DEVELOPMENT OF A DIGITAL RIVER BASIN MODEL

By

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OBJECTIVE

Most water supply forecasting methods currently in use use some form of multiple correlation to relate runoff for a specific period to the physical phenomena responsible for runoff, such as snowpack or precipitation, on the basis of the historical relationship between these parameters. Other possible methods of water supply forecasting might include basin accounting or digital basin modeling. However, even in basin accounting and modeling, it is necessary to resort to historic records to define relationships between variables.

The River Forecast Center in Sacramento, California, undertook a research project in basin modeling this last year. The objective of the research project was to develop a method of modeling watersheds digitally for the specific purpose of preparing water supply forecasts. Since an electronic computer is available to the research unit, the computer was to be used both in development and operation of the digital model.

It was proposed to develop independently models for basins which lie primarily below the snowline and for basins in which snow is a major factor in determining the annual distribution of runoff.

APPROACH

The general approach was to develop a conventional forecasting technique (multiple regression with weighting of monthly precipitation, etc.) to use as a control or standard of comparison, then to explore the less conventional approach of preparing a digital model of the basin.

The following criteria were set for development of the original model.

1. Initial development, at least, would be on the basis of monthly input of precipitation and computation of runoff, since the amount of data and machine time for, say, 20 years on a daily basis would be prohibitive for exploratory work.

2. The latest 20 years of record was to be used for development of the model, as other studies on California streams have shown time trends in streamflow which may be due to the infringement of man. This effect can be reduced by development of the model upon a shorter time period, at the possible expense of range in basic data. However, in California the past 20 years of record contain an excellent sampling of the range of basic data.

3. The first model was to be developed for a reasonably low elevation basin so that snow would not be a primary factor influencing runoff distribution and losses. A second model in the same vicinity but at high elevation was to be developed to study the influence of snow upon the runoff regimen.

4. Since no Sierra basin is entirely without snow for all years, initial development was to be directed toward minimizing error in annual runoff. Distribution of runoff on a monthly basis was to be considered only of secondary importance.

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STUDY BASINS

The Cosumnes River at Michigan Bar was selected as the study basin for the area below the snowline. The basin is situated just east of Sacramento in the Sierra foothills. The area is 537 square miles, and average annual runoff is 383,000 acre-feet. Elevations range from about 200 feet to 7,000 feet, with the majority of the basin lying at the lower elevations. Although some snow occurs in the basin every year, the effect upon distribution of runoff is normally quite small as compared to most Sierra basins.

The Mokelumne River near Mokelumne Hill was selected as the high elevation basin for study. This basin is adjacent to the Cosumnes River basin. The area is 538 square miles, and average annual runoff is 753,000 acre-feet. Elevations range from 600 feet to over 10,000 feet with a major portion of the basin lying above the average April 1st snowline.

Full natural flows for both streams were provided by the California Department of Water Resources.

SELECTION OF PRECIPITATION BASIC DATA

A number of precipitation stations are located in or near the study basins. Unfortunately no long term stations were located within the Cosumnes Basin and only a limited number of high elevation precipitation stations are available in the Mokelumne basin.

A multiple correlation analysis was made by machine of all likely precipitation stations to determine which stations would most probably give satisfactory results in further study. The following stations were selected:

Cosumnes River
- Tiger Creek Powerhouse
- Placerville

Mokelumne River
- Twin Lakes
- Tiger Creek Powerhouse
- Salt Springs Powerhouse
- West Point

CONTROL FORECAST

After precipitation stations were selected for each basin, a conventional forecasting procedure was developed for each stream using water year runoff as the dependent variable. Monthly precipitation for the period September through June and runoff for the previous year were taken as independent variables. The conventional forecasting procedures were used as controls to judge the adequacy of the digital model.

Results from the conventional forecasting techniques were good. The twenty-year period was used for development, and no smoothing or weighting was done. In one case, the best correlation was obtained with a negative May weighting, which, though probably not acceptable from an operational point of view, did give the smallest standard error. The final standard errors for the multiple regressions were:

Cosumnes	18,010 acre feet
Mokelumne	26,570 acre feet

DIGITAL BASIN MODEL

The digital basin model is merely a problem in accounting for all water entering or leaving the basin, no matter by what means. The general equation for a problem involving conservation of mass is:

Inflow - Outflow = Change in Storage

For the digital basin model the general equation used to determine runoff for a period of time was:

$$RO = P + S_1 - S_2 - L$$

where

RO = runoff for period
P = precipitation for period
S_1 = water stored in basin at beginning of period
S_2 = water stored in basin at end of period
L - summation of all losses during period

all expressed in the same units.

