CURRENT AND FUTURE APPLICATIONS OF REMOTE SENSING FOR ROUTINE MONITORING OF SURFACE WATER

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ABSTRACT

The flow regimes of many rivers, lakes and wetlands around the world are changing rapidly under the influence of increased domestic, agricultural and industrial water consumption and the earth's changing climate, land cover and land use. At the same time, ground based monitoring systems in many river basins around the world have continued to decline due to changes in funding priorities and access problems particularly in developing countries. The shortage of reliable river flow data continues to hamper efforts to effectively quantify the hydrologic impacts of land use and climate change and the associated feed back mechanisms. Examples of the problems of reliance on in-situ gauges during a major flooding event are presented using an example from the Limpopo Basin. The paper also highlights applications of altimetry data from existing satellite missions, such as Topex/POSEIDON, to monitor water storage changes over large lakes and reservoirs in the Zambezi basin in southern Africa. It demonstrates that useful information about reservoir operations such as discharges can be obtained by using altimetry-derived reservoir elevation anomalies. Improved understanding of reservoir releases can lead to more realistic simulations of runoff in rivers with dams and other control structures. These applications illustrate the value of using remote sensing for the routine monitoring of river flow. The Water Elevation Recovery (WaTER) mission proposed by the NASA Surface Water Working Group is suggested as an important step in the search for a reliable technology for routine monitoring of discharge, velocity and water storage in surface water systems globally.

INTRODUCTION

Global monitoring of surface water is important because of its potential impacts on the lives and property of people around the world. The livelihoods and economic activities of many communities are tied to the regular seasonal cycles of rivers. Flood plain agriculture depending on annual flooding events is practised on the banks of major rivers such as the Nile, the Zambezi, the Limpopo and the Ganges rivers. Hydropower remains the most widely used renewable energy source globally, contributing about 20% of all electricity generated. Within the US, hydropower accounts for about 45% of renewable energy and 7% of all energy usage. The cost of production of hydropower is about 30% that of electricity from fossil fuels, and it is less susceptible to price fluctuations resulting from international political events. Water is therefore a valuable economic resource that needs to be monitored globally. Short term and interannual variations in the earth's climate result in departures from the normal flow regimes causing floods and droughts. According to statistics maintained by the Dartmouth Flood Observatory, over 100 major flood events were recorded in almost every year between 1988 and 2003 with a total of over 500 such events occurring in the last two years alone. These events elicit US response because they have implications for US foreign and domestic policy goals for promoting freedom, security and opportunity around the world (USAID, 2002). The US is also a party to international initiatives such as the Global Earth Observation System of Systems (GEOSS) in which it commits to participate in global environmental monitoring, early warning and disaster response activities. The Office of Foreign Disaster Assistance (OFDA) of the US Agency for International Development is charged with responding to international disasters under the Foreign Assistance Act of 1961. In 2003 for example, OFDA spent over $290 million responding to 61 humanitarian emergencies around the world (OFDA, 2004). Additional funds can also available by the US Congress as necessary to respond to extraordinary disasters such as the Indian Ocean Tsumani of 2004. International political events and natural disasters are so variable and unpredictable that it is impossible to produce a typical profile of OFDA's annual expenditure by sector. However, the levels of resources committed to responding to recurring extreme climatic events is sufficiently high to warrant the investment of significant scientific resources towards improving the characterization of these events. Improved monitoring of surface water is also important because of the impacts of hydrology on global climate. Wetland ecosystems and deltas are being impacted by changing hydrologic regimes, and the land surface evapotranspiration rates are potentially impacted by changes in the spatial and temporal distribution of surface water. River basins such as the Congo and the Zambezi have significant discharges into the world's oceans with important impacts on sea surface temperatures and circulation patterns (Wong et al., 1999). The absence of regular flow measurements over these basins poses a major problem to global climate monitoring efforts. Routine monitoring of surface water using remote sensing stands to bridge this gap by providing spatially consistent measurements at regular intervals.

