FLOOD FORECASTING IN THE UPPER MISSISSIPPI VALLEY

by

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The general topic of river forecasting may be roughly divided into two parts: forecasting for upriver points and forecasting for downriver points. The prediction of peaks on the lower Mississippi, for instance, is distinctly a downriver problem. Gage readings on the tributaries and upstream points on the main river give advance warning of the amount of water which is in the river system. The problem is to determine what portions of the hydrographs produced by the various tributary flows will coincide, how much of the flow will go into channel storage, and what stage will be developed at the point in question.

The service of river forecasting gradually made its way upstream and expanded laterally along the tributaries until it reached the point where reports of stage on the headwaters could not be received in time to utilize them successfully in a forecast. Reporting rainfall stations had to be established and the runoff predicted from the reported daily rainfall. Procedures were developed from a study of past rainfall and runoff, and by trial and error. In the light of our present hydrologic knowledge the forecasting rules which were laid down by the past generation of Weather Bureau men in the river district centers are found to be surprisingly sound. The usual procedure was to deduct first a certain amount from the reported depth of rainfall, according to the condition of the soil, to take care of the field moisture deficiency. The remainder was converted into the predicted river stage by means of empirical relationships which varied with the season.

Within the past few years there has developed a demand not only for earlier forecasts of floods but also for more general forecasts of daily flow. With the canalization of the upper Mississippi, it has become important for the men operating the dams, construction crews

working on the banks, and navigation interests to know what quantities and stages may be expected from day to day. In answer to this demand, the United States Engineer Department and the Weather Bureau have made extensive studies for the purpose of devising better forecasting procedures. A great impetus was given to practical research in the field of stream-flow forecasting by L. K. Sherman[1] in 1932, when he presented us with the unit hydrograph which makes possible the construction of a hydrograph of expected runoff within the time allowed for making a head-water forecast.

The entire upper Mississippi Valley is composed of flat or fairly sloping country. The yearly rainfall varies quite uniformly from 25 inches at the northern tip of the valley to 40 inches near St. Louis, and the rains are usually well spaced during the planting and growing season. The winter snowfall is comparatively light but it frequently adds an important amount of runoff to the spring floods of northern streams.

A few streams, such as the Chippewa, Black, Wisconsin, and Rock are subject to frequent minor floods. There is no such succession of floods on the other streams and as a result the people as a whole are not as conscious of flood danger as they should be. In the cities and towns structures of various kinds are being allowed to encroach upon the streams and to restrict their channels to a dangerous degree. The principal flood hazard in the Mississippi Valley is not localized in the areas adjacent to the main river, but occurs at a hundred scattered points on the tributaries. The funds available to the Weather Bureau for the work of the River and Flood Division are at present inadequate to provide satisfactory forecasts and flood warnings on all of the streams where flood danger exists. In order to furnish the type of service which is needed the upper Mississippi Basin must be treated as a whole and the expected runoff from each of the tributaries calculated at some central point, such as the Regional Office. This information would then be furnished daily to the various river district centers for their use in making the specific forecasts.

Methods of determining runoff which make use of a factor applied to the observed depth of rainfall have proved unsatisfactory in this valley. Only a comparatively small percentage of the annual rainfall enters the streams as storm flow. The soil absorbs a far greater part, much of which is later evaporated or transpired by growing plants. The storm runoff factors are accordingly small and

highly variable. For this reason we must treat the runoff as that
portion of the rainfall which is left unabsorbed by the soil, and not
as any definite fraction of the total rainfall. Our knowledge of the
relation of infiltration to runoff has been largely developed by Dr.
R. E. Horton.[2]

In order to determine the runoff it is necessary to know how
much rain fell at a rate exceeding the capacity of the soil to absorb
it. We need values of the infiltration capacity of the soil and a rec-
ord of the intensity of the rainfall. The rate at which a given piece
of ground will absorb water has been found by sprinkling tests to
vary with its condition of tillage, vegetation, field moisture content,
and a variety of other factors. The slope of the ground is also a fac-
tor. The capacity at the start of a rain may be a great deal higher
than the average capacity during the rain.

The first rain entering the soil is retained as capillary moisture
until the field moisture deficiency has been made up. At this point
water commences to leave the upper soil layers under the action of
gravity and a steady downward movement commences. It appears
that this downward-moving layer of water compresses the air which
is in the soil beneath it and that probably vertical columns of water
are formed at points of greater porosity, while the air escapes up-
ward at other points. At any rate, the supporting power of the air
is sufficient to cause a considerable amount of the percolating water
to move laterally and to discharge into the stream channels. This
flow is known as storm-seepage. Its maximum value is reached in
the stream two or three days after the peak of surface runoff and it
contributes a substantial amount of water to the total storm runoff.
It is important to note that the amount of storm-seepage depends
upon the rate and amount of infiltration. It is not affected by excess
rainfall intensities.

