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WESTERN REGION TECHNICAL MEMORANDUM

Limitations of Selected Meteorological Data

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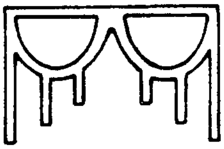

A western Indian symbol for rain. It also symbolizes man's dependence on weather and environment in the West.

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Western Regional Technical Memorandum No. 18, December 1966

LIMITATIONS OF SELECTED METEOROLOGICAL DATA

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Editor's Note:

This Technical Memorandum is a collection of papers originally written for and published in the Pacific Southwest Inter-Agency Hydrology Subcommittee Report "Limitations in Hydrologic Data", February 1966. The papers were selected for this Technical Memorandum because they contain information on the reliability and usefulness of meteorological data which we consider important for all Western Region forecasters to know and have available for easy reference. Agricultural meteorologists should find the information in Section III especially interesting and useful.

Several of the papers were written by Western Region scientists for hydrologists, consequently you will encounter considerable reference to hydrology in them.

We are grateful to Mr. J. van de Erve, Regional Hydrologist, and Mr. Eugene L. Peck, Regional Research Hydrologist, for their assistance in preparing this Technical Memorandum.

L. W. Snellman

L. W. Snellman, Chief
Scientific Services

LIMITATIONS OF SELECTED METEOROLOGICAL DATA

I. INTRODUCTION

A. BACKGROUND

Hydrologic studies are commonly derived from records of numerous meteorological variables, including:

- Insolation and radiation
- Air temperature
- Humidity
- Wind
- Precipitation
  - Rain
  - Snow
- Evaporation and transpiration

No such records, especially those spanning a long term of years, should be accepted at face value and assumed to satisfy the purposes of a particular study in every respect. Both systematic and random errors must be expected. Some of these may compensate over a period of time; others may not. Also, the records of certain variables involve inherent limitations that may influence greatly the strength of the conclusions derived.

Few if any of the variables listed above are independent; several of them are influenced substantially by other, nonhydrologic variables including character of vegetal cover, physical properties of soil and rocks, and relief and orientation of topographic features with respect to wind movement and storm tracks. Such related, but primarily non-hydrologic, variables are not a topic of further discussion in this manual, which is addressed primarily to the novice hydrologist and which seeks to (1) point out inherent limitations in hydrologic records; (2) identify common sources of error in those records; and (3) where feasible, outline procedures for discriminating data that seem to be abnormal and possibly in error. Assuming that a specific cause can be identified, presumably erroneous or inconsistent data sometimes can be adjusted reasonably; otherwise, they may be excluded from further consideration. However, adjustment and exclusion must be cautious and in conformity with sound methods of statistics, lest the hydrologist trap himself into the fundamental error of accepting only data that fit a favored hypothesis.

B. INADEQUACY OF SAMPLING

The natural range of most hydrologic variables is large and some classes of records sample the range most inadequately. Commonly this inadequacy of sampling handicaps the hydrologist much more seriously than errors of measurement at the points sampled.

For example, there is ample evidence that instantaneous rates of precipitation at a given station vary considerably from moment to moment. At the particular station, this variability probably compensates in some degree over the term of a single storm, and more so over a season or year. Similarly, among the stations of a network, substantial compensation occurs within the geographic reach of a particular storm or over any extensive area. Nonetheless, even when spaced more closely than is ordinary, a network of precipitation stations takes only a woefully small sample of the water precipitated. Thus, although the conventional statistical records are a usable index to relative amounts (volumes) of water precipitated on an area, they afford only a rough measure of that volume. If a hydrologic study involves mean depth or volume of water precipitated on an area, the most probable value is that derived from an isohyetal map constructed with due regard to all recognized parameters of precipitation. Any value derived by arithmetical procedures alone would be less defensible. (It should be noted that these limitations of precipitation records are inherent; they are independent of the accuracy of measuring devices and procedures.)

In contrast, a stream-gaging station measures the integrated volume of water running off from the drainage area. Thus, the conventional record of streamflow is limited inherently not by inadequacy of sampling, but by accuracy of techniques for measurement, which are considered later in this manual.

Among the hydrologic variables listed above, and in addition to streamflow, only storage in reservoirs and lakes is measured directly in conventional records. All the other kinds of records produce data that are inherently index values rather than absolute measures of the hydrologic variable being sampled. Probably few samples are integrated in the sense that they reflect, in true proportion, all conditions or aspects of the particular water body for a particular moment or interval of time. Thus, in any hydrologic study that involves correlation among two or more of the variables, and in which the available data are inadequate for computing a sound correlation coefficient by statistical procedures, conclusions should be drawn cautiously.

Special emphasis is warranted in regard to adequacy of sampling for records of chemical quality. Inherently, a single analysis shows only the chemical constituents at a single point within the body of water sampled. Also, unless it represents a composite of samples taken over a period of time, it shows only the constituents momentarily at that sampling point. All too infrequently is a water body sampled at enough points or at enough times to represent all the potential variability within that body. All too few chemical-quality records define point and time of sampling in relation to features of the environment. Thus, an incautious hydrologist easily can be misled into undefensible chemical and geochemical conclusions. The sole defense is to "screen" all data for consistency, search out a full explanation of any seemingly abnormal data, and draw no conclusion by extrapolation.

The difficulties just outlined are compounded in regard to ground-water quality. Here, available data generally are for samples withdrawn from wells that may range widely in depth and that, when pumped, may yield a blend of two or more waters of unlike chemical character, from distinct aquifers. The possible ramifications go far beyond the scope of this manual. Suffice it to point out that (1) a full explanation of all variations in chemical quality may require comprehensive information on depth and casing records of wells, types, and settings of pumps, and regimen of withdrawals for some indeterminate period prior to sampling; but (2) rarely is such ancillary information reported as part of the chemical-quality record.

C. BIAS IN RECORDS OF LONG TERM

Some hydrologic records have been published over a long term of years under a single station name when in actuality the station has been relocated one or more times during the term. In this situation it is unwise to assume that the "same water" has been measured, and that the composite record is not "biased" by environmental differences among the several locations. For streamflow records in Water-Supply Papers of the Geological Survey, the latest station description should be scanned to identify possible relevant changes in location. All such records through October 1950 have been compiled and summarized in Water-Supply Papers 1301 through 1319 and 1372; these reports include the history of gage changes, if any, at stations discontinued prior to the cut-off date of the compilation. For climatologic stations, changes in location are listed in the Weather Bureau's "Substation Histories" (Key to Meteorological Records Documentation No. 1.1). Each change of location should be treated as though a new and independent record had been started, unless the several partial records are shown to be consistent one with another, by double-mass plotting against records for one or more adjacent stations that are in the same environment and that have not been relocated.

Even if station location has remained unchanged, a long-term record may involve progressive bias owing to continual changes in the environment. For example, over the years more and more of the waters in a given river basin may have been diverted for use, and streamflows may have been regulated more and more by construction of successive reservoirs. Even if available, a record of such diversions commonly does not show all the effect on streamflow; for example, a substantial fraction of the water diverted may return to the stream far below the point of diversion. Similarly, owing to evaporation and other losses that commonly are not measured, records of reservoir inflow, content, and outflow yield a distorted measure of the regulating effect.

Some effects of major diversions and regulation may be documented in supplemental water records, so that gaging-station records can be adjusted accordingly. The "remarks" section of the record in Water-Supply Papers should be scanned for relevant clues; some but not all environmental changes will be identified there. Both increasing water-surface area in reservoirs and increasing use of water deplete streamflow; usually, such depletions are not documented. Also not usually documented, numerous small diversions may have been made successively, small but significant quantities of water may bypass gaging stations, and numerous other works of man may have added some effect. Changes in pattern of land use commonly have been large over a long term of years and are claimed widely to have caused substantial changes in the yield of water to streams. That such change has occurred is likely; the magnitude of change, apart from variability owing to natural causes, commonly is difficult to demonstrate.

In this connection, emphasis perhaps is warranted in regard to the effects of dikes, levees, and other river-training works. Commonly these works are constructed progressively in a particular stream basin. As a result, stage at some key station may seem to rise progressively over many years, not because the basin yields more water but because training works upstream constrain a greater and greater portion of the flow to the main channel, or training works downstream cause higher and higher backwater, or both. Effects may reach many miles from the works that cause them; they may be large and relatively obvious, or small and obscure. Commonly neither their magnitude nor their timing can be discriminated precisely. Failure of a levee or other training work reverses the effect.

Such change may occur not only in agricultural and rural areas but also in urban and industrial areas. For example, in the urban-industrial environment the rate and volume of storm runoff, the volume of fluid wastes, and stream temperatures are likely to increase perhaps substantially and at times sharply, but in most instances gradually and obscurely. Ground-water levels and potential yields are likely to be affected, and commonly depressed.

Even after all reasonable adjustments have been applied, many long-term streamflow records may retain a progressive, man-caused bias. As a result, the later part of the record may, in comparison with the earlier part and with the natural stream regimen, be abnormal in daily, seasonal, or yearly runoff; in extremes of flow; or in any combination of these. In some instances, magnitude of the abnormality will be suggested by double-mass plotting against records from adjacent stations presumably not so biased. In other instances, there is no ready means for demonstrating magnitude. As a consequence, long-term correlations between streamflow and other hydrologic variables must be interpreted with caution.

Long-term records from climatologic stations in and near metropolitan areas well may embody substantial man-caused bias. In such areas, large and generally increasing amounts of waste heat have been and are discharged into the atmosphere; industrial smoke and dusts inject abundant nuclei that may induce precipitation, and that probably modify the natural regimen of thermal radiation; also, ever-changing structures interpose variable barriers to the movement of low-level winds and may affect the "exposure" of climatologic instruments. Currently, atmospheric physics is not understood sufficiently well to appraise all the potential influences on climatic records. In some instances, the amount of influence will be suggested by double-mass plottings against records from outlying stations.

Such bias is not restricted to metropolitan areas--witness the familiar change in humidity regimen, and probably in air-temperature regimen, that has been induced in areas of extensive irrigation. Exposure of climatologic stations may have been changed by the growth or felling of trees, construction or demolition of buildings, and the like. The hydrologist must ever be alert to the possibility of such bias in any of the longer records with which he deals.

D. SHORT-TERM ABNORMALITIES AND "STEPS" IN RECORDS

Man's activities and natural events may both cause short-term abnormalities or lasting "steps" in hydrologic records--more commonly in streamflow records. Among numerous examples are the effects of temporary cofferdams and bypass channels, initial filling of reservoirs, and emergency sluicing; the perennially repeated abnormal flow regimen downstream from a "peaking" hydroelectric plant is common. The larger of such events may be well known and may be documented in the "remarks" section of the station records in Water-Supply Papers. However, many will not be documented in the usual sources of information. If of consequence in a particular hydrologic study, the possibility of such an event can be tested by plotting records against one another, and searching out an explanation for data that deviate markedly from the general regimen.

II. COMMON ERRORS AND LIMITATIONS IN HYDROLOGIC AND METEOROLOGICAL RECORDS

The preceding part of this manual has considered limitations that are inherent to hydrologic records and data, even when those records comprise accurate measurements or determinations. Here considered are the more common sources of error in the records--error in the sense that the quantities recorded differ from those that actually pertained.

Errors have been and always will be present in hydrologic records, largely because the instrumentation and procedures of measurement are of necessity a compromise between the ideal and the practical. Over the years, instruments and procedures have been improved so that certain sources of error have diminished; further improvement will ensue but error-free records probably never will be realized.

Certain errors are random in time and in magnitude and may compensate within a period shorter than the term of study. If so, conclusions derived from the study may not be influenced substantially. Other errors may be systematically plus or systematically minus; or, even if random in magnitude and algebraic sign, they may be much more prevalent in a particular part of the record. In this event, conclusions may be distorted if the errors are not identified.

Further, most hydrologic records have been tabulated, totaled or averaged, typed, and proofread by human beings—of whom all are prone to error now and then. Misplaced decimal points, tranposed or extra digits, and typographic errors occasionally survive meticulous checking and proofreading, and so become published. Some such errors can be discovered readily and the cause may be deduced by a diligent user of the record--for example, in a series that defines a relatively steady hydrologic state, an erroneous value commonly can be discriminated with assurance. On the other hand, a similar error in a series that spans an unsteady state could be isolated only by going back to the original data.

In a presumably continuous record it is obvious that "the maximum today must be at least as great as the minimum of yesterday, today, and tomorrow; and the minimum today must be at least as small as the maximum of yesterday, today, and tomorrow." Philosophically that principle is inviolate, yet some violations that have been published are too numerous to be considered inadvertent or typographic. The philosophically impossible record must be verified or discarded.

In every hydrologic study, therefore, an early step should be to test the pertinent data for internal consistency and, as has been stated, to discriminate data that appear abnormal and may be susceptible to adjustment. Tests must be devised to suit objectives of the particular study. Common procedures are double-mass plotting of records for a given variable from various stations, pairing mass diagrams of unlike but related variables, "routing" streamflows through successive stations, and arraying data by magnitude and examining the environmental aspects of extreme values. Other procedures will be suggested by the kind of study.

III. DISCUSSION OF SOME METEOROLOGICAL OBSERVATIONS

A. INSOLATION AND RADIATION

1. Introduction

Available information on the four fluxes of radiation near the earth's surface (downward shortwave, upward shortwave, downward longwave, and upward longwave) sheds relatively little light on dependability of the data, on representativeness of observations, or even on instrument accuracy. While radiation measurements long have been recognized as important in many geophysical processes, they have not been made in networks for very long. The older records are likely to be highly individual in type of instrument and installation, being parts of agricultural studies in which only local readings were needed. Recently the Weather Bureau's observational network for downward shortwave radiation has expanded; energy-balance approaches in experimental studies of snow melting, evaporation, and evapotranspiration have become widely accepted; and the International Geophysical Year and associated program have greatly stimulated interest in radiation. In most areas of hydrologic operations, radiation stations are still scarce, but it is to be hoped that in time small networks will be installed in the larger drainage basins of the West, somewhat as networks of precipitation-intensity stations were installed in the thirties for operational purposes.

