HEAT TRANSFER IN HYDROLOGY

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In 1968 Price and Heindl carried out an extensive library search and came up with 31 definitions of the term hydrology currently being used in the literature. Obviously, for any rational discussion of heat transfer in hydrology it is imperative that only one of these definitions be accepted and for this talk I would like to use the following. Hydrology refers to the study of all phases of the hydrologic cycle (precipitation, evaporation, interception, infiltration, soil moisture movement, surface and ground water flow, etc.) and also the interactions between water and its environment - physical, chemical, economic and political - in relation to human interests.

The "hydrologic cycle" is a concept which treats the processes of motion, loss and recharge of the earth's water as a continuum. The cycle may be divided into three principle components: precipitation, evaporation and runoff, either through the ground or along the ground surface. Within each of these components water undergoes transportation, temporary storage and a change in phase. For example, in the precipitation component there occurs vapour flow, vapour storage in the atmosphere and condensation or formation of precipitation.

Heat transfer processes are important in all parts of the hydrologic cycle. Significant precipitation only occurs when an air mass is lifted by some mechanism such as: by a mountain range or differential heating.
OF LAND AND AIR MASSES OR AGAIN THROUGH ADIABATIC EXPANSION AND
SUBSEQUENT COOLING AT A FRONTAL SYSTEM. ON COOLING, CONDENSATION OR
SUBLIMATION OCCURS WHICH RESULTS IN DROPLET FORMATION. SIMILARLY,
EVAPORATION IS A HEAT TRANSFER PROCESS. CONSIDER ALSO THE CASE OF A
MELTING SNOWPACK. THE TIME AND RATE OF MELT DEPENDS ON THE NET HEAT
EXCHANGE IN THE SYSTEM. IT IS THIS NET HEAT EXCHANGE WHICH DETERMINES
THE RATE OF RUNOFF, THE AMOUNT OF WATER WHICH IS AVAILABLE FOR INFILTRA-
TION INTO A FROZEN SOIL, OR THE AMOUNT OF EVAPORATION.

THE ABOVE FEW EXAMPLES DEMONSTRATE THE IMPORTANCE OF HEAT TRANSFER
PHENOMENA IN HYDROLOGY. KNOWLEDGE OF HEAT TRANSFER MECHANISMS IS THERE-
FORE ESSENTIAL IF WE ARE TO GAIN A PHYSICAL UNDERSTANDING OF ANY
HYDROLOGIC COMPONENT OR SYSTEM. HOWEVER, IT MUST BE RECOGNIZED THAT
"HYDROLOGY" IS NOT AN "EXACT SCIENCE". THE INFINITE NUMBER OF BOUNDARY
CONDITIONS WHICH EXIST IN NATURE AND AFFECT THE THERMAL REGIME OR
EXCHANGE PROCESSES MAKE THE ANALYSIS AND UNDERSTANDING OF THE SYSTEM
EXCEEDINGLY DIFFICULT. IN THESE REGARDS, IT IS A MUCH MORE CHALLENG-
ING TASK TO APPLY PRESENT DAY HEAT TRANSFER THEORY TO NATURAL FIELD
SYSTEMS THAN UNDER RELATIVELY WELL-CONTROLLED LABORATORY CONDITIONS.

INDEED, FOR MANY NATURAL SYSTEMS IT IS VIRTUALLY IMPOSSIBLE TO CONDUCT
A LABORATORY EXPERIMENT WITH ANY SIGNIFICANT RESULT. IN THE CASE OF A
MELTING SNOW PACK, FOR EXAMPLE, THERE ARE SOME 30 INDEPENDENT PARAMETERS
WHICH NEED TO BE CONTROLLED - A VIRTUAL IMPOSSIBILITY IN THE LABORATORY.
SIGNIFICANT CONTRIBUTIONS TO HYDROLOGY CAN BE MADE BY PERSONS WITH
EXPERTISE IN HEAT TRANSFER THEORY. OUR EXPERIENCE HAS SHOWN THAT IT IS
Much easier for a person with a strong theoretical background in heat transfer to adapt and become familiar with hydrologic phenomena than for a person trained as a hydrologist within a classical earth science discipline to become proficient in heat transfer theory. We believe that the primary thrust in hydrology should be directed to the gaining of a physical understanding of the individual processes in the hydrologic cycle so that they may be described and simulated mathematically. The major objectives of these studies should be directed toward the development of valid techniques for the transposition of results obtained from a given point in space and time to a spatial basis with a view to helping those people responsible for managing our water resources to assess future needs on a rational basis. This requires that all theories proposed must be applicable on a regional scale and the data and instrumentation requirements must be consistent with those included in a national network.