The average infiltration capacity in a natural basin does not ap-
pear to vary as erratically as in small test-plots of ground. The
Weather Bureau has met with some success in predicting its value
experimentally from antecedent rainfall. It is believed that for
practical forecasting purposes the infiltration capacity may be as-
sumed to be constant during the rain and that the actual rate of infil-
tration may be taken as nearly equal to the rate of rainfall for all
periods when the rate of rainfall does not exceed the infiltration
capacity. The Weather Bureau is preparing to utilize reporting in-

dex basins, as proposed by Dr. Horton,[3] for determining the infiltration capacity at the time of any given storm. These basins will be fifty square miles or less in area, and equipped with water stage recorders and recording rain gages. Studies are being made of data from two such basins now in operation near Iowa City. One of these, Ralston Creek, has an area of 3 square miles and the other, Rapid Creek, an area of 25 square miles. The peak discharge from an index basin occurs almost immediately after the rain which produces it and the storm runoff can be determined in time to make use of it in forecasting for the larger basins nearby. The Iowa, Cedar, Skunk, and Des Moines basins are now covered by a network of 12 recording rain gages and studies are being made by the Weather Bureau to determine whether excess rainfall intensities can be estimated at intermediate points equipped with non-recording rain gages. Records of rainfall intensity and discharge are also being ob-

FIG. 1.—IOWA RIVER AT MARSHALLTOWN AND IOWA CITY: OBSERVED RAINFALL, OBSERVED DISCHARGE, AND STORM FLOW.

tained on the Galena River in cooperation with the U. S. Engineers, for an index basin study.

In setting up a procedure for practical forecasting on a large scale, speed of handling the data and a simple routine of computations are two very important considerations. Some of the refinements of the methods proposed by Dr. Horton and others will probably have to be sacrificed to these ends. The determination of excess rainfall from a recording rain gage chart, using an assumed constant value of the infiltration capacity, is very simple. It consists essentially of determining the total time during which the rainfall rate was greater than the infiltration capacity, determining from this the amount of excess rainfall by subtracting total infiltration from the total rainfall occurring at a greater than the infiltration rate.

Our studies show that a value of the excess rainfall during a storm, calculated by the use of an assumed value of the infiltration capacity, may be converted with little error into a figure correspond-
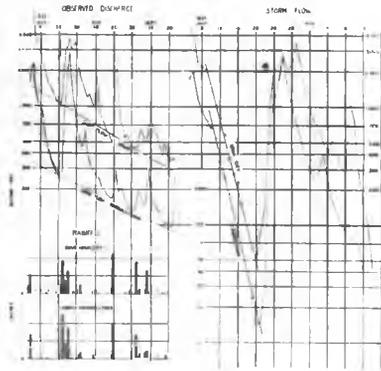
ing to a different value of the infiltration capacity. A simple relation
curve is used for the purpose. It is expected that many of our re-
porting observers will be able to calculate the excess rainfall, using
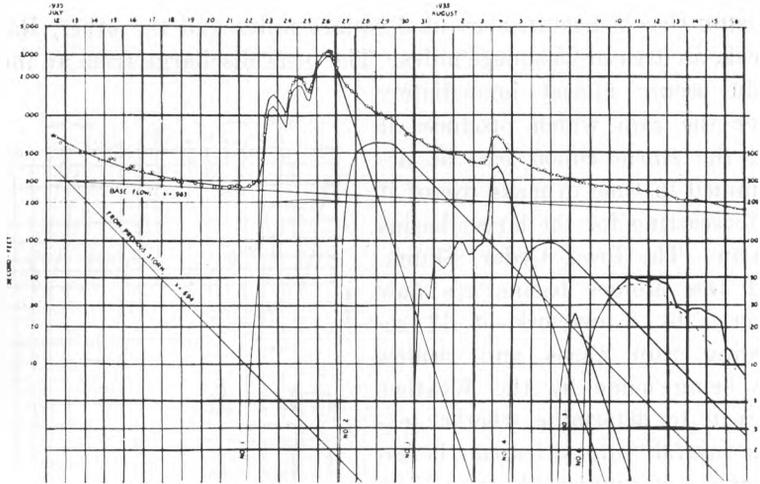an assumed value of the infiltration capacity, and include it in their

FIG. 2.

telegraphic rainfall reports. At the Regional Office this figure would
quickly be converted into a value based on the actual infiltration
capacity as determined from our index basins or otherwise predicted.

