GJ TheGeographicalJournal

Royal Geographical Society with IBG
Advancing geography and geographical learning

The Geographical Journal, 2015, doi: 10.1111/geoj.12155

Crossing the (Watershed) Divide: Satellite Data and the Changing Politics of International River Basins

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This paper was accepted for publication in July 2015

Acquiring freshwater resources is a necessary component of sustainable human settlement subject to increasing pressure from population and climate changes. This sometimes scarce resource primarily comes from rivers, and international river basins (IRBs), where watersheds and watercourses cross political boundaries, are often spaces of great political tension and conflict worldwide. Such conflict potential has garnered interest from a wide range of research communities, and each emphasises public access to hydrologic data as integral to successful international management of IRBs. However; these hydrologic data, especially measurements of river flow rate, are often closely guarded state secrets. Satellites have been cited as a key technology set to challenge this data monopoly that have yet been unable to calculate river flow rate without some form of guarded ancillary data. Now, at-many-stations hydraulic geometry (AMHG) offers a means of circumventing data limitations without any *a priori* information, and the forthcoming NASA/CNES Surface Water and Ocean Topography (SWOT) satellite also promises to estimate flow rates solely from its novel measurements following launch. In this paper, we explore how these newly available estimates of river flow rate could reconfigure water-management and interstate relations in IRBs, and demonstrate AMHG, for two cases: the Ganges–Brahmaputra and Mekong. For these basins we find that satellite flow rate retrievals will likely reinforce and favour state-level negotiations of water resource governance. Also, satellite flow retrievals can have the direct, concrete effect of improving hydrologic understanding of the upstream Ganges–Brahmaputra, a sorely needed advance that will positively benefit millions of Bangladeshis and affect state-level interactions between India, China, and Bangladesh. Finally, we avoid offering prescriptive water management solutions for each case, as local stakeholders will ultimately determine if and how such satellite retrievals will be used.

KEY WORDS: international river basins, ungauged basins, at-many-stations hydraulic geometry, AMHG, SWOT, political geography, China, Mekong, Ganges, Brahmaputra

Introduction

Precipitation and snowmelt generate liquid water that flows downhill and collects in larger and larger rivers until it reaches the ocean. These rivers provide water for irrigation, human consumption, ecosystem services, and transportation, and life in many regions of the world is tightly coupled to particular rivers. These river systems, both watercourse and watershed, frequently flow from one upland state through one or more downstream states, and in many cases upstream users are able to affect the quantity and quality of water delivered to downstream users significantly. Hence, there is potential for conflict in these international river basins (IRBs).

Trends in population growth and climate change have placed increasing pressure on water resources, exacerbating the potential for such conflict. Coupled with sometimes fractious political history, the increasing stress on water resources in IRBs has led some to suggest that armed conflict over water resources is likely (e.g. Gleick 1993). This ‘water wars’ thesis represents one of the most dire opinions for the future of IRBs under climate and population pressures. However, recent work has argued that few if any armed conflicts have arisen over water and that cooperation has proven more likely in IRBs (De Stefano *et al*. 2010; Yoffe *et al*. 2003 2004). Still others have emphasised risks other than armed conflict, for instance unilateral actions that might reduce water quality or quantity from an upstream source that could seriously harm downstream users (Wolf 2007). As such, while armed conflict appears unlikely, water resource conflict will continue in IRBs with sometimes serious consequences.

The changing physical and political landscapes of IRBs are thus an object of great interest to several different research communities, each with its own imperatives. Climate scientists have studied physical effects of climate change on IRBs (Ahmad 2003; Dulal 2014; Goulden *et al*. 2009; Jeuland *et al*. 2013, 48; Swain 2011), and hydrologists have advanced understanding of physical processes shaping the quality and quantity of water resources in IRBs (e.g. Biancamaria *et al*. 2011; Conway 1997 2000; Conway *et al*. 1996; Hossain *et al*. 2007; Islam *et al*. 1999; Lu and Siew 2006). These physical science insights offer critical information to policymakers and resource managers, and much attention has been given to the social and political impacts of the physical manifestation of changing water resources. Scholars of resource politics have traced how power relationships between states and non-state actors affect mechanisms of water delivery, developing theory specifically to deal with IRBs (e.g. Bakker 1999, 218; Dore and Lebel 2010; Sneddon and Fox 2006; Zeitoun and Allan 2008; Zeitoun and Warner 2006). Scholars interested in international relations or international law have investigated the frameworks of water related treaties and institutions (e.g. Brochmann and Hensel 2011; Browder and Ortolano 2000; Uprety and Salman 2011), and these organisational structures have been credited with increasing the resilience of treaties and the suppression of overt conflict (Bakker 2009; De Stefano *et al*. 2012). Though some have imposed generalised positivist theories to this effect (e.g. Dinar *et al*. 2010 2011; Espey and Towfique 2004), most scholars prefer to study the historical, intrastate, and interstate context of a particular basin (Giordano *et al*. 2002). Despite their different priorities, all of these research communities seek deeper understanding of IRBs in an effort to uncover sustainable solutions to current divisions between water resources users and minimise conflict potential.

One cause of conflict all these research communities highlight is the problematic lack of shared hydro-data, especially in regard to the key variable of river flow rate (also termed ‘discharge’ or ‘runoff’). Flow rate is most commonly measured at a gauging station, where measurements of river depth are transformed via a rating curve into flow rate: the volume of water passing the gauge per unit time. This critical quantity reflects both the volume and temporality of water availability and is directly impacted by upstream watershed activities. Flow rate data collected in this manner are termed ‘gauge data’, and gauge data are considered as a scientific standard for understanding watershed behaviour and other fluvial processes. The Global Runoff Data Center (GRDC) collects and publically distributes these data via direct agreements with states. However, many states choose not to release gauge data, an issue compounded by data collection difficulties that means that water data scarcity is ‘universally experienced by poor countries’ (Hossain 2006, 265). While certain states construct water scarcity for political convenience (Alatout 2008; Barnes 2009; Phadke 2002), it is unclear if the data scarcity encountered in IRBs is similarly constructed or if there is a real lack of data collection. Regardless, this lack of transparency allows states to report flows within their borders as they see fit, allowing them to meet formal treaties and obligations while withholding key data and preventing thorough transboundary water resource management analysis. Hoarding data is also a political tool that allows upstream states to exert a measure of *de facto* control over downstream state claims of improper water management. As such, geographically distributed flow rate data are of paramount importance to both upstream and downstream states.

In the absence of gauge data, remote sensing has been identified as an important innovation that could provide much needed flow rate and flood forecasting data to downstream countries, and possibly alter power relations accordingly (Biancamaria *et al*. 2011; Hossain 2006; Wolf 2007). However, until recently, remote sensing has been unable to calculate river flow rate without some form of tightly controlled *in situ* calibration data, and the forthcoming NASA/CNES Surface Water and Ocean Topography (SWOT) satellite that promises to deliver flow rate estimates from its observations is not scheduled for launch for another half decade (Pavelsky *et al*. 2014). Now, a recent advance in geomorphic theory has enabled flow rate estimates to be obtained solely from available satellite imagery with no ground-based information whatsoever, provided certain geomorphic criteria are met. These estimates are made possible via at-many-stations hydraulic geometry (AMHG) and the associated discharge estimation algorithm advanced by Gleason and Smith (2014) and Gleason *et al*. (2014). This discharge retrieval algorithm has been tested on numerous rivers worldwide, and results indicate that flow rate estimations may be made with an expected 26–41% error compared with traditional *in situ* gauge observations of flow rate on most rivers (Gleason *et al*. 2014). While these flow rate estimations are less accurate than *in situ* measurements or the expected 5–10% error of a gauge observation and are made at discrete times dictated by available imagery, they afford meaningful calculation of flow rate to address water use issues in IRBs that may be obtained independently of access permission from individual states. This AMHG flow rate estimation procedure may well affect the political and social *status quo* of many different IRBs by empowering any interested stakeholder with the means to calculate river flow rate – a sometimes defiant act giving the critical missing link in many understandings of IRBs.