The following assumptions were made:

1. As a result of the model being based upon monthly precipitation, runoff for the month is a function of total water available in the basin for that month, which is in turn a function of:

   a. Precipitation during the month
   b. Storage in the basin at the beginning of the month
   c. Losses during the month

2. Total loss for the month was assumed to be made up of the following:

   a. A loss which is a function of precipitation occurring during the month (physically this might represent interception losses, evaporation, and other losses dependent upon the amount of water available on the surface and thus subject to loss.)

   b. A loss which is a function of the total water in storage at the beginning of the month (physically this might represent a portion of the transpiration, and other losses resulting from availability of water in the soil mantle and accessible parts of the groundwater reserve.)

   c. A loss (Cm) which is a constant (from year to year, but variable by months) which occurs when and if water is available. (Physically this might represent evapotranspiration not included under items a and b, as well as other losses dependent upon time of year.) The distribution of this loss throughout the year is based upon pan evaporation, but the order of magnitude is developed by the machine program. In the case of the Mokelumne River it was found necessary to alter the distribution of loss throughout the year by decreasing the winter and spring values below that indicated by pan data.

Using the above assumptions, we can develop the following relationships:

a.) $R_2 = f(W_2)$

and:

b.) $W_2 = P + W_1 - f_p(P) - f_w(W_1) - Cm - R_1$

or:

$$W_2 = (1-f_p)\,P + (1-f_w)\,W_1 - Cm - R_1$$

where

W_1 = total water available for previous month
W_2 = total water available for current month
P = precipitation during current month
R_1 = runoff during previous month
R_2 = runoff during current month
Cm - constant loss (if water is available) for current month.

There are obviously some discrepancies in timing of the various factors in the relationship. Results from the model shown seemed to give the best results of several models tested. If the time interval taken were shorter, the timing problem would become less critical. As a result of the monthly time period selected, precipitation, runoff, etc., are computed as occurring instantaneously at some time during the month. In the illustrated model, some of the water available during the month (W_2) will run off that month, while the remainder will go into storage to produce later runoff.

We have assumed before that $R_2 = f(W_2)$. At extremely high values of "W", incremental runoff should approach incremental precipitation. When "W" is zero, there will be no runoff. Early season runoff (i.e., for months where runoff from equation a. is completely or almost completely, dependent upon precipitation falling during that month) was used to develop the "W"-runoff relationship which was run through zero at the lower end, and approached the limit of 100% runoff asymptotically at the upper end. (Fortunately California Sierra streams have adequate data for this type of development.) A relatively good power relationship was found on the Cosumnes which, with some modification, worked quite well on the Mokelumne and other basins tested.

It was planned to make the model continuous from year to year using the September "W" as carryover. However, better results were obtained by basing carryover on the previous year's runoff and reinitializing the program each October.

An adjusted standard error was computed to compare the model with the control forecast, since this statistical measure is not readily adaptable to the model. (The model was given the same number of degrees of freedom lost as the statistical correlation.)

Adjusted standard errors for the two streams by the basin models were:

Cosumnes	15,500 acre feet
Mokelumne	28,000 acre feet

These values were quite close to the values obtained from the multiple regression.

EFFECTS OF SNOW

The Cosumnes River basin will be taken as the example here, as the range in snowpack water content is greater than on the Mokelumne.

If we were to prepare a plot of predicted cumulative monthly runoff from the model against actual cumulative monthly runoff, assuming no storage in the snowpack, we should expect to get a line at approximately 45°, with some deviation possible as a result of imperfect correlation, and the timing difficulties. (Fig. 1).

However, since snow does have some effect on the distribution of runoff throughout the year, we might expect, and do actually get in years with appreciable snowpack accumulation, a curve showing overforecast during the snow accumulation period and underforecast during the melt period (Fig. 2).

Moreover, we find a very good relationship between the departure from the 45° line and the snowpack accumulation at snow courses in or adjacent to the basin. Lumberyard snow course on the Mokelumne River, but adjacent to the Cosumnes, seemed to have the best correlation. (Fig. 3). Similar results were found on the Mokelumne River, but as a result of snowpack distribution over the basin, it was necessary to use a snow course index made up of a number of snow courses.

