

1 **Snowmelt runoff modeling: Limitations and potential for mitigating**
2 **water disputes**

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27 1. Introduction

28

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

39

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

46

47 Territorial and water disputes have been endemic to relations between India and Pakistan since
48 the partition of British India in 1947. State boundaries were drawn with little consideration for

49 natural watershed boundaries, which quickly led to conflicts over water resources (Patz et al.,
50 2009). Specifically, the headwaters of the Indus River and some of its major tributaries are
51 entirely upstream from Pakistan, predominantly in India. Substantial portions of the UIB are
52 within the disputed territories of Jammu and Kashmir. While the negotiated Indus Water Treaty
53 of 1960 has had notable success managing transboundary water resources, disputes over treaty
54 interpretation remain, with a number of current issues being particularly contentious.

55
56 The recent article “Unquenchable thirst” in *The Economist* highlights the controversies that have
57 surrounded the construction of the Baglihar dam on the Chenab River (allocated to Pakistan by
58 the Indus Water Treaty) in India-administered Jammu and Kashmir, noting that “Pakistanis cite it
59 as typical of an intensifying Indian threat to their existence, a conspiracy to divert, withhold or
60 misuse precious water that is rightfully theirs” (2011, p. 27). For its part, India argues that
61 Baglihar is simply a run-of-the-river dam, temporarily delaying but not consuming the volume of
62 water allocated to Pakistan. This particular conflict underscores the important distinction
63 between water runoff modeling and water resource accounting. While extant runoff models are
64 able to estimate basin discharge from available data, they remain inherently limited in their
65 ability to account for the net water balance within the basin. In other words, runoff models are
66 well suited for solving problems concerning estimated water supply for irrigation, consumption
67 and hydropower, but are far less suited for handling issues centered on water diversion, storage
68 and withholding. With several hundred dam projects presently under consideration along rivers
69 of the Himalaya and trans-Himalaya ranges (Dharmadhikary, 2009), there is an immediate need
70 for a hydrological modeling framework to manage impending issues of water accountability.

71 Compounding the historical rivalries between India and Pakistan (including three wars since the
72 partition of British India) are an array of interrelated hydrological concerns, including expanding
73 demands for water under population growth, urbanization, industrialization, increased reliance
74 on irrigated agriculture, and uncertain future water resources under changing climate (Patz et al.,
75 2009). The potential for crisis and conflict surrounding water disputes between India and
76 Pakistan cannot be overstated and is presented in depth by Patz et al. (2009) and Wirsing and
77 Jasparro (2007). Before presenting a research agenda that addresses this critical problem, we
78 briefly review snowmelt runoff modeling, its limitations, and recent literature from applications
79 to basins within the UIB.

80

81

82 2. Snowmelt model applications and limitations

83

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

94 assessed by the difference of volume (D_v in %) and Nash-Sutcliffe (NS) coefficient statistics
95 (Martinec et al., 2008).
96
97 SRM has been applied to numerous river basins in the Himalaya, as of Martinec et al. (2008).
98 Since then, a surge of additional studies has explored the use of SRM in the Hindukush and
99 Karakoram (i.e. trans-Himalayan) ranges of northern Pakistan with MODIS remote sensing data
100 as input for snow-covered area (Bashir and Rasul, 2010; Tahir et al., 2011; Dahri et al., 2011;
101 Butt and Bilal, 2011). Statistically, SRM model results have been very promising. For example,
102 Tahir et al. (2011) employ the current version of the Snowmelt Runoff Model (WinSRM 1.12)
103 for discharge simulation of the Hunza River Basin of the Karakoram Range in northern Pakistan.
104 Annual D_v ranged from -4.8% (discharge volume is underestimated) to 12% (discharge volume
105 is overestimated) over three model validation years. For the snowmelt period (April-September),
106 D_v ranged from -0.3% to 9% . Corresponding Nash-Sutcliffe (NS) coefficients over both time
107 frames ranged from 0.78 to 0.97.

108
109 In the present context, the SRM equation can be conceptually rendered as

$$110 \quad Q_{n+1} = f(T_n, P_n, S_n) + Q_n + \varepsilon_n$$

111 where Q is daily discharge (m^3/s) at the daily time step n ; T , P , and S are daily model input
112 variables of accumulated degree-days, precipitation, and snow-covered area, respectively; and ε
113 is the residual term representing the physical processes not accounted for by SRM. Basin-
114 specific parameters must also be established, but do not require calibration from historical data.
115 The presence of an error term is implicit in any hydrologic model; however, in the UIB, this
116 error term represents more than a measure of model accuracy. It represents a volume of water

117 that is in a sense “missing,” a fact that has substantial economic and political implications for
118 two countries historically at odds and both heavily reliant on water resources from mountain
119 catchments. A more refined understanding of this term is necessary in a region where disputes
120 or conflict can arise when water cannot be accounted for.

