summer melt seasons. In addition, layers of dirt or dust may accumulate in summer. This dirt and the discontinuities in physical properties allow annual accumulations to be distinguished in pit walls. In order to save labor, coring augers and snow samplers are sometimes used, but the cores from these tools must be studied very carefully to determine annual layers. Frequently it is found that the average bulk density in a limited elevation interval is relatively constant. If this is true and if the density is known, the accumulation of snow in this interval can be measured easily at many points by using a thin probe.

The second difference between these surveys and conventional snow surveys is that the glaciologist is interested primarily in the total accumulation over a large area whereas the conventional snow surveyor is interested more in the accumulation at a few fixed points as an index to time variations. Glaciological data is usually compiled and reported in the form of maps of snow depth (water equivalent) distribution. Fortunately these data are not difficult to obtain because many glacier surfaces are quite smooth and small scale drifting effects are not important. Crevassed areas and steep slopes limit the accuracy obtainable with these surveys.

A third great difference between glaciological and conventional snow surveys is that the glaciologist can obtain data on the net accumulation of previous years at a single field excursion. Records of the difference between accumulation and ablation are preserved at depth (see Fig. 2) and these data can be obtained simply by digging deep pits or drilling deep holes. Furthermore, on some glaciers which have a very simple flow pattern the annual layers of accumulation emerge at the surface below the firn limit and can be identified. Even though these annual layers of snow are eventually recrystallized into hard glacier ice, the water content per layer does not change appreciably with time. Therefore, if a layer can be identified below the firn limit, it measures the excess of accumulation over ablation that occurred at a certain spot in the accumulation area sometime in the past. In glaciers that have nonuniform distribution of accumulation it is necessary to determine exactly where this spot in the accumulation area was. Furthermore on many glaciers it is quite difficult to identify annual layers without some ambiguity or uncertainty. A long record of snow-survey data may be quite valuable in helping to establish the dating of annual layers. On some glaciers in the Rocky Mountains it appears that the accumulation excess can be determined quite accurately from outcropping annual layers as far back as 170 years. These data might be of considerable value in extending hydrologic records backwards in time.

Studies of glaciers, therefore, involve special snow-survey techniques and draw on conventional snow survey data. These same studies may contribute to fuller knowledge of the long- and short-term variations in precipitation and runoff.

WATER-SUPPLY FORECASTING DEVELOPMENTS, 1951-1956

By

Max A. Kohler[1]

I'm sure it is realized that the ten minutes allotted for discussion of developments in the field of water-supply forecasting during the past six years is in no manner indicative of the volume of published material on the subject. In reviewing the literature, I find 12 papers on the subject have appeared in the Proceedings of the Western Snow Conference alone, and about as many elsewhere.

Perhaps the most nearly universal aspect of the works reviewed is the reliance upon the analytical, statistical approach. Since available observations are at best only reliable indices to the factors involved, we must resort to some form of correlation analysis, but it is imperative that we not lose sight of the physical assumptions inherent in the derived forecast relations. Statistical tests of significance assume the analyst has no *a priori* knowledge of the relationship considered, and they can never supplant the need for physical reasoning. From the physical point

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of view, the water-supply forecast is a solution of the water-budget equation for a basin. Although available data may not permit precise solution of the water-budget equation, the equation can serve as a basis for comparative evaluation of forecast relations. With this in mind, I have prepared a slide which depicts the water-budget equations applicable to both the water-year and April-September periods.

WATER BUDGET
(Outflow = Inflow - Change in Storage)

Water Year	April-September
1. OUTFLOW	1. OUTFLOW
(a) Total streamflow	(a) Total streamflow
(b) Evapotranspiration	(b) Evapotranspiration
(c) Diversions	(c) Diversions
2. INFLOW	2. INFLOW
(a) Precipitation	(a) Precipitation
(b) Diversions	(b) Diversions
3. INITIAL STORAGE	3. INITIAL STORAGE
(a) Surface reservoirs	(a) Surface reservoirs
(b) Soil moisture	(b) Soil moisture
(c) Groundwater	(c) Groundwater
(d)	(d) Snowpack
4. FINAL STORAGE	4. FINAL STORAGE
(a) Surface reservoirs	(a) Surface reservoirs
(b) Soil moisture	(b) Soil Moisture
(c) Groundwater	(c) Groundwater

It will be noted that the only difference between the two, other than the base period, is the snowpack storage term which enters the April-September water budget. Although generalization is difficult, those procedures which forecast April-September runoff without regard to the October-March flow are comparable to the April-September budget. Those which predict water-year runoff and those which predict April-September runoff using October-March flow as a factor should be compared to the water-year budget.

