Paper No. 329

The Phenomena of Losses and Gains in the Indus River System

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Synopsis

The phenomena of losses and gains in the Indus River System has an important offect on the river supplies available for irrigation. In considering any plan involving changes in the historical river flows, the effect of the latter on the historical pattern of losses and gains has to be considered for a proper appraisal of the adequacy of river supplies for irrigation and other uses. Past attempts in the Indo-Pakistan subcontinent to determine a satisfactory relationship between river flows and losses and gains on the Indus System proved unsuccessful. This paper reports a new relationship obtained after a theoretical consideration of all the important factors causing losses and gains and a detailed analysis of the historical data *for a large number of years*.

The theory, as well as the analysis, has indicated that concurrent and antecedent river flows are important factors contributing to losses and gains and that the gains are also affected by the time lapsed since the previous high flows and the extent of drop in river stage in the falling hydrograph periods. Multiple correlation has provided a practicable and useful tool in the analysis of the data and in obtaining the relationships. Statistical tests have shown that the relationships are significant. The recurrence of the same relationships in all the 14 independent river reaches considered in the analysis provided a further reliable measure of significance. The estimated results of the formulæ were compared with the actual historical values for all the years for which data was available and there was a remarkable correspondence between the estimated and observed values. It is believed that the theory developed and the relationships obtained provide an adequate basis for estimating the losses and gains in the various reaches of the Indus River System under varying conditions of river flows.

Introduction

The Indus River System comprises the main Indus and its major tributaries, the Kabul on the right bank and the Jhelum, the Chenab,

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the Ravi, the Beas and the Sutlej on the left bank. The Kabul river joins the main Indus soon after it debouches from the mountains, while the other rivers join lower down in the plains. All rivers rise in the Himalayas or its western extensions and are snow fed. The entire Basin covers an area of about 348,000 square miles, out of which 204,000 lies in Pakistan, 29,000 in India, 52,000 in Jammu and Kashmir and the balance in Afghanistan and Tibet (Fig. 1).

The Indus Valley is a great alluvium filled depression between the triangular Southern peninsular massif and the alpine folded and faulted Himalayan Range. The depth of alluvium in the valley has been estimated to range from 5,000 to 10,000 feet. Presumably, the alluvium is all subaerially stream deposited, although marine and deltaic deposits may occur in the lower part of the section. [1] The rivers pass through vast alluvial plains which gently slope towards south and southwest along the rivers with extremely flat gradients varying from 1 foot per mile in the Punjab to as low as 0·5 foot per mile in the lower parts. From the conditions of the great rivers it is apparent that the plains are most recent deposits and are being formed by the very rivers.[2] This is a normal feature of a depositing river as most familiarly known in deltaic regions. By periodic overflow during the high flow season, the rivers gardually raise their banks and at the same time their beds and so finally run on broad ridges of their own creation. If left to themselves they will finally break into the lower grounds on either side through some hitherto small channels of overflow and take up a new course. All the rivers of the Indus System have undergone such changes. Within historical times, the Sutlej followed a very different course from its debouch at Rupar. The Beas deserted its old course and joined the Sutlej. Many historically proved rivers disappeared in course of time. They are known under the name of the lost rivers. It is even often impossible to locate their site. The Hakra or Wahindah river, which was a boundary between Sind and Hind (India) dried out and disappeared in the eighteenth century, [3] after the Jamuna changed its course to join the Ganges. The Indus Main was flowing into the Rann of Cutch in the fourteenth century but changed its course more than 100 miles to the west, turning its new course into a desert now called the Thar Desert.

The precipitation in the head reaches of most of the streams is in form of snow. Lower down in the submountainous tracts the rainfall averages from 30 to 4o inches, gradually decreasing to less than 5 inches in the West. In the plains the average rainfall varies from 15 inches in the Punjab to less than 5 inches in the South. The plains may, therefore, be classified as semi-arid to arid. Local rainfall shows great variation from year to year in respect to quantity, incidence and duration and is mainly concentrated during the monsoons (June to September). The plains, owing to their arid nature and remoteness from the sea, are subject to extremes of climate. The average summer temperature is 95° with maximum up to 120°. The average winter temperature is 60° with minimum reaching freezing point occasionally.

The rivers of the Basin are subject to extreme variations of flow, the normal summer discharge being about 20 times the winter minimum. The mean annual flow of the whole system is 168 MAF of which the Indus Main contributes about 90 MAF. The runoff is characterized by the absence of any pronounced duration of mean flow, but shows a marked periodicity. There is generally a period of low water flow from October to March. The main rise usually begins in April with the melting of the Himalayan snows, reaching a maximum during July or August, as a result of the monsoon rainfall and falling off in September. This does not fit in very well with the agricultural calendar. The gross area of the Indus Basin in Pakistan is 131 million acres of which 75 million are culturable, but the net area sown to crops is only 27·5 million, of which 90% produces one crop per annum. The area actually irrigated is 21 million acres, which represents 76% of the cropped area.

The phenomena of losses and gains in the Indus River System is typical of rivers flowing through flat alluvial plains. During high stages the river loses water partly in filling the river channels, partly by percolation through the porous bed and bank formations and partly by evaporation and transpiration within the river valley. When the river stage falls, the water stored in the river channels appears back as gains from Channel Storage, and when the river attains the low stage, part of the water lost through the bed and bank formations returns into the river as regeneration or gains from Bank Storage.

The above phenomena is typical of every river in the Indus Basin and has a profound effect on irrigation. The losses during the months of April, May and early June, determine the available river supplies for sowing the Kharif crops. The maturing of these crops depends to a large extent on the gains from river channel storages during September and October. The regeneration in the rivers from mid-October to March contributes substantially to the raising of the Rabi crops. In fact, the Rabi irrigation on some important projects, such as Islam, Trimmu, Panjnad and Kotri (Fig. 1) depends almost entirely on the regeneration in the rivers.

The magnitude of the losses and gains in the Indus System is very great. On the Western Rivers, viz., Indus, Jhelum and Chenab, which carry a mean annual flow of about 135 MAF, the total annual losses are over 35 MAF on the average and the total mean annual gains are as much as 13 MAF. The mean annual losses on these rivers are almost equal to half the entire mean annual flow of the Columbia River at the Grand Coulee Dam and twice as much as the mean annual flow of the Colorado River above the Hoover Dam.

The Problem

Any plan for development of the river supplies for irrigation and other uses involves changes in the historical pattern of river flows. For a proper appraisal of the adequacy of the river supplies, it is important to consider the effect of these changes on the historical losses and gains. Apart from changes due to new projects, the varying hydraulic conditions from season to season and year to year necessitate an advance forecast of the losses and gains in the various reaches for an efficient, and equitable distribution of the river supplies. The problem, therefore, is to find out a method which provides an adequate basis for estimating the losses and gains in the various reaches of the Indus River System under varying hydraulic conditions.

This problem confronted the various expert committees constituted during the past 30 years for examining the adequacy of the supplies in the Indus River System for various irrigation projects. Several solutions were proposed but none of them were considered satisfactory by the expert committees who examined this problem from time to time. The writer was engaged on this problem during the last two years in connection with the Indus Basin Water Dispute. This paper reports the relationship obtained after a theoretical consideration of all the important factors causing losses and gains and a detailed analysis of the historical data for a large number of years.

Analysis

Like all hydrological problems the phenomena of losses and gains in alluvial rivers is a product of multiple causation of complex and varying factors which tend to obscure the true cause and effect relationships. The basic factors causing changes in losses and gains are as follows :—

Basic Factors Causing Losses :—

(1) Absorption.

(2) Evaporation.

(3) Consumptive use of vegetation in the river valley.

(4) Channel and Bank Storage.

Basic Factors Causing Gains :—

(1) Percolation from Ground Water.

(2) Return Flow from Channel and Bank Storage.

(3) Rainfall and Unmeasured Inflows.

Each one of the above factors depends upon many other subsidiary factors. Some of the subsidiary factors vary with the changes in river flows and are considered as Dependent Variable Factors denoted by the letter V for losses and v for gains. The other subsidiary factors that are largely independent of the changes in the river flows, although they themselves may be varying from site to site and from season to season on account of other causes, are considered as Independent Variable Factors and are denoted by the letter C for losses and c for gains. The subsidiary factors causing changes in losses are summarized below :—

(1)	Losses due to Absorption :—	
	(a) Wetted Perimeter	V_1
	(b) Depth of Water	V_2
	(c) Soil Conditions	C_1
	(d) Degree of saturation of the soil at the time of flow	V_3
(2)	Losses due to Evaporation :—	
	(a) Water Surface	V_1
	(b) Depth of Water	V_2
	(c) Climatic Conditions	C_1
(3)	Losses due to Consumptive Use of Vegetation :—	
	(a) Water Surface	V_1
	(b) Nature of Vegetation	C_3
	(c) Climatic Conditions	C_1
(4)	Losses due to Channel and Bank Storage :—	
	(a) Shape and Size of the River Valley	C_4
	(b) Slope of the River	C_5
	(c) River Stage - Rising or Falling	V_4
	(d) Rate of Change in Discharge	V_5
	(e) Soil Conditions	C_2

The subsidiary factors causing changes in gains (denoted by the letters v and c) are summarized below :—

(1)	Regeneration or Percolation from Ground Water :—	
	(a) Ground Water Elevation	V_1
	(b) River Water Elevation	V_2
	(c) Rate of Change of River Water Elevation	v_3
	(d) Soil Conditions	c_1
	(e) Specific Yield of the Water Bearing Area	c_2

(2) Bank and Valley Storage :—

(a)	Shape and Size of River	c_3
(b)	Slope of the River	c_4
(c)	River Stage—Rising or Falling	v_4
(d)	Rate of Change in Discharge	v_5
(e)	Soil Conditions	c_1

(3) Rainfall and Unmeasured Inflows :—

(a)	Rainfall	c_5
(b)	River Water Surface	v^6
(c)	Catchment Area	c^6
(d)	Run-off	c_7

If any of the above factors operates independently, and changes in a certain manner without causing any change in the other variable factors, and if the latter remain unchanged, it would be a simple matter to evaluate its loss or gain effect. For instance, suppose the wetted perimeter V_1 only varies and the other factors V_2 to V_5 and v_1 to v_6 remain unchanged, then the result would be a change in the losses which would be in ratio of the wetted perimeter at the beginning and end of the interval. The problem, however, is not so simple. If the wetted perimeter V_1 changes, the water depth V_2 also changes. This may cause a further change in the river stage V_4 and the rate of change of flow V_5. The factors V_2, V_4 and V_5 may together cause either an increment in the losses due to V_1 or they may decrease the effect of V_1. The problem becomes more complicated on account of the gain factors v_1 to v_6 also operating simultaneously with the loss factors. In every river reach each Dependent Variable Factor will be continuously changing and in doing so causes a change in the other Dependent Variables and will also be affected by the changes in the latter. All the Dependent Variable Factors operating independently and in conjunction cause changes in the loss effects and the gain effects and the result may either be a net loss or a net gain.