In this paper, we use two case studies to illustrate the expected impact of satellite flow rate retrievals on the geopolitics of IRBs: the Ganges–Brahmaputra and Mekong. These basins are both IRBs that have received much attention from the international community, and both basins are at risk with regards to their water resources under increasing climate and population pressures (De Stefano *et al*. 2012). For each case study, we first review the IRB's historical physical and political geography as they relate to water resources. We then employ the AMHG flow rate retrieval method to estimate flow rates on the main watercourse in each IRB, and compare these estimations to historical gauge data to affirm that the method accurately retrieves flow rates in these basins. Following our contextualisation of each basin and flow rate estimation in each case, we draw larger conclusions about the expected outcomes given adoption of AMHG and other emerging satellite technologies on natural resource governance. The purposes of this paper are modest in scope: we seek to contextualise present disputes using historical data analysis and consider the impact of novel AMHG flow rate estimations in specific settings. We do not presume to offer independent, data-based solutions to current conflicts, nor do we presume authority to publish data that are considered secret, and thus avoid demonstrating AMHG retrievals for ungauged portions of basins.

Methods: remote sensing of discharge and AMHG

No currently operating or planned satellite mission can directly measure river discharge, as no sensor can measure depth without optical attenuation techniques (e.g. Lyzenga 1978; Lee *et al*. 1999; Legleiter *et al*. 2009) that require careful calibration with *in situ* data and are only applicable to those areas for which field data are taken. As such, the current state of remote sensing does not include any methods that are able to estimate discharge within a river channel without assistance of field data, site-specific hydrodynamic models, or site-specific assumptions about physical properties of the channel.

Despite the inability to measure discharge directly from satellite platforms, researchers have shown the utility of empirically combining remotely sensed observations with field measurements to obtain useful discharge estimates (e.g. Smith *et al*. 1996; Smith 1997; Ashmore and Sauks 2006; Calmant *et al*. 2008; Smith and Pavelsky 2008; Nathanson *et al*. 2012). In addition, researchers have combined orbital measurements and hydrologic models to estimate river discharge, commonly invoking data assimilation techniques (e.g. Andreadis *et al*. 2007; Brakenridge *et al*. 2007 2012; Durand *et al*. 2008 2010, Biancamaria *et al*. 2011; Tarpanelli *et al*. 2013). However, both of these approaches require *in situ* or *a priori* knowledge of a river. While these *a priori* river data exist for many of the world's rivers, they are often tightly controlled in IRBs and render these techniques less useful in these cases.

The AMHG approach proposed by Gleason and Smith (2014) provides the first known means of estimating river discharge without any *a priori* knowledge, *in situ* data or ancillary data. AMHG is based on theory of hydraulic geometry as proposed by Leopold and Maddock (1953). Leopold and Maddock found that the width, depth and mean velocity of a given cross section of a river (the two-dimensional plane orthogonal to the flow at any point along the channel) exhibit a power law relationship to discharge, giving the now classic equations they termed 'at a station hydraulic geometry' (AHG):

$$W = aQ^b \tag{1}$$

$$D = cQ^f \tag{2}$$

$$V = kQ^m \tag{3}$$

where W=width, D=depth, V=velocity, and a, b, c, f, k and m are empirically fitted parameters. AHG has remained a powerful tool in hydrology, despite evidence that its empirical power law form is coincidental with typical channel geometry and not required by first principles (e.g. Richards 1973; Ferguson 1986).

AMHG holds that the coefficients and exponents of AHG are functionally related for a given river reach and shows there is a log-linear relationship between each of a and b, c and f, and k and m (Gleason and Smith 2014). Gleason and Wang (2015) give a derivation of AMHG and show that it arises because individual AHG curves intersect at the same point in hydraulic space (e.g. the same values of width and discharge). It is the width-AMHG that enables remote sensing of discharge, which is formulated as:

$$b = -\frac{1}{\log(Q_{cw})}\log(a) + \frac{\log(w_c)}{\log(Q_{cw})} \tag{4}$$

where Q_{cw} and w_c are the rating convergence points of a river's AMHG. Gleason and Wang further show that in practice for rivers with a strong AMHG, Q_{cw} and w_c are given as the spatial modes of time–mean width and discharge per cross section because ordinary least squares regression is invoked at a station.

Gleason and Smith (2014) were able to simplify Equation (1) by replacing b with a function of log(a), as provided by AMHG [Equation (4)]. This simplification reduces the number of unknown parameters in Equation (1) from $2n$+1 to n+1 for any n

Table 1 Landsat images acquired over the Ganges and Mekong rivers

Ganges		Mekong	
Image date	Landsat scene ID	Image date	Landsat scene ID
4/11/2011	LE71380432001308SGS00	24/10/1972	LM11360491972298AAA05
20/11/2001	LE71380432001324SGS00	11/11/1972	LM11360481972316AAA04
5/10/2004	LE71380432002279SGS00	16/1/1976	LM21360491976016AAA04
4/5/2004	LE71380432004125ASN02	3/2/1976	LM21360481976034AAA05
24/8/2004	LE71380432004237PFS03	16/11/1978	LM31360491978320FAK02
11/10/2004	LE71380432004285PFS01	11/11/1979	LM31360491979315AAA05
27/10/2004	LE71380432004301ASN00	29/11/1979	LM31360491979333AAA09
12/11/2004	LE71380432004317PFS00	17/12/1979	LM31360491979351AAA05
28/11/2004	LE71380432004333ASN00	22/1/1989	LT41270481989022AAA02
14/12/2004	LE71380432004349ASN00	23/2/1989	LM41270491989054AAA03
31/1/2005	LE71380432005031PFS00	11/3/1989	LM41270491989070AAA03
16/2/2005	LE71380432005047PFS00	20/4/1989	LT51270491989110BKT00
21/4/2005	LE71380432005111PFS00		

cross sections in a mass conserved reach, as Q is equivalent in such cross sections and W is easily given by remotely sensed observations. In this paper, W was manually measured from remotely sensed images (Table 1) at 15 cross sections for each of the two rivers in a 10 km reach either containing or abutting the gauge used for validation. This simplified system of AHG curves per cross section is then sufficient for unconstrained, heuristic optimisation of unknown parameters in Equation (1) to solve for Q, for which Gleason and Smith used a genetic algorithm. Gleason *et al*. (2014) give a recommended 'global' parameter set for use of this method in ungauged basins that includes recommended ranges for parameter tolerances and maximum and minimum possible flows, and we follow these parameters here save that we assume that minimum depth and velocity for the two very large rivers in this study are 1 m and 1 ms^{-1}, respectively.

AMHG enabled flow estimation is only applicable if a river's AMHG [Equation (4)] may be predicted without *in situ* data: otherwise this method relies on *a priori* knowledge that limits its usefulness for our purposes here. Gleason and Wang (2015) suggest an empirical estimate for $1/\log(Q_{cw})$ as –0.30, and suggest using the spatial mode of time–mean observed discharges as $\log(w_c)$ following their derivation of AMHG. Combined with the recommended 0.10 tolerance for AMHG parameters given by Gleason *et al*. (2014), this yielded a remotely sensed estimate of the slope [$1/\log(Q_{cw})$] and intercept [$\log(w_c)/\log(Q_{cw})$] of AMHG as –0.30±0.10 and 0.99±0.10, respectively, for the Ganges and –0.30±0.10 and 0.90±0.10, respectively, for the Mekong. Using gauge data to verify each river's AMHG revealed that the Ganges AMHG slope was equivalent to –0.25 and AMHG intercept equivalent to 0.84, while the Mekong AMHG slope and intercept were –0.28 and 0.83, respectively. Thus, following the procedure of Gleason and Wang to define each river's AMHG yielded good agreement between remotely sensed AMHG and true AMHG. The results of discharge estimation using these AMHG estimates are given below in each of the respective case studies.

