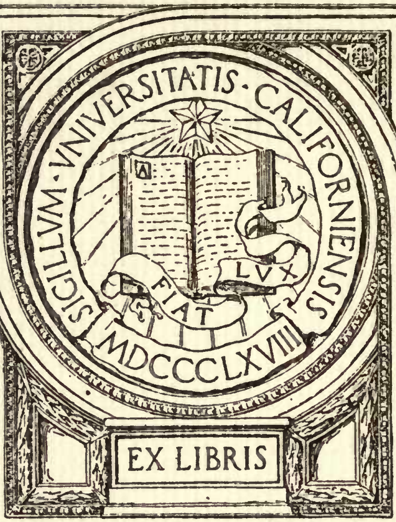

Engineering Science Series

THE HYDRAULIC PRINCIPLES GOVERNING RIVER AND HARBOR CONSTRUCTION

ENGINEERING SCIENCE SERIES

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THE HYDRAULIC PRINCIPLES
GOVERNING
RIVER AND HARBOR CONSTRUCTION

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RIVER AND HARBOR CONSTRUCTION

CHAPTER I

INTRODUCTION

During his professional career the writer has prepared numerous projects, and has answered many criticisms of the methods employed in the improvement of rivers and harbors. The following pages are derived principally from these sources. In replying to complainants, the author came to the conclusion that there was a commendable interest among the American people in the subject of the improvement of rivers and harbors, and a deplorable ignorance of the fundamental principles governing the flow of water in natural channels. Such is his apology for this publication.

The ordinary textbook on hydraulics treats principally of the flow of water in pipes and conduits, and the ordinary engineer is apt to consider a river as merely a large conduit governed by the same laws, ignoring the change in conditions arising from the fact that the walls of a pipe are not affected by the velocity of flow through it, while the channels of a silt-bearing stream expand or contract with every change in the volume of discharge. This fact is ignored also by many writers on river hydraulics, whose textbooks contain more or less elaborate discussions of the formulas $Q = VA$, and $V = C\sqrt{RS}$, which are authoritatively stated as guides for determining the depth in a contracted waterway.

In a rock cut, these formulas give as accurate results as they do when applied to a sewer or to a pipe, but in the alluvium of the Mississippi or Missouri rivers, scour caused by the contraction produces a radical change in the hydraulic radius. Water flowing in a river channel is governed by the same immutable laws as when flowing in pipes, but these laws are so modified in the river by those governing the flow of sediment that effects are produced which are erroneously termed exceptions to general laws.

For example if a given pipe is replaced by one of less diameter, the head (slope) must be increased to obtain the same discharge.

In a stream with a mobile bed, however, if the channel is contracted and at the same time straightened, the resultant increase in velocity produces a scour which enlarges the hydraulic radius to such an extent as to reduce the slope through the contracted section.

In the discussion of hydraulic problems, there is too great a tendency to draw conclusions from special cases without taking into consideration all the conditions which surround them. Thus, if one side of a hill is covered with trees and the other side is cultivated, the rapidity with which the snow melts is attributed to the forest growth, without taking into consideration the fact that one may have a southern exposure and the other a northern, and that the inclination of the sun's rays to the surface of the ground may have a greater effect in melting the snow than the surface covering. As another illustration, if one year's flood, attaining a height X at a locality A, produced a height Y at a point B further down a river, it often has been assumed that upon a repetition of the height X at A, the height Y would recur at B unless there had been an enlargement or diminution of the river section between the two localities, thereby ignoring the influence of the discharge of the tributaries below B on the river's regimen.

While harbors were improved before the Christian Era, and canals were constructed in the Middle Ages, the improvement of rivers is of recent origin, and owes its development to the invention of the steamboat. The early efforts to regulate rivers were generally unsuccessful, and it is only within the past thirty years that the correct principles of river regulation have been evolved, principally by French and German engineers.

There is a strong temptation for the author of a textbook to compile data from the works of earlier authors. An American unfamiliar with foreign languages is practically limited in his knowledge of European practice in river improvement to translations of certain French and German works made by officers of the Corps of Engineers, U. S. Army, forty or fifty years ago, which are now out of print, and to the proceedings of the various navigation congresses. Some of our textbooks therefore quote with approval methods of river regulation long since abandoned by the nations in which they originated. For example, the project of 1882 for improving the Danube river, though vitally modified by the Austrian Government in 1899, is still given as an illustration of the proper method of improving a river.

As this book has been derived principally from reports and addresses in advocacy of certain propositions, the author recognizes that he is prone to discuss a subject as a lawyer would present the evidence before a jury, and that he may at times give too great weight to his own views instead of judicially summing up the concensus of opinion among engineers. He has also failed to give proper credit to the numerous authors from whom he has derived his ideas. He makes no claim to originality, but his notes extend over an active professional life of forty years, and he has now forgotten the sources of much of his information.

De Mas' *Rivières à Courant Libre*, and Harcourt's *Rivers and Canals* and *Harbours and Docks*, are the foundations of the structure; Jasmund's *Die Arbeiten der Rheinstrom-Bauverwaltung*, and the Report of the Italian Commission appointed in 1903 to investigate the internal navigation of the valley of the Po, have been quoted freely. The student will also recognize extracts from Van Ornum's *Regulation of Rivers*, Thomas and Watts' *Improvement of Rivers*, Shield's *Principles and Practice of Harbour Construction*, and Wheeler's *Tidal Rivers*. The ANNALES DES PONTS ET CHAUSSÉES, the transactions of the various engineering societies, the PROCEEDINGS OF THE PERMANENT ASSOCIATION OF NAVIGATION CONGRESSES, THE PROFESSIONAL MEMOIRS, CORPS OF ENGINEERS, U. S. A., and the REPORTS OF THE CHIEF OF ENGINEERS, U. S. ARMY, are mines of information on river and harbor construction.

While a proper conception of the theory of engineering construction is necessary, a knowledge of existing practice is also indispensable. In river and harbor construction, every engineering district affords data for an extensive treatise on that subject, and there is urgent need of a condensed work on American practice in the improvement of estuaries, of the mouths of rivers, and of harbors, similar to Van Ornum's book on *River Regulation*, and Thomas and Watts' chapters on lock and dam construction in their book on *Improvements of Rivers*.

A statement of the principles of river hydraulics within the limits of a single volume has required intense condensation and to attempt to illustrate the applications of these principles in practice would require a large addition to its pages. By request, notes, indicated in the text by numbers, have been appended which, while not attempting to give a complete bibliography, will show the student where he can find practical applications of the principles discussed, and the pros and cons of subjects which may have been too positively stated in the text. These notes are of more value to officers of the Corps of Engineers and others who have access to the library of the Engineers School of the U. S. Army, or to the Congressional Library at Washington, D.C., than to the general reader, as the writer has found by experience that, ordinarily, libraries are limited in volumes on river hydraulics to the textbooks quoted above.

CHAPTER II

THE FORMATION OF RIVERS

The origin of the water supply, of rivers and streams, is the ocean into which they in turn discharge. Aqueous vapor evaporated from its surface is carried by the winds over the land, where it condenses and is deposited as rain or snow. A certain portion of this precipitation returns to the sea over the surface of the ground, while another part is absorbed by the soil, and after a subterranean flow of variable duration appears on the earth's surface in springs.

In this general flow of moisture from ocean to land and return, there are, however, numerous short circuits. Evaporation occurs not only from the surface of rivers and streams, but also from the soil itself, and in such quantities during summer months as to materially reduce the surface flow. Over large lakes, the evaporation may be sufficient to cause a local precipitation along their borders. The roots of trees and of other vegetation, under certain conditions, extract a large percentage of the water absorbed by the soil, and return it to the atmosphere through their leaves, thus reducing the subterranean flow of streams. Also at the mouths of rivers there is frequently a large ebb and flow of salt water from the sea, due to tidal influences.

The ratio of surface flow to absorption is dependent on the permeability of the soil, the surface covering, its surface slope, and the intensity and duration of the rainfall. A sandy soil absorbs more water than one whose principal ingredient is clay, and even rock, especially limestone, frequently contains permeable seams and crevices, which permit a large subterranean flow. A sandy soil in summer may absorb a rainfall which in early Spring would have flowed off its surface, due to its frozen condition.

In forests, the decayed leaves and mosses create a humus which will absorb a large amount of water, but many kinds of vegetation produce roots which seriously interfere with the flow of such waters in the underlying soil, retaining it in the humus as in a reservoir. The roots of Bermuda grass form a more impermeable covering than those of wheat, corn or cotton. A root of an Osage orange tree may extend a long distance in a horizontal direction in its search for moisture and open up a sub-surface channel around it which ultimately may be destructive to a levee; while roots of other species of forest growth may retard such flow.

The surface slope affects the degree of saturation of the soil. A hillside retains less water than a plain, since both the surface flow and the subterranean flow are accelerated by the slope. Even with porous soils, there is a period during every rainfall when the precipitation exceeds the capacity of the soil to absorb it and of the subterranean channels to remove it; the surplus water then flows on the surface.

The surface flow is therefore a function of the intensity of the precipitation, the slope of the ground, and the roughness of its surface covering. During a light rainfall, in a plowed field, the degree of saturation and the velocity of the surface discharge is affected by the direction of the furrows. Vegetation materially retards the flow. In forests, fallen trees, branches, and brush may collect in heaps which create timber dams, similar to the rafts which formerly obstructed some of our western rivers.

A heavy precipitation on a steep mountain slope produces such a volume and velocity of discharge as to create a powerful erosive action which not only removes particles of soil and its vegetable covering but, when concentrated in the channels of ravines, can move large boulders and forest growth. Every hillside is being degraded by this force, and it is assisted in its destructive work by frost, which disintegrates rock masses and renders them susceptible to its action.[1]

The material eroded from the hills is transported as far as the waters which dislodged it maintain the velocity they originally

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[1] As an example of the transportive force of rapidly moving water, the following personal experience of the writer may be cited. He was requested by the Insular Government of the Philippines to inspect a road which had just been completed in the valley of the Bug River, which flows in the mountainous regions of the province of Benguet, Island of Luzon. At a certain locality, in order to form a shelf on which to construct the roadway, a large amount of rock had been blasted from the mountain side and had fallen into the valley below. At the the time of the inspection, the channel of the river was so choked with debris that its flow, then insignificant, was through the dump pile.

A few days afterward a rainfall of eighteen inches occurred in the valley, most of the precipitation occurring within twenty-four hours. Three days after the storm, the writer made a return trip over the remnants of the road. The Bug River was again an insignificant stream, but the rock pile had disappeared, and the river was placidly flowing in its original bed. The debris was scattered through the lower valley, masses of rock weighing at least ten tons having been transported long distances.

acquired, but in the channels of streams flowing from a mountain peak to the sea the slope of the earth's surface rapidly diminishes. At first the concentration of the flow in gullies and ravines, by reducing the frictional resistance, will maintain the velocity acquired on the steeper slope, but as the ravine widens into a valley the carrying capacity of its waters is diminished and a deposition of the material transported occurs. With a reduction in the velocity, the boulders are first deposited, then successively smaller stones, gravel, and the heavier sands. The finer sands and clays are frequently transported long distances, a sufficient reduction in velocity not occurring to cause their deposition until the stream empties into a lake or sea.

Since the velocity of flow varies in different parts of the cross-section of a torrential stream, as in other channels, finer material is deposited intermingled with the boulders. A boulder once at rest induces whirls and eddies which cause the settlement around it of sand and gravel, imbedding it in the channel so that a flood of greater intensity or longer duration is necessary to set it in motion again. In the disintegration of stratified rock masses, the fragments, even those of the size of gravel, are in the form of slabs when they are first detached, and they may be deposited overlapping one another so as to form a pavement which may oppose a great resistance to erosion so long as the current maintains the direction that caused the deposition, yet a change in the direction of the flow attacking these slabs from the side instead of on the surface may destroy the pavement. For example, a gravel bar in a river may resist the flow of floods for ages, but if a dam is constructed on such a foundation, the percolation under it may first remove particles of sand and clay mixed with the gravel and thus create a channel through which the velocity of the discharge, though less than that of an unobstructed flood, may dislodge the gravel by reason of the change in direction of its attack.

The imbedding of detritus in stream channels tends to reduce the area of deposition of the coarser materials to narrow limits. But as rock masses roll down a stream they impinge upon one another, producing a grinding effect which reduces the dimensions of the boulders, breaks the slabs into smaller pieces, converts stone into gravel and gravel into sand, and tends to give a spherical form to all the elements set in motion. This facilitates the movement and causes a gradual reduction in the size of the elements which form the deposits, the farther the debris is transported from the zone of degradation. Since material rolling along a stream bed has a smaller velocity than the current, and since a heavy precipitation is of short duration, the movement of such material is intermittent and the distance traveled is relatively short during each storm; but material fine enough to be carried in suspension moves with the velocity of the stream, and is less subject to this intermittent deposition.

The subterranean flow of waters is slow except through rock crevices, due to the obstructions which particles of the soil offer to its passage. It is governed by the same laws as is other flowing water, its velocity being a direct function of the head and an inverse function of frictional resistance. However, as will be explained in discussing the laws governing the flow of water, the ordinary hydraulic formulas are inapplicable to subterranean flow, for it has been found by experiment that the velocity varies approximately as the head instead of as the square root of the head. There is also a great diminution in the velocity,—that in pipes for instance being ordinarily measured in feet per second, whereas that in ordinary soil is measured in feet per day.

Since the permeable crust of the earth is of vast extent and is frequently of great depth, there exists an underground water-system of streams, rivers, and lakes similar to those which appear on the surface, but these underground streams flow with very much smaller velocity. Wherever the surface of the ground intersects the surface of one of these subterranean streams, springs appear. These springs increase the discharge of a river at all stages, and they are its principal sources of supply during low water. If this intersection takes place in the bed of a stream, the difference of head of the underground waters and of the surface waters determines the rate of discharge; and when the head of the surface water is the greater, the surface stream may even disappear and be absorbed in the sub-surface flow. The failure to recognize this fundamental principle has caused large errors in estimating the capacity of reservoirs to store water and of drainage ditches to discharge it.

Variations in precipitation cause a rise and fall of the surface of these underground waters, similar to the floods in rivers. On account of the sluggishness of the flow and the great reservoir capacity of the permeable strata, a long period of time may elapse before these changes manifest themselves on the earth's surface. For example, at the head waters of the Mississippi River, a yearly minimum rainfall does not produce a minimum stream flow until the low water season of the year succeeding its occurrence.

The water which filters through soils for long distances carries little material in suspension, but it may contain a large amount of soluble matter, which, by evaporation of the water, may produce deposits of considerable extent. If the head of the subsurface flow exceeds one-tenth of the distance it travels, however, the water may acquire sufficient force to remove particles of the soil, which is an important consideration in designing levees and other structures whose foundations rest on permeable material.

While subterranean flow is the principal source of a river's water supply during low water, the higher stages of the river are created by the addition thereto of surface flow. Hence a river's stage becomes a function of the relative amount of the precipitation that is absorbed by the ground and by the surface flow, but it is modified by the reservoir capacity of the channel, and by evaporation. A lake tends to diminish a river's maximum discharge and to increase the minimum discharge. If the precipitation is greater during the winter and early spring than during the summer and early fall, evaporation will diminish the low water flow. But in localities where the conditions are reversed, evaporation will reduce the discharge during the summer high stages, particularly where reservoirs expose a large surface to the action of winds and of the sun's rays.

During extreme low stages, the velocity of the discharge is usually insufficient to move the heavier material along the stream bed and only a small amount of fine material capable of being carried in suspension flows into the stream. As the discharge increases, however, the capacity of a stream to transport solid material rapidly increases, though the amount and character of the material transported is more dependent on the character of the soil on which the rain falls than on the capacity of the river channel to carry it away. The surface flow from a prairie contains a large amount of fine sand and clay which is readily carried in suspension, while the detritus from a rocky hillside consists principally of gravel and coarse sand which is rolled along the river bed.

Material that is in suspension while moving with the velocity of the water is also deposited when this velocity is reduced for any cause. As a stream's discharge increases, low lands are gradually submerged, and since the velocity of the overflow is much less than that of the main stream, there is a deposit of sediment, which is greatest where the change in velocity first occurs, and gradually diminishes as the amount of material in the water is reduced by the deposition. By this means a silt-bearing stream builds up its bank, producing the characteristic of alluvial valleys that the ground close to the river channel during medium stages of the water is higher than the land more distant. The rainfall in such valleys, instead of flowing directly into the river, flows away from it and toward the area of deposition from the bordering hills, where (augmented by the discharge from the hills) it creates a stream which gradually attains sufficient volume to erode a channel through the ridge which forms the banks of the main river and thereupon discharges into the river.

As these silt deposits have been made during geological eons of time, they frequently attain great depth, and the main river which has been depositing sediment in its bed as well as on its banks may be flowing on a ridge, its *thalweg* having a higher elevation than the surface of the ground at the foot of the hills that limit its valley. The alluvium thus formed is readily eroded whenever it is attacked by water flowing with a greater velocity than that which deposited it, and a change in the direction of the current even at medium or low stages may cause the banks to cave. For this reason also the closure of a crevasse in a levee line on such alluvial soils as are found in the Mississippi Valley becomes a difficult problem, if the water is flowing through it with a depth exceeding six feet.

When the precipitation takes the form of snow, it neither enters the soil nor flows off its surface immediately. The density of a snow covering varies from that of ice, when it falls as sleet or hail, to a light fluffy substance which is exceedingly porous when first deposited but which is liable to be drifted by winds into large snow banks where it becomes more compacted. A light rain followed by freezing weather may convert the surface of porous snow into a crust of impervious ice.

When snow is exposed to the melting effect of the sun's rays, its transformation into water is gradual, on account of its latent heat, and its run-off resembles that from a spring; but if exposed to a warm rain or warm winds, unless a crust of ice exists which will protect it from percolation, the snow becomes saturated with water, which, absorbing the latent heat, suddenly melts it. The resulting flow is added to that of the delayed precipitation, and the entire mass starts with destructive violence on its path to the sea. A layer of ice also prevents soil percolation, and thus increases surface flow. The combination of a layer of sleet formed in early winter, making an impervious crust on a hillside, and covered later with a thick coating of porous snow melted in the spring by a heavy fall of rain, will produce a most destructive flood. Freezing weather largely reduces surface flow by converting the water into ice, but even with the surface flow thus diminished, high stages may occur in a stream on account of the formation of ice gorges.

