THE OROGRAPHIC GRADIENT OF RUNOFF IN THE NEPAL HIMALAYA

Donald Alford
1831 Poly Drive
Billings, Montana USA 59102
Dalford8@aol.com

Abstract

The hydrologic regime of Himalayan catchment basins is not well-defined. The lack of a basic understanding of runoff sources and timing in the rivers of South and Central Asia creates problems in resolving questions related to specific aspects of the importance of elements of the water budget cycle, such the current concern over the impact of the retreat of Himalayan glaciers on water supplies. As a result of a general unavailability of data describing the hydrology, climate and topography of the Himalayan catchment basins, application of hydrologic concepts and models developed for mountain catchments in Europe or North America is problematic. Initial definitions of this regime could be based on existing data describing streamflow, and topography from available maps. As a first approximation, spatial variations in streamflow formation have been calculated from published data as the product of the variation of specific runoff (depth/unit area) and surface area with altitude in the catchment basins of the Nepal Himalaya. This paper presents the results for 15 gauged catchments, together with some speculation in the significance of the concept and results.

Mean annual specific runoff for the rivers flowing from the Nepal Himalaya decreases with increasing mean basin altitude, ranging from maximum values of approximately 3000 mm at 1000 m, to values between 500 – 1000 mm at 5000m. This negative orographic gradient of runoff contrasts sharply with the positive gradient characterizing most mid-latitude mountain catchments in Europe and North America. A direct transfer of generally-accepted procedures in hydrologic modeling based on assumptions, concepts and procedures developed for the mountains of North America and Europe will require modification when applied to the catchments of the Himalaya as a result of the differences in meteorology, altitude and local relief.

I.   INTRODUCTION

It is generally recognized that the Himalaya mountain chain is a major source of the water in the rivers of South and Central Asia. (e.g., Rao, 1981; Sharma, 1983). . The primary input to the hydrologic regimes of Himalayan catchment basins is the summer monsoon, but the distribution of this input with the mountain topography, and the ensuing partitioning into the output components of runoff, storage and evaporation is understood, at best, in highly qualitative terms. This partitioning occurs as a result of the complex interaction among topography, geology, climate and, in some cases, water uses practices.

In recent years, compelling evidence has been presented (IPCC, 2007) that a major change in historical patterns of the global climate may be occurring.. Unfortunately, much of the debate over the significance of aspects of the IPCC data has been conducted as a political, rather than a scientific, debate . This may be particularly true of mountain hydrometeorology and glaciology. The IPCC data contain few data from mountain sites. To compensate for this lack, activists have pointed to the general retreat of mountain glaciers as indicators of the current climate trend. It has become conventional wisdom among many that mountain glaciers are the chief source of streamflow in many major rivers originating in mountain catchments. It has been suggested that the Indus, Ganges and Brahmaputra Rivers recievr as much as 80-90% of their total annual streamflow from glaciers, and will shrink to 5% of the present-day flow volume with the disappearance of the glaciers of the Himalaya within a few decades (e.g., Slavin and Mehra, 2008, Rees and Collins, 2008)).

II.   ASSUMPTIONS AND PROCEDURES

It is the primary assumption of this study that the dominant interaction determining the hydrologic characteristics of the majority of Himalayan catchment basins is between the extreme relief of the mountain catchments, and the summer monsoon. This interaction produces hydrologic environments ranging from low altitude tropical jungles to arctic deserts at the highest altitudes. Streamflow from the mountain catchment basins is composed of runoff from all these environments. .

The water budget equation (Eq 1) is a useful first approach to an analysis of many water resources problems. While it is rare to find data bases for each element in the equation for mountain catchments, data from stream-gauging stations is relatively common and serves as a useful first approximation for assessments of mass and energy exchange within the basin (e.g., Rasmussen and Tangborn, 1976; Miller, 1977).

$$Q_s = P - E_t +/- S \qquad\qquad (1)$$

Where:

Q_s = Specific Runoff, mm
P = Precipitation input, mm
E = Evaporation, transpiration or sublimation output, mm
S = Change in storage (either groundwater, or as snow/ice), as mm

Streamflow volumes, in m^3/s, are converted to mean annual specific runoff, Qs, mm:

$$Q_s = \frac{(Q_v * t)}{A} \qquad\qquad (2)$$

Where:

$Qs =$ Specific Runoff, mm
$Qv =$ Streamflow volume, m3/s
$A =$ area of gauged catchment basin above hydrometric station in km^2.
$t =$ time in seconds.