In hydrology, the laws of conservation of mass and energy apply to the system and its individual components. We believe that the conservation laws are a viable framework within which it is possible to gain a physical understanding of the hydrologic cycle, to discuss the relative magnitudes and importance of its components and to evaluate measurement and analytical techniques. In order to illustrate this point I would like to discuss the energy budget approach as applied to various hydrologic investigations.
A major activity of the Division of Hydrology in this University during the next few years is the development of a snow melt model for the prairie environment. This model must be capable of predicting the usual hydrologic parameters such as melt water runoff, rates and volumes. In addition, it will also be used to predict other physical parameters such as soil moisture and soil temperature.

We feel that a model of this complexity with so many potential outputs should be based on a good understanding of the physical processes involved in the snow melt, runoff and infiltration phenomena. Hence, it is necessary to carry out a detailed investigation of the energy budget for a prairie snow pack and to use the energy budget as the core of the model. We hope that if the model is given as much physical reality as possible we will be able to transpose the results to other areas and to make full use of inevitably sparse input data.

Over snow the energy budget has the following form:

\[
\frac{du}{dt} = Q_N + Q_{SH} + Q_{SM} - Q_{GC} - Q_{GM}
\]

Where \( u \) = the internal energy of the pack,
\( t \) = time,
\( Q_N \) = the net all wave radiation at the snow-air interface,
\( Q_{SH} \) = sensible heat transfer at the snow-air interface,
\( Q_{SM} \) = the net energy flux into the pack due to mass transfer at the snow-air interface (evaporation, condensation, snow, rain),
\[ Q_{GC} = \text{the heat flux by conduction from the snow to the ground, and} \]

\[ Q_{GM} = \text{the net energy flux from the pack due to mass transfer at the ground-snow interface (melt water, vapour movement).} \]

Note that the equation has a very simple form and, of course, the principle on which it is based is very well known.

However, the evaluation of each of these terms is not easy. The radiative term can be measured with reasonable accuracy by conventional methods (net radiation - Funk pyratiometer, solar radiation - Kipp and Zonen pyranometers) provided the instruments are operated efficiently and properly maintained.

The sensible and latent heat fluxes are normally calculated using formula which have been derived on the assumption that a boundary layer is developed at the ground-air interface in which wind speed, temperature and humidity profiles are established. The presence and the size of the boundary layer can only be determined from field measurements. In our own case, although we took every care in selecting our site it was not until the first years data had been analyzed that we were able to confirm that we had a measurable boundary layer.

A considerable number of sensors are required for this type of work (show fig. 2).

In our case 7 levels each of wind, temperature and humidity sensors are used. These are spaced logarithmically up to 2 meters above the snow.
IN ORDER TO CALCULATE THE ENERGY CHANGES WITHIN THE SNOW PACK THE 
DENSITY OF THE SNOW, ITS DEPTH AND THE TEMPERATURE VARIATION WITHIN THE 
PACK AS WELL AS THE LIQUID WATER CONTENT DURING THE MELT PERIOD MUST 
BE MEASURED. THE GROUND HEAT FLUX CAN BE MEASURED USING HEAT FLUX 
PLATES. IF AN ENERGY BUDGET IS TO BE CALCULATED DURING THE MELT PERIOD 
IT IS ALSO NECESSARY TO MEASURE THE RATE AT WHICH MELT WATER IS PRODUCED. 
A SNOW LYSIMETER WAS DESIGNED FOR THIS PURPOSE AND THE ENTIRE APPARATUS 
MOUNTED ON LOAD CELLS SO THAT EVAPORATION AND CONDENSATION RATES CAN BE 
MEASURED DIRECTLY.

THE FREQUENCY WITH WHICH MEASUREMENTS SHOULD BE TAKEN IS ALWAYS 
DIFFICULT TO DECIDE BUT FOR OUR PURPOSES BUDGETS OVER A TIME PERIOD OF 
LESS THAN ONE HOUR ARE CONSIDERED TO HAVE NO VALUE AND TO OBTAIN MEANING-
FUL HOURLY AVERAGES REQUIRES READINGS EVERY 5 OR 6 MINUTES. OBVIOUSLY, 
THese MEASUREMENTS CANNOT ALL BE MADE BY HAND - A COMPUTER CONTROLLED 
DATA ACQUISITION SYSTEM IS NEEDED.