Case I: the Ganges–Brahmaputra

Current and historical geography of water resources

Ten percent of the people on earth live within the Ganges–Brahmaputra–Meghna basin (Jeuland *et al*. 2013; Rasul 2014). The Ganges and Brahmaputra rivers both arise in the Himalayas and enter the Bay of Bengal in Bangladesh below their confluence with the Meghna River upstream of the Bangladeshi delta (Figure 1).The Ganges watercourse flows directly from Nepal into India and then Bangladesh, and 80% of its basin lies within India (Ahmad 2003). Conversely, the Brahmaputra flows east across Tibet, then makes a 90° southerly turn into northeast India and Bhutan before flowing into Bangladesh. Thirty-four percent of the Brahmaputra basin is in India, while 50% lies within China, leaving these two powerful states in control of the majority of the river basin, although China controls the upland area. Bangladesh receives nearly all the water from these two mighty rivers and is extremely vulnerable to monsoon-driven river flooding, yet Bangladesh contributes very little to their flow: only 3.6% of the Ganges basin and 8.7% of the Brahmaputra basin are within Bangladesh (Islam *et al*. 1999). The Meghna river basin is almost completely contained within Bangladesh and therefore is of less interest to the present paper, despite its importance to the people of Bangladesh.

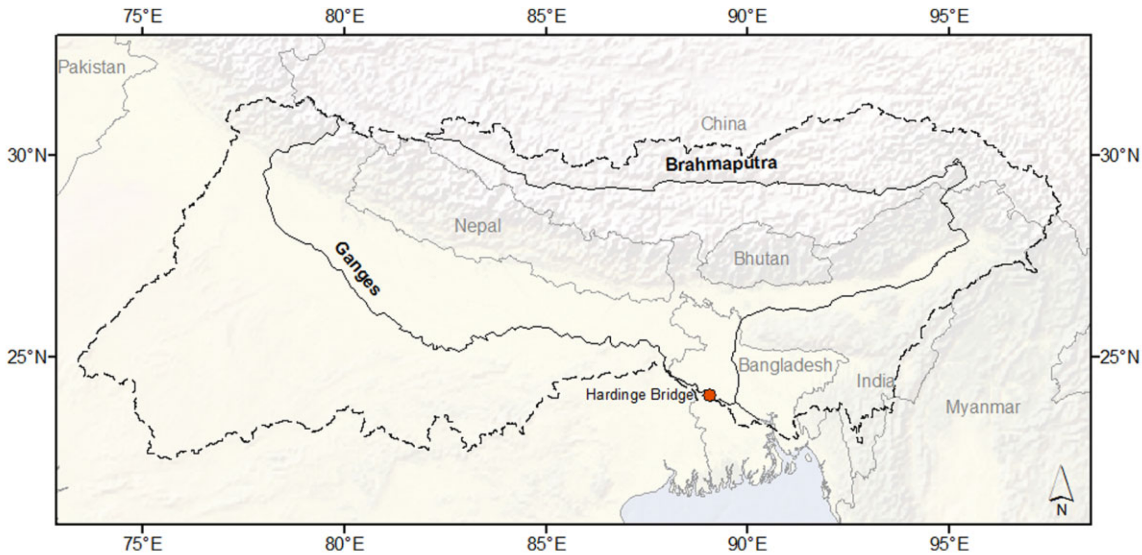

Figure 1 This map shows the Ganges and Brahmaputra rivers (solid lines), as well as their combined watershed (dashed line). Bangladesh receives nearly all the water from these mighty rivers, but contains less than 10% of each river's basin by area. Guaranteeing dry season flows and predicting floods for downstream states are the principal water resource conflicts in this basin, and basin politics are dominated by China and India. AMHG discharge estimation was performed on the Ganges River using gauge data from the Hardinge Bridge, marked with an orange circle

Both the Ganges and the Brahmaputra rivers are strongly affected by the Indian monsoon and exhibit huge variations in flow rate: flow in the Brahmaputra, for instance, can vary from 1200 to 28 000 m^{3-1} in the same year (Brichieri-Colombi and Bradnock 2003; Sarma 2005). This strong seasonal flow variability has made flood management and guaranteeing dry season flow the pre-eminent challenges in managing the waters of the Ganges and Brahmaputra rivers (Jeuland *et al*. 2013). Climate change is expected to have significant impacts on water resources in these basins and may affect the seasonality of the monsoon, yet synoptic assessment of climate change in these basins is difficult and severely limited by available data (Dulal 2014; Jeuland *et al*. 2013).

In contrast to the Mekong case study, there is little institutional history and currently only one treaty in place for either the Ganges or Brahmaputra rivers. The 1996 Ganges Water Treaty between India and Bangladesh provides a formula for sharing water passing the Farakka Barrage, a structure that diverts the Ganges into a more manageable system of channels just upstream of the India–Bangladesh border. This is based on the flow rate at the barrage, and also calls for discussion on 53 other rivers that flow from India into Bangladesh. However, this discussion has not occurred, and providing water from the barrage during dry season flows remains a thorny issue between the two states (Uprety and Salman 2011). These dry season flows are critical, as the relatively low flows can lead to water scarcity downstream if upstream users withdraw or impound too much water. There are currently no valid treaties concerning the Brahmaputra, but there are memoranda of understanding signed between India and China that promise to share flood season information. Relations, however, are poor: China denied constructing a dam on the Brahmaputra in Tibet even when presented with satellite images revealing the site operations (Ho 2014). Such denial could play a strong role in shaping how satellite flow rate retrievals are implemented in the Ganges–Brahmaputra.

In sum, India and China dominate water resources management and diplomacy in the Ganges–Brahmaputra basin, as these powerful states also enjoy upstream positions. Of the less powerful states in the basin, Nepal and Bhutan are also upstream with ample water resources, but relations between these states and downstream states are generally good. This leaves Bangladesh in a vulnerable position as a downstream state with little bargaining power against its large upstream neighbours. There are also few formal agreements in effect in the basin, leaving states to develop water resources unilaterally as they see fit.

Flow rate data and AMHG in the Ganges–Brahmaputra basin

There is a history of limited water data sharing in the basin, yet, 'amazingly, there are no publicly available streamflow records for the rivers in the Gangetic plain in India' (Jeuland *et al*. 2013, 48). This has exacerbated one of the principal conflicts of the basin: Bangladesh's inability to forecast floods due to India's reluctance to share upstream flow data. Currently, India provides data from five gauges to Bangladesh, but these data are from stations located at or near the Bangladeshi border and are not sufficient to forecast floods beyond 2–3 days (Ahmad 2003; Biancamaria *et al*. 2011; Hossain and Katiyar 2006; Hossain *et al*. 2007). This is a critical issue, as Bangladesh is quite vulnerable: in 2000 the country was devastated by a major flood that it was unable to forecast far enough in advance (Ahmad 2003; Babel and Wahid 2011). Therefore, 'from a Bangladeshi perspective, the upstream Ganges and Brahmaputra catchments must be considered as the two largest un-gauged river basins on the planet' (Jian *et al*. 2009, 354). Clearly, there is a need for additional and transparent flow rate data within the basin that can be provided in part by AMHG.

In this study, we use AMHG to estimate Ganges river discharge on the furthest upstream station where public records of streamflow may be obtained, located at Hardinge Bridge, just downstream of the India/Bangladesh border (Figure 1). We feel that making discharge estimations further into the Gangetic plain where flow data are not publically available constitutes an intervention into local politics for the basin, so we restrict our demonstration of AMHG to this downstream location. Landsat TM images were acquired (and therefore discharge was estimated) for 13 days spanning 2001–5, and images were taken on the same day as reported gauge flow for five images and within 2 days of reported gauge flow for all other images (Table 1).

AMHG discharge estimation had a root mean square error (RMSE) of 11 600 m^3s^{-1} and relative RMSE (RRMSE) of 56% for the 13 images in this study. This error is obviously very large, but this large error is expected as images span both wet and dry seasons and encompass huge variations in flow: the AMHG method is not expected to perform well in this situation (Gleason *et al*. 2014). Using only the nine dry season images available in this study gives an RMSE of 1570 m^3s^{-1} and RRSME of 28%, showing the efficacy of AMHG when only one of the monsoon seasons is considered (Figure 2). Without this separation, flow estimations are of less use as peak flows are severely underestimated. This accurate dry season performance is especially encouraging, as negotiation of dry season flows is a critical issue in Ganges water negotiations (Uprety and Salman 2011; Jeuland *et al*. 2013).

