Striving towards Assessment of Mountain Water Resources

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Abstract

A large portion of the earth's surface is covered by mountains, and an even higher portion of global water resources originates from mountainous areas. There is a consensus on the lack of knowledge of mountain water resources and the hydrology of mountainous areas on the global scale. There are a number of reasons for this, such as difficult access to numerous drainage basins, sparse settlement with limited services (electricity, telephones, etc), and harsh environments hindering the development of hydrological observations in many mountainous regions. These conditions make it difficult to install and to maintain instruments. Often a special, more expensive, design of heavy-duty instrument is needed which is capable of withstanding the harsh conditions. Field studies of water resources in the mountains are therefore far more difficult and demanding than most other hydrological activities.

Despite the recommendation of the World Meteorological Organization (1994), it is seen that hydrological networks in mountainous regions are less dense than elsewhere, and budgetary constraints have even led to the abandonment of hydrological stations - sometimes to the detriment of a long-term series of valuable observations. An additional problem in the assessment of mountain water resources is connected with the boundaries between countries. Remote sensing offers a considerable potential for studying the hydrology of mountainous areas. Because of difficult access and the expensive operation of hydrological stations, radar or satellite data are particularly appropriate, but of course ground-truth data are indispensable in the calibration and verification of remotely-sensed data. For research and operational needs, a systematic data collection network for measuring precipitation in mountainous areas is urgently required. It is of paramount importance to try to launch a GIS-supported assessment of fresh-water resources in mountain areas and to estimate the contribution of these areas to global water resources. It is also noted that the implementation of recommendations on data and information activities in Chapter 13 of the Agenda 21 (1992) devoted to managing fragile eco-systems, and in particular to ensuring sustainable mountain development, are to date practically non-existent.

Introduction

A large portion of the earth's surface is covered by mountains. As the mean altitude of the land area of the Globe is 875masl, it is no wonder that about 28 per cent of the land area rises above 1,000m. Yet the portion of global water resources originating from mountainous areas is thought to be significantly higher. Sources of all major rivers in the world are located in mountains. Mountains remain the dominating control factor in the flow of most major rivers for thousands of kilometres.

There is a consensus on the lack of knowledge of the hydrology of mountainous areas. As noted by Rodda (1994) in his paper 'Mountains - A Hydrological Paradox or Paradise,' although mountains are the source of the bulk of the water resources of the world, knowledge of mountain water resources is 'generally much less extensive, reliable and precise than for other physiographic regions'. Klemes (1990) has made a similar statement: 'Hydrology of mountainous areas is lagging behind many other areas of hydrological inquiry in proportion to its greater difficulty'.

Yet mountain hydrology is a challenge to researchers wishing to improve understanding of this hydrological paradox on which a plethora of challenging and rewarding hydrological studies can be undertaken. This backs Rodda's (1994) concept of a hydrological paradise.

The Special Hydrological Characteristics of Mountains

The particular structure and form of high mountains provide them with three important attributes.

a) Delayed runoff: There is a temporary storage of water in the form of snow and ice which provides delayed runoff. Snow cover building up in the higher mountains in winter produces snowmelt in spring and contributes a large volume of water to the discharges of rivers.
b) High hydropower potential: Huge amounts of potential energy are available that can be used to generate hydroelectricity. There are many countries in whch much of the national energy demand is covered by hydropower from mountainous areas.
c) Large volumes of natural and man-made storage: Man-made reservoirs in mountainous areas may be constructed for different purposes, such as flood protection (holding surplus water before it reaches the lowlands where it might otherwise cause catastrophic flooding), water supply, irrigation, water power, water quality (e.g., augmentation of low flows downstream), and recreation.

Mountains usually enjoy increased precipitation compared to the adjacent lowlands. One observes an increase of precipitation with elevation - the so-called orographic effect, which is present up to some maximum elevation, after which the tendency reverses.

The orographic effect can be caused by a number of mechanisms, and their relative importance depends on topography and storm type. Smith (1979) distinguished three principal orographic mechanisms, including convective instability (lifting of air as it flows over hills) and large-scale air-mass lifting over mountain ranges, which increases precipitation by both stratiform and convective mechanisms and entrainment of liquid water droplets near the ground (low-level growth).

