Research Technical Completion Report

EVALUATION OF METHODS FOR ESTIMATION OF AQUIFER RECHARGE FROM PRECIPITATION ON SEMI-ARID LANDS

by

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ABSTRACT

Precipitation falling on semi-arid, non-irrigated lands may represent a significant percentage of total aquifer recharge in areas such as the eastern Snake River Plain in southern Idaho. Direct measurement of precipitation recharge is usually not feasible due to large areal concerns and non-uniformity of controlling conditions. A water budget may be applied in several forms, but often lacks the accuracy necessary. Inaccuracy of frequently used basic data such as precipitation is a primary deficiency. It was estimated that measured annual precipitation on the eastern Snake River Plain is in error by 15 to 20 percent. Application of sophisticated recharge estimation models is not justified due to errors in primary data.

INTRODUCTION

Ground-water recharge resulting from precipitation falling on semi-arid sparsely vegetated land is often incorrectly assumed to be of an insignificant magnitude. In many areas several factors work in concert to provide the mechanism for significant recharge. These factors include areal and temporal non-uniformity of precipitation, runoff accumulation, and limited soil moisture storage.

This project was an evaluation of methods for determining aquifer recharge from precipitation on the eastern Snake River Plain. Although the relative contribution of precipitation to the aquifer water budget on a unit area basis may not be large, the total magnitude is significant. Accurate estimates are necessary for a comprehensive understanding of the hydrologic system, and for calibration and operation of ground-water models used in managing the State's ground-water resource. This report discusses potential approaches and problems in estimating recharge from precipitation on non-irrigated lands. Recharge from precipitation on irrigated lands cannot be treated in a similar fashion and is not discussed.

PURPOSE AND OBJECTIVES

The purpose of this project was to investigate and critically evaluate the feasibility of methods to estimate recharge from precipitation on the non-irrigated lands of the Snake River Plain. The objectives were to examine data availability and accuracy of potential procedures and assess the impacts of data deficiencies upon anticipated results. If a superior method of estimation exists, procedures would be recommended for application of the method.

DESCRIPTION OF THE AREA

The Snake River Plain is a broad expanse of relatively flat land extending in an arc across southern Idaho (figure 1). The Plain follows the course of the Snake River, extending to mountains on both sides of the river. Irrigated agriculture has developed using water from the Snake River and other streams flowing from the surrounding mountains, and from ground-water sources. Most of the Plain remains unirrigated and is vegetated by sagebrush and grasses. There is little or no vegetative growth in some areas where the soil cover is thin and basalt outcroppings occur. Figure 2 shows the distribution of land use on the Snake River Plain.

The Snake River Plain is hydrologically divided into eastern and western portions, interconnected primarily by the Snake River. The 10,000 square mile eastern Snake River Plain extends from about Bliss in the southwest to Ashton in the northeast (figure 1) and is the focus of this project.

