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1. Introduction

For regions where water resources derived from snow and glacier melt are a subject of intense disputes and potential conflict, we present the distinction between methods of snowmelt runoff modeling and water resource accounting. Whereas conceptual and physically-based hydrologic models have been developed to estimate the contribution of melt water from mountain snowpack for water resource management (e.g. irrigation supply and hydropower potential), refined water accounting methods designed for dispute arbitration are currently lacking. We discuss the exemplary case of contemporary disputes between India and Pakistan over the snowmelt-derived water resources of the Upper Indus Basin (UIB) in support of a future research agenda to develop robust water balance accounting methods applicable to regional or international dispute mitigation.

Both Pakistan and India are highly dependent on water from melting snow and glacier ice originating in the mountain ranges of the UIB (namely, from west to east, the Hindukush, Karakoram, Ladakh and Greater Himalaya). The agriculture-based economy of Pakistan relies on this supply for irrigating its arid lowlands (Archer et al., 2010). India maintains an equivalent dependence on Himalayan-fed streamflow for the agricultural, industrial and hydropower demands of its expanding economy and population (Patz et al., 2009).

Territorial and water disputes have been endemic to relations between India and Pakistan since the partition of British India in 1947. State boundaries were drawn with little consideration for natural watershed boundaries, which quickly led to conflicts over water resources (Patz et al., 2009). Specifically, the headwaters of the Indus River and some of its major tributaries are entirely upstream from Pakistan, predominantly in India. Substantial portions of the UIB are within the disputed territories of Jammu and Kashmir. While the negotiated Indus Water Treaty of 1960 has had notable success managing transboundary water resources, disputes over treaty interpretation remain, with a number of current issues being particularly contentious.

The recent article "Unquenchable thirst" in *The Economist* highlights the controversies that have surrounded the construction of the Baglihar dam on the Chenab River (allocated to Pakistan by the Indus Water Treaty) in India-administered Jammu and Kashmir, noting that "Pakistanis cite it as typical of an intensifying Indian threat to their existence, a conspiracy to divert, withhold or misuse precious water that is rightfully theirs" (2011, p. 27). For its part, India argues that Baglihar is simply a run-of-the-river dam, temporarily delaying but not consuming the volume of water allocated to Pakistan. This particular conflict underscores the important distinction between water runoff modeling and water resource accounting. While extant runoff models are able to estimate basin discharge from available data, they remain inherently limited in their ability to account for the net water balance within the basin. In other words, runoff models are well suited for solving problems concerning estimated water supply for irrigation, consumption and hydropower, but are far less suited for handling issues centered on water diversion, storage and withholding. With several hundred dam projects presently under consideration along rivers of the Himalaya and trans-Himalaya ranges (Dharmadhikary, 2009), there is an immediate need for a hydrological modeling framework to manage impending issues of water accountability.

Compounding the historical rivalries between India and Pakistan (including three wars since the partition of British India) are an array of interrelated hydrological concerns, including expanding demands for water under population growth, urbanization, industrialization, increased reliance on irrigated agriculture, and uncertain future water resources under changing climate (Patz et al., 2009). The potential for crisis and conflict surrounding water disputes between India and Pakistan cannot be overstated and is presented in depth by Patz et al. (2009) and Wirsing and Jasparro (2007). Before presenting a research agenda that addresses this critical problem, we briefly review snowmelt runoff modeling, its limitations, and recent literature from applications to basins within the UIB.

2. Snowmelt model applications and limitations

Numerous conceptual and physically-based snowmelt runoff models have been tested worldwide, assessing their capacities to estimate meltwater discharge from mountain snowpack and glaciers. The choice of model follows from application objectives and available input data. Conceptual models have been favored for use in Himalayan catchments given the region's lack of dense meteorological and gauging station networks, plus the difficulties of obtaining the extensive field observations required by physical models over inaccessible terrain. The Snowmelt Runoff Model (SRM; also known as the Martinec-Rango model) has proven favorable for Himalayan applications due to its weaker sensitivity to the precipitation forcing and greater sensitivity to the snow-covered area and temperature inputs (Tahir et al., 2011), and due to the fact that model parameter calibration is not required (Martinec et al., 2008). SRM accuracy is assessed by the difference of volume (D_v in %) and Nash-Sutcliffe (*NS)* coefficient statistics (Martinec et al., 2008).

