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6. AUTHOR(S)
Mark Williams, Tissa Illangasekare, Caine Nelson, and Tad Pfeffer

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Institute of Arctic and Alpine Research
and
Department of Geography
University of Colorado
Boulder, CO 80309-0428

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13. ABSTRACT *(Maximum 200 words)*

This final report for ARO grant DAAH04-96-1-0033, a project jointly funde by the National Science Foundation under separate award, (NSF-9526875), summarizes the research accomplished during the project at the Niwot Ridge research site in the Colorado Front Range established by the PI and upgraded during the coutrse of this project by an ARO research instrumentation award Near-infraed photographs of melting snow were analyzed using a moving windows procedure that can be used to define the correlation lengths in the snow reflectance surface. Liquid water contents of surface snow were measured with a dielectric sensor at 0.5 m intervals on two 100x100m grids. A circular array of 16 snow lysimeters, each with a catchment area of 0.2 cubic meters, was operated for two winter season s and larger arrays of 36 and 106 snlw lysimeters were operated over the winters of1999 and 2000, respectively . The characteristics of ice columns and frozen rills present during spring snowmelt were investigated. Snow and ice temperature profiles in normal and melting snowpacks were determined The results of the research suggest that ice colums and rills that develop in the snowpack during snowmelt provide preferential flow paths for meltwaters and that a positive feedback system develps such that certain areas of the snowpack receive more meltwater than others as snow melt advances in time. Four students were supported on the grant and seven publications resulted from the project.

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Activities and Findings

Project Activities and Findings:
Near infrared aerial photos of melting snow have been analyzed using a moving window analysis which can characterize correlation lengths in the reflectance of the snow surface.
Near infrared is sensitive to snow grain size which indicates the concentration of melt water; the grains grow faster if the liquid water content is higher.
The probability of finding such correlation lengths was about 0.22 in May, 1997 when the melt had just started and rose to 0.68 by June when the melt was well established.
Correlation lengths for all sampling dates ranged from 5 to 7 m.

Liquid water content at the snow surface was sampled with a dielectric sensor at 0.5 m intervals on two 100-m^2 grids.
Semi-variograms showed a sill at 5 to 6 meters.
The liquid water measurements at the snow surface suggest that the correlation lengths derived from the infrared aerial photos represent surface expressions of vertical flowpaths through the melting snowpack.
A circular array of 16 snowmelt lysimeters each with areas of 0.2 m^2 was operated for two years at Niwot Ridge in the Colorado Front Range.
Variograms indicated that flows were correlated over a distance of 5 to 7 m.
These three independent methods all suggest a correlation length of 5-7 m for vertical flowpaths draining ripe snowpacks in the Rocky Mountains.
The presence of ice columns and frozen rills in late season snowpacks may provide insights with which to understand the spatial distribution of preferential flowpaths in melting snowpacks.
In July and August of 1996 and 1997 we found ice columns in every one of the more than 50 snow fields we investigated.
The ice columns showed a consistent morphology; each column was approximately 75\|cm in vertical extent, with about 5\|cm projecting above the snow surface and 70\|cm extending into the snowpack.
An analysis of variance test shows that the 81 ice columns on the south-facing slopes were significantly greater than the 57 ice columns on the north-facing slope ($p = 0.01$).
There were about 3 ice columns per square meter on the south facing slopes and 2 ice columns per square meter on the north-facing slopes.
There was an interesting hysteresis in snow and ice temperatures that became stronger with increasing depth in adjacent thermocouple arrays.
This hysteresis in the temperature profiles is consistent with the release of latent heat from the freezing of greater amounts of liquid water in and near the ice columns compared to the surrounding snowpack.
At the Martinelli catchment, spacing between the frozen rills averaged 2.6\|m ($n = 73$).
We interpret these 'ribs' of solid ice to be the remnants of surface rills.
Vertical ice columns were connected to these frozen rills.
The ice columns and frozen rills may provide a snapshot or 'schematic' diagram of the major flowpaths in a ripe and draining snowpack.

We also operated an array of 36 snow lysimeters in 1998 and 106 snow lysimeters in 1999 and 2000.

