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The current status of global river discharge monitoring and potential new technologies complementing traditional discharge measurements

BALÁZS M. FEKETE & CHARLES J. VÖRÖSMARTY

Water Systems Analysis Group, Complex Systems Research Center,
Institute for the Study of Earth, Oceans, and Space, University of New Hampshire,
211 Morse Hall, 39 College Road, Durham, New Hampshire 03824, USA
balazs.fekete@unh.edu

Abstract River discharge is one of the most accurately measured components of the hydrological cycle, but it is rarely utilized in climate system studies. Collection, archiving and distribution of river discharge data globally is limited and often restricted. Besides the difficulties in accessing discharge data globally, the currently operating network is clearly inadequate in many parts of the Earth and is still declining. The present paper gives an assessment of the current state of discharge monitoring. The paper also provides a coarse estimate about the network density needed for climate system studies and discusses some of the emerging new technologies, which may provide supplemental information about river discharge in the future.

Key words discharge; monitoring

INTRODUCTION

The hydrological cycle plays an important role in regulating the climate system of the Earth. Furthermore, water is essential for any form of life, therefore it is one of the most important controlling factors of the biosphere. The need for monitoring the components of the hydrological cycle is widely recognized, yet our monitoring capacity (particularly the discharge monitoring capability) has declined rapidly (Shiklomanov *et al*., 2002; Vörösmarty *et al*., 2002). River discharge is one of the most accurately measured components of the hydrological cycle (Hagemann & Mimenil, 1998; Dingman, 2001), but the access to river discharge is typically limited. The monitoring network is sparse in a large part of the globe, and there is no mechanism in place to collect and distribute river discharge data globally on a real-time basis. A few hydro-meteorological agencies are releasing river discharge information via the World Wide Web, but the data formats are different. Establishing data retrieval capabilities would require developing web-mining tools for each individual data provider.

The present paper focuses on the current state of river discharge monitoring globally and attempts to provide an accurate assessment of how well the presently operating network is capable of capturing the spatial patterns of the runoff generation. The paper also briefly discusses the potential optimization of the global discharge monitoring network and estimates the costs of running such a network.

Finally, the paper describes some of the emerging new technologies to measure discharge from space-borne remote sensing platforms and their potential to supplement traditional ground-based monitoring. The paper discusses a couple of successful experiments, briefly evaluates the practical applicability of the different techniques, and looks at future plans.

CURRENT STATE OF RIVER DISCHARGE MONITORING

River discharge monitoring and sharing is typically viewed as a regional task and the availability of such information is much more limited than other meteorological variables. The first compilation of river discharge data was published by UNESCO in the mid 1980s as a result of the Hydrological Decade (UNESCO IHP, 1984). The UNESCO publications, which were released as a series of printed books, were digitized in the late 1980s and became the core for several global discharge compilations (Vörösmarty *et al.*, 1996a; Bodo, 2001) and the basis of the Global Runoff Data Centres (GRDC) data archive. GRDC hosted by the Bundesanstalt für Gewiisserkunde (Federal Institute of Hydrology, Koblenz, Germany) was established in 1988 and operates under the auspices of the World Meteorological Organization. The GRDC data archive is probably the most complete global discharge data set, since they are mandated by WMO to collect, archive and disseminate hydrological data. The access to their data is limited according to WMO's guidelines. Although, the access to the actual discharge time series is limited, GRDC makes the catalogue of their data holding available, which contains numerous attributes regarding monitoring stations and the quality of the discharge time series (e.g. station name, location, length of records, percent of missing data, etc.) However, more complete regional data sets exist (e.g. USGS Archive and Realtime discharge data (http://water.usgs.gov), R-ArcticNet (http://www.R-ArcticNET.sr.unh.edu) and Arctic-RIMS (http://RIMS.unh.edu) (Lammers *et al.*, 2001; Shiklomanov *et al.*, 2002), LBA-Hydronet (http://www.LBA--HydroNet.sr.unh.edu/), etc.), but the consolidation of these regional archives with global data sets would require a significant effort.

In the present study, we demonstrate the current state of global discharge monitoring by highlighting some of the key characteristics of the GRDC data archive, primarily focusing on their data catalogue. Figure 1 shows the number of operating discharge monitoring stations over time, according to the GRDC data archive. The figure shows a steady increase up until the mid 1980s (the end of UNESCOs Hydrological Decade) and a rapid drop of stations ever since. However, this rapid drop in number of gauging stations is largely due to the time delay between the data collection and its entry into the GRDC data archive (which by itself is alarming, since it shows the inefficiency of the current condition under which GRDC operates) but the decline is also a sign of the worldwide gauge closings (Shiklomanov *et al.*, 2002; Vörösmarty *et al.*, 2002).

