#1067

RELATION OF WATERSHED CONDITION TO FLOOD DISCHARGE

A Theoretical Analysis

Luna B. Leopold

FOREWORD

The following paper by Luna B. Leopold presents a method of determining runoff rates that may be new to many of the staff in Region 8. In its present unperfected state, this method requires that certain assumptions be made in determining the final result. To date, data that would allow such assumptions to be made in a rational manner are not available.

That this is true is not as severe a criticism of the method outlined as would be expected, because few data are available that can be applied to give correct runoff values by any method now in general use in the Region. The deficiency is being rapidly overcome by the collection of rainfall-runoff data at many locations in the Region through rainmaker experiments and experimental watersheds. Furthermore, the method does have a very great value in the fact that factors influencing runoff are placed in their proper relation to each other and may be evaluated.

The importance of Leopold's presentation, other than giving the application of a method, is that it expresses the effect of various runoff factors in a definite or numerical form arrived at through a logical and rational analysis. These effects are not unexpected as they have been noted by all of the staff at one time or another; but so far as is known, this is the first time that a method showing the relative effect of certain factors has been presented.

Leopold presents certain conclusions as to the effect of watershed conditions and corrective works on runoff, but it is to be noted that his conclusions deal only with peak flows from a rather small area. It should be pointed out that a reduction in peak flow does not always make for a reduction in total discharge, a question of great importance where water supplies are critical. So many other factors enter into a discussion of this latter question that it was not taken into consideration in this paper. Although the conclusions found in this paper are based on a given rainstorm, this particular storm has the usual rainfall pattern and is not infrequent and should represent a rather common occurrence in this Region.

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DEFINITION OF TERMS

f	Infiltration capacity - the rate in inches per hour at which a soil under given conditions will absorb water.
n	Coefficient of roughness - the factor expressing the roughness of a surface over which water flows. This "n" is applicable to the Manning formula.
δ_o	Initial detention - the amount of water (expressed as inches depth on the watershed) either in depressions or in transit when active surface runoff begins.
T_o	Critical tractive force - force required to initiate movement of a particle when water is picking up a sediment load.
T_1	Total tractive force - the total force of water available for expenditure on debris movement.

RELATION OF WATERSHED CONDITION TO FLOOD DISCHARGE

A Theoretical Analysis

Until some future time when soil-conservation measures have been put in operation for a period sufficiently long to have obtained maximum effect, a true evaluation of effectiveness of different measures is impossible. To supplement the meagre data available from evaluation surveys and experimental plots, the present analysis has been made. In spite of the limitations inherent in a theoretical analysis, the results will help answer certain questions which arise, particularly in the preparation of a flood-control program, and as new data on different factors affecting runoff are obtained giving a better basis for the assumption of these factors, the method of analysis may have wide applicability.

This study is a mathematical and graphical computation of a series of hydrographs of runoff from a given area as a result of a particular rainfall on the area, assuming different conditions of vegetation and gullying. A flood-control report on the Rio Puerco is in preparation at present and for this reason the study involves an area typical of many valleys in the Rio Puerco watershed. In choosing a small watershed for such a study, it would be possible to use a topographic map of an area which may be considered a typical valley, or a theoretical valley could be assumed. Since only the average slope of the valley sides and average gradient of the valley floor would be taken from the topographic map, it was considered equally satisfactory to assume an ideal valley whose gradients were considered typical. The cross section of the assumed valley is shown in figure 1. It was given a symmetrical profile concave upward, a total width of 2,000 feet. The gradient of the valley floor is 2 percent; the length of the section on which the rain was assumed to fall is 2 miles.

Since the slope from the watershed to the center line of the valley was of interest only in its effect on surface runoff, a uniform slope was computed which would give an average velocity of runoff. This constant slope from the lateral boundaries of the watershed to the center line of the valley was used throughout the computations.

Rainfall is a constant factor in the study in that the same rainfall was used for all examples wherein the ground conditions affecting runoff were varied. The rainfall used in this study was recorded at Santa Fe, N. Mex., September 3, 1909, a typical heavy thundershower in which 1.10 inches fell in 40 minutes. The elevation of Santa Fe is about 7,000 feet, and that of the area near San Luis, in the upper Rio Puerco, is about 6,500 feet. The character of rainfall is not dissimilar.

The factors affecting surface runoff are infiltration capacity, coefficient of roughness, initial detention or the amount of water on the ground either in depressions or in transit when active surface runoff begins, and slope, - each of which has been assumed. Variations in watershed condition have been approximated by assuming different combinations of the runoff factors. Indications from rainmaker data are in line with the infiltration rates assumed in this study and summarized in the following table:

TABLE OF ASSUMED VALUES OF RUNOFF FACTORS

Condition of watershed	Infiltration capacity	Coefficient of roughness "n"	Initial detention	Channel characteristics		
				Area at 1-foot depth	Slope	Coefficient of roughness "n"
	In. per hr.		Inches	Sq. ft.		
Range in original condition - valley not gullied	.75	.04	.10	250	.02	.045
Range depleted - valley not gullied	.50	.03	.05	250	.02	.045
Range depleted - valley gullied	.50	.03	.05	12	.02	.03
Range in original condition - valley gullied	.75	.04	.10	12	.02	.03
Range depleted - gully check dammed						
a. Spillway level with valley floor	.50	.03	.05			
b. Spillway at half the depth of gully	.50	.03	.05			