EXISTING APPROACHES FOR CONTINUOUS MONITORING

In this paper, we examine the capabilities and limitations of existing and planned surface water monitoring systems using examples from the Zambezi and Limpopo River basins in southern Africa. The focus of the paper is not the capability or accuracy of the sensors involved. Rather, we will examine the datasets produced from these monitoring systems in terms of the types of information that can be derived from them in the identification of anomalous hydrologic conditions. The two basins were chosen because of their physical characteristics as well as their location in a region of high seasonal and interannual climate variability in southern Africa. The region is at the confluence of cold Antarctic and warm Indian Ocean currents. It is also located along the natural pathway of cyclonic systems originating in the Indian Ocean. The Zambezi River is a large river basin with a surface area of 1.33 million km^2 and an annual discharge of approximately 3400 m^3/s (Beilfuss and dos Santos, 2001). It contains several large complexes of reservoirs and lakes including Lakes Kariba, Kafue, Cahora Bassa and Malawi as well as a large delta complex. The Zambezi River presents a complex modelling problem for hydrologists trying to monitor processes at the continental scale because discharges arriving at the mouth of the river are heavily altered by the operations of the reservoir systems, particularly at Lake Kariba and Cahora Bassa.

With a surface area of 421,000 km^2, the Limpopo River is another international basin whose waters are shared by four countries, namely Botswana, Zimbabwe, South Africa and Mozambique. In 2000, a series of four cyclonic systems made landfall over a period of three months dumping large quantities of rainfall over the basin. The runoff from already saturated soils and spillage from overburdened reservoirs coupled with already high river levels resulted in record floods in the basin (Christie and Hanlon, 2001). The record floods of 2000 have been followed by four years of below normal precipitation, resulting in severe drought in many parts of the basin. With their limited in-situ gauging infrastructure, the two basins are excellent examples of the need to adopt remote sensing technologies in monitoring surface water systems.

In-situ Surface Water Monitoring

In situ gauging is easily the most widely accepted approach for monitoring of surface water. In-situ gauging methods range from simple staff gauges which are read periodically by gauge readers to automated gauges which either store readings for periodic download or transmit the data through satellite or telemetry networks. While in-situ gauging is indispensable because of its ability to produce highly reliable streamflow observations at high frequencies, it does have its limitations. The spatial extent of the river is not measured and estimates of river stage (and consequently depth) are generally measured at one location along the river cross-section. Within the US, data access is generally not a problem. However, many of the large basins of the world are not monitored regularly due to access and funding problems. For an even larger number of basins, data collected at gauges is not accessible to the general public for use in scientific studies and early warning applications. The result is that global coverage of hydrologic data is extremely non-uniform in space and contains significant temporal discontinuities. The World Meteorological Organization has sought to improve global access to hydrologic data in near real time through its Hydrologic Cycle Observation System (HYCOS) which employs networks of automated flow gauges linked to regional hubs via satellite transmission. In southern Africa, the HYCOS network is operated by the SADC Water Division through subcontract to the South African Department of Water Affairs and Forestry. While the network does provide useful information on river levels, it is still too limited in density and reliability to be an effective surface water monitoring system. In the Zambezi River basin for example, there are currently 16 SADC-HYCOS gauging stations recording river stage. Only two of these stations have rating curves for the conversion of river stage to flows. A variety of maintenance problems including equipment malfunction, vandalism by humans and wildlife, and destruction by natural disasters such as cyclones and floods also compromise the reliability the HYCOS monitoring system. A snap shot of the status of the gauges in the Zambezi basin on the 15th of August, 2005 indicated that no recent data transmission had been received from eleven of the sixteen stations. During the southern African floods of 2000, every major gauging station along the main-stem of the Limpopo River from Botswana to its mouth at the Indian Ocean was destroyed or rendered inaccessible as shown by the declining number or reporting stations in Figure 1 below. Many data recording and transmission activities were abandoned for those gauges that were not affected as attention shifted to the more urgent disaster response activities. While some hydrographs of the event were reconstructed, the magnitude of the unprecedented flood peak cannot be determined with as much certainty as flow values based on daily gauge readings. The comparison serves to illustrate that in-situ hydrometric stations can easily become unavailable during major flooding events when they are most needed for early warning purposes.