The precipitation at any locality is very variable, not only in the amount which falls per day, per month, and per year, but even in averages of ten-year intervals. Thus in the records of precipitation at New York City, a period of ten years can be selected in which the average rainfall exceeds forty-eight inches per annum, and another in which it is only thirty-five inches. There is also a great variation in the amount and intensity of the rainfall at different localities in the same basin. Even within the limits of a city there may be a marked difference in the discharge of sewers during the same storm, due to this cause.

The discharge of a river which drains a large area is affected not only by the variation in the amount of precipitation but also by the difference in the time required by both the subterranean and the surface flows to empty into it. In a stream that derives its waters from a single hill, extreme variations in high and low water are frequent; but as the drainage area increases, the probability of the superposition of either the extreme high or low stages of the various tributaries which form the main stream diminishes, since the shorter tributaries or those with the steeper slopes deliver their maximum or minimum discharge earlier than those of greater length or those of gentler slope. The subterranean flow is similarly retarded.

The reservoir capacity of the river bed also tends to diminish the maximum discharge and to increase the minimum discharge, because a large amount of water is expended in filling the bed as the river rises, and runs out as it falls, the duration of the stage being thereby increased, and the maximum or minimum discharge correspondingly modified. Both high and low stages may be so prolonged, however, that the reservoir capacity of the channel is exhausted, but the longer the river and the greater its drainage area, the less frequently either extreme high or low water occurs. As a result, a river, even at low stages, flows on its lower reaches with sufficient velocity to cave its banks and create a channel proportionate to its volume in the fine sediment which has been deposited there.

The degradation of the hills and the filling of the valleys has continued for geological ages, gradually raising the surface of the ground in the valley of a river and increasing its length by deposits at its mouth. During the period, the water which has been transporting this material has been creating and maintaining a channel through the deposits, so that at the present time it has been found by observation that, while the beds of streams near their head waters are slowly rising, an unstable equilibrium exists between the forces which are filling and those which are excavating the channel, at a relatively short distance from their sources. At certain stages at a given locality the river bed may be enlarged and at other stages a fill may occur. If high stages predominate, for several years, the capacity of the high-water channel may be increased, and during a series of low-water seasons the capacity may be diminished. But when former conditions recur, while there may be numerous local changes, the same channel capacity of the river as a whole will be reëstablished, unless the forces of nature have been modified in the interim by the works of man. Under these conditions, the average discharge of solid matter over the banks of a river and at its mouth equals the average amount it receives.

The areas of deposition at the head waters of a stream have an effect on the supply of solid material to a river, similar to the effect of a lake on the supply of its fluid contents. During a storm they retain a large amount of the heavier debris, gradually delivering it to the river during minor floods. They thus act like huge rock crushers, grinding the larger fragments which pass through them into small particles. When they emerge from the area of deposition these particles are readily moved by the current which exists on the lower portions of the stream.

While the valleys of most of the rivers of the United States have been formed as explained above, there are some which have been created by glacial action. Moving ice also has a powerful erosive effect, and the eroded material, when once imbedded in a glacier, may be carried long distances before being deposited. Its area of deposition is the moraine at the foot of the glacier where the ice is being melted by the sun's rays, and where there is formed a heterogeneous pile of boulders, stone, sand, gravel, and clay, far different from the graded material found in alluvial valleys.

As the glacier recedes, the eroded valley is paved with a similar heterogeneous mixture. The glacier also excavates deep holes in its valley which later become lakes. When the glacier finally disappears, and the erosion of the hills is resumed by water derived from precipitation, a different condition exists than in those valleys which owe their formation through geological ages to such precipitation alone. At the foot of the hills limiting the valley, areas of deposition are formed which gradually encroach on the valley, but the water escaping from these areas flows into the existing lakes and there deposits its solid matter. Emerging from the lakes it flows as a clear water stream of diminished velocity and passes over the surface of ground that had been eroded by a force far greater than it possesses. Its sinuosities and depth become functions, not of its discharge, but of the character of the deposits left by the glacier. Instead of having steep slopes at its source gradually diminishing toward its mouth, it is liable to flow with gentle slopes in its upper reaches until it comes to obstructions deposited by the glacier, over which it flows in rapids, not having sufficient force to excavate its channel through them. As such a stream carries little sediment, it is incapable of building up its banks and the rain which falls in its valley, instead of flowing from the river to the foothills, as in alluvial streams, has a reverse flow.

In such valleys, the lakes are gradually filling and are being converted into marshes, and in future geological ages they will be transformed into valleys similar to those first described. In certain valleys, the transformation is more complete than in others, and there is found a foundation of glacial drift covered by a relatively thin layer of alluvial deposits.

A glacier has a powerful erosive effect on rock, but is very eccentric in its action, occasionally leaving rock ridges extending across its valley which the clear water of the river which forms on the glacier's disappearance is unable to remove. In the upper valleys of streams formed by water derived from precipitation, deep canyons may be excavated through rock by the erosion of the debris which is being carried down them.

In the area of deposition of an alluvial valley, as in one formed by glacial action, the channel formed by a stream is dependent on the eccentricities of the deposition of debris. A flood carries the sand, gravel, and boulders down the ravines and spreads them in a fan-shaped mass across their entrances. As the flood subsides, pools will be scoured out where the deposit is of sand and gravel, and between the pools the water will flow in shallow ripples over material it is incapable of moving. Such a channel is not permanent but is liable to be obliterated by the deposits from the next flood, and a new channel may be formed where, due to some freak of nature, material more readily moved is found.

But as the detritus becomes broken up into smaller particles in its passage through the area of deposition, it becomes more amenable to the action of the stream currents, and the channel assumes a more stable form. There is still a large amount of material being carried down the river during floods, but after each flood there is a greater tendency for the stream to return to the channel it formerly occupied at similar stages. The pools develop in the bends of the stream, and are separated by bars of heavy material. In other words, the sediment flows in accordance with certain laws, and it is as important to comprehend clearly these laws as it is to comprehend those of the flow of water (1).

CHAPTER III

LAWS GOVERNING THE FLOW OF WATER IN RIVERS

The Chezy formula[1] and those derived from it, such as Bazine's, Fanning's, and Kutter's, are the result of careful experiments from which numerical values have been deduced for empirical coefficients which render the formulas of great assistance in solving hydraulic problems, but they have the defect of all empirical formulas that great caution must be exercised in applying them where conditions differ from those of the experiments.

These formulas as a class were first derived from the flow of water in pipes and conduits, and it was attempted to concentrate in a coefficient c all the variations of the flow which prevented v from being equal to $\sqrt{rs}$. It was soon observed, however, that c was a variable function of both r and s, and tables were prepared giving values of the coefficient for changes in both these quantities. It was also found by experiment that the condition of the enveloping surface affected the velocity of the discharge, a smooth iron or vitrified clay conduit discharging more water in a given time than a brick one of the same diameter and laid to the same slope. Changes in the value of the coefficient then became necessary to provide for the change in velocity due to the roughness of the surface of the material composing the conduit.

The frictional resistance of a liquid flowing over a solid substance is slight and affects only the thin layer that is in contact with the solid. In a large conduit, such resistance is negligible and the retarding effect of a rough surface on the flow is due, not to such frictional resistance, but to the eddies which it creates in the liquid itself and which absorb a portion of the energy that would otherwise be expended in producing a velocity of discharge through the conduit. Hence the term *coefficient of roughness* does not give a proper conception of this force. The velocity may be such as to develop frictional resistance only.

There exist two critical stages, as they have been termed, a minimum stage when the velocity is so low that eddy action is

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[1] $v = c\sqrt{rs}$ in which v = the velocity; c = a variable coefficient; r = the hydraulic radius; and s = the slope.

not developed, and a maximum stage in which there occurs the greatest retarding eddy action the velocity can create (1). This maximum stage is dependent on the form assumed by the particles producing the roughness. Both below the minimum critical stage and above the maximum critical stage there is a tendency for the flow to follow rectilinear lines instead of producing eddies. As an illustration, suppose that a straight channel be excavated through rock and that the sides and bottom be left as blasted. If the slope is gentle, a small discharge will flow through the cut without a serious disturbance of the water surface. As the discharge and its velocity increase, boils and eddies begin to appear, which attain a maximum at a certain stage. Above this stage the eddies gradually disappear on the surface, having been limited to certain distances from the bottom and sides of the cut, beyond which the current tends to flow in straight lines. On the contrary, if the same discharge flows in a channel of sand which has been deposited in sand waves, the minimum critical stage is not attained so soon, *i.e.*, the water flows tranquilly at low stages, but at the velocity of a maximum discharge, the water moving up the surface of the ridges continues on the same path to the water surface and boils and eddies of great magnitude result.

Furthermore the length and height of the sand wave affect its capacity to reduce velocity. Sand waves deposited during low water, though composed of the same material and more frequent in number, have a lower coefficient of roughness during floods than those deposited during high stages.

As the experiments from which the ordinary formulas were derived were for ordinary flow between the critical stages described above, their application to either extremely low or extremely high velocities should be made with caution. The subterranean flow of water is so slow that it is below the minimum critical stage, and the velocity has been found to vary almost directly as the head. The same rule applies to the discharge of small pipes. With brass pipes of a diameter as great as two inches under low heads a formula $v^{1.76} = crs$ has been found to be applicable. Hazen and Williams have proposed a formula with a variable exponent for v as a substitute for the ones generally employed, and this is theoretically more exact.

When it is attempted to apply these formulas to river channels, as in the experiments of Kutter, serious difficulties arise. The formulas were derived from uniform flow in conduits or pipes which had the same hydraulic radius in different sections, and uniform slope. Such conditions do not exist in rivers, for no two cross-sections of a river have the same area, and the area of the same cross-section changes from day to day. Moreover, the slopes are exceedingly variable, being not only steeper over bars than in pools, but frequently varying on opposite sides of the same pool. Finally, the coefficient of roughness varies from section to section, being greater on a gravel bar than in a sandy pool.

In applying a formula it is therefore necessary to consider long reaches of the river, obtaining a mean hydraulic radius and a mean slope. If it is attempted to apply the formula to a short stretch which happens to have a uniform section and slope, the velocity of approach becomes a disturbing factor, the propelling force being not the difference in head at the two extremities of the section, but that created by slopes further upstream. Even a strong wind influences the discharge of a river, since it raises or lowers the thread of maximum velocity. At the mouths of rivers, tides may have sufficient force (on account of the funnel-shaped form of the estuary) to cause a flow in a reverse direction to the low-water slope; when the tides introduce salt water into the channel, they produce a most complicated flow, incapable of mathematical analysis.

It is therefore advisable when discussing questions of river hydraulics to determine by actual measurements the various elements entering a formula. When this is impracticable, the reader is cautioned to employ a liberal coefficient of safety, bearing in mind that most mathematical computations are applicable to average conditions, and that in treating such questions as floods, and depths of channel during extreme low water, it is not the average but the exceptional that has to be considered.

In a pipe the velocity of flow is determined by the head. In a river the living force of the water also must be considered. When the flow of water in a pipe is suddenly checked, the pressure on its surface is merely increased, as the water has no means of escape. But in a river, when the flow is restricted at any locality, the force of the approaching water causes an elevation of the contracted section corresponding to the pressure existing in the pipe. A rapid current impinging perpendicularly on a river bank may reverse the river slopes. This was forcibly illustrated in the Mississippi River at Vicksburg after the Centennial Cut-off of 1876. The old river bed around the island created by the cut-off then became the harbor of Vicksburg and was connected to the river during certain stages at both its upper and lower ends. The flow through the cut-off during high stages impinged on the Vicksburg bank with sufficient force to cause such a local elevation of the water surface as to create an upstream current through Vicksburg harbor until the river fell to about mid-stage, and caused a heavy deposit of sediment, necessitating the closing of the upper entrance to the harbor and the diversion of the Yazoo river into it to restore and to maintain its navigability.

At the outlets of rivers the tidal wave frequently has a force far exceeding that produced by the natural slope of the river and causes a rising of the river's waters in excess of that existing in the ocean. The impetus of the outflowing tides may also lower the river level below that of low water in the ocean.

The flow of water in bends has such a vital effect on a river's regimen that it merits a more careful analysis than it ordinarily receives in textbooks on hydraulics. While there have been numerous experiments upon the retardation of flow caused by bends in pipe, the subject usually is dismissed with the statement that the loss of head in bends is equivalent to adding a certain amount to the length (2). It is more fully discussed in an article by M. R. H. Gockinga on *La Pente Transversale et son Influence sur l'Etat des Rivières* (ANNALES DES PONTS ET CHAUSSÉES, 1913, p. 112).

In a straight paved conduit the filaments of water flow in straight lines, with the exception of those near its bed, which are disturbed by the roughness of the material with which they come in contact. The thread of maximum velocity lies in the vertical plane passing through the deepest section, and the variations of velocity of the filaments of water in that plane will conform to the arc of a parabola whose apex is near the water surface. A similar curve will determine the variations in velocities from the plane of maximum velocities to the sides of the conduit. In a cross-section the water surface will be horizontal. If the flow is uniform, the longitudinal surface slope will conform to that of the conduit.

If a circular curve be introduced into the conduit, however, there is a derangement of this regularity of flow. The inertia of the water resists the change of direction, and there is an elevation of the water surface on the concave side of the conduit and a corresponding lowering on the convex side. The mid-stream longitudinal slope remains the same, but there has been created a transverse slope in the bend which causes a marked difference of head on the opposite sides. The cross-section of the water surface becomes a curved line. For the case in which the cross-section of the conduit is trapezoidal, Mr. Gockinga deduced the equation

$$y = 0.235V^2 \log (1 + x/R),$$

where V denotes the longitudinal velocity, R denotes the radius of curvature of the axis of the conduit in meters, and x and y are coördinates of a point on the surface referred to a system of rectangular axes through the intersection of the axes of the conduit and the water surface. For a trapezoidal conduit whose width is 200 meters and whose radius is 500 meters, and whose depth is such that a longitudinal slope of 0.0001 produces a velocity of one meter per second, he computes a difference of head of 4 centimeters on opposite sides of the conduit, *i.e.* a transverse slope twice that of the longitudinal.

These theoretical computations have been confirmed by observations on the Mississippi River, where differences of head of about 1 foot have been observed on opposite banks of bends, with mean mid-section longitudinal slopes of about 0.4 foot per mile. Under such conditions the thread of maximum velocity no longer corresponds with the mid-stream section, but approaches the concave bank.

When two bodies of water whose surfaces have different elevations, are connected by a pipe, there is a flow through the pipe from the one having the greater head, which will continue until the heads are equalized. The velocity of the flow through the pipe is a function of the difference of head. If a variation in head exists in different parts of a lake, which usually results from a wind blowing over its surface, the same tendency to restore the normal levels is created, but since the force of the wind is compelling the surface water to travel in the same direction as the wind, the return flow is along the lake bed. This rises to the surface where the lake level is lowest, thereby giving the water a curvilinear path (3).

Under certain conditions this subsurface flow may attain great force. The vertical piers constructed on the Great Lakes have to be protected by heavy rip-rap in depths of thirty feet to prevent scour from this cause.

In a river, the centrifugal force created by bends produces a similar action, but the curvilinear path of the water in a lake is modified in a river by the motion of the water downstream, due to the longitudinal slope. Hence the water in a river assumes a helicoidal motion. The motion of translation downstream is retarded, but in the circumference of the helicoid the filaments of water have acquired a velocity much greater than that which exists in a straight reach due to the longitudinal slope alone.

The dimensions of the helicoid are functions of the longitudinal slope and the radius of curvature of the bend. They conform to the section in which the water flows only when it is permitted to construct its own path, *i.e.*, in a stream in its natural state. Beyond the sphere of its flow, eddies are produced which also interfere with the motion downstream.

The helicoidal flow of water in bends was practically demonstrated by Professor James Thompson before the Institution of Mechanical Engineers of Glasgow in 1879, and the direction and velocity of such currents on the Dnieper River were measured by M. Leliavski, as described in a paper presented to the Sixth International Navigation Congress held at the Hague in 1894. From the results of his experiments, Leliavski came to the conclusion that in a bend, surface currents converge toward the concave bank, along which a stream of water flows to the bottom of the river, thence move to the convex side in divergent currents, and then gradually rise to the surface. He found not only that these currents have sufficient force to cause caving of banks of clay, sand, or gravel, but he found evidences also that they had caused erosion in the lava rock which forms the bed of the river at the Dnieper rapids. The greatest depth was found where the greatest number of surface filaments of water converge on the concave bank. If the radius of curvature of the bend is uniform, this point occurs at some distance below the middle of the bend.

The influence of a circular bend, moreover, affects the straight sections of a conduit for a considerable distance above and below it. Below the bend, it is evident that a considerable distance is required to transform the helicoidal motion again into a rectilinear motion, since this transformation depends on the inertia and the frictional resistance of the particles of water. Above the bend there is a similar back-water effect, since the surface of the cross-section cannot suddenly change from a horizontal to an inclined line, *i.e.* the transition must be gradual. The helicoidal motion of the water therefore begins considerably above the bend, attains its maximum velocity when the transverse slope adjusts itself to the radius of curvature, then remains constant to the end of the curve, and then gradually diminishes. The locus of the maximum velocity moves away from the axis of the conduit in a corresponding manner and there is a disturbance in the longitudinal velocity of flow in the straight sections as well as in the curve.

In a paved conduit the location of the thread of maximum velocity is of minor importance, but as this line is also the one of greatest scour, it determines the navigable channel, and river regulation consists principally in its proper location and maintenance.

Another question which requires more elucidation than is contained in the ordinary textbooks is the effect of obstacles on the flow of water. It is recognized that the sudden expansion and contraction of a conduit entails a loss of head, due to the eddies formed, but the paths followed by the water in passing the obstacles have received little consideration.