It is assumed in this study that water flows laterally to the valley floor as a thin sheet, the velocity of which is dependent on the coefficient of roughness, the slope, and the depth. On a watershed covered by sod, this would be essentially true; but in the Rio Puerco area, a 2-mile section of valley in depleted condition would ordinarily be cut by some lateral gullies, or at least by rills. Flow of water in rills or gullies is faster than as sheet flow, so the peak flow computed for depleted range is probably too small. For the purpose of computation, however, the increase in runoff after range depletion is assumed to be due to a lowered rate of infiltration caused by decrease in vegetation, a lower coefficient of roughness, and a smaller initial detention. It is assumed that even under the new conditions the water flows as a sheet with no rills, gullies, or channels.

Computation of lateral flow was done graphically by the method proposed by Horton, the result of which is a hydrograph of runoff on a strip of unit width from the lateral watershed boundary to the center line of the valley, the runoff measured at the center line.(1) The total inflow to the valley floor is a summation of the flow of all the unit strips.

The flow along the center line of the valley floor is the result of contribution from both sides of the valley. In the curves, this lateral contribution is labeled "Inflow Hydrograph." The hydrograph of discharge from the 2-mile length of valley, labeled "Outflow Hydrograph," was computed by a graphical method designed by Goodridge for routing floods through reservoirs.(2) That such a method is applicable

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(1) Horton, R. E. Surface Runoff Phenomena, Pt. I. Horton Hydro. Lab. Pub. 101, 1935, pp. 58-62.

(2) Goodridge, R. S. A graphic Method of Routing Floods through Reservoirs. Trans. Amer. Geophys. Union Pt.II, 1937, pp.433-439.

to the present study is demonstrated by Horton when he shows that the equation relating channel storage to outflow for any stream system is identical in form to that which would apply to a reservoir concentrated just above the outlet having the same relation of stage to outflow.(3) Horton observes that "The fact that . . . . channel storage behaves like water concentrated in a single reservoir is not altogether easy to explain, especially when one takes into consideration the fact that the channel storage in a drainage basin . . . (in many cases) . . . is distributed through several thousand miles of stream channels and may be interrupted by rapids or even abrupt falls interposed along the course of the stream." The reaction of any inflow change reaches the point of outflow as fast as wave motion travels in the medium and does not depend on an actual transmission of water from the point upstream to the point of measurement.

An examination of the inflow hydrographs of figures 1 and 2 shows that the peak discharge flowing to the valley center line was increased by range depletion from 460 c.f.s. to 650 c.f.s., or 41 percent. The decrease of initial detention by range depletion is an important factor in determining this increase in peak flow. All other factors being held constant for the case in which the range was assumed to be in original condition, changing the initial detention from .10" to 0" increased the peak discharge 21 percent. A given depth of initial detention has a greater percentage effect for small rains than for heavy rains, but it is an important factor in determining peak flow, particularly for rains of short duration.

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(3) Horton, R. E. Natural Stream Channel-Storage (second paper), Trans. Amer. Geophys. Union, Pt. II, 1937, pp. 440-456.

The increase of initial detention is probably the main flood-control value of range furrows and basin listing, though such practices may also increase the rate of infiltration to some extent. Furrows plowed 4 inches deep with average spacing of 5 feet would theoretically provide depression storage of 0.2 inches over the area. If all the assumed watershed were treated in this manner, the peak inflow contributed to the valley floor would, for this particular rain, be reduced by about 30 percent.

Reduction of peak flow by increase of initial detention is most effective for rains whose maximum intensity comes at the beginning of the storm. For the most part, summer-type thunderstorms typical of the Rio Puerco watershed fall in this category.

The great decrease of peak discharge from the inflow hydrograph to the outflow hydrograph is attributable to the storage afforded by the nearly level valley for a given depth of water. In figure 1, of the total water that had been discharged into the valley-bottom channel, at the time of peak discharge only 16.5 percent had passed the point of measurement at the end of the 2-mile reach and the other 83.5 percent was still held as channel storage in the valley. This storage characteristic of an uneroded valley cannot be overemphasized as a factor affecting peak flow.

The peak discharge from the valley channel was increased by range depletion from 105 c.f.s. to 162 c.f.s., or 54 percent. Figure 3 shows the additional effect on peak flow of a gully cut in the valley channel. The maximum discharge for depleted range was increased from 162 c.f.s. to 430 c.f.s. by a gully 4 feet deep and 12 feet wide. The new discharge is 409 percent of the peak for the range in original condition. Since the assumed gully was deep enough to carry the maximum discharge without overflow, additional deepening of the channel would not affect the peak flow since deepening would change neither the storage-depth nor the discharge-depth relations.

The effect on rate of discharge is directly attributable to loss of channel storage. This difference in storage can be seen by comparing the storage-depth curves for the gullied and ungullied valleys.