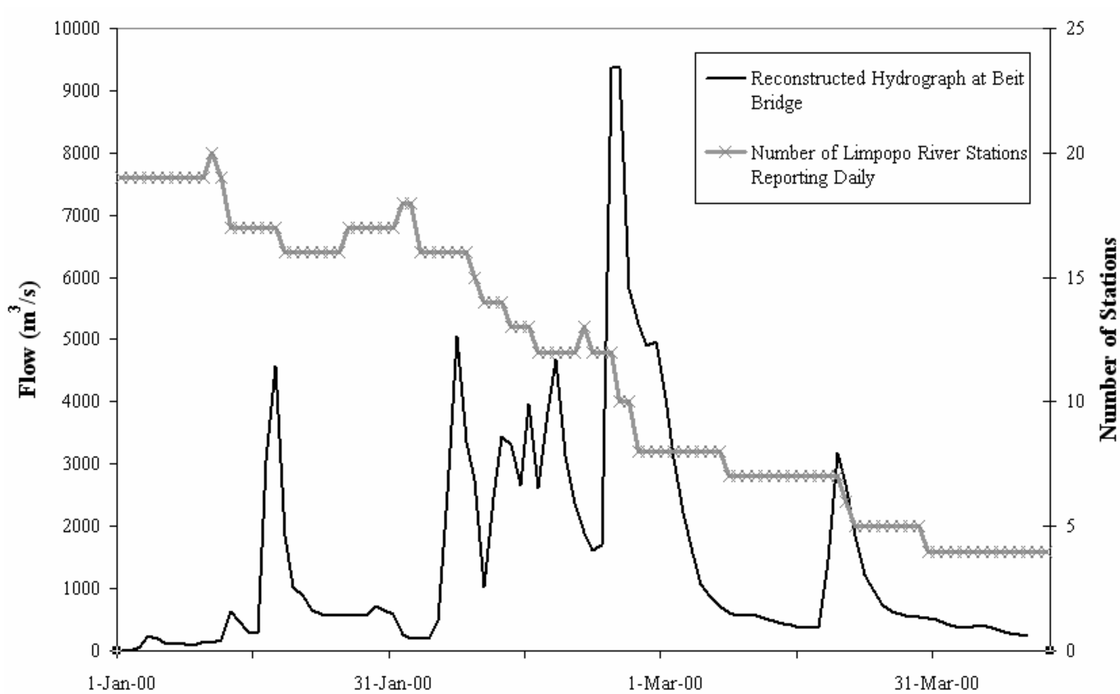

Figure 1. A graph showing reconstructed Limpopo river flows at Beit Bridge in South Africa and the number of automated hydrometric stations reporting daily flows within the basin in South Africa. The flood peak on the 24th and 25th of February, 2000 could not be determined accurately because it exceeds the maximum value on the rating curve at the location.

Monitoring Surface Water with Continuous Simulation Models

Continuous hydrologic models are also widely used for surface water monitoring. The premise for this type of monitoring is that given an understanding of the physical characteristics of a hydrologic system and current information on its inputs and extractions, the current state of the system can be predicted. Precipitation is the most important input, and a number of remote sensing missions have been direct towards its characterization. Beginning in the mid-1980's, infrared imagery from geostationary weather satellites have been used to estimate rainfall based on cloud top temperatures. This was augmented with microwave imagery which detected rainfall drops from earth-orbiting satellites in during the 1990's. With the coming of the Tropical Rainfall Measurement Mission (TRMM), active space-borne radar instruments were used to monitor rain drop size distribution and consequently rainfall rates for the first time. The Global Precipitation Mission (GPM) will seek to extend TRMM's coverage to include areas outside of the tropics where snow, ice and mist occur by including instruments for monitoring these alternate forms of precipitation. GPM will also seek to increase the revisit rates for any region of the earth's surface by incorporating microwave imagery from a constellation of other existing and planned missions. While there is currently no dedicated mission, active or planned, for its measurement, progress is also being made on the monitoring of evapotranspiration rates using remotely sensed data. For ongoing FEWS NET crop monitoring activities, potential evapotranspiration is computed by USGS/EROS using output fields from NOAA's Global Data Assimilation System and the Penman-Montieth method (Verdin and Klaver, 2002). More recently, actual evapotranspiration is being computed from remotely sensed imagery based on energy balance analysis using short wave reflectance and the thermal emissions of vegetated surfaces (Allen et al, 2005). Also, the Gravity Recovery and Climate Experiment (GRACE) is offering scientists a first opportunity to monitor changes in total water storage using remote sensing, and the prospects for retrieving ground water storage changes from these data are encouraging. However, the datasets are currently not suited for incorporation into operational modelling efforts because of their spatial and temporal scale.

