Analysis of the Soil Conservation Service Project Formulation Program - Hydrology
by Orrin Albert Ferris

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Civil Engineering
Montana State University

Abstract:
The ability of the Soil Conservation Service method to accurately predict the peak discharge of a rain-caused runoff event on Montana watersheds is studied. Runoff hydrographs are developed for actual and hypothetical storms by using a computer program entitled "Project Formulation Program - Hydrology", previously written for the Soil Con- x serration Service, to effect solutions of the SCS runoff prediction equations.

The actual storm of June 16, 1965 on Duck Creek watershed near Brockway, Montana is simulated. The basin characteristics for Duck Creek and the storm characteristics of the June 16, 1965 storm are described for use with the computer program," which then constructs the predicted runoff hydrograph as calculated using SCS synthetic hydrograph criteria. The agreement between the calculated runoff hydrograph and the actual known hydrograph is not close. Possible reasons for this discrepancy are discussed. Chief among them is the fact that the various equations (used to simulate runoff hydrographs) are sensitive to the various parameters and variables (describing the basin and storm characteristics) when applied to storms of low rainfall excess.

Hypothetical storms are also described to the computer program to demonstrate the way in which they could be used to predict peak discharges on a watershed from a storm of a given frequency.

I It is concluded that the SCS method is a logically organized procedure that has been effectively programmed for computer solution.

Furthermore, successful use of the method requires careful definition of watershed and storm parameters.

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ABSTRACT

The ability of the Soil Conservation Service method to accurately predict the peak discharge of a rain-caused runoff event on Montana watersheds is studied. Runoff hydrographs are developed for actual and hypothetical storms by using a computer program entitled "Project Formulation Program - Hydrology", previously written for the Soil Conservation Service, to effect solutions of the SCS runoff prediction equations.

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Chapter I

INTRODUCTION

Inundation of river flood plains by occasional flood discharges has been a threat to the life and property of man since the dawn of civilization. Man has long sought means of predicting floods and averting their danger. Modern man's need for quantitative information concerning flood flows becomes even more pressing as he alters natural waterways with structures, realignments, and diversions.

A major problem continually faced by highway designers, urban planners, and watershed management engineers is that of determining the frequency of peak flood discharges from stream and river basins. For large river basins (in excess of 100 square miles) flood frequency information is generally available by virtue of long term records of precipitation, stream flow, etc., which have been collected by various public agencies (including the U. S. Environmental Science Services Administration, Geological Survey, Bureau of Reclamation, Agriculture Research Service, and others). For watersheds smaller than 100 square miles in area there is generally a shortage of hydrologic data. Only within the past few years has significant research been directed toward a study of flood frequencies on basins of this size.

The "Drainage Correlation Research Project", which was initiated by the Department of Civil Engineering and Engineering Mechanics, Montana State University, Bozeman, Montana, in 1963, addresses itself to the problem of predicting the frequency with which a peak discharge of given magnitude may be expected on small watersheds in Montana. This investigation is sponsored by the Montana State Highway Department and the U. S. Bureau of Public Roads. The work is being done under the direction of

Theodore T. Williams, Associate Professor of Civil Engineering and Engineering Mechanics at Montana State University.

The Drainage Correlation Research Project is a two phase study: a) to determine flood frequency relationships on watersheds smaller than 100 square miles from long-term climatological data already in existence; and b) to make comprehensive hydrologic studies of four small watersheds in eastern Montana. The watersheds selected for study are Bacon Creek in Wheatland County, Duck Creek in Prairie and McCone Counties, Hump Creek in Sweet Grass County, and Lone Man Coulee in Pondera County. Continuous records of climatic factors and streamflow are being obtained from these four basins. A variety of peak-flow prediction techniques, which utilize data such as that being collected, are being examined.

Among the techniques being considered under the second phase of the Drainage Correlation Research Project is one which was developed by the Soil Conservation Service, U. S. Department of Agriculture (SCS). The SCS method possesses many desirable features, and seems to have considerable potential as a tool for predicting flood frequencies. The study reported in this thesis analyzes the method developed by the SCS; describes the use of a related computer program; tests the program's ability to reproduce actual hydrographs from a selected watershed; and evaluates the possible utility of this method on Montana watersheds.