Each one of the Dependent Variable Factors has some relation to the river flow (Q) which can be expressed as a function of the river flow in the following manner :—

(a) Wetted Perimeter $V_1 = f(Q^m)$

(b) Water Depth $V_2 = f(Q^n)$

(c) Degree of Saturation $V_3 = f(\Sigma Q)$

(d) River Stage $V_4 = f(\Delta Q^m)$

(e) Rate of Change of Discharge $V_5 = f(\Delta Q)$

(f) Ground Water Elevation $v_1 = f(\Sigma Q)$

(g) River Water Elevation $V_2 = f(Q^n)$

(h) Rate of Change of River Water Elevation $V_3 = f(\Delta Q^n)$

(i) River Stage $v_4 = f(\Delta Q^m)$

(j) Rate of change of River Flow $v_5 = f(\Delta Q)$

(k) Water Surface Area $V_6 = f(Q^m)$

If only the dependent variable loss factors V_1 to V_5 and the independent variable loss factors C_1 to C_5 operate and if the cumulative effect of all the dependent and independent variable gain factors is zero, then the result would be a True Loss which can be expressed as follows :—

TRUE LOSS

$$= f(V_1, V_2 \ldots V_5) + f(C_1, C_2 \ldots C_5)$$
$$= F[f(Q^m), f(Q^n), f(\Sigma Q), f(\Delta Q^n), f(\Delta Q)] + f(C_1, C_2 \ldots C_5) \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots (1)$$

Similarly, if the cumulative effect of all the loss factors is zero and only the gain factors are effective, the True Gain may be expressed as follows :—

TRUE GAIN

$$= f(v_1, v_2 \ldots v_5) + f(c_1, c_2 \ldots c_7)$$
$$= F[f(\Sigma Q), f(Q^n), f(\Delta Q^n), f(\Delta Q), f(Q^m)] + f(C_1, C_2 \ldots C_7) \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots (2)$$

In the above equations,

Q is the river discharge,

m, n, are numerical exponents.

and $C_1, C_2 \ldots C_5$ and $c_1, c_2 \ldots c_7$ are the several factors, such as soil conditions, climatic conditions, nature of vegetation, shape of the river, etc., which also influence the losses and gains in the river but are not directly related to the river discharge Q.

In practice, however, both the loss factors and the gain factors incorporated in equations (1) and (2) operate simultaneously and the known historical data of losses and gains is actually the cumulative net effect of all these factors which is either an Apparent Loss or an Apparent Gain. The general equations for the Apparent Losses and Gains can be expressed in the following form :—

$$\text{Apparent Losses} = (\Sigma V + \Sigma C) - (\Sigma v + \Sigma c) \ldots \quad \ldots(3)$$

$$\text{Apparent Gains} = (\Sigma v + \Sigma c) - (\Sigma V + \Sigma C) \ldots \quad \ldots(4)$$

in which

ΣV and Σv are the cumulative effects of the loss factors and gain factors respectively which depend on the river flow Q.

ΣC and Σc are the cumulative effects of the loss factors and gain factors respectively which are independent of the river flow Q.

The above analysis bring out one unmistakable fact, namely, that the losses are not a simple direct function of the concurrent river discharge Q. The Method of Proportionality, which has been advocated as a simple solution of the problem and according to which changes in losses are worked out in direct proportion to the changes in river flows, is therefore basically incorrect. Even historically there has been no direct relationship between the concurrent river flows and the losses as shown in Appendices I and II.

Similarly, the gains in a river reach depend on many factors and are not related solely to the concurrent flow (Q). The most important among the basic factors causing gains are regeneration and valley srorage. These are further analyzed in the following.

Regeneration

The term "regeneration" as used in the Indus Basin is not the same as "return flows" as commonly used in U.S.A. Regeneration consists mainly of seepage water (invisible return flow) entering the river channel through its bed and bank formations. The term return flow as commonly used in the United Stetes includes in addition surface run-off from irrigation, drainage from canal structures and escapes at lower end of canals, as well as drainage recovery from irrigation. Thus, the experience of return flows on irrigation projects in the United States, which mainly relates to visible return flows, is not applicable in the Indus Basin.

The main source of regeneration is the Bank Storage, i.e., the water stored in the zone of saturation within the river bed and banks which gradually discharges in the form of seepage back into the river during low river stages. The possible sources of recharge to the bank storage are the following, separately or in combination.

(1) The river flows during the high flow season when the river floods its banks and when the river stage is higher than the zone of saturation.

(2) The Ground Water in the doab, if it has a sufficient

gradient towards the zone of saturation in the river banks, the main source of the Doab Ground Water consisting of the seepage from irrigation canals, irrigation fields, and the infiltration from rainfall in the Doab.

Detailed investigations were carried out to determine the influence of the above sources of recharge on the magnitude of regeneration. Data of river flows and regeneration for 20 years was tabulated for each reach and by correlation analysis it was found that the higher the river flows during the high flow season, the greater is the magnitude of regeneration in the following low flow season. The studies also showed that the magnitude of regeneration also depended on the concurrent flows in the low flow period. The higher the concurrent flow, the lesser was the magnitude of regeneration. Analysis of the data for all the 14 reaches of the Indus River System which were studied gave the same relationships. These results agree with the formula for True Gains which includes the factors $f(\Sigma Q)$, the cumulative antecedent flows recharging the bank storage, and $f(Q^n)$, the river stage in the concurrent period which influences the extent of discharge (regeneration from the bank storage.

In order to determine the influence of the ground water in the doabs on the regeneration, an extensive study of the conditions in Rechna Doab (land between Chenab and Ravi rivers) was carried out. Since the advent of irrigation the ground water levels in the Rechna Doab have risen progressively (see Fig. 2) and at present the water table at many places is within a few feet from the ground surface. Theoretically, with the rise in the water table, the gradients towards the river should also increase, which should result in a progressive increase in the magnitude of regeneration. That is, the annual regeneration in the rivers should also increase progressively with the rise in the ground water table. The historical regeneration in the reaches Khanki—Trimmu and Rasul-Trimmu is plotted in Fig. 3. For each reach the total regeneration in the low flow period as well as the regeneration in the month of November is shown. The latter was included as during this month the rainfall is negligible and almost the whole of regeneration consists of seepage from bank storage. The study showed that the magnitude of regeneration varied considerably from year to year and there was no relation between the progressive rise in the doab ground water shown in Fig. 2, and the annual regeneration in the rivers (Fig. 3). A study of the regeneration data of the Ravi River also led to the same conclusion.

Ground water contour plans of Rechna Doab were prepared for the years 1882, 1920 and 1950 to study the behaviour of the ground water. The contour plan for 1882 (pre-irrigation) indicated a high ground water ridge along the rivers, particularly in the lower reaches, with deep depressions in the centre of the doab indicating river contribution to the doab ground water. The plans for 1920 and 1950 showed a similar picture except that the depressions in the doab were largely filled up. The general flow of the ground water was in a south-westerly direction parallel to the rivers with higher levels along the rivers which again indicated that the rivers were not acting as drainage outlets.

In a second study ground water contour plans for Chaj, Rechna and Bari Doabs for the years 1925, 1935 and 1945 were prepared. This study led to the same conclusions that the rivers were not acting as drains. The general direction of flow was towards that Arabian Sea on one side and to the deep ground water depressions in Rajastan and Bahawalpur deserts with humps along the rivers. A separate study for the lower reaches of the Indus River in Sind was carried out. The ground water contours in this region sloped away from the river on both sides with a aigh ridge along the river. Ground water plan for the entire Indus Basin was prepared for the year 1945 and this study also led to the same conclusions.

These resulls agreed with the previous observations of foreign experts who investigated the ground water problem. Mr. Maierhofer, Chief of the Ground Water Division, U.S. Bureau of Reclamation writes[4] :—

> "As is common in broad, flat valleys, natural surface and subsurface drainage is very poor. The topography is such that ponded waters from monsoon storms and canal losses and surface wastes cannot readily move off the lands into the streams, and the streams channels are generally aggraded to the extent that only comparatively small differences in elevation exist between the water surface in the streams and the land surface. Likewise, appreciable lateral movement of subsurface water out of the area does not occur because where the underlying coarser strata have good capacity to transmit ground water and thus to furnish adequate under-drainage, they do not have outlets or sufficiently steep gradients into deep cut open channels. As a result, the basin has gradually filled until ground waters are much nearer the suaface than they were prior to Irrigation. These factors have contributed greatly to the salinization and waterlogging of the lands."

A comparative study of river reaches with almost equal lengths, but having different magnitudes of flows, was carried out. The groups of reaches compared were Khanki-Trimmu (180 miles) and Trimmu-Punjnad (189 miles) Balloki-Sidhnai (240 miles), Sukkur-Kotri (298 miles) etc. The comparative studies showed that in reaches where the magnitude of river flows during the flood months was higher, the regeneration in the following low flow period was also greater and vice versa, snd this relation was not affected whether the reach was passing through highly developed irrigated areas or not.

The above studies led to the following conclusions :—

(i) River flows are the main source of recharge to the bank storage.

(ii) There is definite relationship between the magnitude of river flows and the magnitude of regeneration.

(iii) Irrigation developments which caused an increase in the ground water table did not show any practical effect on the regeneration in the rivers.

Valley Storage

River channels are commonly characterized by alternations of pools and rapids, narrows and inter vales, which in aggregate have much the same alternating effect as reservoir storage. In alluvial rivers, like the Indus System, with wide and shallow valleys, the volume of water stored in the channels during high river stage is very substantial. In the whole Indus River System the volume of water stored in the channels per foot depth above the full berm level was estimated as 8.2 MAF.([5]) Historically the gains on the Westean Rivers during the Kharif period average to about 15 MAF. These gains are mainly from channels storage and occur mostly in the falling hydrograph periods of August to October.

In order to measure the effect of valley storage under various conditions of river flows, it was necessary to determine the storage capacities of the rivers in the various reaches and to establish a relation between the drop in the river stage and the volume of water released from storage. Flood Routing methods provide an adequate procedure for measuring the effect of valley storage on the river flows. The Stage-Storage Method of flood routing was found to be the simplest and most appropriate for this problem. The basic equation ([6]) is

$$\bar{O} = \bar{I} \pm \frac{\Delta S}{\Delta T} \quad \ldots \quad \ldots \quad \ldots(5)$$

in which $\bar{O}$ = Mean outflow during routing period ΔT,

$\bar{I}$ = Mean inflow during routing period ΔT,

ΔS = Net increase or decrease in storage during the routing period ΔT.

The above equation involves the assumption that there are no losses or gains in the reach other than those due to channel storage. In alluvial rivers, the true losses (Lt) and the gains from Bank Storage (Gg) are important factors. Incorrporating these factors and considering the recession part of the hydrograph, the modified equation would be

$$\bar{O} = \bar{I} + Gg - Lt \pm \frac{\Delta S}{\Delta T} \quad \ldots \quad \ldots(6)$$

$$\text{i.e. } \frac{\Delta S}{\Delta T} = \bar{O} - \bar{I} - Gg - Lt\ldots \quad \ldots \quad \ldots(7)$$

The rainfall and unmeasured flows within the river reach also affect the above equation but for want of basic data and because they are relatively small, they are neglected.

Now $\bar{O} - \bar{I} = G_A$ the apparent gain

$$\text{Therefore } \frac{\Delta S}{\Delta T} = G_A - Gg + Lt \ldots \qquad \ldots \qquad \ldots(8)$$

G_A is known from the records.

Gg and Lt can be estimated from the historical data.