Progress is also being made in the characterization of the land surface for hydrologic modelling by various groups. At the USGS/EROS, the Geospatial Streamflow Model (GeoSFM), is set up for operational streamflow monitoring in many large basins around the world (Artan et al., 2004). GeoSFM is a semi-distributed hydrologic model which is set up and parameterized for datasets available globally. It uses global topographic data from HYDRO1k and derivatives for defining river and catchment networks. Data from the Global Land Cover Characteristics (GLCC) database (Loveland et al., 2000) and the FAO/UNESCO Digital Soil Map of the World are also introduced to determine the predominant land cover and soil texture classes in each catchment. Based on these classes, published values are assigned to each catchment for corresponding hydrologic parameters including Soil Conservation Service (SCS) curve number, Manning roughness coefficient and soil parameters such as water holding capacity and hydraulic conductivity. Substantial uncertainties remain in the magnitude of forcing datasets and the value of hydrologic parameters as evidenced by the results of the recent Distributed Model Intercomparison Project (Smith and Georgakakos, 2004). Aquifer recharge rates and spring flows are also difficult to quantify accurately, and man made structures such as dams can modify natural streamflow patterns, considerably. Surface water modelling efforts will therefore continue to require observed streamflow data from in-situ or space-borne sources for calibration.

Monitoring Surface Water with Space-Borne Imagery

Polar orbiting satellites with optical and radar sensors can be used to monitor the spatial extent of flooding. The discrimination of water from other surfaces such as vegetation and bare soil is easily accomplished using the rather distinct surface reflectance signature of water. Optical imagery is available from a number of sensors including the Landsat Series, SPOT, MODIS and AVHRR. Many of these sensors have a long time series which can be used to establish a historical profile of surface water conditions at a location. The Dartmouth Flood Observatory has developed an archive of inundation extents associated with major flood events around the world using these time series. A major limitation of optical sensors is that they are hindered in their monitoring of inundation extent by their inability to penetrate cloud cover which is often present during major storms. Data acquisition must also be accomplished during the day as optical imagery contains little relevant information when acquired at night. On the other hand, active radar sensors can acquire imagery irrespective of the presence of cloud cover or sunlight. The commercial satellite, Radarsat, and the European Resource Satellite (ERS) Synthetic Aperture Radar (SAR) mission are examples of such space-borne radar imaging systems. However, the signature of wet soil is very similar to that of water in radar imagery. It is consequently difficult to objectively define a threshold for distinguishing between flood inundated areas and soils that have been wetted under the influence of direct precipitation or subsurface runoff. The first image in Figure 2 shows a Landsat image acquired on March, 1st, 2000, over the mouth of the Limpopo River during the 2000 flooding event. The second image shows a similar acquisition over the same area on August 8th of the same year. The cloud cover observed in this image extended over much of the zone of inundation within the river reaches in middle sections of the basin, making determination of the full flood inundation extent a difficult and subjective undertaking. The image also serves to illustrate the magnitude of the inundation extent which was over 15 km wide and 12 m deep in some places.

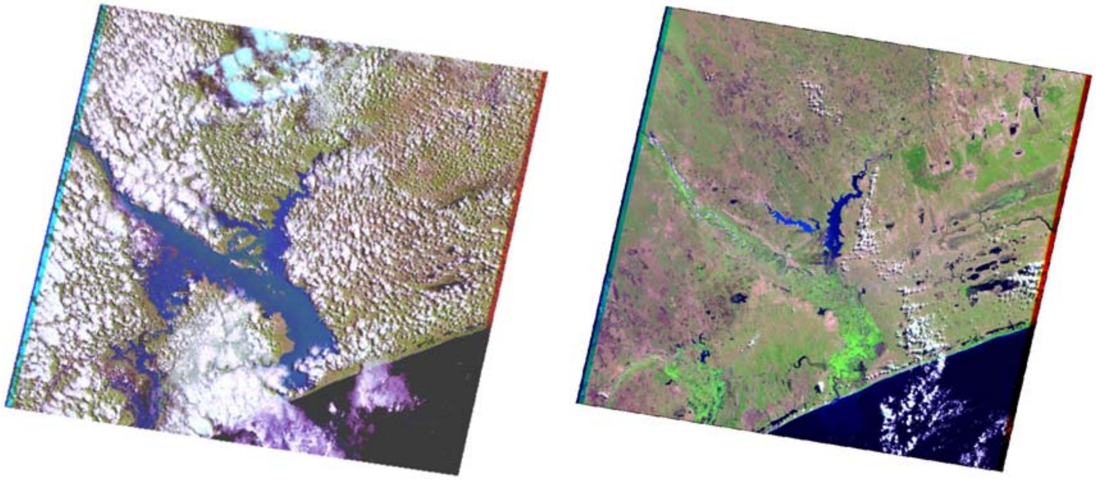

Figure 2. A Landsat image acquired on the 1st of March, 2000, over the mouth of the Limpopo River during the flood event while a second image shows a similar acquisition over the same area on the 8th of August of the same year.