2. Effects of station location

Radiation stations are few in number and there is a strong temptation to extend their records over areas much more extensive than is warranted. Exposure and location of stations become important for this reason.

Because radiation sensors must be connected with instruments to record continuously a small electrical output, the recording equipment is not only bulky, fragile, and expensive but also needs frequent checking and servicing. This requirement tends to confine radiation measurements to stations having technical personnel; most of these are in lowlands or valleys. Mountains are poorly sampled. For example, although the present network for downward shortwave radiation includes stations at considerable altitudes (Albuquerque, Ely, and Grand Junction), these are in valleys.

A few mountain stations have operated over short periods, but none is now functioning continuously. Some comparisons suggest that extrapolation of lowland records to mountains may be difficult except on a day-to-day basis, with observations of cloudiness at both places. For example, Davis and Soda Springs, California, have entirely different regimes of winter radiation, the valley being filled with fog for long periods while the mountains are sunny. The summer regimes differ oppositely, the mountains being commonly cloudy.

Cloudiness regimes also may differ in other geographic situations, which are less distinctive topographically than mountain and lowland. Coastal and inland regions may have different amounts of cloud cover, and their regimes of shortwave and longwave radiation are different. Thus, caution should be taken in extrapolating radiation data over any long distance.

The expensive recording equipment for radiation also tends to favor stations in cities. But even while atmospheric pollution is becoming regionwide in some parts of the United States, too many cities are distinguished from surrounding rural areas by the domes of polluted air over them. Comparison of city and rural radiation stations in several parts of this country, as well as in Europe, indicates that city influence reduces radiation by a fifth or more, especially in the season of low sun (Landsberg, p. 318).

Radiation stations usually are sited to avoid obstructions on the horizon that would shorten the length of day and reduce the area of the sky as a source of diffuse radiation. This aspect should be checked before records are analyzed. Horizon obstruction is likely to exist in the places to which radiation data are being applied--for example, in studies of snow melting. There are geometrical means of dealing with obstructions, provided it is known how much of the shortwave radiation comes direct from the sun and how much is scattered in traversing the atmosphere and arrives in diffuse form. At a mountain station radiation may be both diminished by loss of shortwave radiation at the end of the day, and increased by reflection from slopes that face the instrument, especially if those slopes are snow-covered. Reflections from clouds cause short, abrupt rises in the radiation record, which might not entirely cancel out with time if clouds form regularly at the same place.

Aside from measurements of the solar beam at normal incidence for research purposes, most measurements of downward radiation, both shortwave and allwave, are made on horizontal surfaces. In hydrologic studies of snow melting or transpiration on slopes, observation on horizontal surfaces are inappropriate. Most methods for converting them for slopes of various degrees of aspect and steepness are valid only for the direct solar beam. Conversion of diffuse shortwave radiation and of longwave from the sky has to be done separately.

A characteristic of radiation stations that might be overlooked is the fact that they are under the open sky. Thus, radiation beneath a forest canopy, necessary in some studies, has been measured only experimentally, and in types of forest that are described too poorly for the measurements to be transferred easily to other forest types.

3. Limitation of instruments and recording equipment

This discussion does not try to go deeply into problems of instrument design, manufacture, and calibration; it may be said, however, that radiation equipment is not entirely standardized. There is worldwide agreement on two kinds of instruments but not yet on others, although the increasing use of energy-balance concepts and the impetus of the International Geophysical Year will bear fruit eventually in instruments of greater comparability and reliability. The best source for information on radiation instruments is an instruction manual published by the U.S. Special Committee for the International Geophysical Year (1958).

At this point it is well to state explicitly what until now has been implicit--namely, (1) shortwave and longwave radiations are physically distinct flows of energy; (2) each has its unique relationships with clouds and other meteorological factors; and (3) each is influenced differently by topography, forest cover, and other physical features of the region upon which it is incident. Thus, each enters geophysical relations in a different manner. It is risky to lump them in analysis. Moreover, in studying hydrologic phenomena at the earth's surface, upward flows must be separated from downward flows. Thus, four fluxes make up the radiation picture. To understand the role of radiation in a hydrologic process, all four have to be considered.

Some studies make use of one instrument alone--that for measuring the net exchange of radiation of all wavelengths, a net exchange which is the resultant of the four separate, more or less independent fluxes of upward and downward shortwave and upward and downward longwave. These values of net radiant energy available at a given site are useful. However, since it is difficult to break them down into their shortwave and longwave components, they are not easily applied to problems in which the separate flows are influenced differently by meteorological, vegetal, or topographic factors. For example, the same net radiant energy may occur on a cloudy day with small downward shortwave and large downward longwave radiation, as on a clear day of bright sunshine and small downward flux of longwave radiation. Yet a given hydrologic process may proceed quite differently on these two days--for example, snow responds differently to shortwave than it does to longwave. The simplicity of a single instrument, with perhaps only an inexpensive totalizing recorder, should be weighed by the investigator against (1) the incomplete understanding he can derive from the single observation on the one hand, and (2) on the other hand, the real complexity of the four flows of radiant energy and their differing receptions by vegetation, snow, and soil.

In most geophysical experiments in the field, three or four fluxes of radiation are measured. The cost of a recorder for each flux can be reduced where a multichannel recording system is available. The four fluxes usually measured are: shortwave downward (insolation, incident solar radiation); shortwave upward (reflected from the surface); allwave downward (hemispherical radiation of both short and long wavelengths);

and the net exchange of allwave radiation (difference between upward allwave and downward allwave). From these four measurements, longwave radiation upward and downward can, at least in theory, be determined by subtraction.

It may be possible to dispense with continuous measurements of upward shortwave radiation by measuring albedo at intervals. However, albedo varies in response to meteorological and other forces, often over a large range; its regime must be understood before available handbook values of albedo can be applied to many practical problems.

Instrumental limitations of the radiation sensors, beyond those caused by such special conditions as pollution by aerosols or topographic shading, include the effects of (1) temperature on output of thermocouples, (2) wind on unshielded allwave instruments, (3) dust and dew on glass shields of shortwave sensors and on polyethylene shields of longwave sensors; and (4) precipitation on both shielded and unshielded sensors. There remains a question whether polyethylene films change transparency during exposure to the weather. For further discussion of such limitations, reference should be made to the I.G.Y. Manual.

Rapid variation of the radiation fluxes with passage of clouds has brought about the use of continuously recording potentiometers that produce great mileages of strip charts, often in more detail than a given problem may require. Digitizing, tape-punching recording systems may use longer intervals between measurements; also, they offer the possibility of computer processing of the record. Since few studies have been published on variation of radiation in different types of weather, each investigator should examine his own problem to be sure he is getting needed detail without incurring unneeded costs for chart reduction. Attachment of electrical or mechanical integrators to the potentiometer increases the investment in recording equipment but reduces the operational cost of chart reduction, if daily totals are needed or suffice. In some installations, it may be possible to dispense with the intermediate strip chart and go direct to a counter giving daily totals.

Radiation sensors usually are calibrated by the manufacturer. Maintaining calibration in field use is a problem, sometimes requiring shipment back to the manufacturer, or comparison against a standard instrument taken from station to station of a network. Homemade calibration equipment is also in use. Users of records should assure themselves that instruments have been kept in calibration.

Since the downward fluxes of shortwave and longwave radiation vary on a large geographic scale, they may need to be measured at only one place in a region of homogeneous cloudiness. The upward flux of shortwave radiation (if taken as albedo) and of longwave radiation vary abruptly with changes in surface cover and in temperature, but less abruptly with time than with distance. Thus, they may be amenable to aerial observation.

Of the four fluxes usually measured, only downward shortwave radiation enjoys a geographic coverage that approaches what might be termed a network, with measurements systematically taken, documented, and published. The Weather Bureau operates this network (which includes cooperating stations of several other organizations), processes the strip charts, deposits them at the National Weather Records Center at Asheville, N. C., and publishes daily sums in "Climatological Data, National Summary."

There are some stations whose records are not published, commonly because operation is tied to short-term experimental studies. However, their records may fill gaps at a critical period in a hydrologic investigation, and should be used after the station history is checked for exposure of instruments, and in other pertinent respects. Many allwave radiation instruments have been sold, and some may be in more or less continuous operation, perhaps in conjunction with micrometeorological programs tied to some resource-management activity. Such stations would be found by inquiry among local meteorologists and geophysicists.

4. Use of radiation data

Problems such as deterioration of an observational site, which have been studied intensively in regard to precipitation, have scarcely been touched for radiation. There is reason to believe that in cities like Fresno, which is beginning to experience severe air pollution, radiation has decreased significantly. If records so biased were used to estimate radiation in adjacent wildland areas, the possibility of change in relation should be considered. However, distances between stations are so great that double-mass techniques cannot be applied confidently to correlation of radiation records.

The scarcity of radiation stations has led to a variety of mean for extending coverage in space and time. Downward shortwave radiation has been related to such consequences as soil temperature or daily maximum temperature of the air (Landsberg, section 37), and to meteorological factors such as 700-millibar height, (Miller, 1955), or cloud type and cloud coverage (Haurwitz, 1945; Fritz and MacDonald, 1949). Sunshine duration can be related to insolation; for example, see Hamon, Weiss and Wilson (1954) for daily values. Clear-day shortwave radiation can be estimated from astronomical data with consideration of absorption by dust and water vapor in the atmosphere (Landsberg). The relationship of upward longwave radiation to surface temperature is well known, as is that of downward longwave radiation to vapor pressure and temperature of the lower atmosphere (Brunt, 1941). There are also relationships between downward shortwave radiation and the net allwave balance (Shaw, 1956). Many of these relationships are summarized by Landsberg and by Budyko (1958, section 3).

Some of the relationships of downward fluxes of radiation involve properties of clouds not always observed; however, current work in cloud physics may make it possible to extend the validity of these relationships. Another class of relationships includes those that might be developed between radiation fluxes and conditions at the earth's surface, such as daily maximum air temperature. These relationships are valid as long as the balance between radiative and advective forces remains the same; unfortunately, the climate-generating forces are not always in balance but may shift radically with changes in daily weather. The balance between radiative and advective influences also varies spatially with changes in ventilation--that is, the intermingling of surface and upper air caused by topographic roughness. Therefore, relationships between any radiation flux and meteorological measurements derived at a particular station cannot be extended far from that station.

These considerations suggest that attempts to fill gaps in radiation data will be most successful for a few missing days of record, where relationships to various meteorological factors can be developed at that place and in that weather situation. Attempts to fill long gaps in a record become risky. Attempts to fill spatial gaps between radiation stations, much-needed as they are by reason of coarseness of the network, should be confined to the same climatic region, to weather situations bringing the same type of cloudiness, and to the same topographic areas.

In conclusion, it may be said that the radiative heat transfers offer at least as much danger that the hydrologist will fall into errors of use and interpretation as does any other hydrologic factor. Also, that the temptation is so large because data are sparse. In hydrologic factors such as precipitation, many sources of error have been identified by past workers, who also have developed procedures for minimizing them. Radiation has a shorter history; not all the possible errors have yet been identified, and few have been studied enough that procedures for minimizing them are available. The hydrologist wishing to employ radiative-heat factors in his investigation should be prepared to work in developing and testing procedures to assure quality of data and to fill gaps in the record.

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B. AIR TEMPERATURE

1. Effects of location and installation of measuring equipment

Many hydro-meteorological studies involve free-air temperature, which is difficult to measure accurately owing to the radiative heat transfers considered in the preceding chapter. At best, the ordinary records of temperature serve only as an index to the true free-air temperature.

The dependability of a temperature measurement as an index for the surrounding area is determined in large part by the exposure of measuring equipment. Variations in temperature as measured under different exposures, although commonly small in comparison to those for some other meteorological factors, may be highly significant. The equipment must be protected against direct solar radiation. Ideally, it should be sited in a flat open area that assures adequate ventilation of the instrument shelter by free movement of the air. It should not be exposed on a steep slope, on the roof of a building, or in a small depression. At official climatological stations, the standard height of temperature instruments is approximately 5 feet above the land surface.

Upper-air temperatures are measured by means of radiosonde instruments. These measurements by radiosondes, when adjusted for lapse rate, should represent the temperature of free air as it moves over the higher mountains.

2. Types of temperature records and equipment

At virtually all temperature stations, daily maxima and minima are recorded, using mercury-in-glass thermometers to measure the maxima and alcohol-in-glass thermometers to measure the minima. At most stations such records are for the 24-hour period ending between 5:00 and 8:00 p.m., local standard time. At a few stations, however, the maxima and minima are observed by calendar days; at others, by the 24-hour period ending at 8:00 a.m.

In procedures of the U.S. Weather Bureau, "mean daily temperature" is computed by averaging the daily extremes--that is, maximum plus minimum divided by two. "Mean (average) daily maximum temperature" is derived by adding the daily maxima for a month and dividing by the number of days in the month; "mean daily minimum temperature" is derived likewise. "Mean temperature" for a month is taken to be the average of the mean monthly maximum and mean monthly minimum temperatures. "Mean annual temperature" is taken to be the average of the monthly means for the particular year.

At some stations, a continuous trace of temperature is obtained from a thermograph. Most such instruments are clock-driven and will operate up to eight days without servicing. They are not as accurate as the official mercury-in-glass or alcohol-in-glass thermometers, but records from them are adjusted to readings from those official thermometers.