Total volume of runoff, Qvt, from 1) the gauged catchment basin, A1, 2) the basin above 5000 m, A2, and 3) the glaciers reported as being in the three major basin, A3

$$Qs * A1, A2, A3, \dots An = Qvt \qquad\qquad (3)$$

Where:

$Qvt =$ Total Runoff, milliom cubic meters
A1, A2, A3, …An = Area of gauged catchment basin

Runoff from the glacierized portions of any altitudinal belt containing glaciers or permanent snowfields will be:

$$Qvg = Ag * Qn \qquad\qquad (4)$$

Where:

$Qvg =$, Volume of glacier runoff component
$Qn =$ Net balance of glaciers in altitudinal belt
$Ag =$ Glacierized area of altitudinal belt

**Variation of Specific Runoff, mm
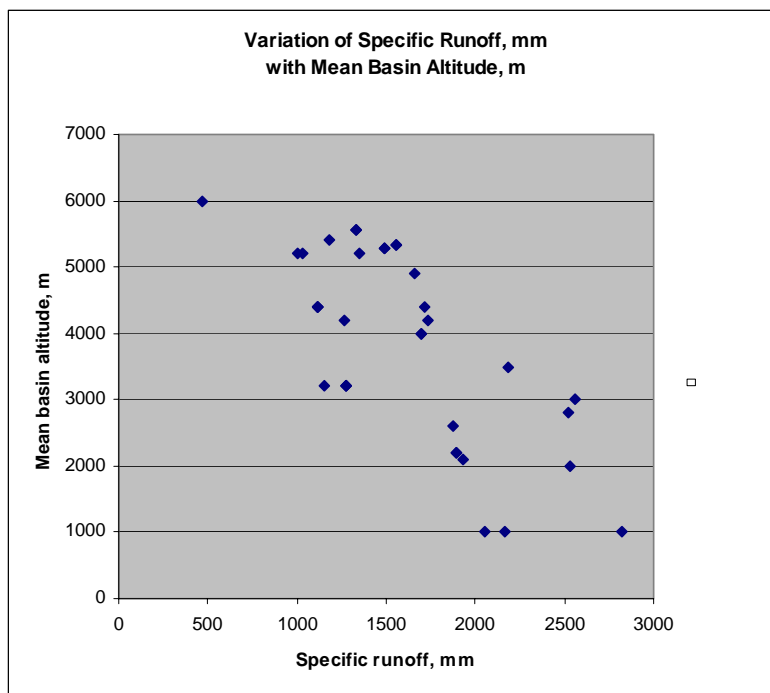with Mean Basin Altitude, m**

Figure 1. The relationship between mean annual specific runoff depths, mm, and mean catchment basin altitudes for gauged basins in the Nepal Himalaya. Although there is considerable scatter at lower altitudes, there is a definite negative gradient of runoff, above altitudes of approximately 2000 – 3000 m. Data from DIHM, 1976, 1977, 1989, Grabs, 1989; Alford, 1992.

III. RESULTS

In assessing the hydrologic regime of mountain ranges at the scale of the catchment basins, a logical starting point is to consider the relationship between the water budget and topography. The most dominant topographic characteristic of mountain catchments is altitude, and relief above the adjacent piedmont. Results of a comparison of the relationship between mean annual specific runoff, as measured at gauging stations maintained by the Nepal Department of Irrigation, Hydrology and Meteorology, with the mean altitude of the basin in which each gauging station is located for the catchment basins of the Nepal Himalaya are presented here. .

The most salient results of this study are presented primarily in graphical and tabular form.

Figure 1 is a plot of measured values of specific runoff with mean basin altitude shows a distinct negative gradient with increasing altitude, with values decreasing from a maximum near 3000 mm at the mean altitude of the lowest gauged basins to a value 0f 500 – 1000 mm at 6000 m. This range of values corresponds to the few glacier net values reported for the Himalaya in the literature (e.g., Bethier, et.al., 2007; Kulkarni, et. Al., 2004).   At the higher altitudes, above 5000 m, it is probable that all runoff is produced by snow and ice melt.