Twenty years data of river flow, (Q), the apparent gains (G_A) the estimated true loss (Lt) and the gains from bank storage (Gg) during the falling hydrograph period were tabulated for each reach by 10-day periods (ΔT) and the values of ΔS worked out from the above equation. The cumulative value of ΔS from the lowest stage represented the volume of water in the channel storage corresponding to the river stage (Q). Stage-Storage curves were separately drawn for each reach. A typical curve is shown in Fig. 4. For any given drop in river stage from Q_1 to Q_2, the difference in the storage values S_1 and S_2 read from the curve represents the approximate volume of water released from channel storage. Historically the greater the drop in river stage during a specified period, the greater were the gains from valley storage.

Development of the Hypothesis

Based on the detailed analysis of the various elements involved in the problem, a theoretical discussion of their functions and their consistency with the actual experience of the rivers, certain Basic Principles relating to the phenomena of losses and gains in the Indus River System have been formulated and are summarized below :—

1. In a river flowing through alluvial plains there is always some True Loss and always some True Gain taking place simultaneously in a reach at all times.
2. Generally the True Losses due to absorption, evaporation and the consumptive use of vegetation, increase or decrease with the concurrent flows but not in direct proportion.
3. The losses due to the Valley Storage depend upon both the concurrent flows as well as the antecedent flows.
4. Historically the day-to-day or the 10-daily Apparent Losses do not show a definite pattern of variation with the concurrent flows. The range of percentage variation is within wide limits and sometimes the apparent los-

ses show a decrease with the increase in the concurrent flows.

5. Historically the cumulative apparent losses in a river reach increase with increase in the river flows and diminish when the river flows are reduced but not in direct proportion.

6. The historical apparent losses are a function of the concurrent and antecedent flows.

7. In the hydrologic cycle in the Indus Basin there is a close interrelationship between river flows and the gains. The banks and bed of the wide and shallow alluvial river channels form a temporary detention reservoir which is filled during high flows and depleted during low river stages. This natural reservoir forms the major source of gains in the river.

8. If the falling hydrograph of a river is changed, then both the magnitude of the historical releases from Valley and Ground Water Storages, as well as their timing, would change.

9. Not all the losses due to absorption and valley storage are real or permanent losses since a part of these losses would appear back in the rivers as gains in the subsequent period. Water that is not really lost cannot result in True Salvage.

10. The loss potential and the gain potential of a river are interrelated. The loss potential will be maximum at a time when the gain potential is minimum and vice versa. It also follows that when the loss potential is increasing, the gain potential is decreasing and vice versa.

11. The loss potential of a river decreases and the gain potential increases with the increase in antecedent flows and vice versa.

12. The gains increase with increase in antecedent flows and decrease if the antecedent flows are reduced.

13. If in a river reach the high flows are kept the same as historic and if the concurrent flows in the low flow period are reduced, the gains would increase with consequent increase in losses in the rising flow period.

14. Other factors remaining the same, the gains in the low flow period decrease with the length of time from the high flow period.

The above Principles lead to the setting up of the following hypothesis as to the important elements which are involved and of the ways in which they are related :—

(i) Losses increase with increase in concurrent flows and decrease when the concurrent flows are reduced.

(ii) Losses decrease with increase in antecedent flows and increase if the antecedent flows are reduced.

(iii) Gains decrease with increase in concurrent flows and increase if the concurrent flows are reduced.

(iv) Gains increase with increase in antecedent flows and decrease if the antecedent flows are reduced.

(v) The gains in the falling hydrograph periods increase with the increase in drop in the river stage and decrease if the drop in river stage is reduced.

(vi) Gains in the low flow period decrease with increase in time lapsed since the previous high flows.

Division of Hydrograph

In order to establish the facts of the relationships as set forth in the hypothesis, the various factors affecting losses and gains have to be measured according to some unit of time which can either be a day, a 10-day period, a month or a longer period. On account of the complex nature of the varying causal factors, a 10-day period is too short to eliminate the overlapping influences of the unimportant factors which obscure the true relationships of the dominant causal factors. Studies indicated that if the effect of the causal factors on the losses and gains is considered over a sufficiently long period, depending upon the hydrograph characteristics and the other dominant hydrological factors in that period, then the wide range of variation which masked the true relationships can be isolated and a more complete understanding of the cause and effecs relationship in the period as a whole would be possible. After a detailed study of the data of individual river reaches, the flow hydrographs have been divided into the following periods :—

Rising Period I	—April to 10th June
Rising Period II	—11th June to 31st July
Falling Period I	—1st August to 10th September
Falling Period II	—11th September to 10th October
Low Flow Peried	—11th October to 31st March

The above are the general periods for the eleven reaches on the Western Rivers. The actual periods for individual reaches, however, vary slightly depending upon their peculiar characteristics. This method of division of hydrograph is in accordance with the method adopted by the Upper Colorado River Basin Compact Commission[7] for the study of channel losses in the Upper Colorado River System. The hydrograph periods selected for the Colorado River, Green River and San Juan River compare with the Indus periods as follows :—

(1) "Losses—rising river, dry channel" corresponding to Rising Period I for the Indus System.

(2) "Losses - rising river, wetted channel (considered wet if stage upto or higher within 30 days)"—corresponding to Rising Period II for the Indus System.

(3) "Losses minus Bank and Channel Storage-diminishing flows" — corresponding to Falling Period I for the Indus System.

(4) "Bank and Channel Storage minus Losses-diminishing flows" —corresponding to Falling Period II for the Indus System.

(5) "Losses—uniform discharge (fluctuation no greater than 300 second-feet)"—corresponding to the Low Flow Period for the Indus System.

Basis for Measuring the Various Factors

There can be different criteria for measuring the effect of the various factors. For instance, the effect of Concurrent Flows on losses can be measured by the volume of flows, the magintude of individual peaks within the period and by the magnitude of rise and fall in river stage. To include all these elements as an index of the effect of Concurrent Flows during the period would involve complicated calculations. By and large, the volume of concurrent flows is a good index of its effect on losses. Similarly, the effect of antecedent flows can be measured by the volume of those flows. The influence of Valley Storage on gains will be most pronounced in the Falling Periods I and II when the river drops rapidly and the accumulated Bank and Valley Storages in the river, particularly the latter, are released rapidly. The effect of Valley Storage is measured by the Stage-Storage Method for Flood Routing as discussed before. The effect of the time lapsed since the previous high flows, which will be significant on the gains in the low flow period is measured in terms of the number of days from the center of gravity of the high flow mass to a fixed reference date of the Low flow period.

Correlation Analysis.

As the factors involved in the problem are many, the relationships have been determined by the Method of Multiple Correlation. For problems of this nature, the Method of Multiple Linear Correlation provides a simple, practical and usefuld tool in the analysis of hydrogical data and has, therefore, been adopted. The multiple linear regression is of the following form ;—

$$Y = a + b_2x_2 + b_3x_3 + \text{---} + b_nx_n \qquad (9)$$

in which

Y is the dependent variable (loss or gain),

X_2, X_3, X_n are several independent variables (causal factors),

a = constant term of the regression equation,

b_2, b_3 --- b_n are the several regression coefficients.

Upon determination of the values of these respective multiple regression coefficients (b's) and of the constant (a), a value for Y may be computed from the above equation for any set of values of the independent variables. The analysis is based on the promise that the correct values of the constants are those which yield estimates of Y, the dependent variable, which are in closest agreement with the observed values for a period of record. With this minimum deviation between etsimated and observed values as a criterion, the values of the constants may be determined mathematically by the method of least squares. This procedure has been followed in the correlation analysis. Graphs have also been drawn giving the relation between the various factors.

The independent variables (X factors) considered in the anaysis are the Concurrent Flows, the Antecedent Flows, Valley Storage and the Time lapsed since previous high flows. In the analysis of some reaches the data on precipitation was also included. The correlation analysis was carried out for all the eleven reaches on the Western Rivers—Indus, Jhelum and Chenab—and for three reaches on the Eastern Rivers—Ravi and Sutlej. Historical data for 20 years (1926-27 to 1945-46) was used in the analysis of all the reaches except the Sukkur-Kotri reach in which 14 years data (1932-33 to 1945-46) since the construction of the Sukkur Barrage has been used. Separate equations were developed for each reach and for each hydrograph period. The equations obtained for the Sukkur-Kotri reach on the Indus Main are given in Appendix III as illustrations. Graphs for the same reach shown in Figs. 5 and 6. Similar relationships have been obtained for all the reaches on the system.

The analysis has shown that

(a) Concurrent and antecedent flows are important factors contributing to losses and gains ;

(b) Gains in the falling period are also affected by the amount of releases from the valley storage ;

(c) Gains in the low flow period are also influenced by the time lapsed since the previous high flows.

These results are in agreement with the theory and confirm the validity of the hypothesis.

Significance of the Relationships

Statistical measures such as the coefficient of correlation, standard error of estimate, etc., are available for determining the significance of the relationships and for judging the confidence that can be placed in an individual estimate or forecast obtained from the formulæ. These methods apply only when the correlations are determined from samples which have a normal distribution. Analysis of the data shows that the coefficient of Skew, which is a test of normality, is as high as 6.6. For a coefficient of Skew as large as one, statistical measures of reliability have a less precise meaning but may still be valuable as a caution on the use of results, particularly if these are the only measures to judge from. The coefficient of correlation (R) and the standard error of Estimate ($\overline{S}$) for the relationships are listed in Appendix IV. In the 53 correlation equations, the "R" values are over 0·5 in 76% of the relationships and in some cases they are as high as 0.82. The "R" values are less than 0.4 only in 8% of the cases. As a rough approximation an "R" value of 0.6 may be considered as significant for 20 to 1 odds and a value of 0.4 for 10 or 12 to 1 odds. These coefficients could, no doubt, be improved by the inclusion of other relevant factors such as precipitation, temperature, unmeasured flows, etc., in the analysis.

The Standard Error of Estimates obtained for the relationships (Vide Appendix IV) also indicated significance. Furthermore, significance was indicated for individual factors, i.e., concurrent flows, antecedent flows, etc., by standard errors of the coefficients of Partial Regression. The tests also showed the absence of inter-correlation between the independent variables.

Practical Procedure in Judging the Reliablity of Estimates

The above mathematical procedures for judging the confidence that can be placed in an individual estimate are based solely on the information given by the individual sample from which the estimating (regression) formula was derived. Where only one set of sample data is available, the statistical measures discussed above are the only means to judge the reliability of the relationships. On the other hand, if a series of samples, each one throwing light on a different aspect of the same pheonomena, are available and if the results of the several different approaches are all consistent with one another, the whole set together will provide a more dependable basis for the confidence that can be placed in the significance of the relationships and reliability of the estimates than the correlation coefficients or the calculated standard errors for any one sample separately.(8)

In the present problem, fortunately, several independent reaches are involved and in each reach the relationships between losses and gains and river flows and other factors have been determined. All the

53 formulæ for losses and gains for the eleven reaches on the Western Rivers-Indus, Jhelum and Chenab-give the same consistent relationships between losses and gains and the rive flows. Analysis of data of three reaches on the Ravi and Sutlej rivers has also led to the same results. The consistency of the relationships in all the hydrograph periods and in all the reaches included in the analysis provides a more reliable measure of their significance than is indicated solely by the mathmatical procedures.

Comparison of Estimated and Actual Values

In problems involving time series, testing the actual forecasting efficiency of the regression equation by studying the results of its application in other years not included in the analysis, is a standard technique. The regression equations obtained are based on the historical data for the 20-year period, 1926-45. Similar basic data exists for 11 years (1921-25 and 1946-51) which have not been used in the analysis. The formulæ when applied to these 11 years gave results in close agreement with the actuals in most cases.

