Improved methods of assessment of snow and glaciers as water balance and river flow components

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ABSTRACT New technologies and techniques are providing detailed information on the hydrological properties of snow and glacier basins. This paper reviews progress in the integration of remote and proximate monitoring techniques for snow and ice hydrology studies; the potential for analysis of these with other georeferenced data to provide inputs to hydrological models; and the role of multiscale hydrological studies and multiple-variable chemical studies for identifying water source areas and routing and for separating hydrographs. Multidisciplinary catchment studies are needed to underpin the development of distributed hydrological models for snow and glacier basins.

INTRODUCTION

The enormous significance of both snow and ice as components of the fresh water balance of the earth (Martinec, 1987) and as major controls upon (Meier, 1983) and responses to (Rango and Martinec, 1987; Martinec and Rango, 1989) world climate and climatic change, render their accurate assessment as water balance and river flow components a very high priority for both researchers and water managers. It is scarcely surprising, therefore, that great emphasis is currently being placed upon improving our knowledge of snow and ice hydrology. This review will consider recent advances in the assessment of snow and glacier ice in the evaluation of catchment water resources (water balance components) and the assessment of temporal variations in catchment water yield (river flow components).

In taking a catchment-based approach to the assessment of snow and glaciers, it is useful to consider more general trends in hydrological research. In particular, the development of catchment-scale distributed hydrological models over the last ten years has now reached a state where applications can be attempted (Anderson and Rogers, 1987). Extensions of such models to incorporate areas of snow and ice would be very profitable (snow, for example, is already incorporated within the Institute of Hydrology Distributed Model; Harding et al., 1989) and could build upon the semi-distributed manner in which some current operational methods estimate runoff from glacierised (Fountain and Tangbourn, 1985) and snow covered (e.g. Baumgartner et al., 1986) basins.

There are many challenges in working towards the operational use of distributed hydrological models in snow and glacier basins but these challenges fall into two main groups. The first group is the assembly and processing of spatially distributed data on the required variables at a suitable spatial and temporal resolution. Whilst information on static catchment characteristics can be obtained through traditional or remotely sensed sources, information on the hydrological variables is not so easily acquired. Information from well-designed networks of ground data collection sites needs to be efficiently collected and merged with a variety of remotely sensed data from both satellite and airborne platforms, and rapidly processed if the results of modelling are to be useful in the management of all magnitudes and frequencies of hydrological events. These objectives can be achieved with the development of rapid data transmission media and with the integration of complex data sets through the development of geographic information systems. With the increasing capacity and power of microcomputer systems, these data could be processed using hydrological models in remote field offices, although the development of expert systems may be necessary to ensure correct applications of the models (Rango, 1987). The second group of challenges relates to devising ways of calibrating the distributed models for the local routing characteristics of the snow and glacier systems. Both snow and glacier basins exhibit enormous temporal and spatial variability in meltwater storage and routing. In the case of snow, remote sensing techniques are providing increasing detail of snowpack condition which provides a partial solution to the assessment of storage and routing, whereas this has not proved possible in relation to glaciers. Whilst the
development of theory provides a basis for modelling englacial and subglacial water storage and routing (Rothlisberger and Lang, 1987) and the storage and routing characteristics of snow, measurement and analysis of the quality and quantity of water draining from snow and glacier basins allows the refinement of such theory to match local catchment circumstances.

REMOTE SENSING OF THE HYDROLOGICAL PROPERTIES OF SNOW AND ICE

There are many excellent technical reviews of the application of remote sensing techniques to the estimation of the physical properties of snow and ice (eg Chang and Rango, 1982; Deutsch et al, 1981; Dozier, 1987a; Foster et al, 1987; Hall and Martinec, 1985; Rango, 1983; Rees and Squire, 1989; Rott, 1987, Zwally, 1987) and so this discussion will centre on the hydrological content of these applications. The advantages of remote sensing approaches to catchment hydrological studies are threefold. First, if the sensors are mounted on satellite or airborne platforms, they provide detailed, spatially distributed information on hydrological variables over the whole study area. Indeed, with satellite mounted sensors, global monitoring of some variables is possible. Second, these data can be repeatedly collected to provide time series information, although the frequency of repeat survey and the level of interference presented by atmospheric conditions varies enormously between sensors and platforms. Thirdly, whilst the response of the sensor is usually supplying surrogate information for the variable of interest, surrogates can often be identified for hydrological variables which are extremely difficult to measure even at a point using other techniques.

Table 1 provides some examples of published studies which are relevant to catchment-based snow and ice hydrological studies through the monitoring of gamma ray, visible, near infrared, thermal infrared and microwave wavelengths.