In a straight conduit not susceptible to erosion, if a vertical dike extending above the water surface be constructed perpendicular to one of its sides, the reduction of the area of cross-section will cause a local elevation of the water surface, reducing the slope above the obstacle and increasing it below. This elevation, while extending across the entire cross-section, will be greatest near the side of the conduit above the dike, due to the greater retardation of the longitudinal velocity at that locality, and the least on the opposite side. This difference of head will induce a flow toward the points of lower elevation and the locus of the thread of maximum velocity will be diverted from the straight line it followed when the conduit was unobstructed. For a certain distance above the dike, back-water effects will produce a difference of elevation on opposite sides of the conduit, and a helicoidal motion will be imparted to the water similar to that in bends. Below the dike conditions are suddenly reversed. The water behind the dike has lost its longitudinal velocity and tends to sink to a lower level than formerly existed, while on the opposite side the elevation has increased. A portion of the water flowing around the obstacle seeks to fill this void, but because it has a high longitudinal velocity as it passes the dike, it forms an eddy of a very complicated flow but with a large spiral component with a vertical axis. In experiments on the Rhine it (4) was found that this spiral eddy attacked the bank at a distance below the dikes equal to about two and one-half times its length. Another component has a quasi-helicoidal flow diagonally toward the opposite side, which also converts some of the longitudinal velocity into eddy currents.

If a similar dike is constructed on the opposite side of the conduit in the same cross-section, the water surface between the dikes assumes a curved form, higher at the extremities of the dikes than in mid-stream. The locus of maximum velocities divides into two lines diverging upstream from the axis of the conduit to the ends of the dikes, and gradually returning to the middle section below them. Two powerful eddies are produced behind the dikes, but the remainder of the flow tends to follow lines more rectilinear than those which exist when only one obstruction is formed.

There is also eddy action above a dike, but its nature and extent is a function of the inclination of the dike to the direction of the current. If the dike is inclined sufficiently downstream, it has an action similar to that of a curve and a tendency to scour develops along its face. This tendency is diminished as the dike is given a greater inclination upstream.

If the dike be submerged there is a tendency toward the creation of a *jump* in the water surface over it. A very complicated flow results. The overflow produces a powerful scouring effect immediately below the dike, and interferes with the eddy action around its end.

On a concave bank, a dike causes a curvature of the line of maximum velocity, but it cannot ordinarily overcome the centrifugal force created by the bend and the line soon returns to its normal position.

The discharge of a tributary does not immediately mingle with the water of the main stream, but flows beside it until bends and obstacles (by their helicoidal and eddy action) interfere with the regularity of flow.

Near the mouths of rivers, a very complicated flow frequently results from the difference in density of fresh and salt water. The water of the inflowing tide has a greater specific gravity than that of the river discharge. At certain periods of the tide the salt water flows up the river along its bed, while the fresh water is flowing out above it. On account of irregularities in the river bed, there may also be an upstream surface flow in certain portions of a river section with a downstream flow in others, until the inertia of the moving water is overcome and the salt and fresh waters have an opportunity to mingle.

CHAPTER IV

THE FLOW OF SEDIMENT IN NON-TIDAL RIVERS

Material is transported down a river in solution, in suspension, and by being rolled along its bed. The material in solution is carried to the mouth of the river without deposition unless there is excessive evaporation. Streams flowing in valleys formed by glacial action not infrequently carry more material in solution than in suspension, as is demonstrated by the observations of the Geological Survey on the Mississippi River at Minneapolis, where the mean of the observations shows 200 parts per million in solution and 7.9 parts per million in suspension.

In a river flowing in an alluvial valley, the reverse is the case except occasionally at extreme low water, and the amount of material carried in suspension is primarily dependent on the character of the soil of the watershed from which it flows and on the intensity of the rainfall. The western tributaries of the Mississippi River carry a greater amount of sediment per unit of volume of water, termed *the degree of saturation*, than its eastern tributaries, and (for the same discharge) the degree of saturation is greater in summer than in the winter, due to the frozen condition of the soil in winter. The light clays and sands which are carried in suspension become intimately mixed with the water as it flows over the soil and (moving with the velocity of the water) are carried to the river's mouth unless the velocity is checked, as in the flow through a lake.

In a watershed whose soil contains a large amount of clay and is of a relatively uniform character over the drainage area, the degree of saturation rapidly increases with an increase in the discharge. In the Mississippi system of rivers, however, the Missouri carries so much more sediment in suspension than any of the other tributaries that it determines the degree of saturation of the main stream, and a flood from the Missouri River carries more material in suspension to the Gulf than one from the Ohio, although the amount of water flowing from the latter in floods largely exceeds that from the former.

When material carried in suspension has once been deposited, and is afterwards eroded, only a comparatively small portion is again placed in suspension. The original deposit contains a large amount of water, and assumes gentle slopes, but it becomes more compacted and is capable of maintaining a steeper slope when additional deposition occurs. If the river falls to such a stage that the deposit is above the water surface, and the water is drained from it, the binding force of its clay contents may be sufficient to enable the material to assume a vertical slope, and thus produce the steep banks found above low water in the concave bends of alluvial streams. Below the water surface, the adhesive force of the clay diminishes, and the water contents of the deposit increase. When such a bank is eroded, there is a local deepening of the river bed, and an increase in the under-water slopes, which cause large masses to slide into the river. These masses do not mingle with the water sufficiently to be carried in suspension. When rain falls on a plowed field every drop of water picks up a load of clay or sand which it can transport; but a mass of water which acts on a concave bank moves a mass of earth too heavy to float, and which therefore is rolled along the river bed.

There is also a relation between a river's low-water slope and the amount of sediment it carries; the greater the amount of sediment, the steeper becomes the slope. This is particularly noticeable at the junction of two streams. If a river carries relatively little sediment, its slope above the junction with a turbid stream is less than that of the tributary, and increases below it. If the reverse is the case, the slope of the main stream above the junction is increased, and below it more nearly conforms to that of the tributary.

Exceptions to the rule result from the geological formation of non-erosive beds in the vicinity of the junction. For example, the upper Mississippi carries less sediment than the Minnesota, its first large tributary, but the falls of St. Anthony above the junction and the rapids produced by the detritus from the falls create an exceptional condition.

The rule is illustrated by the following instances: The waters of the next large tributary, the St. Croix River, have been clarified during their passage through Lake St. Croix, and the mean slope of the Mississippi above their junction is about 0.4 foot per mile, below it 0.2 foot. At the junction with the Chippewa, which transports a large amount of coarse sand and but little finer material, the low-water slope through Lake Pepin is zero, and immediately below the mouth of the Chippewa 0.9 feet per mile. At the mouth of the Wisconsin, which also carries large amounts of sand during floods, the slope of the main river above it is 0.1 foot, and below 0.6 foot per mile. The western tributaries of the river below have sufficient material in suspension to maintain an average slope of 0.4 foot per mile to the Illinois River, with the exception of the Rock Island and DesMoines rapids. The Illinois River carries little sediment, and the slope above its junction exceeds 0.4 foot per mile; below it a gentler slope is observed as far as the Missouri River. Below the Missouri River a slope exceeding 0.8 foot per mile is created, gradually reducing to 0.6 foot, and below the junction with the Ohio still gentler slopes exist for a considerable distance.

These phenomena are usually explained by the assumption that they are caused by the relative degree of saturation of the two streams, and that when their waters mingle they are capable of increasing their capacity for transporting material in suspension, the less turbid waters increasing their load from material eroded from the bed of the river(1). Observations by the Mississippi River Commission fail to confirm this assumption. At the junction of the Missouri and upper Mississippi it was noted that the waters of the two rivers have a tendency to flow side by side without mingling, the waters of the upper Mississippi following the Illinois bank of the river and the waters of the Missouri the opposite bank. At low stages of the Missouri, this tendency continues considerably beyond the portion of the river having a steep slope. Boils and eddies cause a gradual mixing of the waters, and during certain high stages, at the first concave bend below the junction which occurs on the Missouri bank, there is a decided movement of the water of the upper Mississippi across the channel on the surface, and an opposite bottom flow of Missouri River water, which is exhibited in the observations of sediment taken at that locality.

A more logical explanation of the changes of slope at the mouths of tributaries is to be found in the deposition of material in suspension, and its conversion into sand waves which are moved along the river bed. As the crests of floods of rivers rarely coincide, when a clear-water stream empties into a turbid river there will be a period during a high stage of the tributary when its discharge will act as a dam on that of the main river, diminishing the velocity of flow above the junction and causing a deposit of material carried in suspension which will reduce the river's cross-section. Below the junction its added waters will tend to enlarge the cross-section.

When the tributary falls to its normal relation to the main stream, the velocity above the junction is increased and the deposits tend to scour, being slowly rolled along the bottom as sand waves instead of being carried in suspension with the velocity of the current. There is a tendency for this scoured material to deposit in the enlarged section below the junction, but before the equilibrium can be established a second rise occurring in the tributary causes a repetition of the process.

If the main stream is less turbid than the tributary, a flood in the latter flows into an enlarged section and consequently deposits sediment due to a reduction in velocity. As the tributary falls, the main stream has an increased burden in removing the deposits below the junction, a work it also fails to accomplish before a second rise occurs in the tributary.

The serious problem in river regulation is the movement of material along the river bed. In straight reaches it moves in sand waves which are functions of the velocity of the current and of the depth of water, being greatest when for any cause the current is suddenly increased. At such a time, the most rapid erosion of the bottom takes place. Conversely, the movement of material is least when the velocity of the current is suddenly decreased, since the greatest deposit of sedimentary matter occurs at that time.

The sand waves have an irregular motion downstream, and the maximum size and rate of progress is attained when the stage of the river is at its highest and is nearly stationary, their height, length, and rate of motion being dependent on their location with reference to the line of maximum velocity. The waves have the least dimensions and slowest rate of travel at low water. They move downstream by material being pushed or rolled up their flat anterior slope and dropped over their crest, where it remains until the wave has progressed far enough downstream to expose it again to the action of the current, to be again rolled or pushed forward. The amount of material thus moving is greatest in high water, or when the velocity for any cause has been suddenly accelerated. Changes in the form of waves are gradual, the waves retaining their form and individuality as long as the velocity of the current remains nearly uniform. They disappear by the deposition of sediment carried in suspension, if the velocity is suddenly decreased, and again make their appearance when the velocity approaches uniformity for any length of time.

On the lower Mississippi River, sand waves have been observed that have a length of 1000 feet, a height of 22 feet, and a maximum rate of travel of 40 feet per day. At New Orleans the amount of material transported in sand waves during a year was estimated at less than 1 per cent of that carried in suspension, at Lake Providence Reach about 10 per cent. In some of the tributaries of the upper Mississippi, the amount rolled along the river bed largely exceeds the amount carried in suspension. This variation in the relation of material rolled along the bed to that in suspension is due to the relative sizes of the particles in different portions of the river bed.

At New Orleans a large amount of material was observed intermittently in suspension, the ratio of the material in suspension at the water surface to that near the bed being in some cases 1 to 1.83. Furthermore, a difference in the degree of saturation of floods from the Ohio and the Missouri rivers respectively could readily be observed, notwithstanding the enormous caving of banks which occurs during every flood below the mouth of the Ohio River. At St. Louis it was observed that some of the material from the bed did not sufficiently mingle with particles of water to remain in continuous suspension until it reached the sea, but was "detached for a time by some energetic impulse and described a longer or shorter path, moving in or out with the surrounding water"(2).

In bends, the helicoidal flow impressed upon the water affects the motion of sand waves, and every eddy also changes their form to some extent. The axis of maximum flow in bends is diverted from the axis of the channel which it occupies in straight reaches toward the concave bank, and causes an erosive action on that bank, which is intensified by the transverse slope created in the bend combining with the longitudinal slope. The material scoured from the bank,together with that brought down the river in sand waves, is diverted from the direction followed in straight reaches to a diagonal path across the river. It forms a sand bar extending downstream a distance from the origin of scour which is dependent on the original slope of the river and on the radius of curvation of the bend. This sand bar usually forms the convex bank throughout the curved section; but when the river changes its section to one that is straight or has a curvature in the opposite direction, the intensity of the helicoidal velocity gradually diminishes; the water no longer has sufficient energy to transport the material across the river, and deposits it in a bar extending across an unimproved channel in a diagonal direction, so that the length of its crest largely exceeds the river's width. A dam is thus soon created which reacts on the local slopes and velocities, diminishing those above the bar, and increasing those of the water passing over it. This process continues until the velocity in the pool above the bar is insufficient to produce scour, or until an equilibrium is established between the material brought to the bar and that which passes over it. On a rising river the tendency is to produce the equilibrium by an elevation of the crest of the bar and by a reduction of velocities in the pool. On a falling river there is a tendency to scour a channel through the bar and to attain the equilibrium by the resulting increase of velocity over it.

While the movement of sand waves in straight reaches is a slow process, averaging about forty feet per day when the river current has a mean velocity of six feet per second, the movement of the particles of sand which form them is much more rapid, and the elevation of the crest of the bars also rapidly increases with a rise of the river stage. On the Mississippi River the rise of some of the bars is at the rate of one-half the change of stage. On the Rhone River a ratio of one to five has been observed. On a falling river there is a similar scouring of the bar. The rate of rise and fall of the crests of bars, however, varies greatly in different reaches of the same river, being dependent not only on the velocity of the water and the radius of curvature of the bend, but also on the eddies formed, on the character of the material moved, and on its distribution on the bar. On a falling river the channel tends to form across the bar along the line of the deposited material which is most susceptible to erosion; and since the coarser material of sand waves is usually found in the line of greatest velocity, the location of the channel across bars on an unregulated river usually differs on rising stages from that which is created on falling stages.

The divergence of the thread of maximum velocity toward the concave bank of a bend tends to produce a triangular cross-section in pools, and the slope of the concave bank becomes a function of the radius of curvature and of the character of the soil of the bank. If this soil is readily eroded, the amount of material falling into the stream is greater than the helicoidal flow can transport. In that case, the thalweg depths are reduced, and gentler slopes obtain, than those when material of greater resistance to scour is encountered. In the fine sediment of the lower Mississippi, slopes of one (vertical) to three (horizontal) are not infrequent even in sharp bends. Coarse sands will assume slopes of one to two. If the concave bank is composed of rock, a nearly vertical slope may exist.

On a bar there is a tendency to a trapezoidal form until a channel is scoured through the bar during a falling river.

The radius of curvature of a bend, while it is primarily a function of the material that composes the bank, is also affected by the volume of the discharge, and by the slope. In a river flowing through glacial drift, the variations in the soil are the determining factor in the river's course. In an alluvial valley, however, the greater the discharge, and the gentler the slope, the longer becomes the radius of curvature in the bends, though it is modified by conditions that exist in the bank. Thus in the Mississippi River below St. Paul, the radius of curvature of the bends varies from 1500 to 4500 feet, while in the bends above Greenville, Mississippi, it varies from 8000 to 15,000 feet.

Similarly, at low water a river tends to flow with curves of less radius than in flood stages, when its volume has been very largely increased. This tendency to a change of curvature at different stages has an injurious effect on the river's regimen, causing a variation in the location of the thread of maximum velocity, transferring the caving from one bank to the opposite one, and making a fill at high stages where the river strives to create its channel during low water. When the low-water channel has excavated sharp bends, the volume of water during floods may be too great to conform to the path that the radius of curvature strives to create and a large flow follows a chord of the bend, frequently with sufficient velocity to scour a secondary channel and to produce an eddy action at its junction with the current along the bend, which will form large deposits of sediment. A powerful scouring effect is also produced on the portion of the bank on which it impinges.

An interesting example of the influence of discharge on the form of the river bed is afforded by the Atchafalaya River (3). Originally the Atchafalaya was obstructed by an accumulation of snags and drift called a raft, which limited the amount of water which could flow through it at both high and low stages. The removal of the raft and the construction of levees along its banks has largely increased its discharge both at high and at low water. As a result the river has attempted to enlarge its section, but instead of retaining its old sinuosities and forms it has created new ones, cutting a channel through bars on convex points, and thus attempting to adjust its curvature to its discharge.

In the Illinois River where the low-water discharge has been increased from about 1000 second-feet to over 5000 second-feet by the flow from Lake Michigan through the Chicago sanitary drainage canal, a corresponding change in the radius of curvature of its bends is also taking place.

When a dike is constructed in a river, the resulting disturbance of the slope causes the shape and the distribution of the sand waves to change. In the reduced section the increased slope scours a deeper channel, and the scouring effect is most intense at the end of the dike. The eddy below the dike deposits material in its vertex and has a gradually reducing scouring effect along its outer elements, which tends to create a channel extending from the end of the dike toward the bank to which it is connected. A second channel tends to form diagonally across the river toward the opposite bank, on account of the helicoidal motion generated in that direction. When these currents lose the force imparted to them by the obstruction, a bar with a curved crest is formed, which incloses both channels. The navigable channel of the river is determined by the scour across this bar, which occurs on a falling river, and which may be toward either bank, dependent on the local character of the deposits in the bar. Above the dike, a deposit is formed from sand waves by eddy action and from material in suspension by a reduction of the velocity. Along the face of the dike, there is a narrow channel due to eddy action, if the dike makes an acute angle with the direction of flow, and a pronounced scour if it is inclined downstream.

Observations in the Mississippi River indicate that in alluvial rivers depths in pools are a function of the river's discharge, while depths over bars vary with the slope. For the same slope, the depth in pools increases with the discharge. For the same discharge, the depth over bars increases as the slope diminishes. However, a slight increase in the depth over bars accompanies an increased discharge.

These conditions may be reversed, however, in rivers flowing through glacial drift, as is forcibly illustrated by a comparison of the regimen of the lower Mississippi River with that of the St. Clair River, of Lake St. Clair, and of the Detroit River, which connect Lake Huron and Lake Erie. In the lower Mississippi River wherever steep slopes exist, shoals occur, and wherever the slope is reduced to 0.2 foot per mile, a channel of ample depth for navigation exists. In the connecting waters between Lake Huron and Lake Erie, the greatest depths are formed where the slopes are relatively steep, and when the slope becomes less than 0.1 foot per mile the natural crossings are extremely shallow.