Perhaps a few words on the relative merits of the two periods are in order. The original premise of the snow survey was that "The snowpack constitutes the season's water supply in storage." While this is largely true, study of the April-September water budget will show that the season's supply contains elements not represented in the April 1st snowpack, and that somewhat less than 100 percent of the pack actually reaches the discharge station during the period April-September. Thus, the forecaster has found that the introduction of factors such as fall precipitation, initial base flow and spring precipitation improve the relation. Another reason for considering only the shorter period was the lack of current discharge data, although this deficiency is rapidly being eliminated. Where the "flow to date" is known, the water-year budget has important advantages. The water-year concept was introduced because the changes in storage are minimized for this period and conditions are relatively most stable at the termini, thus facilitating assessment of the moisture status within the basin. Another advantage is the relative ease of preparing residual forecasts progressively through the season which are consistent, one with the next. In the water-year approach, snowpack measurements are perhaps best considered as independent measurements of winter precipitation.

Attention is next directed to the fact that the water-budget equation is of the simple additive form. Algebraic addition of the lettered items listed in the slide, other than streamflow, would provide the required estimate. This does not mean that a substitute regression equation based on indices would be so simple in form, but it seems unlikely that a log-regression equation of several terms can be derived which is truly realistic.

In applying the water-year budget in an empirical sense, the dependent factor is item 1(a), the total annual streamflow. Estimated flow during the forecast period is obtained by subtracting the "flow to date" from the water-year flow. Although evaporation from the snowpack may be small and relatively constant, year-to-year, total annual evapotranspiration, item 1(b), is an important factor and subject to wide variations. It is extremely difficult to evaluate since, point-by-point, it is highly dependent upon available moisture. More will be said in this connection, but I believe concentrated effort should be made on this phase of the problem. Known diversions, item 1(c), can be considered in deriving the relation, but must be estimated in forecasting (or required adjustments indicated).

Turning, now, to item 2 of the budget, inflow is a function only of precipitation during the period, except for possible diversions and subsurface flow across the surface divide. It is believed this factor can be evaluated with sufficient precision using precipitation and snow-survey data as indices, provided the networks are sufficiently dense. The big bugaboo, here, results from attempting to force these data to serve as indicators of other items in the budget. Having introduced precipitation subsequent to the forecast date in the relation, however, a statistical average must be used in preparing the forecast. It is to be hoped that we will eventually have long-range precipitation forecasts which are appreciably better than a statistical value.

The change in surface reservoir storage presents no problem in deriving the forecast relation. The final storage is not known at the time a forecast is prepared, since it depends on many factors, including operational decisions. This difficulty is commonly avoided by designating the forecast as one of natural flow. In many cases, the value of the forecast would be considerably enhanced if an adjustment were made for the estimated change in reservoir storage.

The change in soil moisture could conceivably be determined by direct observation. With the realization that it is impracticable to obtain enough samples for absolute determination of this factor, we are forced to rely upon the index value of a few samples, and the Soil Conservation Service is now collecting observations for the purpose. To serve as an index, the observations must cover many years, and it has not yet been demonstrated that consistent observations can be maintained over a period of years with presently available equipment. One is forced to use a statistical average for the final storage value in preparing a forecast, but for practical purposes, departures in late summer precipitation and final soil moisture are compensating factors. Moreover, the net change over a water year is fortunately not large.

The change in groundwater storage is a function of base flow at the beginning and end of the period. Although the final base flow is not known at the time a forecast is prepared, it is essentially a function of the initial base flow and the inflow for the year. Thus, the change in groundwater storage can readily be taken into account. It should be pointed out, however, that the functional relation may not be such that the inclusion of an initial base flow term in an additive regression will suffice.

An obvious question one might ask at this point is, "Why does analytical correlation show that fall and late spring precipitation are relatively ineffective?" Apparently, this results primarilty from the fact that evapotranspiration losses and soil moisture storage are omitted from the correlation. The day-by-day losses are dependent upon the available soil moisture, as well as upon the current meteorological conditions. Thus, a year with the precipitation all concentrated in the winter months would be expected to have more runoff than one with heavy fall precipitation, both years having the same total annual precipitation. Even so, the application of fixed monthly weights does not constitute a very realistic approach to the problem and can be justified only because of expediency. It is evident, for example, that all fall precipitation in excess of that which can be depleted from the runoff-generation area by evapotranspiration should be just as effective as winter precipitation. It would be far more realistic to subtract estimated losses from the observed fall precipitation (taking into account temperature and time distribution of precipitation), but this would become rather unwieldy. Nevertheless, the importance of an integrated approach with respect to soil moisture, evapotranspiration and precipitation can not be over-emphasized. It is here that we can expect the greatest advances in the field of water-supply forecasting.