**Gamma radiation**
Sensing of the contrasting emission of natural gamma radiation in the presence and absence of snow cover has been used to estimate the snow water equivalent. Problems of calibration arise if there are major changes in soil moisture content between the pre-snow and snow-covered surveys. Deep snowpacks cannot be accurately monitored using this technique and surveys have to be carried out by using low flying aircraft because of the attenuation of the radiation by the snow and the atmosphere. The requirement for low altitude flying renders the technique expensive. It is also too dangerous for use in very mountainous terrain. Nevertheless, it is a sufficiently effective operational technique to be used for snow water equivalent and soil moisture surveys along 1250 flight lines in North America (Carroll, 1987).

**Visible, near infrared and thermal infrared wavelengths**
Visible and near infrared images for cloud-free conditions provide good definition of snow cover, and ice cover is also usually clearly-defined where the ice surface is well exposed. In the visible wavelengths, snow reflectance is insensitive to grain size but sensitive to small amounts of impurities, whereas in the near infrared wavelengths, snow reflectance is sensitive to grain size but not to impurities (Dozier, 1987a). These properties are important in assessing the spatial distribution of snow quality and snow metamorphism. Of particular hydrological significance is that ice crystals grow in response to vapour transfer through the snow pack and form clusters within melting snow, the clusters increasing in size through successive melt-freeze cycles (Colbeck, 1987). These changes in crystal and cluster size affect the permeability of the pack. The albedo of the snow pack underpins energy balance calculations from the surface reflectance information gathered by a remote sensor. A model of the bidirectional reflectance distribution of snow is required (Rango, 1983) but "to date, no reliable model for determining the BRDF of snow exists" (Foster et al, 1987).

Where snow and glacier ice occur together, it is possible to differentiate various surfaces of hydrological significance. In some circumstances shadow effects can allow surface catchment areas to be defined (eg Thomsen and Braithwaite, 1987). In addition, it is possible to separate snow and ice surfaces (eg Clark et al, 1987). Indeed, Williams (1987) distinguishes all the major ice facies on Vatnajökull from Landsat MSS data. At the end of the ablation season, these data may be used to estimate the position of the annual equilibrium line and, if a relationship can be established for a particular glacier or extrapolated from nearby glaciers, the equilibrium line altitude (ELA) may provide a basis for estimating glacier mass balance (Braithwaite, 1984; Østrem, 1975; Pelto, 1987). In the absence of such calibration data, the accumulation area ratio (AAR) is a useful glacial hydrological parameter. The ability to estimate ice surface velocities through the identification of the changing position of features on the ice surface (eg Orheim and Lucchitta, 1987) also provides information relevant to glacier mass balance.
Thermal infrared wavelengths provide information on radiometric surface temperature patterns. This could provide a useful input to energy balance studies, although atmospheric effects and, in the case of snow, effects from the liquid water content and crystal size of the pack (Foster et al, 1987), interfere with the temperature relationship.

**Microwave wavelengths**

Microwave remote sensing is undertaken either by sensing the emission of microwaves (passive microwaves) or the return of a microwave signal (active microwaves). Emission and reflection are both heavily influenced by subsurface properties. Depending upon wavelength, microwave radiation will penetrate clouds and most precipitation, providing an all weather capability (Rango, 1983). The intensity of microwave emission from snowpacks has been related to many hydrological properties of the pack including the temperature, density, depth, snow water equivalent and grain size characteristics. This sensitivity to a range of snow pack properties means that the provision of detailed ground data for calibration purposes is essential (e.g. Hallikainen and Jolma, 1986).

Airborne and satellite active microwave studies have differentiated dry from wet snow, have separated a variety of ice facies on glacier surfaces (e.g. Rott and Mätzler, 1987) and have defined surface morphology and topography, and subglacial topography. Single surveys provide estimates of the hydrological boundaries of glacier basins (from surface and subsurface topography) and repeat surveys can underpin the evaluation of glacier mass balance by indicating changes in surface topography. In addition, the repeated identification of features on the ice surface permits estimation of ice surface velocity. Ground based surveys have also defined subglacial topography and ice thickness as well as internal layering including the identification of cavities.

In summary, a variety of remote sensing techniques employing different wavelengths and platforms are beginning to reveal spatial and temporal variations in the hydrological properties of snow and glacier basins. Some of these techniques are operational whilst others are still at an early stage of research, but in combination they can provide information on the spatial extent, depth, internal and surface hydrological properties of snow and ice and, in the case of glaciers, information on their flow velocity. These are all variables which are of major relevance to hydrological modelling in snow and glacier basins, but in virtually all cases the patterns detected by the remote sensors require calibration using ground data. Thus, the operational application of remote sensing to runoff prediction from snow and glacier basins not only requires further remote sensing research but also the provision of well designed ground data networks to calibrate the remotely sensed information.