During storms from a northerly quadrant a large amount of sand, gravel, and shingle is transported along the shores of Lake Huron, a portion of which enters the St. Clair River. An insignificant amount of this material is in suspension. The sand waves instead of being propagated along the river bed as in alluvial rivers, enter the mouth of the St. Clair River along its banks, and contract the river instead of shoaling it. The steep slope and swift current which are thus created scour out the finer material and pave the banks with a deposit of gravel and shingle which protects them from scour as efficiently as a revetment. As the slope diminishes further downstream, coarse sand is deposited, in an enlarged river section of less depth. The finer sands are carried to Lake St. Clair, where the slope is inappreciable, and a bar is then formed through which channels originally existed having depths varying from two to six feet.

At the foot of Lake St. Clair, there is a similar movement of sand into the Detroit River during northerly storms, which, though less in amount than in Lake Huron, has been sufficient during geological ages to form a bar at the mouth of the Detroit River similar to that at the mouth of the St. Clair River.

The formation of these lake bars is similar to the delta formations of rivers in tidal seas, and also resembles the deposit which occurs where an alluvial river overflows its banks. They are highest where the water first leaves the confined bed.

Both in alluvial rivers and in those formed by glacial action, however, the pools tend to form in the bends and the bars in the straight reaches between them. If the forces acting in a bend produce a diagonal bar in the reach below it, and if the bar has a long crest line when compared with the river's cross-section, the water flows over the bar in a thinner sheet than it does when the bar is located more nearly at right angles to the axis of the channel. This dispersion of the water prevents so great a scour during falling stages as results from a more concentrated flow, and there exists a shoal crossing that obstructs low-water navigation. The modern science of river regulation consists in converting such poor crossings into good ones by so directing the river currents as to cause the bars to assume a position more nearly at right angles to the axis of the river than they do in a state of nature.

From what precedes, the flow of a river may be summarized as follows:

In every river bed the uplands are being continuously eroded, and the material thus removed is being deposited in the valleys or transported by the streams to a sea or lake, and is gradually being reduced in size the further it is removed from the zone of erosion. In an alluvial river the heavier material is being slowly and intermittently rolled along the river bed, while lighter sands and clays are transported long distances in suspension. The water supply causing these changes flows over steep slopes with great velocity through the zone of erosion, but its slope and velocity are gradually diminished toward the river's mouth.

At the sources of rivers there are great variations between the high-water and the low-water discharge, but the longer the river and the greater the drainage basin, the smaller the ratio of the high-water discharge to the low-water discharge becomes, although they both increase.

Through the area of deposition, a river's bed is gradually rising. Its channel is not fixed, but is liable to a change in location after every flood. Below this area, the river assumes a sinuous course, with pools formed in its bends and bars in its straight reaches. The crests of these bars rise and fall with the rise and fall of the river. The slope of a river is not uniform, but is steeper over the bars than in the pools. The material carried in suspension tends to be deposited whenever the velocity is reduced. The material that rolls along the river bed moves in sand waves, or is intermittently in suspension. The movement of the water is periodic. The movement of material follows the periods of the movement of the water, but in place of being continuous is intermittent; "its journey to the sea is effected by a series of *étapes*"[1] (4).

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[1] This expression *étapes* can appropriately be translated in its military meaning: *a day' march*, with its stoppages for rest and refreshment.

CHAPTER V

A RIVER'S DISCHARGE — FLOOD PREDICTION

For water flow in a conduit a curve can be constructed which gives the relation between the height of the water surface and the discharge. This curve can be expressed mathematically by the equation

$$\text{(A)} \qquad Q = cd^{\frac{2m+1}{2}}\sqrt{s},$$

where Q is the discharge, c is a constant, s is the slope, d is the greatest depth, and m is an exponent varying with the shape of the conduit. The exponent m is 1 when the sides are vertical, between 1 and 2 when the side-wall is a curve concave to the water surface, 2 when the side-wall is triangular in shape, and greater than 2 if the side-wall is composed of convex curves that form a cusp at the deepest part (1).

If the slope remains uniform at different stages, the equation can be reduced to the form

$$\text{(B)} \qquad Q = c'd^{\frac{2m+1}{2}}$$

which represents some parabolic curve. The exponent of d varies with the shape of the conduit. Such a curve is frequently employed to express the relation between the stage and the discharge of a river, but it is liable to give erroneous results as ordinarily used.

As a river changes its stage, its slope does not remain constant, but is greater on a rising river than on a falling river. Instead of having the parabolic form of equation (B) shown in Fig. 1 by the line AB, the curve assumes the complex form given by equation (A). If a relation between height and slope could be expressed mathematically, the relation (A) would be represented graphically by some such curve as XBY, which is a curve of two branches, one for a rising river and one for a falling river. Since the slope is dependent, not on the actual rise and fall of the river, but on the *rate* of rise and fall, which is a varying quantity, a mathematical relation between the stage and the slope cannot be obtained, and the line XBY merely limits an area in which the discharge for a given height will be found. The exact value of the discharge depends on the rate of rise or fall.

Not only is the slope of a river perpetually changing, but also the area of the cross-section of the river varies as sand waves are propagated downstream in an unimproved section, or as the bed rises and falls in a section that has been regulated. These changes in the area of the cross-section occur irregularly and cannot be expressed mathematically in terms of the stage. Hence the curve of discharge, instead of being capable of representation by a parabolic curve, degenerates into a tangled skein within the area XBY, Fig. 1. If numerous discharges are measured indiscriminately on rising and falling stages, however, the mean of the discharge observations will produce a line AB, which should always be characterized as the ***mean discharge curve.***

When only a few discharge observations have been made, those at low stages may have been taken on a rising river and those at high stages on a falling river, or vice versa, producing for the mean discharge curve the line *abcd*, or the line $a'b'c'd'$. If these lines are extended beyond the sphere of the actual observations, as has often been done, the resulting errors are large, especially if the curves are extended as straight lines, according to a practice which is usual.

A river's slope may be affected also by the inflow from a tributary below the discharge station; and if the discharge measurements are taken during a sudden rise or fall of the tributary, still greater perturbations in the discharge curve occur, as represented in Fig. 1 by the lines *abef* and $a'b'e'f'$.

The reader is cautioned particularly against extending a mean discharge curve, no matter how accurately it has been determined up to a bank-full stage, to unmeasured discharges at flood stages. When a river overflows its banks, there is a violent change in its regimen which will be reflected in the mean discharge curve unless the river's flow be restrained by levees.

The reason that the slope of a river is more dependent on the rate of its rising and falling than on the actual stage is that the river bed possesses a reservoir capacity. On a rising river, a certain portion of the flow is expended in filling the bed, and the maximum discharge at a lower station is diminished by the amount of water thus expended. On a falling river, the water thus stored has to escape, and the discharge becomes greater at the lower station on account of this excess flow. Hence the time required for a rise or a fall becomes an important factor in determining

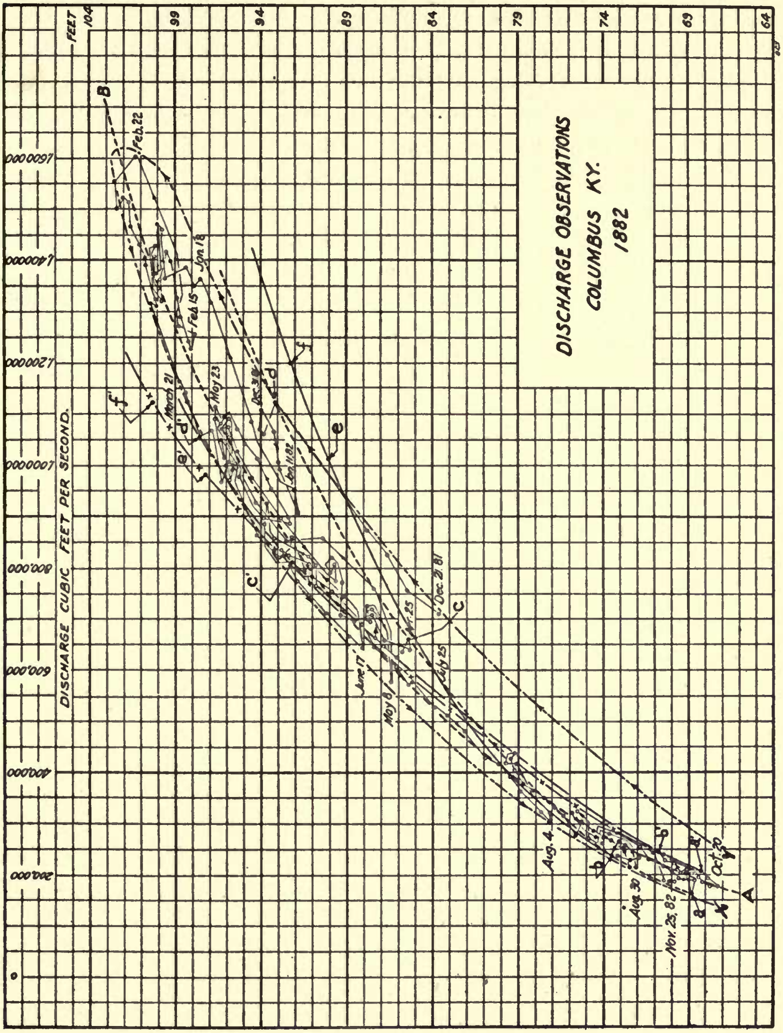

Fig. 1

the difference in elevation of the water surfaces at the two stations. If a river rises slowly, its slope will be gentler than if it rises rapidly.

A tributary can perform the work of filling the river bed, and thus affect the slope and the discharge at the lower station. Moreover, if one rise rapidly follows another down the river, the delay resulting from the filling and emptying of the pools will cause the second rise to overtake the first and add its waters to it.

On the long rivers of the United States, the rapidity of the rise and fall sometimes has a large effect on the slope and the discharge. Thus the crest of a flood of fifty feet in the Ohio River at Cincinnati may cause a variation of from thirty to fifty feet in the heights of floods at Cairo due to this cause, and Humphreys and Abbot cite a case where the maximum discharge of a flood-wave on the Mississippi River was reduced on this account by 400,000 second-feet in its passage from Columbus, Ky., to Natchez, Miss. (2).

The rate of transmission of a flood is a variable quantity that changes with the river's slope and with the area of land subject to overflow. The investigations of von Tein on the Rhine and its tributaries would indicate that, for the basin of the Rhine, with the possible exception of the Moselle, the rate of transmission is a function of the stage; and he has deduced an equation for the time of transmission of the flood-wave in terms of the stage and the distance, which he applies to the portion of the Rhine between Waldshut and Caub for stages between 2 meters and 5.50 meters. He submits a table of the rates of transmission of certain flood-waves, which shows that the flood of September, 1893, whose elevation was 220 centimeters on the Waldshut gage, was transmitted to Kehl, 189 kilometers, in 20 hours, while the crest of the flood of June, 1876, rising to 667 centimeters on the gage, required 54 hours to pass over the same distance (3).

On the Mississippi River at midstage, the rate of propagation of the flood-wave is a function of the slope. Between Cairo and the mouth of White River (392 miles), the slope is about 0.4 foot per mile, and the time of transmission of a flood-wave is about five days. From the mouth of Red River to Fort Jackson (274 miles), the slope is about 0.1 foot per mile and the time of transmission is about one day. Above a bank-full stage, however, on account of the time required to fill and empty the basins at the mouths of the St. Francis, White, and Arkansas rivers, the time required for the crest of the flood-wave to be transmitted from Cairo to the mouth of the White River varies from 5 to 10 days, while it is not affected below the mouth of Red River. If a crevasse occurs in the levees of the St. Francis basin, the maximum flood at the mouth of the White River may occur two weeks after the flood passes Cairo. On the Ohio River the rate of transmission of the flood-wave is about 75 miles per day; on the Missouri and on the Tennessee it is about 100 miles per day.

The rate does not exceed 4 kilometers per hour on the Saône or on the Seine below Paris, while it attains 6 kilometers per hour on the Garonne, and 8 to 10 kilometers per hour, or over, on the Rhône and on the Danube (4).

The time of transmission of the flood-wave of the Ohio from Cincinnati to Cairo is about six days, but the floods from the Cumberland, the Tennessee, and the upper Mississippi may so combine with it that the flood attains its maximum at Cairo ten or twelve days after the crest of the flood passes Cincinnati. There can also be such a combination of the discharges of the different rivers that the maximum flood height at Cairo will occur four days after that at Cincinnati.

During the so-called June rise of the Missouri River, the discharge of the upper Mississippi frequently determines the height of the flood at Cairo. If the crest of a flood-wave from the Ohio River arrives at that locality at a later date, it merely prolongs the flood stage.

One of the most difficult problems the engineer can be called upon to solve is the prediction of flood heights. Such predictions are required not only for the benefit of navigation, but also for agriculture. They are also a necessity for the preservation of the life and property of communities in valleys subject to overflow.

Many attempts have been made to predict flood heights by measuring the rainfall over the river's basin, and by computing therefrom the river's discharge. These attempts have met with little success, since the difficulties attending this method of prediction are practically insurmountable. The extreme variability of the rainfall would necessitate the establishment of an enormous number of rain-gages to record accurately the precipitation over a river's basin. The rain on a mountain peak differs from that in a valley; that over forests differs from that over cleared land; that over a city differs from that over the surrounding country; and even the records of rainfall in a gage on the roof of a building may differ materially from that of one established in a neighboring street. With measurements of precipitation in only a few large cities of the basin, a very inadequate conception of the rainfall of the entire area drained by the river is obtained.

The computation of the run-off leads to other difficulties. A geological survey may be made of the valleys and the permeability of the soil classified under certain conditions. The conditions are constantly changing, however. A rainfall preceded by a drought may be entirely absorbed by the soil, while if the ground has been saturated by preceding rains, the run-off may be a large percentage of the precipitation. If a field is plowed preparatory to planting a crop in the spring, its absorbing power largely exceeds that of the same field when the crop is being gathered in the fall. If a calm cloudy day succeeds a rainfall, the amount of water evaporated from the earth's surface is much less than when the sky is clear and a strong wind is blowing.

The great flood of 1912 in the lower Mississippi River was almost entirely due to a moderate rainfall in the Middle Western States, which fell on a soil which had become impermeable by its being covered with a layer of sleet formed earlier in the season.

An attempt has been made to provide for these variations by means of a different coefficient for the run-off for different months of the year. Thus on the German river Main, it is estimated by von Tein that in January 55% of the precipitation flows over the surface, in February 55%, in March 68%, in April 45%, in May 23%, in June 15%, in July 13%, in August 15%, in September 17%, in October 20%, in November 30%, and in December 33%. The evaporation varies from 40% to 55%, the absorption by plants from 0% to 28%, and the absorption by the soil from 0% to 40%. Von Tein employs these figures to determine the amount of the rainfall necessary to produce a flood in different seasons of the year. They are of little value in determining the height that the flood will attain.

The water flowing down the hillsides moves with much greater velocity than that collected in the swamps and marshes of the valley, so that the determination of the percentage of the precipitation that will enter the river from the various portions of the basin at the same time becomes a very intricate problem. The Burkli-Ziegler equation and those of a similar nature have been deduced from average conditions in an area, and are of value in determining the dimensions of sewers and drains. But it cannot be too strongly emphasized that floods result from exceptional conditions. In order to be of value, a flood prediction must differentiate between the exceptional and the average.

While it is impracticable to determine the absolute height of the flood by the methods referred to, they may afford early information when a large flood is threatening, and for this purpose an attempt at great accuracy is not desirable. A few rain-gages in impermeable torrential valleys of the basin will give indices of the flood which may be obscured if the attempt is made to combine with them the rain records of more permeable portions with gentler slopes. In the prediction of floods in the Department of Ardèche, France, where this method is employed, a flood warning is issued when the rainfall in 48 hours attains over 250 millimeters in the mountainous valleys (5).

Another method of flood prediction is by measuring the discharge at the origin and at various stations established on the tributaries, and computing the discharge at the lower station from these measurements. This method has been employed on the Elbe (6). It removes many of the difficulties resulting from attempting to determine the discharge from the precipitation. The process consists in determining the mean discharge curve at the different stations by numerous discharge measurements. From the curves are taken the discharge at such a time that the sum of the discharge of the main river and of its tributaries will be a maximum at the lower stations, and from its discharge curve the height the flood will attain is determinined. On account of the reservoir capacity of both the river and its tributaries on the discharge, the proper time to make the computation is difficult to determine and it frequently happens from this cause that the computed discharge at the lower station does not conform to the measured discharge. On the Elbe, the flood is derived from three tributaries which have a tendency to deliver their maximum discharge to the main river simultaneously, so that the computation is much simpler than would usually obtain in rivers.

A third method of flood prediction is based upon a study of the relations that exist between the heights of the gages on the river and on its tributaries. This method seeks to obtain corrections for the perturbations caused by the tributaries and to add them to a standard flood-wave propagated down the main stream. On the Rhine, where this method of prediction has been employed extensively, there is first determined a primary flood-wave, that is to say, the wave which would be produced if the tributaries did not exist, the relations between the stages attained by the primary flood at different stations being shown both graphically and by equations of the form $h_2=ah_1+b$, in which a and b are constant, while h is contained between certain limits.

The equations employed between Waldshut and Maxau (above the Neckar river) are in meters:

$$h_{mx}=1.01\ h_{wt}+1.28 \qquad 1.72<h_{wt}<3.73$$
$$h_{mx}=0.89\ h_{wt}+1.72 \qquad 3.73<h_{wt}<4.84$$
$$h_{mx}=1.27\ h_{wt}-0.11 \qquad 4.84<h_{wt}<6.30$$

in which h_{mx} is the height in meters at Maxau and h_{wt} is the height in meters at Waldshut.

For the perturbations caused by tributaries, similar equations have been prepared, and it is claimed that with some exceptions the differences between the floods as predicted on the Rhine and as they actually occur do not exceed 20 centimeters (7).