A comparison of the estimated values of losses and gains with the actual values in all the 31 years of available data was also carried out. In all 156 comparisons were made considering all the hydrograph periods and reaches. This study led to the following results :—

(1) In about 75 percent of the cases, the estimated values of losses and gains agreed closely with the actual historical values.

(2) In the remaining 25 percent of the cases, a detailed study of some of the years revealed that the departure between the estimated and the actual values was due to an extraordinary value of loss or gain in one of the reaches which was completely out of line with what happened in the rest of the years. Such years were generally years of exceptionally high floods or exceptionally high or low rainfall.

Considering the number and complexity of the variable factors involved in the problem and the extreme range of variation of the historical values of losses and gains, the degree of agreement between the estimated and historical values is satisfactory and indicates the importance of the causal factors considered in the correlation analysis.

Adequacy of the Formulae for the Water Studies

The water studies for new irrigation projects are based on the historical data of river flows which is projected in the future years with the assumed changes introduced by the new project. The problem in such studies is to estimate the change in the known historical values of loss or gain for given changes in the historical flows. In such cases the formulae would give relatively more accurate results as they measure the relationships between losses and gains and those very factors which would change in the water studies. Any error due to the varying effects of the other factors, such as rainfall, unmeasured flows, etc., which were not separately measured by the formulæ would be eliminated as the water studies assume no change in these factors.

Adequacy of the Formulæ for Forecasting

In preparing river development plans it is often necessary to estimate the most probable value of the losses and gains under the new conditions of flow in the future. In series involving time relations, this becomes the problem of forecasting. As long as the new values of the independent variables are within the observed range of the original sample used in the development of the formulæ, the maximum error in theforecast will not be greater than the calculated standard error of estimate for each fomula. The standard error of estimate could be improved if other relevant factors such as rainfall, temperature, unmeasured flows, etc., are also included in the analysis. The present formulæ, however, take into account only the mean cumulative effect of these factors over the study period and to the extent their actual value in any year in the future differs from the mean value, the forecast would differ from the actual values of losses and gains.

Application of the Formulæ to Extrapolation Beyound the Observed Range

The formulæ give the relationships between the dependent and independent variables which are determined from a given sample of the observed or historical values of the variables. In practice it is sometimes necessary to make estimates of the dependent variable for new observations of the independent variables which lie beyond the range included in the original sample. Any forecast is hazardous, for the future can never be perfectly known. As far as possible estimates beyond the observed range should not be made as they would be subject to an extra degree of error, beyond that given by the calculated standard error. Yet life always consists in making plans for future and sometimes the success or failure of such plans depends in large measure upon the accuracy of those estimates.(8)

When extrapolations beyond the observed range have to be done, estimates based on the analysis of the past relations will provide a surer guide than estimates based on hunches, waves of opinion or blind guess-work. Such forecasts should always be aided by judgment based on other information on the phenomena. The more the technical operations on the statistical side can be reinforced by the knowledge, theories, experience and judgment, the more valuable will be the estimates based on informed and useful projection from the events of the past into the stillmalleable future.(8)

Comparison of Results of the Formulae with the Proportional method

The adequacy of any method can be judged from the degree of agreement between its estimated values and the actual observed values. For comparing the relative accuracy of formulae and the Proportional Method, river flow data for two years (1942-43 and 1940-41) with a wide range in magnitude of flows, was selected. Of these two years, 1942-43 was a very wet year with a total inflow of 191 MAF at the rim stations, while 1940-41 was one of the driest years with a total inflow of only 149 MAF. Assuming that the river flows for 1942-43 in the various reaches of the river system were reduced to the 1940-41 values, the losses and gains for 1940-41 were estimated from the formulae as well as from the Proportional Method. The formulae were also used to forecast the 1940-41 losses and gains directly from the river flows of that year. A comparison of the estimates of losses during the early Kharif period with the actual figures for 1940-41 is given in Appendix V. The results are summarized below :—

(i) Contrary to the popular view that with reduced flows the losses would also decrease, the losses in 1940-41 were twice as high as those in 1942-43 in spite of reduced flows. The estimates based on the formulae also gave the same results. The results from the Proportional Method, on the other hand, were in the opposite direction.

(ii) The total losses estimated from the formulae based on changes in flows and actual flows were 8.45 and 8.37 MAF respectively, as against the actual loss of 8.30 MAF. The Proportional Method, on the other hand, gave a value of 2.11 MAF only.

(iii) A comparison of the estimates for individual reaches also shows that the formulae gave results in close agreement with the actual values in most of the reaches.

A similar study was carried out for estimating the gains in the Rabi period and the results are given below :—

Actual Gains 1942-43	1.88 MAF
Actual Gains 1940-41	2.77 MAF
Estimated Gains 1940-41	
(a) From the Formulae	
(i) Forecast	2·35 MAF
(ii) From Changes in Flows	3·00 MAF
(b) By the Proportional Method	3·42 MAF

These results also indicate that the formulae give more accurate results.

Conclusions

Analysis of the phenomena of losses and gains has shown that both concurrent and antecedent flows are important factors contributing to losses and gains and that gains are also affected by the magnitude of releases from the valley storage and by the time lapsed since previous high flows. By correlation analysis the facts of the relationships between losses and gains and the above causal factors have been established. Statistical tests, comparison of estimated and actual values and the consistency of the relationships in all the reaches included in the analysis indicated that the formulae are adequate as estimating equations for past years or as forecasting equations for future years.

Acknowledgements

The writer wishes to express his gratitude to Messers. M.A. Hamid, S.I. Mahbub and Dr. M.S. Quraishy, Chief Engineers, for their encouragement and guidance. Mr. P.M. Ford of the Bureau of Reclsmation made valuable contribution on the Correlation Analysis and the development of the formulae and his help is gratefully acknowledged. At various stages of the analysis of the problem Messrs. R.J. Tipton and Olin Kalmbach, Consulting Engineers, Messrs. Dr. Herbert S. Reisbol, Gordon K. Ebersole and Victor A. Koelzer of the Bureau of Reclamation, and Mr. Franklin F. Snyder of the Corps of Engineers were consulted and the writer is grateful for their help and suggestions. The problem was discussed at great length with Messrs. John Drisko, B. Russler and E. Roland of Tippets-Abbott-McCarthy-Stratton, Consulting Engineers, and their suggestions proved very valuable in the solution of this problem. The writer also wishes to express his deep appreciation of the valuable contribution of Mr. Sa'adat M. Ali, Executive Engineer.

RELATION BETWEEN CONCURRENT FLOWS AND LOSSES

Appendix I

YEAR 1944-1945

(All figures in cusec-days)

Marala-Khanki				Khanki-Trimmu			
Period	Q	L	%	Period	Q	L	%
7/4—16/4	6,710	+1,337	+20	8/4—17/4	3,234	+1,012	+31
17/4—28/4	16,058	+1,502	+9	18/4—29/4	11,136	+ 3,116	— 28
2914— 9/5	17,868	+1,015	+6	30/4—10/5	11,158	+2,555	— 23
10/5—20/5	32,098	—4,343	— 14	11/5—21/5	23,019	—7,956	— 35
21/5—30/5	17,675	+ 323	+2	22/5—31/5	12,634	—621	— 5
31/5— 9/6	17,441	+ 454	+3	1/6—10/6	6,689	—531	— 8
10/6—19/6	1 9,934	—294	—1	11/6—20/6	8,997	—992	—11
20/6— 1/7	19,228	+680	+4	21/6—2/7	8,106	—550	— 7
2/7—11/7	26,134	— 91	—	3/7—12/7	14,013	—1,782	— 13
12/7—22/7	49,348	— 4,091	—8	13/7—23/7	33,005	—1,910	— 6
23/7— 1/8	77,955	—24,393	— 31	24/7—2/8	62,528	+3,784	+ 6
2/8—11/8	86,182	—13,344	— 15	3/8—12/8	64,728	+6,528	+ 10
12/8—22/8	108,455	— 417	—	13/8—23/8	88,623	+ 19,682	+ 22
23/8—31/8	105,346	—6,624	—6	24/8—1/9	87,784	+11,594	+ 13

STUDY OF PERCENTAGE VARIATIONS OF LOSSES AND THE FLOWS **Appendix II**

YEAR 1944-1945

Marala-Khanki			Khanki-Trimmu		
Period	$\frac{\Delta Q}{Q}$ (%)	$\frac{\Delta L}{L}$ (%)	Period	$\frac{\Delta Q}{Q}$ (%)	$\frac{\Delta L}{L}$ (%)
7/4 — 16/4			8/4 — 17/4		
17/4 — 28/4	+139·14	— 12·34	18/4 — 29/4	+244·34	+407·91
29/4 — 9/5	+11·27	+32·42	30/4 — 10/5	+0·20	— 182·00
10/5 — 20/5	+79·64	+527·88	11/5 — 21/5	+106·30	+411·39
21/5 — 30/5	— 44·93	— 107·44	22/5 — 31/5	— 45·11	— 92·19
31/5 — 9/6	— 1·32	— 40·56	1/6 — 10/6	— 47·06	— 14·49
10/6 — 19/6	+14·29	+319·66	11/6 — 20/6	+34·50	+86·82
20/6 — 1/7	— 3·54	— 331·29	21/6 — 2/7	— 9·90	— 44·56
2/7 — 11/7	+35·92	+113·38	3/7 — 12/7	+72·87	+224·00
12/7 — 22/7	+88·83	+4,395·60	13/7 — 23/7	+135·53	+7·18
23/7 — 1/8	+57·97	+496·26	24/7 — 2/8	+89·45	— 298·12
2/8 — 11/8	+10·55	— 45·30	3/8 — 12/8	+3·52	— 72·52

NOTE :— Positive sign means increase.
Negative sign means decrease.

Appendix III

FORMULAE FOR LOSSES AND GAINS

SUKKUR-KOTRI REACH

1. Rising Period I (April-May)

   $L = 1858{\cdot}60 + 0{\cdot}2723\,(F_5 + F_6) - 1{\cdot}0365\,(F_3 + F_4) - 1{\cdot}8429\,(F_1 + F_2)$

   L = Losses (1,000 A.F.)

   $F_5 + F_6$ = Concurrent flows (April-May) in 10,000 A.F.

   $F_3 + F_4$ = Antecedent flows (11 Nov.-March) in 10,000 A.F.

   $F_1 + F_2$ = Antecedent high flows (June-11 Nov.) in 100,000 A.F.

2. Rising Period II (June-July)

   $L = -4{\cdot}0241 + 0{\cdot}2610\,(F_X) - 0{\cdot}1101\,(F_5 + F_6)$

   L = Losses

   F_X = Concurrent flows (June-July)

   $F_5 + F_6$ = Antecedent flows (April-May)

   All units in MAF.

3. Falling Period I (August-10 Sept.)

   $L = -3{\cdot}6070 + 0{\cdot}1678\,(F_Y) - 0{\cdot}5379\,(S_1 - S_2)$

   L = Losses

   F_Y = Concurrent flows (August-10 Sept.)

   $S_1 - S_2$ = Valley Storage releases due to fall in river stage.

   All units in MAF.

4. Falling Period II (11 Sept.-10 Nov.)

   $G = -0{\cdot}8438 - 0{\cdot}0198\,(Fs) + 0{\cdot}3931\,(S_1 - S_2) + 0{\cdot}0153\,(F_Y)$

   G = Gains

   Fs = Concurrent flows (11 Sept.-10 Nov.)