The investigation reported herein consisted of the analysis, using the SCS method, of a single rain-caused runoff event which occurred on Duck Creek, the largest of the four watersheds being studied by the

Drainage Correlation Research Project. Duck Creek is an ephemeral stream typical of most eastern Montana streams which drain small watersheds. It is dry most of the time, but occasionally has surface flow after a rain-caused runoff event or during spring snowmelt. In the four years for which data have been obtained at Duck Creek, there have been only a few runoff events of consequence, and only an event which occurred on June 16, 1965 lends itself to an analysis by the SCS method.

A number of events would need to be analyzed before conclusive statements as to the validity of the SCS method could be made. Nevertheless, it is believed that the results of the analysis of this one storm will be a valuable contribution in estimating the applicability of the method to Montana watersheds.

Chapter II

LITERATURE REVIEW

Scientific hydrology is a relatively new area of study. Application of the scientific approach to hydrologic problems has had its greatest growth in this century, and especially in the last thirty years. However, the first hydrologic measurements probably were made several centuries B. C. Many interesting articles about the beginnings in hydrologic study have been written and a few of these will be described below, after which a description of modern hydrologic fields will be presented.

Historical Hydrology

Biswas (1966, 1967) and Hoyt (1942) have each authored historical accounts telling of early efforts to cope with the problem of peak flood discharge.

Records of the level of the Nile River in Egypt can be traced back to about 3000-3500 B. C. Nilometers were used to record the maximum levels reached during each flood season.

There were three general types of nilometers used. The first was simply a cliff on the river's edge upon which yearly maximum flood stages were recorded by carvings. A second type had stairs on the banks of the river which gave easier access to the flood stage level. The most accurate type was a reservoir connected to the river by underground conduits. Stairs gave access to a central column or the reservoir walls where the levels were recorded. In a section of the second cataract at Semna, no fewer than 179 distinct engravings have been found dating back to 1750-

1800 B. C. or earlier.

Heron of Alexandria, who lived in the second century B. C., established some fairly clear ideas about water measurement. This is shown by the following quotation from his Dioptera, Chapter 13, where, according to Hoyt (1942), Heron states that,

> "Observe always that it does not suffice to determine the section of flow, to know the quantity of water furnished by the spring. This we said was twelve square digits. It is necessary to find the velocity of its current, because the more rapid the flow, the more water the spring will furnish, and the slower it is, the less it will produce. For this reason, after having dug a reservoir under the stream, examine by means of a sun-dial how much water flows into it in an hour, and from that deduce the quantity of water furnished in a day."

Apparently, this knowledge was not well understood for many years. One example of this comes from the writings of Sextus Julius Frontinus, superintendent of Rome's water supply who wrote in his De Aquis around 97 A. D. about the Roman system. He had only a hazy idea of velocities of running water and failed to appreciate the time element with regard to flow rates.

Leonardo de Vinci (1452-1519 A. D.) also aided the development of hydrology considerably. His writings describing the reasons for variation of discharge from a canal through an orifice demonstrate his fundamental knowledge of hydraulics.

Pierre Perrault (1628-1703) made measurements on a portion of the Seine River basin in France to compare rainfall and runoff. His results indicated that the total precipitation in the form of rain and snow was nearly six times that carried by the river. For the first time it was proved that normal precipitation was more than adequate to supply water to the rivers and springs. Edme Mariotte (1620-1684) extended Perrault's work to include the entire Seine basin above Paris and found similar results.

An English astronomer Edmund Halley (1656-1742) contributed to the field of hydrology by his experiments with evaporation. He demonstrated that the water evaporated from the ocean was more than sufficient to supply all the streams and rivers.

In 1768, a French engineer, M. Chezy, developed the well known formula bearing his name, $V = C\sqrt{RS}$, for calculating flow velocities where R is the hydraulic radius and S is the friction slope. C is a variable known as the Chezy C, and was probably considered to be a measure of boundary roughness. However, it has been shown that C is also a function of channel shape. Ganquillet and Kutter developed a formula for evaluating C in 1869 which, although complicated, found popular use. However, Henderson (1966) reports that independent work by Gauckler in 1868 and Hagen in 1881 demonstrated that the simpler relationship