**TABLE 1**

Some examples of applications of remote sensing to snow and ice hydrology studies.

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<thead>
<tr>
<th><strong>GAMMA RAY SENSORS - SNOW SURVEY</strong></th>
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<tr>
<td>BERGSTROM and BRANDT, 1985: experimental comparison of snow water equivalent estimated from gamma radiation in comparison with traditional snow course data and as an input to a catchment flow forecasting model for the Kultsjon catchment, northern Sweden.</td>
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<td>CARROLL, 1987: operational airborne surveys of soil moisture and snow water equivalent maintained by the National Weather Service, USA (see also Peck et al, 1980).</td>
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<td>CARROLL and CARROLL, 1989a: impact of uneven snowcover on snow water equivalent estimates; correction methodology applied to western Canada and Colorado flight line data.</td>
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<tr>
<td>CARROLL and CARROLL, 1989b: impact of forest biomass on snow water equivalent estimates; correction methodology proposed.</td>
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<td>KUITTINEN, 1989: comparison of snow water equivalent from ground data, airborne gamma ray spectrometry and NOAA AVHRR data in Finland.</td>
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<td>VERSHININA, 1983: assessment of applicability of aerial gamma radiation surveys to snowmelt runoff forecasting in USSR drainage basins.</td>
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<th><strong>VISIBLE/NEAR INFRARED/TEHERMAL INFRARED SENSORS - SNOW SURVEY</strong></th>
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<tr>
<td>BAUMGARTNER et al 1987: snow cover determination for different altitudinal zones in the Rhein-Felsberg basin, Switzerland. An assessment of snow cover estimates derived from Landsat MSS (good spatial resolution) and NOAA AVHRR data (good temporal resolution) as inputs to the SRM (Martinec-Rango snowmelt runoff model).</td>
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</table>
BIRNIE, 1986: snow condition assessed from snow pits and oblique air photos in comparison with Landsat MSS data, to assess the potential of Landsat data for identifying snow condition in Scotland.

DEY et al 1983: early April snow cover estimates from NOAA VHRR data for Kabul (88600 km²) and Indus (162100 km²) river catchments, Pakistan; seasonal regression of runoff on snow cover for runoff estimation.

DOZIER, 1987a,b; DOZIER and MARKS, 1987: methodologies to distinguish snow cover from cloud cover, compensate for rugged terrain and atmospheric scattering effects; to distinguish snow from other surface covers and to classify snow according to grain size and contamination based upon the combined analysis of digital terrain and Landsat TM data.

GUPTA et al 1982: snow cover estimation from Landsat MSS data, snow cover related to subcatchment characteristics, snow area correlated with snowmelt runoff for the Beas catchment (12916 km²), India.

LUCAS et al 1989: a snow mapping scheme based upon unsupervised classification of NOAA AVHRR data (potential operational technique for mapping weekly snow cover in the UK).

RANGO, et al 1983: assessment of the suitability of inputs from various remote sensors and platforms to operational snow cover monitoring in drainage basins of different spatial scale.

SØGAARD, 1983: combination of NOAA and ground data to estimate snow water equivalent depletion in Greenland catchments.

SØGAARD and THOMSEN, 1988: combination of NOAA AVHRR data with either a degree-day approach or a hydrological simulation model to assess snow pack water equivalent.

ZHANG SHUNYING and ZENG QUNGZHU, 1986: Low resolution TIROS satellite images were used to map snow extent. Snow cover estimates were combined with air temperature and precipitation observations to provide real-time forecasts of snowmelt in the Qilian Mountains area of China.

VISBILE/NEAR INFRARED/TEHERMAL INFRARED SENSORS - GLACIER SURVEY


FUJII et al 1987: identification of bare ice, snow and glazed surfaces in Antarctica from NOAA AVHRR data.

HALL et al, 1987: analysis of Landsat TM data for Grossglockner area, Austria and the McCall and Meares glaciers, Alaska. The ice surface was classified into up to three zones (one approximates the ablation area - a basis for estimating AAR, the other two in the accumulation area) and radiometric surface temperature patterns were assessed.

HOWARTH and OMMANNEY, 1986: base mapping to identify areas of glacier change on the Steacie ice cap, Axel Heiberg Island and Kaskawulsh glacier, St Elias Mountains from Landsat MSS data.

NOSENKO, 1986: monitoring of ice/firn/snow boundaries using 600-700nm band black and white and multi-spectral colour photographs from Salyut 6 and 7 space station and Kosmos satellite platforms; inferences about glacier equilibrium line position, glacier mass balance, snow storage and runoff.


PELTO, 1987, 1989: combination of analysis of satellite imagery, local weather records and some mass balance determinations to extrapolate mass balance estimates in time and space, SW Alaska and NW British Columbia.