SRM has been applied to numerous river basins in the Himalaya, as of Martinec et al. (2008). Since then, a surge of additional studies has explored the use of SRM in the Hindukush and Karakoram (i.e. trans-Himalayan) ranges of northern Pakistan with MODIS remote sensing data as input for snow-covered area (Bashir and Rasul, 2010; Tahir et al., 2011; Dahri et al., 2011; Butt and Bilal, 2011). Statistically, SRM model results have been very promising. For example, Tahir et al. (2011) employ the current version of the Snowmelt Runoff Model (WinSRM 1.12) for discharge simulation of the Hunza River Basin of the Karakoram Range in northern Pakistan. Annual D_v ranged from −4.8% (discharge volume is underestimated) to 12% (discharge volume is overestimated) over three model validation years. For the snowmelt period (April-September), D_v ranged from −0.3% to 9%. Corresponding Nash-Sutcliffe (*NS)* coefficients over both time frames ranged from 0.78 to 0.97.

In the present context, the SRM equation can be conceptually rendered as

$$Q_{n+1} = f(T_n, P_n, S_n) + Q_n + \varepsilon_n$$

where Q is daily discharge (m^3/s) at the daily time step n; T, P, and S are daily model input variables of accumulated degree-days, precipitation, and snow-covered area, respectively; and ε is the residual term representing the physical processes not accounted for by SRM. Basin-specific parameters must also be established, but do not require calibration from historical data. The presence of an error term is implicit in any hydrologic model; however, in the UIB, this error term represents more than a measure of model accuracy. It represents a volume of water that is in a sense “missing,” a fact that has substantial economic and political implications for two countries historically at odds and both heavily reliant on water resources from mountain catchments. A more refined understanding of this term is necessary in a region where disputes or conflict can arise when water cannot be accounted for.

3. Future research objectives

Recent research has highlighted the applicability of snowmelt runoff models such as SRM for resource management purposes, but has not presented a methodological framework and agenda for addressing water dispute mitigation. Tahir et al. (2011) mention an agenda for applying SRM to additional catchments in the UIB, with the goals of water resource management for the larger-scale Indus Basin Irrigation System and evaluation of future climate impacts for the region. However, based on the abundance of prior research in the domain of SRM testing and assessment, the results of such studies will remain constrained by the same model limitations previously discovered. We propose a future research agenda that extends beyond continued SRM testing in the region, exploring the geographic variability of this model’s error term and establishing a metric describing ranges of acceptable modeling error. Ultimately, a complete water resources accounting framework for addressing water disputes may be possible, involving both the physical hydrological processes and the policies and regulations governing the UIB. We constrain the following discussion to those hydrological contributions pertaining to snowmelt runoff needed for such a framework.

A reasonable starting point for this task is a comparative assessment of all snowmelt runoff applications to date from the Upper Indus Basin. Following such an assessment, the subjective selection of a viable model (including requisite source data and parameter selection methods) can be made, establishing parity for subsequent analysis of modeling error. Such a selection is not meant to preclude development and testing of new or refined models for operational or resource management purposes, but rather is based on the current need for a water accounting framework grounded in an established, well-tested and logistically manageable snowmelt runoff methodology. Based on previous statements herein, SRM seems a likely candidate for this purpose and we refer to its usage in the continued discussion.

Next, the performance of SRM must be assessed in the context of varying climate regimes. The different climate regimes throughout the UIB have been well documented (Fowler and Archer, 2006; Thayyen and Gergan, 2010). These regimes are predominantly a function of a basin's geographic siting relative to continental westerly versus tropical monsoon atmospheric circulations. Thayyen and Gergan (2010) identify three distinct glacio-hydrological regimes within the UIB alone, namely: Alpine (Karakoram Range), Cold-Arid (Ladakh Range), and "Himalayan catchment" (Greater Himalaya). Fowler and Archer (2006) observe reduced ablation and increased accumulation of Karakoram glaciers over the second half of the 20th century, in contrast with widespread glacial retreat and decay in the Eastern (Greater) Himalaya. An analysis of SRM accuracy in the context of such regimes has, to our knowledge, not been conducted, and may well shed light on the regional processes contributing to error and uncertainty associated with SRM.