Table 1 shows the calculated variation of specific runoff with altitude for fifteen gauged catchment basins in the Nepal Himalaya. Values of specific runoff were taken from Figure 1 by visual inspection, and have an estimated error of plus/minus 500 mm

IV. Discussion

The proper planning, design and management of water resource development projects is dependent upon an understanding of the hydrological characteristics at the project site. Ideally, an analysis of site-specific hydrological characteristics of volume and variability should be based upon an extrapolation of data from gauging stations in settings similar to that of the project site.

At the present time, this is not generally possible for the catchment basins of the mountains of the Himalaya-Hindu Kush region.   For a variety of reasons – chief among which are a reluctance to share data among the countries of the region, and the general inaccessibility of many of the mountain catchment basins – there is a lack of information on which to base either regional or local, site-specific, hydrologic models and analyses.

If there is a genuine interest in developing a better understanding of the hydrology of the rivers of South and Central Asia, it is suggested that there are two related activities that will produce the most immediate benefits:

1. A general model of the hydrologic regime(s) of the mountains of the Himalaya-Hindu Kush region could be developed. Initially, this model should be empirical, based on the catchment basin as the basic unit, and should emphasize the relationship between water budgets, topography and climate.

2. A water atlas could be developed, based on existing maps and monitoring records. Of necessity, preparation of a water atlas would involve a collaborative effort among the riparian countries of South and central Asia. This atlas could list characteristics if the three major rivers of the region – the Indus, Ganges and Brahmaputra Rivers -

Development of a general model of the hydrologic regime(s) of the mountains of South and Central Asia at a scale consistent with the needs of planning and managing water resources development in the region will not be a simple undertaking. The mountain catchment basins of the region consist of a complex three-dimensional mosaic formed by the interaction of topography, meteorology, geology, and land use.   While these are the characteristic controls on the hydrology of all mountain catchments, the scale at which they operate in the mountains of Asia differs greatly in degree from those mountains where these interactions have been studied in depth, such as the European Alps. Two major differences are the total altitude of the Asian mountains , exceeding 8,000 m, and the fact that the upper 4000 m of these mountains has few permanent habitations or roads and is visited only by tourists and herdsmen, for the most part. Throughout the total altitudinal range present, the biophysical environments range from tropical jungles to arctic deserts, with corresponding variations in water and energy budgets.

There is a general lack of hydrological and climatological data on which to base empirical models, or against which to test most hypotheses. There is no history of collaboration among the riparian countries of the region in water resources studies. To date, there have been no serious attempts to develop hydrological models appropriate to the scale of the catchment basins of the mountains of the region. Given this background, it is suggested that the most realistic near-term approach to development of an understanding of the hydrologic regime(s) of the mountains of South and Central Asia could be based on existing hydrological and climatological data for the region. These data, consisting primarily of measurements of streamflow, air temperature, and precipitation at low to mid-altitude sites may be used to develop a preliminary assessment of lapse rates and orographic gradients for elementary property-process relationships controlling the mountain water budgets. This initial assessment may be used to identify additional data needs, or additional levels of sophistication that may used in the modeling efforts.   Until such initial steps are taken, development of the water resources of South and Central Asia will continue to be largely unplanned, and unmanaged.

Table 1
Calculated runoff from gauged catchment basins of the Nepal Himalaya.

Basin	Subbasin	ID #	Altitude Belt m	Area km^2	Qs mm	Qv m^3*10^6
Karnali	Karnali	240	0 - 3000	1460	1000	1460
			3000-5000	7680	1250	9600
			5000+	10420	500	5210
	calc			19560		16270
	meas					15926
Karnali	Seti	260	0-3000	3640	1000	3640
			3000-5000	2620	1250	3275
			5000+	3400	500	1700
	calc			9660		8615
	meas					9524
Karnali	Bheri	270	0-3000	1440	1000	1440
			3000-5000	7450	1250	9315
			5000+	3400	500	1700
	calc			12290		12455
	meas					13718
Narayani	Kali Gandaki	410	0-3000	2600	2000	5200
			3000-5000	2650	1500	3975
			5000+	1395	500	700
	calc			6645		9875
	meas					8420
Narayani	Seti Khola	430	0-3000	375	2000	750
			3000-5000	160	1500	270
			5000+	55	500	27
	calc			590		1047
	meas			582		1640
Narayani	Marsyangdi	439	0-3000	2375	2000	4750
			3000-5000	1170	1500	1720
			5000+	355	500	175
	meas			3900		6645
	calc					6686
Narayani	Chepe Khola	440	0-3000	200	2000	400
			3000-5000	80	1500	120
			5000+	70	500	35
						555
						757