ROTT, 1988: assessment of potential of Landsat TM data for the estimation of glacier area, snow and ice area and AAR (see also Della Ventura et al 1987).

SCHARFEN et al 1987: analysis of DMSP, Landsat MSS and NOAA VHRR data to discriminate snow covered from ponded/flooded ice surfaces, Arctic sea ice.

THOMSEN and BRAITHWAITE, 1987: low sun angle Landsat MSS data to identify ice surface morphology, Greenland.

WILLIAMS, 1987: Identification of surface morphology, glacier ice facies (transient snow line, slush zone, wet zone, percolation zone, dry snow) on Vatnajokull, Iceland from analysis of Landsat MSS data.

PASSIVE MICROWAVE SENSORS - SNOW SURVEY

CAMPBELL, et al 1987: comparison Nimbus 7 SMMR data and ground determination of snow pack properties in the Colorado river basin indicates sensitivity of SMMR data to water equivalent and to the spatial and temporal evolution of crystal size in snow packs.
CHIANG et al 1987a: snow cover maps for the Northern Hemisphere from Nimbus 7 SMMR data.
CHIANG et al 1987b: development of snow parameter retrieval algorithm to estimate snow water equivalent in mountainous terrain (Colorado river basin) from Nimbus 7 SMMR data.
GOO DIISON et al 1986: development of algorithms for airborne and satellite (Nimbus 7 SMMR) passive microwave mapping of regional snow water equivalent in Canada calibrated from ground snow survey and airborne gamma-ray surveys. Derived algorithms worked well for dry snow areas without trees.
GRODY, 1986: classification of dry snow, sea ice, dry and flooded land and open water using Nimbus 7 SMMR data.
HALL et al 1982: influence of forest cover on analysis of snow cover properties from Nimbus 7 SMMR data.
HALLIKAINEN and JOLMA, 1986: assessment of algorithms to estimate snow water equivalent in Finland from Nimbus 7 SMMR data; requirement for ground data on water equivalent and, in spring, on snow pack surface temperature, to calibrate response.
JOSBERGER and BEAVILLAIN, 1989: comparison of analysis of Nimbus 7 SMMR data with images from visible wavelengths (DMSP) to establish threshold microwave characteristics for snow-free pixels; can then use more frequent SMMR data to monitor detailed temporal change in snow cover (Colorado basin).
ROTT and KUNZI, 1983: potential of Nimbus 7 SMMR data for monitoring snow areal extent, water equivalent and onset of snowmelt on a global and large river basin scale.

ACTIVE MICROWAVE SENSORS - SNOW AND GLACIER SURVEY
BAMBER, 1987; DOWDIESWELL et al, 1984; KOTLYAKOV and MACHEKET, 1987: airborne surveys; ice thickness and warm/cold ice layers in Spitzbergen glaciers.
BENTLEY et al 1987: airborne radar and seismic studies; mapping ice streams, grounding lines of Ross ice streams and shelf; inferences on mass balance and bed conditions.
BINSCHADLER et al 1987: identification of surface undulations, ice flow lines, crevasses, icebergs, lakes, streams and possible extent of ablation and wet snow zones from airborne and Seasat SAR data.
BJORNSSON, 1982: drainage basin definition on Vatnajökull from ground survey.
DOWDIESWELL, 1986: definition and classification of ice drainage basin characteristics, Svalbard, from airborne surveys of ice surface and bed rock topography.
HALL and ORMSBY, 1983: combined analysis of Landsat MSS and Seasat SAR data to enhance surface features of Malaspina glacier.
JACOBEL and RAYMOND, 1984: changing englacial water conditions during surging of Variegated glacier from ground surveys.
KENNETT, 1989: identification of englacial cavities at Storglaciers from ground survey.
MUSIL and DOAKE, 1987: ground-based pulsed SAR to determine subglacial topography, Bach ice shelf, Antarctica.
ROTT, 1984: airborne and spaceborne SAR studies of snow and ice; identification of glacier morphology and landforms, differentiation of wet snow from snow-free areas, snow from ice surfaces on glaciers.
ROTT and MATZLER, 1987: differentiation of dry firm, wet firm, slush and bare ice from airborne and Seasat SAR data.
WALFORD et al, 1986: interpretation of glacier bed and internal targets, Storglacier, from ground survey.
ZWALLY et al, 1987: surface elevation data from Seasat radar altimetry and morphological features from Landsat imagery to define form, boundaries and grounding line for areas of Antarctic ice shelf (see also Partington et al, 1987).