Project Training and Development:

1) Given that this switch between gravity-flow dominant and capillary-flow dominant regimes seems to occur at relatively high meltwater flux values, possibly as high as 2 mm hr-1, this has considerable implications for other work and models

which ignore capillary effects in their treatment of water movement through snow, as they are likely to be in some degree of error at lower meltwater flux ranges, in which much of the seasonal melt will occur under natural conditions at most locations. The switch between flow regimes will occur diurnally, with a switch between capillary-flow and low lysimeter discharge during the morning, and gravity-flow and high lysimeter discharge later in the afternoon, this would also go some way to explaining daily patterns of chemical concentration in the meltwaters, which are high at low discharge as capillary water flows around grain boundaries removing impurities. and lower at high discharge, when flow consists largely of gravity-flow which has been moving through snowpack pore-space with limited interaction with individual grains. All the wavespeeds analyzed in this study were based on the falling limb of the diurnal hydrograph, when gradual drainage would result in a slow change from gravity- to capillary-flow.

Three independent techniques were used to test the hypotheses presented in the introduction: (1) low pass spatial filtering to identify multimodal brightness distributions in near infrared images of melting snowpacks; (2) variograms of the spatial distribution of meltwater from the bottom of melting snowpacks; and (3) capacitance measurements of the liquid water content of the upper surface of melting snowpacks.
The three
techniques support the hypotheses presented in the introduction.
.IP [1]
The characteristic distance separating bimodal reflectance peaks from aerial photographs of a draining snowpack in Colorado would be the same as that reported by Sommerfeld et al. [1994] for a Wyoming snowpack. The characteristic distances from the aerial photographs reported was approximately 6m.
.IP [2]
The frequency of bimodal distribution of brightness values from aerial photographs of snow covered area would increase from early in the melt season to later in the melt season.
The probability of finding multimodal
brightness distributions increased from 0.22 to 0.60 and 0.68, corresponding to the extent of snow melt.
.IP [3]
Direct measurements of the liquid water content of the snow surface will have the same characteristic distance as bimodal distributions of brightness values.
Although there was a finer spatial structure evident in the
liquid water measurements, regions of higher and lower liquid water content segregated into separate areas of about 5 m in diameter.
Variograms showed
a sill at about 5 m and appeared to indicate an anticorrelation at about 10 m although the data at this distance is limited. The characteristic length of meltwater discharge measured in snow lysimeters at the base of the snowpack will have the same characteristic length as the bimodal brightness distribution of aerial photographs.
Variograms indicate that correlation length of the meltwater collectors is 5 to 7 m and there is an indication that the melt is anticorrelated at about twice that distance.
Our results suggest that
there is a positive feedback
system such that as snow melt
advances in time certain
areas receive more meltwater
than others.
As rill areas form on the snow surface
the flow fingers and ice columns associated with these features carry

more meltwater than the lateral contributing areas.
These ice columns continue to grow in diameter as liquid
water freezes on the outside of the existing ice columns.
a growth mechanism analogous to the formation of icicles.
In contrast.
once the surface rills are formed much less liquid water
flows in the fingers or ice columns in areas between rills.
Consequently these small ice columns do not grow in size
and melt out over time in a warm snowpack.

.IP [4]

Research Training:
STUDENTS SUPPORTED
.XP
Erickson, Tyler.,
matriculates Fall, 2000,
with a one-year Keck Foundation Fellowship.
He has a masters in Engineering from CalTech,
where he had an NSF Pre-doctoral Fellowship.
.XP
Hood, Eran.
received a 2-yr GRT Fellowship in Hydrology
and a one-semester International GRT Fellowship
to conduct research in South America.
Masters: Sublimation from a seasonal snowpack,
Niwot Ridge, CO,
Geography Department,
University of Colorado, Boulder,
.XP
Rikkers, M. R.,
Spatial Variability of Liquid Water Content
in an Alpine Snowpack, Niwot Ridge, CO,
Department of Geography,
University of Colorado, Boulder,
1997.
.XP
Mrugala. R. J.,
Effects of Original Snow Density and Magnitude of Temperature
Gradient on Grain Growth and Sintering Processes in Snow
A.S. Geological Sciences, University of Colorado, Boulder. 1997.