Hourly air temperatures are taken at approximately 300 first-order Weather Bureau stations in the United States, also at some Federal Aviation Agency stations.

Upper-air temperatures are measured at selected Weather Bureau stations, by radiosonde flights every 12 hours up to an altitude of about 100,000 feet.

3. Dependability of observations

a. Effects of exposure

Temperatures measured at stations on steep south- or west-facing slopes are likely to average too high, owing to the angle of the sun's rays in daytime and to drainage of cold air away from the slope at night. Thermometers exposed on a roof top usually indicate higher minimum temperatures than those at the standard level, owing to the usual nighttime temperature "inversion" near the land surface. Temperature observations taken in a hollow usually will show average minima much lower than in the surrounding area, owing to nighttime drainage of cold air. Although the effect is small, average temperatures in urban areas tend to be higher than in adjacent rural areas. Generally, the average temperature at a city station has been found to increase as the city expands. These effects should be considered if the records are to be used for disclosing climatic trends or for detailed correlations. Accumulation of snow around a temperature station may bring the point of observation too close to the effective land surface and so within a nonrepresentative layer of air. In such instances, rough adjustments may be made according to a generalized vertical temperature profile.

b. Hour of observations

Since June 1948, maximum and minimum daily temperatures have been recorded and published as of the day on which the observations were made. Thus, at a station where the daily observations are taken at 8:00 a.m., the maximum temperature as recorded nearly always occurred on the previous day. The hour of observation at each station is published in the station index of the monthly climatological bulletins. Monthly means are affected by different hours of observation. Thus, the nearer the hour of observation is to the hour at which maximum temperature occurs ordinarily the higher the mean will be, especially if the observations are made earlier than 5:00 p.m. Observations late in the evening are the most consistent.

c. Other sources of error

Possible errors in temperature measurements include those due to reading a maximum thermometer in the horizontal position; in a minimum thermometer, the indicator displaced by vibration; separation of the alcohol or mercury column in the thermometer; and, "retreater" maximum thermometers. In such instances of instrumental error, also in errors of technique, commonly there is no rational basis for adjusting the published records of temperature.

d. Consistency of records

The ideal temperature record is one that has been collected at a representative site where there has been little or no change in exposure, instrumentation, or procedure in observing. Very few are the stations whose records satisfy these criteria, so that in most uses the records first should be tested for consistency or homogeneity. Linsley, Kohler and Paulhus (1949) describe a method for so testing homogeneity. Briefly, observed values of temperature at the station in question are plotted against the average of values at several nearby stations, with the plotted points identified according to year of observation. On such a plot, a break in continuity of the regression line may indicate a marked change in exposure or in some other aspect of the station environment. Commonly the full record plots in a series of regression lines that are en echelon but substantially parallel. In such a situation, the early records can be adjusted to match the current record by the algebraic addition of a constant or constants. Any such adjustments of a temperature record should be conservative. Under-adjustment is much to be preferred to over-adjustment. In general, an adjustment should be made only when justified by a known change in exposure of the station, or in some other competent factor.

The Weather Bureau's "Key to Meteorological Records Documentation, No. 1.1, Substation Histories," published by States, summarizes information on location, altitude, exposure, kind of record, and observers for climatological substations. Although not all are complete, these histories are very useful when testing records for consistency.

4. Use of data

a. Determining averages or normals

In computing "normal" or average values of air temperature, care should be taken that the measurements represent the same interval of time and unchanged environmental conditions. As the standard periods for temperature normals the Weather Bureau has adopted consecutive 30-year periods as follows: 1 January 1921 to 31 December 1950, 1 Janaury 1931 to 31 December 1960, etc. "Average" or "long-term mean" should be used for reference to any other period.

b. Correlation with hydrologic parameters

Correlations of monthly average temperature with other hydrologic parameters can be misleading. Thus, a near-normal month that includes a short period of abnormally high temperature may be much more critical than a month in which all the daily temperatures are slightly or moderately above average. Also, the arbitrary period of a month is not necessarily the best interval for hydrologic correlations. Temperature expressed as accumulated degree-days may be much easier to correlate than temperature expressed as an average over successive periods of fixed duration, however long.

c. Upper-air temperatures

The great utility of upper-air temperature in hydrologic studies is overlooked commonly. For example, as reported from radiosonde observations, such temperatures may serve as a better index to the altitude at which snow melts than temperature measured on the land surface. This is true especially in mountainous terrain as has been implied. In addition, upper-air temperatures may be predicted with greater accuracy than those for stations on the land surface.

5. Reference cited

Linsley, R. K., Jr., Kohler, M. A., and Paulhus, J. L. H., 1949, Applied hydrology: New York, McGraw-Hill, 689 p.

C. HUMIDITY (ATMOSPHERIC WATER VAPOR)

1. Location and installation of measuring equipment

The quantity of water vapor in the atmosphere, or the degree of humidity, varies with (1) altitude above the land surface; (2) type of surface--that is, land or water, vegetated or barren; (3) hour of the day, with attendant changes in sunshine, air temperature, and barometric pressure; and (4) characteristics of the air mass that surrounds the point in question. In a cloud or fog the water-vapor content may well be greater than in the air elsewhere. Usually, humidity diminishes rapidly with distance from a lake or seashore. Humidity tends to be greater in forested areas than over barren soil, even when both are under the influence of the same air mass. Thus, a measurement of humidity, especially one made at low altitude above the land surface, commonly represents only its immediate vicinity.

At the land surface, instruments to measure humidity generally are exposed in the same shelter as the thermometers, and hence are subject to the same criteria of location and exposure. Upper-air measurements are transmitted from sensing elements of a radiosonde carried aloft by balloon. These elements are well ventilated and protected from direct solar radiation and from precipitation.

2. Measurements and measuring equipment

The amount of water vapor in the air, or degree of humidity, may be expressed in various terms, according to intended use of the data. The terms defined in this section include only those which the hydrologist is likely to find in hydrometeorological or hydrologic literature.

"Actual vapor pressure" is the partial pressure of the water vapor present in the sample of air under consideration. "Saturation vapor pressure" is the maximum vapor pressure that can occur at the existing temperature. "Relative humidity" is the ratio of actual vapor pressure to saturated vapor pressure, expressed as a percentage. "Dewpoint temperature" is that temperature to which a parcel of air must be cooled at constant pressure and water-vapor content for saturation to occur. "Precipitable water" is the depth of water that would result over a unit area if all the water vapor in a column of air of unit cross section were condensed and precipitated. Its computation is based on the water-vapor content at all levels in the column. In a sense the term is a misnomer as there is no natural process that will completely remove all water vapor from the air.

Air and dewpoint temperatures are observed hourly at about 750 stations on the land surface in the United States. About 300 additional stations are equipped with recording instruments which provide weekly charts of temperature and relative humidity. Upper-air humidity is observed by radiosonde at about 60 stations in the United States, usually twice daily.

The standard nonrecording instrument for measuring humidity, the psychrometer, consists of two identical thermometers, of which one has its bulb covered with wet muslin. After adequate ventilation, by whirling or by fan, the "dry bulb" and "wet bulb" temperatures are read. Then, the relative humidity, dewpoint temperature, or vapor pressure are determined by means of psychrometric tables or special slide rules.

The more common recording hygrometer, or hygrograph, is actuated by a human-hair or other element which expands and contracts in proportion to the relative humidity of the air. These physical changes move a pen arm over a chart on a drum which is rotated by clockwork to record a continuous curve. Another type of recording hygrometer depends on change of electrical properties of the sensing element due to absorption of moisture; these lend themselves to use in radiosondes and in remote installations from which the measurements are transmitted electrically.

Hygrothermographs are, as the name implies, combination hygrographs and thermographs. Usually they consist of a hair element and a bimetallic thermometer, both activating pens which trace relative humidity and temperature on a chart on a rotating drum.

3. Reliability of observations

a. Instrumental errors

The measurement of atmospheric water vapor is one of the least accurate instrumental procedures in meteorology. The psychrometer, besides being subject to the same observational errors as the thermometer, is subject to errors due to improper wetting of the wick, inadequate ventilation, or impure water. The speed with which hair hygrometers and hygrographs respond to changes in humidity varies with temperature. The response is very slow at low temperatures, the lag becoming almost infinite at - 40° F. Such lag may increase with age of the instrument, as the mechanical parts wear. In consequence, the recorded values may be too large when humidity is diminishing and too small when humidity is increasing. Because error from this cause can be substantial when the relative humidity changes rapidly, as in upper-air soundings, use of hair elements in radiosondes has been discontinued.

Instrumental error due to effects of temperature may remain even after standard measures are taken to correct the indicated readings. This applies in particular to the hair hygrometer.

In recent years, upper-air soundings have been with electrical hygrometers. These instruments also may develop some lag as they age, as the electrical properties of the sensing element change. Ordinarily, however, their error due to lag is inconsequential.

b. Environmental errors

As has been implied, a measurement of humidity represents, strictly, an atmospheric property at only one point in space at one instant of time. The atmosphere can vary widely and abruptly in this property from one place to another (geographic), from one altitude above land surface to another, and from one time to another. Consequently, substantial error can result if data on humidity are applied uncritically to land-surface environments, altitudes, or times that differ from those which the data represent.

4. Uses of data on humidity

The ratio of the water precipitated in a given storm to all the water vapor present in the atmosphere at that place and time--that is, to the precipitable water--is used in deriving estimates of probable maximum precipitation. Precipitable water is used also in preparing quantitative forecasts of precipitation.

The vertical gradient of vapor pressure, determined by observations at two altitudes, has been used to estimate evaporation. Almost all formulas for estimating evaporation from a water or snow surface show evaporation to be proportional to the difference between the vapor pressure of the water and that of the air. When the vapor pressure of the air exceeds that of a snow surface, condensation, hence melting, will take place instead of evaporation.

In computing snowmelt resulting from rainfall, wet-bulb temperature of the air is substituted for actual temperature of the rain.

D. WIND

1. Measurements and types of equipment

a. Surface instruments

The speed, direction and gustiness of the wind near the land surface are measured by anemometers and wind vanes installed on poles or towers at or near the site of the instruments used to measure other meteorological elements such as precipitation, temperature, and humidity. The height of the installation is determined by the purpose of the measurement. For example, winds near the surface are required in connection with evaporation studies, but even for aviation or climatological purposes the height of installation is usually no more than a few tens of feet.

The instruments commonly used for measuring wind speed fall into three types, as follows:

Rotational	Vertical-axis rotating cups, horizontal-axis windmill or propeller.
Pressure	Pitot-static, Venturi-static, pressure plate, or bridled cups.
Heat exchange	Hot wire or thermistor, kata-thermometer.

The majority of installations are of the rotating-cup type. The propeller type usually is for portable or hand-held use. Pitot and Venturi tubes measure pressure gradient of the air flow. The ordinary pressure-plate type hangs on a horizontal axis perpendicular to the wind and is swung from the vertical by the wind's force. The normal-plate type remains perpendicular to the air flow and its deflection measures the pressure of the wind against it. The bridled-cup type is nonrotating and measures the torque resulting from the wind force. Hot-wire types measure either the variations in current required to maintain the wire temperature or the variations in resistance of the wire as its temperature is cooled by the air flow. Kata-thermometer anemometers measure the cooling power of the air flow ventilating the bulb of a thermometer; wind speed is determined from the time required to depress the temperature from 40° C to either 38° C or 35° C.

The gustiness, or short-period fluctuations of wind speed may be measured by any of the anemometer types. Some are more suitable than others depending on the scale of the variations it is desired to measure.

The instrument used to measure the direction of the wind is the wind vane. Usually it has a relatively long tail and is mounted on a vertical axis. The lateral forces of the wind on the tail cause the vane to align itself with the horizontal component of the flow. Small mass relative to tail area and a bifurcated, spread or split shape are incorporated into vanes designed for sensitive response to small changes in direction, especially with light winds. Omni-directional wind vanes--that is, those mounted in gimbals so that they may point in any direction--afford three-dimensional measurements of eddy patterns. By convention, wind direction is defined as the direction from which the wind blows.

Most anemometers represent a compromise between sensitivity and the weight and sturdiness suitable for all ranges of wind speed from that of a mere puff to that of a hurricane. No single type is ideally suitable for the entire range, yet few stations have more than one type of anemometer.

b. Upper-air instruments

Speed and direction of winds aloft are measured by observing the motion of some visible object being pushed along by the force of the wind. By far the most common object is a small lighter-than-air balloon that is released at regular observation times, and observed by single or double theodolites or by radar. Other objects include a puff of smoke, a visible meteor trail, chaff thrown from an airplane, or a cloud.

2. Location and installation of measuring equipment

As observed, most wind speeds and directions are not instantaneous values but average values over a short interval of time. Wind speed varies substantially with height above the land surface and this variation is a complex and not very well understood function of the roughness of the land surface and the "stability" of the air, as well as of the speed itself.

Recently, the Weather Bureau has relocated the wind instruments of all its airport stations at a uniform height of 20 feet above the land surface. The relation of velocities measured at this standard height to those at other heights is expressed approximately by the following empirical formula.

$$\frac{V_{20}}{V_h} = \left(\frac{20}{h}\right)^{\frac{1}{n}} \qquad (1)$$

in which V_{20} = velocity at height 20 feet

V_h = velocity at height h (between 20 and 1,000 feet)

$1/n$ = a power ranging from 1/7 for a strong wind under a dry-adiabatic condition, through 1/3 for an average wind and intermediate stability, to 1/2 for a light wind and a stable condition.

