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THE AGRICULTURAL USE OF MELT WATER IN HOPAR SETTLEMENT, PAKISTAN

by

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ABSTRACT

Agricultural irrigation is an important use of melt water in the Karakoram Range of Pakistan; indeed all crop cultivation relies on melt water from small glaciers and/or snow and ice patches in the zone above 3500 m. Inhabitants of Hopar settlement utilize run-off from a cirque-shaped basin covering about 11.5 km^2 between 3600 and 4900 m a.s.l. to irrigate 280 ha of cultivated terraces in the altitudes 2500–3000 m. The characteristics of discharge from this basin require specific adaptions to be made by irrigators. In particular, access, turbulent flow, water temperature and sediment load are problematic, although water allocation is not an important concern because supply exceeds demand for most of the local growing season. Supply characteristics are outlined in the paper and are related to features of the indigenous irrigation system.

INTRODUCTION

Farming villages in the Karakoram Range of northern Pakistan are currently the focus of numerous agricultural and economic development efforts. The aridity of the agricultural zone in this area determines that these efforts focus on improving irrigation techniques, or on integrating existing irrigation systems with other agricultural modernizations. Successful development requires both a hydrological and a cultural and ecological appreciation of water supply and the pattern of its indigenous utilization. In the Karakoram Range irrigation water is supplied almost exclusively by melt water from small snow and ice patches. Although melt-water irrigation is not unique to this area, it is limited globally to small farming communities in a few poorly studied high mountain regions. As a result melt-water irrigation systems are poorly understood by development agency personnel working in the Karakoram area, who rely largely on literature and expertise developed for rain-fed or ground-water-fed systems in other parts of the world. Case studies which describe and relate melt-water supply and irrigation use in successful indigenous irrigation systems can help improve understanding.

This paper offers the example of Hopar settlement, in the Karakoram Himalaya as a step in the right direction. It summarizes the Hopar melt-water irrigation system in terms of (a) its source above 3600 m (b) the timing, volume and quality characteristics of discharge from that source into the main melt-water stream, Hopar Nala, and (c) the adaption of melt-water supply by villagers to meet their irrigation requirements. Investigations were conducted during July 1985, and from May to August 1986.

SETTING

Hopar is a community of five agricultural villages and about 4000 inhabitants, located at 36°N, 75°E in the central Karakoram region of northern Pakistan (Fig. 1). It is the highest permanent settlement in the former feudal kingdom of Nagyr, and today the 73 villages of Nagyr are a small and remote part of Gilgit Administrative District.

The five villages of Hopar have traditionally survived mainly, if not totally, from subsistent agricultural production. In the past century the community has become less dependent upon what it could produce for itself and more involved in the regional monetary economy. Today, Hopar is far from self-sufficient in terms either of agricultural produce or of total requirements. Despite this, most of the essential food is either grown in the villages or is obtained from other communities in exchange for Hopar produce. Thus the health and wealth of Hopar continues to depend to a large extent upon the ability of villagers, individually and collectively, to interact effectively with the natural environment.

Features of the natural environment which are most important to agricultural adaption in the Karakoram are altitudinally-controlled temperature regimes, local terrain, and water supply. Altitude is primarily a large-scale agricultural control, because as altitude increases the number of potential food crops diminishes. Temperature gradients effectively prevent farming above 3000 m. Hopar, at the upper threshold of single cropping, produces apricots, walnuts, wheat, barley, beans, potatoes, alfalfa, and small quantities of vegetable crops.

Terrain limits the situation of agricultural villages within the broad constraints of altitude. Terraces are built only on relatively flat and unconsolidated slopes which have some potential for rapid soil development. Agriculture is therefore limited to depositional features, not only primarily alluvial fans but also moraine deposits, kame terraces, and ancient lake beds. Hopar occupies the remains of a kame terrace that has been modified by glacial lacustrine deposits and also by several small moraines.

The ultimate and most local physical constraint upon agriculture is water supply. Maximum precipitation occurs above 3500 m; below 3500 m amounts are hydrologically and agriculturally insignificant except during a brief period in spring. Most precipitation in the cropping zone falls as snow in winter and is lost to agriculture in early spring as evaporation or run-off. In Hopar potential evaporation below 3500 m is consistently several times greater than growing-season rainfall.