The next step in such a forecasting scheme would be to enter
each reported value of the excess rainfall in its proper place on a
blank map of the region and to plot the lines of equal excess rainfall.
It is hoped that calculated values of the excess rainfall at stations
which report only the total rainfall depth can be used to increase the
concentration of points on the map. The expected surface runoff
from each of the basins outlined on the map would be picked off and
telegraphed to the appropriate river district center together with
the predicted amount of storm-seepage. The centers would already
have received as much of the basic data as they could use for making
preliminary forecasts or revising earlier ones.

The distribution of the predicted runoff with respect to time
can best be accomplished at the river district centers. The most
practical method is by the use of the unit hydrograph principle.

The unit-graph of surface runoff as observed in the case of Mississippi Valley streams has a recession curve of the form

$$Q_t = Q_0 k^t$$

where Q_0 is the value of the discharge at any instant and Q_t is the value t units of time later. The constant k is called a depletion factor because the discharge at any time may be multiplied by k to give the discharge one unit of time later. The recession curve of a single event or a series of events of surface runoff will plot as a straight line on semilogarithmic graph paper. The fact that recessions from several events may be present at the same time will not change the value of k. It is therefore not necessary to make use of hydrographs from unit storms in constructing the unit hydrograph of surface flow. All that we need is the shape of the accession curve and crest, and the value of k. The United States Geological Survey has rendered us a great service in furnishing original gage-height charts and rating curves for this purpose.

The relation of time to depletion in the case of storm seepage is precisely the same as for surface flow, except that the value of k is much greater. The accession curve does not rise as steeply and the peak is rounded off to a much greater degree. The depletion factor for storm seepage is more easily determined than that of surface flow. Examination of a hydrograph of storm flow as plotted on semilogarithmic paper will show that certain portions of most of the longer recessions appear as straight lines. The surface runoff from the preceding rain has been reduced to a negligible quantity and the rise of the next event has not yet commenced. The trial hydrograph of ground-water flow must be adjusted until as many as possible of these storm-flow recessions contain straight lines which are parallel to one another. The slope of these lines then gives us the depletion factor for storm seepage. The hydrograph of base flow, also, has been defined in the same process.

It is now much easier to determine the depletion factor for surface flow. Momentary values of the storm flow are plotted on semilogarithmic paper, using intervals of from two to six hours for the first day or two following each peak. The first straight line of storm seepage is extended downward on the sheet, following the accepted or average slope. The values of storm seepage are picked off of this line and tabulated in order until they become so small as to be negli-

gible.   These values are subtracted from the corresponding values
of the total storm flow and the remainders are plotted on the same
hydrograph sheet.   The remainders, when plotted, will appear as
the rise and peak of an event of surface flow.   The first few hours
following the peak will plot as a straight line and the depletion
factor of surface flow may be determined from its slope.   This line
may now be prolonged downward and its values tabulated in turn
and subtracted from the remainder of the storm flow.   Values of
the second remainder may be plotted as before and will define the
rise and peak of the next storm-seepage event.   The process may be
carried on indefinitely unless the total storm flow becomes too small
to be broken down accurately, errors in the basic record are found,
the position of the base flow is in doubt, or a period of freezing
weather is encountered.

The separation of surface runoff by the method just described
is particularly easy to accomplish on index basins, but the discharge
immediately following the peak will usually have to be calculated
at intervals of one hour or less.   On basins of 4,000 square miles or
more, where the concentration of surface runoff is slow, too much
overlapping of the two flows may occur and the actual separation
may have to be made by trial and error.

The advantage of dividing storm runoff into its two components
is that it changes one rather unpredictable quantity into two which
are more easily predictable. It also permits the use of a shortcut in
distributing the runoff from a succession of unit rains. All of the
elements of surface flow which are receding may be added together
and their sum placed in a column headed "combined surface flow."
This figure, when multiplied by the daily depletion factor k for
surface flow, will give the corresponding figure for the day follow-
ing. As additional elements of surface flow pass their maximum and
commence to recede, their values are simply added to the current
figure in the column. The same procedure is followed with storm-
seepage, using the proper depletion factor.

Dr. Horton[2] has demonstrated that the relation of time to deple-
tion of ground-water flow may be expressed by the same form of equa-
tion which we are using with surface flow and storm seepage.   Values
of the daily depletion factor will be close to unity. In the upper
Mississippi Valley we cannot make much use of this principle because
there is an almost continuous recharge to ground water during most

of the year. A satisfactory prediction of the fluctuation of ground water during an event of storm runoff can usually be made from the known amount and trend just previous to the event, because any rise which occurs during the event would result entirely from antecedent rains. The determination of the ground-water depletion factor is of particular interest, however, because it enables us to calculate the rate of recharge directly from the hydrograph of ground-water flow. The total amount of ground water remaining in live storage at any time is equal to the rate of its outflow divided by the natural logarithm of k. The difference, for any period, between the change in content and the normal depletion gives the amount of recharge.