Since the Rhine rises in the Alps, and since its discharge is regulated by Lake Constance, it frequently has a flood when its lower tributaries are discharging little water. Hence the primary wave is more readily determined than in the rivers of the United States, whose tributaries, flowing at all stages with great irregularity, interfere with the primary wave flowing down the main stream. On the long rivers of the United States this method would not give as satisfactory results. Gage stations on the Rhine are less than 20 kilometers apart on the average; while on the Ohio River and on the Mississippi River they are frequently more than 100 miles apart, and it is necessary to make predictions over river distances of from 300 to 1500 miles. An error of 20 centimeters between stations on the Rhine may readily correspond to an error of from 10 to 20 feet on the Ohio between Cincinnati and Cairo, since the principal tributaries of the Rhine empty into the main stream within a distance of 150 kilometers.

On the Seine, M. Belgrand developed a method of prediction of floods by rises. Reporting on this method, M. Babinet says, "It eliminates an important source of error by taking account of the inequalities of the initial stage on the gage for which the predictions are made. To this stage (variable according to the circumstances which have preceded the flood considered) we add a probable rise calculated by the aid of actual rises at the stations of observation above. It will generally be a function of the first degree if the development of the series which corresponds to the influence of each gage up the river allows of considering them as converging rapidly enough"(8).

M. Belgrand selected eight stations at the headwaters of the tributaries of the Seine, in impermeable valleys. He considered the gage-readings at these stations as indicators of what was occurring in the entire extent of the basin, and he deduced an empirical law which gives the relation of the rises of the tributaries to that of the main river. He found that the rise in the main river is twice the mean of the total rises at the eight stations for a normal flood, but that the multiplier should be reduced to 1.55 when a second flood followed and was precipitated on one which was falling. He was able to predict flood heights at Paris within 40 centimeters three days in advance of the flood. By considering the inequalities of the initial stage of the gage for which the predictions are made, he recognizes the influence of the river slope on gage-heights. Herr von Tein introduces a correction for slope to a certain extent by adopting different equations for different stages, but it is self-evident that there cannot be the abrupt change at gage-readings of 3.73 and of 4.84 on the Waldshut gage that his equations indicate; such a change must be gradual.

A combination of the methods of Belgrand and von Tein has given good results at Cairo at the junction of the Mississippi and the Ohio rivers. It was adopted by the author when he was assistant to the Mississippi River Commission, and was constructing levees above Vicksburg, Miss. (1890–96). By this method he was able to prepare for the high-water protection of levees, nearly two weeks before the arrival of the crest of the flood, and he predicted in 1912 that the flood of the Mississippi would exceed in height all records at New Orleans, nearly one month before the flood arrived there.

Instead of attempting to determine the primary wave when there was no flow from the tributaries, a wave representing the mean of the heights at the different stations corresponding to a given stage at the origin was established. The variations from this height due to changes of slope and to perturbations caused by the tributaries is computed as explained in Appendix B. To calculate the formulas for this method of flood prediction, it is necessary to have gage-records extending over a period of at least ten years, and it is desirable to have records for at least twenty years.

CHAPTER VI

RIVER REGULATION

The various methods which have been proposed for improving the channels of rivers for navigation may be classified under five heads:

1. By regulation when the deepening of the low-water channel across the bars is caused by works of contraction.
2. By canalization, which consists in the construction of a series of dams across the river-bed, and overcoming the difference in elevation at the dams by means of locks.
3. By dredging and the removal of obstructions.
4. By reservoirs which impound the water during the high stages, and release it during the low stages, thus increasing the discharge when navigation becomes difficult.
5. By levees which confine the flood discharge, and utilize it to enlarge the low-water section.

The great necessity for obtaining increased depth in rivers for navigation has arisen from the utilization of the steamboat as a propelling power in place of animal traction. Conversely, the substitution of the steam engine for the horse has permitted the extensive improvement of our rivers. Prior to the invention of the steamboat, the flat-boat and the raft which were employed for transporting merchandise usually floated downstream with the current; but in ascending a river, animal traction was required, for which purpose a tow-path was built close to the bank and the boats were towed by horses, since the horse is a more economical source of power than a man handling an oar or a pole.

The first efforts to improve navigation consisted in bank revetment. This was done not only to prevent the land from caving into the river, but also to preserve the tow-path. When bank protection was afforded by projecting dikes, a longitudinal dike was frequently constructed close to their channel-ends as a tow-path. Many of the longitudinal dikes of the Rhine river were built originally for this reason.

When a sand bar obstructed navigation a longitudinal dike was constructed on one side of the channel to serve as a tow-path.

A second longitudinal dike was built near the opposite bank and connected to it, sometimes by a perpendicular spur-dike, but frequently by a dike which gave a funnel shape to the river channel. The distance between the dikes was computed by the ordinary hydraulic formulas, so as to give the desired depth for the low-water discharge with the local slope existing over the bar before the improvement was inaugurated.

When low-water depths not exceeding three feet were desired over gravel bars, this method of improvement by parallel dikes gave fairly satisfactory results. Frequently, however, greater scour would occur than was anticipated. The upper pool would be lowered, and a sand bar would be formed by the eroded material below the improvement. By the extension of the dikes so as to include in the contracted channel the new bar which had formed, a gentler slope would be created over the crossing, and the tendency to excessive scour on the bar would be checked. The resulting slight lowering of the upper pool did not seriously affect the slopes on the bar above. The Meuse River (1) in France, the upper Tennessee (2), and the Gasconade River (3) afford examples of this method of improvement.

With the introduction of steam power, greater depths were required in river channels to meet the competition resulting from the reduced cost of transportation on land. When it was attempted to increase the channel depths in a river whose bars had been deepened by parallel dikes, serious difficulties were encountered. A further contraction across the bar became necessary, and this involved the construction either of a new longitudinal dike or of a system of spur-dikes extending into the channel from the dike opposite the tow-path. The increased velocity generated caused the erosion even of gravel. An abnormal scour occurred across the bar, large deposits were formed in the pool below, and an excessive lowering of the pool above diminished the depths across its upper bar.

It was then attempted to modify the slopes in the pools, reducing their curvature as much as possible by the construction of longitudinal dikes of gentle curvature along their concave banks, and building submerged sills across them. The purpose was to give the river as straight a course as practicable with a uniform slope, in place of the natural sinuous course with gentle slopes through pools and steep slopes on bars.

The tow-path formerly had an importance on European rivers that it never attained in the United States. It could readily be maintained along a river thus straightened, but the flowing water was not as amenable to the change. The river through geological eons had been adjusting its length, its curves, and its slopes through pools and over bars to the character of the soil through which it flowed and of the material which it was transporting, and it had to adapt itself to the new conditions. The straightening of the river would reduce its length and therefore increase its slope. The slope through the pools would be further augmented by the change in the relation of the slope on the bars to the slope through the pools, and by the contraction of the area of the waterway. The transverse slope of the pool would become reduced by the straightening, the longitudinal velocity become largely increased, and the bed rapidly deepened even when the revetment of the bend preserved its bank from erosion. Unless the submerged sills were so numerous as practically to convert the river bed into a paved conduit, this deepening frequently became so great as to undermine the revetment and to destroy it, and if the revetment was of the mattress type extensively employed in the United States, the material on which it rested tended to slide into the river. If there was a longitudinal dike of rip-rap, so frequently found as a bank protection on European rivers, a serious settling occurred.

The material thus eroded would be added to the sand waves that were being transported down the river, and be slowly moved through the contracted section, increasing the height of the sand waves during rising stages of the river; and, during falling stages, channels usually of insufficient depth for navigation became scoured through them.

These sand waves following one another through the contracted section produced below it a bar which raised the water surface, and combining with the lowering of the water surface in the pool above, created a slope sufficiently gentle to reduce the scour to normal proportions. The mean slope through the improved section finally became gentler than that of other portions of the river, and the channel was locally improved, but at the expense of the slopes and depths at other localities. Since the total fall in a river from its source to the sea is a fixed quantity, a diminution of slopes in one section must be accompanied by an increase at others.

M. Girardon cites as an example of the injurious effects of straightening a river, the Canal de Miribel on the Rhône. An excellent example is also afforded by the improvement of the Mississippi River in front of the city of St. Louis. On account of the commercial importance of that city, the river channel was so constructed as to follow the Missouri bank, within the city limits. This contraction and straightening has reduced the slope to 0.2 foot per mile on a river which normally has an average slope of 0.6 foot per mile, and an excellent channel exists in front of the city, but the slopes on the Chain of Rocks immediately above have been injuriously affected and annual dredging is required on the crossings below the city.

At the Sixth International Navigation Congress in 1894, M. Girardon presented a project for improving the river Rhône, in which (instead of attempting to straighten the river and equalize its slopes), he proposed to allow it to pursue its natural sinuous course, with gentle slopes in the pools and steeper ones on the bars, and to create the improvement by converting poor crossings wherever they occurred into good ones. The result was to be brought about by giving a suitable direction to the river currents across the bars.

According to M. De Mas, this suggestion of M. Girardon caused a revolution in river regulation. When combined with the investigations of M. Fargue on *The Influence of Bends on Channel Depths*, it led to an entirely new conception of the proper functions of the works constructed to improve channels. The direction which the works of contraction gave to the confined waters became of more importance than the relative amount of contraction; and since the steamboat had finally displaced animal traction, the river channel became free from bank control, and could be given such a direction as to produce the proper effect on the bars. This method of river regulation may be called the French method, as distinguished from river straightening, of which the ablest exponents were German authors.

When this method is followed, the sinuous course of the river is preserved, or even intensified, so as to render more stable the location of the bars. No attempt is made to obtain uniform depths, nor uniform slopes. The bars are permitted to form in the crossings and their crests to rise with a rise in the river stage, but during a falling stage the currents are given such a direction as to scour a channel of the desired depth across them.

The curved *tracê,* instead of permitting sand waves to move unrestrained along the river bed, removes them from the pools, and permanently locates them in the crossings. By giving a proper curvature to the bends, the obliquity of the bars to the axis of the channel is diminished, and the volume of the flow across them is concentrated to the extent necessary to produce suitable channel depths. The most characteristic difference in the two systems of river improvement is shown in the use of ground sills. In the German system, the ground sill was used generally to modify the slopes in the pools. M. Girardon employs it to restore the steeper slope of the crossing, and to preserve the pool level, if by any means the scour has become too great for the natural formation of a bar at that locality.

The investigations of M. Fargue[1] have been presented in the form of the following six laws:

> "I. The Law of Deviation. The deepest and the shallowest points in the channel are below the vertex and the ends of the curve, respectively. On the Garonne, the displacement is about one-fifth the length of the curve, but is less than that on the shallower crossings.
>
> "II. The Law of Greatest Depth. The point of maximum depth is the deeper as the curvature of the vertex of the curve is sharper. The relation between depth and curvature on the Garonne is given approximately by the formula
>
> $$C = 0.03\,H^3 - 0.23\,H^2 + 0.78\,H - 0.76,$$
>
> where C represents the reciprocal of the radius of curvature at the vertex of the curve expressed in kilometers and H is the low-water depth at the deepest point of the channel expressed in meters.
>
> "III. The Law of the Tracé. In the interest of both the average and maximum depths, the curves should neither be too short nor too long. On the Garonne, this length is preferably about one and one-third kilometers.
>
> "IV. The Law of the Angle. For equal lengths of curve, the average depth of the pool is the greater as the central angle

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[1] Étude sur la Corrélation entre la Configuration du Lit et la Profondeur d'Eau dans les Rivières à Fond Mobile, par M. Fargue, Ingénieur des Ponts et Chaussées, Annales des Ponts et Chaussées, Mémoires et Documents, 1868, p. 34.

subtended by the curve is the smaller. The equation derived from this analysis on the Garonne is

$$H = 1.50 + \sqrt{C^2 + 1.71C}$$

in which H represents the average depth of pool at low water in meters, and C the reciprocal of the average radius of curvature in kilometers.

"V. THE LAW OF CONTINUITY. The longitudinal channel profile shows gradual variations only when the curvature changes gradually. Abrupt modifications of depth accompany rapid variations in curvature.

"VI. LAW OF THE SLOPE OF THE BED. If the curve varies continuously, an increasing radius of curvature marks a reducing depth and a decreasing radius of curvature is accompanied by a deepening. The rate of change in depth which is the slope of the bed is approximately represented on the Garonne by the equation:

$$Q = 0.1553p + 0.0114p^3,$$

when Q is the variation per kilometer of the reciprocal of the gradually changing radius of curvature expressed in kilometers, and p is the variation per kilometer of the depth given in meters (4)."

In the improvement of European rivers, a longitudinal dike frequently is constructed in bends. As such a dike can be given any desired form, there has been considerable discussion as to whether it should be constructed in the curve of a parabola, a lemniscate, or a sinusoid. The arc of a circle extended by tangents across the bars conflicts with Fargue's laws. In the United States, there is not the same latitude in selecting the proper curve, since bank revetment by mattress construction has been substituted almost universally for the longitudinal dike in the protection of bends. This construction must follow the sinuosity caused by the natural caving of the bend, but even with this method of construction there is considerable latitude in the direction to be given to the currents, since fortunately the caving of a bend only exceptionally conforms to the arc of a circle, and the point of divergence of the current from the bend is optional, to a certain extent, with the engineer.

To comprehend the importance of Fargue's laws, let us assume that a river flowing along the bluff which limits one side of a valley is diverted by some cause to the opposite bluff, that it leaves one bluff and approaches the other in circular curves, and that it is required to improve the crossing between them. The extension of the bank by dikes on lines tangent to the curves, as shown by broken lines in Fig. 2, is forbidden by Fargue's laws, and the reason is obvious from a little investigation.

In the curve created as the river leaves the bluff, a steep transverse slope is produced with a resulting helicoidal movement of the water, which causes the channel to "hug the concave bank," as river pilots say. The sand scoured from the channel is deposited on the convex side, at a distance from its point of departure varying with the longitudinal slope of the river, and the sharpness of curvature of the bend.

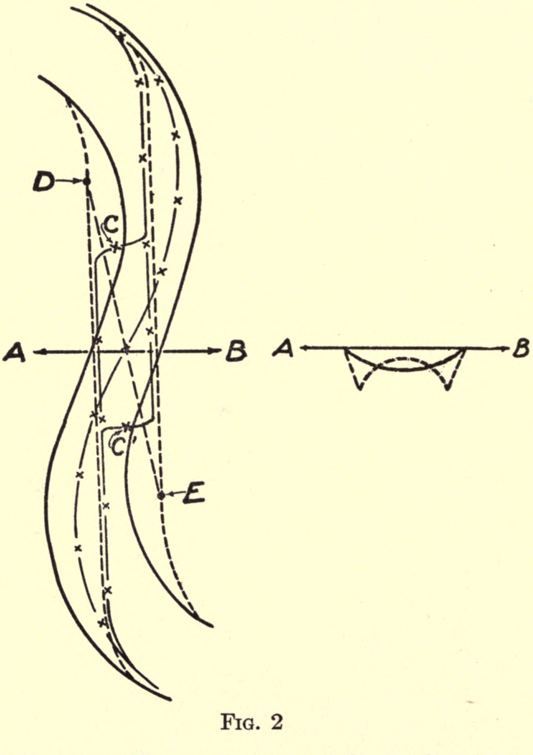

FIG. 2

While the tangent to the curve has no power to produce a transverse slope, it will conserve for long distances one that is already created, and the thalweg will continue to hug the dike tangent to the concave bank until the helicoidal force created by the transverse slope has exhausted its energy. There will also be a deposit of sediment on the opposite side of the river, which will form closer to the channel as the energy is diminished and will finally attach itself to the dike near the point where the transverse slope becomes again horizontal. This will result in the formation of a long diagonal bar *DE* across the river during rising stages (Fig. 2).

As the river falls the water flows over this bar in a thin sheet, with no concentration of force at any particular point, and it finally scours through it at some point as *C* or *C′*, where finer material was deposited accidentally during the rising river. Such conditions usually produce a shoal and crooked channel difficult to navigate at low water. If, however, the bank curves so as to produce a reduced degree of curvature below the vertex of the curve, instead of the circular form first assumed, or if a dike is constructed as shown by the full lines of Fig. 2, the transverse slope created at the vertex of the bend has an opportunity to flatten out, and the line of deepest water, instead of remaining close to the dike, tends to return to the middle line of the channel. The helicoidal flow diminishes and the longitudinal flow along the convex bank increases.

The bar across the channel leaves the dike connected to the convex bank further downstream, and attaches itself to the opposite dike further upstream, creating a shorter crest over which the currents have a greater erosive effect while the river is falling. The thalweg follows a straighter line and is deeper and much easier to navigate at low stages.

As the river approaches the curve at the lower bluff, there is a reaction which also merits consideration. On account of the inertia of the water, the transverse slope which is created there cannot be formed suddenly. If a dike tangent to a circular arc extends upstream, a gradually diminishing transverse slope is propagated along it by the reaction similar to the one transmitted downstream along the tangent to the curve at the upper bluff.

This creates a gradually increasing helicoidal motion as one approaches the lower bend, with the result that the thalweg also hugs the tangent to the lower curve and will not conform in direction with the one above the bar. The scour across the bar will tend to produce a river cross-section shown by the broken line *AB* in

Fig. 2, with a mobile channel across the bar approximately at right angles to those in the upper and lower pools. It is therefore necessary to modify the curve of approach to the lower vertex in a manner similar to that necessary after leaving the vertex of the upper bend, thus forming the sinusoidal curves advocated by M. Fargue.

Not only are proper curves necessary in the upper and lower pools, but also their lengths must be such that both thalwegs will pass through what M. Fargue calls the point of inflection for curves turning in opposite directions, or the point of surflection when the curves continue in the same direction. This leads to the law of the tracé that, in the interest of both the average depth and the maximum depth, the curves should neither be too short nor too long. Their proper length is a direct function of the difference in level on the opposite banks of the bends, and an inverse function of the river's longitudinal slope.[1]

In the case assumed, the location of the curves was fixed by the configuration of the ground. When the natural curves are too short or too long, the problem of overcoming this condition presents itself. If the curves are too long, the difficulty frequently can be obviated by introducing additional bends. If the curves are too short, the slope over the crossing will be destroyed, the low-water surface will be permanently lowered, and it can be restored only by the construction of submerged sills, which will limit the depth during low stages.