Figure 1. Location of the Snake River Plain

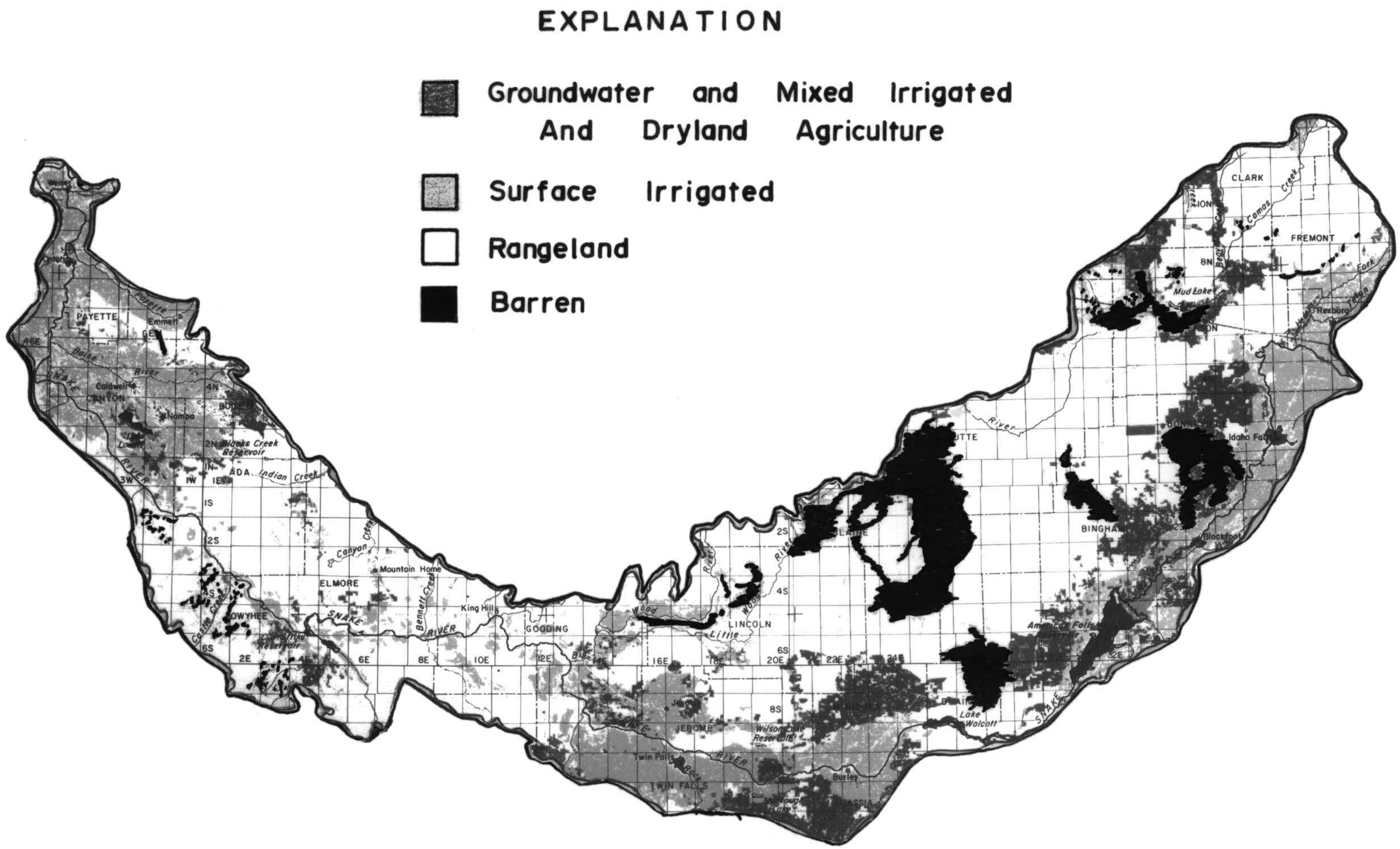

Figure 2. Snake River Plain land use map.

Annual precipitation on the eastern Plain ranges from about 8 inches in the central portion of the Plain to more than 22 inches in the northeast. About half of the annual total falls between October and March, contributing to winter snowpack accumulation. Spring snowmelt produces some surface runoff which accumulates in local depressions where it either infiltrates or is lost in evaporation.

The eastern Snake River Plain is underlain by the Snake Plain aquifer. The aquifer transmits large volumes of water (8 million AF/year) from recharge areas in the northeast to the southwest where most discharge is in the form of spring flows to the Snake River. The aquifer is recharged by percolation from irrigation, surface and underground flow from tributary valleys, losses from the Snake River, and by precipitation falling directly on the Plain. The approximate magnitude of recharge from these sources is given in table 1.

Table 1. Snake Plain aquifer recharge components.[1]

Sources	(Acre-feet/yr)	%
Surface water irrigation	5,095,500	60.3
Snake River loss	880,500	10.4
Tributary streams and canal loss	491,800	5.8
Tributary valley underflow	1,226,700	14.5
Precipitation	763,200	9.0
Total	8,457,700	100.0

[1] After Garabedian (1984); 1980 water year.

RELATED RESEARCH

Recharge from precipitation falling directly on the Plain accounts for an estimated 760,000 acre-feet of recharge which is 9% of the total annual recharge. Garabedian (1984) found this to be the least accurate estimate in the aquifer water budget. Previous investigators have estimated precipitation recharge by several indirect methods. Mundorff and others (1964) derived a rough relationship between precipitation and water yield in tributary basins and applied the relationship to parts of the Snake River Plain, assuming all water yield contributed to groundwater recharge. They concluded that precipitation recharge was about 500,000 acre-feet/year but emphasized the rough nature of the estimate and stated that it was probably an underestimate of actual recharge. Garabedian (1984) modified the estimates of Mundorff and others (1964) by incorporation of the effects of soil depth and water holding capacity. Kjelstrom (1984) performed a water budget on the Snake Plain aquifer and estimated recharge from precipitation to be about 600,000 acre-feet/year. All of these methods contain gross assumptions and yield only crude approximations.

EVALUATION OF ESTIMATION METHODS

Direct measurement of aquifer recharge resulting from precipitation can be accomplished at discrete points by measuring water movement through the soil profile. Extrapolation of discrete and probably sparse measurements to an extensive and highly variable landscape is difficult or impossible to achieve with a reasonable degree of confidence. Recharge at any point is sensitive to precipitation amount and intensity, runoff, soil characteristics and depth, vegetation type and density, slope, aspect, and climatic conditions. Attempting to classify and account for the effects of these factors over a large area such as the eastern Snake River Plain is a task of enormous proportions which results in estimates with a high degree of uncertainty. It is necessary to search for more simple, accurate methods of determining recharge from precipitation.

Indirect determination of precipitation recharge through solution of a water budget appears to be the only alternative. A water budget may be applied in any of several forms. A water budget on an aquifer balances recharge (including direct precipitation), discharge, and changes in ground-water storage. A total water budget for an area (such as a river basin) includes surface water inflows and outflows, subsurface flows, irrigation consumptive use, and precipitation recharge. A water budget can also be applied at land surface. This application balances precipitation, evapotranspiration, surface runoff, changes in soil moisture, and ground-water recharge. This form will be referred to as a soil water budget.

Procedures and problems expected in applying each form of water budget are discussed individually in the following sections.

Aquifer Water Budget

An aquifer water budget balances all components of aquifer recharge and discharge and changes in ground-water storage. The budget can be solved for a single unknown component assuming all other factors are known. As with all forms of water budgets, errors in known (estimated) components of the budget are carried into the value of the unknown parameter. Budget analysis is most successful when the unknown component is large relative to the other terms. The magnitude of precipitation recharge relative to other components is, in fact, the major concern in application of any form of water budget.