PROXIMATE MONITORING TECHNIQUES AND THEIR INTEGRATION INTO DATA GATHERING NETWORKS
The most significant hydrological properties of snow for the estimation of catchment runoff are its areal extent, depth, albedo, water equivalent and the condition of the snow pack, particularly its grain size and water content. Information on all of these properties can be abstracted from remotely
sensed data but ground calibration information is essential. Goodison et al. (1981) describe the
commonly used methods for determining snow depth (rulers, boards and stakes), snow fall
(precipitation gauges), snow water equivalent (gravimetric techniques using snow samplers, snow
pillows, radioisotope gauges, ground natural gamma radiation and microwave monitoring) and Barry
(1986) surveys the status of snow cover data and the differences in national practices for the
collection of snow cover data for hydrological purposes. Whilst these proximate monitoring
techniques provide suitable ground calibration data for remotely sensed surveys, there is a continuing
need for: (i) improvements in instrumentation siting and network design (eg Ferner and Wigham,
1987; Galeati et al., 1986); (ii) the development of methodologies to combine measurements of
hydrological variables from different sampling geometries, densities and levels of accuracy to define
spatial patterns and areal averages; particularly the problem of combining proximate monitoring and
remote sensing data (Peck et al., 1983); (iii) the development and improvement of automatic
measuring instruments that can contribute real-time observations via telemetering snow monitoring
networks.

Recent advances in ground instrumentation include the development and testing of methods
for monitoring the water content, depth and density of snow (eg Akitaya, 1985; Bergman, 1987;
Boyne and Fisk, 1987; Denoth et al., 1984; Edey et al., 1987; Kattelman et al., 1983; Siholva and
Tiuri, 1986), snow fall (correction and intercalibration of precipitation gauges: Goodison et al.,
1989; Sevruk, 1983; ground-based radar: Kleppe and Liu, 1983) and components of the energy
balance above the snow pack surface (eg Harding, 1986; Strangeways, 1980).

If reliable, automatic, proximate-monitoring systems can be developed then data transmission
from these automatic stations by satellite relay can provide real-time inputs to hydrological models
(Goodison et al., 1983; Rango, 1987). The SNOTEL (SNOW TELetry) system developed by the
US Soil Conservation Service provides an excellent example of such a near real-time snow
monitoring system. It is capable of receiving data transmissions from as many as 1000 remote sites
using up to 16 digital or analogue sensors at each site. Snow water content, accumulated
precipitation and temperature are monitored at each site but transmission of data from the monitoring
sites to two ground receiving stations is achieved through reflection of radio signals by ionised
meteor trails (Rallison, 1981) rather than by satellite relay.

In addition to the role of snow cover, the hydrology of glacier basins is dependent upon the
size and mass balance of the ice mass. The great importance of areas of permanent snow and ice
to world climate and water resources has resulted in the development and continuous updating of
a world-wide inventory (Haeblerli et al., 1989), which provides an excellent resource for hydrological
studies. The inventory is compiled by the World Glacier Monitoring Service (WGMS) of
IAHS/IUGG, which since 1986 has taken over the collection and publication of standardised glacier
fluctuation data. The series of publications on "Fluctuations of Glaciers" (of which the most recent
volume is Haeblerli and Müller, 1988) include information on fluctuations in glacier positions and
also mass balance information for some glaciers. These sources provide baseline data for studies of
glacier basin hydrology which are invaluable given the laborious and time-consuming nature of the
evaluation of a glacier's mass balance (see for example Young, 1981). Methods are urgently
required for more rapid methods of mass balance evaluation which are applicable to large and
remote glacier basins. Possible approaches include the establishment of regional relationships
between easily estimated glacier characteristics and full mass balances evaluated for a sample of
glaciers (eg Braithwaite, 1984; Pelto, 1987); the reduction of ablation stake network density coupled
with the development of algorithms to assess the balance from the reduced stake network (eg
Braithwaite, 1986; Reynaud et al., 1986); and estimation of the mass balance from a single sector
of a glacier at a location close to the equilibrium line, for which the velocity and cross sectional
area are determined (eg Reynaud et al., 1986; Young and Schmok, 1989). The last technique can
be cross-checked from other information such as the measurement of inter-ogive distances to
corroburate velocity measurements (Young and Schmok, 1989) and the estimation of net
accumulation at different points in the accumulation area from physical and chemical layering studies
in snow pits (eg Wake, 1989). Since the ablation component of the mass balance is of particular
importance to river flow (for example Young (1982) illustrates the link between distributed patterns
of snow and glacier melt and runoff for the Peyto glacier), it would be extremely useful to develop
instruments for continuous monitoring of ice ablation (eg Lewkowicz, 1985) as well as the energy
budget above the glacier surface. Such instruments need to be refined to minimise their maintenance.
They would then provide invaluable information for mass balance calculations and, if integrated into
telemetric networks, would permit refinements of short-term flow forecasting. In the absence of such
information, flow forecasting in glacier basins must depend upon the establishment of time series
relationships between proglacial river flow and climate variables monitored at any convenient nearby
climate stations (eg Lang and Dayer, 1985; Lang et al., 1987). A hydrological data system, using
Improved methods of assessment of snow and glaciers

Satellite data transmission and with local sensing and logging facilities designed for severe climatic conditions (down to -40°C), has been set up by the Greenland Technical Organisation (Thomsen, 1983, 1989) specifically for monitoring and modelling the hydrology of sections of the Greenland ice cap and adjoining glacier and glacier-free basins. This system monitors information from climate stations as well as gathering data on river flow, water and ground temperature, and so provides the bases for effective flow forecasting.