I think we can all agree that continued effort to improve our procedures for predicting the seasonal volume of runoff is amply justified. Equally important, however, is the periodic review of user requirements. Does the seasonal or residual volume forecast meet all needs? Should the forecasts be modified during the month if meteorological events appreciably change the outlook? It is known, for example, that some irrigators are more vitally concerned with the date when flow will drop below some specified value. Delivery forecasts for the next 10 or more days may be of service to some users. We can be certain, I think, that the ultimate requirements will involve frequent forecasts of the hydrograph many months in advance, based on up-to-the-minute knowledge of existing conditions of the basin.

And, now, before closing this discussion, I suppose I should touch more closely upon the subject assigned by the program chairman — "Water Supply Forecasting Developments, 1951-56." To aid those wishing to pursue this subject, I have prepared an annotated bibliography which perhaps can be published in the Proceedings.

ANNOTATED BIBLIOGRAPHY

1. WORK, R. A., H. G. WILM and M. W. NELSON, Use of Snow Surveys in Planning Regulation of Columbia River Floods, Proc. West. Snow Conf., pp. 1-29, April 1951.

Illustrates use of April 1 snow surveys to forecast April-June flow volume, which in turn is used to forecast peak flow (notes "that the forecasting of river stages for public release is an official activity of the U. S. Weather Bureau."). Later, and more accurate, forecasts are made by using additional precipitation data for April and first half of May. Points out that much of the error in the peak flow forecast is due to error in the volume forecast.

2. KOELZER, VICTOR A., Cumulative Snowmelt Runoff Distribution Graphs and Their Use in Runoff Forecasting, Proc. West. Snow Conf., pp. 30-46, April 1951.

Presents a technique wherein snowmelt distribution graphs (developed by plotting cumulative temperature against cumulative snowmelt runoff) are used for successive refinement of the runoff forecasts as derived by conventional methods. The technique can be used only after the snow-melt season has started.

3. GAY, ROBERT W., Forecasted Temperatures and Snow Melt Floods, Proc. West. Snow Conf., pp. 1-7, April 1952.

Uses forecasted temperatures to predict the spring flood hydrograph for the Boise River in Idaho. Multiple correlation analysis of temperatures prior to and following April 1 (approx.) is the basis for forecasting temperature for 19 five-day periods after March 29. Lagged excesses (degree-days) of the forecasted temperatures are used to predict the shape of the spring hydrograph — this method does not predict the flood volume, but does distribute the volume after it has been predicted by some other method.

4. FULCHER, MARTIN K., An Approach to Streamflow Forecasting, Proc. West. Snow Conf., pp. 18-23, April 1953.

Describes revised USBR water supply forecast procedure for Green River, of which the important and distinguishing features are:

(1) Uses only precipitation and temperature for index values.
(2) Weights precipitation stations by Thiessen polygon method.
(3) Breaks precipitation into two periods — December through March, and September through November.
(4) Uses least-squares analysis of 2, 3 or 4 variables.
(5) Stresses the necessity of breaking large basin (above Lake Mead) into smaller sub-basin areas for individual treatment.

5. BARTON, M., A Systematized Regression Forecasting Method, Proc. West. Snow Conf., pp. 24-29, April 1953.

Describes a format of tables for advancing computations annually of two-variable least-squares analysis.

6. POLOS, A. J., The Use of Precipitation and Snow Survey Data in Water Supply Forecasting, Proc. West. Snow Conf., pp. 30-35, April 1953.

Discusses new procedures for Clearwater in which the U. S. Weather Bureau total precipitation index and April 1 snow course data are combined as a single weighted index. Using the combined data reduces the average error by almost half for the Ahsahka procedure. Pederson, in his discussion, finds the improvement slightly less favorable for forecasts as of April 1.

7. NELSON, M. W., C. C. McDONALD and M. BARTON, Base Flow as a Parameter in Forecasting the April-June Runoff, Proc. West. Snow Conf., pp. 61-68, April 1953.

Describes use of base flow (as of Nov 1 or Feb 1) as an index of soil moisture deficiency and ground water storage on four streams of the Columbia basin. Least-squares analysis is used in developing logarithmic equations involving up to three independent variables.

8. NELSON, M. W., H. G. WILM and R. A. WORK, Soil Priming in Relation to Snow Surveys and Flood Regulation, TAGU, pp. 240-248, April 1953.

A continuation of work described in an earlier reference, but with additional refinement of a fall precipitation index as a soil-priming factor. The authors note a 40 percent improvement in the standard error of the forecasts as of April 1, by inclusion of the soil-priming variable.