Thus, assuming an anemometer relocated from a former height of 100 feet to the standard height of 20 feet, and assuming also a power of 1/7 in the preceding equation, the standard 20-foot-high velocities would be 0.8 times the former 100-foot-high velocities.

Since measured wind speed is affected strongly by features of the site and by height of the instrument, proper exposure for the purposes in mind is very important. For determining general movement of the air, the exposure should be as free as possible from obstructions to the flow. Measurements in connection with evaporation studies are made near the land surface, sometimes at several heights. For special studies the instruments may be mounted at various heights or at intervals on towers.

3. Consistency and reliability of records

Relatively few records of wind movement have been obtained over a long term of years devoid of changes in location of the station, in the surrounding environment, and in height of instruments above the land surface. Thus, most records are likely to embody inconsistencies, which are difficult or impossible to identify and evaluate. Common sources of inconsistency include the following:

> Although efforts have been made to standardize height of instruments, wide variations occur. The effect of variable height of installation has been summarized.
>
> Wind movement close to the land surface may be affected greatly by growth of grass, crops, or brush. These small-scale changes in environment should be considered in regard to records of wind movement at an evaporation station.
>
> Larger-scale changes in environment must be considered in regard to all other stations. Many stations have been located in cities, where continual construction and destruction of buildings probably has affected the exposure of most anemometers and wind vanes. The recent trend toward placing stations at airports has not eased this situation; construction to accommodate the phenomenally rapid increase in air traffic has forced all-too-frequent relocation of wind instruments. At another extreme, after a forested area is logged or burned, wind-speed measurements can increase abruptly; then, as normal growth is re-established, the measurements revert gradually toward their former value.

Instrumental errors in measurement of wind velocity and direction usually are relatively small, excepting those due to mechanical failure or improper maintenance. Most types of anemometers lag due to inertia, and to any play in gear trains or dials--they do not respond instantly to changes in wind velocity. Thus, rapid perturbations are smoothed and peaks of short duration may under-register substantially. The most common anemometer, the cup type, registers too much total movement during a variable wind because the cup wheel accelerates more readily than it decelerates.

Anemometers developed specifically to measure high wind velocities commonly are not suitable at low velocities. Among wind vanes, one that is heavy may oscillate less than one that is light and so may mask short-period changes in direction, or may over-swing on sudden changes. A vane that is large and that has a relatively long tail tends to smooth out many whirls and eddies to which a short vane would respond.

Mechanical failure during periods of low temperature may involve complete stoppage by accumulated ice or snow, or substantial under-registry owing to congealed lubricant in bearings. An instrument improperly cleaned and oiled may under-register at any time. As will be obvious, erroneous records so caused are all but impossible to identify and adjust.

4. Use of data on wind

Wind records are useful for a wide range of purposes, including (1) the selection of sites for airports, industrial plants, wind-power generators, and meteorologic stations; (2) estimating wind loads on buildings, television towers, or other structures; (3) study of the distribution and dilution of dust, pollen, pollutants, and cloud-seeding nuclei; (4) determining wind effect on the formation and movement of ice in streams and lakes; also on wave action and its relation to shore erosion and to loading and movement of ships; and (5) weather forecasting, both in general and in particular regard to forest-fire warning and fighting, frost warning, and air-borne commerce.

Wind is a principal variable in the investigation, forecasting or calculation of evaporation. Its speed, direction, eddy structure and variation with height influence the rate at which the vapor molecules are removed from the immediate vicinity of the liquid surface.

Wind is responsible for drifting of snow and strongly affects the deposition of snow around and on obstacles such as buildings, fences, bridges, and roofs. It is a parameter in the estimation and study of snow-melt rates and amounts.

Wind is known to have substantial influence on the catch of precipitation gages, the catch diminishing as wind speed increases. This effect is much more marked with snow than with rain. It can be countered by shielding the gage orifice and by locating gages at sites protected from the wind.

The orography of a region has a pronounced effect on wind flow, which in turn strongly influences the rate and distribution of precipitation. These orographic influences can result in more precipitation on windward slopes and on steep slopes than on lee slopes and gentle slopes.

E. PRECIPITATION

1. Types of gages

By far the greater part of the published records of precipitation have been derived from the non-recording 8-inch precipitation can with funnel and measuring tube which has been the standard gage for more than a century. In such gages the catch of precipitation is measured periodically by an observer, commonly once each day. Daily, monthly, and yearly amounts of precipitation so measured are published currently by the Weather Bureau for about 13,000 stations, in "Climatological Data for the United States."

Precipitation amounts that are measured less frequently than once a day are published separately. Most such records are from non-recording storage gages in remote areas. Examples are the standpipe, "Sacramento," and extended 8-inch cans which have capacities for storing large amounts of precipitation. Oil and anti-freeze solution generally are placed in these gages to retard evaporation and prevent freezing.

Recording gages are installed at first-order stations of the Weather Bureau and at other locations to measure precipitation rates by hourly or shorter intervals (3,500 stations). These gages generally embody an 8-inch-diameter funnel to catch the precipitation and a clock-driven chart on which the catch is recorded. Three types of recording gages are in common use. In two of the three the catch passes to a receiver, from which the recording mechanism is actuated by the increasing weight or the rising water level. In the third type, the catch passes to a "tipping bucket" whose action marks a tick on the chart for each 0.01 inch of precipitation (or by some larger increment).

At Weather Bureau stations, recording precipitation gages commonly are of the weighing type. Where both a recording and a non-recording gage are installed, the official amounts of precipitation are those indicated by the recording gage.

Records published by the Weather Bureau from its recording precipitation gages show hourly, daily, monthly, and yearly amounts. So published, the amounts of hourly precipitation are those for clock hours; they should not be construed as instantaneous rates of precipitation, which may be several-fold greater and which can be derived from the recorder charts.

2. Exposure and spacing of gages

The amount of precipitation occurring at any given point is controlled primarily by meteorological conditions, by the location in relation to storm paths, and by large-scale physiographic features such as the oceans, plains, and mountain ranges. In turn, the percentage of the true precipitation that is measured or observed in a gage is dependent upon small-scale features such as the orientation and steepness of canyons; upon nearness of the gage to trees, buildings, and other obstructions; and upon the type of gage, its condition, and the care exercised by the observer.

Many investigators have shown that strong wind or sudden changes in wind direction commonly diminish the precipitation catch in comparison with actual or true precipitation. Shields have been developed to offset the adverse effects of wind, but these lose effectiveness if the wind is strong, especially if the precipitation is in the form of snow. Thus, desirable gage sites are those that have natural protection from strong wind. Best is a small forest clearing with angles from the lip of the gage to the nearest tree tops between 20° and 30° from the horizontal. In general an obstruction should not be nearer to the gage than its own height. Sites which might receive snow blowing from nearby ridges also should be avoided.

Thus, the precipitation caught in any of the conventional gages is basically only an index to the actual precipitation on the surrounding area. The degree to which the precipitation catch by gages correlates with the actual precipitation over an area depends upon physiographic and other terrane features, and upon spacing of the stations. For the same spacing the records of precipitation catch may reflect accurately the yearly or seasonal basin-wide fall, but may be much less reliable in regard to monthly or storm amounts. Records from average-spaced stations (20 to 25 miles apart) may be misleading in regard to isohyetals of a single storm because the storm center may miss all stations.

3. Dependability of observations

a. Sources of error

Considerable information has been published on the possible sources of error in precipitation measurements. Many of these are associated with gage exposure while others depend upon the type of equipment and the observer's ability. Ordinarily, little can be done by the hydrologist to ascertain and adjust for possible errors, except those associated with exposure and only on a current basis. Certain specific sources are summarized below.

a-1. Improper exposure.--Criteria have been given for properly locating a gage in relation to nearby obstructions. When such criteria are violated, both speed and direction of wind as well as catch of the gage are likely to be abnormal. The abnormality can be identified and evaluated by comparing the catches of adjacent gages between windy and non-windy periods, certain of the gages being properly exposed.

a-2. Catch of snow.--Snow may bridge and cap a precipitation gage, so that the apparent time of snowfall may be displaced (in the case of a recording gage), or the catch may be grossly in error. Also, the gage may become partially filled with unmelted snow, so that its catch efficiency is diminished temporarily. Such events may be presumed if there are erratic differences among the catches of adjacent gages. In general, reported catches of snow could be mistrusted whenever they exceed 50 percent of gage capacities.

a-3. Snow density.--On occasion, an observer may record the depth of new-fallen snow instead of melting a sample and recording the water content. In such cases, the published precipitation amount is sometimes estimated by assuming a density of 0.10 for the new-fallen snow (one inch of snow equals 0.10 inch of precipitation). Such estimates now are identified in "Climatological Data" by a footnote, "D". Some of the earlier publications did not identify these estimates, which could be disclosed only by examining the original records. The 1-to-10 rule can be considerably in error for some storm periods.

a-4. Minimal amounts of precipitation.--At substations, hours may elapse before the precipitation catch in a light storm is measured on the once-daily schedule. During that interval an appreciable portion of the catch may be lost due to evaporation. First-order and recording stations have shown a greater frequency of days with precipitation $\geq$0.01 inch than stations that measure only once a day.

a-5. Unnoted change in location of station.--As will be treated at greater length, a change in location of a station may divide a precipitation record into parts that are not consistent one with another. If the changed location is overlooked or is not of record, a substantial error may result.

a-6. Recording gages at remote stations.--At high altitude, remote sites where precipitation may fall as either rain or snow, and where several months may elapse between servicing, presently available recording gages commonly fail to operate continuously. Consequently there are serious gaps in knowledge of short-term precipitation rates at such sites, with resultant possible errors in interpretation.

b. Hour of observations

Care must be used in comparing or correlating precipitation data from station to station, or in computing the precipitation over a given basin during a particular time interval. Amounts of daily precipitation as published in "Climatological Bulletins" under a given date may not be for the same interval of time; the hour of observation is listed in the bulletin. Thus, at first-order Weather Bureau stations that are equipped with recording gages, amounts of daily precipitation are determined on the midnight-to-midnight basis. At substations, however, the daily amounts are generally from once-daily readings of the gage--commonly near sunset or early in the morning but neither strictly at 24-hour intervals nor at a common hour among all the substations. Thus, for storms of short duration or of highly variable intensity, amounts of precipitation recorded under a particular date might differ substantially among a group of stations whereas the actual amounts were essentially equal and simultaneous. The original-observation form (WB Form 612-14, formerly 1009) has a space for indicating the beginning and ending of precipitation. Many observers keep meticulous records in this regard; this information, which is not published, can be of considerable assistance in special studies. If such information is desired, a copy of the records can be obtained from the respective State Climatologists.

Also, an erroneous date of observation may have been entered in the record. Errors and inconsistencies such as those here described can, in many instances, be disclosed by constructing isochronal maps.

c. Consistency of records

No record of precipitation should be assumed to be consistent throughout, unless it is known to be devoid of changes in exposure, observer, location, and equipment. Available information on such changes is contained in the substation histories published by the Weather Bureau ("Key to Meteorological Records Documentation No. 1.1"). These histories were compiled from information available at the time of publication (early fifties); they were not the product of a concerted program to accumulate such information over the entire period of record. Some apparent inconsistencies in the observed records might be explained if the historic information were complete.

Especially in the mountainous West, even a small move in gage location may cause a substantial change in the relative catch of precipitation. However, some records have been published under one name for a long period of time, even though the station may have been moved about within the vicinity, either short or long distances. Changes in exposure such as the construction of buildings, and the cutting or growth of trees and plants, may cause a change in the precipitation catch. Installation of a windshield often will increase the catch. This increased catch may be more nearly equal to the actual precipitation at the gage site, but will not be consistent with the catch prior to use of the windshield.

In testing a precipitation record for consistency, the first step should be a review of the station-history information. Next, the record should be compared with those from nearby stations considered to be in the same environment, either by double-mass plotting or by the ratio method. The latter method compares the records for various periods of time to determine whether the ratio is consistent. When the source of moisture changes substantially from winter to summer as in the Southwest, it is desirable to test consistency for each season separately. Double-mass analysis has been used in most areas of the Southwest to test the consistency of winter records (October-April); the ratio method to test summer records (May-September totals).

If inconsistencies are apparent, appropriate adjustments sometimes are warranted. However, caution should be used in such adjustment and the safest approach is to adjust only if presumptive causes coincide with dates of inconsistencies.

In the case of a long record at a station documented as having had changes in location, and if double-mass analysis shows each to be consistent within itself, the record for each location should be treated separately.

4. Use of data

a. Determining averages or normals

The World Meteorological Organization has defined the term "normal" as the average computed for a uniform and relatively long period that comprises at least three consecutive 10-year interim periods. The standard periods adopted by the U.S. Weather Bureau for climatological normals are the following consecutive 30 years: 1 January 1921 to 31 December 1950, 1 January 1931 to 31 December 1960, etc. "Average" or "long-term mean" should be used for reference to any other period. The length of record required to establish a suitable climatologic average depends to some extent upon the variability of the record. Beginning January 1, 1962, the Weather Bureau has used the 1931-1960 normal for all stations. If part of a station record is inconsistent, use of all the record may lead to an incorrect normal or average.

Normal or average precipitation for a period longer than the observed record for a station may be estimated by various comparison techniques. In the Pacific Southwest, five years or more of precipitation records may be sufficient to compute an October-April normal by the double-mass technique; ten years or more to compute a May-September normal by the ratio method.