By creating proper curves in bends and by extending them by dikes, the French method of river regulation seeks to give a proper direction to the river currents so as to obtain suitable depths on the crossings; the material scoured from the channel is deposited on the banks opposite the dikes in such a manner as to create proper widths both across the bars and in the bends; and according to the investigations of M. Fargue, the river assumes a greater width in the bends than on the crossings. This assumes that the *filaments of flowing water have the same radius of curvature as the dikes they follow.* Such an assumption, however, can be true only for certain stages. During a flood, a river's discharge is ordinarily

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[1] Figure 2 is inserted to illustrate a general principle, and is not drawn to scale, since this would necessitate further assumptions in reference to the distances and the slopes. Under certain conditions, the contraction by the tangents, instead of permanently locating the bar along the line *DE*, would induce a motion of sand waves through the reach, and the cross-section *AB* of the bed could be maintained only by submerged dikes.

from 20 to 50 times that of low water, and the water tends to flow with a much larger radius of curvature. The thread of maximum velocity may then have a gentler curvature than the bend, and may impinge upon the dike at some point lower in the bend than the vertex. The filaments of water are then forced by the dike into a change of direction with a sharp radius of curvature.

Above this point there is a tendency to eddy action, which may fill the channel scoured at lower stages, and a channel may scour across a chord of the bar on the convex bank.

Below the new vertex thus formed, the dike ceases to conform to M. Fargue's law of continuity, and the obliquity of the bar below to the center line of the channel is affected. To reduce these disadvantageous conditions as much as possible, the works of regulation are given a low elevation, so that the great mass of the flood-waters will pass over them.

On the Rhône (5), the elevation of the curved dike is one meter above low water at its vertex, gradually diminishing to the elevation of low water at its extremities. In the latest project for the improvement of the Po (6), it is proposed to give longitudinal dikes an elevation of one meter above low water.

To protect the longitudinal dikes from scour behind them during floods, it is necessary to join them to the bank by means of spur-dikes which have a slope from the bank to the dike with the same elevation as the dike at the point of junction. To prevent the current during floods from scouring across the points of bars, a series of spur-dikes on the convex banks of bends is necessary. These are given as low an elevation as practicable at their channel ends so as to interfere with the flood discharge as little as possible, and are made to slope gradually upwards towards the bank, so that, as the stage falls after a flood, the river will gradually revert to the regulated form that has been given it at low water.

While the dimensions of the channels across the bars are carefully computed, reliance is placed on ground sills and spur-dikes to maintain the desired channel, and submerged dikes are frequently employed to assist the longitudinal dikes in giving a proper direction to the river currents. In fact, reliance is placed on dike construction to correct any errors that may have been committed in the mathematical computations. By these means, the crossings are given a fixed position with a scour over them in a proper location during falling stages.

While the French method of river regulation is considered the proper one, the student is cautioned that river improvement is not susceptible of the rigid mathematical analysis which obtains in certain other engineering fields, such as bridge construction for example. The principles are immutable, but the conditions that exist in nature are not susceptible of mathematical expression with our present knowledge. Each river has its own equation.

Even the process of river straightening which Fargue's laws condemn has been applied successfully to the lower Rhine River, where low-water depths of three meters are maintained with a reasonable amount of dredging. Herr Jasmund (7) calls attention to the fact that in former days the lower Rhine was given an abnormal degree of curvature by the enlargement of the islands, which were crown lands. The increase in size of the islands was accompanied by a caving of the adjacent bends, and natural conditions have now been restored by the works of river regulation. On the upper Rhine, river straightening has produced a lowering of the river, but M. Coblenz states, in a description of the Rhine, that notwithstanding the straightening of numerous bends between Mannheim and Mayence, the slope and the velocity are still extremely feeble. He adds that, in the project for the improvement of the river above Strasburg, a sinuous course for the low-water channel has been adopted (8).

CHAPTER VII

DIKE CONSTRUCTION AND BANK PROTECTION

A rigid adherence to the French system of river regulation would require a longitudinal dike along the concave bank of a sinusoidal form and of low elevation to give proper direction to the low-water flow. This dike would have to be connected to the bank by a system of spur-dikes to prevent scour behind it, and a system of similar dikes on the convex bank would have to be built, to prevent scour of that bank during high stages. These dikes would be given as low an elevation as practicable at the limiting line of the low-water channel, and would be made to slope gradually upwards as they recede from it, so as to bring the river back to the low-water channel on declining stages. The crossings also must be protected by spur-dikes to prevent the high stages from producing an injurious scour.

When the low-water discharge of a river is small and the maximum depth on bars must be attained to provide the depths required by navigation, a rigid adherence to these requirements may be necessary. In the United States, the low-water discharge of most rivers that are being regulated is fortunately large, and the projects for improvement of these rivers do not require the maximum practicable development of the depth on bars. This fact permits a considerable latitude in the curvature which can be given to the bends, and economical considerations have therefore led to a marked difference between the methods of construction employed in river regulation in the United States and those at present prevailing on most European rivers.

The excessive cost of a longitudinal dike of rip-rap, in the depths found in the bends of the large rivers of the United States, almost precludes its employment for bank protection, not only on account of the expenditure in its original construction, but also on account of the large amount of money required for maintenance due to the great scour that the dike creates in the river bed. Consequently, there has been substituted very generally a bank revetment consisting of a subaqueous brush mat covered with a sufficient amount of stone to hold it in place, and an upper bank pavement consisting either of rip-rap, of stone more carefully laid, or of concrete.

The extensive growth of willows on the bars of our western rivers furnishes a cheap material for the construction of the mats, which also can be employed economically in many localities to form the body of the spur-dikes on the opposite bank. The substitution of the revetted bank for the longitudinal dike necessitates the utilization of the natural curves created by caving, instead of the theoretically perfect form which can be given to the dike. There is a resultant loss in the scouring power over the crossing below, but this loss is justified by reasons of economy if the depth obtained across the bar exceeds the limits prescribed by the project. There still remains, however, considerable latitude in determining the direction to be given to the river in its passage from one bank to the other.

The large amount of sediment carried in suspension in many American rivers has also led to the substitution of permeable dikes instead of spur-dikes of gravel or stone. These dikes consist of one or more rows of piles, strongly braced, on which was originally suspended a wattled screen of willow brush, to check the current and cause a deposit of the sediment. In the turbid waters of the Missouri and the middle Mississippi, the screen is now omitted as the piles themselves have been found to check the flow sufficiently to cause a large deposit. The piles are spaced about two feet apart in two or more rows in quincunx order and are bound together in groups of three. This forms a structure of considerable resisting power to floating ice or debris.

By means of such spur-dikes the banks are raised by river deposits to any elevation below a bank-full stage that may be desired, and there is no reason why the same method could not be employed to induce deposits during flood stages if it were considered necessary. There is, however, a practical limitation to the height of such dikes in rivers that carry a large amount of drift during floods or of ice during freezing weather. If there is not a sufficient deposit of sediment before the drift or ice can accumulate above the structure in quantity, the dike may be destroyed by lateral pressure. Thus, in a river in which the deposits between permeable dikes can readily attain the mid-stage height during a single rise, the attempt sometimes is made to raise them to such a height that the made ground can be used for agricultural purposes. This will require the action of several floods. Before this can be accomplished, the tops of the dikes will retain a mass of floating debris which may exert enough lateral pressure on the piles composing them to cause their destruction.

The French method of regulation, which requires low dikes at the limiting line of the low-water channel, gradually increasing in height as the dike recedes from this line, tends to minimize this danger, since the greatest accumulation of drift usually takes place at the outer end of the dikes, and will pass over low dikes as the river rises to high stages.

When stone is abundant, as on the middle Mississippi River, the drift can be sunk as it forms against the dike, and instead of destroying it, increase its stability.

On the upper Missouri River, there has recently been substituted for the permeable dike the *retard*, which consists of a mass of trees whose butts are anchored to piles in the river bed, thus artificially creating a structure similar to the drift which accumulates against a permeable dike. The branches of the trees check the flow of water and induce a deposit of sediment, but they are sufficiently flexible to permit the passage of ice and drift over them, without destroying the structure. There is also not as great a scour at the outer end as in ordinary dike construction.

Retards have been efficient as substitutes for bank revetment, particularly when the river has not been regulated systematically and detached protection is required for bridges or landings. They adjust themselves to changes in the curvature of the river current more readily than mattresses which have been sunk several years. At localities where trees are of little value and stone is expensive, they are cheaper than the ordinary mattress construction.

When the amount of material carried in suspension is small, as on the upper Mississippi River, the permeable dike is not as successful. Not only is there danger of its destruction by drift and ice, but the portions of the piles above low water, not being protected by sand deposits, become alternately wet and dry, and rapidly decay. On this river (1) spur-dikes made of brush fascines and covered with stone to hold them in place have been employed extensively. These dikes are protected from being undermined by the water flowing over their crests by extending the lower layer of brush about ten feet below the dam proper, while the sand which settles in them affords a partial protection from settlement due to decay. On many rivers of the United States, the dikes are constructed of rip-rap or of gravel covered with rip-rap.

On the Rhine, prior to 1880, gabions made of woven brush and filled with gravel were employed extensively in dike construction to the level of low water, the upper portion of the dike being composed of gravel covered with rip-rap. Since that date, the channel has been deepened extensively by dredging, and the body of the dikes is now generally composed of the gravel obtained from the dredging and is protected from scour by rip-rap. The downstream faces of such dikes are steep and are protected by rip-rap. The upstream faces have gentle slopes, about 1 to 4, and they are left unprotected when the current is not too strong.

Since dredging has been introduced as an auxiliary to the improvement of the upper Mississippi River, there is also a tendency to construct dikes of the material dredged from that river, and to cover them with mattress and stone revetments similar to those used in bank protection.

Considerable study, particularly by German authors, has been given to the subject of the proper distances between spur-dikes, and their proper inclination to the direction of the river flow. The early German practice on the Rhine was to construct the dikes with a considerable inclination downstream. Such dikes induced a scour along them which caused considerable settlement, and such a caving of the banks between them that it was necessary to connect the outer end of one dike with the inner end of the one next below it. This produced the *triangle werk* (2), which was employed to a considerable extent on the German Rhine.

As a result of many years of investigation, the practice on German rivers, as described by Schlichting (3), is to give dikes an inclination upstream of 105° to 110° on straight reaches, 100° to 102.5° on concave banks, and 90° to 100° on convex banks. They are located so that their axes intersect in the middle of the channel. They are spaced at 5/7 of the channel width in straight reaches, at half the channel width on concave banks, and at the full width on convex banks.

The French and Italian practice is also to give spur-dikes a slight inclination upstream, while in the United States they are approximately perpendicular to the river currents, though examples of dikes can be found that are strongly inclined downstream. This is true particularly in work done by railroads to protect their tracks from caving where they are constructed along a river bank. A spur-dike perpendicular to the current produces the maximum contraction with the least expenditure of material. European spur-dikes are usually given an excess of rip-rap at their outer ends for the purpose of filling the hole scoured by the current passing around them. The proper inclination to reduce the dimensions of this scour is of more importance in Europe than in the United States, where the scour is prevented by sinking a mat at the end of the dike similar to that used in bank protection.

When it is considered necessary to construct spur-dikes on the concave bank of a river, the permeable dike has a great advantage over one that is not permeable, provided the river carries a large amount of material in suspension. In the discussion of the laws governing the flow of water, attention was invited to the eddy action produced below it by an obstruction extending toward the channel from the bank of a river. This eddy not only induces a deposit behind the dike, of material that is being rolled along the river bed, but also produces a caving of the bank a short distance further downstream. If a permeable dike is constructed, the flow along the river bank is only partially checked, and therefore the eddy action is greatly reduced. The fill behind the dike, instead of being entirely due to material rolled along the bed, is caused principally by the deposit of material in suspension; and the point of attack of the eddy current on the river bank is moved such a distance downstream that a second spur-dike can be constructed economically to prevent its action. By means of permeable spur-dikes it is thus possible to build up by deposits a new bank of any curvature desired at a cost less than that of the dikes which are employed in Europe to connect the curved longitudinal dike to the bank. The cost of revetting the new bank line thus formed is much less than the cost of constructing a longitudinal dike.

Spur-dikes on a concave bank are much more liable to be destroyed by floating debris and ice, however, than are those on the convex bank, since the helicoidal flow of water in a bend carries material floating on the surface of the river toward the concave bank. The downward flow of the water along the newly built-up bank gives it a steep slope towards the river, so that the ends of the dikes project considerably above the river bed. After the new bank has been formed, it is therefore necessary to cut down the outer ends of the spur-dikes to the slope of the new bank, and to protect the bank with a revetment, or the work will be gradually destroyed.

When a longitudinal dike is not constructed in a bend, the method of bank protection at present usually adopted on European rivers is a covering of rip-rap. "Quarry stone is deposited on the tracé of the work and there takes its natural slope. On rivers with a movable bed, the first rip-rap sinks, the mass is reënforced, the soil is consolidated, and after a greater or less length of time, according to the mobility of the bed and the swiftness of the current, stability is acquired, and the slope then assumes the form of a concave curve" (4).

Earlier French authorities (5) for reasons of economy recommended the substitution of gabions filled with gravel for a portion of the rip-rap, a method of bank protection which also has been employed extensively by the Italians on the Po River. The rip-rap is generally given a slope below low water of 1 vertical to 2 horizontal, though there are examples on the Po of slopes of 1 to 1½. The thalweg depths in bends thus protected are usually large.

In the first attempts to protect the banks of the Rhine (2), the Germans employed masses of brush made into fascines and sunk along the bank to be protected, which fascine mass had a width approximately equal to the river depth. This method of bank protection was called *bleeswerk.* Following the practice in Holland, the slope of the protection facing the river was first made vertical, but excessive scour resulting therefrom, the *bleeswerk* was given a slope of 1 to 1 by a royal decree of 1744. The undermining and destruction of the work still continued, however, as illustrated by the attempts to protect the bank at the city of Wesel. There was substituted for *bleeswerk* first the spur-dike inclining downstream, and then the *triangle werk.* These methods also gave such unsatisfactory results that for a time all methods of bank protection were abandoned, and recourse was had either to diverting the river from important localities threatened with destruction by caving banks, by cutting an auxiliary channel through the neck of land opposite them, as at Wesel, or by moving the smaller villages further inland. Much of the river straightening of the lower Rhine has resulted from this cause.

Later Herr Nobling, when in charge of the improvement of the Rhine, employed a submerged spur-dike called a *Nobling*, which has been successfully used in bank protection, particularly on straight reaches. The Noblings were originally constructed of gravel, protected from scour by gabions filled with gravel, and more recently of gravel covered with rip-rap. They extended into the river from the mid-stage on the bank with a slope of about 1 to 4. The upper bank was given a slope of 1 to 2 and was paved with rip-rap stone.

In concave bends caving occurs between the Noblings, and it has been necessary to protect the bank between them, for which purpose the material obtained by dredging the river has been employed extensively, with a covering of rip-rap. A similar type of structure has been constructed on the Mississippi river to protect the bends in front of the cities of New Orleans and Greenville. At New Orleans it has been necessary to supplement the dikes with a mattress revetment between them. At Greenville, the floods of 1890, '91, '92, and '93 caused such a caving between the dikes that several were undermined and destroyed, and have been replaced by mattress revetments.

In the United States, while the rip-rap of stone has been employed occasionally for bank protection, the great depth found in the bends of the western rivers and the scour that is caused by the revetment has rendered this method very expensive. Except for small streams, there usually is substituted a subaqueous mat of brush with an upper bank protection either of rip-rap, of stone more carefully laid as a pavement, or of concrete. There are great variations in the method of constructing the mat, due principally to the character of the brush that is found in the vicinity of the work. In the Mississippi River, between St. Paul and the mouth of the Missouri (1), the brush is made into fascines about twelve inches in diameter, which are bound together by binding poles and laid parallel to the bank. On the Mississippi, between Cairo and Vicksburg (6), the fascines have a diameter of about sixteen inches and are laid perpendicular to the bank. Between St. Louis and Cairo (7) the brush is woven through the binding poles. On the Missouri River (8), a much smaller willow brush is employed than on the Mississippi, and the method of weaving gives to the upper surface of the mattress the appearance of a woven basket.

Where brush is difficult to obtain, a mattress of boards has been employed (9). The boards are of the class commercially known as culls, and are from 4 to 8 inches in width and one inch in thickness. They are woven through the binding poles similarly to brush. This form of revetment has been successful on the upper and middle Mississippi but has quite generally failed on the Red River. It is believed that this failure is due to faulty construction. Recently extensive experiments have been made on the lower Mississippi in utilizing concrete as a subaqueous bank protection (10). Both thin reënforced concrete slabs and reënforced concrete blocks have been used.

The essential conditions that a mattress must fulfil are that it should have sufficient thickness to protect the soil on which it is laid from the action of river currents, and sufficient pliability to adapt itself to the irregularity of the ground. The various types of mattresses conform to these requirements. There are, however, certain precautions which must be observed in mattress construction, or serious breaks are liable to occur in the revetment.

A caving bank ordinarily assumes under water the natural slope of the material of which it is composed, due to the constant supply of such material by the caving. When the revetment is constructed, this supply ceases along the part protected. Since the eroding force still continues to act, there is a tendency to deepen the portion of the river beyond the revetment. Hence the scour at the outer edge may be very great if the mattress does not extend beyond the thalweg. This produces a surface with a steeper slope than the saturated material of which it is composed can maintain, and large masses will slide into the river, carrying the revetment with it. The mattress therefore must extend a sufficient distance beyond the thalweg to protect the slope and to prevent it from attaining an unstable inclination.

A sufficient amount of stone must be placed also on the outer edge of the mattress to force it to sink into the deepened channel as fast as the scour occurs. If not, the mat will be undermined. When green willow brush is first cut, it is very pliable, but after several seasons of exposure to water, it becomes quite brittle. A change in the direction of the currents may produce a deepening of the channel by increasing the scouring power several years after the mat has been laid, and unless an excess of stone is added originally, the old mat cannot follow the change. A stiff mat projecting into the river currents and unsupported by the river bank is liable to destruction by the vibrations caused by whirls and eddies.