I DO NOT WISH TO SPEND TOO MUCH TIME ON THE DETAILS OF THIS TYPE 
OF INSTRUMENTATION. NOTE, HOWEVER, THAT ALTHOUGH THE BASIC EQUATION IS 
SIMPLE, THE NUMBER OF INSTRUMENTS REQUIRED ARE CONSIDERABLE AND THE 
MONITORING OF THEM REQUIRES CONSIDERABLE EFFORT AS DOES THE DATA ANALYSIS. 
IN ADDITION, THE COST OF EQUIPMENT, THE DESIGN OF THE SYSTEM AND ITS 
MAINTENANCE REQUIRES A CONSIDERABLE INVESTMENT OF MONEY, THE DATA 
COLLECTION AND DATA ANALYSIS SYSTEMS MUST BE COMPATIBLE. FOR THIS TYPE 
OF WORK IT IS IMPERATIVE THAT DATA BE ANALYZED QUICKLY TO CHECK ITS 
QUALITY. IN THIS PART OF THE COUNTRY SNOW MELTS OVER A RELATIVELY SHORT
PERIOD OF SOME TWO WEEKS AND ANY LOST DATA CANNOT BE DUPLICATED. IT IS MOST UNLIKELY THAT CONDITIONS OF ONE YEAR WILL BE REPEATED THE NEXT.

THE MEASUREMENT PROBLEMS ARE INCREASED MANY FOLD WHEN "LINE" POWER IS NOT AVAILABLE - AS IS FREQUENTLY THE CASE IN THE FIELD. OUR PARTICULAR EXPERIENCE HAS INDICATED THAT THE MOST DIFFICULT PARAMETER TO MEASURE ACCURATELY AND RELIABLY AND THE ONE WHICH CREATES THE LARGEST NUMBER OF PROBLEMS IN TERMS OF POWER USAGE IS THE DEWPOINT TEMPERATURE.

ONCE THE ANALYSIS IS COMPLETE THE ENERGY BALANCE LOOKS LIKE THIS, (SHOW 3 DAY PERIOD).

EACH TERM IN THE BUDGET WAS CALCULATED INDEPENDENTLY OF THE OTHERS. THUS, IT IS POSSIBLE TO CALCULATE THE CUMULATIVE MEASUREMENT ERROR. WITHOUT THIS CALCULATION IT IS IMPOSSIBLE TO CARRY OUT A CONTINUOUS EVALUATION OF INSTRUMENT PERFORMANCE. FOR EXAMPLE, ON THE MORNING OF THIS PARTICULAR DAY THE ERROR CLOSELY FOLLOWS THE SENSIBLE HEAT TERM. THIS WAS A PERIOD OF LIGHT WINDS AND A STRONG TEMPERATURE GRADIENTS NEAR THE GROUND - A SITUATION IN WHICH THE VARIOUS FORMULA USED TO CALCULATE SENSIBLE HEAT PERFORM POORLY. ON THE SECOND DAY THERE IS A PERIOD WHERE THE ERROR follows THE NET RADIATION - OBVIOUSLY FOR THAT PERIOD THE PYRADIOMETER WAS EITHER NOT FUNCTIONING PROPERLY OR SEEING SOME ANOMALY (FOG PERHAPS?).

ON THE THIRD DAY THE SNOW MELTED AND THE ERROR INCREASED CONSIDERABLY MAINLY BECAUSE IT IS NEXT TO IMPOSSIBLE TO MONITOR THE INTERNAL ENERGY CHANGES IN A MELTING PACK, GIVEN CURRENTLY AVAILABLE INSTRUMENTS.
IT IS COMMON PRACTICE WHEN CARRYING OUT ENERGY BUDGET STUDIES TO OMIT MEASURING ONE OF THE TERMS IN THE EQUATION AND CALCULATING IT AS A RESIDUAL. THE DANGERS INHERENT IN SUCH A PROCEDURE ARE OBVIOUS FROM THESE EXAMPLES.

FOR ANY BUDGET CALCULATION IT IS ALSO IMPORTANT TO CARRY OUT AN ERROR ANALYSIS OR SENSITIVITY ANALYSIS TO DISCOVER WHICH MEASUREMENT HAS THE POTENTIAL FOR CAUSING THE GREATEST ERROR IN THE BALANCE. FOR THIS PARTICULAR INVESTIGATION IN WHICH THE BOUNDARY LAYER DEVELOPMENT IS KNOWN TO BE COMPLETE IT IS INTERESTING TO NOTE THAT ONE OF THE MOST IMPORTANT MEASUREMENTS AND THE ONE WHICH CAUSES THE GREATEST DIFFICULTY IS THE MEASUREMENT OF SNOW DEPTH. IT IS NOT ALWAYS EASY TO TELL WHERE THE SNOW STOPS AND THE GROUND BEGINS.