In general, the delineation of flood inundation extents from space-borne imagery is hampered by technical difficulties and subjective classification methods. Even when accurate land-water delineations can be made, it is not always possible to translate the results into flow rates and storage changes since changes in water level may not translate into detectable changes in surface area.

Monitoring Surface Water with Radar Altimetry

When radar altimetry is used to monitor surface water, both water surface extent and elevation are measured. Topex/POSEIDON (1992-2002) and the follow-on Jason missions are designed to monitor the changes in the elevation of the earth's oceans and ice using satellite altimetry. The altimeters used in these missions are optimized for monitoring elevation changes in large water bodies using a coarse sampling interval. Hydrologists at NASA and USDA have taken advantage of these sensors to monitor variations in the levels of approximately 100 large lakes and reservoirs (Birkett, 1998). The goal of this monitoring program is to improve drought monitoring and crop production, particularly in regions where reservoir storage is used for irrigation. The extension of the methodology to river flow monitoring would provide scientists and decision makers in the water supply, hydropower, agriculture and disaster management sectors with near real time information on the condition of rivers around the world. Within the Zambezi basin, water levels are monitored at Lake Kariba, Cahora Bassa, Kafue and Malawi. Lake Kariba and Cahora Bassa are particularly interesting because they are located in series approximately 300 kilometres from each other along the main stem of the Zambezi River. They have surface areas of 5,580 km^2 and 4,363 km^2, respectively. A simulation model was set up for the Zambezi basin using the USGS/EROS GeoSFM modelling system and remotely sensed precipitation and evapotranspiration forcing data. The resulting inflows into Lake Kariba were converted to corresponding changes in reservoir water surface elevation by assuming a constant surface elevation and converted to monthly inflow anomalies by normalizing with mean monthly flows from the simulation period. A comparison of the simulated inflow anomalies and water surface elevation anomalies is presented in Figure 3. From this figure, it is clear that the two sets of anomalies do not match very well. This difference could be attributed to reservoir releases made in the course of normal and emergency reservoir operations. Assuming that the difference between the two sets of anomalies is attributable to releases, the difference gives a significant indication of the inflows into Lake Cahora since the Kariba catchment generates a little over 50% of the flows into Cahora Bassa.