The normal depletion rates of the components of flow in a stream are altered by the arrival of freezing weather. While ice is forming on the stream channels a part of the flow is being used in the production of ice and another part is being impounded as storage, backed up by the ice. It is likely that the increased viscosity of water at low temperatures slows up the rate at which water seeps from the ground. Both the amount and the depletion rate of storm seepage will be affected by a frozen layer of subsoil. A frozen and impervious ground surface will prevent the occurrence of storm seepage altogether and practically all of the rain which falls upon it will appear at once in the streams as surface runoff. On the other hand, when the rays of the sun have gradually melted a layer of snow and the water has all entered the soil and frozen there, the sudden advent of warm weather may produce a large event of storm seepage with no surface runoff at all.

The winter's snowfall is an important factor in the spring freshets on some of the northern streams. The amount of snow which is actually on the ground before the spring thaw is determined by taking samples of the snow at selected points and melting them to obtain their water equivalent. The data obtained in this way sometimes give a serious underestimate of the total amount of snow and frost available for runoff, because in many cases solid ice has formed in ditches and furrows or in the soil. It is therefore necessary to compare the observed depth of snow with a calculation of the total depth of precipitation over the basin during the winter period, subtracting the estimated amounts of evaporation, percolation, and runoff which have occurred during the winter. The total runoff

which may be expected from the accumulated snow, ice, and frost will depend entirely upon the rate at which it thaws and the ability of the soil to absorb it.

It is generally believed that a warm rain is capable of melting snow very rapidly. Actually this is not the case. Warm winds accompanying the rain usually have a great deal more melting power than the rain itself. From the heat content of the rain and the heat of fusion of snow it is easy to demonstrate that rain at 70° Fahrenheit will melt only one-quarter of its weight in snow before becoming chilled to the freezing point. The most serious menace presented by a spring rain upon snow-covered ground occurs when the ground surface is frozen and impervious. Under these conditions any rain falling on the snow will penetrate to the ground surface and accumulate there, where it is prevented from running off by the interlocked crystalline structure of the snow blanket. As the rain continues to fall and the snow to melt, the skeletons of the snow crystals will retain their power to impound the water in the form of slush until nearly all of the snow has been melted. The entire volume of the rain and melted snow will then be released at once into the stream channels, to concentrate in a sharp peak of surface runoff.

The gradual thawing of snow over unfrozen soil may permit all of the water to enter the ground so slowly that no runoff will result. Under similar conditions a heavy rain may be absorbed by the snow and pass steadily into the ground at such a rate as to cause a large event of storm seepage with no surface runoff. This will produce a stream flow hydrograph with a comparatively low, flat peak and a slow recession.

Ice gorges in the spring are an annual menace on many streams. An ice gorge is the least predictable of all of the ordinary sources of flood damage. A series of gorges, forming simultaneously on the same stream, may create an extremely hazardous situation in a very short time. If the gorge at the upstream end of the chain is the first to break, the flood wave released by it is likely to burst the next one, and so on down, the flood peak becoming greater with each new release of impounded water. It is necessary to obtain accurate information in regard to the location and size of all ice gorges as soon as possible after they have formed and to warn resi-

dents below of the amount of flooding which their breaking might cause.

The maintenance of reporting rainfall stations and the collection of reports by telegraph and telephone are among the most important duties of the River and Flood Division in the upper Mississippi Valley. These reports give the total depth of precipitation during the twenty-four hours previous to 7:30 a. m., the hours of beginning and ending of the rain, and a rough statement of its intensity. In some cases additional amounts of rain occurring later in the day are reported in a second telegram. The information is used by the river forecasters of the Weather Bureau and is also furnished to the U. S. Engineer offices at St. Paul and Rock Island for use in the operation of their locks and dams. Arrangements are being made with the American Radio Relay League to furnish an emergency transmitting service in the case of failure of the telegraph and telephone lines. Some of our reports are now being transmitted over the private lines of public service corporations. No telegraphic reports of momentary intensities are now being received from recording rain-gage stations, but charts are received monthly or oftener from recording rain gages operated by the Weather Bureau, Soil Conservation Service, and the University of Iowa. Intensity data taken from these charts are filed in the regional office at Iowa City, where they are used in our studies and are also available to any persons wishing to make use of them.

In our work of river forecasting, the Weather Bureau proposes to make use of the best modern developments in the study of the behavior of storm water. We plan to furnish our river district centers with the most complete and reliable information possible and to set up and maintain a sound routine for utilizing it. We shall then place our faith in the experience and skill of the river forecasters.

REFERENCES

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