9. Review of Procedures for Forecasting Inflow to Hungry Horse Reservoir, Montana, Water Management Subcommittee, Columbia Basin Inter-Agency Committee, 27 pp., June 1953.

Reviews and evaluates existing procedures for forecasting April 1- September 30 inflow. Weather Bureau and Soil Conservation Service make forecasts for public release; Bonneville Power Administration and Bureau of Reclamation make forecasts for use within their agencies.

Compares the individual forecast results with the historical data from which they were developed, but notes limitation imposed by shortness of record on such a comparison. Adds further that rationality of a forecasting method is an important test of reliability — a good balance should be sought between statistical fit of historical data and sound hydrologic reasoning.

10. FORD, PERRY M., Multiple Correlation in Forecasting Seasonal Runoff, U. S. Bureau Reclamation Eng. Mono 2, 38 P, June 1953.

Revision of an earlier monograph — dated April 1949 — of same title.

Outlines the methods of multiple correlation as applied to problems of water-supply forecasting. Gives detailed instructions for the various steps in the procedure from the double mass analysis of precipitation data through the Doolittle solution.

11. PECK, E. L., Hydrometeorological Study of Great Salt Lake, Bulletin 63 of Utah Eng. Exp. Stn., Jan. 1954.

Presents an analytically-derived procedure which may be used to forecast the water-year volume change in Great Salt Lake, which in turn may be used in forecasting the maximum stage. The development of the precipitation index and analysis of the carry-over effect is described. Outside examples are brought in to show consistency between the objectively-derived carryover indices and the geologic formations.

12. PECK, E. L., Low Winter Streamflow as an Index to the Short- and Long-term Carry-over Effects in Water-Supply Forecasting, Proc. West. Snow Conf., pp 41-48, April 1954.

Shows that introduction of February flow as a parameter tends to eliminate time trends in streamflow and provides necessary measure of carry-over.

13. BISSELL, L. M. and K. D. EARLS, Volume Inflow Forecasting Procedures, Hungry Horse Reservoir, Montana, Proc. West. Snow Conf., pp 74-82, April 1954.

Describes and compares two approaches to forecasting Hungry Horse inflow: (1) January 1 forecast (linear, least-squares) using precipitation records of two stations, arbitrarily weighted, broken down by periods, May-Dec., Jan-Jun., and Oct-Jun. of previous year; (2) April 1 forecast (log, least-squares) which makes use of April 1 snow survey data index and also Apr-Jun. precipitation and Apr-Sep. base flow volume.

14. Review of Procedures for Forecasting Seasonal Runoff of Columbia River near The Dalles, Oregon, Water Management Subcommittee, Columbia Basin Inter-Agency Committee, 66 pp., August 1954.

Reviews and evaluates procedures of four agencies; includes table comparing results; concludes with list of recommendations. All of the four procedures reviewed, either directly or indirectly, divide the basin into numerous sub-basins. Two forecast the runoff from the sub-basins and carry the forecast values progressively down-stream to The Dalles; the other two involve an actual forecast only for The Dalles, but weight causal factors on the basis of the contributing sub-basins.

15. STRAUSS, FRED W., Forecasting Water Supply Through Snow Surveys, Jour. Amer. Water Works Assn., pp 853-863, Sept. 1954.

A history and description of water-supply forecasting in California is given. Forecast procedures use April 1 snow pack indices plus precipitation indices for various periods and one or more of several carry-over indices. Some of the applications to reservoir operation are noted. A temperature-runoff diagram for the Kern River is explained. The radioactive snow gage and aerial snow surveying are noted as advances in the snow survey field.

16. Forecasting Seasonal Runoff by the Water-Balance Method, Research Note No. 22, Corps of Engineers, No. Pac. Div., Portland, Oregon, September 1954.

Describes a water-balance approach for forecasting the runoff of a basin in which true evaluation of various components -- rainfall, snowfall, loss, and snow water-equivalent on the ground -- is attempted through index relations. Introduces a "generated runoff" concept to account for effect of natural storage time of ground and channel storage in basin.

17. A Coastal Winter-Flow Index Method of Forecasting Seasonal Runoff of Columbia River near The Dalles, Oregon, Research Note No. 23, Corps of Engineers, No. Pac. Div., Portland, Oregon, 17 pp, September 1954.

Relates winter flow of four coastal basins to seasonal runoff of Columbia River near The Dalles. Winter temperatures and spring precipitation are additional parameters which are used (coaxial correlation) to refine the forecasting relation. A comparison is made with other index procedures.