Aquifer water budgets cannot be successfully applied to estimate precipitation recharge to the Snake Plain aquifer. The budget solves for precipitation recharge as the sum of surface and underground flow from tributary valleys, gains and losses in the Snake River, irrigation application, crop consumptive use, seepage from streams and canals, and changes in ground-water storage. Recharge from precipitation is only about 9% of total aquifer recharge. Small errors in any, or all, of the other relatively large components creates unacceptably large errors in solution for precipitation recharge. The situation is complicated by a large degree of uncertainty in estimates of some terms. Garabedian (1984), using independent estimates of precipitation recharge, computed the Snake Plain aquifer water balance with a residual of 331,000 acre-feet/year. That is equivalent to 43% of the estimated precipitation recharge.

Total Water Budget

A total water budget balances all surface and ground water sources and losses for an area. The total water budget includes surface water elements as well as ground-water budget components. Therefore, items such as river-groundwater interaction are of no concern in the total water budget. The complexity of the budget is dependent on the area hydrology. In it's simplest form the budget may only include precipitation, evapotranspiration and stream discharge.

Application of a total water budget to the Snake River Plain is complicated by the numerous sources and losses of water. The budget components include precipitation, tributary surface flow, tributary ground-water flow, evapotranspiration from irrigated and non-irrigated lands, and Snake River discharge at the southwest corner of the Plain. Additional uncertainty exists in estimates of changes in ground-water storage. The component estimated with greatest relative accuracy is the Snake River discharge. A 5% flow measurement error is, however, equivalent to 400,000 acre-feet/year which is about 50% of the precipitation recharge. Estimation confidence of other components is less although the absolute magnitude of error may be no greater due to the smaller total magnitude of the component. Due to the overall uncertainty in budget components and the small relative magnitude of precipitation, a total water budget approach is not feasible. Application for total water budgets are limited to situations where errors in individual components are not large relative to the unknown term.

Soil Water Budget

A soil water budget maintains a balance of all elements effective at the soil surface. The components, illustrated in figure 3, include precipitation, evapotranspiration, runoff, soil moisture storage, and ground-water recharge. In this application, the ground-water recharge is determined as the sum of all other components. An advantage to the soil water budget is that recharge is determined independent of aquifer or river flows, which are often difficult to estimate with the necessary accuracy.

The number of independent terms in the water budget relationship can, in some cases, be reduced by simplifying assumptions. Application of the balance over a one year period, using average annual values for all terms, reduces potential errors resulting from changes in moisture storage in the soil profile. The soil moisture term can then be