Above 3500 m precipitation in the Karakoram Range is in the order of 110–160 cm a^{-1} (Hewitt, 1968). Certain locations at extreme heights receive much more precipitation than this (Wake, 1987). Most precipitation falls as snow (Batura Glacier Investigation Group, 1979; Snow and Ice Hydrology Project, 1986). Such high altitude snowfall sustains agriculture through melt-water irrigation. Thus crop moisture depends critically upon accumulation and melt conditions at high altitudes, but below the zone of perennial frost, rather than upon precipitation in the crop zone. Agriculture is possible only where suitable terrain is accessible to melt water from higher altitudes. Hopar settlement exemplifies this utilization of the resources from two climatic zones. The valley is naturally arid and parched, yet effective irrigation has transformed it into a verdant agricultural oasis. Over 300 km of channels link melt water from snowfall above 3600 m to 280 ha of cultivated terraces and 160 ha of sloping alfalfa fields in the area between 2500 and 3600 m.

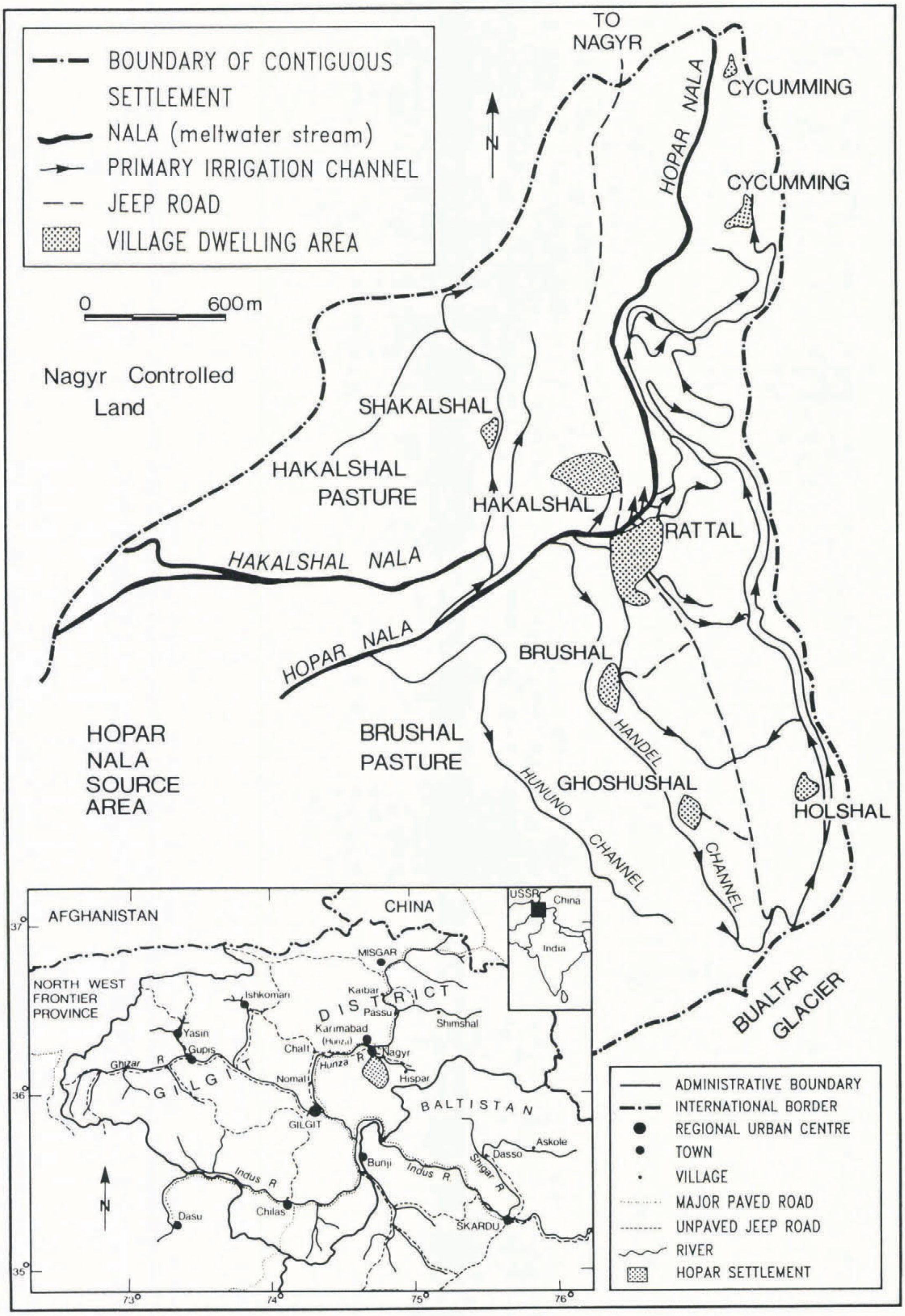

Fig. 1. Hopar community, central Karakoram Range, Pakistan.