With the valley still gullied, restoration of the range to its original condition reduces the peak flow from 430 c.f.s. to 295 c.f.s., a reduction of 135 c.f.s. in 430, or 31 percent (fig. 4). With no change in condition of the watershed, the gully is responsible for an increase of peak discharge of 181 percent over that for the range in original condition.

It is of interest to note that the peak of the inflow hydrograph in no case causes more than a slight hump in the outflow curve. The peak discharge on the outflow curve is in all cases at or near the point where outflow equals inflow. This is to be expected because the channel storage acts as a concentrated reservoir, and, therefore, the effect of inflow on outflow is practically an immediate reaction. Outflow cannot increase when inflow is less than outflow.

Horton has pointed out that when the hydrograph of stream flow is plotted on the same graph as the supply causing runoff, the point of inflection on the recession side of the hydrograph is approximately at the time when supply equals zero.(1) If ground-water contribution is eliminated, that part of the recession side of the hydrograph which is concave upward represents water being contributed largely by channel storage. This same principle applies to the present data except that the inflow hydrograph is the supply curve, while in the other case the curve of precipitation minus infiltration would be the supply. This relation of supply to outflow is best shown on figure 3. All water discharged after the inflow ceases is water held in channel storage.

The changes in discharge due to range depletion and gullying have a significant effect on the stream's ability to erode and transport sediment. To demonstrate this fact, let T_o be the critical tractive force, or the force required to initiate movement of a particle. Let T_1 be the total tractive force of the water; then $T_1 - T_o$ is the force available for transportation. Under natural condition of a range, the rate of deposition or erosion is comparatively slow. Therefore, T_1 is approximately equal to T_o. Let T_1' be the tractive force available under the new conditions of range depletion and consequent increased velocity. The ratio of the new to original transporting power is expressed by $\frac{T_1' - T_o}{T_1 - T_o}$. Any increase in velocity would, therefore, tend to greatly increase transporting power even though the actual increase of T_1' over T_1 may be relatively small. This corroborates the statement that a depleted range cannot long preserve conditions of sheet flow and demonstrates how rill or gully erosion is accelerated once water concentrates in a channel where it can travel at higher velocities.

Figure 5 shows the hydrograph after the gully on the depleted range has been check dammed. It was assumed that the spillway of each dam was built up to the level of the valley floor, the dams spaced so that silt deposited level behind one reaches the toe of the structure above. The relation of discharge to depth was determined by assuming the spillway to be a broad-crested weir. In practice, check dams are rarely built up to valley-floor level and seldom have such close spacing. The assumed check dams represent the optimum in terms of flood reduction and also the most intensive and most costly treatment.

The peak flow from the depleted range after intensive check damming of the gully, was reduced from 430 c.f.s. to 48 c.f.s. The peak was reduced to a discharge even lower than that for original conditions. This is due to the fact that the water is spread over the valley floor, affording a storage capacity approaching the order of magnitude of the original storage, and the character of the new spillway is such that a relatively large head is required to produce a given discharge. Watershed treatment to restore the range to original condition would give even greater reduction of peak. Had the assumed dams not been built high enough to spread water over the valley floor, there would have been a relatively small reduction in peak discharge. This is shown by figure 6, in which it is assumed that the check dams were built half as high as the gully is deep.

In the first assumption of a gully only 4 feet deep, check dams 2 feet high would cause the peak discharge to exceed the capacity of the gully and spread over the valley floor. To prove the point, therefore, that gully plugging without spreading of water does not significantly affect peak outflow, a new gully was assumed with the same width as the one in the first assumption, 12 feet, but deep enough so that when dammed to half its depth the channel would carry the peak without overflow. This depth is approximately 10 feet; the dams, therefore, are 5 feet high, and the peak flow fills the channel to within 8 inches of the valley-floor level. The silt was again assumed to be deposited level. Under these conditions the peak outflow was 362 c.f.s., which, compared with the 430 c.f.s. from the untreated gully, represents a reduction of only 16 percent. This intensity of treatment is commonly applied in practice and as shown above, accomplishes practically no flood reduction.

Restoration by watershed management without gully treatment caused a decrease in peak flow of 31 percent, while gully plugging without water spreading and without watershed management caused a decrease of 16 percent. Moreover, in all cases wherein the gully was not treated, the velocities of flow were sufficiently great to erode the channel bottom. In the following table the velocities of water at the times of peak flow are compared for the different assumed conditions.

CHANNEL AND FLOW CHARACTERISTICS AT TIME OF PEAK DISCHARGE

Watershed condition	Slope of channel	Velocity of peak discharge	Stability of channel
	Percent	Feet per second	
Original condition	2	1.8	Noneroding
Range depleted	2	2.1	Noneroding
Range depletion plus gullying	2	11.3	Eroding
Watershed treatment without gully control	2	10.0	Eroding
Depleted range: gully check dammed			
a. Spillway level with valley floor	Silt bed level	Negligible	Noneroding
b. Spillway at half the depth of gully	Silt bed level	7.2	Eroding

It can be seen, therefore, that in the assumed watershed the untreated gully would tend to deepen. When check dammed without water spreading, the gully would discharge the peak flow at eroding velocity even though the grade were level between the dams. This means that the silt deposited level would be eroded until the increased channel section reduced the velocity to a nonsilting, noneroding condition. This erosion would tend to undercut the toe of each dam and failure would be imminent.