By determining the relationship between a snow course index and the runoff retained

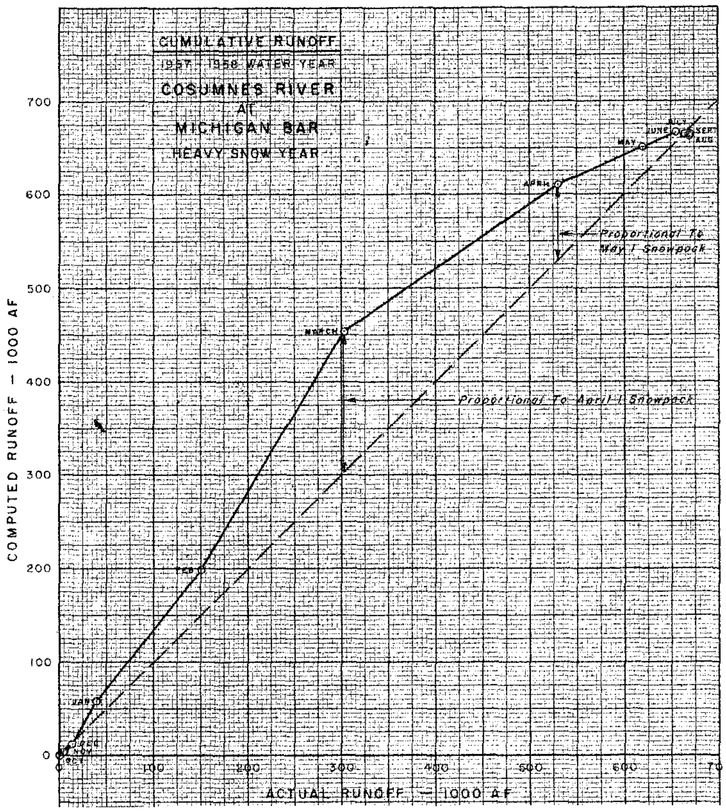

Fig. 1

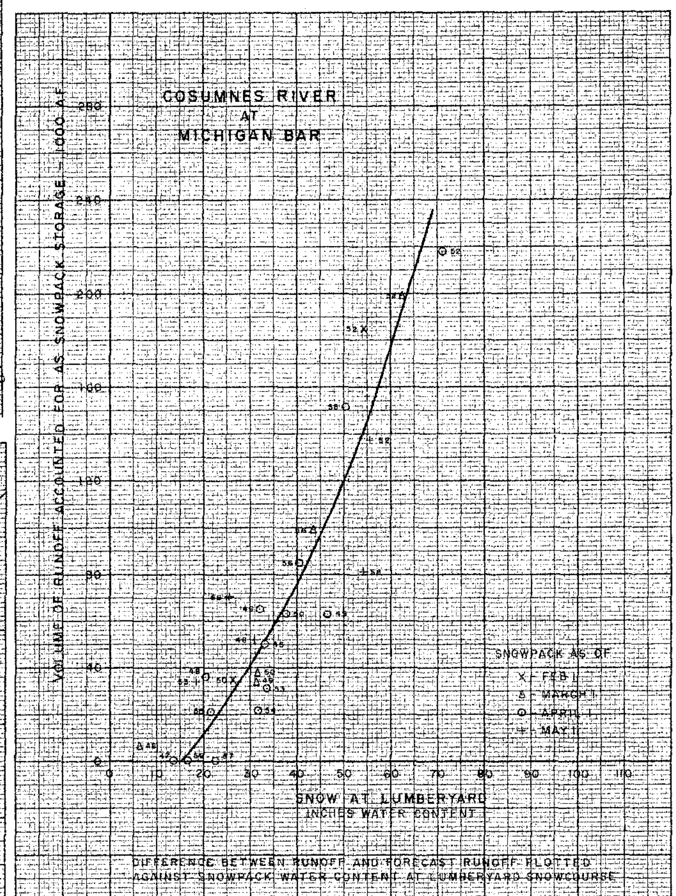

Fig. 3

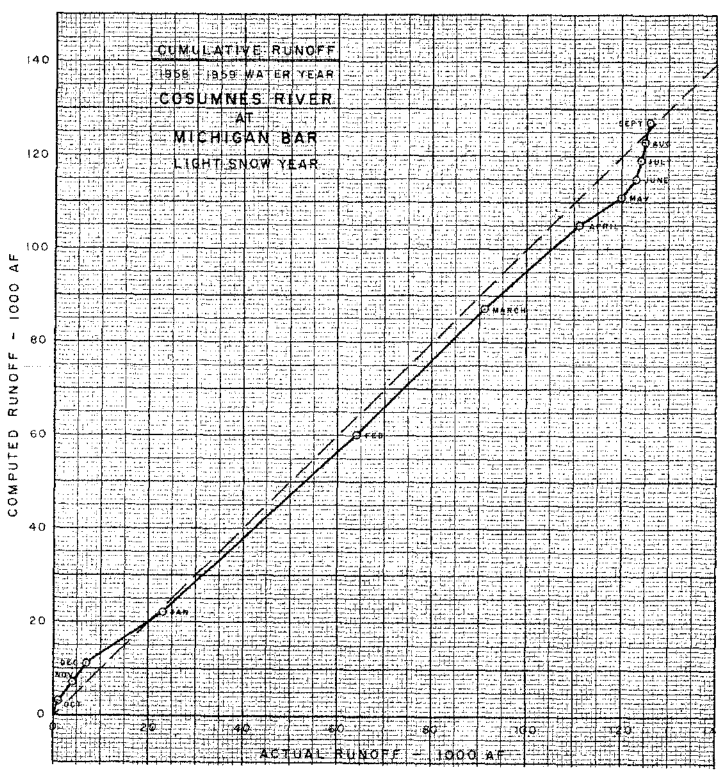

Fig. 2

as snowpack (deviation from the 45° line) we can then distribute with fair accuracy the annual runoff knowing our forecast and the snow on the ground. In practice, this is more a matter of hydrologic interest rather than a forecasting tool, but it does help in accounting for the total water budget.

COMPARISON BETWEEN BASINS

Comparison of basin models for the Mokelumne and Cosumnes reveals, as expected, that the somewhat higher precipitation on the Mokelumne River is partially responsible for the higher runoff of the Mokelumne. Geology may be an important factor in producing higher runoff on the Mokelumne. However, losses on the Mokelumne, particularly during winter and spring months, are relatively lower than on the Cosumnes as indicated by the lower "constant" losses (Cm) required for those months. There is also an indication that losses on the Mokelumne are higher in a low runoff (and consequently a low snowpack) year than in a high runoff year as indicated by lower losses from water in storage in the basin. This is as might be expected, but it does suggest the possibility of two different types of losses dependent upon two types of storage in the basin. One would be a loss dependent upon storage as used in these models, and the other would be a loss somewhat smaller in magnitude dependent upon snowpack (or snow cover).

CONCLUSION

Most of the findings from the river basin models resulted in verification of ideas which hydrologists would intuitively expect to be true. Only the degree of verification is impressive. Although the river basin model does not show promise of fantastic reduction in forecast relationship errors, it does point the way to better understanding of the relationship of