EXPERIMENTAL WATERSHEDS AS A TOOL
IN HYDROLOGIC RESEARCH

by

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INTRODUCTION

The role and value of 'selected small watersheds' in a hydrologic research program has been established and accepted throughout the world. In essence, they serve the dual function as a research facility and as a field laboratory for the education of students in hydrological sciences. As a research facility, their principal function is to provide an area on which hydrologic phenomena (e.g. precipitation, evapotranspiration, infiltration, soil moisture, surface runoff, groundwater and others) may be studied in detail to gain a physical understanding of the phenomena.

It is intended that the results from studies undertaken on small watersheds may be extrapolated both with respect to space and time to similar physiographic units to provide more accurate predictions for flood forecasting, reservoir regulation and other water management problems.

In watershed research, the term 'small' must be considered in a relative sense for 'small watersheds' may vary in size from a few acres to perhaps more than 100 square miles. Size is predicated on the nature and objective of the study. Mathematically, the term can be assumed as a boundary condition chosen so that detectable responses in the hydrologic variable can be sensed with available equipment, yet not so large that the study must be constrained due to physical and financial factors. For example, studies of the character (spatial and temporal) of thunderstorm
precipitation must be conducted on relatively large areas in order to obtain viable results, whereas useful information about the evapotranspiration of different crops may be obtained from small plots on which soils and microclimate are reasonably uniform and homogeneous.

With the inception of the International Hydrological Decade program (IHD) in 1965, sponsored by the United Nations Educational Scientific and Cultural Organization (UNESCO), watersheds have been categorized to two types:

1. **Representative Basins:** those basins where intensive studies are conducted related to either the water cycle in its entirety or on specific problems under relatively unchanged natural conditions. Research in these basins is generally orientated either to the methodology of scientific hydrology and fundamental studies of the mechanics of hydrologic phenomena, or to an ultimate regional analysis for the estimation of water resources and hydrological forecasting.

2. **Experimental Basins:** those basins on which fundamental studies on the water balance and its components are conducted in order to evaluate the effects on the hydrologic characteristics of an area by changes in land use (e.g. deforestation) and/or land management (e.g. terraces, contour banking), the conservation of water (quantity and quality) and soil, and use of groundwater resources through pumpage, artificial recharge, etc.
In these descriptions it is implied that the essential difference between a Representative Basin (RB) and an Experimental Basin (EB) is that on the latter, natural conditions are deliberately changed in order to quantitatively evaluate the effect of the manipulative treatment on one or more phases of the hydrologic cycle. However, it should be recognized that on Representative Basins and Experimental Basins the goal is not to collect data but rather to obtain a solution to a specific hydrologic or water resource problem.

As a matter of interest, in 1965, it was estimated that there were approximately 500 Representative Basins and 200 Experimental Basins either under investigation or proposed, all over the world. Today, in Canada, under the IHD program there are approximately 34 Representative Basins and 11 Experimental Basins, located throughout the country. Studies on these watersheds range in scope from the study of the ground-water component alone to complete mass water balances under forested, semi-arid or glacier conditions.

**BASIN SELECTION**

In selecting a research basin for study, the first consideration is that it must meet the objectives of the research program. The second is that it must be as simple as possible.
No results from research conducted on basins can possibly make sense unless the objectives are clearly stated in the planning stage, even though experience and understanding gained during the course of the work may lead to their modification. A pre-conceived idea of the hydrologic cycle influences the kind of information one sets out to obtain, but it is hoped that in turn this information will lead to a better understanding of hydrology.

All basin studies, regardless of classification, should therefore be planned so as to further the development and understanding of the mathematical and physical relationships between the various components of the hydrologic cycle and to resolve some of the complexities of the science of hydrology. If these objectives can be realized it is presumed that some type of model, whether it be conceptual, statistical, mathematical or physical may be generated to accurately reproduce past conditions and to predict future events. In this context, it is accepted that this synthesis should be attempted first on small watersheds (Representative Basins and Experimental Basins). The adequacy of such models depends upon the use to which they will be put. For example, a given rainfall-runoff model may be adequate for predicting the peak discharge rate from a storm but inadequate for predicting the total yield.

Much can be done using existing models, particularly those developed for large catchments and river systems. For example, a company
has been established in the United States whose sole function is to run a computer programmed model of a watershed using data supplied by clients, in order to provide water management information.

The objectives in watershed hydrology of understanding the physical processes may be divided into five major research areas. These are:

1. To describe the time-space distribution of precipitation as the input to the watershed system.
2. To describe the passage of water to a well-defined channel.
3. To describe the passage of water along a channel or system of channels.
4. To describe the entry of water through the surface of a soil, its movement downward and groundwater flow.
5. To describe evaporative losses from the system.