Average precipitation over an area during any particular storm or period may be determined by computing the average of the records available, by the Thiessen-diagram technique, by the isopercental method, or from an isohyetal map (lines of equal precipitation). In mountainous areas the isohyetal-map approach is recommended if the map is based on a knowledge of topographic influences and characteristics of the particular storm.

b. Preparing isohyetal maps

All records to be used in preparing isohyetal maps first should be checked for consistency. A specific period of record should be chosen and all averages should be for that period. To arrive at a yearly isohyetal map for any part of the Pacific Southwest, with the possible exception of California, it is desirable first to prepare separate October-April and May-September maps because of the change in source regions and storm paths from winter to summer.

c. Frequency analyses

Several techniques are used for frequency analyses of precipitation data, according to the particular type of study. Care must be taken that the data used in the frequency analysis represent the same time interval. For example, hourly precipitation records are published for clock hours and do not necessarily represent the maximum precipitation in any one-hour period. Likewise, reports from daily precipitation stations may not represent maximum 24-hour precipitation amounts. Various technical papers that have been published by the Weather Bureau will, in many cases, furnish the required frequency information.

d. Estimating missing records

Missing records should be estimated only when it is reasoned that the estimated data will be of definite advantage. Simple ratio methods of normals or averages (based on a common period), or comparison of slopes on double-mass plottings may be used for estimating yearly or monthly amounts from adjacent stations. The Weather Bureau estimates missing records by the normal-ratio method and, when they are available from daily snowfall amounts according to the conventional density of 0.10, these estimates are included in the monthly totals published in the annual climatological bulletins. It should be noted, however, that the ratio between stations may change from season to season. Missing daily or storm amounts generally are best estimated by constructing isohyetal maps. For shorter intervals the most desirable procedure would be to compare mass curves with those of adjacent stations. Hour of measurements should be reviewed to assure that the records used are comparable.

e. Statistical analyses

In using precipitation records for statistical analyses the greatest pitfall is non-consistent records. Accordingly, a check should be made on the consistency of all records prior to such analyses. Inconsistency in a record, for example, tends to increase the apparent auto or serial correlation.

f. Early published data

Early published data, especially those in "Bulletin W," include many estimates of monthly and yearly precipitation. Certain of these estimates have been shown to be in error; depending upon the intended use of the records, adequate checks should be made of these estimates. In tabulating the records in "Bulletin W," no effort was made to check their consistency. For some stations the data actually were composed from two or more sites fairly well separated in distance or in altitude. Footnotes were used to indicate when records were so combined.

F. EVAPORATION AND TRANSPIRATION

1. Introduction

Evaporation is defined as the physical process by which water vapor escapes from a water surface. The rate of evaporation depends fundamentally on many factors including radiation (both short- and long-wave), vapor pressure, air temperature, wind movement and atmospheric pressure. It is also affected by impurities such as dust, films on the water surface, and matter dissolved or suspended in the water.

This section will be restricted to discussion of methods for estimating evaporation from a lake or reservoir (free-water surfaces), and limitations of these methods. Knowledge of evaporation losses is highly important in design of reservoirs and in planning their most efficient operation for irrigation, hydro-electric power, water supply, or other purpose. In the arid parts of the West, where evaporation greatly exceeds precipitation, serious consideration must be given to the reduced water yield which will result from the construction of a reservoir. It should be emphasized that evaporation loss from the reservoir area is always greater than the evapotranspiration loss under pre-reservoir conditions. In humid areas, the increased loss may be of no consequence, but in arid areas the utility of a regulated water supply must more than balance the reduced water yield.

2. Methods of determination

a. Water budget

The simplest method for determining lake evaporation would seem to be the water-budget method, which can be expressed by the volumetric equation:

$$E = P + I - O - \Delta S \qquad (1)$$

in which E = lake evaporation

P = precipitation on lake surface

I = inflow, by streams or effluent ground water

O = outflow, by streams or influent ground water

S = increase in stored water

Reliability of the method depends on the accuracy to which each item of the budget can be measured or estimated, also on the magnitude of each item in relation to the evaporation. For each of the budget items, acceptable percentage error diminishes about in inverse proportion to relative magnitude of that particular item. Thus, unless evaporation is of about the same magnitude as the largest of the budget items, its determination by the water-budget method may not be reliable.

Usually all the surface outflow is measured, at the outlet of the lake or reservoir. However, only major components of surface inflow may be measured, at a gaging station or stations above the lake. Inflow from the intervening ungaged area may be substantial and can only be estimated. Unmeasured ground-water inflow or outflow may or may not be significant; it is difficult to evaluate (Langbein, Haines, and Culler, 1951). It is also difficult to determine the change in storage accurately. First, it is necessary to conduct detailed pre-reservoir surveys or subsequent "hydrographic" surveys to provide reliable area and capacity curves. In many instances, there is the added complication of evaluating bank storage. For example, Langbein (1954) estimated that, owing to bank storage, the effective capacity of Lake Mead is 12 percent greater than that indicated by the accepted area-capacity curves. It is also difficult to obtain an accurate mean lake level since wind effects can so distort the lake profile that a single gage reading may be significantly in error. (See separate chapter, this handbook, on "Reservoirs and lakes.")

Another item of the water budget is the precipitation on the lake surface. Ordinarily, such precipitation is measured by a single gage or a network of gages along the shore. For large lakes, it is questionable whether measurements at shore stations provide a true value of precipitation over all the Lake (Kresge, Blust, and Ropes, 1963).

In summary, water-budget values of evaporation generally can be considered more reliable, percentagewise, over intervals of a month or longer than over intervals of a day or less. Measurements of daily inflow and outflow may embody both random and certain systematic errors that tend to balance over longer periods of time (see following chapter of this handbook on "Streamflow"). The effect of errors in other measured budget items tends to diminish likewise. Budget items that are unmeasured commonly can be estimated fairly closely over all of a year-long water cycle, but not for periods of a month or less. The difficulty of obtaining reliable daily values by the water-budget method is demonstrated by the considerable effort expended in selecting Lake Hefner for critical water-loss investigations (U. S. Geol. Survey, 1954).

b. Energy budget

The energy budget per unit area and time is given by the equation:

$$Q_e = Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_h - Q_w - Q_k \qquad (2)$$

in which

Q_e = energy utilized by evaporation

Q_s = incoming short-wave (solar) radiation

Q_r = reflected short-wave radiation

Q_a = incoming long-wave (atmospheric) radiation

Q_{ar} = reflected long-wave radiation

Q_{bs} = long-wave radiation emitted by the body of water

Q_v = net energy advected into the body of water, including that of precipitation but excluding that of evaporated water

Q_h = energy conducted from the body of water to the atmosphere as sensible heat

Q_w = energy advected by evaporated water

Q_k = increase in energy storage of the body of water

The computations are usually made in units of calories per square centimeter per day.

The energy-budget theory long has been accepted as sound, but only subsequent to about 1950 have instruments of the required accuracy become available. The main objections to the technique are the needs for expensive instrumentation and careful maintenance to assure reliable observations. The computations are laborious, but this limitation has been partially overcome by the advent of high-speed electronic computers.

In principle, the most convenient method for evaluating the five radiation terms of equation (2) would be by net radiometer installed on a barge or float in the lake. However, net radiometry by a single instrument currently is not sufficiently precise; also, a barge installation involves serious difficulties in operating and adequately maintaining instruments of all kinds. Therefore, the usual and more practical installation is on land and includes (1) usually an Eppley pyrheliometer, facing upward, to measure the incoming short-wave radiation (Q_s); and (2) a total or "hemispherical" radiometer, which measures the sum of the incoming short-wave and incoming long-wave radiations ($Q_s + Q_a$). Thus, incoming long-wave or "atmospheric" radiation (Q_a) is determined by subtracting the Eppley observation from the hemispherical observation. The Eppley pyrheliometer should be corrected for temperature effect although this has not been common practice in the past. Currently, it is possible to purchase temperature-compensated instruments.

In principle, the reflected short-wave radiation (Q_r) can be measured by a separate Eppley pyrheliometer facing downward, over the water. However, this leads to the difficulties of a barge installation, previously mentioned. In the previously cited Lake Hefner investigations, Anderson found that the reflected short-wave radiation could be estimated adequately by the equation:

$$R_t = aS_A^{\ b} \tag{3}$$

in which R_t = reflectivity ratio (reflected to incoming)

S_A = sun altitude, in degrees

a, b = "constants" which vary according to percentage of cloud cover and its height: a, from 2.20 to 0.20; b, from - 0.30 to - 0.98

It is not always necessary to measure reflected long-wave radiation (Q_{ar}) since a reflectivity of 3 percent may be assumed in most instances.

To compute the long-wave radiation emitted by the lake (Q_{bs}), the water temperature at lake surface must be measured and inserted into the equation:

$$Q_{bs} = 0.97\sigma(T_o + 273)^4 \tag{4}$$

in which σ = Stefan-Boltzmann constant

T_o = water temperature at lake surface, in ^oC

As the Q_{bs} term is one of the largest in the energy-budget equation it must be determined accurately. To this end, the true mean water-surface temperature must be determined as closely as is feasible, ordinarily within 0.5^{o}C.

Aside from radiation, two potentially decisive factors in the energy budget are advected energy and change in energy storage. A part of these two energy components is expended in modifying water-surface temperature, which in turn modifies the amounts of back radiation and of sensible-heat transfer. Methods for determining the part that is expended by the evaporation process are described by Kohler and others (1955), by Harbeck and others (1959), and by Harbeck (1964).

Computing advected energy requires the measurement of the volumes of water inflow and water outflow, also their mean temperatures. Precipitation on the reservoir or lake surface must be included as an inflow term; ordinarily, its temperature is assumed equal to the wet-bulb temperature.

Computing the change in energy storage requires that the temperature and volume of water in storage be measured at the beginning and end of each budget interval. Usually, temperature profiles must be measured at 25 to 30 selected points to define adequately the thermal stratification of the entire water body at the given times. From the temperature profiles, mean temperatures are derived to correspond with successive horizontal layers of the water body. Then, the product of mean temperature and corresponding volume of water in a particular layer indicates the energy content of that layer above a selected temperature base. The sum of the energy contents of the several layers is the total energy content of the water body. The algebraic difference between the energy contents at the beginning and end of the budget interval is the total increase in energy storage. For insertion in equation (2), this difference must be divided by the product of the mean water-surface area during the budget interval times the number of days in the interval, to express the increase in the usual energy-budget units (Q_k, in calories per square centimeter per day).

Energy-storage computations, therefore, require the availability of area and capacity curves of suitable accuracy. The change of energy storage may be relatively large if the body of water is deep, especially over periods during which the body overturns or changes its thermal stratification notably.

The measured or estimated terms discussed thus far yield the sum $Q_e + Q_h + Q_w$, rather than the desired single term Q_e. However, Q_w and Q_h can be expressed in terms of Q_e according to the relation:

$$Q_w = \frac{cTQ_e}{L} \qquad (5)$$

in which c = specific heat of water

T = temperature at which evaporation takes place, taken usually as that of the water surface

L = latent heat of evaporation

Also, according to the Bowen ratio (Bowen, 1926). Although there is controversy over validity of the Bowen-ratio theory, it seems to be generally applicable for computating reservoir evaporation. Bowen's ratio is expressed as:

$$R_B = \frac{Q_h}{Q_e} = \frac{cP(T_o - T_a)}{1,000(e_o - e_a)} \qquad (6)$$

in which c = a coefficient, 0.61 under ordinary atmospheric conditions, but ranging between 0.58 and 0.66

P = atmospheric pressure in mb (millibars)

T_o = water-surface temperature in ^oC

T_a = air temperature in ^oC

e_o = vapor pressure of saturated air in mb, at T_o

e_a = vapor pressure in the air in mb, at the height of the T_a observation

To evaluate the Bowen ratio, it is necessary to measure water temperature, air temperature, and dewpoint. It is preferable that T_a and e_a be measured vertically above the sites of the T_o measurements.

In general, for intervals of a week or longer, evaporation can be determined with good precision by the energy-budget method provided all the budget items are evaluated with utmost care. The method is not recommended for intervals shorter than a week, chiefly because, for such intervals, the change in energy storage cannot be determined with satisfactory accuracy. The advected-energy term requires data on temperature and volumes of water inflow and water outflow. However, the accuracy required of such volumes is less critical in the energy budget than in the water budget. Herein lies the principal advantage of the energy-budget method.

A basic limitation of the energy-budget method is that certain of the radiation terms always are several-fold larger than the net energy that drives the evaporation process. Hence, a small percentage error in one such item may cause a large percentage error in the computed amount of evaporation. For example, energy-budget values of evaporation from Salton Sea, California, determined recently by Hughes (in preparation, 1965) are seasonally biased. Hughes concluded that most of this bias may be ascribed to shortcomings in the radiation instruments. Although considerable progress has been made in recent years in the development of total hemispherical and net radiometers, additional improvements in the accuracy and dependability of these instruments is essential before the energy-budget method can be invoked routinely.

c. Mass-transfer (aerodynamic method)

Many techniques have been advocated for computing evaporation according to aerodynamic theory. These have been described and evaluated in the reports on water-loss investigations at Lake Hefner and at Lake Mead (U. S. Geol. Survey, 1954; Harbeck and others, 1958). The only technique that produced good results in both studies was that based on an empirical equation of the form:

$$E = Nu\,(e_o - e_a) \tag{7}$$

in which

- E = evaporation
- N = a coefficient
- u = average wind speed
- e_o = vapor pressure of saturated air at water-surface temperature
- e_a = vapor pressure of ambient air

This technique has been named the mass-transfer method, although implications of this name may not be completely correct. The investigations at Lakes Hefner and Mead in the United States and at Lake Eucumbene in Australia (Webb, 1960) indicate that the value of N may be assumed to be nearly constant when vapor pressure, water-surface temperature, and wind speed are measured within the vapor blanket over the lake. The coefficient N so obtained at Lake Hefner yielded reliable estimates of evaporation at Lakes Mead and Eucumbene. The observations of vapor pressure and wind speed should be at a height of 2 or 4 meters above the water surface, preferably the former. Also, it is imperative that the barge or float for making observations should be far enough from shore to assure that the 2- or 4-meter observations of vapor pressure (e_a) are within the vapor blanket.