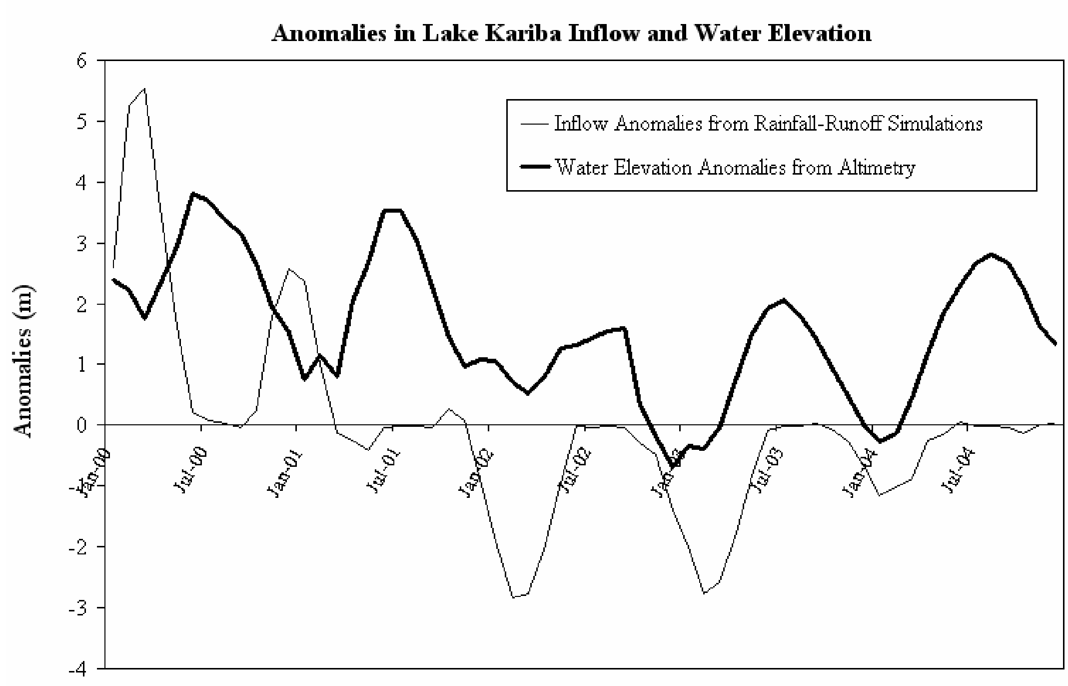

Figure 3. A comparison of the simulated inflow anomalies and water surface elevation anomalies over Lake Kariba. Reservoir filling and emptying cycles are not well captured by inflow from rainfall runoff simulations because reservoir operations are not included in model simulations.

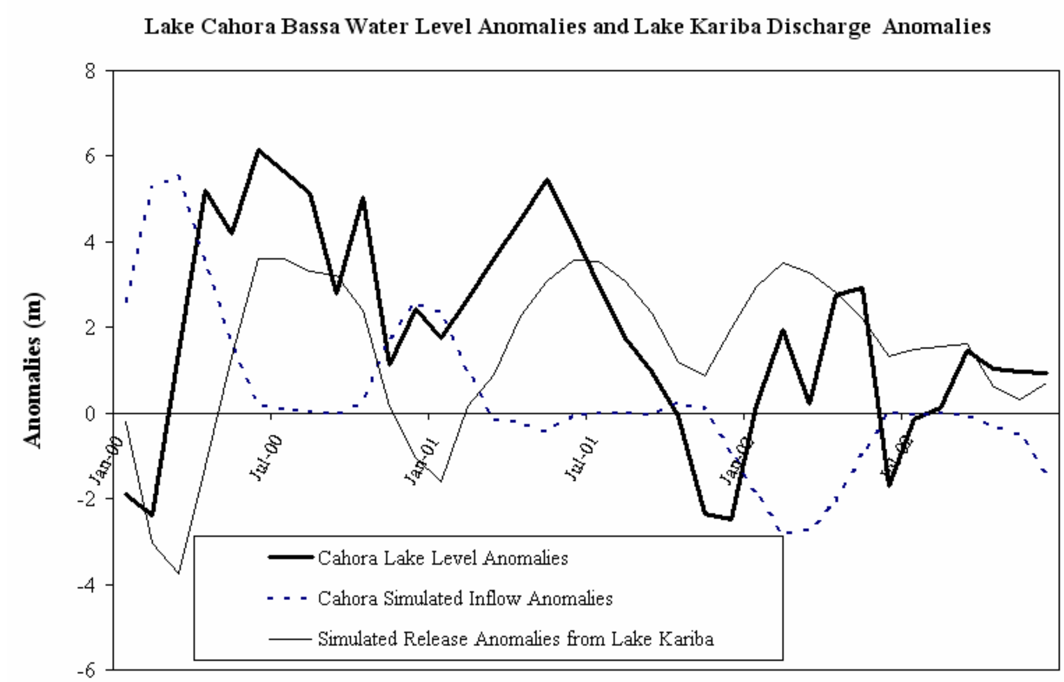

Figure 4. A comparison of altimetry-derived lake level anomalies at Cahora Bassa with inflow anomalies simulated by rainfall-runoff simulation and simulated release anomalies from Lake Kariba located upstream.

As shown in Figure 4, the simulated release anomalies from Lake Kariba track the lake level anomalies at Lake Cahora better than the inflow anomalies simulated from rainfall-runoff modelling. Simulated release anomalies track the downstream lake anomalies better than natural inflows. The graph provides a basis for designing reservoir regulation rules in the hydrologic model which simulate actual reservoir operations. It serves to illustrate the point that by monitoring surface water from space, we are able to incorporate the impact of flow regulation structures on downstream flows even without access to real reservoir operation information from the operators.