$$C = \frac{R^{0.167}}{n} \qquad (1)$$

fit the same data used by Ganquillet and Kutter just as well as the more complicated expression. R is the hydraulic radius and n is a measure of the boundary roughness. "n" is generally referred to in the United States as the Manning roughness coefficient, after R. Manning, an Irishman, who was wrongly given credit for the Gauckler and Hagen formula by a Frenchman named Flamant. Therefore, Chezy's equation for flow velocity can be converted to the "Manning equation" giving

$$v = \frac{1.49\, R^{0.667}\, S^{0.5}}{n} \qquad (2)$$

where $1.49 = \sqrt[3]{3.28}$, 3.28 being the number of feet in a meter. When the metric system is being used, the constant 1.49 is simply 1.00.

Hydrologic measurements were not considered to be of much importance during the early history of the United States. Population centers developed along the rivers and lakes and so no shortage of water was experienced until the westward expansion into the arid and semi-arid regions. The beginning of systematic collection of hydrologic data in this country can probably be taken to be in 1888, when the U. S. Geological Survey under the direction of Frederick H. Newell set up its first river-measurement station on the Rio Grande River at Embudo, New Mexico.

Modern Hydrology

Since about 1930, the increase in the amount of printed information made available in the field of hydrology has increased very rapidly. This indicates something of the increased need there has been in recent years to obtain more data and develop better prediction methods.

The study of hydrology can be subdivided into the two general areas of stochastic and deterministic hydrology. Deterministic hydrology can be further separated into physical or analytical, dynamic and parametric.

Stochastic hydrology attempts to predict future events or reconstruct past events based on the statistical properties of the known record. White (1967) states that if the value that a variable has implies an element of chance, then it is a stochastic variable. Thus if the record available for some variable (the value of which is random in nature or stochastic) is restricted in time, then the predicted future projection of this record is done by statistical means.

Physical (analytical) hydrology addresses itself to particular specialized problems of the hydrologic process. It does not try to supply any answers to peak discharge, annual yield, or frequency studies. In a sense this branch of hydrology is pure research in that it seeks to establish relationships between variables operating in the hydrologic cycle but does not attempt to solve any related practical problems.

Dynamic hydrology is the term for hydrologic studies involving the dynamic wave theories of fluid flow. These wave theories have been applied to overland flow as well as open channel flow to derive synthetic runoff hydrographs.

Parametric hydrology attempts to discover the relationships among physical parameters that are involved in the particular hydrologic events that are of interest and then to use them to simulate non-recorded events. Amorocho and Hart (1964) list methods of correlation analysis, partial system synthesis with linear or nonlinear analysis, and general system synthesis as methods used in parametric hydrology.

In the prediction of peak runoff from a small watershed, by a method such as that developed by the SCS, both stochastic and deterministic hydrology come into play. The streamflow itself, being the result of precipitation, is a stochastic process. Watershed characteristics, which modify or affect the streamflow, are, by themselves, physical parameters. Dynamic hydrology must be considered in the flood routing process while parametric hydrology is utilized to find correlations among the various watershed parameters.

A discussion of the technique for predicting flood frequencies which is currently in use by the Soil Conservation Service, is reserved for Chapter III, because it is the basis for this thesis.

Chapter III

SOIL CONSERVATION SERVICE RUNOFF PREDICTION METHOD

The Soil Conservation Service method of predicting runoff from ungaged watersheds is characterized by the development of a synthetic unit hydrograph. Under this method the storm characteristics are transformed into a synthesized flood runoff hydrograph by the basin characteristics, the shape of the synthetic unit hydrograph and the baseflow hydrograph. The general procedure which is followed in developing a flood runoff hydrograph is shown by the block diagram in Figure 1.

As shown in Figure 1, the storm runoff volume must first be derived from the storm characteristics and the basin characteristics. This storm runoff volume is then shaped into a storm hydrograph by use of a synthetic unit hydrograph which in turn is derived from the basin and storm characteristics. A baseflow hydrograph then is added to the storm hydrograph as indicated in Figure 1 to produce the flood runoff hydrograph. This sequence of operations involved in producing the flood runoff hydrograph comprises a mathematical watershed model. The general framework of the watershed model has been incorporated into a program for solution by a digital computer. The basin characteristics of a particular watershed must be supplied as input to the computer to transform the general model into a specific model for the watershed in question.

