1997). The current model covers most of Bangladesh including some 156 rainfall-runoff catchments, and the much of the river system as shown in Figure 2.
Figure 2 Map of the major rivers in Bangladesh and selected cities or locations. The current model includes all the rivers shown.

Figure 3 Display of the forecast status information using GIS
The management of dissemination and the display of flood information and flood warnings form an integrated part of the flood management system. The display of status information within the GIS environment allows the user to achieve an effective overview of the flooding situation (Figure 3). This data is transformed into bulletins (Butts et al., 2002, Jørgensen and Høst-Madsen, 1997) and special maps for nation-wide transmission on national television, Figure 4. Flood warning and status information is disseminated from FFWC in Dhaka to the relevant local authorities and emergency organisations and to those at risk via radio, newspapers and television.

Figure 4 Example of a flood warning status map as issued by the Flood Forecast and Warning Centre, Dhaka, Bangladesh, showing flood warning codes for each Thana (county). Gray: Danger. Black Thanias with Severe Flooding.

**Forecasting model validation using satellite imagery**

Extensive calibration and validation of the model has been carried out (Jørgensen and Høst-Madsen 1997, Jakobsen et al, 2004) against both water level and discharge measurements. An evaluation of the model results (Chowdhury 2000) has demonstrated their usefulness during flood events. One of the potentially most powerful use of satellite remote sensing is to provide independent validation of the spatial predictions made by hydrological models. In this case the prediction of flooding outside of the river system is difficult to capture using traditional monitoring methods. Since in Bangladesh extensive flooding occurs outside the river system, it is important to capture this correctly for flood forecasting. A comparison with remote sensing images provides a strong test of the predictive ability of the forecasting model. Examples of the independent validation of the simulations of both flood extent and flood depth can be obtained using estimates of flood extent (Figure 5) and flood depth (Figure 6) from satellite imagery. The flood depth is deduced by combining a digital elevation model with the flood map based on satellite data.
Figure 5 Comparison of the flood extent derived using the flood mapping with MIKE 11 GIS and satellite imagery showing the cloud cover and flooded areas during the 1995 floods.

Figure 6 Comparison of flood depth during September 2002 along a 120 km transect through the inundated area in north east Bangladesh estimated using the forecasting model and satellite imagery.
Satellite-based precipitation nowcasting

The current forecasting system is based on operational data and forecasts within Bangladesh. A key source of uncertainty therefore is the forecasts of the behaviour of the inflows from the Ganges and Brahmaputra rivers at the boundaries between Bangladesh and India. At present only limited traditional operational data is available outside Bangladesh. Nor is it currently feasible to gather detailed traditional rainfall information over the extensive Ganges, Brahmaputra and Meghna basins. On the other hand daily rainfall estimates in the tropics have been made using geostationary satellites like GOES (US), METEOSAT (EU) and GMS (Japan). Therefore one method of improving the boundary forecasts is to use the daily rainfall estimated over the Ganges and Brahmaputra basins from satellite imagery as input into a large-scale hydrological model of these basins. As a first step, the feasibility of such an approach was examined.

The satellite data in this feasibility study were recorded by the geostationary METEOSAT 5 satellite for the four months of the monsoon (June-September) of 1999. Thermal Infra-Red (TIR) data were provided by EUMETSAT, Darmstadt, free of charge at two hour intervals on a 5 km grid scale.

For the estimation of daily distributed rainfall at basin or regional scales, variants of the TIR-based Cold Cloud Duration (CCD) techniques presently surpass other methods applied in tropical rainfall regimes (Dybkjær, 2003). The strength of CCD techniques lie in the relatively high sampling frequency obtainable from geostationary platforms and the fact that the TIR data used in CCD algorithms are available more or less real-time as would be required for flood forecasting.

The simplest and most widely used CCD technique to estimate rainfall is the GOES Precipitation Index (GPI) suggested by Arkin and Meiser (1987), (Equation 1)

\[
GPI = rr \cdot Fr(th) \cdot D
\]

where \(rr\) is the mean rainfall rate (mm/h), \(Fr\) is the fractional coverage by cloud temperatures below a given rainfall temperature threshold, \(th\) and \(D\) is the duration of cloud cover with temperatures less than \(th\). In this paper results are shown for the GPI which was found to perform best. A more comprehensive investigation of both the GPI and integrated GPI methods and continuous self-calibration methods for Bangladesh are presented in Dybkjær (2003).