   Fy = Antecedent flows (August-10 Sept.)

   $S_1 - S_2$ = Valley Storage releases due to fall in river stage, All units in MAF.

5. Low Flow Period (11 Nov.-31 March)

$$G = 1344{\cdot}27 - 0{\cdot}7572\,(F_3 + F_4) + 0{\cdot}8955\,(F_1 + F_2) - 12{\cdot}7591\,(Dg)$$

G = Gains in 1,000 A.F.

$F_3 + F_4$ = Concurrent flows (11 Nov.-March) in 10,000 A.F.

$F_1 + F_2$ = Antecedent high flows (May-10 Nov.) in 100,000 A.F.

Dg = Lapse of time in days since previous high flows

Appendix IV

COEFFICIENTS OF MULTIPLE CORRELATION "R" AND STANDARD ERROR OF ESTIMATES $\overline{S}$ FOR THE FORMULAE FOR VARIOUS PERIODS

Reach	Rising Period I		Rising Period II		Falling Period I		Falling Period II		Low Flow Period	
	R	$\overline{S}$	R	$\overline{S}$	R	$\overline{S}$	R	$\overline{S}$	R	$\overline{S}$
1. Kalabagh-Ghazighat.	0·60	1·330	0·65	1·554	0·75	2·740	0·55	0·700	0·55	0·270
2. Ghazighat-Mithankot	0·42	0·727	0·64	1·401	0·54	0·995	0·55	0·553	0·51	0·392
3. Mithankot-Sukkur	0·65	0·680	0·24	2·650	0·61	1·140	0·59	0·535	0·67	0·275
4. Sukkur-Kotri	0·72	0·378	0·82	1·162	0·60	1·790	0·63	0·306	0·76	0·209
5. Mangla-Rasul	0·81	0·366	0·61	0·376	0·46	0·356	0·33	0·074	0·58	0·183
6. Rasul-Trimmu	0·55	0·431	0·52	0·329	0·46	0·433	0·51	0·104	0·54	0·189
7. Marala-Khanki	0·50	0·122	0·66	0·354	0·58	0·407	0·48	0·173	0·71	0·103
8. Khanki-Trimmu	0·68	0·218	0·38	0·407	0·50	1·190	0·75	0·163	0·50	0·165
9. Trimmu-Shershah	0·58	0·287	0·48	0·804	0·76	0·692	0·61	0·179	0·32	0·187
10. Shershah-Panjnad	0·79	0·169	0·41	0·532	0·49	0·807	0·41	0·157	0·44	0·150
11. Panjnad-Mithankot	0·74	0·107	*	*	*	*	0·80	0·435	0·82	0·090

* Formulae for these periods not worked out.

Values of $\overline{S}$ are in M.A.F. units.

Appendix V

COMPARISON OF RESULTS OF THE FORMULAE WITH THE PROPORTIONAL METHOD

Period-Early Kharif (Rising Period I) (Figures in MAF)

Reach (1)	Actual Losses		1940-41 losses forecast from flows using the formulae	1940-41 losses estimated from the changes in river flows from 1942-43 to 1940-41	
	1942-43	1940-41		Formulae	Proportional Mathod
	(1)	(2)	(3)	(4)	(5)
Kalabagh-Ghazighat	— 0·47	— 5·44	— 4·06	— 3·66	— 0·97
Ghazighat-Mithankot	— 0·81	— 0·39	— 0·70	— 1·35	— 1·11
Sukkur-Kotri	— 0·49	— 0·86	— 0·84	— 0·55	+0·56
Mangla-Rasul	— 0·45	— 0·20	— 0·32	— 1·04	+0·44
Rasul-Trimmu	— 0·72	— 0·55	— 0·73	— 0·38	— 0·53
Marala-Khanki	0	— 0·09	— 0·26	— 0·21	+0·04
Khanki-Trimmu	— 0·24	— 0·46	— 0·37	— 0·37	— 0·22
Trimmu-Shershah	— 0·28	— 0·39	— 0·48	— 0·21	+0·36
Shershah-Panjnad	— 0·91	— 0·35	— 0·32	— 0·32(2)	— 0·64
Panjnad-Mithankot	0	— 0·05	— 0·10	— 0·04	0
Shahadra-Balloki	+0·04	— 0·08	— 0·06	— 0·03	+0·04
Ferozepur-Suleimanki	— 0·10	— 0·12	— 0·14	— 0·13	— 0·04
Suleimanki-Islam	— 0·04	— 0·10	— 0·07	— 0·08	— 0·04
Total	— 3·91	— 9·08	— 8·45	— 8·37	— 2·11

(1) Mithankot-Sukkur reach not included as the historic losses both in 1940-41 and 1942-43 for this reach were not considered in the formulæ owing to their extraordinary values. The loss for 1940-41 as per formulæ works out to —1·62 MAF as against the actual gain of +0·64 MAF.

(2) Based on estimated values from flows and not on changes from 1942-43 value as the latter being an unusually high figure was omitted while working out the formula.

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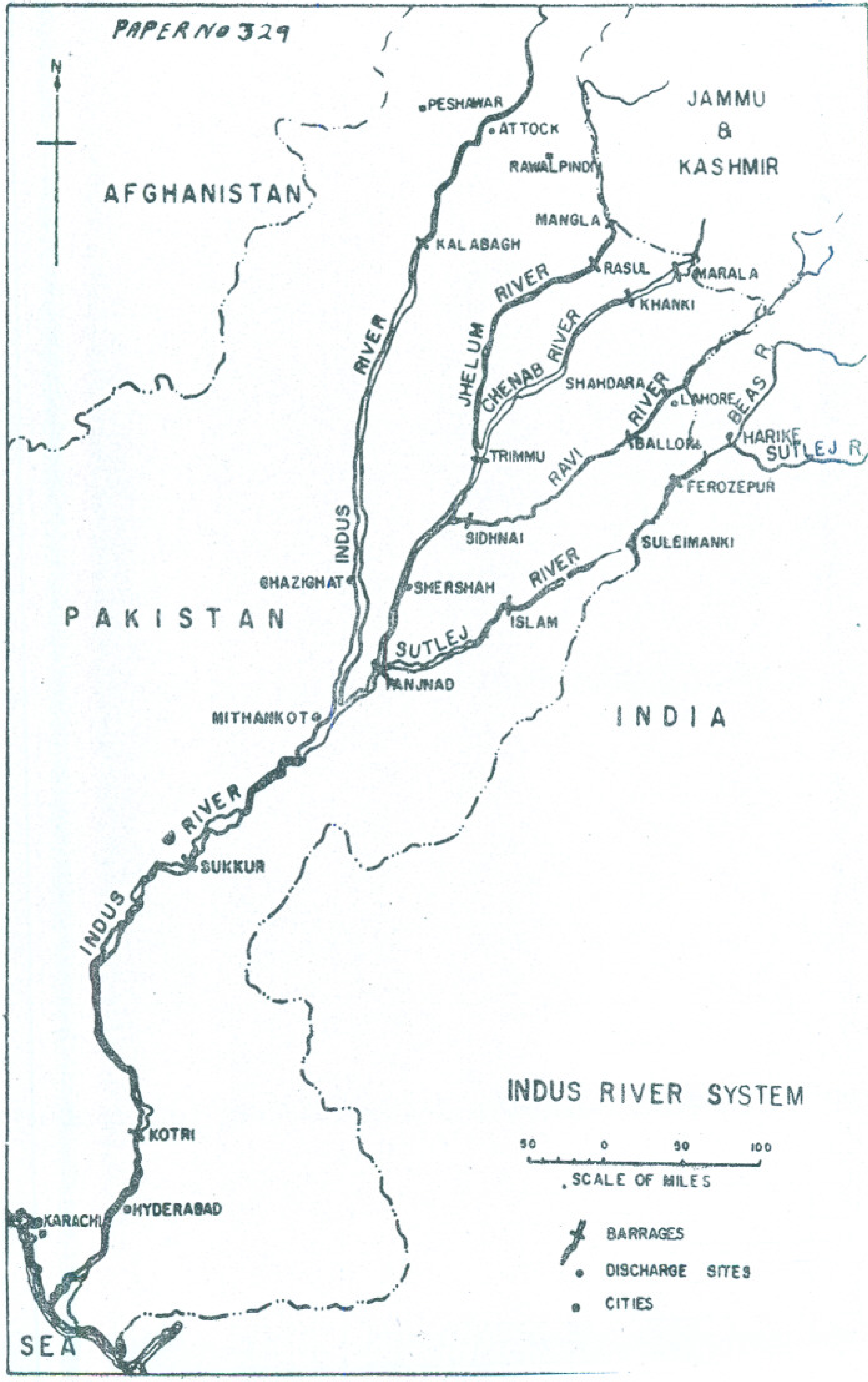
FIG. I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CHENAB RIVER
INDUS RIVER
SHAHDARA
LAHORE
RAVI RIVER
BEAS R
HARIKE
SUTLEJ R
BALLOKI
TRIMMU
FEROZEPUR
SIDHNAI
SULEIMANKI
GHAZIGHAT
SHERSHAH
SUTLEJ RIVER
ISLAM
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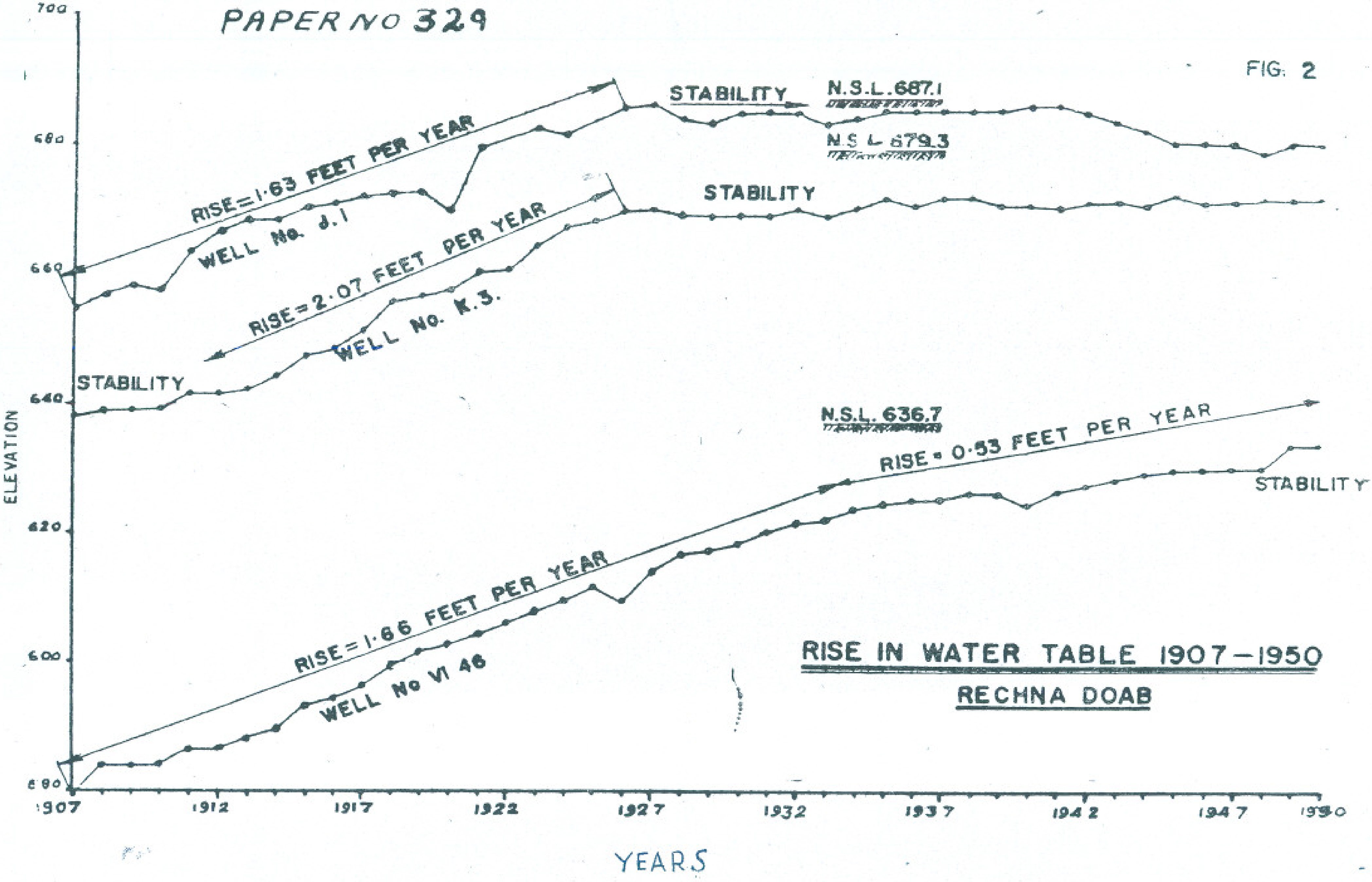
FIG. 2