The main shortcoming of the over-the-lake equation is the difficulty of obtaining reliable values of vapor pressure. It is preferable to obtain continuous records of the several factors; these in turn require considerable effort to maintain recording instruments in good operating condition on a barge, where only battery-driven or spring-driven devices are practical. Admittedly, further tests should be conducted to verify that the coefficient N is nearly constant if all factors are measured near midlake.

To avoid this difficulty of reliable measurements over the lake, Harbeck (1962) measured vapor pressure (e_a) at a land site, upwind. In applying such upwind vapor pressures at numerous lakes, Harbeck found that the coefficient N is a function of the surface area of the lake. Although the correlation between area and N was quite good in general, in certain cases it could be in error by 25 percent or even more. Therefore, Harbeck advocates extreme caution in using values of N from his correlation. He recommends that, if practical, a mean value of N for each particular lake or reservoir be determined to match a year-long energy budget or water budget of that lake. Then, the mass-transfer equation with such a value of N may be used to estimate evaporation routinely in subsequent years.

Thus, the overall accuracy of evaporation determined by the mass-transfer method would be neither better nor worse than the accuracy of the water budget or energy budget to which the value of N had been matched. In the particular case of an N-value matched to a water budget, it should be borne in mind that some of the uncertainties in such a budget, although potentially rather large over a term of a month or less, tend to compensate within each year's water cycle. Accordingly: (1) the mean N-value matched to year-long water-budget evaporation presumably minimizes short-term and seasonal bias in the water budget; and (2) values of monthly or shorter-term evaporation by the mass-transfer method, using the mean or year-long value of N, presumably are more dependable than water-budget values.

The principal advantage of the mass-transfer method is that it eliminates advected energy and energy-storage change as independent factors. The effects of these two factors appear in the water-surface temperature, and so in the e_o factor of equation (7). Accordingly, potential causes of seasonal bias seem to be fewer in the mass-transfer method than in either the energy-budget or the water-budget method. The mass-transfer method, therefore, seems the most reliable of the three methods for determining evaporation by months or shorter periods.

d. Combination of aerodynamic and energy-budget theories

A widely used technique to estimate lake evaporation from meteorological factors is based on a combination of aerodynamic and energy-budget theories (Penman, 1948; Ferguson, 1952; Kohler, 1955; Slatyer and McIlroy, 1961). The Penman method involves the three equations:

$$E = \frac{\Delta H + \gamma E_a}{\Delta + \gamma} \tag{8}$$

$$H = R_a (1 - r)(0.18 + 0.55\, n/N) - \sigma T_a^4 (0.56 - 0.09\sqrt{e_d})(0.1 + 0.9\, n/N) \tag{9}$$

and

$$E_a = b(a + u)(e_a - e_d) \tag{10}$$

in which

E = evaporation

H = net radiation

Δ = slope of the saturation vapor-pressure curve at air temperature T_a

γ = the constant in the pyschrometric equation

R_a = "extraterrestrial" radiation

r = coefficient of reflectivity

n/N = percent possible sunshine

σ = Stefan-Boltzmann constant

T_a = air temperature

e_a = vapor pressure of saturated air at temperature T_a

e_d = actual vapor pressure of air

u = wind movement

a, b = constants

The Penman equation is basically a derivative of the energy-budget equation. However, because it considers the energy-storage and advected-energy terms to be negligible, the Penman method is defendable only for very shallow water bodies, except over year-long periods. Because it does not bring in water-surface temperature, the method cannot account adequately for sensible-heat exchange between air and water. The latter factor may be small over year-long periods, but can be appreciable over shorter periods. The method involves theoretical values of short-wave radiation, based on percent sunshine; observed values should be used whenever available. Finally, the computed value of net long-wave radiation, $\sigma T_a^4 (0.56 - 0.09 \sqrt{e_d})$, will be in error whenever water-surface and air temperatures differ.

For potential applications, in the United States, of equations such as that by Penman, records of solar (short-wave) radiation are taken currently at about 80 stations only. Records of percent sunshine (or of cloud cover) and of dewpoint are, for the most part, taken only at the first-order stations of the Weather Bureau. Fortunately, for computing evaporation by periods of a week or longer, each of these three variables may be assumed to be fairly uniform to moderately great distances from the stations of record.

Likewise, records of wind movement are available from only a limited network of stations. There is the additional complication that the observed wind movement must be reduced to a specific height--2 meters for the Penman method and at anemometer height of a Class-A pan for the Kohler method. The ordinary wind-reduction formulas, which are in exponential or logarithmic form, are not completely adequate for estimating values at levels near the land surface, as required by the Penman and similar methods. Fortunately, in these methods an error in estimated wind movement does not introduce as large a percentage error in computed evaporation. Even so, wind values which are nonrepresentative or which are converted through an appreciable height range can introduce errors of 20 percent or more.

e. Pan coefficients

Probably the most widely used method for estimating evaporation from lakes and reservoirs is the application of an appropriate coefficient to the evaporation as measured by one of the standard pans. Not only can the method be applied to estimate evaporation from existing lakes, but also it is the most practical means for estimating evaporation from a proposed reservoir. Thus, several years of pan-evaporation observations at the site will provide a reliable estimate of the yearly evaporation loss to be expected.

Several types of evaporation pans are used in the United States--Class A, Colorado, Bureau of Plant Industry, and Young Screened. The pan most commonly used and having the most station-years of record is the Class-A. Specifically, as of 1965 the Weather Bureau's network of Class-A pans consists of about 450 stations.

The reliability of estimates of lake evaporation depends on the validity of the assumed pan-to-lake coefficients. The American Society of Civil Engineers (1934) has recommended that a coefficient of 0.70 be applied to the Class-A pan and 0.78 to the Colorado pan. At Lake Hefner (U. S. Geol. Survey, 1954), the coefficients derived for various pans were: Class-A, 0.69; Bureau of Plant Industry, 0.91; Colorado, 0.83; and Young Screened, 0.91. Many persons feel that estimates of lake evaporation by the Young Screened pan are more reliable because the pan-to-lake coefficient is more nearly unity. A coefficient of unity may simplify the arithmetic, but does not make results more reliable. Actually, the screen intercepts some of the solar radiation and diverts it from the evaporation process. On the other hand, the Class-A pan has been criticized severely because it is exposed above the land surface and so is subject to radiation on the sides, with greater evaporation the consequence. Since it is now generally accepted that pan-to-lake coefficients vary according to the climatic regime, the above-land-surface exposure of the more numerous Class-A pans is not a disadvantage.

The pan-to-lake coefficient for the Class-A pan ranges from 0.60 to 0.80. In arid climates the rate of pan evaporation is high--owing to latent heat of vaporization, the temperature of water in the pan tends to be depressed below that of the air, heat is transferred from air through sides and bottom of the pan, and pan evaporation is aggravated. Such a transfer of heat does not occur in a lake or reservoir and so the appropriate pan coefficient is near 0.60. The converse is true in humid areas, where pan-water temperature tends to rise above that of the air, heat is lost from pan to air, pan evaporation is restrained, and the coefficient approaches 0.80.

The sunken pans also are subject to gain or loss of heat from or to the soil, with a consequent effect on the pan-to-lake coefficient. However, in order to evaluate the heat transfer, both soil temperature and soil moisture would need be determined; reliable values of the latter are difficult to obtain. Even if reliable values were available, the evaluation would be complex since it is a function of both soil temperature and soil moisture.

Kohler and others (1955) describe a technique by which to adjust the observed Class-A-pan evaporation for the transfer of heat to or from the pan. Then, based on Lake Hefner results, it is assumed that a coefficient of 0.70 applies to the adjusted pan record, as though air temperature and pan-water temperature were equal. Such application of the coefficient would indicate probable evaporation from an extensive water surface of film thickness--that is, evaporation from a very shallow lake, over intervals as short as a week. Still further adjustment would be required in applying a pan coefficient to estimate true evaporation from a lake or reservoir, especially evaporation over a short interval, if that lake or reservoir is influenced significantly by advected energy or by changes in energy storage. Commonly deep lakes or reservoirs and "run-of-river" reservoirs would require such further adjustment.

Deep lakes store energy in the spring months and so tend to diminish evaporation; they release this energy from storage in the fall months and so accelerate evaporation. This effect is clearly demonstrated by Lake Mead, where pan evaporation is maximum in June but the lake evaporation is maximum in August. Lake Mead also exemplifies the effect of advected energy--during the summer, temperature of the inflowing water is high, but the outflow is released from lower, cooler levels in the lake. Consequently, there is a very large energy advection into the lake. On the average, this advective-energy effect increases the evaporation from Lake Mead about 5 inches yearly, an amount which the standard pan-to-lake coefficient would exclude. Lake Mohave and Lake Havasu, on the Colorado River below Lake Mead, exemplify a different aspect of the advected-energy effect. These two are "run-of-river" reservoirs. In them, inflow and outflow commonly differ little in temperature, but energy advection is large because through-flow is large. (As to adjustments for the effects here discussed, see Nordenson, 1963; Kohler and others, 1955; Harbeck and others, 1959; and Harbeck, 1964.)

Care should be exercised in the location, operation, and maintenance of all pan-evaporation stations. In general, the station site should be typical in the surrounding area--that is, neither extremely windy nor completely sheltered sites would be suitable. To obtain estimates of evaporation from a lake the station should, if possible, be on the side of the lake toward the prevailing wind. Surrounding vegetal cover should be trimmed frequently to maintain a consistent pattern of wind movement over the pan. The pan should be cleaned at regular intervals to avoid contamination of the water surface or change in radiation characteristics. It is important to maintain the water level within the prescribed range--for the Class-A pan, 2 to 3 inches below the rim. It is recommended that water temperature be measured; this practice is now standard for Class-A-pan installations (U. S. Weather Bureau, 1962). It is extremely important that a Class-A pan should not be painted. Painting would change the reflective characteristics and, therefore, the amount of radiation absorbed. For this reason, the Weather Bureau now recommends that Class-A pans be made of monel metal.

Despite these standard precautions and pan-to-lake coefficients, unrecognized aspects of pan exposure may bias some of the factors that control evaporation from an adjacent lake. At Lake Hefner, for example (U. S. Geol. Survey, 1954, p. 142), observed evaporation from two adjacent pans differed by 4.3 percent. There, the only obvious difference in pan exposure was that one of the two pan stations had accessory intruments in standard shelters whereas the second station had neither such instruments nor such shelters.

Observed data for evaporation pans should be reviewed carefully to discriminate any that are unrealistic. Thus, computed evaporation for days of heavy rain may be greatly in error owing to overflow of the pan, to unlike catch by the pan and by a standard rain gage, or to splash-out. For days of unusually great wind, computed evaporation also may be in error because water is blown out of the pan.

3. Variation of evaporation with altitude

Despite the many studies conducted over the years, few have demonstrated the effect of altitude on the rate of evaporation. The presumed effects of increasing altitude and their influence on evaporation rate are:

1. Air temperature tends to decrease, evaporation rate to decrease.

2. Wind movement tends to increase, evaporation rate to increase.

3. Potential short-wave radiation increases, potential evaporation rate tends to increase. In mountainous areas, however, cloudiness usually tends to increase, to the extent that radiation and evaporation rate tend to decrease.

4. Long-wave radiation tends to decrease, evaporation rate to decrease.

5. Vapor pressure of the air decreases, evaporation rate tends to increase.

All in all, it seems to be generally accepted that evaporation decreases with increasing altitude, but not by as much as would be indicated by the decrease in ir temperature. As of 1965, a project to study the effect of altitude on evaporation is in progress in the Wasatch Range near Salt Lake City, by the Weather Bureau and the Forest Service in collaboration.

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5. EVAPOTRANSPIRATION

a. General considerations

Evapotranspiration is the dissipation of water from the soil into the atmosphere, by evaporation from moist soil and by transpiration of plants. The plants may be native or cultivated; if cultivated, they may or may not be irrigated.

Transpiration by plants responds to the same energy sources as does evaporation from a water surface. (See preceding chapter, this handbook.) In the case of transpiration, however, the response is modified by physical properties of the soil and by processes of plant physiology, in ways imperfectly understood. In general, in a given climatic environment with water abundance non-limiting, the rate of transpiration depends on the species of plant, its "cover density" (p.66), and its stage of maturity; also on the salinity (or alkalinity) of soil and water. Conversely, for a given plant species the rate depends principally on temperature and humidity of the air, wind movement, radiative energy fluxes (p. 7), and phase of the growing season.

This chapter will consider the means for determining evapotranspiration where abundance of water is non-limiting, as in an irrigated field or a stand of native phreatophytes. Phreatophytes are those land plants which require, and whose roots seek out, a perennial source of moisture, generally ground water.