There are also transport processes which are often studied in research of watersheds. They are concerned with water quality and sediment.

A particular study may take one of several forms. It may be comprehensive and attempt to include all these processes in a total system study. This is normally referred to as a 'water balance' and it is attractive in that it allows the idea of continuity to be used as a check on the model. This approach is not usually successful, however, because the calculation of quantities contributed by each of the component processes is difficult to assess.
Often, one component in particular is more difficult to determine than the others. The idea of continuity is then used to evaluate the missing term as the residual in the water balance equation. This missing term can be almost any component of the water balance, depending on the circumstances of the study. For example, one study of the Great Lakes uses 'calculated evaporation' and the water balance to estimate 'precipitation', whereas in the Big Quill Lake study, precipitation is measured, evaporation calculated and this is then used with the water balance to estimate groundwater movement into or out of the lake.

There is a tendency now, however, to be less comprehensive in the approach to watershed research and to concentrate efforts on one of the above defined research areas. Further to this, in an effort to understand the processes themselves better, each hydrologic process may be subdivided for intensive study. For example, such studies, may simply encompass the vertical movement of water in a snow pack in relation to spring runoff floods.

A second objective in basin research is to survey time and/or space distributed parameters such as the groundwater regime or precipitation statistics. At first glance, such studies do not seem to be research so much as compilation of data. However, this is not entirely true, for experience gained from such work is a necessary part of any basin research program. It provides an opportunity of obtaining evidence of phenomena
whose existence would not otherwise be known. For example, continuous
snowfall measurements made under normal, highly-exposed, Prairie conditions
may indicate high runoff potential. However, due to redistribution of the
snowpack by wind, large gully accumulations are produced. Often snow
melts and disappears from adjacent flat areas before any measurable
runoff occurs because the gully accumulations act as a storage reservoir
for runoff contributions from the adjacent areas. As a consequence, the
movement of water to the outlet or gauging site may be delayed, its peak
cflow will be attenuated and the total amount of water leaving the watershed
in the channel may be reduced.

It is partly such experience of a system that enables us to propose
models of it. On the other hand, it is the understanding gained by such
efforts to model the system that enables us to recognize the significant
new evidence. In this connection, it might be mentioned that whereas
mission-orientated work adds economic justification and incentive to a
program and enables objectives to be well defined, insofar as it does not
look for unexpected events, it cannot be considered sufficient research on
its own.

The experience gained by observations which are made specifically
for process models has a more fundamental place as an objective however.
This is because it is necessary to describe the system itself before one
can give an account of the processes taking place within it.

This presents problems of technique which in turn require subsidiary research programs. For example, in studying runoff from a Prairie watershed, one of the important parameters is topography. Even when there is a very detailed topographic map of a watershed available, this map in itself does not describe topography in a way that lends itself easily to comparison of areas. It is necessary to abstract from it some quantitative description of such factors as relief, frequency distribution of elevations, stream densities and drainage development. Similar problems arise in the simple delineation of the topographic divide of a watershed in a region which has a rather flat topography. In mountainous areas, the primary problem may be one of delineating the groundwater divide or whether the basin can be considered as 'leaky'.

This leads to the second requirement in the selection of a research watershed; namely, it should be as simple as possible. Both the processes of the hydrologic cycle and the physical system in which they take place are very complex and difficult to describe. Consequently, they present severe theoretical and practical problems to anyone attempting to do research on them. However, this is often an attraction of hydrologic research.

These problems may be restricted somewhat if a basin can be selected in which the system parameters are homogeneous. However, this criterion
leads to the problem of defining basin homogeneity.

The knowledge which is required in order to make such a selection is the observational data whose acquisition is part of the objective. Hence, we have the dilemma that we need the research results in order to decide where to conduct the research. A compromise is necessary. Regional data are collected sparsely and, on the basis of this survey, details are filled in where they seem necessary. The watershed is then selected and it is hoped that the research program will vindicate the choice.