If the caving bank is not homogeneous, but is composed of layers possessing different resistances to erosion, the slope that it will assume during caving on a rising river will not be regular, but will be steeper in those portions which most resist erosive action. Such a bank may be in an unstable equilibrium and as the river falls, a slide may occur where the slopes are too steep to sustain the pressure exerted by the weight of the soil above. By giving a gentle slope to the portion of the bank above low water, this tendency may be minimized, but even with slopes as gentle as 1 to 4, such slides occur, carrying the mattress with them and causing a break in the revetment near the low-water line. On the portion of the Mississippi River above Cairo such breaks are comparatively small and can be repaired readily during the next low-water season; but on the lower river, on account of the great depth in the bends, they may attain large dimensions, and may seriously damage the revetment.

Another cause of failure of mattresses is the passage through them of the material composing the bank in sufficient quantities to cause the bank to settle. This action is rarely due to the scour of river currents through the mat, but arises during low stages from a flow of water from the bank into the river, carrying a large amount of sand with it. The source of the water supply is usually a neighboring pond and the bank must contain a layer of sand readily acted upon by the flow through it. This danger usually can be removed by the proper drainage of the land in the vicinity of the revetment. The borrow pits for levee construction frequently become stagnant pools of this character.

The most serious breaks in revetments, however, have resulted from failure to complete the improvement of a bend by the construction of the necessary spur-dikes on the convex bank after the concave bank has been protected. Attention has been invited to the tendency of the river currents to assume different radii of curvature at different stages. It has happened not infrequently that a revetment has been constructed and the construction of the spur-dikes opposite it has been deferred either from lack of funds or from a desire to protect some other threatened locality. A flood then occurring scours a channel across the projecting point and the river currents impinge almost perpendicularly on some portion of the revetment. A sudden change of direction with a short radius of curvature is created which scours a deep hole at the foot of the revetment, and the revetment slides into this. The channel along the revetment above the point of impact frequently is filled with sediment deposited by eddy action and a serious disturbance of the river's regimen results. A cut-off will cause disastrous caving in a similar manner by changing the river slopes and thus affecting the radius of curvature of the flow.

The mattress usually is carried up the bank to the elevation of the water surface at the time of construction, but the portion above low water is subject to decay and should be covered by a rip-rap of stone to insure the permanence of the work.

The upper bank is graded to the prescribed slope (from 1 on 2 to 1 on 4) and either is paved with stone laid so as to give a thickness of about one foot, or is covered with about four inches of concrete (11). The grading frequently is done by manual labor or by scrapers. On the high banks of the lower Mississippi, hydraulic grading usually is employed.

The use of stone or concrete for the upper bank pavement is dependent on the proximity of stone or gravel to the work. Where stone can be quarried in the vicinity, it is more economical than concrete, but if it has to be transported long distances, concrete may be cheaper. Concrete offers a greater resistance to the action of ice than a stone pavement, because the ice freezes around the individual pieces of stone and is liable to remove them from the bank when it starts to flow downstream in the spring. Floating ice will also more readily slide over a concrete revetment, while it tends to dislodge fragments of a stone pavement.

Both types of revetment require protection from rain water flowing down the slopes and washing out cavities under them during low stages of the river. A ditch at the top of the bank, with occasional properly paved drains down the slope, will eliminate this danger. Wave action from severe wind storms is more destructive to a bank paved with stone than to one covered with concrete.

While the brush mat affords a more economical method of bank protection than a deposit of rip-rap, it is usually too expensive a method to be employed profitably for the protection of agricultural lands except when the revetment is an adjunct to the improvement of the river channel for navigation, and numerous substitutes have been suggested, many of which have been patented. There is a marked tendency in the United States to rediscover methods of bank protection which have been tested in Europe for many years and have been found defective. Thus, the *bleeswerk* abandoned on the Rhine in 1796 has its advocates on the upper Missouri River. Fine examples of dikes extending downstream, rejected by the Germans over one hundred years ago, are to be found in the protection of railroad tracks on the Kaw River in Kansas; and the *triangle werk* which failed at Wesel has been reproduced on some of our western rivers. The suspension of the trunks of trees along a caving bank is but a weak imitation of the *tunnages ordinaires,* described by Defontaine (5) in 1830, as then employed by the French along the Rhine in Alsace. The Neal dikes are based on the principles of the Noblings, but instead of filling the gabions with gravel on land and sinking them in place, a cellular structure of brush and poles is constructed in the river bed and allowed to fill with sediment, a method of construction used by the Italians in the Po prior to 1682. They have the same defect as the Noblings of requiring bank protection between them in sharp bends. However, where the river bank has been scoured to an irregular slope and there is danger of sliding if protection is afforded by a simple revetment, a cellular structure can be constructed on the revetment which will rapidly fill with sediment and a stable slope will thus be formed. This method has recently been employed successfully for the protection of the abutments of the Iron Mountain railroad bridge across the Arkansas River near Watson.

The Fuller timber dikes inclining upstream, unsuccessfully employed on the Red River, have their prototypes in the *pennelli* (12) of the Po River, constructed in the seventeenth century to protect Cremona. The Brownlow weed and other devices which rely on the floating branches of trees to deposit sediment are similar to the *Epi de Branchage* employed on the Midouze River in France, and described by M. Malezieux in his *Cours de Navigation Intérieure* in 1876, but instead of being anchored to the river bed, the branches were attached to piles.

Attention has been called to the use of permeable spur-dikes to cause deposits on the concave bank of a river. Permeable longitudinal dikes also have been employed for the same purpose, particularly on the Missouri in the vicinity of St. Joseph. Such dikes induce a rapid fill, and floating debris and ice have no opportunity to lodge along them, as is the case with spur-dikes. River currents, however, induce a scour, which renders it necessary to protect the river bed with wide mats; and the fill which accumulates exerts a lateral pressure so that the dike has to act as a retaining wall, for which purpose it is not well adapted. During periods of low water, the piles composing it are subject to decay, and during floods to an erosive action by the movement of debris and ice along them. After a limited life it is usually necessary to replace the structures with some form of revetment.

CHAPTER VIII

RIVER IMPROVEMENT BY CANALIZATION

Wherever a river's slope is locally diminished, the depth over its bars is increased. By building dams across the river channel, pools are created above the dams which have very gentle slopes during low water, the greatest change in the elevation of the water surface occurring at the dam. This principle has been employed extensively in improving the navigation of rivers, and is particularly successful when the low-water discharge and the amount of sediment transported are small.

The material moved by such rivers during low stages is insignificant. During high stages it tends to form bars immediately below the dams, through which channels can be maintained readily by dredging. As the sediment carried increases, the amount of dredging required may become so large as to make the cost of maintenance excessive. By substituting for fixed dams some of the numerous movable types which have been invented, this item of maintenance can be reduced materially.

A movable dam is one in which the portions that obstruct the river's flow may, when it is desired, be lowered to an elevation previously determined above the river bed, or removed from the river channel. By properly operating such dams when the amount of sediment moving in a river increases, its velocity may be so regulated that material in suspension does not tend to deposit, and the material rolled along the bed conforms to the laws governing it in an unobstructed river. During high stages the unobstructed portions of the river bed become navigable passes. It is then unnecessary for vessels to pass through locks to overcome the difference of level that exists at the dam during low water. They also reduce the gage-heights which fixed dams cause in the flood discharge, which is an important consideration in thickly populated valleys.

Dams have been divided into two classes, fixed and movable. Movable dams are divided into certain types dependent on their moving parts. In recent construction, it is exceptional that a dam is constructed of a single type. Even fixed dams have sluices controlled by movable gates, and a movable dam has frequently one type of closure for its navigable pass, and possibly two types of gates for its weirs. Occasionally a dam is of the fixed type to a certain elevation and is surmounted by a movable crest which is employed not only to regulate flood heights but also to afford a navigable pass during high stages when the fixed portion of the dam is drowned out. On a rising river, the stage increases more rapidly at the foot of a dam than on its crest, but the rate is variable and depends on the stage, on the slope of the river, and on the form of the valley below the dam. At some stages, a rise of one foot on the crest of the dam is frequently accompanied by a rise of from two to three feet at its foot. Hence, at certain stages, the slope over the dam becomes so slight that boats can navigate the main river channel, provided there is a sufficient depth over a portion of the crest of the dam, and boats can thus avoid the delays incident to the passage through a lock.

Movable dams were first practically used for improving navigation by the French. In their early construction, Poirée (1) needles were employed extensively, but the inventive genius of the French and of other nations has led to a confusing multiplicity of types, even on the same river and frequently on the same dam. While there has been considerable discussion of the advantages and disadvantages of the different types, it is not always evident that even local conditions justify many of the variations.

The ***Poirée needles*** are of timber, usually of rectangular cross-section. In the earlier designs, they were of such weight that they could be placed readily in their proper position by hand. When placed in the dam, their lower ends rest against a sill of timber or preferably of concrete, and their upper ends against a bar which is supported by trestles hinged to the base of the dam so that they can be lowered behind the sill when the needles have been removed. The free ends of the trestles are connected by a chain. The process of raising the dam consists in pulling on the chain till the trestles are in an upright position. The bar is then placed against the trestles, and the needles are placed side by side, supported by the sill and the bar. A foot-bridge is constructed on the trestles to enable these operations to be performed.

As the needles were made larger, difficulty was experienced in removing them and the supporting bars were replaced by escape bars so arranged that the bar of any pair of trestles could be tripped. This released the needles between two trestles, and they were allowed to float down the river, held together by a rope so that they could be recovered. A hook was also fastened to the upper end of the needle, so that power could be applied through a winch.

By substituting stop-planks for the needles, the ***Boulê gate-dam*** was evolved (1). The ends of the stop-planks rest against the faces of the trestles, and slide along them. The sliding friction limits the size of the gate which can be handled readily, but by causing it to move on rollers this friction can be largely reduced, and the size of the gate increased. By inserting between the gate and the support a chain of rollers, the ***Stoney Gate*** is created. This form of gate can be manipulated with a small expenditure of power, so that gates of large size can be constructed.

When weirs are regulated by large gates, masonry piers are frequently substituted for the metallic trestles, and a masonry structure is substituted for the wooden foot-bridge, so that the sluice-ways become openings in the face of the dams. Over the navigable pass both the trestles and gates may be supported by a steel bridge of sufficient clearance to permit boats navigating the stream to pass under it when the movable parts are raised. Such bridges may be utilized as road-bridges, as are some of those constructed over the Mohawk River on the New York Barge Canal. The Emergency Dams of the Panama Canal (2), and those at Sault Ste. Marie, consist of swing-bridges which are swung across the channels and from which the trestles and gates are lowered when required.

For the gate there has been substituted in some cases the ***Camerê curtain*** (3), which "consists of narrow horizontal strips of wood hinged together, and capable of being rolled up by an endless chain which passes round them, each curtain reaching from the surface of the water to the sill." For the curtain there has been recently substituted the ***rolling dam*** (4), which consists of a metallic cylinder resting on masonry supports. When not in use, it is rolled up an inclined plane above the water surface by powerful machinery.

In the dams described above, the parts which prevent the flow of the water are removed from the dam during floods. In a large variety of types, they are lowered to the river bed. The ***Thenard shutter*** (1) was one of the early forms of movable dams adopting this principle. It consists of a shutter hinged to the base and held in position by a prop resting against the shoulder of a casting, called a *hurter*. It was soon developed into the ***Chanoine wicket*** (1), which has been adopted very extensively for the navigable pass both in France and in the United States. In this type of dam the shutter, instead of rotating about its lower end, is hinged above its middle third to a frame called a *horse*. The horse also rotates about a hinge connecting it to the base, and is held in position by a prop supported in a hurter.

The Thenard shutter offered such a resistance to the water while being placed in position, that an auxiliary dam of counter shutters had to be erected before the props could be engaged in the hurter. The horse of the Chanoine wicket, however, can be raised and its prop placed in position while the shutter is floating on the water's surface; and after the horse is erected, the wicket can be swung into position by pressure on its lower extremity.

Two methods are employed for lowering the dam, and the hurters have to be adjusted to the method employed. For narrow passes, a *tripping bar* is frequently used. It consists of a flat steel bar with projecting teeth which moves in a groove on the hurters close to the props, the projecting teeth being so arranged as to press successively against them. The tripping bar is manipulated by gearing in the piers or abutments, and the teeth force the props from the shoulder into a groove beside it, along which the prop slides until the horse and wicket assume a horizontal position.

Another method of lowering the dam is to pull the wicket forward until the prop is released from the shoulder of the hurter, and the groove is so constructed as to cause the hurter to slide into it in this advanced position. Such an arrangement is called a ***Pasqueau hurter***. In addition to the groove which guides the prop while the wicket is falling, there is a second groove which guides it to its proper position on the shoulder when the horse is raised. The wickets can be raised and lowered from a footbridge or from a maneuvering boat.

The ***Girard shutter*** (1) is a modification of the Thenard shutter, in which the prop is connected to an hydraulic piston which forces the shutter into its proper position and holds it there by means of water pressure against the piston. By reducing the water pressure the shutter is lowered.

In the ***Desfontaines drum-wicket*** (1), the shutter which closes the weir is rigidly connected to a second shutter operating in a chamber called the *drum*, which is constructed in the masonry of the dam. By applying water pressure to the proper side of the leaf inclosed in the drum, the upper shutter is raised and held in position, and by removing the pressure the dam is lowered. By locating the drum on the downstream side of the shutter, and placing in it a floating pontoon which rises and falls by hydraulic pressure, the shutter can be raised and lowered. The ***Krantz wicket*** (1) with pontoon works on this principle, the pontoon being pivoted to the dam along its lower edge and the shutter pivoted on the pontoon and sliding along a masonry face as it rises and falls.

In the original ***Brunot gate*** (1), the shutter is connected to the dam by hinges, and the pontoon slides along it when being maneuvered. In the modified Brunot gate, the caisson and shutter rotate around the same pivot, and the shutter becomes the deck of the pontoon.

The ***Chittenden drum-wicket*** (3) works on the same principle, but the shutter is supported by a frame which forms the sector of a water-tight cylinder, and the bottom of the pontoon is removed.

The ***Taintor gate*** (3) is similar in form to the Chittenden drum-wicket, but the axis of rotation is placed above the water surface, and the stresses are reversed, the sector of the cylinder closing the opening instead of the upper radii. The gate is raised to permit a flow through the weir, and frictional resistance is largely reduced because rotating motion is substituted for sliding motion.

In the ***bear-trap dams,*** two shutters are used which overlap one another when the dam is lowered. Through a chamber under the leaves, hydraulic pressure can be applied which will cause them to rise. In the first dams of this type constructed (10), both shutters were hinged to the foundation of the dam and one leaf slid along the other as the dam rose. In the ***Carro dam*** (1), the downstream leaf is hinged to the dam, while the upstream leaf is hinged to the downstream leaf and slides along the crest of the weir as the gate is maneuvered. The bear-trap dam of the Chicago Drainage Canal is of this type, except that the upstream leaf slides along the face of the dam, instead of along its crest, and the gate is balanced by counterweights.

In the ***Lang bear-trap dam*** (3), the upper leaf consists of two parts, one hinged to the dam and the other to the lower gate. These parts slide on one another as the gate is maneuvered. In the ***Parker bear-trap dam*** (3), the two parts of the upper gate are also hinged together, so that the gate folds as it is lowered.

In the ***Thomas A-frame dam*** (3), the shutter is rigidly connected to its prop, and both are hinged to the dam so that they can be lowered into a recess on the masonry along the crest of the dam.

There are numerous minor modifications of these types. An attempt to discuss their relative merits would extend this book unduly and invade the domain of a treatise on mechanical engineering. The Poirée needles and Chanoine wickets with Pasqueau hurters are the types usually employed in the United States for closing navigable passes; the original bear-trap dam is used for closing weirs which require rapid manipulation; and for closing sluices on fixed dams, the Stoney and Taintor gates usually are favored on account of the small frictional resistance in operating them.

In early days timber was extensively employed not only for the movable parts of dams, but also for fixed dams in the form of timber cribs filled with stone. At the present time, metal replaces timber as far as practicable in the movable parts, and the fixed dams generally are made of concrete. Gravity types of dams also have been replaced in some cases by hollow dams of reinforced concrete or of steel. They are sometimes given an arched form, with their stability depending on transferring the stresses to which they are subjected to the abutments. In a gravity dam, the necessary weight given it to prevent overturning usually affords an ample coefficient of safety against sliding, but in movable dams, and in fixed dams for which reliance is placed on water pressure to hold them in position, a special study of this source of failure is necessary in connection with their design.

When water power was developed from the water wheel and was utilized in the local mill, dams of low elevation prevailed, but with the development of electric power, there has been a tendency to build higher dams, even when the dams are adopted primarily for purposes of navigation. As a result, foundation difficulties have increased greatly. Failures due to sliding have occurred in movable dams founded on rock, and they have been quite numerous where reliance has been placed on a foundation of gravel, sand, or silt.

Homogeneous impermeable rock makes a perfect foundation for a structure, but it is rarely found in river beds. Crevices and fissures usually exist which permit the passage of considerable water under high heads. This exerts an upward pressure on the base of the dam. Little reliance should be placed on the adhesion of concrete to rock, particularly to slates or to shales. Failures have occurred by the rock itself breaking under the lateral pressure exerted. A mass of concrete of sufficient weight to resist sliding, itself keyed and fastened to the rock by drift bolts for increased safety, is recommended for the foundation of all dams. De Mas has well stated that in river construction economies should be limited to the work above water which can be observed.

Next to rock, a gravel bar usually is considered the best location for a dam, and it is unquestionably true that gravel offers a greater resistance to a dangerous subsurface flow than sand or silt. However, it is not safe to make assumptions regarding the difference, and foundations based on such assumptions are liable to fail. On a gravel bar, it is difficult to drive the wall of water-tight sheet-piling which it is usual to rely upon to increase the length of the path of subsurface flow in sand or silt, and dams have been constructed on a timber grillage without pile support in gravel. On the Osage River, the water excavated a hole under such a dam several years after its completion, which carried the entire low-water discharge; and a section of a dam on the upper Mississippi was destroyed before the cofferdam was removed. The cause of such failures is explained in Chapter II.