The number of discharge monitoring stations is not necessarily a good measure of the degree to which the river systems are monitored. Significantly fewer stations is sufficient to monitor terrestrial river discharge from the ocean's point of view, since such an application requires only the most downstream gauging stations as close to the river mouth as possible. Fekete *et al.* (1999) demonstrated that approximately 200 key

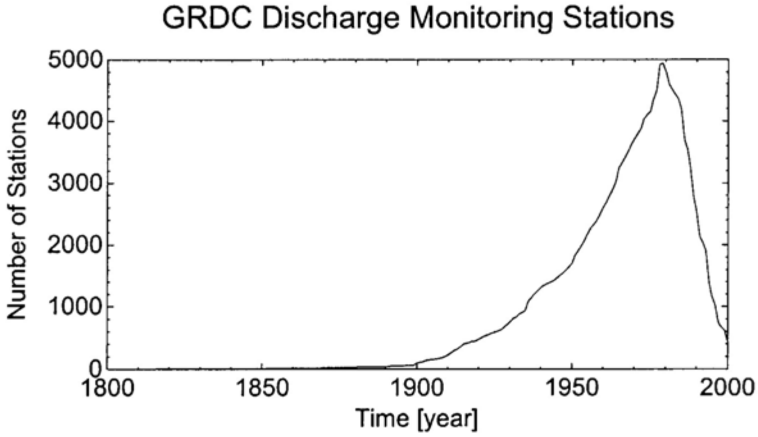


Fig. 1 Number of operating discharge monitoring stations according to the discharge data archive of the Global Runoff Data Centre, Koblenz, Germany

Table 1 Discharge monitoring of the continental landmass.

	Area km^2	%	Discharge km^3 year^{-1}	%
Monitored	67×10^6	50.4	20700	52.7
Unmonitored Rheic	26×10^6	19.5	18600	47.3
Unmonitored Arheic	40×10^6	30.1	–	–

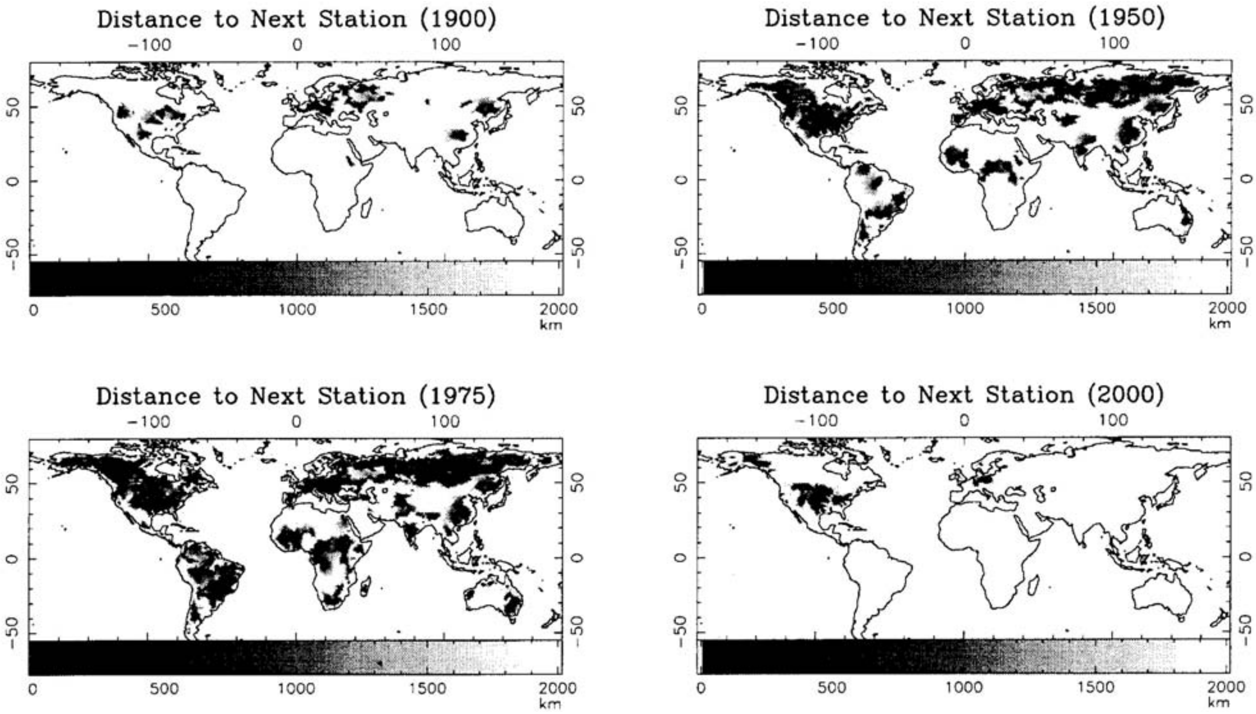
stations monitoring over 67 × 106 km^2 of land capture the discharge from 50% of the continental landmass (Table 1). This actually represents over 70% of the actively contributing portion of the continents. Thirty percent of the continents are arheic (i.e. too dry to deliver any water to the oceans). The remaining ~26×10^6 km^2 unmonitored but rheic (actively flowing) area is remarkably close to ~25×10^6 km^2, which is the sum of the catchment area in coastal basins with less than 25 000 km^2 catchment area. This finding suggests that the current monitoring network at the full extent actually captures most of the large river systems but is limited in depicting the small coastal basins. Monitoring of small basins is increasingly difficult. For instance, adding an additional 1600 gauges to measure river basins with catchment areas between 5000 and 25 000 km^2 would still leave more than 9×10^6 km^2 unmonitored.