loss, storage and runoff in a watershed. Although many improvements and refinements are possible, the model gives us a hydrologically sound method of accounting for all water in the basin for a better understanding of basin characteristics. At the present state of the art, basin modeling will probably not replace conventional methods of water supply forecasting in most cases because of the difficulty of making such solutions without an electronic computer. With such a computer, the solution is extremely simple.

Outlined below are some ideas for possible future work on this project.

1. Further development of the idea of a separate storage reservoir in the snowpack subject to losses different from those to which other storage in the basin is subject.

2. Development of a model on a shorter time base (say, daily) for better correlation of monthly flows and a better understanding of the storage relationships which exist. Models developed on a shorter time base will permit updating of forecast as data is available.

3. Development of relationships between basin losses and the various climatic factors which may affect losses (Ref., Kohler and others). Work in this field may permit a truly continuous model which would carry over storage from year to year without reinitialization.

4. Development of relationships between losses, runoff and the various geological and topographical characteristics of the basin to permit forecast relationships to be developed for basins where only a minimum amount of historical data and the physical characteristics of the basin are available.

REFERENCES

Kohler, M. A., and M. M. Richards,

Multicapacity basin accounting for predicting runoff from storm precipitation, J. Geophys. Research, 67, 5187-5197, 1962.

Crawford, N. H., and R. K. Linsley,

The synthesis of continuous streamflow hydrographs on a digital computer, Tech. Report No. 12., Department of Civil Engineering, Stanford University, 1962.