Basin	Subbasin	ID #	Altitude Belt m	Area km^2	Qs mm	Qv m^3*10^6
Narayani	Buri Gandaki	445	0-3000	975	2000	1950
			3000-5000	1125	1500	1685
			5000+	2170	500	1080
					calc	4715
					meas	5046
Narayani	Trisuli	447	0-3000	420	3000	1260
			3000-5000	1240	2000	2480
			5000+	2450	1000	2450
					calc	6190
					meas	5456
SaptaKosi	Bhote Kosi	610	0-3000	300	3000	900
			3000-5000	470	2000	940
			5000+	1330	1000	1330
					calc	3170
					meas	2491
Sapta Kosi	Balephi Khola	620	0-3000	271	3000	813
			3000-5000	194	2000	388
			5000+	120	1000	120
						1321
						1671
Sapta Kosi	Sun Kosi	630	0-3000	1500	2000	3000
			3000-5000	460	1750	710
			5000+	140	500	70
						3780
						3753
Sapta Kosi	Tama Kosi	647	0-3000	600	3000	1800
			3000-5000	800	2000	1600
			5000_	1400	1000	1400
						4800
						4573

Basin	Subbasin	ID #	Altitude Belt M	Area km^2	Qs mm	Qv m^3*10^6
Sapta Kosi	Dudh Kosi	670	0-3000	1200	3000	3600
			3000-5000	750	2000	1500
			5000+	1500	1000	1500
						6600
						7033
Sapta Kosi	Likhu Khola	660	0-3000	370	3000	1120
			3000-5000	150	2000	300
			5000+	280	1000	280
	calc					1700
	meas			800	823	1798
Sapta Kosi	Tamur	690	0-3000	3400	2000	7800
			3000-5000	1050	1750	1750
			5000+	1200	500	600
				5650		10150
						10596
Sapta Kosi	Arun	604	0-3000	2400	3000	7200
			3000-5000	1200	2000	2400
			5000+	25000	250	6250
	calc					15850
	meas			28200	473	13340

Basin 1	Area, At 2	Area 3	Area, Ag 4	Ag/At 5	Qvt 6	Qs 7	Qv 8	Qs 9	Qvg 9	Qvg/Qvt 10
		5000+ m	Glaciers		Total		5000+ m	Glaciers	Glaciers	
	km2	km2	km2	%	mcm	mm	mcm	mm	mcm	%
Karnali	42890	15020	1740	4.1	47241	1101	7510	1000	1740	4
Narayani	31753	6785	2030	6.4	49385	1555	3393	1000	2030	4
Sapta Kosi	51440	33220	1409	2.7	48155	936	16610	1000	1409	3
Totals	126083	55025	5179	4.1	144781	1143	27513	1000	5179	4

Calculated Specific runoff (Qs) and Streamflow (Qv) from 5000 – 7000 Altitudinal Belt and from the Glacierized Area of this Belt (Qvg).. Glacierized area from WWF, 2005. Streamflow Data from: DIHM, 1976, 1977; 1986, Alford, 1992. (mcm = million cubic meters).

V. References

Alford, D., 1992, *Hydrologic Aspects of the Himalayan Region*, ICIMOD Occasional Paper 18, International Centre for Integrated Mountain Development, Kathmandu, Nepal, 68 pp.

Alford, D., 1985 *Mountain hydrologic systems*, Journal of Mountain Research and Development, Vol. 5, No. 4, pp. 349-363.

Bruijnzeel, L., and Bremmer, C., 1989, *Highland-Lowland Interactions in the Ganges Brahmaputra River Basin: A Review of Published Literature*, ICIMOD Occasional Paper 11, International Centre for Integrated Mountain Development, Kathmandu, Nepal, 135 pp.