RISE IN WATER TABLE 1907 – 1950

RECHNA DOAB

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HISTORICAL REGENERATION

FIG: 3

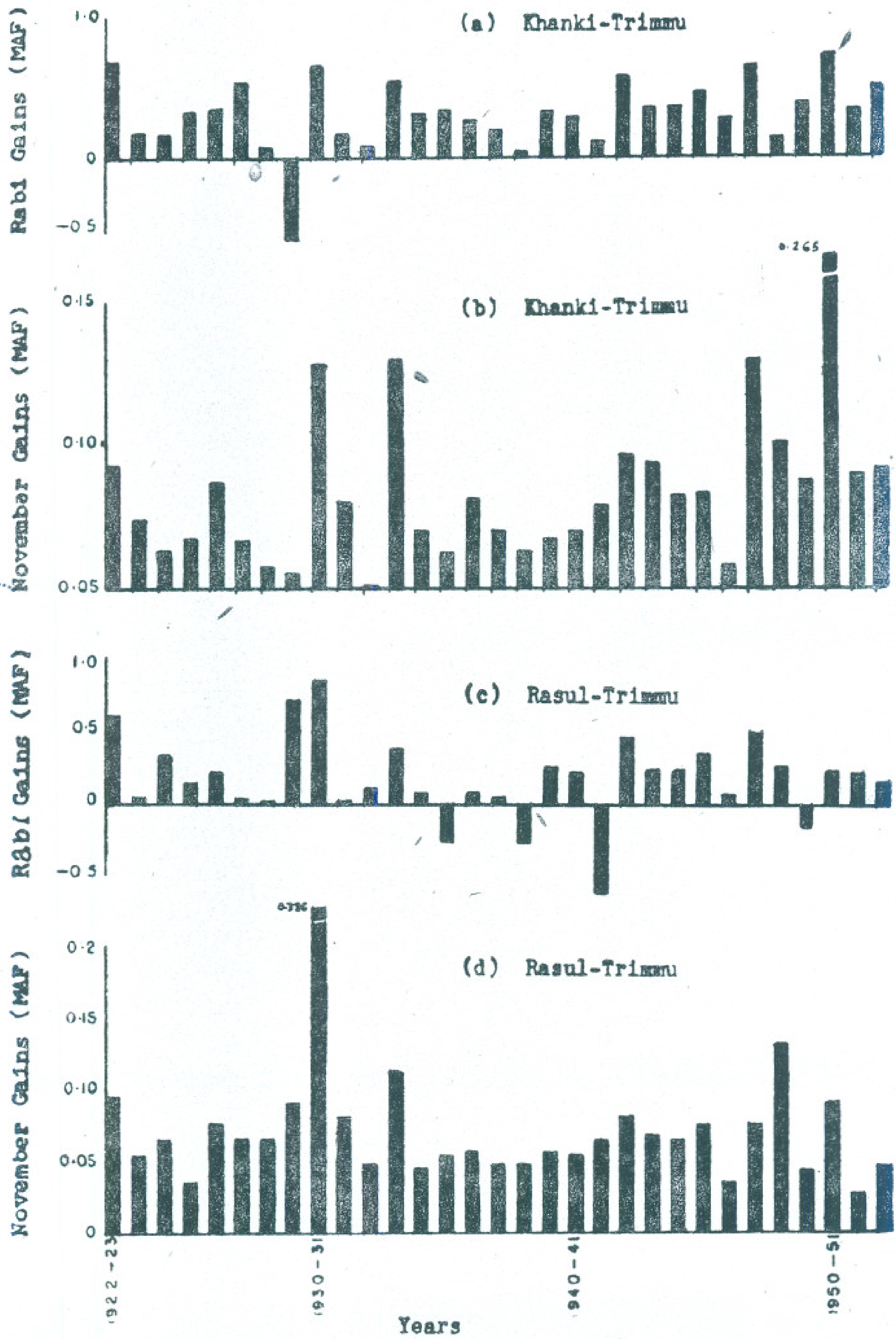

FIG. 4

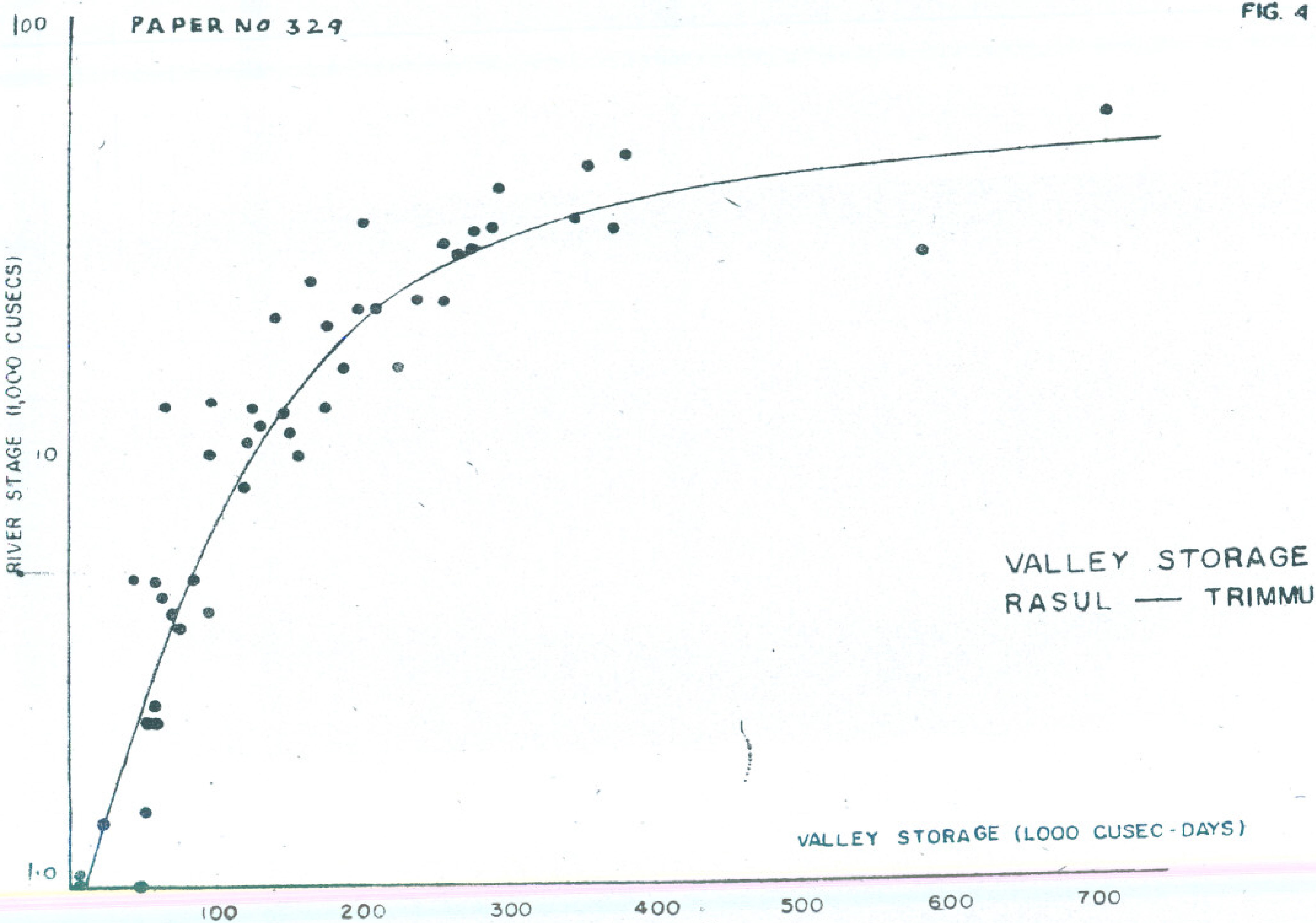
100
10
1.0
RIVER STAGE (1,000 CUSECS)
VALLEY STORAGE (1,000 CUSEC-DAYS)
100
200
300
400
500
600
700
VALLEY STORAGE
RASUL — TRIMMU