This analysis shows that under the assumed conditions the check dams would fail under the peak flow unless the dams were sufficiently high to spread water over the valley floor.

The velocity in the nongullied valley where there are no rills or channels is only about 2 feet per second, even for conditions of range depletion. However, stability is only theoretical. Discontinuous channeling, typical of the Rio Puerco in its original condition, and small rills on spots where the grass had been weakened on the valley floor are incipient gullies. In these small channels the velocity is sufficient to erode and gullies cut at an accelerating rate.

New data will make it possible to express more reliably the runoff factors for different watershed conditions, but if the present assumptions are rational, the effect of watershed condition on peak discharge for this area may be summarized as follows:

(See table on the next page).

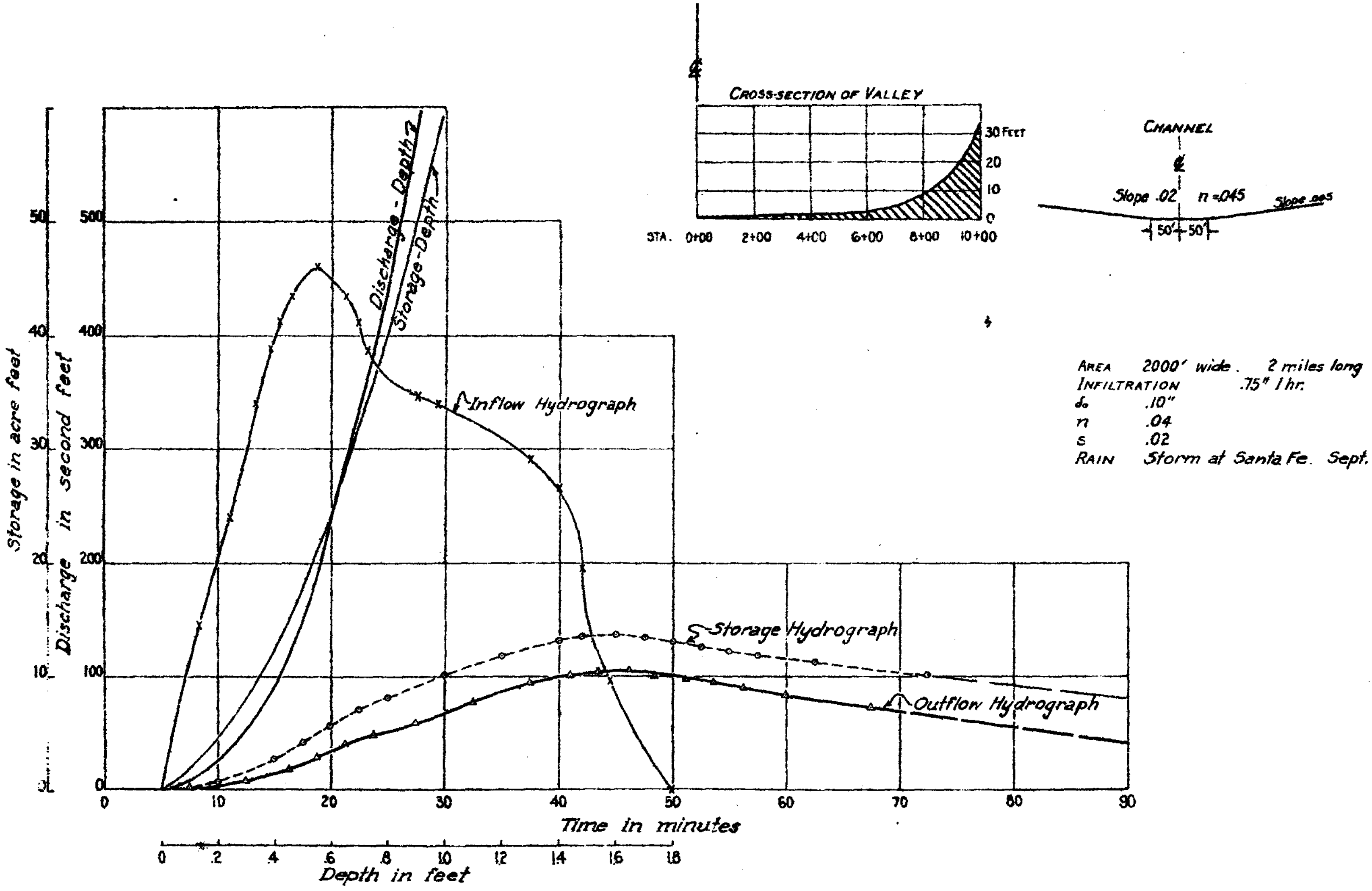
SUMMARY OF EFFECT OF WATERSHED CONDITION ON PEAK DISCHARGE

Watershed condition	Peak discharge (C.f.s.)	Peak discharge as percentage of the peak for original condition
Range in original condition	105	100%
Range depletion	162	154%
Range depletion plus gullying	430	409%
Restoration by watershed management without gully treatment	295	281%
Gully treatment on a depleted range		
a. Spillway level with valley floor	48	46%
b. Spillway at half the depth of gully	362	344%

The author wishes to acknowledge the invaluable assistance of Thomas Maddock, Jr. for his constructive suggestions and his help in the graphical analysis.