THE WAY FORWARD: THE WATER ELEVATION RECOVERY (WaTER) MISSION

Under the leadership of the NASA Surface Water Working Group, an effort has been initiated to undertake a remote sensing mission devoted to the monitoring of surface water elevation (Alsdorf et al., 2005). The Water Elevation Recovery (WaTER) mission evolved out of a white paper by Vörösmarty et al. (1999). The white paper identified four technological alternatives worth investigating in the search for an approach for monitoring the earth's fresh water resources from space. The basic approaches involved altimeters made from different configurations of lidar, Doppler and SAR radar sensors. The approaches also had to take into account the need to maximize spatial coverage of the land surface while minimizing the time between repeat visits. A detailed review of the limitations of these technologies was conducted by independent sensor teams (Rodriguez and Moller, 2004; Rodriguez, 2004) with funding from NASA's Terrestrial Hydrology Program. Based on these reviews, a mission concept has been developed for the WaTER Mission. In a report to the National Research Council, the WaTER mission team has indicated that the proposed instrument for the mission is Interferometric Synthetic Aperture Radar (InSAR) with look angles limited to just over 4 degrees to maximize returns over water. Two sensors will be deployed on the same platform in order to increase the swath width to approximately 120 km. Individual elevation estimates will be made at intervals of 5m within the footprint of the swath. Revisit rates could vary from 10 to 16 days depending on the maximum allowable threshold of missed rivers and lakes. Higher repeat frequencies would require coarser sampling frequencies and thus more water bodies could be missed on the land surface. The main data returns from this mission will be land surface elevation including both land and water. The land surface will be distinguished from the water surface using radar imagery, and differences in height obtained from interferometric analysis of the radar imagery will allow changes in water surface elevation to be computed. The WaTER mission will in effect be similar to the Shuttle Radar Topography Mission (SRTM) which used a radar altimeter carried onboard a space shuttle to acquire what is now the highest resolution topographic data with near global coverage available in the public domain. SRTM used C-band radar with incidence angles of 30 to 60 degrees which yields little or no returns over water surfaces. The WaTER mission will increase returns over water surface by reducing the maximum look angle. The feasibility of this technology has already been demonstrated in the radar altimetry satellites used for monitoring sea level change over ocean. The WaTER mission will only defer from those missions in the sense that it seeks to produces two large footprints each 60 km by 60 km with a matrix of elevation estimates being generated approximately 10 m apart within the each footprint.

Additional parameters such as water storage, flow and velocity will be computed from the elevation estimates using simple hydraulic analysis as demonstrated in Smith (1997). The rate of advection of water in the river system can be characterized in two ways. The kinematic wave celerity is a measure of how quickly a flood wave is transported from one point in the river network to another. A 2D field of kinematic flood wave velocity is computed from potential energy considerations based on the difference in water surface elevation between adjacent cells in the water surface profile. On the other hand, the Eulerian velocity is a measure of how quickly water is being transmitted through a given location. To compute the Eulerian velocity for individual grid cells, Manning's equation is applied using the computed flow depths and water surface slopes and estimates of channel roughness assigned based on vegetation type and channel geometry. The volume of water stored in each grid cell at the time of acquisition is easily computed by multiplying the depth of water with the surface area of each cell. The flow rate through each cell is likewise computed by multiplying the Eulerian velocity by the depth and width of the cell. Flow rate at any river cross-section is computed by aggregating the flow through cells along the cross-section.

CONCLUSIONS

In-situ flow gauging currently provides the most accurate means of monitoring of streamflow and water surface elevation in locations where gauges are installed. It can also provide very high sampling frequencies on the order of hours to minutes if required. However, it only provides limited information on the spatial dimensions of the river; existing systems do not measure the width and depth of flow or the area inundated as one moves away from the in-situ gauge location. In-situ gauges can also be destroyed during major flood events, eliminating a critical source of early warning information. In addition, there are numerous rivers around the world where there are no gauges to provide this information. Therefore, the evolution of a complementary space-borne monitoring system can only strengthen the hydrologic community's ability to provide useful early warning information to the public. The remote sensing technology still will not provide data at the temporal resolution of in-situ gauges. However, it can provide improved spatial coverage globally. The meteorological community has successfully achieved this complement of in-situ and space borne monitoring systems in the measurement of precipitation, and have been rewarded with two NASA mission (TRMM and GPM) in addition to their weather satellite system (GOES). The meteorological agency of each southern African country now has a satellite receiving station to retrieve satellite imagery from the meteorological satellites. The temporal resolution of these datasets have improved from two images an hour to 4 images an hour under Meteosat Second Generation, and the spatial resolution has improved from grid cells of 10 km to 1 km. By comparison, most hydrological agencies have never accessed or used remotely sensed imagery. The entire hydrologic community stands to benefit from the WaTER mission which seeks to inject new technology and data as well as new NASA funding for ground validation, research and applications into the hydrologic sciences.