MELT WATER AS A SOURCE OF IRRIGATION WATER

Most of the irrigation water in Hopar is supplied by melt water from permanent snow and ice patches, and from seasonal snow cover accumulated in a series of cirques between 3600 and 4900 m a.s.l. Intermittent streams drain from these into a steep east-facing gully-cum-gorge cut through a melt-water stream which as locally called a *nala*. The local catchment area is approximately 11.5 km^2, about 2.1 km^2 of which is covered by ice and another 6 km^2 by permanent snow. Seasonal snow covers the entire basin in winter, but the transient snow line moves up-slope from a lower elevation of about 3600 m in early April as temperatures increase to 4100 m by mid July. Maximum transient snow-line retreat is at 4500 m; above that altitude, and in shaded or north-facing side valleys, accumulation exceeds melting. Avalanche redistribution down-slope from the higher steeper areas contributes to dense and dirty snow deposits as far down as the mouth of the basin.

Winter snowfall on the western slopes above the cultivation zone and outside of the main source basin also contributes small quantitites of melt water to Hopar. The steep slopes receive direct radiation during the period from sunrise to mid-afternoon, so that by the middle of May almost all the snow has melted except for that in a small area to the north of the main melt-water basin. This micro-basin, between 3800 and 4100 m a.s.l., is sufficiently high and shaded to retain the majority of its snow until early July, after which it releases peak afternoon discharges of approximately 0.2 m^3/s until sometime in late August. Hoparis have diverted the small melt-water stream into their irrigation system.

The cultivated area of Hopar receives snow accumulations of 60–90 cm in the winter months. In most years this snow has melted by early March, although accumulations occasionally persist until early May and thus contribute to moisture for crop germination.

DISCHARGE THROUGH THE HOPAR NALA

Hopar Nala flows continually, although minimum discharge between November and March is less than 0.1 m^3/s. Discharge begins to increase towards the end of March when shallow snow patches and avalanche deposits at the mouth of the basin start to melt. Flows increase until the combined effect of greater radiation and the upward migration of warmer temperatures allow melting at altitudes with progressively deeper and more extensive snow accumulation. During March, April and early May, however, melting is unpredictable and highly irregular. By late July melting occurs throughout the source basin, from avalanche deposits at 3600 m to perennial snow and ice patches above 4900 m. Peak afternoon discharges reach 11 m^3/s, and melting of this magnitude continues on into early August, causing rapid depletion of the remaining seasonal snow-pack. In late August a decline in melting corresponds with diminishing snow surface and decreasing heat input until winter flow of approximately 0.1 m^3/s resumes in November (Fig. 2). The period of substantial melt is prolonged by the existence over a variety of aspects and elevations of several types of snow ranging from seasonal snow through perennial snow and avalanche deposits to a core of about 2.5 km^2 of glacial ice. Discharge variability both throughout the season and between seasons is greater than in predominantly glacierized basins, but less than in rain-fed basins (see Röthlisberger and Land (1987), Whiteman (1985), and Young (1977) for a discussion of the variability of melting and its association with snow density).

Several observations may be made concerning the diurnal flow of Hopar Nala. The predominant aspect of the basin is easterly so that peak daily discharge occurs relatively early in the day, at around 14.00 h in mid-July. This contrasts with observations for Askole, a village in Baltistan with similar altitudinal characteristics but a south-facing aspect where peak flow occurs around 17.30 h. Early onset of melting is also enhanced in this region by particularly steep east-facing valley walls which allow almost perpendicular exposure to direct radiation early in the morning. The presence of a variety of slopes, aspects nd snow types has the same effect upon diurnal melt as it has upon seasonal discharge; it tends to prolong melting and diminish peaks.