Proposed Use of SCS Method

The proposed way of testing the SCS method* is to use it on an actual

*This method is outlined in the Hydrology section of the SCS National Engineering Handbook (1964).

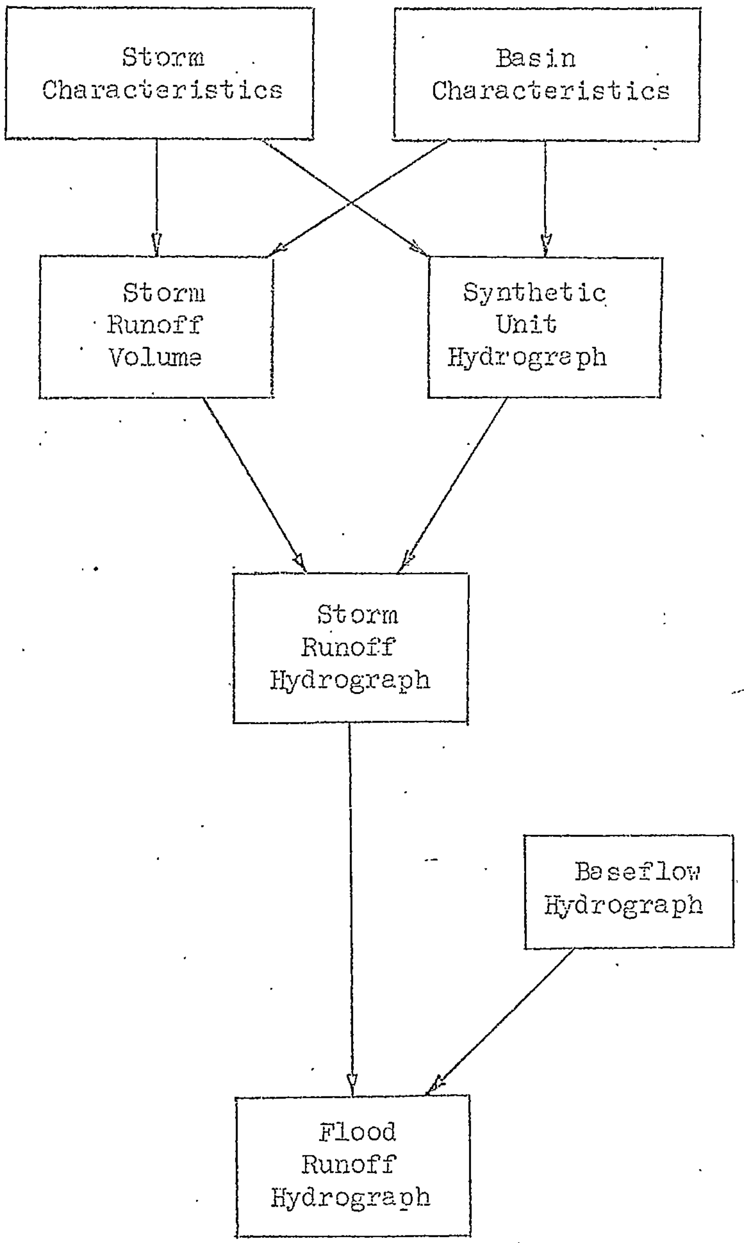

Figure 1: Block Diagram Depicting Soil Conservation Service Runoff Prediction Method

storm where the input (storm) and the output (runoff hydrograph) are known. The procedure should be to supply data characterizing the watershed and storm characteristics as input to the computer program which then uses the watershed model to simulate a runoff hydrograph. The volume of the simulated hydrograph is compared with that of the actual event. If there are major discrepancies in the volumes, the values characterizing the basin parameters may be altered, and the computer program run again. When the volumes are adjusted to be essentially the same, the model is considered to be a valid representation of the watershed. The validity of the SCS method depends upon the ability of the adjusted model to accurately reproduce the actual runoff hydrograph, including the peak discharge.

After the model has been adjusted, it is then possible to route design storms through the model and thereby simulate design hydrographs.