The parameters most frequently used as a measure of basin homogeneity are:

1. Stratigraphy.
2. Soil type.
3. Topography.
4. Climate.
5. Vegetal cover.

In mountainous areas it is not usually possible to fulfill all these requirements and so they must be relaxed. This means that one may be forced to assume a trend in each parameter associated with elevation. This constraint is perhaps not too severe a problem because results from such studies can probably be used in a similar area, but it does mean that the individual hydrologic processes may vary considerably throughout the watershed. For example, both precipitation distribution and snowmelt depend strongly upon elevation.
There is another aspect of the homogeneity requirement involved in the selection of a Representative Basin, and that is, there should be a high degree of regional homogeneity. Some variation is acceptable because it is the intention of the study to gain an understanding of the effect of the system parameters on the hydrologic processes. For example, in a mountainous, forested region some allowance may be made for the variation in watershed size such that the results obtained from one watershed may be directly applicable to another. Clearly, however, such results would be of little use applied directly to Prairie conditions.

If the watersheds are chosen to represent regions which are defined by their homogeneity, there is little problem. However, if a study is to be conducted in a large area, defined for example, by a regional economic development, then it may prove difficult to select a satisfactory watershed for study. In particular, there should not be artificial changes in the regime of a watershed during the period of study or calibration, and since urban or industrial development is closely associated with water management, it is rather difficult to achieve such control.

On an Experimental Basin, where the effects of artificial or land management changes on the hydrologic cycle are to be studied, it may be necessary to introduce additional criteria in the selection of a suitable basin. These criteria have to be considered in terms of industrial
development and advancement in technology. For example, a basin could be selected on the basis of uniformity of stand of merchantable saw timber. However, after the calibration period of the watershed, it might be found that the major regional development was to be concerned primarily with timber for the pulp industry, in which case, because of the differences in logging techniques, the original basin could be considered as being poorly selected. Certainly, an Experimental Basin, if it is to incorporate prediction in industrial demands, requires a more visionary outlook in its selection than a Representative Basin which is selected simply on the basis of the five homogeneity parameters listed above.

In concluding the remarks on Representative Basin selection, it should be pointed out that whereas homogeneity is easier to achieve in a smaller watershed, nevertheless physiographic details which may be unimportant on a regional scale can in a small watershed become significant and thereby offset some of the advantage in selecting it. Also there may be processes occurring on a regional scale which are difficult to detect and account for when the research is confined to a small watershed. For example, there is frequently a regional groundwater regime which may interact with the local groundwater flow processes occurring in the watershed.

There is, however, one particular advantage which is gained in the selection of a small watershed and that is in the amount of instrumentation
required. In general, the amount of instrumentation needed to meet the data requirements is proportionately less, and the travelling time and the personal requirements for servicing instruments are correspondingly reduced. This is especially true in remote areas where even the means of access may limit the practical extent of a research project.

BASIN INSTRUMENTATION

From the foregoing discussions it is apparent that the detailed objectives and physical circumstances of a study vary. This has lead to a variety of instrumentation problems.

There is, of course, a large variety of commercially available equipment, or equipment manufactured especially for government agencies, which is readily available for making hydrological measurements. Because they are so numerous it is not possible in this presentation to describe all these instruments in detail. It may be useful, however, in order to provide some indication of the variety of instrumentation available, to review briefly just those instruments used for the measurement of rainfall.

There are three different kinds of recording rain gauge. They are referred to by their principles of measurement - siphoning water level, tipping bucket and weighing. Each is available in a variety of forms and they may record on charts or perforated tape. In addition, there are innumerable non-recording rain gauges. These are simply vessels whose
catch of rain is measured periodically by a visiting observer.

The quality of measurements from rain gauges varies considerably in reliability, resolution and so on. Many are quite unsuited to watershed research and, in spite of substantial effort by independent research groups, there is no method of avoiding errors in measurement of 20\% or more in the catch due to the aerodynamic effect caused simply by the presence of the gauges.

Some effort has been made to devise other means of measurement, but at the moment this has to be considered as instrument research and its benefits are not yet available to watershed research.

These problems are not all associated with the instruments themselves. Sites have to be found for them and even when sites are found that provide good exposure and convenient access, they may not give representative records if they are not typical of the environment.

Other parameters of the hydrologic system and its processes have their problems of measurement, but the variety of instruments of qualified suitability and the difficulties of selecting good sites for them are common. Many of the commercially available instruments have the advantage that they has simple because they were designed either for use by untrained observers or for use in national networks where they receive minimum maintenance. One of the reasons they are frequently used in research watersheds is because their ruggedness gives a better chance of continuous
records being maintained. Simplicity also makes for inexpensive instruments. The disadvantage, of course, is that they may not be collecting data of adequate quality, and data from inexpensive instruments may be expensive to collect and process. (A fact frequently overlooked.)

In response to this dearth of suitable instruments, much original thought is being contributed and the use of modern instrumentation techniques alone has revolutionized measurement methods. An example of such a development is the neutron soil moisture meter. Although this instrument is far from perfect, in comparison with previous methods, it is a tremendous improvement.