FLOW CHARACTERISTICS
ON VALLEY FLOOR

RANGE IN ORIGINAL CONDITION VALLEY NOT GULLIED



AREA	2000' wide. 2 miles long
INFILTRATION	.75" / hr.
δ_o	.10"
n	.04
s	.02
RAIN	Storm at Santa Fe. Sept. 3, 1909

Fig. 1

FLOW CHARACTERISTICS ON VALLEY FLOOR

RANGE DEPLETED **VALLEY NOT GULLIED**

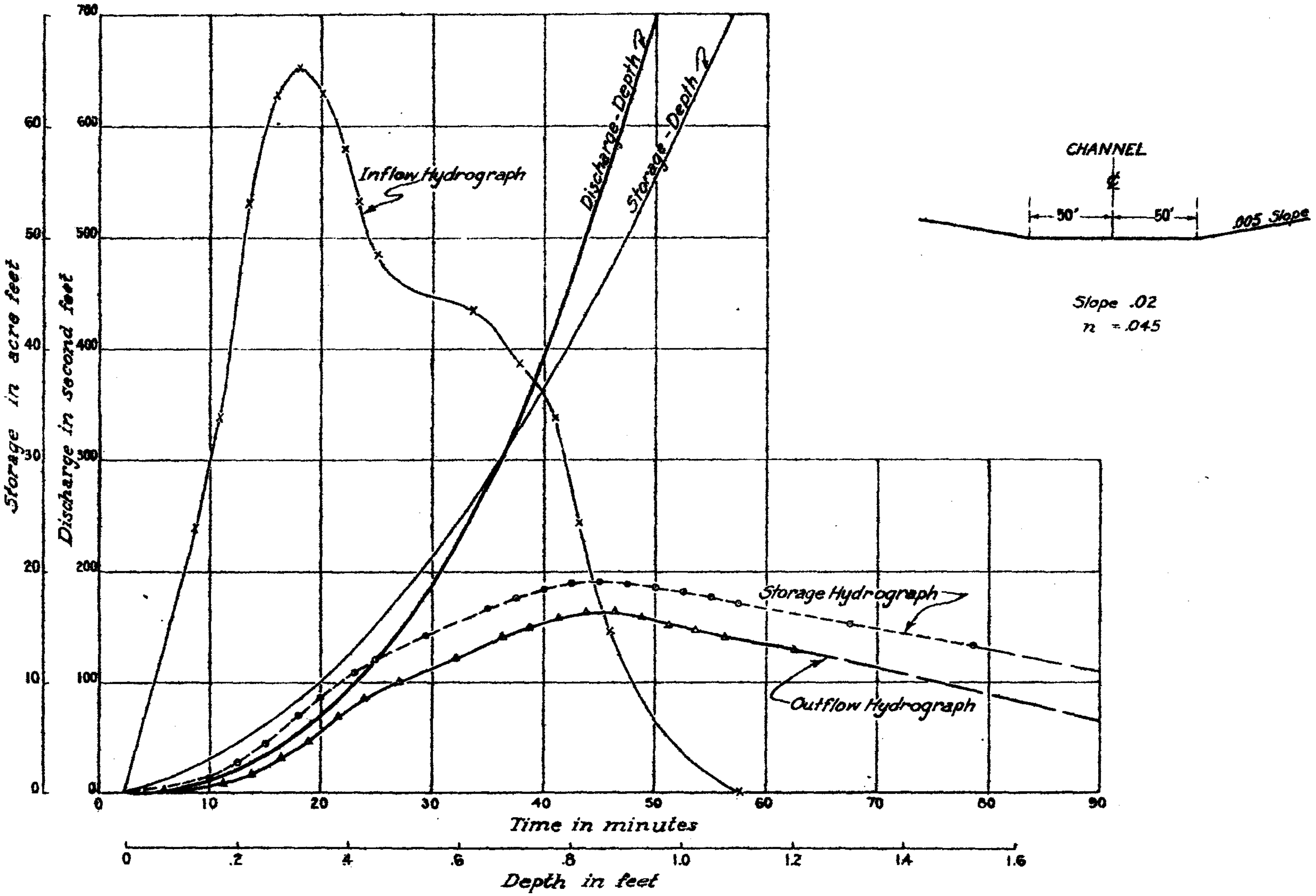


FIG. 2

FLOW CHARACTERISTICS ON VALLEY FLOOR

RANGE DEPLETED VALLEY GULLIED