Unit Hydrograph Theory

The unit hydrograph (UH) for a given watershed is defined as the discharge-to-time relationship that yields one inch of runoff from a storm of given duration over the entire watershed area. Unit hydrographs are generally derived from as many actual recorded storms as possible and then generally are assumed to represent the unit runoff functions for all storms of similar durations. Sherman (1932) is given credit for formulation of the unit hydrograph theory while Snyder (1938) first introduced a method for constructing a synthetic UH which may be used for the study of ungaged watersheds. Several other methods for defining synthetic

UH have been developed since Snyder including those by Commons (1942), Mitchell (1948), and Gray (1961).

System Synthesis and Analysis

Where no actual hydrographs are available for a watershed, the SCS method of predicting runoff can be classified as a method of general system synthesis. If an actual unit hydrograph is available, on the other hand, the SCS method would be one of partial system synthesis with linear system analysis.

System synthesis according to Amorocho and Hart (1964) is a method of describing the operation of a physical system with a combination of components that exist in the system and whose functions are known and predictable.

System analysis, on the other hand, is a method by which the relationship between the input and output to the system is established mathematically by measuring only the properties of the input (storm data) and output (runoff) without regarding the nature of the system.

An explanation of the linear and nonlinear properties of runoff prediction methods will follow later in this chapter.

On a gaged watershed since an actual UH is available, it is an analytic (as opposed to synthetic) function since the internal characteristics of the system are not known or synthesized. Even though the actual hydrograph is available, however, synthetic modifications are necessary. Interception of precipitation by vegetation and baseflow characteristics, for instance, must be synthesized. Therefore, even on a gaged watershed, the SCS method is partially synthetic, and may be classified as one of partial system synthesis with linear analysis.

On an ungaged watershed, where it is necessary to use a synthetic UH the entire system is synthetic; thus the classification of general synthesis method applies to the prediction of runoff hydrographs on ungaged watersheds.

Functioning of a General Synthesis Method

The system which transforms rainfall to runoff can be thought of as made up of three separate subsystems when the unit hydrograph approach is being considered. 1) The first subsystem, which creates a "rainfall excess" function, modifies the total rainfall input to account for infiltration, interception, and depression storage. The rainfall excess thus computed is the amount of rainfall that is available for runoff. 2) The second subsystem creates a "storm runoff" function by operating on the rainfall excess function. This subsystem makes use of the basin's topographic characteristics. 3) Finally, the third subsystem, which creates the "flood runoff" function uses baseflow information to alter the storm runoff function. The combined effect of these three subsystems is assumed to duplicate the natural processes which occur on the actual watershed being studied. The paragraphs that follow describe in detail these three subsystems as synthesized by the SCS method.

Rainfall Excess: The rainfall excess function (produced by the first subsystem) is given, according to the SCS method, by equation (3).

$$Q = \frac{(P - .2S)^2}{(P + .8S)} \qquad (3)$$

where Q is the amount of rainfall excess in inches over the watershed, P is the storm rainfall in inches, and S is defined as the maximum potential difference between P and Q (hence the maximum infiltration capacity) at the time of the storm's beginning.

Equation (3) is based on a hypothesis. If the equation can be shown to be true, then the hypothesis can be assumed to be true. The original hypothesis can be stated as such:

$$\frac{G}{S} \text{ and } \frac{Q}{P} \rightarrow 1 \text{ as } P \rightarrow \infty \qquad (4)$$

where G is the actual retention during a storm, S is the potential maximum retention, Q is the direct runoff (or the actual runoff), and P is the total storm rainfall (or the potential maximum runoff). So when flood producing storms are considered, it can be said that:

$$\frac{G}{S} = \frac{Q}{P} \qquad (5)$$

Equation (5) cannot be proven mathematically, however, it follows from equation (3) which empirically has been found to be valid.

Since $G = P - Q$, equation (5) can be rewritten:

$$\frac{P - Q}{S} = \frac{Q}{P} \qquad (6)$$

The SCS Hydrology Handbook begins the development of equation (3) with the statement of equation (6).