Interestingly, the sum of the mean annual discharge monitored at the 200 key stations (representing mostly the large river systems) is a little bit more than 50% (20 700 km^3 year^{-1}) of the mean annual discharge estimates (Table 2). As we stated before 30% of the continents are arheic (i.e. do not deliver any water to the oceans) the remaining active but unmonitored area (which appears to be 20% of the continental landmass) delivers almost as much runoff to the oceans as the monitored 50%. This finding highlights the importance of addressing the issues of the unmonitored river basins.

The lack of monitoring of small coastal basins is just one side of the problem. The degree of monitoring of large basins is quite misleading since it does not take into account the proximity of the nearest downstream gauging station from any smaller tributary within the basins. From a land surface hydrology point of view, a basin with the nearest downstream gauge far away is almost as much unmonitored as a similar sized coastal basin with no discharge gauge at all. Figure 2 shows the evolution of the

Table 2 Global discharge estimates by various authors.

Discharge km^3 year^{-1}	Source
36 400	Korzoun *et al.* (1978)
39 300	Fekete *et al.* (1999; 2002)
39 700	Baumgargner & Reichel (1975)
40 700	Postel *et al.* (1996)
42 700	Grabs *et al.* (1996)


Distance to Next Station (1900)

Distance to Next Station (1950)

Distance to Next Station (1975)

Distance to Next Station (2000)

Fig. 2 Distance to next downstream gauging station. Darker colour means closer stations, while the lighter colours means increasing distance to the nearest downstream stations, which blends into the white coloured unmonitored landmass.

discharge monitoring network by colouring the continental landmass according to the distance to the nearest discharge monitoring stations. This representation of the monitored basins not only reflects the existence of gauging stations within the basins, but gives a better picture of the network density.

Considering one station per 5000–25 000 km^2 catchment area station densities (partitioning the large river systems into smaller tributaries by a series of discharge gauges), the distance to the next downstream station (which would be the same as the maximum travel distance in the tributaries between discharge gauges) would be 120–320 km^2 on average. Assuming 1 m s^{-1} flow velocity, the maximum residency time in such basins would be less than 5 days.

The higher density of gauging stations would require the operation of discharge gauges at somewhere between ~2700 stations (one station per 25 000 km^2 catchment area station density) to ~16 000 stations (one station per 5000 km^2 station density). This level of monitoring is not unrealistic since many of the needed stations are already in place and operating. For instance, the USGS operates over 4000 stations real-time (i.e. their observation is available real-time on the USGS website). The USGS is able to do so for $20 000 per year per station (half of which comes from USGS own budget, while the second half is matched by the individual states (personal communication with Williarn Kirby, US Geological Survey, Reston, Virginia, USA), which includes the costs of the regular calibration, the telemetered monitoring and the posting of the observations on the Internet.