Recent studies present possible explanations of such processes not captured by SRM. Immerzeel et al. (2009) apply SRM to the entire Upper Indus Basin—including the Hunza, Gilgat, Shigar and Shyok sub-basins—and find that streamflow is realistically simulated by SRM ($NS = 0.78$, $D_v = -2\%$). However, they observe that average annual precipitation over a five year period is less than observed streamflow. Noting observed regional warming, Immerzeel et al. (2009) suggest accelerated glacial melting as a logical source of the additional runoff volume. Given the decreased model efficiency of SRM during extreme events (July-August) in the Hunza River Basin, Tahir et al. (2011) also suggest glacial melt contributions as sources of runoff not accounted for by SRM.

To the extent that glacial storage of water (e.g. in snow, firn, ice and liquid forms) is not handled well by current conceptual or mathematical models (Jansson, 2003), glacial contributions to runoff are a reasonable source for modeling error. This is particularly relevant to SRM, where melt dynamics are primarily focused on the surface-air interface through the temperature and snow-covered area inputs. Storage of liquid water in the glacial system over various time scales is presented in depth by Jansson (2003). Additional hydrologic processes not directly captured by SRM include water loss to the atmosphere through sublimation, uncertain lag times and attenuation related to below ground transportation pathways, and the influence of solar radiation (Bookhagen and Burbank, 2010). Bookhagen and Burbank (2010) note the particular importance of the solar radiation factor in low latitude, high elevation sites such as the Himalaya, as it allows for meltwater generation below the freezing point.

Hock et al. (2005) note that, compared to glacier mass balance and glacier size variations under changing climate, far less attention has been given to glacier discharge. Moreover, they observe that very few glaciers are subject to simultaneous mass balance and discharge monitoring. Hewitt (2011) reviews reconstructed terminus fluctuations among major Karakoram glaciers, observing chaotic development, with advances and retreats frequently out of phase with one another. These observations confirm the limitation of SRM in glacial regions, since the snow-covered area input variable will usually be positively correlated with glacier mass balance and extent.

The culmination of past and contemporary research must be a statement of snowmelt runoff uncertainty informed by results from SRM applications and known components of its error term. From these, a metric describing ranges of acceptable error may be possible for incorporation into water dispute mitigation efforts. This proposed research objective is not for quantitative reconciliation of the error term to achieve an improbable (or impossible) complete accounting of water through SRM. Rather, the purpose is to obtain a thorough identification and functional representation of those hydrologic processes occurring regionally and not captured by SRM.

4. Conclusion

Conceptual snowmelt runoff models such as SRM provide a valuable resource for estimating basin runoff and thus informing water resource management decisions throughout the Upper Indus Basin. SRM's most sensitive input variables are an accumulated degree-day temperature index and snow-covered area (Tahir et al., 2011), both of which can be reliably obtained from available datasets and remote sensing imagery, respectively. Physically-based distributed models are probably not viable for the vast expanses of remote, high altitude ranges between the Hindukush and Greater Himalaya where extensive field observations are impractical.

In order to mitigate present and future water disputes between India and Pakistan, we suggest development of an accounting-oriented framework for viewing water resources of the UIB informed by conceptual models and augmented by quantitative analysis of model residuals and thus a metric for acceptable ranges of water balance uncertainty. This proposed agenda reflects the distinction between managing water supply for irrigation, consumption and hydropower versus managing disputes centered on water diversion, storage and withholding. The potential for crisis and conflict surrounding water disputes in this region justifies undertaking this difficult task. While it is unlikely that such work will eliminate water disputes between Pakistan and India, their mitigation through neutral arbitration by the international community can benefit greatly from the refined hydrological insights advanced by this research agenda.

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