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FIG. 5
SHEET 1

RIVER INDUS
SUKKUR-KOTRI
LOSSES 1933-46 INCLUSIVE

$L = 1858.60 + 0.2723(F_5 + F_6) - 1.0365(F_3 + F_4) - 1.8429(F_1 + F_2)$

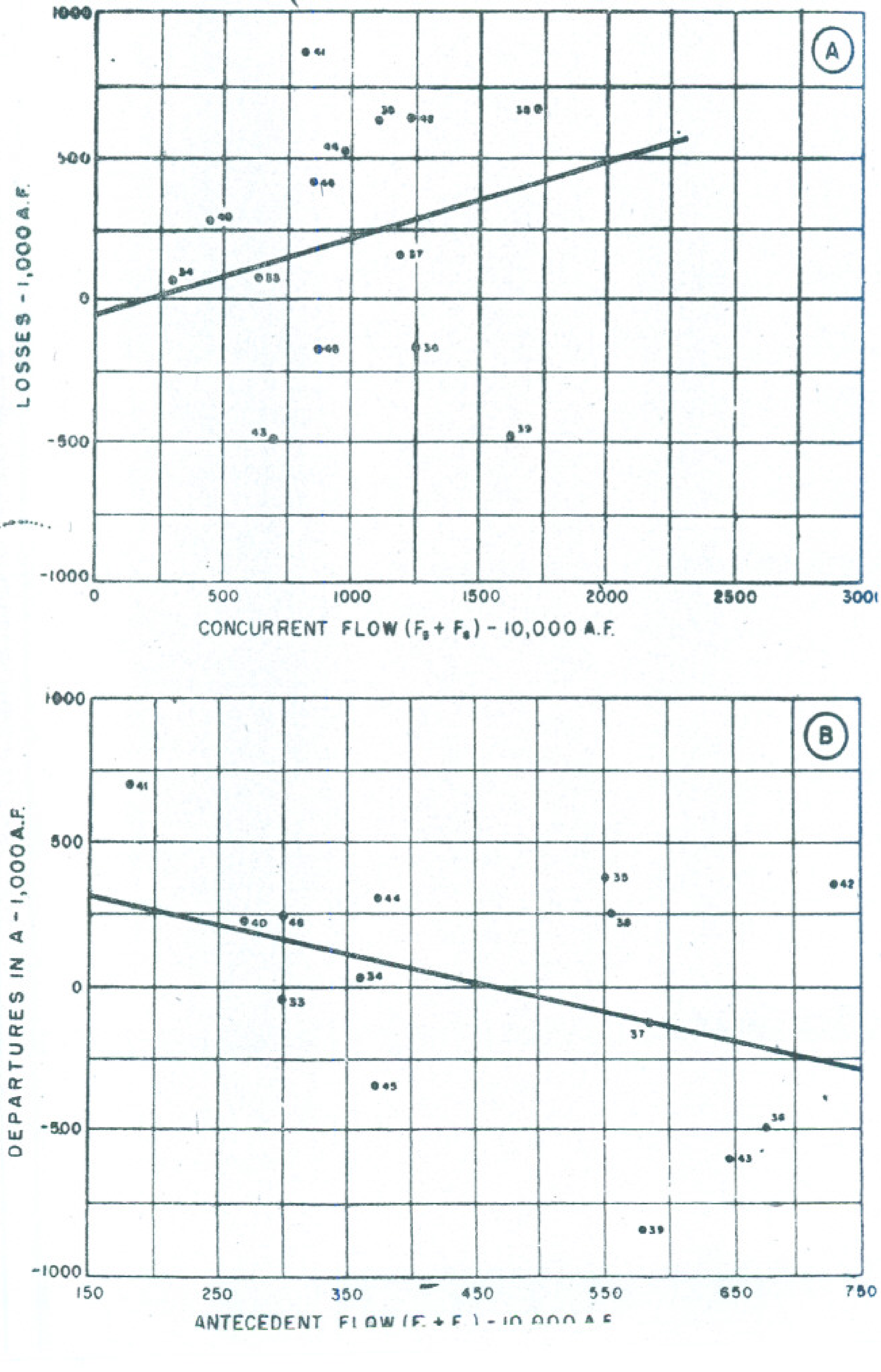


FIG 8
SHEET 2

PAPER NO 329

RIVER INDUS
SUKKUR - KOTRI
LOSSES 1933-46 INCLUSIVE
(CONTINUED)

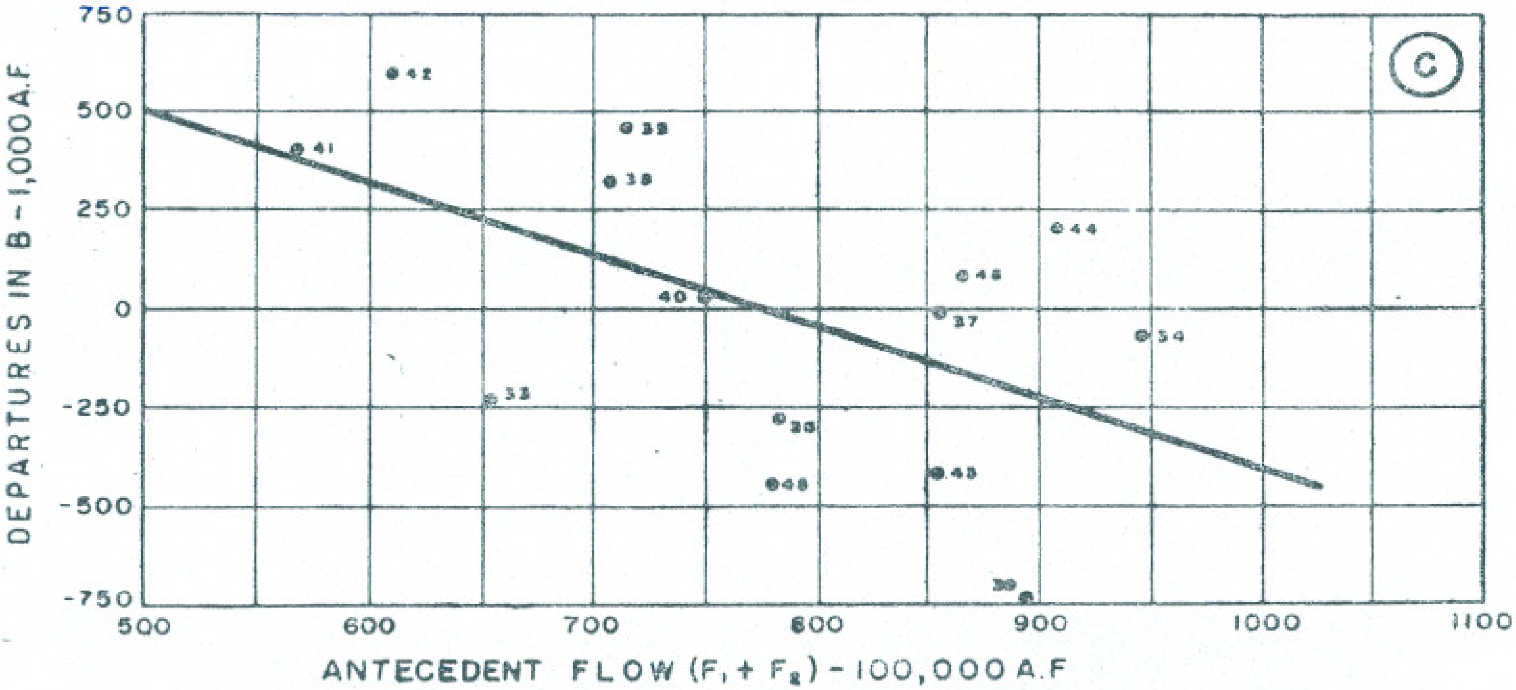
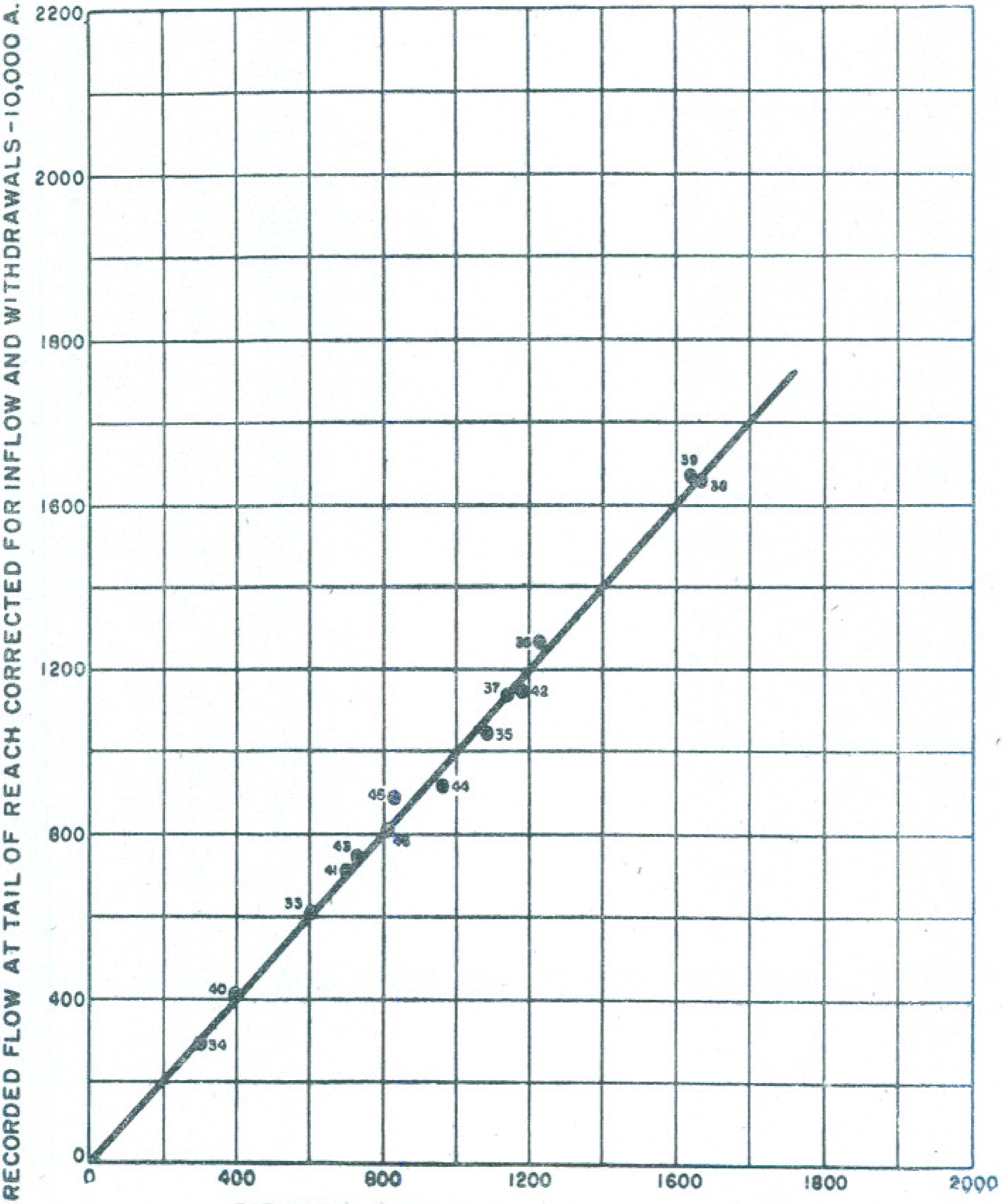


FIG. 5
SHEET 3

PAPER NO 329

RIVER INDUS
SUKKUR-KOTRI
LOSSES 1933-46 INCLUSIVE

$$L = 1858.60 + 0.2723(F_5+F_6) - 1.0365(F_3+F_4) - 1.8429(F_1+F_2)$$



ESTIMATED FLOW AT TAIL OF REACH - 10,000 A.F.
(RECORDED FLOW AT HEAD MINUS ESTIMATED LOSSES)