It is important to note that the estimated flows in this study (and for all AMHG estimated flows) do not constitute a true 'hydrograph:' flow estimations are made at discrete and disconnected times when images were available. AMHG can only provide a hydrograph with daily or monthly sampling if sufficient imagery to do so is available: unlikely in the humid and cloudy Gangetic plain. Thus, while AMHG performance in the dry season is encouraging, AMHG must be coupled with hydrologic models or other satellite products to give a full picture of water resources during the cloudy monsoon season. However; even opportunistic, cloud-free estimates of discharge upstream represent a significant advance in upstream hydrologic knowledge. Despite these challenges, AMHG can provide accurate point estimates of flow in the Ganges without any form of ancillary data, thus directly challenging India's data monopoly and perhaps initiating some of the responses we discuss below.

Case II: the Mekong

Current and historical geography of water resources

The Mekong flows out of China's Yunnan Province past Myanmar, Laos, Cambodia, Thailand, and Vietnam en route to the South China Sea (Figure 3). These latter four countries (the 'lower' Mekong basin) are 77% of the total basin by area and contribute 80% of the river flow (Bakker 1999), and the river and its delta support 65 million people, two-thirds of whom are subsistence fishers (Ziv *et al*. 2012). It is often claimed that the Mekong is a relatively 'untouched' or 'underdeveloped' river system as the basin contains few dams or flow alterations, although numerous projects are on the books (Hirsch 2010; Kummu and Sarkkula 2008; Lu and Siew 2006). A key hydrologic feature of the basin is the Tonle Sap (a fluvial lake) in Cambodia, which alternately feeds and is fed by the mainstem Mekong and supports the livelihoods of over one million people.

The Mekong has been subjected to international and institutional oversight since the mid-twentieth century. In 1958, the Mekong Committee was established by the USA, along with other foreign aid agencies, to work towards a dam cascade on the mainstem Mekong that would provide hydropower to the region (Browder and Ortolano 2000). This institution lasted until 1975 and the end of the Vietnam War, and was replaced in 1978 with the Interim Mekong Committee. In 1995, the Mekong River Commission (MRC) replaced the older institution and continues today, officially including only the four lower basin nations. Much has been written about these institutional structures, and Jacobs (1995 2002) reviews both the Mekong Committee and the MRC thoroughly. In brief, the MRC focuses on the physical watercourses within the basin and only requires member nations to have 'prior consultation' with one another in order to carry out water development projects, contrary to the original Mekong Committee in which members had veto power (Bakker 1999; Sneddon and Fox 2006). The MRC also approves of and adopted the 1997 UN

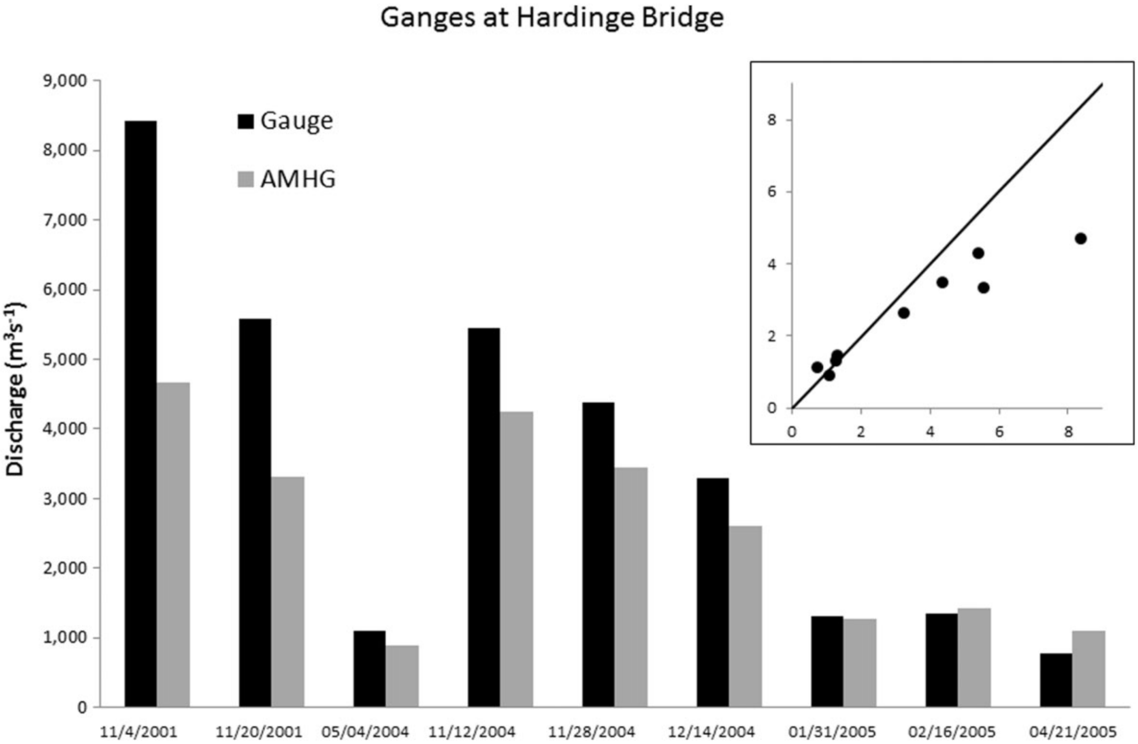

Figure 2 AMHG discharge retrieval was successful (RMSE=1568 m^{3}s^{-1}, RRMSE=28%) in estimating the dry season flows shown here. A scatter diagram is inset (with flow in thousands of m^{3}s^{-1} on either axis), and shows good agreement between gauge reported and AMHG estimated flows. Note that including three wet-season images drastically increased estimation error (RRMSE of 56%), as expected from previous studies of AMHG. While discharge estimation is accurate, the resultant flow values are not a true hydrograph but instead disconnected point estimations of flow. Thus AMHG accurately circumvents data restrictions but does not provide a complete solution to water resources accounting

Watercourses Convention, with its language of equitable use and a purposeful disassociation from watersheds, which China, the upstream state, did not adopt (Browder and Ortolano 2000; Sneddon and Fox 2006).

This institutional environment, coupled with the relatively undeveloped nature of the Mekong, has directly fanned debate over the development of hydropower, the key objective of the MRC and its backers. Hydropower is a sustainable and carbon neutral source of electricity: attractive for the developing Mekong basin. However, The World Commission on Dams used the Pak Mun Dam in Thailand as its key case study to show how hydropower dams rarely deliver on all of their promises regarding electricity distribution, relocation, and livelihood compensation for displaced users of the former river (Hirsch 2010). The effects of current dams in the Mekong basin are numerous and complex: food security has been disrupted and livelihoods diminished in the Tonle Sap, territory has been reorganised, and upstream states have been empowered *vis-à-vis* downstream neighbours, as seen in the Ganges–Brahmaputra (Ziv *et al*. 2012; Kummu and Sarkkula 2008). Even smaller dams are disruptive: Ziv *et al*. (2012) estimate that numerous tributary dams will have far greater impact on the Mekong than the large proposed dams that dominate the headlines. The question of dams has thus led to alarmist calls for immediate cessation of dam building in both the press and in academic publications (e.g. Vaidyanathan 2011).

Most dam building in the Mekong basin is implicitly linked to China. Chinese funding has been cited as a key factor in lower Mekong dam building, but China is also itself a riparian state in the Mekong basin (as in the Brahmaputra). Unilateral Chinese development is also a major concern for the lower riparians, and McNally *et al*. (2009) offer the case of the Nu/Salween basin as a comparison of how unilateral Chinese action can adversely affect downstream riparians. In the Mekong basin, only about 16% of total basin runoff comes from Yunnan, but dam building there has had impacts, albeit

Figure 3 This map charts the course of Mekong River from Yunnan province in China to the sea, with its watershed given as a dashed line. The lower four states of the basin (Thailand, Cambodia, Vietnam, and Lao PDR) contribute 80% of the flow to the Mekong. Despite this water balance, Chinese water management practices can seriously affect downstream states, and dam building within and outside China is the principal source of water resource conflict in this basin. Flow estimations were performed using a gauge provided by the GRDC at Mukdahan, Thailand

disputed, on downstream countries. For instance in 1992, which was not a drought year, filling of a dam in Yunnan corresponded to unusually low discharge as recorded at downstream stations (Lu and Siew 2006). In addition, unannounced water releases from Chinese dams have directly led to loss of life and property in downstream Cambodia (Lebel *et al*. 2005).