As P goes to infinity, the ratio $(P - Q)/S \to 1$ and $Q/P \to 1$. Keeping in mind that P, Q, and S are total volumes for a storm, $(P - Q)$ finally fills the entire soil profile to its maximum value S as determined for the condition of the watershed at the beginning of a storm. Now, solving directly for runoff volume from equation (6):

$$Q = \frac{P^2}{P + S} \tag{7}$$

A further adjustment of P can be made for the initial abstraction I_a which reduces P by the amount of interception, depression storage, and infiltration at the storm's beginning before runoff occurs. Several relationships can now be revised to allow for the initial abstraction (in effect, this amounts to redefining terms which now have slightly different meanings than the corresponding terms in equations (4) through (7)).

$$P = Q + G + I_a \tag{8}$$

$$S \geqq I_a + G = P - Q \tag{9}$$

$$G = (P - I_a) - Q \tag{10}$$

Equation (7) can also be restated:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{11}$$

Existing data from several watersheds were studied and it was found that

I_a can be taken to be equal to .2S. By substituting this value in equation (11), equation (3) is finally derived.

The SCS has prepared a graphical solution (runoff as a function of precipitation) of equation (3), which is shown in Appendix A. As is evident in Appendix A, precipitation is related to runoff through a family of curves, each curve being drawn for a particular curve number (CN). The curve numbers are a function of S and are given by the relationship:

$$CN = \frac{1000}{S + 10} \qquad (12)$$

The parameter CN is used instead of S as integer values of S do not produce curves that lend themselves to easy interpolation. The curve numbers, however, make the P vs. Q plot easier to use.

The runoff equation, equation (3), used by the SCS is a relationship between P and Q involving only one parameter, the parameter being S. S can now be empirically related to as many characteristics as is thought to be necessary. The developers of this method found that soil and cover conditions had the most effect on the value of S (and therefore on the CN). The curve number CN is therefore termed the soil cover complex number.

For various combinations of soil type and vegetal cover, soil cover complex numbers have been developed empirically. To determine such a number, small watersheds were found which had only one type of soil and only one type of cover condition. A number of points were plotted, one point per storm, on a graph of total precipitation in inches versus total runoff in inches. The CN curve that best fits this plot is then taken to be the representative curve number for that soil cover complex. The results of all such plots made by the SCS are summarized in Appendix C.

In using the SCS method, curve numbers (CN) are determined by referring to a table such as that shown in Appendix C, and selecting the CN that corresponds to the appropriate soil type and vegetal cover condition. The soil classification used divides all soils into four groups (A, B, C, and D) according to their permeabilities. The permeability of group A soils is highest and of the D soils, the lowest. The descriptions of the various soil types are given in Appendix B. Musgrave and Holtan, as reported by Chow (1964), have quantified infiltration rates for the four soil groups. Minimum infiltration rates for groups D, C, B, and A are given by the ranges 0 to 0.05, 0.05 to 0.15, 0.15 to 0.30, and 0.30 to 0.45 inches per hour, respectively.

A vegetal cover condition is described as some natural or cultivated condition. For instance the cover may be described variously as fallow, contoured small grain in poor condition, pasture in fair condition, or woods in good condition.

The effect of the antecedent moisture condition (AMC) is accounted for by adjusting the soil cover complex number previously calculated. The curve number was originally developed with average AMC being assumed. However, for conditions of very dry and very wet antecedent soil moisture conditions, type I and type III, respectively, are used. The type II condition is considered to be the average condition. Whether the AMC calls for type I or type III treatment is determined by the guide lines in Table I. The limits on the dormant season apply to unfrozen ground and no snow cover.

After the correct type of AMC is determined, there are standard curves showing the adjustments to be made on the soil cover complex numbers as shown in Figure 2. Values for the adjusted CN can be taken at points between lines shown for types I, II, and III if it is felt that the AMC are sufficiently well known.

Storm Runoff: The second subsystem (that which produces the storm runoff function) is assumed to be a linear convolution by unit hydrograph theory. The purpose of the convolution process is essentially to convert a rainfall excess function of a certain volume into a runoff function having the same volume. The convolution integral describing this runoff function q(t) is given by:

$$q(t) = \int_0^{t'} u(t - \tau)\, i(\tau)\, d\tau \qquad (13)$$

The kernel function $u(t - \tau)$ is the instantaneous unit hydrograph (the unit hydrograph which theoretically results from a rainfall excess occurring instantaneously on all parts of a watershed), $i(\tau)$ is the rainfall excess input function, and t' (the limiting time for τ) is a function of t_0, t_0 being the duration time of the input function (storm). For $t < t_0$, $t' = t$ and when $t \geq t_0$, $t' = t_0$.

The basic convolution process is shown graphically in Figure 3.