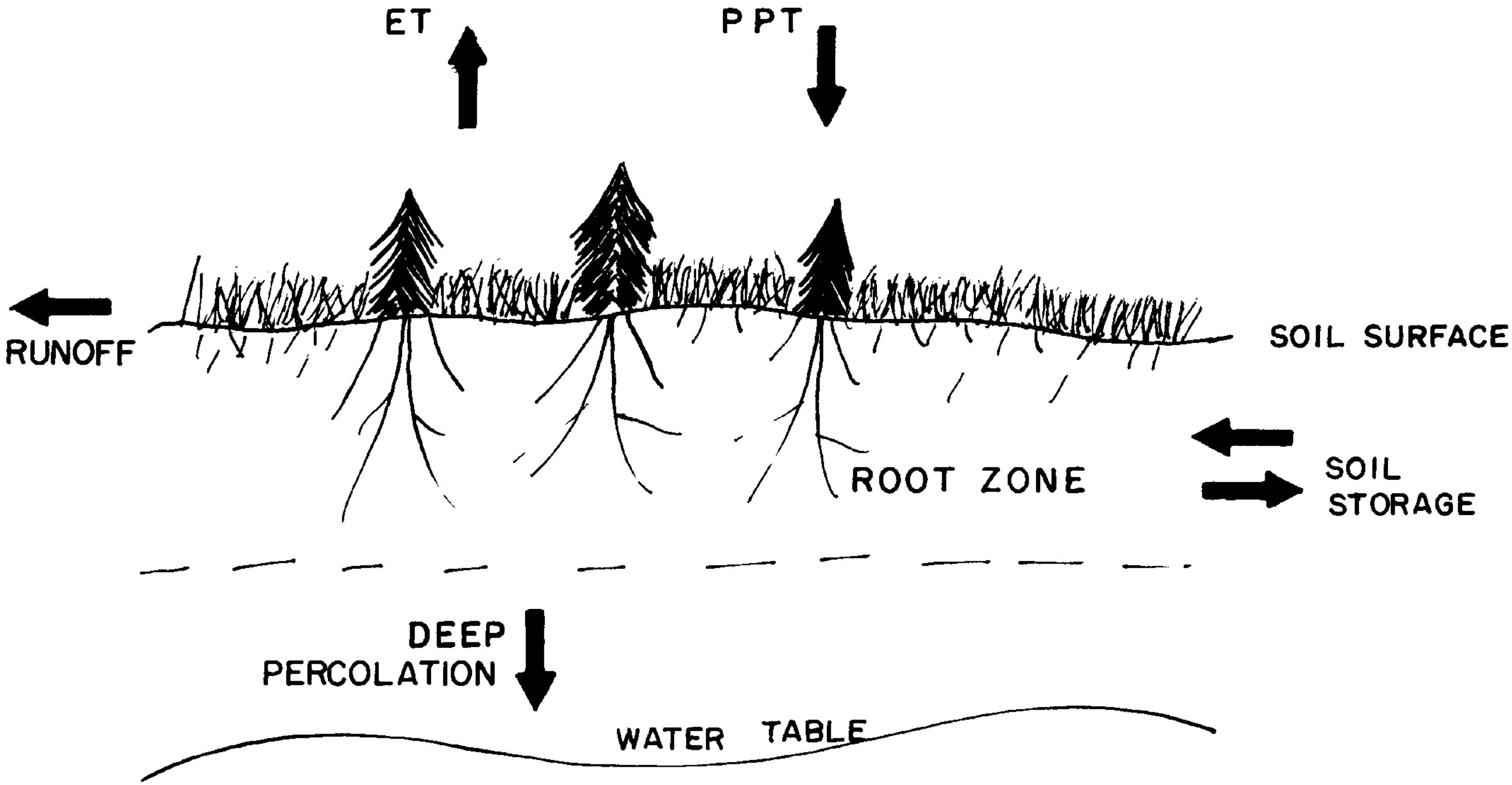

Figure 3. Components of the soil water budget

neglected; however, results are limited to representing average annual conditions. Runoff can also be neglected on the Snake River Plain. Surface runoff, where it occurs, generally accumulates locally in depressions where it infiltrates or evaporates. Little surface runoff leaves the basin. The assumption of no runoff causes errors in areal distribution of precipitation and recharge. The errors, however, are small relative to the size of the Plain.

The simplified water budget resulting from elimination of the two terms becomes:

RECHARGE = PRECIPITATION - ET

Each term represents an annual average over some selected area. Results are most applicable to ground-water modeling if calculations are performed for each cell of the model grid. Each cell in the Snake Plain aquifer model grid is 5000 meters square.

The magnitude of precipitation recharge relative to other water budget components, and the accuracy of the components, is a primary consideration with the soil water budget as it was with the other methods previously evaluated. Recharge from precipitation on the eastern Snake River Plain is small relative to total precipitation or evapotranspiration. Precipitation recharge for the entire eastern Plain may only be 10% of average annual precipitation, and only a slightly greater percentage of evapotranspiration (excluding agricultural areas).

The soil water budget requires accurate areal estimates of average annual precipitation and evapotranspiration. Methods and expected difficulties in determination of these parameters are discussed in the following sections.

Precipitation

Average annual areal precipitation is usually estimated by areal averaging of published isohyetal lines or by direct averaging of gage data. Use of isohyetal lines is often preferred since topographic effects are incorporated into the areal estimates. Both methods, however, rely on the false premise that precipitation gage measurements are always equal to the true or actual precipitation.

Measurement error is caused by wetting and evaporation losses, splash, and wind. The wind induced errors are by far the most significant. Numerous studies have measured gage catch deficiencies and drawn the consistent conclusion that precipitation gage measurements underestimate actual precipitation, and that the deficiency becomes greater with increasing wind speed and with temperatures below freezing (e.g., snowfall).

Relationships between measurement deficiency and windspeed have been reported in two studies. Larson and Peck (1974) derived the three curves shown in figure 4 for rain, and snow with and without a shield. Hamon (1972) developed a dual gage method for estimating actual precipitation at the U.S. Department of Agriculture, Reynolds Creek watershed in southwest Idaho. He determined correction equations for shielded and unshielded weighing gages based on wind and temperature data. The equations determined by Hamon (1972) are as follows:

$$P_{act} = P_s \, e^{aW} \qquad (1)$$

$$P_{act} = P_u \, e^{bW} \qquad (2)$$

where:

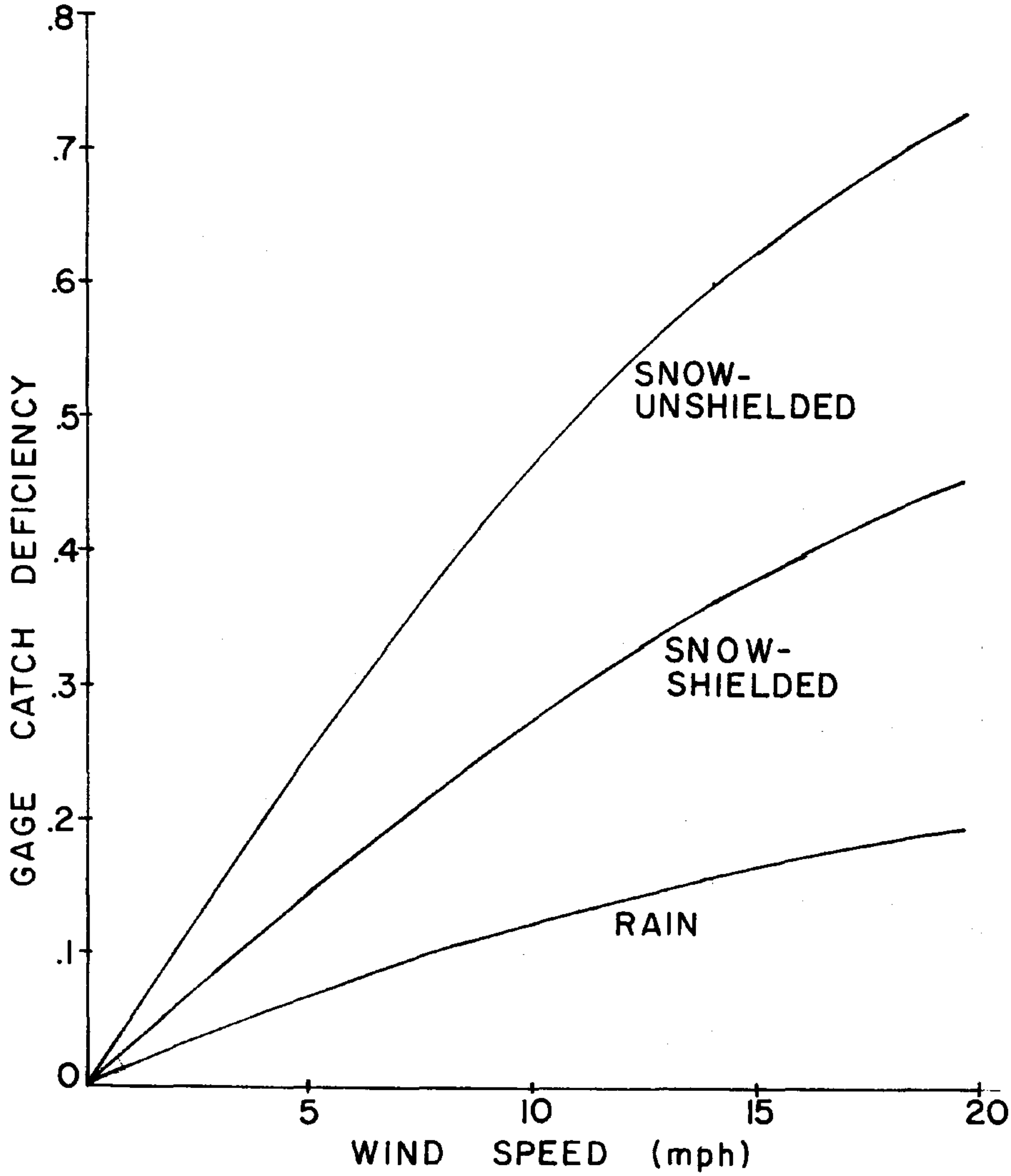

Figure 4. Precipitation gage catch deficiencies after (Larson and Peck, 1974).

P_{act} = actual precipitation

P_s = measured precipitation, shielded gage

P_u = measured precipitation, unshielded gage

W = wind speed at the gage orifice (mph)

a,b = temperature based coefficients

The a and b coefficients were calibrated by Hamon (1972) to arrive at the values in table 2.

Table 2. Coefficients for estimating actual precipitation (Hamon; 1972)

Temperature Range(C°)	a	b
T>1.67	0.0060	0.0146
1.67 > T> 0	0.0121	0.0294
0 > T> -5	0.0217	0.0527
-5 > T>-10	0.0366	0.0889

The dual gage approach was also successfully used by Larson (1972). The shielded to unshielded catch ratio confirmed values determined by Hamon (1972) and the a and b coefficients, although derived differently, also supported the results of Hamon (1972). The correction equations are shown in graphical form for shielded and unshielded gages in figures 5 and 6.

The extent of wind induced error in precipitation measurement on the eastern Snake River Plain is expected to vary significantly with differences in wind, temperature, and precipitation across the Plain. The northern and eastern parts of the Plain generally receive a higher percentage of precipitation in the form of snow. Since gage deficiencies are greatest in snow, the measurement errors are largest in