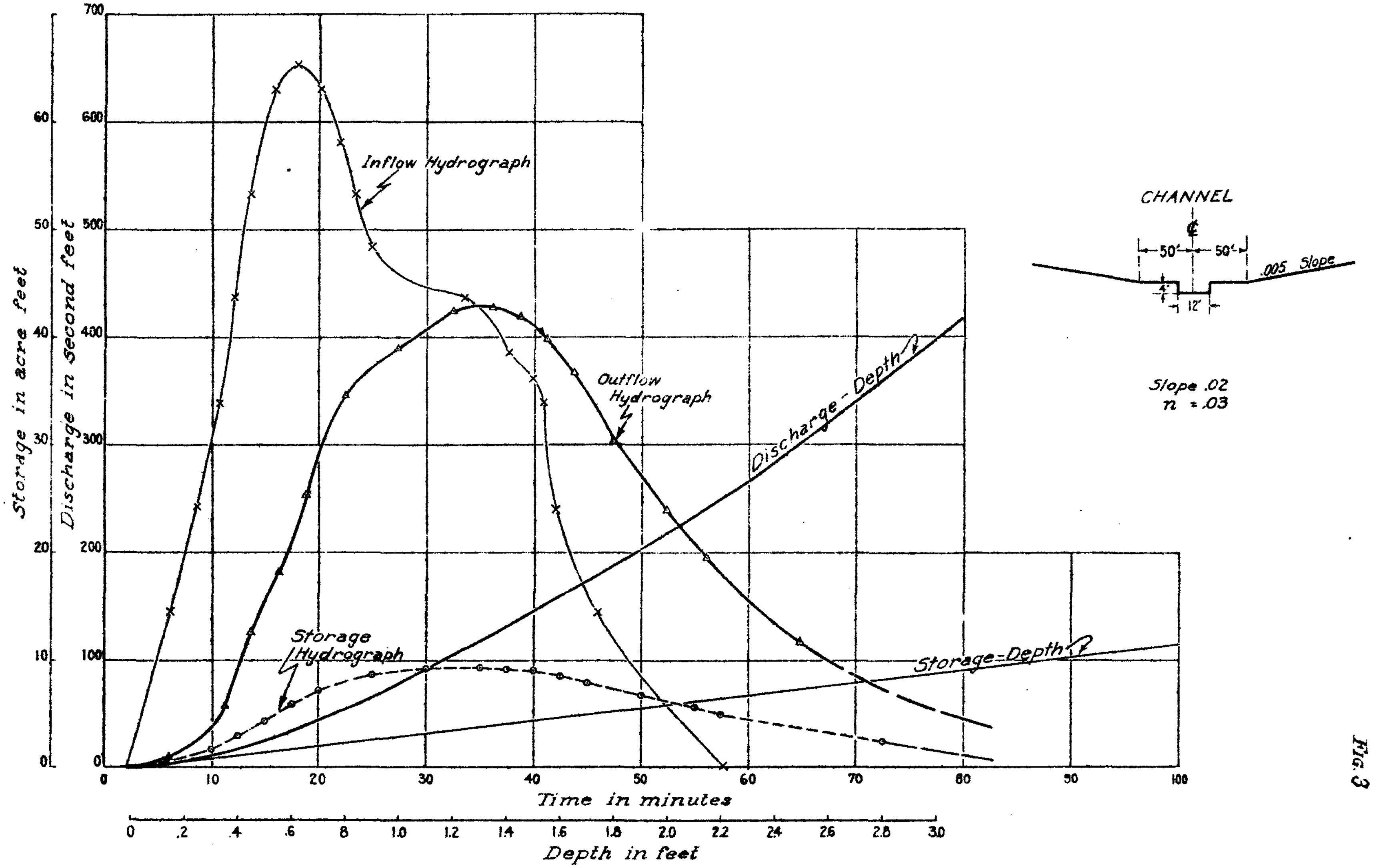


FIG. 3

FLOW CHARACTERISTICS
ON VALLEY FLOOR

RANGE IN ORIGINAL CONDITION VALLEY GULLIED

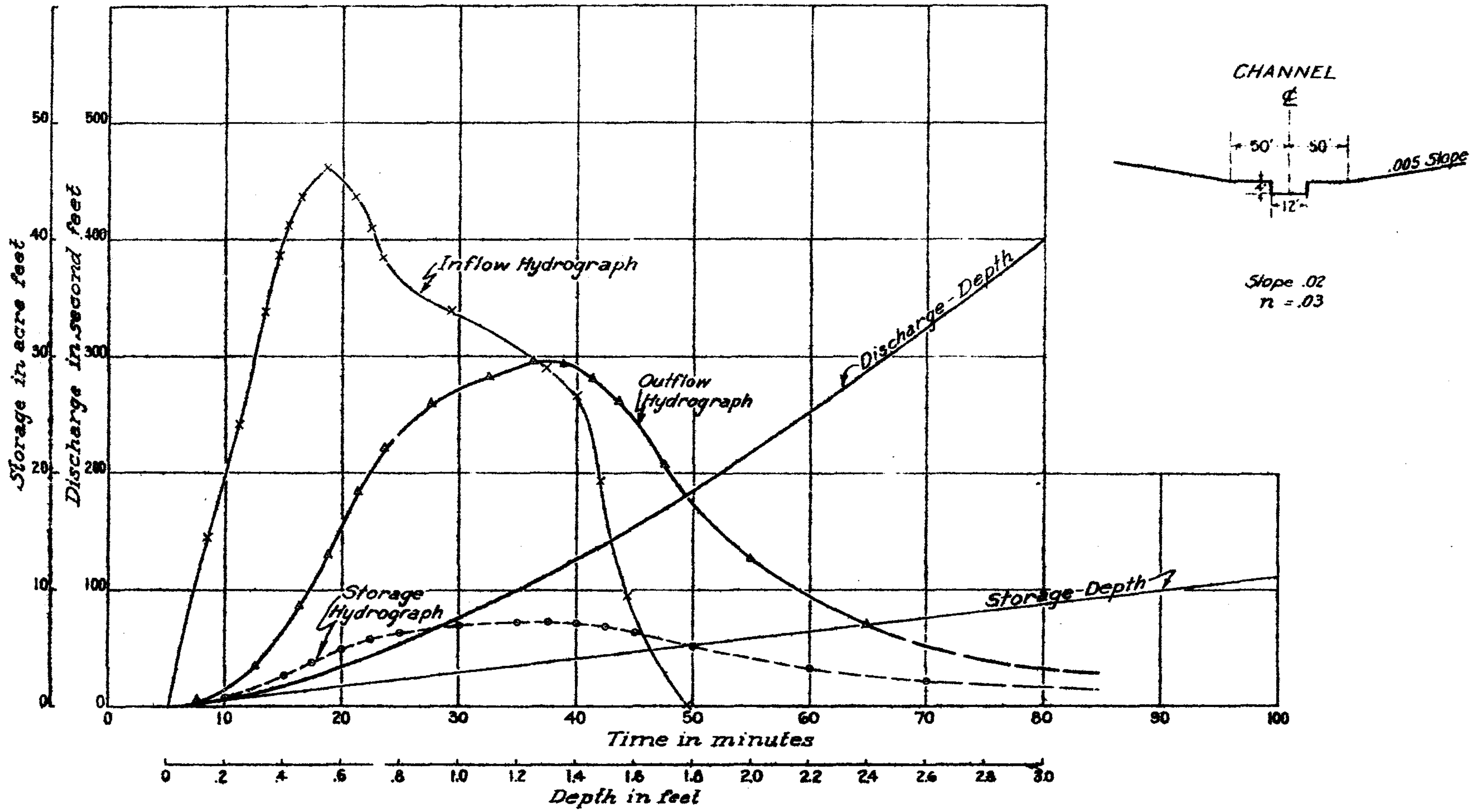
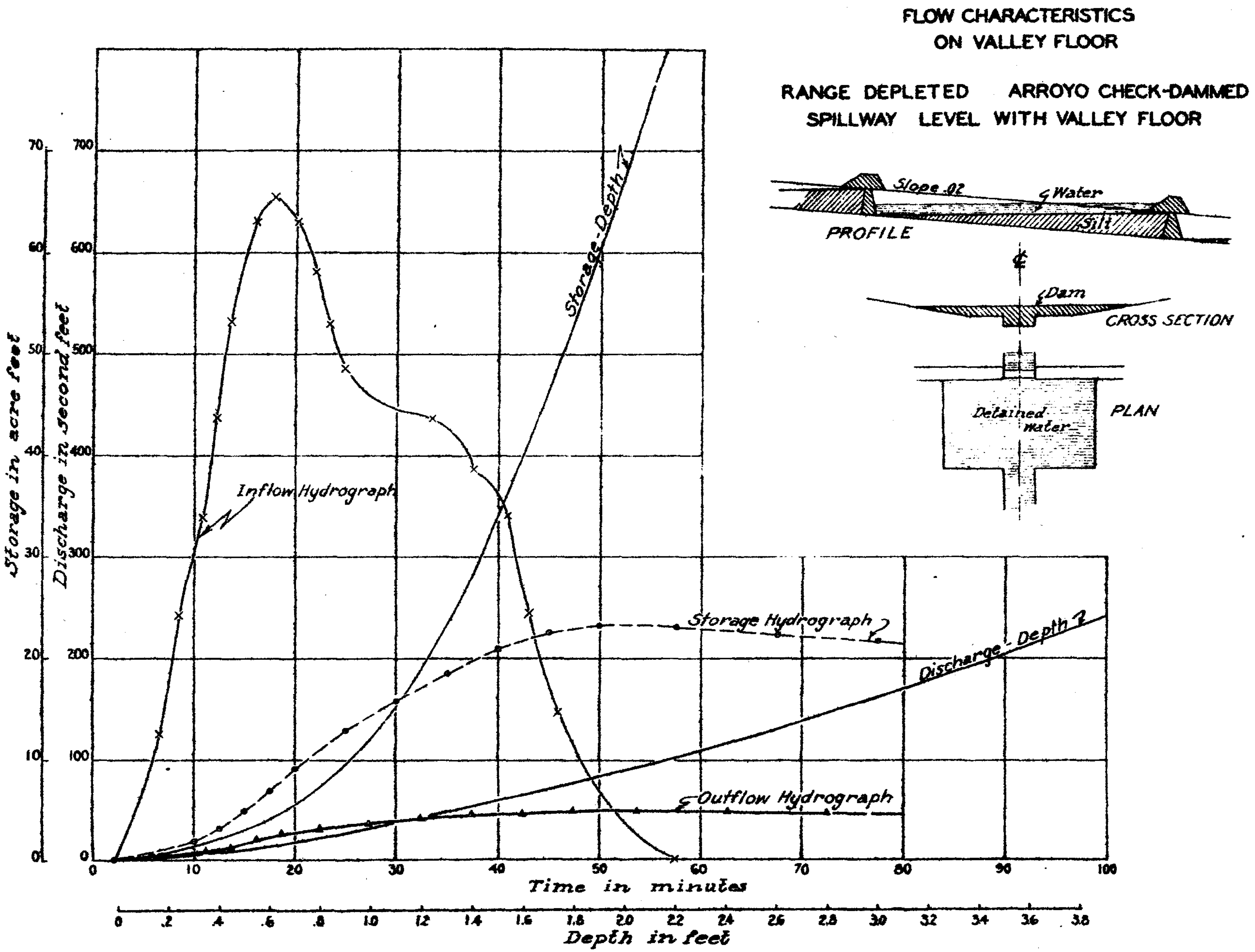