The combination of remotely and proximately sensed data and other geo-referenced data for snow and glacier basins.

The discussion so far has illustrated that ground hydrological observations are required to calibrate remotely sensed data, and that if proximate monitoring stations are linked through data transmission systems for central processing (with or without remotely sensed data), the observations can be used for flow forecasting as well as for water resource evaluation. The effectiveness of such techniques can be enhanced if other geo-referenced data are combined with the hydrological data. For example, the addition of elevation data can provide a framework for the improved estimation and interpolation of point hydrological processes and for the routing of those processes to the basin outlet. Algorithms to derive topographic landscape units for hydrological modelling from digital elevation data have facilitated the derivation of slope angle, curvature, aspect and upslope contributing area classes (eg Moore et al, 1988). Band (1989) extended this approach in a snow-free and glacier-free context by defining drainage basin structure (ie watershed position, subcatchments and hillslope segments and their relationship to the drainage network through thresholds of drainage area required to support a river channel) from digital elevation data. He then used these data to simulate catchment runoff processes using a distributed hydrological model. Table 2 illustrates the application of similar approaches to snow and glacier basins and shows that the emphasis in undertaking the combined analysis of multiple types of data has been on estimating snow pack rather than glacier hydrological properties.

The combined spatial analysis of proximately and remotely monitored hydrological variables and other catchment characteristics is an area which demands increased research attention but to successfully estimate runoff using this distributed approach, it is essential that information on the temporally dynamic nature of runoff source areas and routing is incorporated. This element can be incorporated using the results of field water balance monitoring studies at different spatial scales, but in the context of snow and glacier runoff, a great deal of additional information can be derived from field studies of water chemistry and from tracer experiments.

Table 2 Some examples of the combined use of proximate and remotely sensed data and other geo-referenced data in hydrological studies of snow and glacier basins.

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<tr>
<td>BAUMGARTNER et al, 1986</td>
<td>Estimation of snow-covered areas for river flow estimation</td>
<td>Landsat MSS data</td>
<td>Digital elevation model</td>
<td>Analysis and classification of elevation data to create 205 elevation/aspect/slope classes. Visual classification of cloud covered areas, supervised classification of snow/transition/snow free areas. Analysis of relationship between snow cover and topographic class for interpolation in cloud covered areas and areas without satellite data. Estimation of snow cover in elevation zones for input to SRM (Martinec-Rango snowmelt runoff model).</td>
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<tr>
<td>CAMPBELL et al, 1987</td>
<td>Snow water equivalent mapping</td>
<td>Snow pit data and snow water equivalent data from SNOTEL stations</td>
<td>Nimbus 7 SMMR data</td>
<td>Analysis of synchronous proximate and remotely sensed data for interpolation of snow water equivalent for different parts of the upper Colorado basin.</td>
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<tr>
<td>DOZIER and MARKS, 1987</td>
<td>Snow mapping and classification as a basis for snow-surface energy-balance modelling in alpine areas</td>
<td>Landsat TM data</td>
<td>Digital elevation model</td>
<td>Terrain information provides basis for atmospheric/terrain radiation model. This is combined with calculations of the spectral reflectance of snow to simulate radiance at the top of the atmosphere for different snow grain sizes, levels of contamination and terrain conditions.</td>
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<tr>
<td>ELDER et al, 1989</td>
<td>Identification of spatial and temporal variation in net snow accumulation in an alpine watershed</td>
<td>2. Spatial and temporal surveys of snow depth, density profiles, water</td>
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equivalent. 4. Digital elevation model. 5. Radiation, slope and elevation mapped and clustered for classification of catchment for different time periods; variables and classes assessed for extrapolating snow water equivalent over the basin.

FERRIS and CONGALTON, 1989 1. Estimation of distribution of snow pack properties. 2. SNOTEL snow water equivalent readings synchronous with satellite data. 3. NOAA AVHRR data. 4. Digital elevation data. 5. A GIS containing layers for reflectance in visible, near and thermal infrared, vegetation index, elevation, slope, aspect, shade, sub-basin, SNOTEL sites is used to relate snow water equivalent to other variables and for basin-wide snowpack water volume estimation.