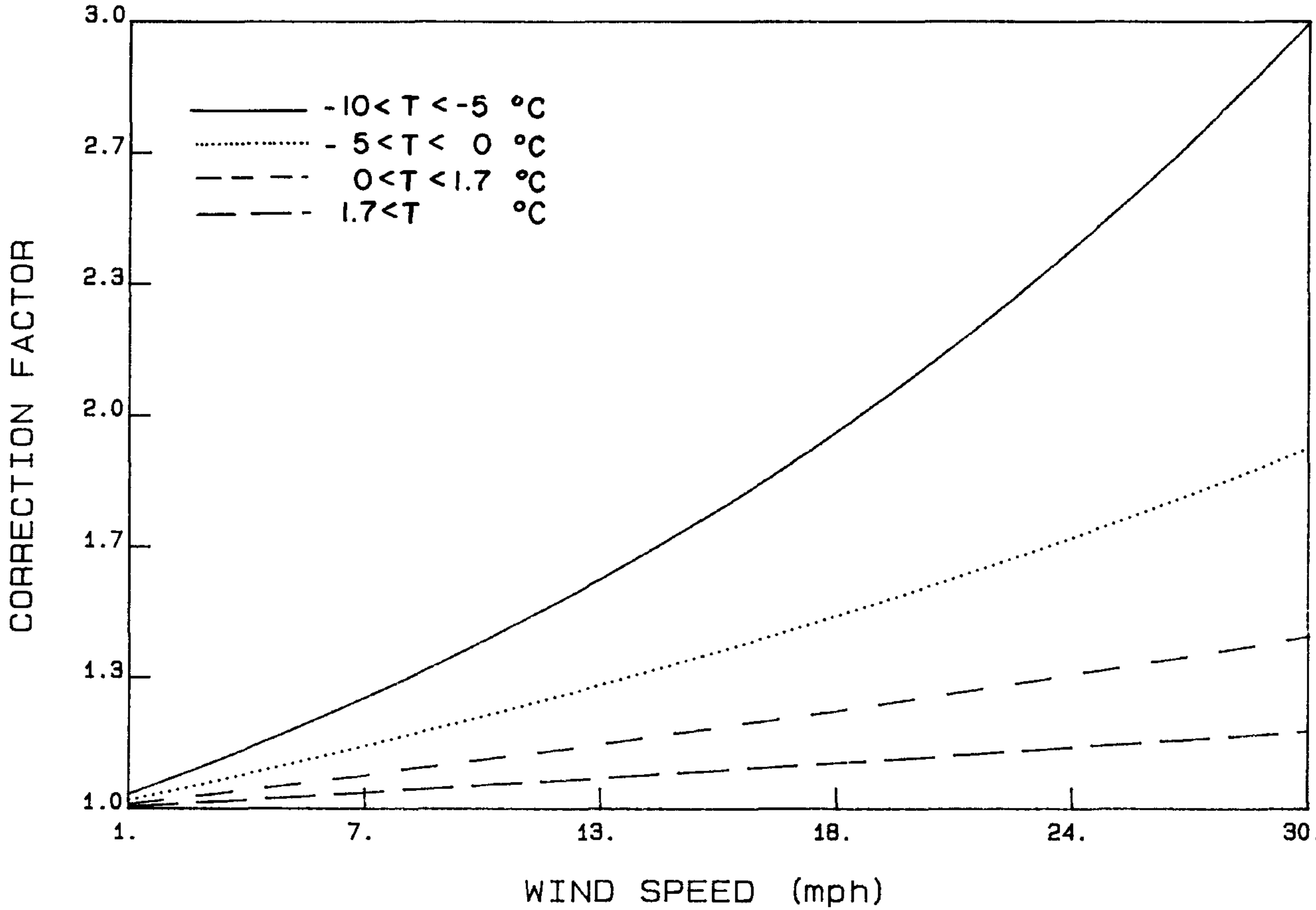

Figure 5. Wind corrections, shielded gage.

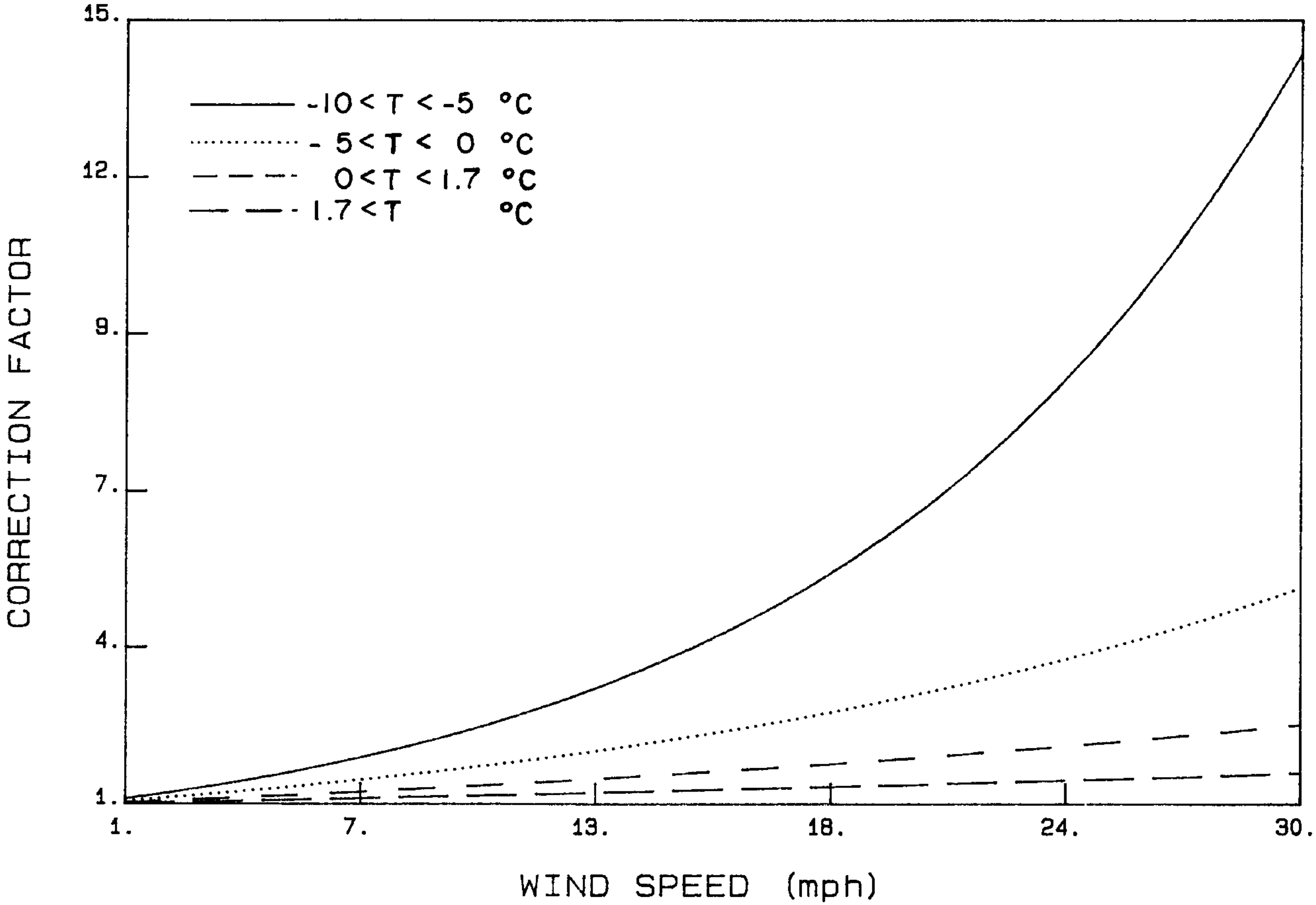

Figure 6. Wind corrections, unshielded gage.

the colder, higher elevations. Quantitative estimates of error using equation 2 were made at 6 stations on the Plain where the required data were available.