Importantly, China lacks a comprehensive transboundary policy and conducts its business case by case with regard to IRBs: the Yunnan provincial government handles policy for the Mekong. ‘Chinese policy’ in the Brahmaputra therefore may not map neatly onto the Mekong, though comparison could still prove beneficial (Ho 2014). In addition, China has shown a preference for bilateral action and has been more cooperative with regard to navigational uses of the Mekong than it has with regard to dam building, where it does not share its assessment of potential downstream dam impacts (Ho 2014; Masviriyakul 2004).

Flow rate data and AMHG in the Mekong basin

Despite current and historic participation in the MRC, the lack of hydrologic data is the basic problem facing all Mekong states (Campbell 2007). Indeed, ‘the lack of basic data about instream flows . . . undermines the ability of downstream countries to negotiate to protect necessary minimum flow levels as outlined by the Mekong agreement’ (Bakker 1999, 218), and flow rate data are considered too thorny an issue to tackle at a general MRC meeting (Sneddon and Fox 2006). While hydrologic modelling work that assimilates rainfall and land cover data has been performed to calculate flow rates within the basin, accurate estimates of flow are not made publically available by states that collect them for much of the Mekong basin (Haddeland *et al*. 2006; Kite 2001).

Flow data for Yunnan province are especially difficult to acquire and China has yet to share it with downstream states. The MRC has therefore officially requested information from China about dam-building activity and flow rates via a Memorandum of Understanding, but such information has not proven forthcoming (Lebel *et al*. 2005). Much like the US Bureau of Reclamation in its original studies of the Mekong, China uses its expertise to impose a ‘technically superior’ science of water on the Mekong without sharing results (Sneddon 2012). This policy constructs a data monopoly – and a bargaining position – that satellite flow retrievals could significantly alter.

Here, we use a publically available (via the GRDC) gauge record to validate an AMHG discharge estimation for the Mekong main stem at Mukdahan, Thailand (Figure 3), using 12 Landsat MSS/TM images collected from 1972 to 1982 (Table 1). Discharge is estimated with an RMSE of 1960 m^3s^{-1} and RRMSE of 36%, commensurate with Gleason *et al*.’s (2014) retrieval from the same satellite images (Figure 4). As with the Ganges (and other world rivers), the method underestimates peak flows, tends to converge toward mean flow, represents discontinuous flow estimates over several years, and is limited by available image data. However, the Mekong case again demonstrates the ability of AMHG to provide useful discharge estimates without ancillary data, in this case challenging the Chinese data monopoly, if not providing a complete water balance for the river.

Discussion: exploring the cases

The flow retrievals given here present point estimations of river discharge without *in situ* data or *a priori* knowledge in two IRBs where upstream data are tightly controlled. This is the first such demonstration of this kind, yet unless there is a significant advance in global image availability, AMHG alone will not be able to provide a full water balance in either case. As such, AMHG will likely be most useful in tuning

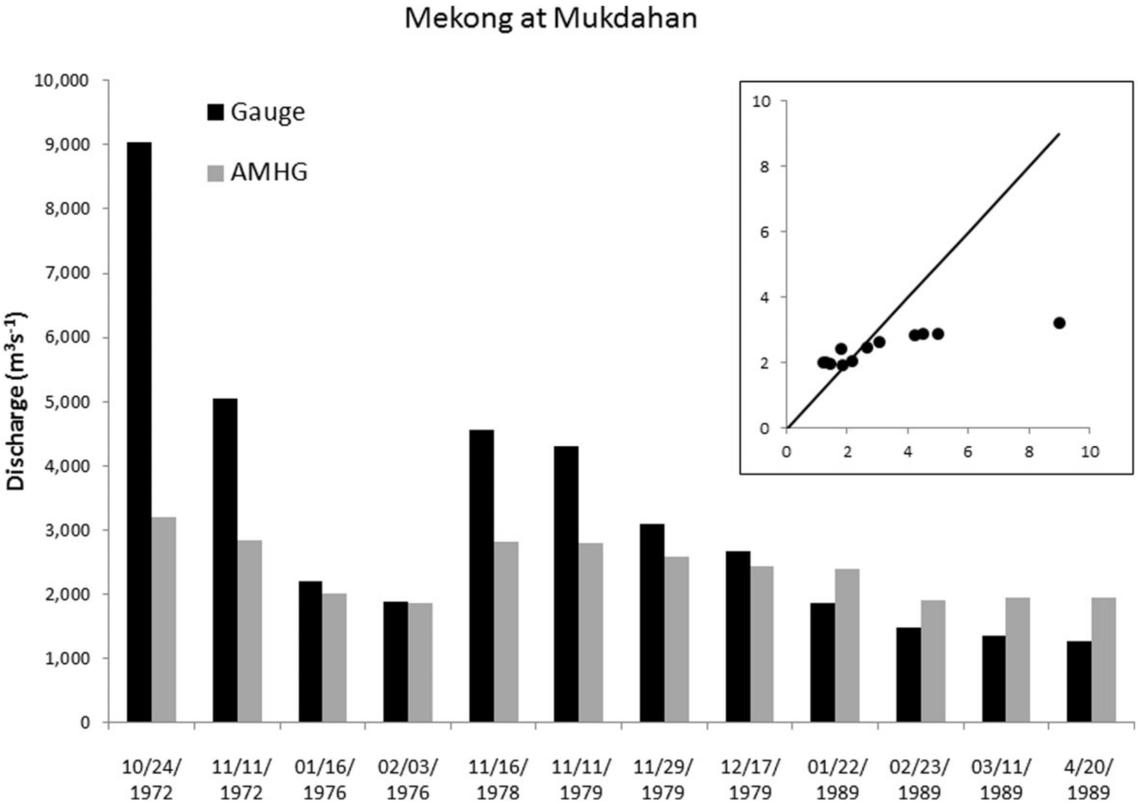

Figure 4 Discharge estimation was less successful in the Mekong (RMSE = 1956 m^3s^{-1}, RRMSE = 36%) than in the Ganges, but there is still good agreement between gauge reported and AMHG estimated flows (see inset scatter diagram with axes in thousands of m^3s^{-1}). As with other AMHG retrievals, peak flows on the Mekong were greatly underestimated, but this could be remedied if enough images of peak flow existed to perform a wet season only estimation. The accuracy of flow estimations on the Ganges (Figure 2) and here on the Mekong lends confidence to our conclusions that AMHG will play an important, albeit limited, role in these two basins.

hydrologic models of these basins or providing specific checks against other streamflow estimates. However, AMHG does represent a significant advance in the public availability of hydrologic data, and it is this advance that we find to be most significant in our two cases. This is especially important when considering that the forthcoming SWOT mission promises to provide at least monthly discharge estimates (unaffected by clouds since SWOT is a radar) solely from the data it collects. Thus, AMHG offers a first look at how new techniques of data collection may affect regional politics.

New technologies like AMHG discharge retrievals and future SWOT measurements stand poised to shape political conditions in IRBs dramatically by reconfiguring human interactions with water resources. Historically, new technologies for measuring, ordering, and allocating natural resources have concentrated and expanded power in the hands of state 'experts' and bureaucrats. Mitchell (2002), for instance, describes how the Egyptian state 'enframed' the Nile River within the techno-centric discourse of economics, one whose application both transformed the river's hydrology and expanded the spaces of state control and violence (Scott 1999; Mitchell 2002; Harris and Hazen 2006; Heatherington 2012). Yet, while major infrastructural projects like dams dramatise this process, seemingly straightforward technologies and information have quite complex effects on state power. On one hand, Meehan (2014) suggests that instead of concentrating state power in Tijuana, Mexico, 'infrastructures clearly intended to *enable* state power may unexpectedly *limit* the scope of stateness' (Meehan 2014, 222, emphasis in original; Mann 1984 2008). On the other, state collection of data in various forms, as well as discourses of environmentalism, can *deepen* state authority in the eyes of citizens in subtle ways, as Agrawal (2005) demonstrates in Kumaon, India (Agrawal 2005; Painter 2006). Technological advances like AMHG that add to knowledge about nature have thus typically privileged state actors and inter-state governance at the expense of civil society users.