The CCD methods used here assume that in regions with free convective rainfall, the rainfall on the ground is correlated to the duration of cold cloud cover over the area of interest. Therefore the relation between the satellite images and the ground rainfall is only indirect. However, the majority of tropical rainfall is known to originate from convective clouds and the probability of cloud cover producing rainfall increases with the thickness of the clouds. Hence the cloud top altitudes and therefore the cloud top temperatures are related to the surface rainfall. In Bangladesh, the fraction of rainfall originating from convective systems is around 70 % (Mohr et al., 1999). Islam and Wahid 1999 report that approximately 50% of the clouds in the monsoon precipitate. This suggests there is a reasonable basis for the estimation of regional rainfall using a CCD method.

In summary, the main advantages of this method for this study are the good spatial and temporal resolution (5km grid every two hours for METEOSAT), the fact that the there are at least 3 geostationary thermal satellites in the area, increasing the reliability for forecasting, the near real-time availability of this data and the relatively low cost. The main disadvantages are the indirect relation between the thermal data and the surface rainfall and the fact that these methods are not well-suited to mountainous areas and may overestimate rainfall in areas covered by thin cirrus and stratiform clouds.
Large-scale hydrological modelling

A relatively simple approach was adopted for the large-scale modelling of the Ganges and Brahmaputra basins. Each basin was divided into 14 sub-catchments, using a 1 km global DEM to delineate the catchment drainage boundaries according to response time, Figure 7. A conceptual rainfall-runoff model (NAM) was used to model the hydrological processes (Refsgaard and Knudsen 1996) and a simple time delay was introduced to account for the channel routing. NAM has been widely used for flood forecasting (Butts et al., 2001; Madsen, 2000) and requires only moderate data inputs. Two discharge stations outside of Bangladesh were used to examine the predictions made using this simple approach with satellite-based rainfall, Pankha and Noonkhawa representing the downstream end of the Ganges and Brahmaputra rivers, respectively, Figure 7.

![Figure 7 Precipitation map for the Ganges, Brahmaputra and Meghna catchments estimated from METEOSAT 5 data for the 15th June 1999. The heavy black lines show the basin boundaries, while the thin lines show the subcatchments.](image)

Results

A comparison of the results obtained using daily rain gauge data from within Bangladesh with daily values estimated using the GPI satellite-based method is given in Figure 8. There appears to be a high degree of correlation between the two estimates. Figure 9 and Figure 10 show the simulated discharge using the satellite-based rainfall against the observed discharge for the Ganges and Brahmaputra stations respectively. Given the relatively crude modelling approach used here the results shown are promising. Some discrepancies at the Pankha station were expected because of the operation of a reservoir, water transfer scheme upstream of this station. At the Noonkhawa station scaling of the estimated rainfall was required to achieve satisfactory results indicating that local calibration is required. However these initial results suggest that further work should be carried out to develop this approach operationally.
Figure 8 Daily values of aggregated rain gauge (rg) measurements and GPI (meteo) rainfall estimates for the 24 stations within Bangladesh.

Figure 9 Simulated discharge at the Pankha (Ganges) station versus observed discharge.
Summary and Conclusions

The combination of satellite-based remote sensing and distributed hydrological modelling provides a powerful tool for hydrological prediction and forecasting. A classification of the different ways in which remote sensing data can be used in combination with hydrological modelling is given. While RS data offers a number of opportunities for improved hydrological modelling, the application of remote sensing data requires a critical evaluation of their limitations. Nevertheless, further exploitation of both routine satellite remote sensing data and emerging developments are required to demonstrate their practical application.

The feasibility of using satellite-based precipitation nowcasting and large-scale hydrological modelling in a flood forecasting application in Bangladesh was investigated. Remote sensing using a cold cloud duration method was able to provide rainfall information over the large-scale basins (Ganges and Brahmaputra) feeding into Bangladesh, where it was neither feasible nor practical to obtain rainfall data from traditional rain gauge networks. This developed approach was able to provide good spatial and temporal resolution (5km grid every two hours for METEOSAT), at near real-time and at relatively low cost. The main disadvantages are the indirect relation between the thermal data and the surface rainfall and the fact that these methods are not well-suited to mountainous areas and may overestimate rainfall in areas covered by thin cirrus and stratiform clouds. Initial verification of the rainfall estimates against the rain gauge network within Bangladesh show good correlation. Satisfactory agreement was found using a relatively simple large-scale modelling approach to predict flows at the borders to Bangladesh. These results suggest that further investigation of this approach for operational forecasting is warranted.

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