Dunne and Leopold (1978) noted that in areas of uniform conditions, precipitation may increase uniformly with altitude. This property allows one to compile isohyetal maps in a straightforward way and to estimate the spatial average value of precipitation over a mountain region. The particular relationship they quoted shows a regular increase of over 300mm in annual precipitation per 500m difference in elevation. The incremental precipitation, corresponding to a one-metre increase of elevation, as described by other authors, is in the range of from a few hundredths to a few millimetres of the total annual precipitation.

However, in general, there is no one single universal relationship between precipitation and elevation, as a number of additional factors play a significant role. Very important is the location of the site considered with regard to the prevailing wind directions (leeward versus windward sides) and the sources of moisture, but topography, season, and type of storm have also to be taken into consideration.

How do other hydrological variables change with increasing elevation? Because instrument networks are generally not adequate, information on the spatial and temporal distributions of such variables as evaporation, solar radiation, soil moisture, overland flow, and erosion is usually rudimentary. However, hydrology provides some guidance, as does the pattern of vegetation. Values of evapotranspiration decrease while overland flow and erosion increase with elevation.

A unique feature of the mountain environment is the substantial cloud moisture input, augmenting the precipitation in the form of rain and snow. Considerable amounts of water are harvested from the atmospheric moisture in clouds in the forests of the humid tropics, over an area of some 500,000sq.km. This additional input of water is particularly important during days without rainfall.

A characteristic of mountain areas which adds to the difficulties of analysing data from them is the large heterogeneity of mountainous environments and the great spatial and temporal variability of hydrological signals. Dramatic changes may occur in slope angle, exposure, geology, and vegetation over a very local scale. One needs to carefully plan observations of processes and characteristics in a number of locations in order to assess the spatial averages meaningfully. This requires, first of all, a proper accounting of the spatial distribution of precipitation over mountainous areas, one that adequately aggregates largely differing windward and leeward values. Very high differences in annual precipitation totals are observed at the same elevation, especially between the high values on the windward side of the mountain range and the significantly lower values on the leeward side; for example, in north-western Scandinavia and the north-western and south-western Americas. Similarly, due to large temporal variability, with episodes of intense precipitation and flash floods, it is important to monitor such variables as rainfall and discharge either continuously or over short time intervals. Variations in solid precipitation from point to point are particularly large, but the measurement of solid precipitation is difficult and inaccurate. This is why the WMO has mounted an international comparison of methods of observation of solid precipitation.

There is very important natural storage in mountainous regions related to low-temperature effects (seasonal snow cover, glaciers, and ice sheets) and to karstic storage. However, if sufficient water storage capacity of the snow cover is not available, e.g., during a winter of little snow, the soil layer over the impervious bedrock is usually too thin to hold much moisture, and rainwater rapidly runs off, causing floods in locations downstream. Overland flow leading to soil erosion contributes to the degradation of watersheds by decreasing the already small capacity to hold water in the soil.

An important water-related environmental problem which affects mountainous areas has been colloquially called 'acid rain'. In mountainous areas with thin soil layers of low buffering capacity, acidic dry and wet depositions cause acidification of soils and waters. Acidification adversely affects soil biota that play an essential role in nutrient cycling. Inhibition of the activity of decomposition occurs. Air pollutants may alter plant responses to pathogens. Nutrient leaching spreads, impoverishing the soil and polluting recipient waters. Aluminium toxicity may grow. Inhibition of nutrient and water uptake by plants progresses, and nutrient and water stress may take place. Forest injury, damage, and even decline has been observed in a range of mountainous locations. They are particularly visible in areas with very high concentrations of air pollutants (e.g. in the Sudety Mountains, subject to emissions from the lignite-based power plants and industry of the bordering countries - Germany, Poland, and the Czech Republic - where the massive die-back of conifers has been observed.