However, there are signs that such knowledge can be used to challenge existing practices of environmental governance. Remote sensing and GIS data have empowered advocacy networks to challenge state projects, environmental or otherwise, in contexts as diverse as democratic Sweden and theocratic Iran (Rocheleau 1995; Sandstrom *et al.* 2003; Aday and Livingston 2009). At the same time, Cold War rival states, the Asian Development Bank, and China have implemented new forms of environmental 'expertise' that have already reshaped environmental and political realities along the Mekong River (Goldman 2005; Sneddon 2012; Sneddon and Fox 2011 2012). IRBs, which are defined by a particularly wide variety of actors, should be seen as uniquely complex assemblages of political, hydrological, and technological forces whose relations are reconfigured in the face of new technological interventions (De Landa 2006; Baghel and Nüsser 2010). It is thus reasonable to suggest that AMHG-enabled data have the potential to effect political and environmental change in the two case-study basins, even if modestly (Barnes and Alatout 2012; Bakker 2012; Dalby 2013).

Access to transparent information does not always result in increased cooperation – especially if it *does not* favour a powerful state actor. In the Ganges–Brahmaputra basin, China has shown an outright willingness to deny even basic satellite imagery, a sign that it views its data monopoly as a valuable political resource. In this basin, the novelty of AMHG flow rate retrievals may very well reinforce this, as their level of accuracy could allow China to claim that the technology is immature and therefore inappropriate for use in negotiations. However, other actors in the basin have a well established history of adopting new water resource measurement technology, as evidenced by previous studies that leveraged then-novel satellite altimetry data to improve flood forecasting in Bangladesh (Biancamaria *et al.* 2011; Hossain *et al.* 2007; Moffitt *et al.* 2011; Nishat and Rahman 2009). The assimilation of satellite flow rate retrievals into basin-scale hydrologic models represents a potential catalyst for better data-sharing with India, which has remained tightfisted with gauge data, citing national security. India may well deny the validity of AMHG retrievals, but this seems unlikely as it would weaken its own negotiating power along the Brahmaputra considering the Chinese data monopoly (Ho 2014). Whether or not India (or China) acknowledges and incorporates AMHG retrievals into new negotiations, Bangladesh benefits dramatically from increased hydrologic knowledge and autonomy in the face of Indian intransigence. At the same time, India's disputes with China will likely lead it to adopt a favourable attitude toward satellite discharge estimation, which may push it into closer cooperation with Bangladesh. A complex environment awaits Indian policymakers following the advent of broadly applied satellite flow rate retrievals.

The Mekong basin is similarly hostage to the Chinese state's unwillingness to disclose gauge data. This is to the detriment of downstream states, but also to subsistence communities relying on the river's abundant fisheries who stand to lose most from the current regulatory impasse (Bakker 1999). But state actors are not the only catalysts for regulatory change: the World Bank has demonstrated how new forms of 'expertise' can transform not only the hydrology of the Mekong (which it implemented in Laos) but also power relations. Thus, local use and ecology are now subject to the whims of international investors and global bureaucrats (Goldman 2005:181–220), as IRBs increasingly include states and actors beyond their bounds. In this context, it is not surprising that Lebel *et al.* (2005) and Dore and Lebel (2010) have pushed for a more open and public production of data in the Mekong basin, which might better protect local users from such distant forces. We believe that an open-access AMHG could challenge the more state-centric and technocratic management regime of the MRC. However, there are technological barriers barring full use of AMHG by local users in the Mekong: access to satellite data and knowledge of certain image processing techniques and computing power are required. These requirements are modest for the developed world, but could pose a serious barrier for non-state actors and ultimately reinforce the MRC's inter-state basis. One way or another, AMHG alludes to a continued trend in which new techniques of data collection increasingly challenge the state monopoly of scientific knowledge within its borders: AMHG is the first such known technique, but others will surely follow.

Technologies like AMHG and the future SWOT mission, and the information they generate, thus make a significant difference to natural resource governance and consequently, political relations among states. Of course, there is a real danger of falling into state-based synecdoche to characterise each basin by highlighting only state actor relations (Bakker 1999; Sneddon and Fox 2006; Wolf 2007). Although our insights are grounded in a thorough examination of each case, each is a highly complex and evolving assemblage of political, hydrological, and technological forces. With time, satellite discharge estimations may empower non-state actors to push for more local, participatory governance within these basins and thus challenge state-based monopoly of technological expertise, as Lebel *et al.* (2005) advocate. For the near future, however, our conclusions reflect the prevailing political order, in which states are arguably the most important actors for natural resource governance, both *de facto* and thanks to international law (Benvenisti 1996; McCarthy 2007). Future research should also direct greater attention to the variety of local actors whose everyday interactions with and demand for these water resources might also change dramatically with the advent of mature satellite discharge retrievals. Great or small, the transformative *potential* of technologies like AMHG flow-rate retrievals is crucial to understanding the changing politics of IRBs, in our cases and elsewhere.

Conclusions

'Water', writes Karen Bakker, 'poses the problem of collective action in a particularly acute way' (Bakker 2012, 620). Indeed, a great many relations constrain and shape how upland runoff reaches the earth's oceans beyond the physical mechanisms of water and energy transport: relations between state and civil society actors and relations between humans and the environment more generally. A third relation can dramatically transform both of these: the relation of technology to governance. It is this general relation that we have explored. In particular, we argue that by offering a more open and transparent source of information, satellite flow rate data retrievals have the potential to alter political relations along two major rivers crossing international borders: the Ganges–Brahmaputra and the Mekong. This is critical, as flow rate data are cited as a key to determining both water resource management objectives and climate change assessments.

We have sought here to imagine the scenarios and pose the questions that policymakers should find important for water resource management given our expectations of satellite-based flow rate retrievals as a transformational catalyst in water resource governance. Satellite flow-rate retrievals will likely have the greatest effect on the Ganges–Brahmaputra basin, where India's tense negotiations with China would benefit from further data to back up its claims, which in turn may shape Indian policy toward Bangladesh and encourage further data-sharing. At the very least, Bangladesh gains increased hydrologic knowledge, which benefit a population beleaguered by repeated floods in the absence of upstream gauge data. The Mekong will likely see fewer alterations in data-sharing or governance, as China's position as both a superpower and an upstream state give it little incentive to change these relationships, from which it unilaterally benefits.

The enabling power of technology to realign relationships between governance and water resources is well established for our cases, but scholars must take into account the political and geographic contexts distinct to each basin when attempting to extend these conclusions beyond these case studies. This means keeping in mind unique hydrological conditions, historical legacies of river development projects, and the ongoing importance of existing institutions like the state. Finally, we are cognisant of the warning provided by Zeitoun and Allan (2008) against uninformed water professionals offering well meaning but ultimately untenable solutions to water resource management in IRBs. As such, we have not provided any prescriptive solutions to any of the water conflicts outlined in the above case studies but have instead contextualised them and explored how flow rate data might affect each case. By not calculating flow rates for contentious or ungauged portions of basins, we hope to demonstrate the efficacy and utility of AMHG flow rate retrievals and characterise the policy environment in each case without imposing AMHG upon local actors who will, ultimately, determine its usage and success.

Acknowledgments

This research was supported by NASA Earth and Space Sciences Fellowship NNX12AN32H to C J Gleason, and by NASA Remote Sensing Theory initiative (grant NNX12AB41G) and NASA Surface Water Ocean Topography (SWOT) mission (grant NNX13AD88G). F Hossain provided gauge data at Hardinge Bridge, and L H Pitcher and M Bennett provided constructive comments on earlier versions of this manuscript. We would like to thank three anonymous referees and K Dodds and K Richards, editors, for constructive reviews that have greatly improved this paper.