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REFERENCES

Allen, R.G., M. Tasumi, A.Morse and R. Trezza (in press). A Landsat-based Energy Balance and Evapotranspiration Model in Western US Water Rights Regulation and Planning. *Irrigation and Drainage Systems*.

Alsdorf, D., E. Rodriguez, D. Lettenmaier and J. Famiglietti (2005). WatER: The Water Elevation Recovery Satellite Mission: Response to the National Research Council Decadal Survey Request for Information. Washington, DC.

Artan, G., K.O. Asante and J.P. Verdin (2004). A Continental Scale Flood Hazard Monitoring System. *Eos Trans. AGU*, *85*(17), Jt. Assem. Suppl.

Beilfuss, R. and D. dos Santos (2001). Patterns of Hydrological Change in the Zambezi Delta, Mozambique. *Working Paper #2*, *Program for the Sustainable Management of the Cahora Bassa Dam and the Lower Zambezi Valley*, Maputo, Mozambique.

Birkett, C.M. (1998). Contribution of the TOPEX NASA radar altimeter to the global monitoring of large rivers and wetlands. *Water Resources Research*, *34* (5), 1223–1239.

Loveland , T. R., B. C. Reed, J. F. Brown, D. O. Ohlen, J. Zhu, L. Yang, J. W. Merchant (2000). Development of a Global Land Cover Characteristics Database and IGBP DISCover from 1-km AVHRR Data. *Int. J. Remote Sensing*, *21*(6), 1303-1330.

Nijssen, B.N., D.P. Lettenmaier, X. Liang, S.W. Wetzel, and E.F. Wood (1997). Streamflow simulation for continental-scale river basins. *Water Resources Research 33*(4), 711-724.

OFDA (2004). OFDA Annual Report for 2003. US Agency for International Assistance, Washington, D.C.

Olivera, F., J. Famiglietti and K. Asante (2000). Global-Scale Flow Routing Using a Source-to-Sink Algorithm. *Water Resources Research 36* (8): 2197-2207.

Rodriguez, E., and D. Moller (2004). Measuring surface water from space. AGU Fall meeting, H22C-08, abstract.

Rodriguez, E. (2004). Surface water ESSP mission radar options, presentation at March 2004 NASA Surface Water Working Group meeting, Irvine CA, 2004.

Smith, L.C. (1997). Satellite remote sensing of river inundation area, stage, and discharge: A review. *Hydrological Processes, 11*, 1427-1439.

Smith, M.D. and K.P. Georgakakos (2004). The Distributed Model Intercomparison Project (DMIP), Editorial. *Journal of Hydrology, 298,* 1-3.

T. Oki and Y. C. Sud (1998). Design of Total Runoff Integrating Pathways (TRIP): A global river channel network. *Earth Interactions, 2*.

USAID (2002). Foreign Aid in the National Interest: Promoting Freedom, Security and Opportunity. US Agency for International Assistance, Washington, D.C.

Verdin, J. P. and R.W. Klaver (2002). Grid cell based crop water accounting for the Famine Early Warning System. *Hydrological Processes, 16*, 1617-1630.

Vörösmarty, C.J., C. Birkett, L. Dingman, D.P. Lettenmaier, Y. Kim, E. Rodriguez, and G.D. Emmitt (1999). NASA Post-2002 Land Surface Hydrology Mission Component for Surface Water Monitoring: HYDRA-SAT HYDRlogical Altimetry SATellite. A report from the NASA Post-2002 Land Surface Hydrology Planning Workshop, Irvine, CA, April 12-14th, 1999.

Wong, A.P.S., N.L. Bindoff and J.L. Church (1999). Large scale freshening of intermediate waters in the Pacific and Indian Oceans. *Nature 400*, pages 440-443.