As the melt season progresses snow both compacts and collects dust and debris. The consequently reduced albedo and higher absorption capacity results in a diurnal melt which shifts toward morning as the summer progresses. Increased exposure of dense and dirty avalanche deposits, perennial snow, and ice as seasonal snow melts enhances this trend (Young, 1977). Discharge measurements taken in 1986 indicate that the timing of peak discharge migrated approximately 2 h toward morning from mid-May to late-July. This migration follows the path of sun height penetrating the gorge as summer progresses.

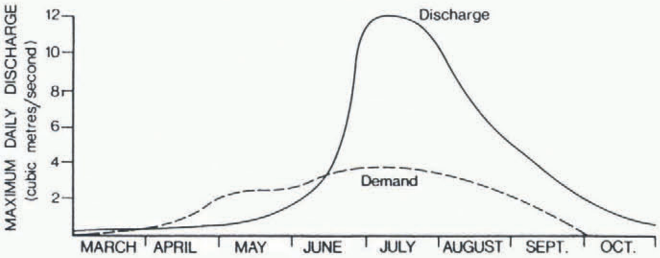

Fig. 2. Discharge through Hopar Nala, central Karakoram Range, Pakistan.

Melt water entering irrigation systems is characterized by low temperatures and high sediment load. During the period of investigation temperatures at Hopar ranged from 0.5°C, where the highest channels cut off from the *nala*, to 7.0°C at the lowest cut-off. Sediment studies were not conducted, yet it is apparent that both steep and unstable slopes and heavy avalanche activity contribute to high bed- and suspended-loads in Hopar Nala.

WATER SUPPLY AND IRRIGATION DEMAND

The relationship between water supply and irrigation demand can be summarized in terms of volume, timing, accessibility, and quality of flow. Irrigators in Hopar, as elsewhere, require sufficient volume throughout the irrigation season, and predictable flows from year to year. The main *nala* carries abundant flow for the period of regular, intensive irrigation from about 15 June to 1 August each year, and also for the progressively lighter irrigation that occurs until potato harvest in September. Flow is insufficient for irrigation from mid-May to mid-June although early melt from snow coverage outside the *nala* basin helps to ameliorate water shortage in terraced areas and triggers alfalfa growth on slopes above 3000 m.

Total seasonal discharge is more reliable in Hopar than in comparable rain-fed basins, because when seasonal snowfall fails perennial snow and ice-melt is enhanced. In this way, glacier melting compensates for vagaries in temperature and regulates seasonal stream flow (Meier, 1973; Young, 1977). The result of this is a relatively consistent flow from year to year which, unlike that of many small rain-fed basins, does not depend greatly upon variable local precipitation conditions.

Average seasonal timing of melt-water supply to Hopar is excellent relative to precipitation timing in the agricultural zones of the Upper Indus River Basin. In contrast to precipitation, which occurs primarily during the cold season, melting above Hopar coincides well both with maximum temperature and with crop water requirements. Average diurnal discharge is also close to the ideal for irrigation. A relatively low, east-facing snow accumulation zone means that farmers can begin irrigation early in the day, when evaporation is low, and finish before sundown. Since the release of melt-water peaks and declines gradually flows rarely reach hazardously high levels and irrigation can occur throughout the day. Unfortunately, the excellent average seasonal timing of melt-water discharge is frequently disrupted by inconsistencies in winter snowfall characteristics and in summer melting conditions. When most of the winter snowfall occurs early it settles and accumulates a thin dusting of debris. The consequent decrease in albedo may cause peak melting before peak irrigation need. When, on the other hand, major snowfalls occur toward spring, melting is inhibited by relatively great albedo (Meier, 1973; Young, 1977). In basins where fresh snow covers perennial snow and ice, low seasonal snow coverage causes earlier and higher summer melt. In addition, cold and cloudy spring conditions delay and inhibit melt. When particular conditions combine villages receive most of their irrigation before or after peak irrigation demand; for example, in 1986 the spring weather conditions in Hopar were unusually cold and wet, and were combined with heavy and late winter snowfall. This produced seasonal flow which was, according to locals, exceptionally low until mid-June, and slightly below average throughout the irrigation period.