References

Aday S and Livingston S 2009 NGOs as intelligence agencies: the empowerment of transnational advocacy networks and the media by commercial remote sensing in the case of the Iranian nuclear program *Geoforum* 40 514–22

Agrawal A 2005 *Environmentality: technologies of government and the making of subjects* Duke University Press, Durham, NC

Ahmad Q K 2003 Regional cooperation in flood management in the Ganges–Brahmaputra–Meghna region: Bangladesh perspective *Natural Hazards* 28 191–8

Alatout S 2008 'States' of scarcity: water, space, and identity politics in Israel, 1948–59 *Environment and Planning D: Society and Space* 26 959–82

Andreadis K M, Clark E A, Lettenmaier D P and Alsdorf D E 2007 Prospects for river discharge and depth estimation through assimilation of swath-altimetry into a raster-based hydrodynamics model *Geophysical Research Letters* 34

Ashmore P and Sauks E 2006 Prediction of discharge from water surface width in a braided river with implications for at-a-station hydraulic geometry *Water Resources Research* 42

Babel M S and Wahid S M 2011 Hydrology, management and rising water vulnerability in the Ganges–Brahmaputra–Meghna river basin *Water International* 36 340–56

Baghel R and Nüsser M 2010 Discussing large dams in Asia after the World Commission on Dams: is a political ecology approach the way forward? *Water Alternatives* 3 231–48

Bakker K 1999 The politics of hydropower: developing the Mekong *Political Geography* 18 209–32

Bakker K 2012 Water: political, biopolitical, material *Social Studies of Science* 42:4 616–23

Bakker M H N 2009 Transboundary river floods and institutional capacity *JAWRA Journal of the American Water Resources Association* 45 553–66

Barnes J 2009 Managing the waters of Ba'th Country: the politics of water scarcity in Syria *Geopolitics* 14 510–30

Barnes J and Alatout S 2012 Water worlds: introduction to special issue *Social Studies of Science Social Studies of Science* 42 483–88

Benvenisti E 1996 Collective action in the utilization of shared freshwater: the challenges of international water resources law *The American Journal of International Law* 90 384–415

Biancamaria S, Hossain F and Lettenmaier D P 2011 Forecasting transboundary river water elevations from space *Geophysical Research Letters* 38 L11401

Brakenridge G R, Cohen S, Kettner A J, De Groeve T, Nghiem S V, Syvitski J P M and Fekete B M 2012 Calibration of satellite measurements of river discharge using a global hydrology model *Journal of Hydrology* 475 123–36

Brakenridge G R, Nghiem S V, Anderson E and Mic R 2007 Orbital microwave measurement of river discharge and ice status *Water Resources Research* 43

Brichieri-Colombi S and Bradnock R W 2003 Geopolitics, water and development in South Asia: cooperative development in the Ganges–Brahmaputra delta *The Geographical Journal* 169 43–64

Brochmann M and Hensel P R 2011 The effectiveness of negotiations over international river claims *International Studies Quarterly* 55 859–82

Browder G and Ortolano L 2000 Evolution of an international water resources management regime in the Mekong river basin *Natural Resources Journal* 40 499

Calmant S, Seyler F and Cretaux J F 2008 Monitoring continental surface waters by satellite altimetry *Surveys in Geophysics* 29 247–69

Campbell I C 2007 Perceptions, data, and river management: lessons from the Mekong River *Water Resources Research* 43 W02407

Conway D 1997 A water balance model of the Upper Blue Nile in Ethiopia *Hydrological Sciences Journal* 42 265–86

Conway D 2000 The climate and hydrology of the Upper Blue Nile River *The Geographical Journal* 166 49–62

Conway D, Krol M, Alcamo J and Hulme M 1996 Future availability of water in Egypt: the interaction of global, regional, and basin scale driving forces in the Nile Basin *Ambio* 25 336–42

Dalby S 2013 The geopolitics of climate change *Political Geography* 37 38–47

De Landa M 2006 *A new philosophy of society: assemblage theory and social complexity* A&C Black Publishers, London

De Stefano L D, Duncan J, Dinar S, Stahl K, Strzepek K M and Wolf A T 2012 Climate change and the institutional resilience of international river basins *Journal of Peace Research* 49 193–209

De Stefano L, Edwards P, de Silva L and Wolf A T 2010 Tracking cooperation and conflict in international basins: historic and recent trends *Water Policy* 12 871–84

Dinar A, Blankespoor B, Dinar S and Kurukulasuriya P 2010 Does precipitation and runoff variability affect treaty cooperation between states sharing international bilateral rivers? *Ecological Economics* 69 2568–81

Dinar S, Dinar A and Kurukulasuriya P 2011 Scarcity and cooperation along international rivers: an empirical assessment of bilateral treaties *International Studies Quarterly* 55 809–33

Dore J and Lebel L 2010 Deliberation and scale in Mekong Region water governance *Environmental Management* 46 60–80

Dulal H B 2014 Governing climate change adaptation in the Ganges basin: assessing needs and capacities *International Journal of Sustainable Development & World Ecology* 21

Durand M, Andreadis K M, Alsdorf D E, Lettenmaier D P, Moller D and Wilson M 2008 Estimation of bathymetric depth and slope from data assimilation of swath altimetry into a hydrodynamic model *Geophysical Research Letters* 35

Durand M, Fu L-L, Lettenmaier D P, Als D E, Rodriguez E and Esteban-Fernandez D 2010 The Surface Water and Ocean Topography Mission: Observing Terrestrial Surface Water and Oceanic Submesoscale Eddies *Proceedings of the IEEE* 98 766–79

Espey M and Towfique B 2004 International bilateral water treaty formation *Water Resources Research* 40 W05S05

Ferguson R I 1986 Hydraulics and hydraulic geometry *Progress in Physical Geography* 10 1–31

Giordano M, Giordano M and Wolf A 2002 The geography of water conflict and cooperation: internal pressures and international manifestations *The Geographical Journal* 168 293–312

Gleason C J and Smith L C 2014 Toward global mapping of river discharge using satellite images and at-many-stations hydraulic geometry *Proceedings of the National Academy of Sciences* 111 4788–91

Gleason C J, Smith L C, and Lee J 2014 Retrieval of river discharge solely from satellite imagery and at-many-stations hydraulic geometry: sensitivity to river form and optimization parameters *Water Resources Research* 50 9604–19

Gleason C J and Wang J 2015 Theoretical basis for at-many-stations hydraulic geometry (AMHG). *Geophysical Research Letters* 42 doi:10.1002/2015GL064935

Gleick P H 1993 Water and conflict: fresh water resources and international security *International Security* 18 79–112

Goldman M 2005 *Imperial nature: the World Bank and struggles for social justice in the age of globalization* Yale University Press, New Haven, CT

Goulden M, Conway D and Persechino A 2009 Adaptation to climate change in international river basins in Africa: a review *Hydrological Sciences Journal* 54 805–28

Haddeland I, Lettenmaier D P and Skaugen T 2006 Effects of irrigation on the water and energy balances of the Colorado and Mekong river basins *Journal of Hydrology* 324 210–23

Harris L and Hazen H D 2006 Power of maps: (counter) mapping for conservation *ACME: An International E-Journal for Critical Geographies* 4 99–130

Heatherington T 2012 The changing terrain of environmentality: EIONET and the new landscapes of Europe *Anthropological Quarterly* 85 555–79

Hirsch P 2010 The changing political dynamics of dam building on the Mekong *Water Alternatives* 3 312–23

Ho S 2014 River politics: China's policies in the Mekong and the Brahmaputra in comparative perspective *Journal of Contemporary China* 23 1–20

Hossain F 2006 Towards formulation of a space-borne system for early warning of floods: can cost-effectiveness outweigh prediction uncertainty? *Natural Hazards* 37 263–76

Hossain F and Katiyar N 2006 Improving flood forecasting in international river basins *Eos, Transactions American Geophysical Union* 87 49–54

Hossain F, Katiyar N, Hong Y and Wolf A 2007 The emerging role of satellite rainfall data in improving the hydro-political situation of flood monitoring in the under-developed regions of the world *Natural Hazards* 43 199–210