Mountainous regions are very susceptible to water-related disasters. They are particularly flood-prone, owing to the increased orographic precipitation, steep slopes covered with thin soil over impervious bedrock (making for a high runoff coefficient), and limited valley storage. Consequently, the forecasting of precipitation and discharge are of utmost importance for mountainous regions. Apart from floods caused by intensive rainfall or snowmelt (or both), or rain-on-ice events, there are a number of non-meteorological causes of floods, as discussed by Starosolszky and Melder (1989). Glacier outbursts, avalanches, landslides, debris flows, ice jams, volcanic events, and earthquakes may lead to the damming of a river, or reduce the effective volume of a reservoir or a lake, or may cause overtopping of a dam and, in consequence, its breach. In all these cases, catastrophic flooding would occur.

An example of a relatively recent water-related disaster was a landslide which occurred in March 1993 in a mountainous region at La Josefina, some 25km north-east of Cuenca, in Ecuador (cf. Rodríguez Fiallos 1994). The landslide effectively dammed two rivers with a high volume (25 million m^3) of rocky material. The 'dam' was some 800m in length, 300m in width, and 120m in height. It existed for 32 days and caused flooding of 920ha of arable land, many factories, houses, roads, and bridges. The subsequent bursting of this dam, which held back some 175 million cubic metres of water, resulted in dam-break type flooding. The disaster took more than 300 human lives and caused material losses in excess of US$ 500 million. Figure 1 (Rodríguez Fiallos 1994) shows the orientation of the landslide and its consequences.

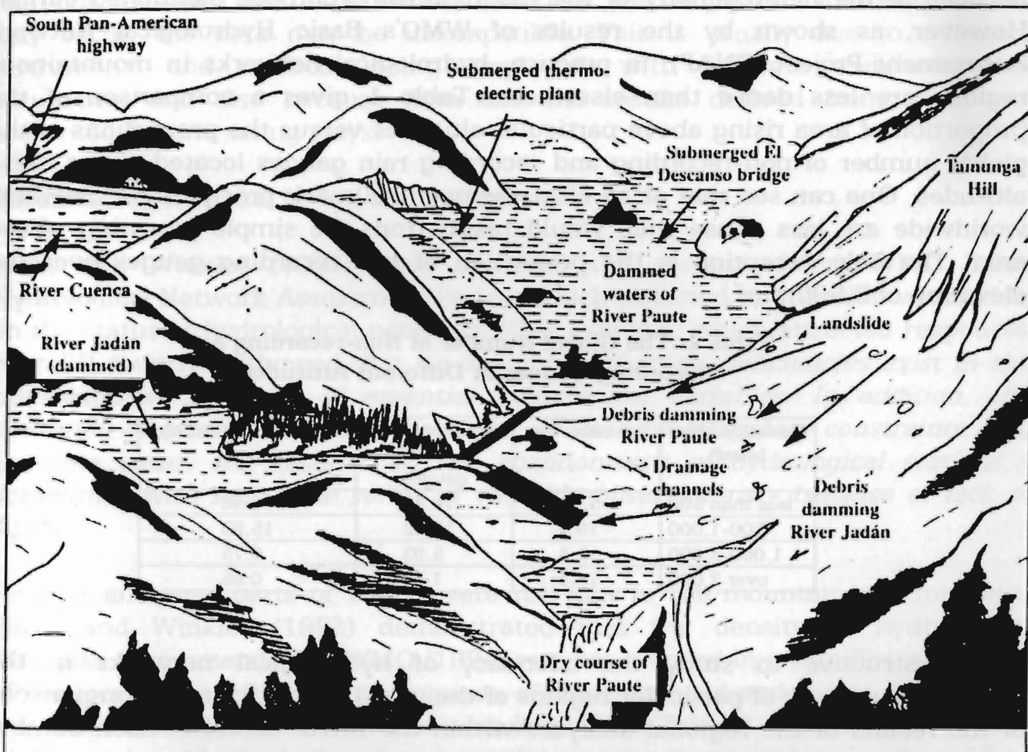

Fig. 1 Sketch of the Landslide at La Josefina (from Rodríguez Fiallos 1994)

Problems in Assessing the Water Resources of Mountainous Areas

There are a number of reasons for the lack of knowledge of mountain water resources on the global scale. Difficult access, sparse settlement with limited services, and the harsh environment hinder development of hydrological observations in many mountainous regions. These conditions combine to make it difficult to install and to maintain instruments. Often a special, more expensive, design of heavy-duty instrument is needed which is capable of withstanding the harsh conditions. These instruments need to function without regular maintenance and independent of an external energy source. Because hydrological variables range across several orders of magnitude, most sensors and methods of measurement have to be specially adapted. Field studies of water resources in the mountains are therefore far more difficult and demanding than most other hydrological activities. There are a number of examples in the literature of these problems and how they have been overcome. In one of these, the theoretical, technical, and management problems related to water level and discharge measurements under the difficult conditions presented by mountainous areas are discussed (Tilrem 1986).