1998.

Outreach Activities:
I have developed an internship program in snow hydrology
for undergraduate students that utilizes the equipment
purchased through this grant.

Journal Publications

Fox, A., M. W. Williams, and N. Caine
, "Equivalent permeability of a continental,
alpine snowpack in the Colorado Front Range", *Water Resources Research*, p. , vol. , ().) Submitted
Mrugala. R. and W. T. Pfeffer. "Temperature gradient and initial snow density as controlling factors

in the formation and structure of hard depth hoar", *Journal of Glaciology*, p. , vol. , ().) Submitted
M. W. Williams, M. R. Rikkers, and W. T. Pfeffer, "Ice columns and frozen rills in a warm snowpack,
Green Lakes Valley, Colorado, USA", *Nordic Hydrology*, p. , vol. , ().) Accepted
Erickson, T. A.,
M. W. Williams, and R. A. Sommerfeld, "Spatial statistics of snowmelt,
Conference on Applied Mathematics in Groundwater Hydrology", *Proceedings of the XIII International Conference on Computational Methods in Water Resources, Calgary, Canada, June 2000, A.A. Balkema Publishers, Rotterdam*, p. 1147, vol. 2, (2000).)

Published
Williams, M. W.,
D. Cline,
M. Hartmann, and
T. Bardsley, "Data for snowmelt model development,
calibration, and verification at an alpine site,
Colorado Front Range", *Water Resources Research*, p. 3205, vol. 35, (99).) Published
Williams, M. W.,
R. Sommerfeld,
S. Massman, and
M. Rikkers, "Correlation lengths of vertical flowpaths
in melting snowpacks, Colorado Front Range, USA", *Hydrologic Processes*, p. 1807, vol. 13, (1999).) Published
Williams, M. W., T. Bardsley, and M. Rikkers, "Oversampling of snow and overestimation of
inorganic nitrogen wetfall using NADP data, Niwot Ridge,
Colorado", *Atmospheric Environment*, p. 3827, vol. 32, (1998).) Published
Williams, M. W., T. Bardsley, and M. Rikkers, "Oversampling of snow and overestimation of
inorganic nitrogen wetfall using NADP data, Niwot Ridge,
Colorado", *Atmospheric Environment*, p. 3827, vol. 32, (1998).) Published

Books or Other One-time Publications

Web/Internet Sites

URL(s):
http://snobear.colorado.edu/Markw/Research/snowhydro.html
Description:

Other Specific Products

Product Type: Data or databases
Product Description:
Meteorological data for snowmelt model development
is collected, archieved, and turned into energy fluxes.

Sharing Information:
Data is available over the web using an interactive browser system
at http://culter.Colorado.EDU/Subnivean/

The data set has been advertised to other researchers through
a peer-reviewed publication in Water Resources Research

Product Type: Instruments or equipment developed
Product Description:
We have developed a snow hydrology research station that includes:
subnivean laboratory, line power, full meteorological station,

106 snow lysimeters, and other helpful instrumentation.

Sharing Information:
Biologists are using the equipment to investigate snow/soil interactions.

Product Type: Instruments or equipment developed
Product Description:
Tomographic visualization of meltwater flowpaths in snow using ground-based radar

Sharing Information:
Nothing yet.

Contributions

Contributions within Discipline:
We are the first research group to show that there appears to be spatial structure in the movement of meltwater through snow. Our research provides the impetus to look at meltwater flow through snow at scales larger than the plot scale.

Secondly, our results indicate that capillary forces are more important than previously thought and must be incorporated in snowmelt models at velocities less than 2 mm/hr.

Third, our preliminary work with ground-based radar provides a new tool by which to non-destructively measure the material properties of a wet snowpack.

Contributions to Other Disciplines:

Contributions to Human Resource Development:

Contributions to Science and Technology Infrastructure:

Beyond Science and Engineering:

Categories for which nothing is reported:

Organizational Partners
Any Book
Contributions: To Any Other Disciplines
Contributions: To Any Contributions to Human Resource Development
Contributions: To Any Science or Technology Infrastructure
Contributions: Beyond Science or Engineering