Phreatophytes are of particular concern because, in the arid parts of the Western States, plants of this category cover some 16 million acres and dissipate some 25 million acre-feet of water yearly by evapotranspiration (Robinson, 1957). Little or no economic return is derived. A single aggressive phreatophyte, saltcedar of the genus Tamarix, occupies about one million acres and is spreading continually. Invariably, as this plant invades an area, evapotranspiration increases.

b. Methods of measurement

Accurate measurement of rates of evapotranspiration from crops or from native vegetation is difficult, complex, and costly. Several approaches are in current use, either on experimental plots or on whole fields or drainage basins. These approaches fall into one of three classes:

Water-loss methods
Aerodynamic and energy-balance methods
Empirical formulas

All these methods are weak in one aspect or another, although several studies currently under way should reduce some of the uncertainties. The limitations or uncertainties in each method will be discussed in the light of present-day knowledge.

b-1. Water-loss methods

b-1.1 Evapotranspiration tanks.--An evapotranspiration tank, also referred to as an evapotranspirometer or as a lysimeter, is a tank or cell filled with soil and provided with a water supply, in which representative plants are grown and the amount of water transpired and evaporated is determined under observed climatic conditions. Such tanks have been constructed of steel, concrete, or polyvinyl "plastic." In size they have varied from cylinders 2 feet in diameter and 3 feet deep, through the 20-foot-diameter tank of the University of California at Davis, Calif., to rectangular plastic-membrane "tanks" as large as 1,000 square feet in surface area by 14 feet deep (Robinson and Bowser 1959). There are two general methods of operation: the flow-through method (used generally with the smaller tanks) and the controlled-level method.

In the flow-through method, water is usually though not always applied to the tanks on the surface. Evapotranspiration is taken to be the difference between such application and any percolate through the soil mass, plus or minus change in soil water. Application and percolate can be measured easily and accurately as volumes; the complementary factor of soil-water change is not measurable either easily or accurately except by weighing the whole tank. Commonly, therefore, all measurements are as weights, especially to determine evapotranspiration either as momentary rates or over short periods. The weighing devices employ mechanical or hydraulic systems, or combinations of these two.

Mechanically, deflection of a set of levers, a strain gage, or a load cell indicates change in weight against a visual scale or on a strip chart. Sensitivity is gained by counterbalancing most of the gross weight, or by floating the entire evapotranspiration cell in an outer tank which is filled with a flotation liquid and fitted with a manometer. Displacement of the flotation liquid in the manometer indicates the evapotranspiration.

In the hydraulic system the evapotranspiration tank is supported by a fluid-filled, flexible bag or "bolster" to which a manometer is connected. Evapotranspiration is calculated from fluctuations of fluid level in the manometer tube.

In weighing devices, errors may derive from undetected temperature effects--changes in the lengths of lever arms, in the viscosity of lubricants at spindles or pivots, or in the density of fluid in manometers. Lubricant viscosity had a marked effect on results from a weighing evapotranspirometer at Coshocton, Ohio. Most weighing devices are costly and require meticulous attention including periodic check calibrations and adjustments. However, a weighing device in good condition can detect very small changes in rate or in total amount of evapotranspiration.

In the controlled-level method, evapotranspiration is taken to be the quantity of water that must be added to maintain a desired constant volume (level) of water in the tank. In the simplest procedure, water is added by hand periodically, usually daily, and the necessary quantity measured as a volume. Water can be introduced automatically and continually from a Mariotte tank or "flask," or from a reservoir or supply main by way of a valve that is controlled by a float or an electric sensor. The Mariotte tank should be insulated, as changes in temperature affect the balance of pressures in that device and so influence its accuracy. Valves and their sensors require periodic inspection--more frequent inspection the more nicely the sensor is adjusted. Earth particles may lodge on, or algae grow around a valve seat, causing continual leakage. Coarse particles can hold the valve widely open or clog it tightly. A water-logged float may hold the valve open. An electric sensor may fail with the valve either open or closed. Worn linkage between sensor and float may cause exclusive backlash; fouled linkage can jam with the valve in any position. Any of these mechanical failures results in a fictitious value of evapotranspiration so long as the failure persists. Further error may derive from a poorly calibrated or insensitive meter in the water-supply line.

In the controlled-level method, dissolved solids in the supplied water accumulate in the tank and eventually become so concentrated that plant growth and rate of evapotranspiration diminish. This effect has been demonstrated in tank studies of phreatophytes at Buckeye, Arizona, and at Winnemucca, Nevada. After the tanks had been leached and backwashed at both these sites, evapotranspiration increased and returned to a normal rate. Thus, to forestall a toxic concentration of solutes--saline or alkaline, and of especially deleterious ions such as boron--both soil and water in the root zone within the tank must be sampled and analyzed periodically.

In all measurements of evapotranspiration by a tank method, environmental conditions within and without the tank should be identical to preclude the "oasis effect"--that is, the phenomenon in which an isolated single plant or small group of plants transpires more water than does an extensive, dense growth of that plant. For example, at Victorville, Calif., an isolated tank planted to tules (Scripus olneyi) within a stand of low-growing saltgrass about 25 feet from the edge of a swamp, used 22.69 feet of water in a 12-month period, while a similar tank of tules within the swamp used only 7.04 feet. (Blaney and others, 1933, p. 74-87.) Thus, use in the swamp was somewhat less than one-third that in the "oasis."

Small-diameter, shallow tanks are unsuitable for measuring evapotranspiration by large plants, shrubs, or trees, although satisfactory for grasses or small plants. In the small tanks root development is restricted, so that both plant growth and evapotranspiration diminish. Tanks of 100 to 1,000 square feet of surface area and depth of 10 to 14 feet, appear to avoid most such effect.

Beyond these specific difficulties, the principal limitation in values of evapotranspiration by the tank method--or by most other methods--lies in the extrapolation from tank to a whole field. This general limitation is discussed on p. 66.

b-1.2 Soil-water budgets.--In principle, evapotranspiration is equal to the algebraic sum of water that infiltrates the land surface, change of soil-water content within the root zone, and deep percolation that passes below the root zone. The principle is applied to plots, fields, or areas where (1) runoff is zero or can be measured readily, (2) the soil is fairly homogeneous, and (3) the water table and its capillary fringe are below the root zone.

Infiltration at the land surface is measured as rainfall (or irrigation application) minus runoff, if any. Changes of soil water are derived from periodic budgets by successive depth increments, commonly 0.5- or 1-foot increments. Limitations of the data on rainfall, runoff, and soil water are discussed in other chapters of this handbook.

Commonly it is practicable to measure soil-water content only through, and a few feet below, the root zone. Any water that percolates beyond this depth of measurement escapes the soil-water budget. Accordingly, the value of evapotranspiration is too great, by the amount of such escape. This limitation of the method becomes stringent if infiltration rate and permeability of the soil both are large.

b-1.3 Water-table fluctuations.--Wherever an extensive stand of a phreatophyte takes it water from a shallow, unconfined ground-water body, commonly the evapotranspiration draft induces a notable daily rise and fall of the water table. The diurnal fluctuation is distinctive: the water table begins to fall at sunrise and continues to fall during the daytime; at or soon after sundown, the water table begins a rise that continues until the next sunrise.

In regard to this phenomenon, W. N. White (1932) theorized that the hourly rate of water-table rise from midnight to 4 a.m. (while transpiration was essentially nil) times the hours in the day (24), plus or minus any net rise or fall of the water table was an index to evapotranspiration during the 24-hour period. The product of this index times mean specific yield of the soil within the range of the water-table fluctuation measured the day's evapotranspiration. Rate of night-time water-table rise and net rise or fall over the 24-hour period are taken from the charts of water-level recorders installed at water-table wells. Specific yield, or coefficient of drainage, must be determined experimentally.

In regard to the particular water-table fluctuations here considered, amplitude increases as evapotranspiration increases or as specific yield decreases. Thus, in highly permeable material, the amplitude of fluctuation may be so small that the method becomes insensitive. Usable results generally are obtained when the amplitude ranges about between 0.04 and 0.20 foot. Evapotranspiration values calculated from water-table fluctuations represent the growth surrounding the well. The sise of the effective area is uncertain.

The Safford Valley study, to be cited, found appreciable night-time transpiration by saltcedar and baccharis. Consequently, it was necessary to apply a coefficient in White's formula. In other areas, night-time coefficients should be verified for saltcedar and baccharis, and should be determined anew for other species.

Water-table fluctuations are not a valid index of evapotranspiration whenever and wherever they are, to a substantial degree, affected by pumping in a nearby well, by changing stage in a nearby stream or lake, by infiltration of rain, or by some other extraneous force. Further, they may be invalid when recorded in an improperly cased well.

Weakest factor in measuring evapotranspiration by the method of water-table fluctuations, by far, is the specific yield or coefficient of drainage. As has been stated, this coefficient must be determined experimentally on suitable samples, either by saturation and drainage or by centrifuging.

Each saturation-and-drainage test requires an "undisturbed" column of the water-bearing material taken at and just above the water table, and in a length somewhat greater than the height of the capillary fringe. Even under favorable conditions, obtaining each such column in the field is laborious. Also, generally it is not feasible to obtain columns in a number sufficient for a statistically sound mean value of the coefficient. Tests by centrifuging require samples of relatively small volume. Again, these must be "undisturbed" and should be taken in the zone of water-table fluctuations. Either of these two experimental methods involves uncertainties of laboratory technique; among these uncertainties is that of matching the degree to which the water-bearing material drains in the field, during the 12- to 18-hour diurnal term that the water table is drawn down by evapotranspiration. Necessary standards for, and sources of error in, laboratory procedures are covered by Johnson and others (1963).

b-1.4 Inflow-outflow budgets.--The inflow-outflow or water-inventory method is adapted to a reach of stream valley between two gaging stations. It invokes the principle that evapotranspiration is equal to the difference between the quantities of water entering and leaving the reach plus or minus any change in storage within the reach. The method was one of those developed in the Safford Valley, Arizona, by Gatewood and others (1950, p. 163-176).

The items to be measured for an inflow-outflow budget usually include stream inflow, channel-storage change, and stream outflow; ground-water inflow, storage change, and outflow; and soil-moisture change. As evapotranspiration is the net algebraic sum of these eight items, reliability of the determination depends upon the accuracy of the several items, especially of any single item that greatly exceeds the evapotranspiration. Commonly the method is invalid wherever the streamflow budget involves numerous diversions or unmeasured inflow, or where ground-water inflow and outflow are relatively large and known only approximately.

b-1.5 Seepage-runs.--The seepage-run is a variation of the inflow-outflow method, limited to a valley reach in which the only significant budget items are stream inflow, ground-water inflow in a relatively constant amount, and stream outflow (Gatewood and others, 1950, p. 154-162). Ground-water inflow is determined by runs--that is, measurements of streamflow at successive points along the channel--in the winter when evapotranspiration and other drafts on the ground-water body are essentially zero. Then, during the growing season evapotranspiration is taken to be the difference between the winter value of ground-water inflow and the net gain or loss of the stream by "seepage."

Each such determination of evapotranspiration is fairly representative of several days or a week before and after each run. Practically, seepage runs are best made at intervals of three to four weeks. Results are approximate, but consistency in results lends confidence. The basic uncertaintiy is whether all the unmeasured water-budget items are constant or inconsequentially small.

b-1.6 Evapotranspiration tent.--The evapotranspiration-tent method, or the Decker-tent method (after J. P. Decker) relates evapotranspiration to the difference in water content (humidity) of the air entering and leaving a ventilated, transparent, polyvinyl tent that encloses a plant or grass-covered plot. Humidities are measured by infrared hygrometers or by psychrometers. Humidity difference multiplied by the ventilation rate yields the vapor production rate of the plant or plot. The method and equipment are new and experimental but are being continually improved and refined. Early tests were by small coverings of single potted plants in the laboratory; now, a field technique has been adapted to shrubs as much as 15 feet high.

Among advantages of the method: (1) the tent can be erected and removed without disturbing the vegetation; (2) the necessary instruments are portable and inexpensive; and (3) rates of evapotranspiration at different hours of the day, by a given species of vegetation, can be compared easily.

Among disadvantages and current limitations are the following: (1) Only a single plant or a relatively small plot of ground can be covered. (2) The polyvinyl material of the tent is essentially transparent to short-wave (solar) radiation but is relatively opaque to long-wave (reflected) radiation. Accordingly, temperature inside the tent may increase markedly. In one tent 12 feet high, set over low vegetation, the temperature build-up was as much as 30° F; however, in the same tent set over a 12-foot tamarisk tree, the temperature did not differ notably from that of ambient air outside. (3) Ventilation rate is generally less than air movement outside the tent; probably this low rate suppresses convective cooling and so is responsible in part for the heat buildup just cited. (4) Prolonged confinement in the tent--more than 8 to 10 hours in the cool spring, or about 3 hours in summer--will injure or even kill the plant. Specifically, after over-long confinement leaves of the plant are dry and brittle, as though transpiration rate had been increased markedly. Injury appears to be least when water supply is non-limiting. Whether temperature rise is the sole cause, or even the principal cause, is not clear. (5) In general, the method is not yet proven.

b-1.7 Evaporation as an index of evapotranspiration.--Recent effort has related measured evapotranspiration to either (1) evaporation as measured by the U. S. Weather Bureau "Class-A" pan, 4 feet in diameter; or (2) "net evaporation," measured as the difference between the evaporation from the black sphere and from the white sphere of the Livingston atmometer.

In each instance, all measurements must be under identical environmental and meteorologic conditions. The relation has been expressed as a simple ratio--a "pan coefficient" or an "atmometer coefficient"--for each particular type of vegetation, by months and for all the growing season. (In this context, the pan coefficient differs from that which expresses the ratio of pan evaporation to natural water-surface evaporation). So far, coefficients have been determined largely for irrigated cotton, alfalfa, sorgum, and pasture grasses (Calif. Dept. of Water Resources 1963; Doss, Bennett, and Ashley, 1964).

Coefficients for a particular plant species vary from one environmental setting to another and from one month to another. For example, take irrigated rye grass grown in a weighing lysimeter in the Sacramento Valley at Davis, California, v. irrigated pasture in mountain valleys at Alturas, California. Altitudes are 50 feet above sea level at Davis v. 4,450 feet at Alturas.