Brthier, E., Arnaud, Y., Kumar, R., Ahmad, S., Wagnon, P., Chevalier, P., 2006, *Remote sensing estimates of glacier mass balances in the Himachal Pradesh (western Himalayan India)*. Institut de Recherche Pour le Development. Science Daily, March 28, 2007

DIHM, 1976, *Climatological Records of Nepal, 1964-1976*, Departmennt of Irrgation, Hydrology and Meteorology, HMG Ministry of Food, Agriculture and Irrigation, Kathmandu, Nepal.

DIHM, 1977, *Climatological Records of Nepal, Vol. 2*, Department of Irrigation, Hydrology and Meteorology, HMG Ministry of Food, Agriculture and Irrigation, Kathmandu, Nepal.

Grabs, Wolfgang., 1989, Personal; Communication, Kathmandu, Nepal.

IAHS, 1982, *Hydrological Aspects of Alpine and High-Mountain Areas*, International Association of Hydrological Sciences, Publication No. 138,

ICIMOD, 2001, *Glacial Lakes and Glacial Lake Outburst Floods*, International Centre for Integrated Mountain Development Profile MDS No. 2, Sep. 2001, Kathmandu, Nepal.

ICIMOD, 2007, *The Melting Himalayas*, International Centre for Integrated Mountain Research, Policy Summary, Kathmandu, Nepal

IPCC, Intergovernmental Panel on Climate Change,, 2007, *Climate Change 2007: Impacts, Adaptation and Vulnerability*, WMO/UNEP/UNESCO.

Iyngararasan M., Li, T., Shrestra, S., and Mool, P., 2002, *The challenges of mountain environments: water, natural resources, hazards, desertification and the implications of climate change*, Thematic Paper E1, Bishkek Global Mountain Summit.

Kulkarni, A., Rathore, B., and Suja, A., 2004, *Monitoring of glacial mass balance in the Baspa Basinusin accumulation area ratio*, Current Science, Vol. 86, No. 1, pp.. 185-186.

Miller, D., 1977 Water *at the Surface of the Earth: An Introduction to Ecosystem Hydrodynamics.* International Geophysics Series, Vol. 21. Academic Press, New York.

Rao, Y., 1981, *The Climate of the Indian Subcontinent,* In: World Survey of Climatology, Vol. 9, Ed. Takahashi, K., and Arakawa, H., Elsevier Scientific Publishing Co., Amsterdam.

Sharma, C., 1983, *Water and Energy Resources of the Himalayan Block*, Bishalnagar, Kathmandu, Nepal.

Rasmussen, N., and Tangborn, W., 1976 *Hydrology of the North Cascades region, Washington:1. Runoff, precipitation and storage characteristics*. Water Resources Research, 12(2):187-202.

Rees, G., and Collinx, D., 2004, *An assessment of the impacts of deglaciation on the water resources of the Himalaya*, Centre for Ecology and Hydrology, Crowmarch Gifford, Wallingford, Oxfordshire, OX10 *BB, UK.

Slavin, T., and Mehra, M., 2008, *Under the weather in India*, chinadialogue, February 21, 2008, London.

Tangborn, W., 1999, *A Mass Balance Model that Uses Low-altitude Meteorological Observations and the Area-Altitude Distribution of a Glacier,* Geografiska Annaler, Series A: Physical Geography 81 (4)..

Tangborn, W., 1984, Prediction of glacier-derived runoff for hydroelectric development, Geogr Ann. 66A(3), pp. 257-265.

Thompson, M., and Warburton, M, 1985, *Decision-making under contradictory certainties: How to save the Himalayas when you can't find out what's wrong with them,* Journal Applied Systems Analysis, Vol. 12, Hexenburg, Austria.

WGMS/MBB, 2003 *World Glacier Monitoring Service/Mass Balance Bulletin*, Dep't of geography, University of Zurich, Switzerland

WWF, 2005*, An Overview of Glaciers, Glacier Retreat and Subsequent Impacts in Nepal, India and China*, World Wildlife Fund, Nepal Program, Kathmandu, 70 pp.