Access to water supply is a serious obstacle to effective irrigation throughout much of the Upper Indus Basin. The main part of the Hopar meltwater basin begins approximately 600 m above and 1 km distant from the upper limits of cultivation. It is therefore much more accessible than many Karakoram villages, especially since the *nala* dissects the lower boundary of cultivation. At the same time building, maintaining and repairing channels from the stream to the cultivated areas across steep, rocky and extremely unstable terrain poses important financial, labour, and organizational difficulties for the community.

Finally, crop cultivation is subject to two water quality problems; namely low temperature and high sediment load. Water temperatures never exceed 2°C at the highest channel cut-offs, and remain between 4° and 7°C at lower cut-offs. Unless these temperatures increase before water reaches crops, soil temperature and growing season are likely to be decreased significantly.

Melt-water irrigation systems are commonly subject to high sediment loads (Whiteman, 1985). Hopar is no exception, due to steep slopes, unstable terrain, and abundant avalanche activity. If sediment is not trapped above the cultivated area it has the potential to clog channels, damage water mills, choke seedlings, and raise terraces. At the same time some sediment input is required to maintain non-organic soil constituents.

In summary, the nature and location of the water supply in Hopar presents primarily physical problems which include controlling turbulent and variable flow, raising water temperature, lowering sediment loads, and routing water from the source basin across unstable and steep slopes to fields. The essentially social concern of water allocation is less problematic in Hopar. Indeed, allocation is extremely flexible and rather nonchalant, because supply exceeds demand for most of the season. This situation contrasts with that of well-studied rain-fed irrigation systems where water shortages require sophisticated and formal allocation procedures, and where improving social control of allocation has been the main focus of development.

The following sections summarize the response in Hopar to the main physical problems created by its melt-water irrigation supply. The irrigation system combats problems of turbulent and variable flow, access, temperature and sediment at three levels: primary canals flowing from stream to villages; secondary or village level channels; and tertiary or field level ditches.

CONTROL OF TURBULENT AND VARIABLE FLOW

The most effective control on meltwater flow occurs where primary canals diverge from the meltwater *nala*. Canals are constructed to traverse gully sides above and almost parallel to the stream itself. Where the two meet, rocks are piled across the stream following the angle of the channel margin, so that some water becomes diverted into the canal. Flow is regulated by altering the density of this simple dam, or by opening and closing sluices built into canal walls downstream of the cut-off. By controlling flow at the irrigation systems' entrance flooding, channel erosion, slumping of downslope walls, and mis-allocation of water are reduced.

Additional control is achieved at each channel level by diverting water into smaller and smaller channels. The meltwater *nala* carries a maximum flow of 11 m^3/s. Twelve primary canals with potential flows from 0.004 m^3/s to 1.1 m^3/s diverge from the *nala*; these supply water to over 100 secondary channels with flows of between 0.001 m^3/s and 0.1 m^3/s. Secondary channels flow into thousands of field-level ditches, none of which carries a flow of more than 0.001 m^3/s. By the time melt water reaches crops its flow energy is dispersed to such an extent that flooding and erosion hazards are inconsequential. The entire network is patrolled continuously during daylight, so that flow to any channel or terrace can be stopped almost immediately. At night, only a very low flow is allowed to enter the cultivated area.

ACCESS

Channelling water from the melt-water basin over steep and unstable terrain in order to cultivate fields a kilometre distant and several hundred metres lower is a challenging and laborious chore. Landslides from above and slumping from below are both serious hazards, as is seepage and channel failure from within. Slumping is minimized by building dry-stone walls and by planting vegetation down-slope. Up-slope, low walls and/or ditches are constructed parallel to canals. These prevent small landslides and debris runs from disrupting water flow. Canals themselves are lined in places with impermeable silt or slatey rocks to prevent the seepage of irrigation water. In addition, canal builders usually attempt to construct canals at slopes of about 3° to prevent both erosion and excessive sedimentation. Where bedrock is encountered, small waterfalls or stepped sections of channel are built in an effort to achieve the necessary vertical drop between source and demand area. Finally, canals are regularly patrolled so as to check for symptoms of seepage or potential channel failure. Despite these precautions blockages and failures do occasionally occur. In this event, villagers are able to divert water flow quickly and organize efficient repair crews.