Unpublished hourly wind and precipitation data from the National Oceanic and Atmospheric Administration (NOAA) Twin Falls Weather Service Office (WSO) at Kimberly, provided a basis for examination of wind during precipitation events. Wind during precipitation events was compared to total daily wind to determine if total daily wind is representative of wind during the event. The ratio of event wind to average daily wind was plotted for four years of precipitation events at the Twin Falls WSO (figure 7). The ratio averages were determined for each month and are shown as a line in figure 7. The graph demonstrates that daily wind totals can be used to approximate wind speed during precipitation events, provided the results are used only to determine long term averages. Point scatter indicates that using daily wind to approximate wind during a single event may result in serious error.

The effects of using monthly mean wind and temperature data in correction equation 1 (shielded gage) were also evaluated using data from the Twin Falls WSO. The use of monthly averages resulted in a 0.2% difference (0.02 inches/year) in calculated actual (corrected) precipitation relative to corrections based on event data. Monthly mean temperature, wind, and precipitation can, therefore, be used in the correction equations to estimate actual precipitation at the Twin Falls WSO. It was assumed this principle also held for the other 5 stations on the Plain.

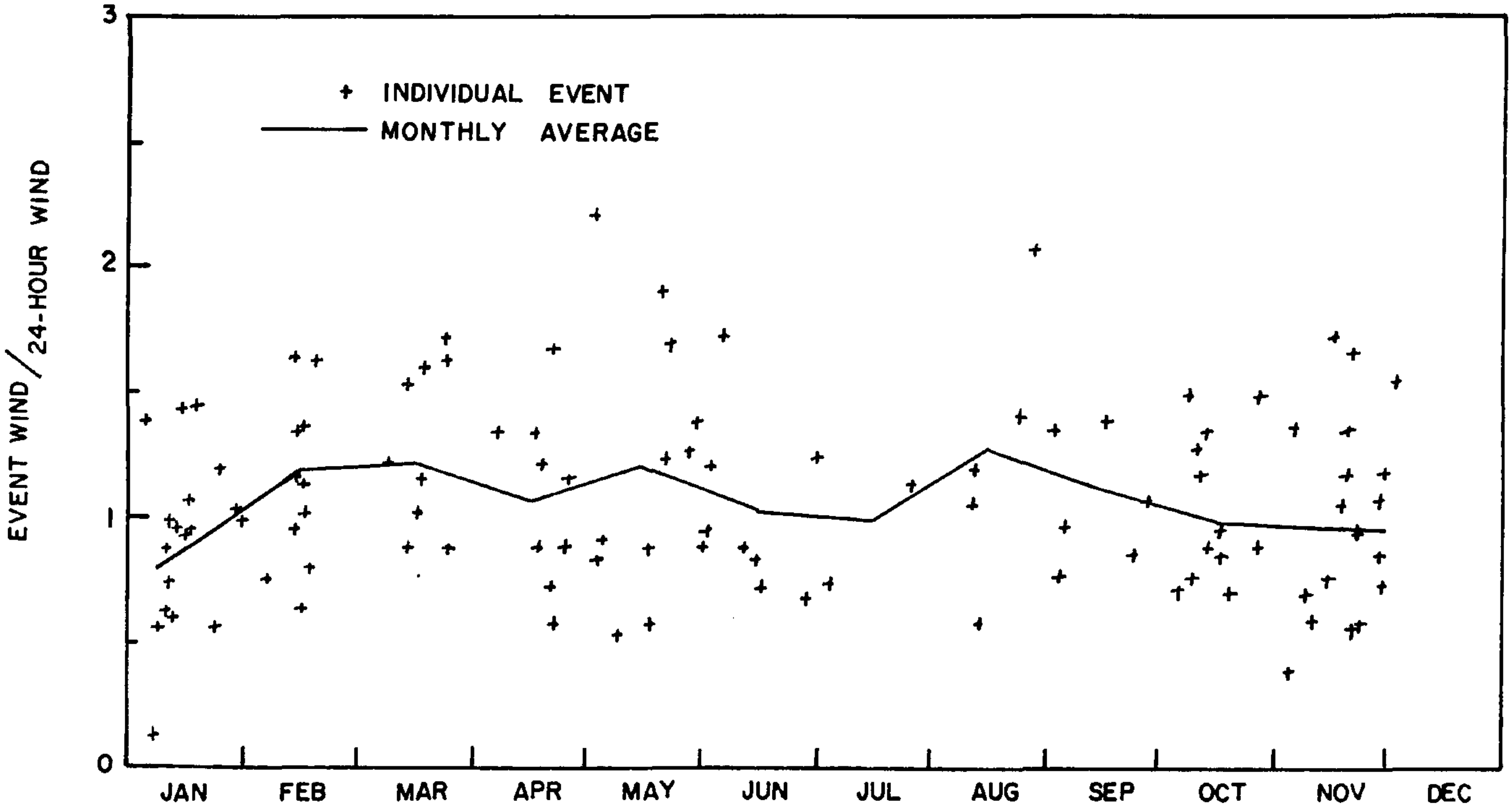

Figure 7. Ratio of precipitation event wind to daily wind.

Monthly precipitation correction coefficients were determined for Burley, Dubois, Pocatello, Gooding, and Idaho Falls. The station locations are shown in figure 1 and the measured and corrected average annual precipitation is given in table 3. Annual precipitation was determined as the sum of monthly averages. Long term mean monthly temperature and precipitation were taken from the NOAA, Climatological Data, 1983 Annual Summary. Mean monthly wind was taken from the Pacific Northwest River Basins Commission Climatological Handbook (Vol. 3, Part A, 1968). Instrument and site conditions used in data collection are not known, however, it was assumed that wind measurements were made at a 20 foot height and precipitation measurements made at 3 feet. Wind data were therefore adjusted downward to be more representative of gage height. A logarithmic wind profile was assumed in making adjustments. Precipitation corrections at the Twin Falls WSO are also given in table 3 and were determined from 17 years of daily precipitation, wind, and temperature data. Twin Falls WSO data were taken from station reporting records.