The pan coefficient at Davis was about 75 percent of that at Alturas; the atmometer coefficient, about 80 percent. These percentage comparisons may have been influenced by either the difference in vegetative species or the difference in climatic setting, or both.

For irrigated alfalfa, Nixon and others (1963) found that over the four-month period June through September, the pan coefficients were greater in the interior San Joaquin Valley and in valleys of the Coast Ranges than in the coastal fog belt, but that the atmometer coefficient was greater in the Coast Range valleys than in either the fog belt or the interior valley.

For alfalfa and bermuda grass, Doss and others (1964) found that pan coefficients were least during the early spring, increased gradually until late June, then remained constant for the remainder of the growing season. For sorgum, the coefficient continued to increase until harvest.

b-2. Aerodynamic and energy-balance methods

b-2.1 Atmospheric-flux.--The atmospheric-flux or eddy-correlation method derives transpiration from vertical transport of water vapor above a vegetated surface. Required measurements cover fluctuations in water-vapor concentration (humidity), also wind speed and direction at a specified height above the vegetation. The theory is simple and under ideal conditions is rigorous (Am. Soc. Civil Engineers, 1964). Total transport is partitioned into two components, one of which is the product of mean water-vapor concentration and velocity, and the other or turbulent component is derived from instantaneous fluctuations of the concentrations and of the velocity about their mean values. The lack of reliable, fast-response sensing and recording instruments has been a serious handicap in the use of this method. Also, the amount of data has been so prodigious as to require processing by computer.

A new instrument, the "Evapotron" (Water Resources News Letter, 1965), senses the fundamental parameters and automatically calculates evapotranspiration rate (Dyer, A. J., and Pruitt, W. O., 1962). However, the instrument is not commerically available; neither does the designer plan to make it so (Dyer, 1965, personal communication).

b-2.2 Energy budgets.--The energy-budget method accounts for the amount of incoming and outgoing thermal energy with respect to the vegetated area of concern. Required measurements include wind speed, humidity, air temperature, soil temperature, incoming and reflected solar (short-wave) radiation, also incoming and outgoing long-wave radiation. It is presumed that the atmospheric mass of concern is adiabatic.

Algebraic summation of components indicates the energy available for evapotranspiration. However, during the early stage of growth, the evaporating and transpiring surfaces of a plant are small; they may utilize only a part of the energy available, of which another part may convert to sensible heat in the soil. Only at maximum rate of growth may the plant expend all the available energy in evapotranspiration. Once mature, the plant limits transpiration to that necessary to maintain its tissue; again at this stage of growth, some energy may convert to sensible heat. Thus, because sensible soil heat ordinarily is not readily determinable, during the early and late stage of plant growth evapotranspiration computed by the energy-budget method may be larger than the actual.

A further complication is advected heat, or that transferred from another area. Thus, if warmer air is advected over a vegetated cover, relatively more of the net radiation converts to evapotranspiration and less to sensible heat. If the air mass is cool the reverse occurs.

Feasibility of the energy-budget method depends upon the accuracy with which all parameters are measured; sensible soil heat and advected heat are especially troublesome. Commonly, instrumentation is held to a compromise minimum so that data processing will be manageable and overall cost acceptable. Inevitably, therefore, some accuracy and reliability are sacrificed.

c. Empirical formulas

Several formulas express empirical relationships among evaporation, evapotranspiration, climatic factors, and coefficients for the particular vegetative species and geographic location. Most formulas assume that water abundance is non-limiting, and that the vegetation shades the ground completely; these assumptions put the calculated values in the "potential" realm. The elements of climate that enter the several formulas include air temperature, relative humidity, wind movement, percentage of daytime hours, and duration of sunshine. Temperature is the only element common to all formulas.

The three formulas most widely used appear well suited to the respective regions for which they were developed--specifically, the Blaney-Criddle formula, the arid western United States; the Thornthwaite formula, the humid seaboard of the eastern United States; and the Penman formula, cool England. Divergence of results by these three formulas is shown by sample calculations of evapotranspiration at Boise, Idaho, by Criddle (1956)--specifically, for an irrigated field of alfalfa, August evapotranspiration was 6.45 inches after Blaney-Criddle, 5.92 inches after Thornthwaite, and 7.18 inches after Penman. Mean of the three values, 6.52 inches, is very near the Blaney-Criddle value.

Two other formulas--the Munson or P. E. formula and the Lowry-Johnson formula--have been developed in the United States to estimate consumptive use over a whole valley or irrigation project. Each applies to an average or "normal" plant cover having an ample supply of water, not to a particular plant species.

c-1. Blaney-Criddle formula

The formula developed by H. F. Blaney (1954) and W. D. Criddle assumes that, when an ample water-supply is available, evapotranspiration is directly proportional to a climatic factor, and that all other factors are constant for a particular plant species. Expressed mathematically:

$$u = kf, \text{ for an individual month} \quad (1)$$

or

$$U = KF = \Sigma kf, \text{ for a term of months} \quad (2)$$

in which u, U = evapotranspiration

k, K = an empirical coefficient for the particular plant species and growth density, in the particular area

f, F = a climatic factor, the sum of the products of mean monthly temperatures and monthly percentages of the year's daytime hours, for the particular term of months

Values of K were derived by correlating available measurements of evapotranspiration with values of F, for the growing season. For irrigated crops in the western United States, K ranges from 0.50 for citrus in southern California to 0.96 for corn at Bonners Ferry, Idaho (Blaney and Criddle, 1962); for natural vegetation, largely phreatophytes, from 0.80 to 1.30 (Blaney, 1954). Also values of K have been developed for phreatophyte stands of different densities, described as "light", "medium", "dense", and "very dense".

The formula was devised for extrapolating measured values of evapotranspiration to other areas, records of temperature being the only common information. Originally the formula covered humidity into the climatic factor. However, for application to areas for which records of humidity are not available, the preceding simplified formula was adopted at some loss in accuracy.

As the coefficient K depends on experimental measurements of evapotranspiration, results can be only as accurate as those measurements. In effect, all uncertainties are transposed into the climatic factor F. Thus, Blaney-Criddle values of evapotranspiration become uncertain if aspects of climate differ greatly from those of measured values. For example, Nixon, MacGillivray, and Lawless (1963) compare measured and Blaney-Criddle rates of evapotranspiration by alfalfa in the coastal fog belt, Coast Range valleys, and the interior San Joaquin Valley in southern California. The Blaney-Criddle rates for the fog belt and interior valley were too large by 31 percent and 15 percent, respectively; for the Coast Range valleys, too small by 12 percent. The fog belt and Coast Range valleys, but not the interior valley, receive a daily supply of cool, moist air from the ocean.

c-2. Thornthwaite formula

The Thornthwaite formula (Thornthwaite, 1948, p. 90) also embodies the parameters of temperature and duration of daylight, but has no consumptive-use factor. Based on catchment-area data and controlled experiments, it is expressed as:

$$E_T = 1.6\ (10T/_I)\ a \qquad (3)$$

in which E_T = potential evapotranspiration for a 30-day month

T = mean air temperature ($^{\circ}C$)

I = a heat index, the sum of 12 monthly indexes

a = a cubic function of I

As defined by Thornthwaite, potential evapotranspiration is "the amount of water which will be lost from a surface completely covered with vegetation if there is sufficient water in the soil at all times for the use of vegetation." A further requirement is that the test site be surrounded to an indefinite distance by actively transpiring vegetation, adequately supplied with water. It is evident the formula is limited to extensive areas that are completely covered with vegetation--that is, to areas such as meadows, fields of alfalfa, or dense stands of phreatophyte. For row crops such as cotton or corn, it would apply only during that part of the growing season when the plants shade all the land surface.

The formula suits the climatic conditions of the Atlantic Coast but not the arid and semiarid climates of the Western States (Thornthwaite and Mather, 1955). It is specifically not suitable for estimating evapotranspiration by phreatophyte stands in the West; most such stands violate the remote-boundary condition, in that they are flood-plain tongues no more than a few miles wide.

Nixon, MacGillivray, and Lawless (1963) compare measured and Thornthwaite-formula rates of evapotranspiration by irrigated alfalfa in southern California; the rates by formula were too small--by 27 percent in the coastal fog belt, by 47 percent in the Coast Range valleys, and by 5 percent in the interior San Joaquin Valley.

Nixon ascribes the evident shortcomings of both the Thornthwaite and Blaney-Criddle formulas to their dependence on temperature rather than on solar radiation. He goes on to state that "no single climatic index, of those investigated (solar radiation, temperature, vapor-pressure deficit, wind, Weather-Bureau-pan evaporation, and evaporation from black and white spherical atmometers) will universally predict evapotranspiration rates."

c-3. Penman formula

Penman's (1956, p. 44; 1963, p. 40) formula requires data on duration of sunshine, air temperature, air humidity, and wind speed. It derives a value for potential evaporation from an open-water surface (p.42), which then is converted to the potential evapotranspiration by applying a suitable coefficient. Thus:

$$E_t = f\left(\frac{\Delta H_o + \gamma E_a}{\Delta + \gamma}\right) \qquad (4)$$

in which f = a coefficient (yearly values for southeast England range between 0.6 and 0.8, according to length of day)

Δ = a temperature-dependent constant, which is the slope of the saturation vapor-pressure curve at mean temperature

H_o = the "heat budget" for open water

γ = the constant of the equation for a wet- and dry-bulb psychrometer

E_a = an expression involving wind speed and saturation deficit

E_t = potential evapotranspiration

Thus far, Penman-formula values have been compared with evapotranspiration measured at a few places in the United States. The Penman value was good at Wagon Wheel Gap, Colorado; unsatisfactory at Coweeta, North Carolina; and 5 percent too great at Waynesville, North Carolina, over a one-year period (Gilbert, M. J., and van Bavel, C. H. M., 1954).

c-4. Munson or P. E. formula

Munson's (1960) procedure is essentially a variation of Thornthwaite's. Thus, Thornthwaite developed a nomogram from which, for any station whose average monthly precipitation and temperature were known, there could be derived a "P. E. ratio" (precipitation/potential evapotranspiration). Munson developed a set of such ratios limited to quantities of precipitation just sufficient for normal plant growth. Then, knowing only the average monthly temperature, potential evapotranspiration was determined from a modified Thornthwaite nomogram.

c-5. Lowry-Johnson formula

The Lowry-Johnson formula derives consumptive use (potential evapotranspiration) as a linear function of accumulated heat units--that is, degree-days above 32° F. Although the method was devised for yearly estimates only, a yearly estimate may be broken down in proportion to monthly evaporation, or according to a ratio of monthly heat units to the total yearly heat units.

d. Extrapolation of measurements to growth areas

Dependable extrapolation of evapotranspiration values from place of measurement--tank, plot, or other experimental area--to whole cultivated fields or to whole natural stands requires that the two environments be equivalent. Principal significant differences may occur in climatic factors or in vegetative density (volume of foliage). Other potentially significant factors include texture, state of tilth, and fertility of the soil; alkalinity or salinity of the soil and soil water; and depth to the water table. These several factors may be inter-dependent to a considerable extent.

Early workers commonly extrapolated according to area of tank or plot v. area of field--in other words, equivalent depth of water transpired was considered transposable. Some adjustment by judgment may have been introduced to cover marked differences in growth condition and in climate. This procedure was and is reasonably satisfactory in regard to meadow grasses and many row crops, each of which ordinarily is fairly uniform in density of cover or volume of foliage. The procedure is not satisfactory for woody plants in general, and phreatophytes in particular; stands of these may range from seedlings to mature plants, and from a few percent to 100 percent cover density. From this cause appreciable errors may persist among coefficients that have been derived and accepted widely for the several empirical formulas that have been reviewed.

In about the last decade, most extrapolations to stands of phreatophytes have been according to volume of foliage on the presumption that transpiration, by each particular plant species, is proportional to total leaf area and so proportional to such volume. The presumption was first demonstrated as a valid principle by Gatewood and others (1950), in regard to native bottom-land vegetation in the Safford Valley, Arizona. For this basis of extrapolation it is necessary to measure cover density, or the percentage of the land area that would be shaded by the foliage when the sun is overhead; also, thickness of the foliage canopy ("depth of crown"). Volume--conveniently in acre-feet--is taken as the product of land area, percentage density, and canopy thickness. Standards and techniques for the volume determination are set forth by Horton, Robinson, and McDonald (1964).

Transpiration rate differs from one plant species to another, in proportion to foliage volume or in proportion to leaf area. Among three phreatophytes--saltcedar, willow, and cottonwood--rate per unit leaf area has been found least for saltcedar and greatest for willow; per unit foliage volume, least for cottonwood and greatest for saltcedar (Tomanek and Ziegler, 1950).

There is suggestive evidence that transpiration rate by a particular species is somewhat greater at a cover density of about 90 percent than at 100 percent. At the small densities, a greater proportional rate would be expected, owing both to oasis effect and to the generally larger average foliage volume of isolated plants.

Evapotranspiration by a stand of a particular phreatophyte has been shown to be less as depth to the water table is greater (Gatewood and others, 1950; Muckel and Blaney, 1945). Comparisons on the basis of foliage volume, however, do not disclose an appreciable difference in transpiration rate if the difference in water-table depths is no more than a few feet. Evidently, at least partial compensation derives from the fact that as water-table depth is greater both cover density and canopy thickness tend to be less. Further evidence is needed to show the degree of such compensation over a wide range of water-table depths.

In a variation of the volume-of-foliage method, evapotranspiration by grasses at Winnemucca, Nevada, was measured by a tank method and expressed as a ratio to dry weight of the grass produced. The rate so measured was extrapolated to all the native meadow on the adjacent floodplain of the Humboldt River in proportion to production of hay by those meadows (Dylla and Muckel, 1964).

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