GUNDERSON et al., 1987 1. Methodology for spatial estimation of snowpack variables for runoff forecasting. 2. Ground data from 'optimal sites': snow depth, water equivalent, temperature, albedo, free water content. 3. Landsat TM data under snow-free conditions. 4. Digital elevation model. 5. Identification of 'optimal sites' for ground data monitoring from terrain zones (elevation/aspect zones identified from digital elevation model) subdivided into land use/vegetation zones using pattern recognition algorithms applied to multispectral data.

ROSSI et al 1986 1. Estimation of distribution and water equivalent of snow for runoff estimation. 2. Meteorological stations, snow depth and water equivalent stations. 3. Classified Landsat images for snow covered, transitional and snow-free ground. 4. Digital elevation model containing basin watershed, elevation, slope and aspect defined for a 'Landsat grid'. 5. Regression of snow depth on elevation and application of mean snow water equivalent to define spatial distribution of snow water equivalent.

SEIDEL et al, 1983 1. Snow cover determination in large catchments. 3. Landsat MSS data. 4. Digital elevation model. 5. Derivation of slope, aspect and angle between surface normal and sun direction at time of satellite overpass; registration with satellite data; classification of snow cover in open areas and interpolation of snow line in woodland. Analysis of snow cover in relation to altitude/slope/aspect categories.

SØGAARD, 1983 1. Snow mapping during melt. 2. Snow pack depth, density (water equivalent) and temperature; snow extent from air photos. 3. NOAA satellite data. 4. Digital elevation model. 5. Maximum snow water equivalent modelled from altitude and geographic co-ordinates. Satellite images for different stages of melt registered to common base, used to estimate surface temperature, adjusted for sun angle and topography to derive albedo estimates. Snow cover classified from albedo and temperature (to isolate melting snow) and checked using air photos as 'ground truth'.

WHITING and KISS, 1987 1. Digital terrain model used to refine ground-based snow and runoff measurement. 2. Flow gauging and snow depth sampling (uniform, random, and transects perpendicular to river channels). 4. Digital terrain model. 5. Slope, aspect, slope and contour curvature, elevation, catchment area defined from DTM and used to construct flow lines to basin outlet. Estimated snow water equivalent and flows compared with measured flows indicated redesign of snow sampling in proportion to channel volumes.

THE USE OF RIVER FLOW AND QUALITY SERIES FOR IDENTIFYING RUNOFF SOURCE AREAS AND FLOW ROUTING AT A BASIN SCALE

The analysis of flow quantity

One approach to studying runoff source areas and routing characteristics is to study flow generation processes at nested spatial scales. Such an approach has been adopted in a number of research studies (eg Braun and Slaymaker, 1981; Fitzgibbon and Dunne, 1981; Price, 1987; Woo, 1983) illustrating differences in the runoff regime with spatial scale as well as with the distribution of snow/ice/frozen ground in the catchment.

Studies at different spatial scales have identified different properties of runoff generation processes in snow and glacier basins. Small plot studies illustrate the complexities of water movement through snow pack (eg Harstveit, 1981; Jordan, 1983; Martinec, 1987), including the influences of the melt rate, snow grain size, snow depth and refreezing and redistribution of water through the pack. More than a day of surface melt may be required before any water drains from an initially dry, moderately deep snow pack, whereas a lag of only 1h may occur if the pack is near melting point with a significant initial free water content (Bengtsson, 1986). Water storage and drainage within the snow/firn zone of glacier basins is also complex. Oerter and Moser's (1982) study of water table levels and flow rates within the firn zone of the Vernagtferner glacier illustrate the lengthy (up to 13 day) residence time of water in this zone, whereas Lang et al (1979) recorded
the peak proglacial discharge of tracer injected into the firm aquifer of the Aletsch glacier approximately 34-36 days after the time of injection.

Hillslope studies reveal details of the role of snow pack properties in the delivery of meltwater to stream channels (eg Bengtsson, 1985 - differences in runoff pathways with vegetation cover; Olyphant, 1984, 1986 - the identification of insolation topoclimates and their impact on snow melt variability; Roberge and Plamondon, 1987 - snowmelt hillslope runoff pathways including role of pipeflow).

Catchment studies identify lags between meltwater release and its transmission to a point on the river network. In the context of snow basins, Kobayashi and Motoyama (1985) show an increase in lag between peak snowmelt and peak runoff of 1.5 to 4 h per 1m increment in snow depth and a power relationship between lag, catchment area and melt rate once the propagation time through the snow pack has been accounted for. Whilst Collins and Young (1981) provide a schematic model for discharge generation from different source areas in snow and glacier basins, Oerter et al (1981) compare distributed measurements of meltwater generation and routing from the firm and bare ice areas of the Vemagtfemter catchment with the proglacial discharge record and propose and calibrate a four reservoir hydrological model for the basin. Other studies have attempted to identify lags between meltwater generation processes in snow and glacier basins through the analysis of outflow hydrographs. For example, van de Griend and Seyham (1985) use a non-linear optimisation technique to analyse complex hydrographs with pluvial/nival/glacial components.