Table 3. Measured and corrected annual precipitation for unshielded, weighing gages.

Station	Precipitation (in/yr) Measured	Precipitation (in/yr) Corrected	Correction Ratio (Measured/Corrected)
Burley AP	10.11	11.77	.86
Dubois AP	11.75	13.87	.85
Id.Falls AP	9.72	12.24	.79
Gooding AP	9.95[1]	11.92	.83
Pocatello AP	10.86	12.83	.85
Twin Falls WSO	9.29	10.80	.86

[1]Precipitation data from Shoshone.

Calculated precipitation measurement error on the eastern Snake River Plain ranges from 14% to 21%. The largest errors are expected to occur in the higher elevations in the northeast part of the Plain. The data do not strongly confirm this, however, the wind data may be in error due to unknown anemometer heights. It is emphasized that the corrections in table 3 are very rough, based on approximate relationships and data.

The uncertainty in precipitation measurement precludes use of soil water balance methods for estimating recharge from precipitation on the Snake River Plain. Measurement error (15 to 20%) is larger than the expected contribution to recharge (10%), resulting in errors which probably exceed 100% of the estimated precipitation recharge.

Evapotranspiration

Annual evapotranspiration (ET) is large relative to recharge from precipitation throughout most of the non-irrigated parts of the Snake River Plain. Recharge estimates by Garabedian (1984) suggest precipitation recharge for the eastern Plain is about 11% of evapotranspiration from non-irrigated lands. The small relative magnitude of recharge requires extremely accurate estimates of areal evapotranspiration to achieve reasonable confidence in calculated recharge.

Evapotranspiration is usually determined as the product of a climate based reference ET times a vegetation or crop coefficient. In non-irrigated conditions, calculation also includes an additional coefficient quantifying the effects of moisture deficiency. Most hydrologic models employ this technique, using empirically determined crop coefficients and maintaining a soil moisture balance to arrive at estimates of moisture deficiency. These methods require enormous amounts of data for application to a large non-homogeneous area, and lack the accuracy necessary for recharge calculations.

Reference ET represents ET from a specific wet surface condition. Typically, the reference is a grass or alfalfa crop. Reference ET is calculated from climatic data which usually includes temperature and may include solar radiation, humidity or dewpoint, and wind speed. Errors in calculated reference ET may result from errors in measurement, extrapolation of measurements over large areas, or from inaccuracy in the method selected for calculation.

Reliability of vegetation and moisture deficiency coefficients is probably of greater concern than accuracy of reference ET. Vegetation coefficients depend upon vegetation type, density, vigor, and stage of development. Moisture deficiency is related to soil water holding characteristics, soil moisture content, and the depth of root zone. Soil moisture content is exceptionally difficult to estimate due to non-uniformity of precipitation, localized runoff and generally unknown amounts of winter snowpack.

Detailed examination of error potential for all the above factors is far beyond the scope of this project. It is apparent, however, that estimation of areal ET within an accuracy of 10% (nearly 100% of recharge) from precipitation is difficult if not impossible to achieve by conventional ET models.

An alternative method of estimating areal ET may be available in the complimentary, or aridity, approach. The method was proposed by

Bouchet (1963) and has been supported by Morton (1975;1983) and Brutsaert and Stricker (1979). The approach is based on the concept that each unit of actual ET reduces available energy and consequently reduces reference ET by an equal amount. By estimating total available energy and reference ET it is possible to determine actual ET. Actual ET is calculated for an area of several square miles surrounding the climate station using only climatic data. Although the approach has been strongly advocated by the cited investigators, it remains generally unaccepted by the hydrologic community. Additional verification under a variety of conditions is necessary prior to widespread acceptance. The method may offer a significant improvement in capabilities for estimating actual ET from non-irrigated lands, if proven reliable.

CONCLUSIONS

Recharge from precipitation on semi-arid, non-irrigated lands may provide a significant percentage of total aquifer recharge, but remains difficult to estimate. Direct measurement is usually not feasible due to the size of areas under consideration and the inhomogeneity of climate, vegetation, soil, and topography. Water budget techniques may be employed but often require data accuracy beyond that which is currently available.

Water budget techniques cannot be used to estimate precipitation recharge on the eastern Snake River Plain. A water budget, in any form, cannot be performed with sufficient accuracy to provide a meaningful estimate of recharge from precipitation. Simpler techniques, such as those of Garabedian (1984) which estimate recharge based on a qualitative analysis of precipitation and soil characteristics, currently are the best available methods.

Future investigations should concentrate on improving basic data and its interpretation. Sophisticated hydrologic models are useless when the basic data are inaccurate and collected under unknown, uncontrolled conditions. Precipitation data are a vital element to most hydrologic analyses, yet even in easily accessible and relatively uniform areas such as the Snake River Plain, data are in error by 15 to 20%. Methods exist for improving estimates of actual precipitation but the importance must be recognized to motivate an investigative program.

Precipitation corrections estimated in this project are very rough, intended only to demonstrate the need for additional work. They should not be used to correct measured precipitation for use in hydrologic studies.

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