WMO's Guide to Hydrological Practices (1994) recommends that observation networks in mountain regions should be denser than in most other areas. This is because of the heterogeneity of the mountain environment mentioned earlier. However, as shown by the results of WMO's Basic Hydrological Network Assessment Project (BNAP), in practice, hydrological networks in mountainous regions are less dense than elsewhere. Table 1 gives a comparison of the proportion of area rising above particular altitudes versus the proportions of the global number of non-recording and recording rain gauges located above these altitudes. One can see that at all altitudes over 500masl, precipitation networks worldwide are less dense than would result from the simple prorating of the area. The only exception is the proportion of non-recording gauges over the elevation of 2,500masl.

Table 1: The Global Number of Non-recording and Recording Gauges at Different Altitudes

Elevation class (masl)	Per cent Area	Per cent Non-recording gauges	Per cent Recording gauges
less than 500	52.7	76.85	76.56
500-1,000	19.5	15.42	15.93
1,000-2,000	15.4	5.93	6.75
over 2,000	12.3	1.75	0.65

It is instructive to study the adequacy of hydrological networks in the mountainous areas of particular regions of the world. Table 2 shows comparisons of the results of the regional analyses within the BNAP exercise. Each number given in the second and third column of Table 2 measures the proportion of the area of the region covered by mountains and the proportion of stage observation gauges located in mountainous areas, respectively. As the recommended density of observations in the mountains is higher than the average for other physiographic regions, the per cent values presented in the third column of Table 2 should be higher than those presented in the second column. However, in all regions, the density of hydrological networks in mountainous areas is lower than the average for all physiographic regions.

Table 2 : Proportion of Mountainous Areas (in %) and the Proportion of the Total Number of Stage Observations (in %) Located in Mountainous Areas for Particular WMO Regions

Region	Per cent Mountainous area	Per cent Mountain gauges
I Africa	16	13
II Asia	39	34
III South America	23	8
IV North and Central America	21	10
V South-West Pacific	26	0.3
VI Europe	22	8
World	22	10

An additional problem in the assessment of mountain water resources is related to the fact that mountainous regions may form frontiers between countries. Sometimes relations between nations on either side of a mountain frontier are quite hostile, and hence there is no willingness to cooperate. Data on water resources are classified and become an important strategic issue. But even if relations between the neighbouring countries are very good, another problem may occur: the data may be incompatible. This is usually due to different instruments and methods being employed, with different standards and accuracies, and also because data and the results derived from them are presented in contrasting ways.

Research, Operational Needs and Policy Issues

Perks and Winkler (1992) have analysed the results of the WMO Basic Hydrological Network Assessment Project which collected information worldwide on the status of hydrological networks. This exercise, which attracted responses from 50 countries, showed that '*in a number of areas, deficiencies exist in the observational networks of essential hydrological variables. In addition, the operation of existing networks has been affected by budgetary constraints and, in some cases, has resulted in the abandonment of hydrological stations - sometimes with long time series of valuable observations - because of lack of funds*'.

In their analyses, parts of which were relevant to the mountain environment, Perks and Winkler (1992) demonstrated that the density of hydrological networks recommended by WMO (1994) was not reached in a significant number of the locations analysed. A comparison of recommended and actual densities of hydrological networks in the mountains is given in Table 3. The number of sub-basins analysed in Table 3 varies, depending on the observed feature, from 52 to 110.