By the time water enters secondary channels the main problems of access are solved. Terraces, vegetation cover and well-developed soils all facilitate water distribution without threat of erosion. The main problem in Hopar is irrigating slopes on the valley side opposite to the meltwater supply. To maintain the necessary head of gravity channels are routed around the upper end of the oval shaped valley to opposite slopes. Moreover, dirt channels and aquaducts have been raised to dissect the cultivated valley floor at elevations of 2 or more metres. These are patrolled and safety standards regularly reinforced to prevent supply failure.

TEMPERATURE

Water entering the highest channels is consistently below 2°C, which is sufficiently cold to kill or stunt all crop varieties. Temperatures increase slightly during the time that water flows through primary channels, but most warming occurs in secondary channels which are dug wide, so that water is shallow, meandering and slow moving. A large perimeter : cross-section ratio ensures maximum radiative and convective warming, and slow and circuitous routing maximises warming time. In addition, shallow ponds are located throughout the cultivated area. These are used mainly for washing and watering livestock, but also help to increase water temperature. Water seldom enters terraces at temperatures below 9°C, and often it is several degrees warmer. These temperatures are still below optimum, but are sufficient for indigenous crop varieties.

SEDIMENT

Sediment is a mixed blessing for mountain irrigators. Thin coatings of fine silt on channel walls help prevent seepage and erosion. In addition, sediment is a source of inorganic nutrients for terrace soils. Unfortunately, too much siltation clogs channels, raises terrace levels and chokes crop seedlings. No efforts have been made to extract sediment at the primary canal level. The aim at this level is to transport sediment down-stream to the next level without threatening primary channel flow. Some siltation is tolerated as a safeguard against erosion.

Secondary channels are relatively easy to clean and also to maintain, so that sediment is allowed to settle out at this level. Wide, shallow, slow and meandering channels interspersed with ponds facilitate the deposition of silt, as well as increasing temperature. Channels and ponds are occasionally dredged and sediment is packed along channel and terrace walls, or else mixed with manure to fertilize fields. Some sediment inevitably enters fields. In plots where this is hazardous water is directed within the field along shallow furrows. Moisture reaches roots laterally through the soil rather than from above and sediment becomes trapped in furrows where it cannot harm seedlings.

CONCLUSIONS

Melt-water irrigation systems must be able to respond to the conditions of flow imposed by the nature and location of the melt-water source. These conditions differ from those needed in regions where irrigation derives from non-melt sources. In Hopar, water quality, reliable access, and control of turbulent flow are more important constraints than the volume or timing of melt. Village irrigators realize this, and have designed their irrigation network accordingly.

Development agency personnel should consider the dimensions of water supply as determined by basin characteristics, and indigenous methods of utilizing those dimensions, in their efforts to improve agricultural irrigation in regions of melt-water supply.

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REFERENCES

Batura Glacier Investigation Group. 1979. The Batura Glacier in the Karakoram Mountains and its variations. *Sci. Sin.*, **22**, 958-974.

Hewitt, K., *ed.* 1987. *Snow and Ice Hydrology Project. Annual report 1986.* Waterloo, Wilfrid Laurier University.

Hewitt, K. Unpublished. Studies in the geomorphology of the mountain regions of the upper Indus basin. (Ph.D. thesis, University College London, 1968.)

Meier, M.F. 1973. Hydraulics and hydrology of glaciers. *International Association of Scientific Hydrology Publication* 107 (Banff symposia — *The Role of Snow and Ice in Hydrology)*, **1**, 353-370.

Röthlisberger, H. and H. Lang. 1987. Glacial hydrology. *In* Gurnell, A.M. and M.J. Clark, *eds. Glaciofluvial sediment transfer; an alpine perspective.* Chichester, etc., John Wiley and Sons, 207-284.

Wake, C. Unpublished. Spatial and temporal variation of snow accumulation in the central Karakoram, northern Pakistan. (Master's thesis, Wilfrid Laurier University, 1987.)

Whiteman, P. 1985. Mountain oases: a technical report of agricultural studies (1982–1984) in Gilgit district, northern areas, Pakistan. Gilgit, Integrated Rural Development/ Pakistan Department of Agriculture (Gilgit). (FAO/UNDP. PAK/80/009.)

Young, G.J. 1978. Relations between mass-balance and meteorological variables on Peyto Glacier, Alberta, 1967/1974. *Z. Gletscherkd. Glazialgeol.*, **13**(1-2), 1977, 111-125.