DATA OF THIS TYPE CAN BE USED DIRECTLY IN THE EVALUATION OF A MODEL AND VERY QUICKLY SHOWS WHICH OF THE PHYSICAL PROCESSES ARE NOT BEING DETERMINED CORRECTLY. HOWEVER, MODELS ARE CUMBERSOME THINGS TO USE AND IN MANY CASES A SIMPLE INDEX IS ALL THAT IS NEEDED TO AID A LAND USE OR RESOURCE STUDY. GIVEN THE INVESTMENT REQUIRED TO OBTAIN MEASUREMENTS OF THIS TYPE IT IS TO BE HOPED THAT RELATIVELY SIMPLE CORRELATIONS CAN BE DISCOVERED FROM THE DATA WHICH CAN BE USED QUICKLY AND EASILY BY A RESOURCE MANAGER AND WHICH WOULD REQUIRE THE USE OF ONLY ONE OR TWO INSTRUMENTS. THE TRADITIONAL APPROACH IN HEAT TRANSFER TO THE REDUCTION OF DATA IS TO SEARCH FOR RELEVANT DIMENSIONLESS GROUPS. THIS IS DIFFICULT TO DO IN THE PRESENT SITUATION GIVEN THE SCARCITY OF DATA BUT WE WILL CERTAINLY BE ATTEMPTING SOMETHING ALONG THESE LINES ONCE THE DATA FOR THIS SPRING HAS BEEN ANALYZED.
IN OUR OWN DIVISION THE BEST EXAMPLE TO DATE OF THE TYPE OF CORRELATION WHICH IS USEFUL AND EASY TO APPLY COMES FROM MEASUREMENTS MADE IN THE N.W.T.; 18 KM SOUTH OF TUKTOYAKTUK. THERE, A CORRELATION BETWEEN NET RADIATION AND THE GROUND HEAT FLUX WAS DEVELOPED IN A RATHER FORTUITOUS MANNER. ONE OBJECTIVE OF THE PROGRAM WAS TO EXAMINE THE APPLICATION OF THE ENERGY BUDGET FOR EVALUATING GROUND HEAT FLUX. BECAUSE OF A SHORT "TOOLING-UP" TIME WE WERE FORCED TO CONDUCT THE STUDY USING EXISTING EQUIPMENT TO PROVIDE DATA TO EVALUATE THE DIFFERENT COMPONENTS - RATHER THAN DEVELOPING A SYSTEM CAPABLE OF MEASURING THEM UNDER THE DIFFERENT BOUNDARY CONDITIONS ENCOUNTERED IN THE NORTH. STANDARD PROFILE TECHNIQUES WERE USED IN AN ATTEMPT TO EVALUATE THE SENSIBLE AND LATENT HEAT FLUX TERMS. MEASUREMENTS WERE MADE OVER AN UNDISTURBED TUNDRA POLYGON IN AN AREA BOUNDED BY GENTLY ROLLING HILLS AND SMALL LAKES. OUR INITIAL REVIEW OF THE DATA SHOWED THAT ALTHOUGH A LOGARITHMIC WIND PROFILE WAS DEVELOPED OVER THE SITE; THE DEVELOPMENT OF TEMPERATURE AND HUMIDITY PROFILES WAS INCOMPLETE GIVING RISE TO LARGE ERRORS IN THE ENERGY BUDGET. THIS IS UNFORTUNATE BECAUSE ENERGY BUDGETS ON THIS TYPE OF TERRAIN WOULD GIVE AN INSITE INTO MANY OF THE PROBLEMS ASSOCIATED WITH LAND USE AND VEHICLE MOVEMENT IN THE ARCTIC. IN PARTICULAR, A KNOWLEDGE OF THE HEAT FLUX INTO THE GROUND WOULD BE A USEFUL INDEX FOR CHARACTERIZING LAND TYPES AND TUNDRA DAMAGE. I WOULD LIKE TO SHOW A VERY SIMPLE CORRELATION WHICH CONCEIVABLY, COULD BE USED FOR THIS PURPOSE.