One consequence of the dissatisfaction with available equipment is that one must ask what constitutes a good instrument. The answer is contained in the research objectives. Consider the modelling of processes. Criteria set by process models can be established beforehand from a preliminary examination of the model which, with other experience, can give the time or spatial resolution required. Analytical exactness is not possible, although it is implied by models without error statements. Error in this sense does not imply failure but a measure of the accuracy of measurements and predictions. The examination of the instrumentation errors and modelling errors constitute a subject in themselves, and there is not space to consider them further here. It should be stressed, however,
that it is the objectives of a study which decide acceptable error and an error is not intrinsically unacceptable because of its magnitude. For example, a prediction of sediment transport to within 10% of the true (but unknown!) quantity may be successful if measurements of actual transport cannot be made within 10% or the effect of changes of sediment transport of less than 10% can be detected.

Even when criteria or data quality are set by process models, they cannot always be met, especially when describing properties of a space – time continuous parameter which can only be sampled at discrete points in space and which, because of instrument properties, is averaged locally in space and time. It does not help to make more and more detailed measurements in either dimension because there is also the problem of signal to noise discrimination. It may merely be adding redundant information. In a paper in preparation Langham describes a new approach to data acquisition which overcomes the problem in the time continuum. The problem of satisfactory description of a spatially variable parameter is severe and with few exceptions seems at the moment to be very difficult to solve.

Successful methods of dealing with the problems of measuring spatially variable parameters will probably be quite different for each parameter. For example, there is under development a method of preparing
time-sampled synoptic maps of rainfall intensity based on ground radar. On the other hand, a promising technique that offers a means of surveying aquifers that are near the surface, depends upon the reflection of very long radio waves transmitted from an aircraft.

It has to be realized, of course, as with the original definition of objectives that the progress of the study may reveal a need to modify these criteria. For example humidity measurements over a regular network may show that fewer instruments would provide just as good data for a particular model.

This lead one to the influence of the second objective – the survey of the system – on choice of instrumentation. What kind of measurements are required when criteria are not set by a process model? Again a dilemma occurs: without prior knowledge of the data required, how can one decide what to measure and in what detail? For example, in gaining experience of the vapour pressure distribution in the study area, should one collect data with the dense network of instruments everywhere at the same height from the ground, or should a vertical profile be sought at a few selected sites? The time response of the instruments has also to be considered.

It is not always possible to make a rational decision because of this dilemma and much depends upon the experience and intuition of the
In general, it may be said that half the problems of hydrologic research are in data acquisition, but since it is from this data that our understanding is to develop, the effort that is needed to overcome these problems is justified.

SUMMARY

In manner of summary, it may be stated that the reliability of results to be expected from watershed research programs is contingent on proper planning, selection and definition of objectives during the initial stage of the program. Unfortunately, in Canada today few people possess the necessary expertise and experience to undertake comprehensive basin studies to fulfill those objectives outlined previously. Thus, "team" approaches need to be used in basin studies, both at the personal level, through combinations of natural scientists with mathematicians and people trained in modelling techniques, and at the agency level, by co-operation by organizations interested in hydrology throughout the scientific sector. Over-proliferation of basin research should be discouraged where as consolidation-of-effort and co-operation should be encouraged.

This leads to the inevitable discussion of the costs involved in basin research. Obviously, annual costs vary widely depending on the
nature of the study, personnel involved, physiographic conditions and innumerable other factors. However, for comprehensive studies, it is necessary that one thinks in terms of a minimum operating budget of $30,000 - $40,000 per year in addition to capital outlay. If a researcher does not have monies in these amounts at his disposal then his program should be scaled down proportionately. Experience gained through the IHD program has shown that many investigators, because of financial constraints, have had to reassess their study. Some of these problems have originated because of the lack of experience in the original planning. Nevertheless, the problem is significant in that it provides another reason for frequent re-examination of objectives and methods in research basins.

Finally, in the latter part of the paper, on the subject of data acquisition, the relative errors of hydrologic measurement and modelling have been stressed. Again, it is clear that the quality of data must be continually reviewed in terms of its use. Ultimately this leads to consideration of the entire data system; its acquisition, storage, retrieval, analysis and output. Too frequently, when considered in these terms studies in research basins are found to be 'over-instrumented' and to be producing a glut of data. To be consistent with the objectives of the program, the 'data system' must be considered in the initial planning stage so that output is reasonably immediate. Otherwise, the purpose of the program is defeated and it becomes an exercise in data collection.