Fig. 4



FLOW CHARACTERISTICS
ON VALLEY FLOOR

RANGE DEPLETED ARROYO CHECK-DAMMED
SPILLWAY LEVEL WITH VALLEY FLOOR

Fig. 5

FLOW CHARACTERISTICS
ON VALLEY FLOOR

RANGE DEPLETED GULLY CHECK-DAMMED WITHOUT
SPREADING WATER OVER
VALLEY FLOOR

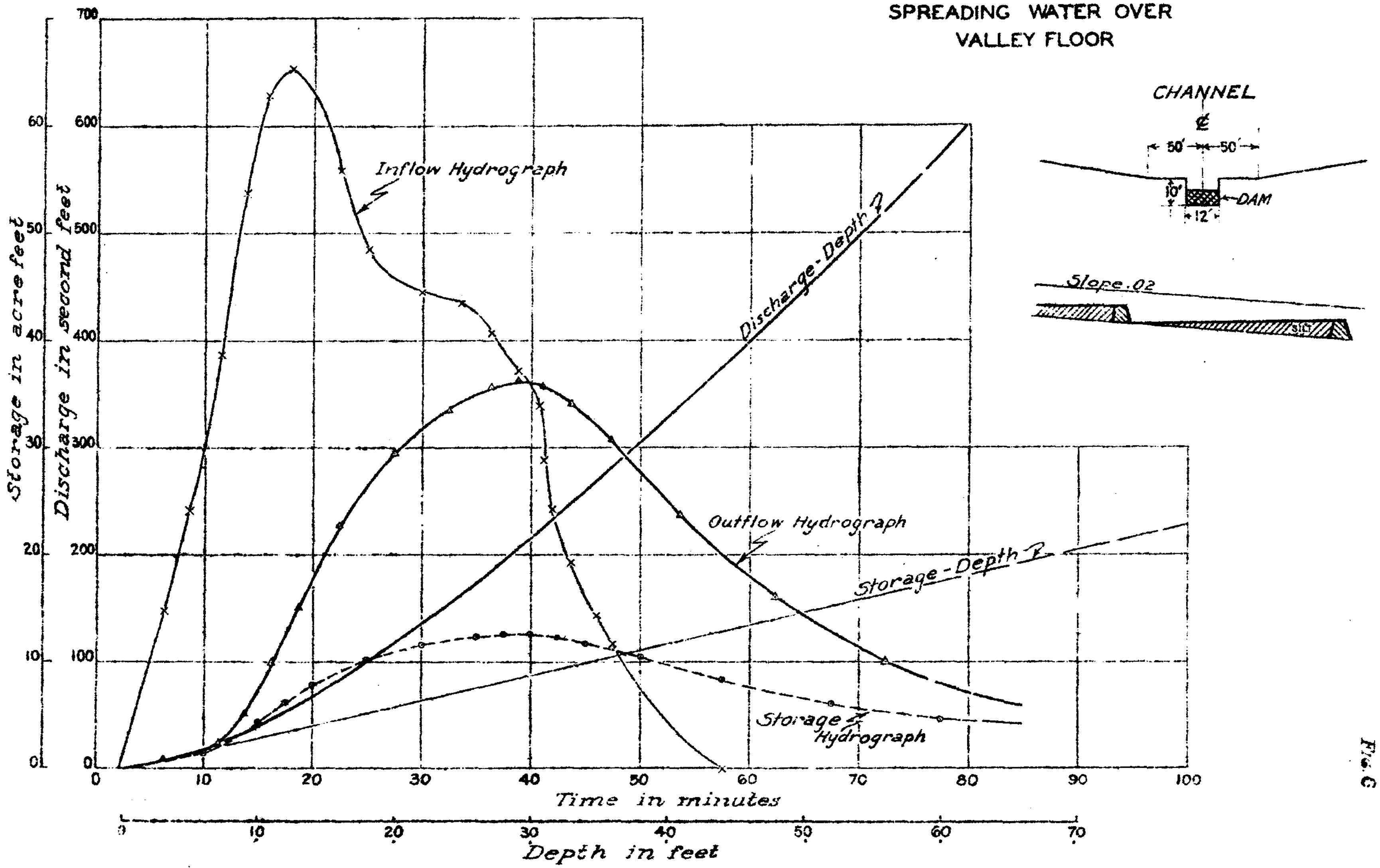


Fig. C