These hydrological studies at different scales provide fascinating insights into the functioning of snow and glacier basins but more nested, multi-scale studies are needed to formalise the identified relationships and to develop and enhance multiple reservoir models by increasing the detail of the distribution and routing characteristics of the component reservoirs.

The analysis of flow quality
Since water quality is the theme of a separate symposium at this conference, the discussion here will be confined to the monitoring of river quality characteristics to define the role of snow and glacier meltwater as river flow components. The quality of meltwater can be used to separate flow source areas and to estimate routing times in both snow and glacier basins. Natural water quality components (concentrations of individual anions and cations, environmental isotopes) have been used to fingerprint source areas and 'chemographs' have provided information on the phasing of flows from those source areas. Artificial tracer experiments have added precision to estimates of flow timing and to differentiation of flow times between different locations within the same water source area (eg Behrens et al, 1983; Hooke et al, 1988; Seaberg et al, 1988).

Early studies employed only simple indices of water quality and simple models to relate river flow to potential source areas. For example, mixing models can be applied to total discharge and its electrical conductivity to achieve flow separation in glacier and snow basins (eg Collins, 1979), but such models, if they are to remain simple, must assume no evolution of meltwater electrical conductivity either in the source area or during routing. A more useful approach is to allow evolution of water chemistry in the source area by redefining the electrical conductivity characteristics of the source areas during the melt season and by using additional indicators of water source characteristics such as the concentration of particular anions or cations to corroborate the flow separations defined by electrical conductivity fluctuations (Brown and Tranter, 1990). Environmental isotopes, particularly $^{18}$O, $^2$H and $^3$H, provide conservative tracers which can be used to develop mixing models for water from different source areas in snow basins (eg Bottomley et al, 1986; Herrmann et al, 1981; Maloszewski et al, 1983; Stichler, 1987) and glacier basins (eg Ambach et al, 1982; Behrens et al, 1979; van de Griend and Arwert, 1983; Theakstone and Knudsen, 1989). The research reported by Behrens et al (1979) is particularly interesting because they use a variety of environmental isotopes with electrical conductivity to achieve a four-fold separation of flow in a proglacial river.

Multiple variable approaches to the separation of outflow hydrographs appear to offer the optimum solution to flow separation problems. Anion and cation concentrations may be helpful in some circumstances. For example Hooper and Shoemaker (1986) compared flow separation in a snow basin using both environmental isotopes and the concentration of major cations and anions. They found that an isotopic separation was satisfactory early in the snowmelt period but that the isotopic content of groundwater and meltwater varied through time and became indistinguishable towards the end of the melt period. A comparison of chemical and isotopic separation indicated that dissolved silica was a conservative tracer for the catchment studied.

It is important to note the complexities of snow and glacier meltwater chemistry, which may render flow separation problematical. The 'preferential elution' characteristics of snow meltwater chemistry, which may give rise to 'acid shocks', have been widely reported (eg DeWalle, 1987;
Gjessing and Johanssen, 1987; Goodison et al, 1986; Gunn and Keller, 1986; Tranter et al, 1986, 1987) and provide a major problem for attempts at chemical flow separation. Similarly, in glacier basins, differential flushing out and leaching of ions from the snow and firn layers, ion exchange mechanisms, selective rejection of ions by regelation processes and selective filtration of ions by particle layers can all affect meltwater chemistry (Souchez and Lemmens, 1987). Of particular importance is the chemical weathering environment at the glacier bed and the associated possibility of variable post-mixing reactions of bulk meltwaters as a result of their closed-system or open-system evolution (Raiswell, 1984). It is clear that multiple conservative natural tracers are required, possibly in combination with artificial tracers, to unravel the source area and routing history of meltwater in snow and ice environments.

CONCLUSIONS

New technologies and techniques have produced significant progress towards the detailed spatial and temporal evaluation of hydrological processes in snow and glacier basins. It is necessary to increase effort in these research areas, particularly in identifying the fundamental hydrological processes and the degree to which they are characterised by new techniques. It is also essential to emphasise multidisciplinary studies which can combine the new research techniques within the same snow or glacier basin since this will underpin the development of realistic distributed hydrological models. Finally, it is essential that the results of research are more rapidly transfered to the development of operational systems and models for evaluating water resources and for flow forecasting, particularly in large drainage basins

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Improved methods of assessment of snow and glaciers


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