SHOW 6 - 13
- Explain Co-ordinates

- Explain that different slopes apply to rain-free and rain periods

- Explain that once curves are established the only instrument necessary to give an estimate of ground heat flux is a net pyrradiometer. Obviously this graph is much easier to use than a two layer model involving the ground-air interface.

Up to now I have confined my remarks to measurement at a single point on the ground. If a model or correlation is to be of any practical use it must be applicable to a large region of the country. The question then rises as to how point measurements can be extrapolated to the surrounding region. In other words—how does one decide whether the point measurements are representative or typical of a larger area?

In certain cases the extrapolation of point estimates may be made with reasonable confidence providing the sensor is "seeing" the parameter under conditions representative of a region. To illustrate this I would like to show some relationships between areally averaged values and point measurements for one of the parameters which often appears in an energy budget—namely the albedo. For those of you who are not familiar with the term the albedo is a ratio of the radiation reflected from the ground surface divided by the incoming radiation. A knowledge of this property and the incoming radiation enables one to determine the amount of radiant energy being absorbed by the ground. The next figure shows the variation in spatial albedo values over snow-covered surfaces on the
PRAIRIES HAVING DIFFERENT VEGETAL COVER. THESE DATA SHOW THAT ON THE OPEN FIELDS THE ALBEDO IS APPROXIMATELY 80 PERCENT WHEREAS OVER THE TREES OR BLUFFS IT DROPS TO A VALUE OF APPROXIMATELY 30 PERCENT. EFFECTIVELY, THESE SMALL BLUFFS ACT AS HEAT SINKS AND AS SUCH PLAY A SIGNIFICANT ECOLOGICAL ROLE IN THE PRAIRIE ENVIRONMENT.

THE NEXT SLIDE SHOWS THE TEMPORAL VARIATION OF ALBEDO MEASURED AT A POINT AND SPATIALLY-AVERAGED VALUES OBTAINED FROM THE BAD LAKE WATERSHED IN SOUTHWESTERN SASKATCHEWAN IN 1972. SEVERAL ASPECTS ARE OF INTEREST:

1. THE ALBEDO OF "OPEN" PRAIRIE SNOWPACKS REMAINS ESSENTIALLY CONSTANT DURING THE MELT-FREE PERIODS SHOWING ONLY SHARP BUT RELATIVELY SHORT-TERM TIME VARIATIONS IN MAGNITUDE CAUSED BY THE FALL OF FRESH SNOW.

2. DURING THE MELT PERIOD THE ALBEDO OF A PRAIRIE SNOWPACK CHANGES AT AN ACCELERATING RATE. THIS CAN BE ATTRIBUTED TO METAMORPHISM OF THE SNOW PACK, THE PENETRATION OF SOLAR RADIATION TO THE UNDERLYING GROUND SURFACE, AND THE DEVELOPMENT OF PATCHY SNOW COVER. AT PRESENT NO PROCEDURE HAS BEEN DEVELOPED TO ACCOUNT FOR THE INCREASE IN THE SUPPLY OF HEAT TO SNOW COVERED AREAS DUE TO ADVECTION FROM THE SURROUNDING BARE PATCHES.

3. THE POINT MEASUREMENTS AND SPATIALLY-AVERAGED VALUES ARE IN REASONABLY CLOSE AGREEMENT. THIS ASPECT IS PARTICULARLY IMPORTANT AS IT PROVIDES A MEASURE OF SUPPORT FOR USING POINT MEASUREMENTS FOR SPATIAL ESTIMATES. THESE RELATIONSHIPS


ANOTHER PROBLEM ENCOUNTERED IN EXTRAPOLATING POINT ESTIMATES OF THE RADIATIVE TERMS IS THAT THEY MUST BE ADJUSTED FOR SLOPE AND AZIMUTH. TABLE 2 SHOWS THE RESULTS OF ENERGY BUDGET CALCULATIONS CONDUCTED OVER TWO SMALL WATERSHEDS OF THE SAME SIZE (0.12 km²) ONLY ONE WAS NORTH-FACING (UNIT 4) AND THE OTHER SOUTH-FACING (UNIT 5). IN THE CALCULATIONS THE DIRECT BEAM SOLAR RADIATION COMPONENT WAS ADJUSTED FOR SUN ANGLE, SLOPE AND ASPECT. IN COMPARING THE VALUES GIVEN IN THE TABLE IT WAS FOUND THAT FOR THE PERIOD OF CALCULATION THE HEAT BALANCE WAS 4.94 M J m⁻² ON THE NORTH-FACING UNIT AND 26.15 M J m⁻² ON THE SOUTH-FACING UNIT.
**TABLE 2**