POTENTIAL NEW RIVER DISCHARGE MONITORING TECHNOLOGIES

Remote sensing (satellite born sensors in particular) have great potential in offering new ways to monitor river discharge. While remote sensing could provide consistent information for large regions, its application to discharge monitoring faces several fundamental problems. First of all, the strength of remote sensing by its nature is a spatial measurement, while river discharge is essentially a point measurement. Furthermore, traditional discharge measurement is not simply recording some tracking variable (typically the stage height), but it also involves intensive field surveys to establish rating curves relating the monitored flow property to actual discharge. Even if remote sensing techniques were able to replace the ground-based monitoring of some characteristics of the river flow (stage height by using altimeter or flow width, considering high resolution image sensors), the satellite records would still need calibration. Otherwise, the missing riverbed geometry information would have to be assessed from empirical relationships relating riverbed geometry to flow regime (Bjerklic *et al.*, 2002). Despite the difficulties in applying remote sensing techniques to monitor river discharge, several promising experiments were carried out in the last couple of years using active and passive remote sensors.

Vörösmarty *et al.* (1996) demonstrated that relatively coarse resolution remote sensing sensors such as Scanning Multichannel Microwave Radiometer (SMMI1) on board of Nimbus 7 satellite could depict the dynamics of the discharge regimes of large river systems. Smith *et al.* (1996) applied Synthetic Aperture Radar (BAR) images to estimate river discharge in braided rivers. These experiments both use imaging remote sensors and estimate the extent of water surface for selected reaches. This approach transforms the problem of point measurement to spatial measurement addressing the first difficulty in applying remote sensing to discharge monitoring.

Alsdorf *et al.* (2000) tested interferometric radar measurements to monitor water level on the flood plains in the Amazon basins. Applying this technique to monitor water heights showed accuracy in the order of a few centimetres. The big limitation of the technology is it can not be applied to clear open water since it relies on the existence of vertical objects (flooded trees or brushes) standing out from the water surface. These vertical objects produce the scatter which would result in polarization change of the emitted radio waves that can be detected by the interferometric measurement.

Birkett (1998) demonstrated the use of the TOPEX/Poseidon radar altimeter data to monitor lake and river height. The TOPEX/Poseidon altimeter was originally designed to monitor sea level height, therefore on-board processing of the radar signals was built into the system to optimize the retrieval of sea level. Unfortunately, some of the on-board processing limits the sensors applicability over land and yet the

TOPEX/Poseidon altimeter could achieve a few centimetre accuracy in ideal conditions (gradually changing land cover, smooth transition in topography, sufficiently wide water surface). The most important limitations of current radar altimeters are their footprint sizes. The TOPEX/Poseidon altimeter has a 3–5 km footprint size, which limits its potential application to large lakes and wide enough sections of the largest rivers. The reduction of footprint size would require the use of different radar bands and/or using larger antenna. There is room for improvement in both aspects, but given the limitation on feasible antenna sizes the minimum footprint size cannot be much less than 200 m, which would considerably limit the number of potential targets for a hydrology oriented satellite. Furthermore, the error characteristic of the altimeter is such that error increases on smaller targets, therefore the few centimetre accuracy is only possible over large (wide) rivers, while the error is likely to significantly increase when narrow rivers are monitored. From a discharge measuring perspective, the accurate height measurement is less critical on large rivers (with tens of metres flow depth) but more critical on smaller rivers (with few metres flow depth).

The National Aeronautics and Space Administration Agency (NASA) is actively studying the potential of designing a satellite system with the appropriate sensors to monitor surface waters such as rivers and lakes. A recent study considered a range of sensors (radar or lidar altimeter, high resolution imager, and Doppler lidar, which could monitor flow velocities) for a hydrology oriented mission (Vörösmarty *et al.*, 1999). However, there is no plan to launch such a satellite in the near future; the feasibility of such a satellite is being tested by using existing and planned missions. For instance, NASA will launch IceSAT carrying a lidar altimeter in December to monitor ice. In the first three months of this mission, the satellite will fly on a different orbit (which is more favourable for river monitoring). NASA will use this opportunity to test the lidar instrument to monitor surface water. Figure 3 shows the candidate