Table 3: Comparison of Recommended and Actual Densities of Hydrological Networks in the Mountain Environment (based on the results of Perks and Winkler 1992)

	Non-recording precipitation	Recording precipitation	Evaporation	Discharge	Sediment	Water quality
Recommended mean area per station (sq.km.)	250	2,050	50,000	1,000	6,700	20,000
Actual mean area per station (sq.km.)	3,879	4,548	11,406	3,261	5,567	5,839
Adequacy of the observatio- nal network	Grossly inadequate	Inadequate	Adequate	Inadequate	Adequate	Adequate, but...

Table 3 illustrates which types of hydrological observations are adequate and which are not. It clearly demonstrates that the actual densities of hydrological networks for precipitation and discharge are significantly lower than the values recommended by WMO (1994). This is astonishing as information on these two basic hydrological variables is indispensable for the assessment of water resources and for their design, planning, and management. However, even if, in average terms, the coverage of mountainous basins with evaporation and sediment observation stations is adequate, estimates of spatial averages are often acutely inadequate.

The number of mountainous basins studied in the BNAP Project (Perks and Winkler 1992) for which the WMO's recommended adequacy condition was not met is 74 per cent in the case of non-recording precipitation, 52 per cent for recording precipitation, 65 per cent for evaporation, 65 per cent for discharge, 58 per cent for sedimentation, and 8 per cent for water quality.

The apparent adequacy of the water quality network is somewhat misleading. It has to do with the less strict criteria for observations of water quality than for the other hydrological variables. Perks and Winkler (1992) consider that the recommended density for water quality networks is far too low. They propose replacing the existing value for the recommended area per station, of 20,000sq.km. by a new value of 3,000sq.km. They claim that the latter figure better reflects the growth of concern with water quality, and also the fact that mountains are not pristine, uninhabited areas any more. If the new threshold is used in Table 3, it becomes obvious that water quality is inadequately monitored in the mountains.

Remote sensing offers considerable potential for studying the hydrology of mountainous areas. Because of the difficult access and expensive operation of hydrological stations, radar or satellite data are particularly appropriate, but of course ground-truth data are indispensable in the calibration and verification of remotely-sensed data. Aerial and satellite surveys are useful in mapping snow lines. The wealth of observational material obtained by remote sensing can be integrated into models, such as snowmelt runoff models, considerably improving the forecast accuracy. Other high-tech developments, such as digital terrain models (DTM) using aerial photographs and satellite images, will play an increasingly important role in analysing the hydrology of mountainous regions.

Mountainous environment offers challenging opportunities (Rodda's 'hydrological paradise') to basic process studies of the hydrological cycle. There are a number of possible avenues to explore such as tracking the origin of moisture and examining flow paths (separation of hydrographs) and the transport of chemicals and particulates. An example of one challenging research area is the study of runoff from intertropical mountain glaciers. Ribstein et al. (1995) analysed a research basin in the Cordillera Real of Bolivia. They found that there was a recent and considerable retreat of the glacier because precipitation does not compensate for loss from melting. It is expected that high runoff may be associated with warm, dry periods during which much water is derived by melting of glaciers. Further, they noted that the most prominent events coincide with El Niño - Southern Oscillation (ENSO) phenomena.

The water resources of mountain areas are important in climate change studies. Information on the advance or retreat of mountainous glaciers is one of the basic indicators of climate change. Observing the natural forest boundaries and the distribution of ecotones, which can be driven by water-related factors, also plays a valuable role in climate change impact studies.

Summarising the research and operational needs, one can say that the creation of a systematic data collection network for measuring precipitation in mountainous areas is urgently required. Gathering data on the hydrology of different hillslope types under various precipitation patterns is recommended. Improvement of the hydrological monitoring of streams and rivers within mountains is necessary, in addition to the monitoring of the same rivers in the lowlands, which is done with far greater accuracy. Studies of processes are needed with an emphasis on field experiments. It is of paramount importance to launch a GIS-supported assessment of freshwater resources in mountain areas and to estimate the contribution of these areas to global water resources.

Challenges to Sustainable Development

It has been recognised that, since the early 1980s, data collection and analysis worldwide are not keeping pace with actual water development and management needs, not to mention the new demands being created by pressures for sustainable development. Hydrological observation networks are in decline. Despite the increasing demand for water and the growing water stress worldwide, calling for improved and scientifically-based water management, governments seem to be unable or unwilling to provide adequate funds for proper maintenance and operation of hydrological services.