DAILY ENERGY BUDGET ESTIMATES FOR EACH OF THE 6 UNITS OF THE WATERSHED

(*the units are N m$^{-2}$*)

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<th>DATE-TIME</th>
<th>WATERSHED UNITS</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>NO. 4</td>
</tr>
<tr>
<td>SLOPE (°)</td>
<td>20</td>
</tr>
<tr>
<td>ASPECT (°)</td>
<td>9</td>
</tr>
<tr>
<td>AREA (km$^2$)</td>
<td>0.12</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>DATE-TIME</th>
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<tbody>
<tr>
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<td>-0.38</td>
</tr>
<tr>
<td>17/1700 - 18/1700 CST</td>
<td>0.71</td>
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<tr>
<td>18/1700 - 19/1700 CST</td>
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<tr>
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<tr>
<td>21/1700 - 22/1700 CST</td>
<td>0.31</td>
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</tbody>
</table>
THE DIFFERENCE IS SIGNIFICANT AND CLEARLY DEMONSTRATES THE NECESSITY OF ADJUSTING THE NET RADIATION TERM FOR SLOPE AND ASPECT IN APPLYING THE ENERGY BUDGET TO WATERSHEDS WITH HIGH RELIEF.

ALTHOUGH CERTAIN HYDROLOGIC MEASUREMENTS (E.G., ALBEDO, AIR TEMPERATURE, CLEAR SKY RADIATION) MAY BE EXTRAPOLATED WITH CONFIDENCE, TECHNIQUES AND METHODS NEED TO BE DEVELOPED FOR OTHERS. THIS PROBLEM MUST BE SOLVED BEFORE A GENERALIZED HYDROLOGIC MODEL APPLICABLE TO DIFFERENT PHYSIOGRAPHIC REGIONS MAY BE DEVELOPED AND SUCCESSFULLY APPLIED AND THE DEVELOPMENT OF THESE TECHNIQUES IS A MAJOR CHALLENGE FOR HYDROLOGY IN THE COMING YEARS.

SUMMARY

1. HEAT TRANSFER PROCESSES; RADIATION, CONVECTION, CONDUCTION AND MASS TRANSPORT ARE IMPORTANT IN ALL HYDROLOGIC PROCESSES. SIGNIFICANT CONTRIBUTIONS TO A PHYSICAL UNDERSTANDING OF THESE PROCESSES CAN BE MADE BY PERSONS COMPETENT IN HEAT TRANSFER THEORY.

2. HYDROLOGIC SYSTEMS MUST BE STUDIED UNDER NATURAL FIELD CONDITIONS. THE VALUE OF THEORETICAL AND LABORATORY STUDIES ARE LIMITED UNLESS CONFIRMED BY FIELD EXPERIMENTS.

3. DETAILED HYDROLOGIC STUDIES DIRECTED TO GAINING AN UNDERSTANDING OF THE PHYSICAL SYSTEM REQUIRE MEASUREMENTS OF MANY PARAMETERS. THE EQUIPMENT REQUIRED MUST BE CAPABLE OF OPERATING UNDER ADVERSE WEATHER CONDITIONS AND
REPRESENT LARGE CAPITAL EXPENDITURES. BECAUSE OF THESE COSTS AND THE FACT THAT HYDROLOGIC EVENTS MAY NOT BE REPETITIVE WITHIN THE MEASUREMENT PERIOD, ANALYTICAL SYSTEMS MUST BE DESIGNED TO BE COMPATIBLE WITH THE ACQUISITION SYSTEMS TO ENABLE THE QUALITY OF THE DATA TO BE CHECKED AT FREQUENT INTERVALS.

4. THE COMPONENTS OF THE ENERGY BUDGET SHOULD BE EVALUATED INDEPENDENTLY.

5. SIMPLE CORRELATIONS SUITABLE FOR USE BY MANAGEMENT AGENCIES MAY FREQUENTLY BE FOUND BETWEEN DIFFERENT HEAT TRANSFER MECHANISMS IN HYDROLOGY. SUCH CORRELATIONS ARE OFTEN THE BY-PRODUCT OF AN INTENSIVE MEASUREMENT PROGRAM, AND IN SUCH CASES CAN BE PHYSICALLY EXPLAINED.

6. A MAJOR PROBLEM IN HYDROLOGY IS THE REPRESENTATIVENESS OF POINT MEASUREMENTS AS THEY MAY BE USED AS ESTIMATES OF SPATIALLY-AVERAGED VALUES.