Islam M R, Begum S F, Yamaguchi Y and Ogawa K 1999 The Ganges and Brahmaputra rivers in Bangladesh: basin denudation and sedimentation *Hydrological Processes* 13 2907–23

Jacobs J W 1995 Mekong Committee history and lessons for river basin development *The Geographical Journal* 161 135–48

Jacobs J W 2002 The Mekong River Commission: transboundary water resources planning and regional security *The Geographical Journal* 168 354–64

Jeuland M, Harshadeep N, Escurra J, Blackmore D and Sadoff C 2013 Implications of climate change for water resources development in the Ganges basin *Water Policy* 15 26–50

Jian J, Webster P J and Hoyos C D 2009 Large-scale controls on Ganges and Brahmaputra river discharge on intraseasonal and seasonal time-scales *Quarterly Journal of the Royal Meteorological Society* 135 353–70

Kite G 2001 Modelling the Mekong: hydrological simulation for environmental impact studies *Journal of Hydrology* 253 1–13

Kummu M and Sarkkula J 2008 Impact of the Mekong River flow alteration on the Tonle Sap flood pulse *AMBIO: A Journal of the Human Environment* 37 185–92

Lebel L, Garden P and Imamura M 2005 The politics of scale position and place in the governance of water resources in the Mekong region *Ecology and Society* 10

Lee Z, Carder K L, Mobley C D, Steward R G and Patch J S 1999 Hyperspectral remote sensing for shallow waters. 2. Deriving bottom depths and water properties by optimization *Applied Optics* 38 3831

Legleiter C J, Roberts D A and Lawrence R L 2009 Spectrally based remote sensing of river bathymetry *Earth Surface Processes and Landforms* 34 1039–59

Leopold L B and Maddock T 1953 The hydraulic geometry of stream channels and some physiographic implications United States Geological Survey Professional Paper 252

Lu X X and Siew R Y 2006 Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams *Hydrology and Earth Systems Science* 10 181–95

Lyzenga D R 1978 Passive remote sensing techniques for mapping water depth and bottom features *Applied Optics* 17 379

Mann M 1984 The autonomous power of the state: its origins, mechanisms and results *European Journal of Sociology* 25 185–213

Mann M 2008 Infrastructural power revisited *Studies in Comparative International Development* 43 355–65

Masviriyakul S 2004 Sino-Thai strategic economic development in the Greater Mekong subregion (1992–2003) *Contemporary Southeast Asia* 26 302–19

McCarthy J 2007 States of nature: theorizing the state in environmental governance *Review of International Political Economy* 14 176–94

McNally A, Magee D and Wolf A T 2009 Hydropower and sustainability: resilience and vulnerability in China's powersheds *Journal of Environmental Management* 90(Suppl 3) S286–93

Meehan K M 2014 Tool-Power: water infrastructure as wellsprings of state power *Geoforum* 57 215–24

Mitchell T 2002 *Rule of experts: Egypt, techno-politics, modernity* University of California Press, Berkeley CA

Moffitt C B, Hossain F, Adler R F, Yilmaz K K and Pierce H F 2011 Validation of a TRMM-based global flood detection system in Bangladesh *International Journal of Applied Earth Observation and Geoinformation* 13 165–77

Nathanson M, Kean J W, Grabs T J, Seibert J, Laudon H and Lyon S W 2012 Modelling rating curves using remotely sensed LiDAR data *Hydrological Processes* 26 1427–34

Nishat B and Rahman S M M 2009 Water resources modeling of the Ganges–Brahmaputra–Meghna river basins using satellite remote sensing data *JAWRA Journal of the American Water Resources Association* 45 1313–27

Painter J 2006 Prosaic geographies of stateness *Political Geography* 25 752–74

Pavelsky T M, Durand M T, Andreadis K M, Beighley R E, Paiva R C D, Allen G H and Miller Z F 2014 Assessing the potential global extent of SWOT river discharge observations *Journal of Hydrology* 519 Part B 1516–25

Phadke R 2002 Assessing water scarcity and watershed development in Maharashtra, India: a case study of the Baliraja Memorial Dam *Science, Technology & Human Values* 27 236–61

Rasul G 2014 Why Eastern Himalayan countries should cooperate in transboundary water resource management *Water Policy* 16 19–38

Rocheleau D 1995 Maps, numbers, text, and context: mixing methods in feminist political ecology *The Professional Geographer* 47 458–66

Richards K S 1973 Hydraulic geometry and channel roughness – nonlinear system *American Journal of Science* 273 877–96

Sandstrom P, Pahlén T G, Edenius L, Tommervik H, Hagner O, Hemberg L, Olsson H, Baer K, Stenlund T, Brandt L G and Egberth M 2003 Conflict resolution by participatory management: remote sensing and GIS as tools for communicating land-use needs for reindeer herding in northern Sweden *Ambio* 32 557–67

Sarma J N 2005 Fluvial process and morphology of the Brahmaputra River in Assam, India *Geomorphology* 70 226–56

Scott J 1999 *Seeing like a state: how certain schemes to improve the human condition have failed* Yale University Press, New Haven, CT

Smith L C 1997 Satellite remote sensing of river inundation area, stage, and discharge: a review *Hydrological Processes* 11 1427–39

Smith L C, Isacks B L, Bloom A L and Murray A B 1996 Estimation of discharge from three braided rivers using synthetic aperture radar satellite imagery: potential application to ungaged basins *Water Resources Research* 32 2021–34

Smith L C and Pavelsky T M 2008 Estimation of river discharge, propagation speed, and hydraulic geometry from space: Lena River, Siberia *Water Resources Research* 44

Sneddon C 2012 The 'sinew of development': Cold War geopolitics, technical expertise, and water resource development in Southeast Asia, 1954–1975 *Social Studies of Science* 42 564–90

Sneddon C and Fox C 2006 Rethinking transboundary waters: a critical hydropolitics of the Mekong basin *Political Geography* 25 181–202

Sneddon C and Fox C 2011 The Cold War, the US Bureau of Reclamation, and the technopolitics of river basin development, 1950–1970 *Political Geography* 30 450–60

Sneddon C and Fox C 2012 Water, geopolitics, and economic development in the conceptualization of a region *Eurasian Geography and Economics* 53 143–60

Swain A 2011 Challenges for water sharing in the Nile basin: changing geo-politics and changing climate *Hydrological Sciences Journal* 56 687–702

Ta T K O, Nguyen V L, Tateishi M, Kobayashi I, Tanabe S and Saito Y 2002 Holocene delta evolution and sediment discharge of the Mekong River, southern Vietnam *Quaternary Science Reviews* 21 1807–19

Tarpanelli A, Brocca L, Lacava T, Melone F, Moramarco T, Faruolo M, Pergola N and Tramutoli V 2013 Toward the estimation of river discharge variations using MODIS data in ungauged basins *Remote Sensing of Environment* 136 47–55

Uprety K and Salman S M A 2011 Legal aspects of sharing and management of transboundary waters in South Asia: preventing conflicts and promoting cooperation *Hydrological Sciences Journal* 56 641–61

Vaidyanathan G 2011 Dam controversy: remaking the Mekong *Nature News* 478 305–7

Wolf A T 2007 Shared waters: conflict and cooperation *Annual Review of Environment and Resources* 32 241–69

Yoffe S, Fiske G, Giordano M, Giordano M, Larson K, Stahl K and Wolf A T 2004 Geography of international water conflict and cooperation: Data sets and applications *Water Resources Research* 40 W05S04

Yoffe S, Wolf A T and Giordano M 2003 Conflict and cooperation over international freshwater resources: indicators of basins at risk *JAWRA Journal of the American Water Resources Association* 39 1109–26

Zeitoun M and Allan T 2008 Applying hegemony and power theory to transboundary water analysis *Water Policy* 10 3–12

Zeitoun M and Warner J 2006 Hydro-hegemony – a framework for analysis of trans-boundary water conflicts *Water Policy* 8 435

Ziv G, Baran E, Nam S, Rodríguez-Iturbe I and Levin S A 2012 Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin *Proceedings of the National Academy of Sciences* 109 5609–14