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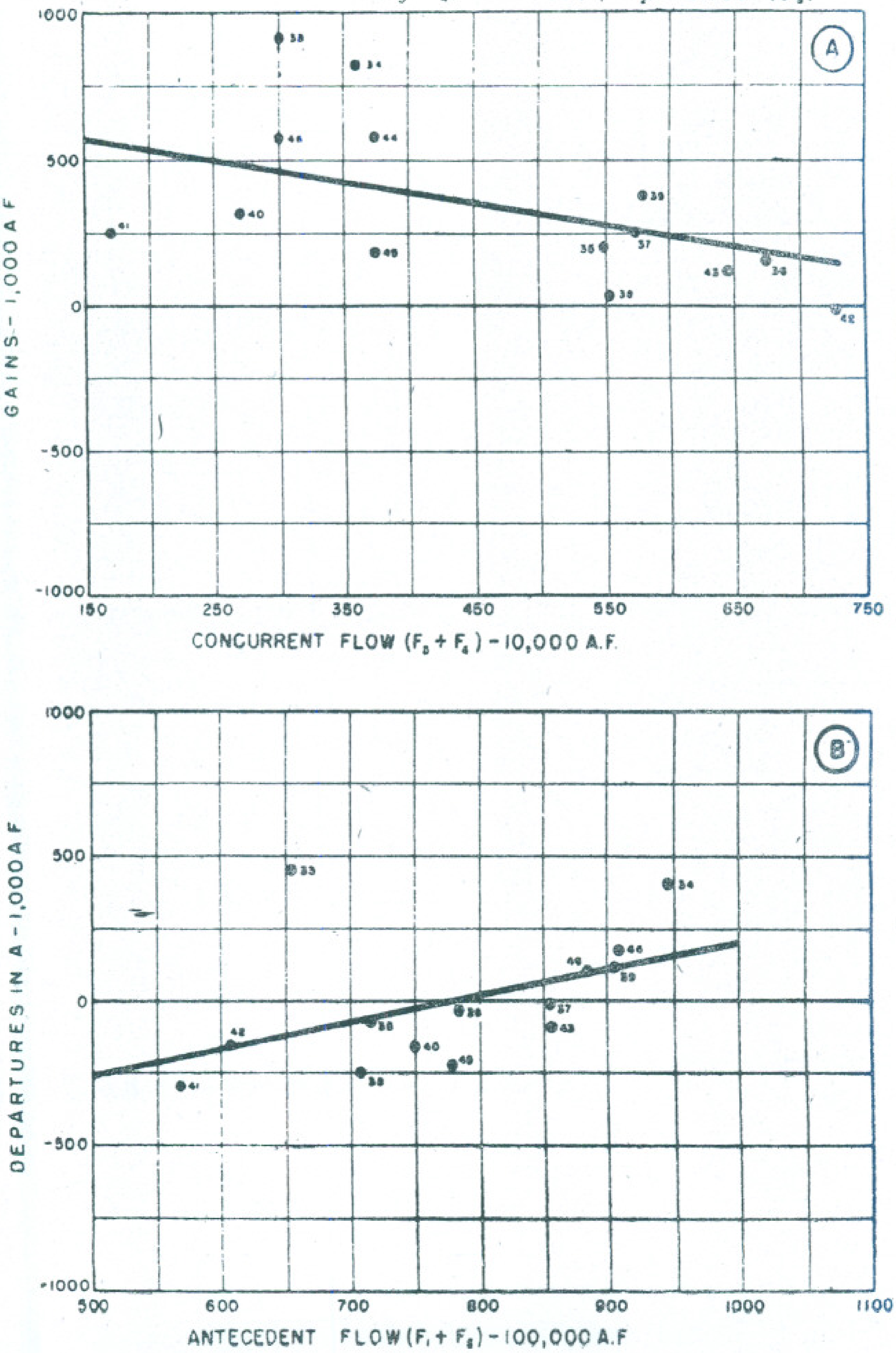
RIVER INDUS
SUKKUR-KOTRI

FIG. 6
SHEET

GAINS 1933-46 INCLUSIVE

$G = 1344.27 - 0.7572\,(F_3 + F_4) + 0.8955\,(F_1 + F_2) - 12.7591\,(Dg)$



PAPER No 329

FIG 6
SHEET 2

RIVER INDUS
SUKKUR - KOTRI
GAINS 1933 - 46 INCLUSIVE
(CONTINUED)

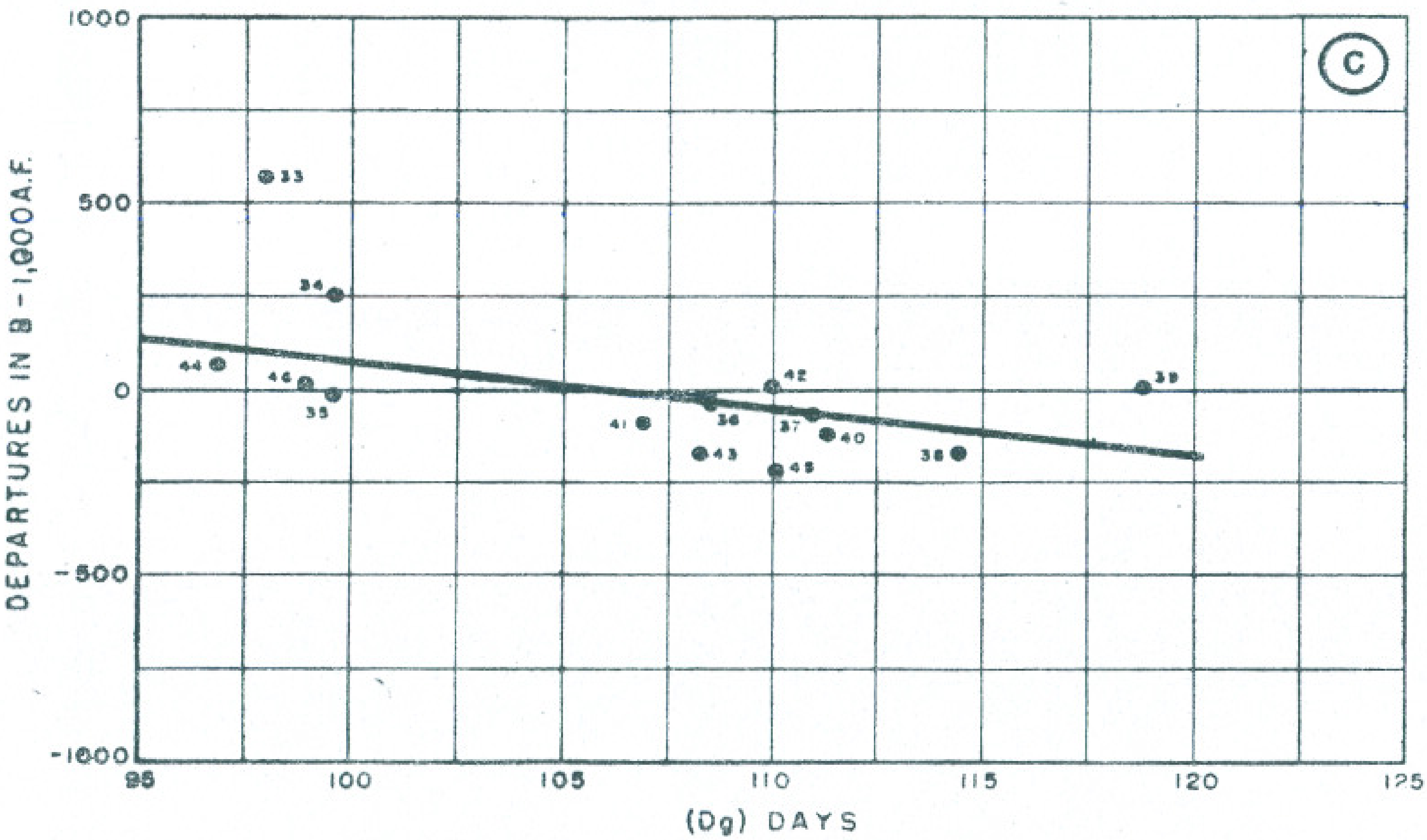
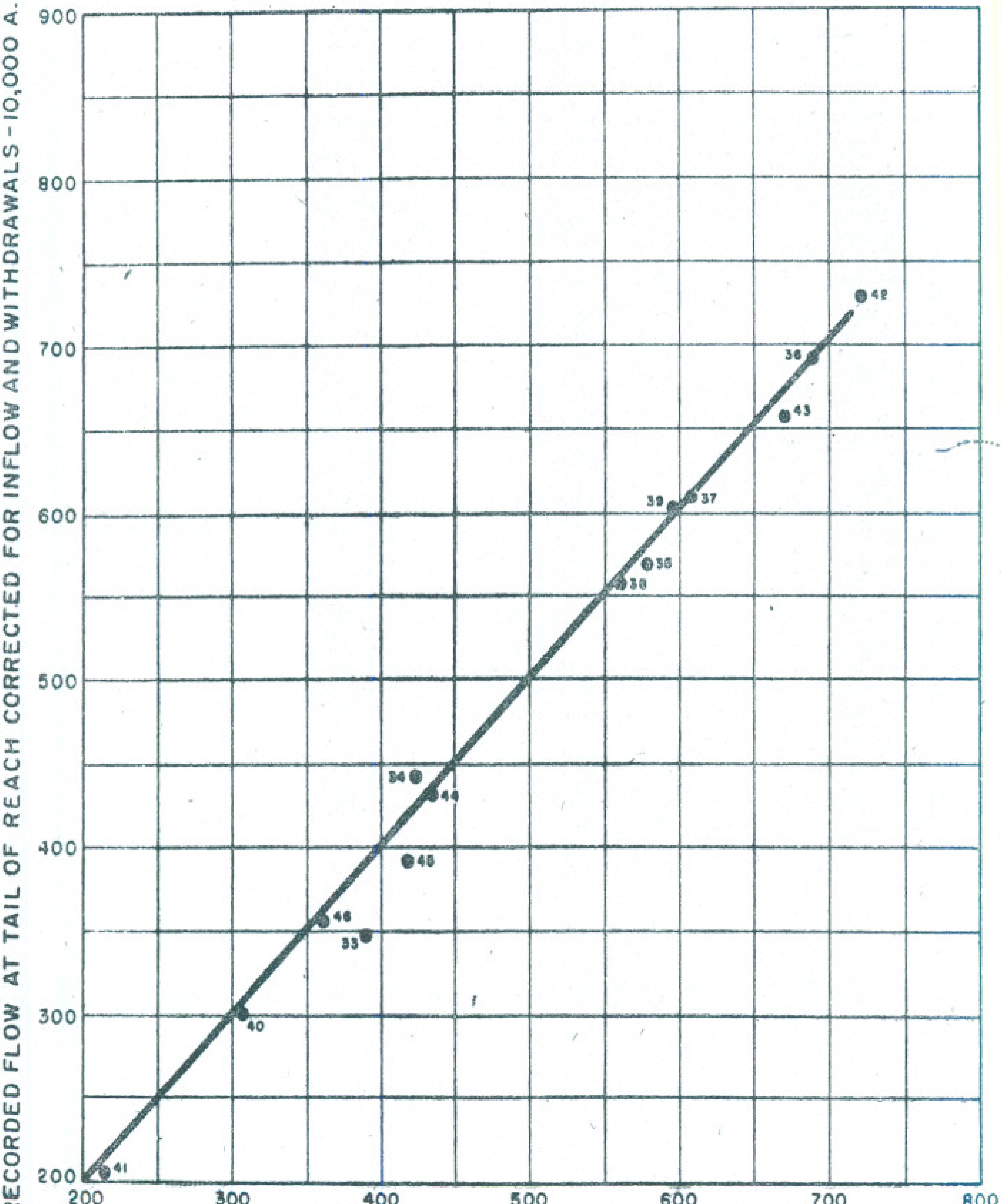


FIG. 6
SHEET 3

PAPER NO 329

RIVER INDUS
SUKKUR-KOTRI
GAINS 1933-46 INCLUSIVE

$$G = -0.7572(F_3 + F_4) + 0.8955(F_1 + F_2) - 12.7591\,(Dg) + 1344.27$$



ESTIMATED FLOW AT TAIL OF REACH - 10,000 A.F
(RECORDED FLOW AT HEAD PLUS ESTIMATED GAINS)