18. BLANCHARD, F. B., Mokelumne River Streamflow Forecasting Analysis, East Bay MUD, October 1954 (processed report - limited distribution).

Presents a series of linear regression analyses which have the expressed objective of obtaining the most reliable forecasting relation for the Mokelumne River. Included in the report are tabulations of basic data, certain computations on each of the analyses and charts illustrating the results of the analyses. The analyses are divided into two series. The "P" series relates annual true natural flow to various combinations of precipitation parameters; the "S" series relates the seasonal true natural flow (April 1 through July 31) to various combinations of water equivalent, precipitation and carry-over parameters. Somewhat unusual in the study is the introduction, in several of the series, of reciprocal terms of previously used water equivalent and precipitation parameters.

19. NELSON, M. W. and W. D. SIMONS, A Modern Forecast for the Columbia River at Birchbank, B.C., Proc. West. Snow Conf., pp 8-11, April 1956.

Describes forecasting procedure -- derived through multiple linear regression analysis -- used on the Columbia River at Birchbank. The use of a water-equivalent index based on the average of March 1 and April 1 snow survey measurements is the significant departure from conventional forecasting procedures.

20. CHARD, A. E., Forecasting Powell Lake Runoff, Proc. West. Snow Conf., pp 11-12, April 1956.

Uses mid-March snow survey and subsequent (through June) precipitation at one station to predict rise (feet) in lake level.

21. HANNAFORD, J. F., Multiple-Graphical Correlation for Water-Supply Forecasting, West. Snow Conf. Proc., pp 26-32, April 1956.

Uses Feather River at Oroville to illustrate a graphical (coaxial correlation) forecasting procedure (Apr-Jul. runoff) in which following parameters are involved: (a) April 1 snow-pack; (b) Oct-Mar. precipitation; (c) Oct-Mar. runoff; (d) Apr-Jul. runoff of previous year; (e) Apr-Jun. precipitation (monthly weights 1.00, 0.80 and 0.50)

Salient features of procedure:

(1) Converts all data to percent of normal, except runoff.
(2) Weights snow courses equally.
(3) Weights precipitation stations equally.

22. KOELZER, V. A. and PERRY M. FORD, Effect of Various Hydroclimatic Factors on Snowmelt Runoff, TAGU, pp 578-587, October 1956.

As noted in their introduction, the authors do not present methods of analysis which can be considered new. They do, however, record the results of an exceptionally large number of analyses (made possible through employment of high-speed electronic computers) on a limited number of forecast points, affording consideration of a variety of factors in a number of different forms.

RUNOFF FORECASTING AND SNOW SURVEYING IN CHILE

By

Enrique S. Arias 1/

I. SITUATION.

Chile is a country with high mountains extending from latitude 18°.5 to 56°.S, from the tropics near the Polar circle. Rivers run from the Andes to the Pacific Ocean covering a very short distance across the country, through the Central Valley and the Coastal Range. This is specially a true picture in the Central Zone. In the great north there is a desert and the extreme south is crossed by channels running north and south, and archipelagos.

II. NEED TO FORECAST

The great part of the population is concentrated in Central Chile: Santiago, the Capitol, has 1.5 million people; the whole country about 6.5 millions. The Central Zone has a mediterranean climate, very similar to the one you have in California. Storms come from the Pacific Ocean. With this kind of climate in Central Chile there is a humid season in winter, when snow is stored in the Andes, and a specially dry summer and fall. Having great part of the land under irrigation and being by way of development of our water resources for other purposes, especially power production, there is a need for forecasting the runoff that is going to be produced every year in springtime and early summer, caused by snow melt.

III. WORK DONE BY ENDESA

(a) Snow Surveys

We have been working in snow surveys in ENDESA, experimentally near Santiago since 1951. There we measure a snow course and a recording snowgage. This last year (1956) we installed five more snow courses and several storage gages in different basins. Our highest snow course is about 10,500 feet over the sea level, the lowest is about 4,000 feet high. The two extreme basins under study are separated by around 600 miles.

The procedure used in field work is the same as the one used in this country. Up to this moment we have obtained good results. Due to the steepness and ruggedness of the terrain we haven't used snow vehicles. Traveling is done by foot.

In the snow course Portillo, with six years of record the maximum water content of the snow pack has varied between 13.1 to 58.3 inches, with an average of 23.6 inches. In the Northern Zone the average water content is lower, around 10 inches, and in the southern snow courses it is higher, around 40 inches. These figures are given only as a guide and they are only approximations.

Our plans are to extend snow surveying in Chile and to apply the data to other fields, especially Agriculture, obtaining for that purpose the cooperation of several other organizations that are concerned with this matter.

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