When confronted with budgetary cuts, it is not standard practice to strive towards an optimal reduction of a network, one minimising information loss. It is not uncommon to eliminate an observation station which is difficult to access and expensive to run. Stations in mountainous areas usually suffer most because eliminating them provides the greatest savings.

Recommendations on data and information activities in Chapter 13 of Agenda 21 (1992) devoted to managing fragile ecosystems, and in particular to sustainable mountain development, read: *'governments at the appropriate level, with the support of the relevant international and regional organizations, should ... maintain and establish ... hydrological ... monitoring, analysis and capabilities that would ... encompass ... water distribution of various mountain regions of the world,... build an inventory of different forms of ... water use ... and ... identify hazardous areas that are most vulnerable to erosion, flood, landslides, earthquakes, snow avalanches and other natural hazards'*. Yet the practical results of implementation of these Agenda 21 recommendations are to date non-existent.

The rationale for performing an environmental impact assessment (EIA) is particularly valid in the case of mountainous areas, given their sensitive ecosystems. All major human interventions in the mountain environment require an EIA. Examples of cases where this need is particularly strong are: dams and reservoirs (aimed at flood protection, energy generation, water supply, etc) and other infrastructure - roads, industry and mining, and housing; further leisure and recreation activities; cultivation of marginal land versus abandonment of mountain agriculture (terraces); livestock grazing; logging forestry practices; and so on. Engineering projects, while contributing to economic growth, may cause adverse environmental consequences. Therefore sustainability issues are of the utmost importance.

Deforestation (caused by timber harvesting, forest die-back due to air pollution or wildfires) in steep catchments induces a dramatic increase in overland flow and material transport. The flood peaks are higher and arrive earlier (i.e., an increase in amplitude and shortened time to peak, of the unit hydrograph is observed), and progressive erosion leads to soil impoverishment, thus jeopardising any move towards sustainable development.

Environmental risk assessment in mountain areas should encompass assessment of natural hazards. That is, mapping of disaster-prone areas and evaluation of hazards is necessary. The next step is raising preparedness.

In order to solve the water-related problems arising from the sustainable development of mountainous areas, a broader social basis is required. Involving indigenous people in consultations and in the decision process is necessary. An important role can be played by women and youth. This is an imperative, as male adult family members often work elsewhere. However, women overloaded with work may find it difficult to devote time to participation in additional activities.

The Priority Action Agenda

Information on the hydrological cycle is indispensable to the sustainable development of water resources. The need for an improvement in the hydrological database of mountainous areas is particularly acute.

A loud appeal must be issued for the adequate recognition of hydrological observations as a component of sustainable development. If the hydrological cycle is not monitored with appropriate spatial and temporal coverage, decision-makers and the general public may not be informed of water problems until it is too late and when the consequences are already severe. Hydrological observations provide essential early warnings of cases in which sustainable development is in jeopardy. Since water is indispensable for life, as a carrier and solvent of substances, hydrological observations are of primary importance in any environmental impact assessment.

The scientific information on water resources of mountainous areas is very fragmentary. The present authors went through several volumes of proceedings of major international symposia on mountain hydrology. One can find there a high number of specific pieces of information relevant to local conditions, but no attempts at generalisation or aggregation. Undertaking such an exercise would be an imperative for assessing and understanding mountain water resources on the global scale. The present authors consulted a number of scientific authorities, asking for their assessment of the magnitude of mountain water resources and, in particular, the portion of global water resources originating in the mountains. These assessments turned were either not available, very rough, or at odds with one another. A GIS-supported evaluation of mountain water resources on the global scale is therefore badly needed.

Agenda 21 calls for integrated watershed development of mountainous areas, which should prohibit further degradation. Integrated watershed management should conserve and upgrade the natural resource base of land, water, plant, animal, and human resources, taking a holistic perspective on the complex processes, including their links and interconnections. It is with much regret that the present authors have failed to notice any substantial steps in the implementation of UNCED recommendations encoded in Agenda 21.

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