121

122

123 3. Future research objectives

124

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

139

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

149

150 Next, the performance of SRM must be assessed in the context of varying climate regimes. The
151 different climate regimes throughout the UIB have been well documented (Fowler and Archer,
152 2006; Thayyen and Gergan, 2010). These regimes are predominantly a function of a basin's
153 geographic siting relative to continental westerly versus tropical monsoon atmospheric
154 circulations. Thayyen and Gergan (2010) identify three distinct glacio-hydrological regimes
155 within the UIB alone, namely: Alpine (Karakoram Range), Cold-Arid (Ladakh Range), and
156 "Himalayan catchment" (Greater Himalaya). Fowler and Archer (2006) observe reduced
157 ablation and increased accumulation of Karakoram glaciers over the second half of the 20th
158 century, in contrast with widespread glacial retreat and decay in the Eastern (Greater) Himalaya.
159 An analysis of SRM accuracy in the context of such regimes has, to our knowledge, not been
160 conducted, and may well shed light on the regional processes contributing to error and
161 uncertainty associated with SRM.

162

163 Recent studies present possible explanations of such processes not captured by SRM. Immerzeel
164 et al. (2009) apply SRM to the entire Upper Indus Basin—including the Hunza, Gilgat, Shigar
165 and Shyok sub-basins—and find that streamflow is realistically simulated by SRM ($NS = 0.78$,
166 $D_v = -2\%$). However, they observe that average annual precipitation over a five year period is
167 less than observed streamflow. Noting observed regional warming, Immerzeel et al. (2009)
168 suggest accelerated glacial melting as a logical source of the additional runoff volume. Given
169 the decreased model efficiency of SRM during extreme events (July-August) in the Hunza River
170 Basin, Tahir et al. (2011) also suggest glacial melt contributions as sources of runoff not
171 accounted for by SRM.

172
173 To the extent that glacial storage of water (e.g. in snow, firn, ice and liquid forms) is not handled
174 well by current conceptual or mathematical models (Jansson, 2003), glacial contributions to
175 runoff are a reasonable source for modeling error. This is particularly relevant to SRM, where
176 melt dynamics are primarily focused on the surface-air interface through the temperature and
177 snow-covered area inputs. Storage of liquid water in the glacial system over various time scales
178 is presented in depth by Jansson (2003). Additional hydrologic processes not directly captured
179 by SRM include water loss to the atmosphere through sublimation, uncertain lag times and
180 attenuation related to below ground transportation pathways, and the influence of solar radiation
181 (Bookhagen and Burbank, 2010). Bookhagen and Burbank (2010) note the particular importance
182 of the solar radiation factor in low latitude, high elevation sites such as the Himalaya, as it allows
183 for meltwater generation below the freezing point.

184

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

193
194 The culmination of past and contemporary research must be a statement of snowmelt runoff
195 uncertainty informed by results from SRM applications and known components of its error term.
196 From these, a metric describing ranges of acceptable error may be possible for incorporation into
197 water dispute mitigation efforts. This proposed research objective is not for quantitative
198 reconciliation of the error term to achieve an improbable (or impossible) complete accounting of
199 water through SRM. Rather, the purpose is to obtain a thorough identification and functional
200 representation of those hydrologic processes occurring regionally and not captured by SRM.

201

202

203 4. Conclusion

204

205 Conceptual snowmelt runoff models such as SRM provide a valuable resource for estimating
206 basin runoff and thus informing water resource management decisions throughout the Upper
207 Indus Basin. SRM's most sensitive input variables are an accumulated degree-day temperature

208 index and snow-covered area (Tahir et al., 2011), both of which can be reliably obtained from
209 available datasets and remote sensing imagery, respectively. Physically-based distributed
210 models are probably not viable for the vast expanses of remote, high altitude ranges between the
211 Hindukush and Greater Himalaya where extensive field observations are impractical.

212
213 In order to mitigate present and future water disputes between India and Pakistan, we suggest
214 development of an accounting-oriented framework for viewing water resources of the UIB
215 informed by conceptual models and augmented by quantitative analysis of model residuals and
216 thus a metric for acceptable ranges of water balance uncertainty. This proposed agenda reflects
217 the distinction between managing water supply for irrigation, consumption and hydropower
218 versus managing disputes centered on water diversion, storage and withholding. The potential
219 for crisis and conflict surrounding water disputes in this region justifies undertaking this difficult
220 task. While it is unlikely that such work will eliminate water disputes between Pakistan and
221 India, their mitigation through neutral arbitration by the international community can benefit
222 greatly from the refined hydrological insights advanced by this research agenda.

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