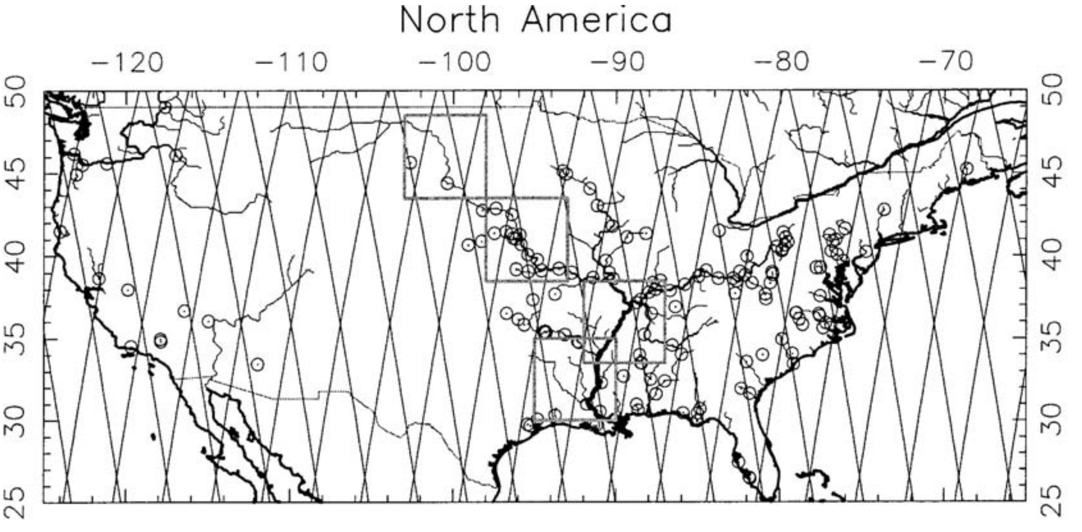


Fig. 3 Potential IceSAT test targets in the United States. River width for 6′ gridded network was estimated by applying empirical relationship (Osterkamp *et al.*, 1982) to mean annual discharge. Discharge gauges monitoring >200 m wide rivers (according to USGS gauge survey data) from USGS real-time data archive were selected. The estimated river width at the 6′ resolution gridded network corresponds well, with the location of discharge gauges monitoring 200 m or wider rivers.

sites, where the rivers are at least 200 m wide, and flow parallel to the satellite track. In this experiment, the off-nadir pointing capability of the satellite will be tested to obtain multiple flow heights along stretches of the targeted river sections (potentially measuring the surface slope). The experiment will also provide information on the cloud penetration capability of the lidar instrument. Normally, lidar does not penetrate cloud (which is a serious limitation in hydrological applications, since the hydrological systems tend to be more active in cloudy conditions), but some airborne lidar experiments suggest that lidar can actually penetrate 40–60% in cloudy conditions (Vörösmarty *et al.*, 1999).

Figure 3 gives a good estimate of the current potential in applying remote sensing to monitor discharge from space. Most of the sensors considered today for river monitoring require a minimum 200 m river width. Figure 3 clearly shows that there are not many rivers which are wide enough for monitoring from space, so the current state of remote sensing is not likely to provide the breakthrough solution to monitor more rivers.

The economy of such a mission is also questionable. A potential, three-year, experimental mission would cost about $150 million, which would buy the three year operation of 7500 gauges at USGS costs.

SUMMARY

River discharge is one of the most accurately measured components of the hydrological cycle. It provides integrated information about the hydrological processes in a larger region. River discharge data are not fully utilized in climate system studies due to the lack of adequate monitoring network and limitation in accessing such data. Only 50% of the continental land mass is monitored, while 30% of the total land mass is inactive (i.e. does not produce any runoff). The remaining 20% unmonitored yet active basins are mostly small basins (<25 000 km^2), which are increasingly hard to monitor. Considering annual discharge to oceans estimates from various sources, the unmonitored 20% land mass appears to produce more runoff to the oceans than the monitored 50%. This finding highlights the importance of either monitoring and/or developing new techniques to assess the discharge from these smaller coastal basins more accurately.

Remote sensing may provide complementary information to the existing discharge monitoring network. Several remote sensing technologies were tested by various research to measure discharge from spaceborne sensors. The currently flying sensors have serious limitations on the potential target size, therefore only the fairly large rivers (which are relatively well monitored anyway) can be targeted successfully. Future, higher resolution sensors may have the potential to break this limitation, and also allow the monitoring of smaller rivers.

Further difficulty in applying remote sensing to discharge monitoring is the lack of necessary river surveying. The high accuracy of the traditional discharge monitoring is the result of the relatively simple measuring of stage height (tracking variable) and the regular, detailed river surveys that allow the accurate calibration of the stage height records and translation of stage height to river discharge. Remote sensing applications without the detailed ground survey have less chance to meet the same accuracy as the traditional methods. Furthermore the flying hydrology dedicated satellite is still a very costly alternative to ground-based discharge monitoring.

The use of remote sensing is still appealing, since it might be the only alternative to compensate for the continuously declining discharge monitoring network. Even without a dedicated hydrological satellite, remote sensing of river discharge is possible by utilizing existing satellites flown for other purposes.

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