Clay is a good foundation on land but it is rarely found in alluvial rivers except at considerable depths, being usually so mixed with sand as to produce what is termed silt. When the water-tight wall of sheet piling can be driven into a layer of impermeable clay, a most satisfactory cut-off wall can be constructed between the two pools, and the danger of percolation can be eliminated.

Sand and silt are recognized as unstable foundations. While numerous failures have been recorded in the past, a stable structure can be erected on them with proper precautions. To prevent settlement, the dam is supported on piles. To limit percolation, a water-tight wall of sheet piling is driven at the upper face of the dam. It is usually impracticable to obtain a clay sub-base into which the sheet piling can be driven and all percolation prevented, but the velocity of the flow can be so reduced as to be incapable of moving the material of which the foundation is composed.

It has been found practically in levee construction on the Mississippi River that if the water is forced to travel through the alluvium of the valley, over a path which exceeds ten times the head, the soil acts as a filter, the material held in suspension is deposited, and the outflowing water is clear. Occasionally, however, while the sediment is deposited, sand boils will appear behind the levee line, indicating that the water still has sufficient force to move small particles of sand. If a sub-levee is built behind the main line so as to reduce the head to 1 in 15 as the space between the levee lines fills with water, this motion of sand ceases. Experiments of a similar character have demonstrated that if the head can be reduced to one foot in twenty, a scouring flow through the fine silt of the rivers of India can be prevented.

In levee construction, the necessary length of path to produce the proper relation to the head usually is obtained by extending the levee base. In concrete dam construction this method is too expensive, and the water usually is forced to a path of the proper length, by constructing under the dam a water-tight wall of sheet piling whose tops are imbedded in the concrete of the base. When such a wall is used, the length of the path of the flowing water is computed as along the base, vertically down one side of the sheet piling and up the other side. If a second wall is constructed under the dam it should be spaced at least twice the depth of the pile penetration from the first wall. This form of structure is not usually favored by American engineers, since the second line of sheet piling increases the water pressure under the dam.

Another danger has recently been discovered in the investigations of the Miami Conservation Commission (5). If the water contains certain amounts of animal or vegetable matter, gas generated by decomposition is liable to accumulate in the space between the walls and to cause a considerable variation in the computed pressures.

Another method of increasing the length of path to be followed by the water is to deposit over the bed above the dam a layer of impervious clay. Nature frequently reduces the percolation under dams by making such deposits, and in the experiments on the Miami River referred to above, the natural deposits of silt were more efficient in reducing the upward pressure under the dam than the walls of sheet piling. In a dam constructed on the Ouachita River, it was attempted to combine the two methods and to reduce the amount of penetration required of the sheet piling cut-off wall by a covering of clay above the dam. The attempt was unsuccessful, and a second line of sheet piling had to be driven to prevent a dangerous subsurface flow.

The water flowing over the top of a dam is also a source of danger. Even when dams are founded on rock, the impact of the falling water frequently will wear away the rock foundation. The dam constructed across the Mississippi River at Keokuk, Iowa (6), in 1913 has already required a concrete protection to portions of its foundations. Where the foundation is gravel or sand, special care must be taken to prevent the overflow from undermining the dam. To receive the impact of the water, an apron is constructed which may be composed of heavy rip-rap, or which may be a timber crib filled with stone and decked over with timbers securely fastened to the structure. A layer of concrete frequently is substituted for the timber floor. The ratio of the width of the apron to the height of the dam is usually from one and one-half to two; but when the bed of the river is a fine silt, as is the case at certain dams in India, the rip-rap apron may extend for long distances. The Dauleshwiram dam (7), with a crest head of 16.8 feet, has an apron 185 feet long. The Laguna dam built by the Reclamation service in Arizona, with a crest 19 feet above the river bed, is a rock-filled dam with three concrete cut-off walls. The apron is combined with the dam and given a surface of concrete of uniform slope. The total width of the dam is 244 feet. The Mahanuddee weir in India, a similar structure whose crest elevation is 13 feet, and whose base width is 173 feet, was seriously damaged during a flood.

The same precautions must be taken to prevent percolation around the abutments of a dam as under its foundation. There is also usually a certain contraction of the waterway at the site of the dam which induces eddy action below it and necessitates bank protection.

There has been considerable discussion of the proper location of dams provided for river improvement, whether they should be placed in straight reaches of a river or in bends, and if in bends whether the lock should be on the concave or convex bank. A dam should have as long a crest as practicable to reduce flood heights, but it may be more economically constructed in straight narrow river sections. The entrance to a lock on a convex bank is more readily obstructed by sand, and one on the concave bank by drift. The deciding questions on lock and dam construction, however, are usually the character of the foundation and the topography of the site. The ideal location for a lock is on one side of an island, with the waste weir of the dam on the other side.

With a small low-water discharge, it is sometimes necessary to substitute a lateral canal for the natural river channel, and to utilize the river merely as a feeder. This is the only practical method of constructing a navigable channel through the area of deposition. The lateral canal also affords a convenient method of surmounting rapids. When a river has an ample low-water discharge, and a gentle slope, the substitution of a lateral canal for river regulation is inadvisable not only on account of the increased cost, but also on account of the necessarily contracted section of the waterway. The resistance of a boat to motion is much less in a wide river.

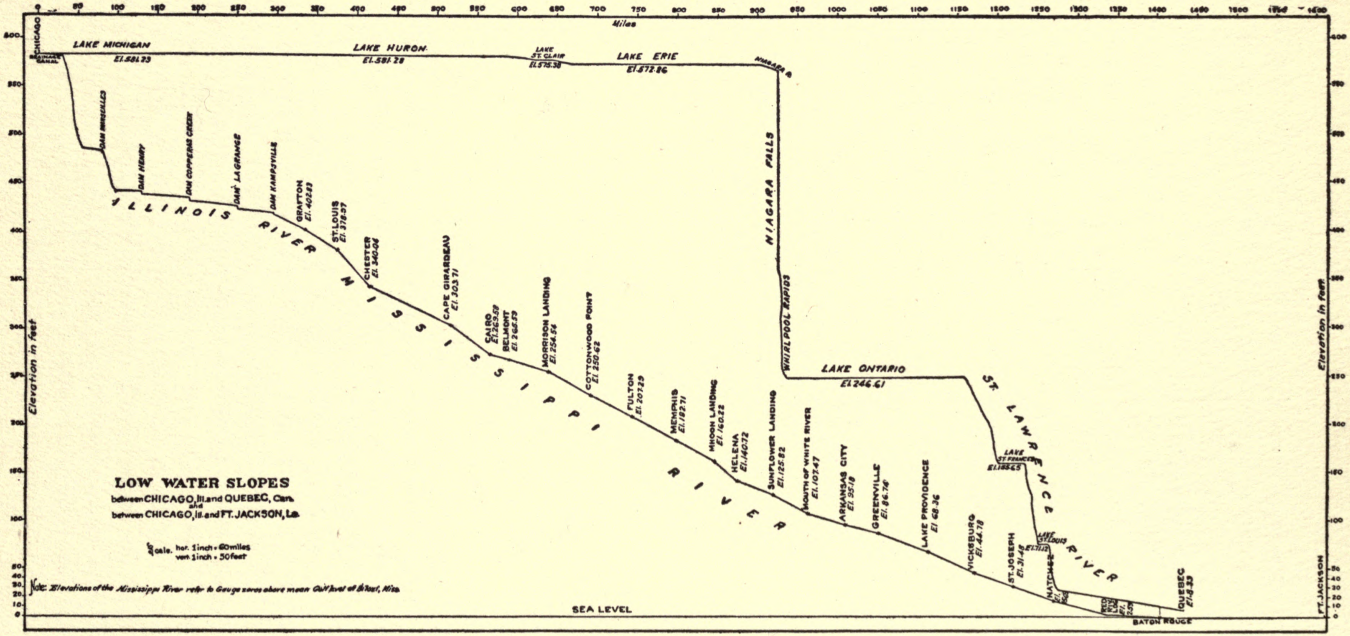
Dams convert the river channel into a series of lakes, and the flow of sediment instead of conforming to that in an unrestrained alluvial stream resembles that which exists in valleys formed by glacial action. The material which is rolled along the river bed as sand waves is deposited in the upper pool and may be insufficient to fill it for a long period. In the remaining portions of the canalized bed, increased depths may result, since the normal supply of material in motion has been reduced. Material in suspension is deposited further downstream. Its deposition resembles that which occurs on the banks of an alluvial river during floods, and is the greatest where the velocity is first checked, and gradually diminishes as the supply of suspended material is exhausted. The downstream slope of a deposit from a sand wave is relatively steep, while that of a deposit derived from material in suspension is very gentle, not infrequently averaging as little as one foot per mile.

There is a shoaling of the channel and an increase in river slopes wherever the deposit occurs, and either periodic dredging is necessary at such localities to maintain the depths required for navigation, or the channel must be contracted so as to remove the deposits by scour. The works of contraction also must be periodically extended, as deposits form in the pool below them. Hence if regulation is relied upon to maintain the channel, the regulation dikes must ultimately extend through the entire section of the river that is canalized, even when the changes in slope caused by the construction of the dams have removed all tendency to bank caving in the river bed.

For this reason a river flowing through glacial drift can be improved by canalization more readily than one flowing in an alluvial valley. In Chapters II and IV attention was invited to the relatively small erosive power of the water of glacial rivers, and to the tendency of such rivers to flow with gentle slopes, until obstructed by rock ridges or by moraine deposits over which the fall is concentrated in rapids or cataracts. The canalization of these short obstructed reaches frequently will create a navigable channel for long distances, from which the deposits of sand waves can be dredged economically. Thus in the St. Lawrence Valley, as shown in Fig. 3, the greater portion of the slope is concentrated in the Niagara River, in which the fall is about 315 feet, and in the upper St. Lawrence River, in which the fall is about 216 feet. The Canadian Government has developed a navigable waterway of fourteen feet depth from Montreal to Lake Erie, by constructing a system of lateral canals around these obstacles, and the United States Government has created and readily maintains a navigable channel of twenty-one feet depth from the foot of Lake Erie to Chicago, a distance of about 900 miles by rock excavation and dredging in the waters connecting Lake Huron and Lake Erie, in which the fall is only nine feet.

In the waterway from Chicago to the Gulf of Mexico, the slopes are more uniformly distributed than in the St. Lawrence Valley. Its canalization, therefore, would necessitate the construction of a series of dams between Chicago and the mouth of the Red River. The pools thus formed in the glacial valleys of either the Desplaines or the Illinois rivers, would not tend to fill with sediment, as they should derive their water supply from Lake Michigan. Below the mouth of the Missouri, however, all attempts to maintain navigation by dredging would be futile on account of the amount of sediment which is carried by that river at all stages, and deposited whenever the velocity of the current is diminished. The estimated yearly discharge of sediment by the Mississippi River is 400,000,000 cubic yards. Some 200,000,000

FIG. 3


LOW WATER SLOPES
between CHICAGO, Ill. and QUEBEC, Can.
and
between CHICAGO, Ill. and FT. JACKSON, La.
Scale. hor. 1 inch = 60 miles
vert. 1 inch = 50 feet
Note: Elevations of the Mississippi River refer to Gauge zeros above mean Gulf level at Biloxi, Miss.
Miles
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
Elevation in feet
600
550
500
450
400
350
300
250
200
150
100
50
40
30
20
10
0
CHICAGO
DRAINAGE CANAL
LAKE MICHIGAN
El. 581.23
LAKE HURON
El. 581.28
LAKE ST. CLAIR
El. 575.38
LAKE ERIE
El. 572.86
NIAGARA R.
NIAGARA FALLS
WHIRLPOOL RAPIDS
LAKE ONTARIO
El. 246.61
ST. LAWRENCE RIVER
LAKE ST. FRANCIS
El. 155.65
LAKE ST. LOUIS
El. 71.12
QUEBEC
El. 8.33
DAM MARSEILLES
DAM HENRY
DAM COPPERAS CREEK
DAM LAGRANGE
DAM KAMPSVILLE
ILLINOIS RIVER
GRAFTON
El. 402.83
ST. LOUIS
El. 378.97
CHESTER
El. 340.06
MISSISSIPPI RIVER
CAPE GIRARDEAU
El. 303.71
CAIRO
El. 269.58
BELMONT
El. 265.59
MORRISON LANDING
El. 254.54
COTTONWOOD POINT
El. 250.62
FULTON
El. 207.29
MEMPHIS
El. 182.71
MHOON LANDING
El. 160.22
HELENA
El. 140.72
SUNFLOWER LANDING
El. 125.82
MOUTH OF WHITE RIVER
El. 107.47
ARKANSAS CITY
El. 95.18
GREENVILLE
El. 86.76
LAKE PROVIDENCE
El. 68.36
VICKSBURG
El. 44.78
ST. JOSEPH
El. 31.48
NATCHEZ
RED RIV. LDG.
El. 2.55
BATON ROUGE
FT. JACKSON
SEA LEVEL

cubic yards would be deposited annually even if the dams were limited in height to a bank full stage. It therefore would be necessary not only to create the pools by canalization, but to contract them by regulation by the amount which is necessary to maintain the velocity of flow that exists in the unimproved river. Such contraction would also reduce to a minimum the storage capacity of the reservoirs which are created by the dams, and limit their capacity to produce a continuous water power.

The advocates of the canalization of the river claim that the large water power developed would justify the enormous cost of the project, and appear to base their estimates on maximum or mean river discharges. Such discharges could not be utilized for power production on the lower Mississippi River. A marked increase in flood heights from dam construction could not be permitted, since the crests of the levees along certain portions of the river have an average elevation of about 20 feet above the surface of the ground under existing conditions. It would, therefore, be necessary to produce the change in river slopes by numerous low dams. Such dams at high stages would be drowned out.

In the development of water power a certain velocity must be produced in the water wheel to create a given electrical energy, and the wheels therefore are designed for an assumed head. A uniform velocity can be maintained with small variations in head by regulating the flow through the intake, but such adjustments are impossible when the heads vary between 30 feet and zero. The drowning out of the dam will suspend the production of electric power. A power derived intermittingly from water is of little value, since a steam plant must be installed for use during the period that it is not in operation and this plant could also operate when the water power was available. The saving in the coal bill while the steam plant is idle is offset by the interest on the cost of the water power plant. In the St. Lawrence Valley variations between high and low water are small and can be regulated readily, since the water wheels which are installed operate at high heads.

When the principles governing the regulation of rivers were not properly understood, and dredging was relatively expensive, a school of engineers arose which advocated canalization as the only method of improving non-tidal rivers, but it is recognized at the present time that "the navigability of rivers having but one current can be improved as it has been stated many times at the Navigation Congresses by various methods such as: Regulation of the bed by permanent works; regulation of the bed by mechanical dredging; increase of depth by an additional water supply furnished by storage reservoirs; canalization of the bed; combined action of two or more of these processes; construction of a lateral canal. The use of one of these methods rather than another depends upon the special circumstances of each particular case." (PERMANENT ASSOCIATION OF NAVIGATION CONGRESSES, REPORT OF PROCEEDINGS OF THE XIITH CONGRESS 1912, p. 386.)

An excessive deposit of material in suspension during the period in which it is necessary to maintain the dams for navigation, a large discharge which creates a river of great width, the difficulty of securing suitable foundations for the dams, low banks through which there is a seepage injurious to crops when the dams are raised, are important factors in determining whether a river should be improved by regulation or by canalization. The Rhine, the Danube, and the Po rivers in Europe and the Mississippi River in the United States can be improved by regulation and dredging to the desired depth more economically than by canalization.

On the other hand, the slope of a river may be so great that, notwithstanding the fact that its discharge may be sufficient to insure adequate depths, the necessary contraction by regulating dikes may increase the velocity of its currents to such an extent that the force required for towing boats upstream becomes greater than that required for hauling a railway train of the same carrying capacity.

The Rhône has been improved by regulation to a low-water depth of two meters. The slopes on this river are excessive, however, and make up-bound navigation difficult. Notwithstanding the success of the improvement, canalization has recently been proposed with dams of such lifts that water power can be developed from them. It is claimed that the power development would pay for the cost of construction. In the revised project for improving the upper Mississippi River, two short lateral canals with locks are being constructed around the Rock Island rapids for the benefit of up-bound navigation, although the channel through the rapids is retained for down-bound traffic.

It can be stated as a general law that mechanical dredging usually affords the most economical method of maintaining a channel of moderate depth near the mouths of large rivers (see Chap. xii), that when compared with dredging the importance of regulation as a means of improvement increases as the low-water discharge diminishes and the slope increases (see Chap. ix), that a further increase in slope may render canalization more economical, and that the substitution of a lateral canal for a canalized river is justifiable under certain conditions, notwithstanding the increased cost of towing within its contracted waterway. Where rapids make navigation difficult a lateral canal may be constructed whose initial cost may be less than that of a dam extending across the river. If, however, water power can be created by building the dam, its utilization may make the canalization of the river bed a more profitable investment. The Keokuk rapids in the Mississippi River were surmounted, formerly, by a lateral canal. A high masonry dam (6), however, has been constructed across the river recently, which not only develops water power, but also facilitates the movement of vessels on account of the substitution of a single lock with a high lift for the locks of moderate lift in the lateral canal. When the banks are so low that movable dams would cause the overflow of the land along the river or cause a seepage that would be injurious to agriculture, the lateral canal may be necessary. The discharge of the river determines whether regulation of the river bed or the construction of a lateral canal is preferable.

The fact that a dam built across the bed of an alluvial stream will cause a deposit of the detritus which is transported down its valley, is of importance not only in river canalization but also in reservoirs constructed for power development and for furnishing cities with a water supply. This deposition continues until the reservoir capacity is reduced to such an extent that the stream will flow with sufficient velocity through the reservoir to transport its sediment, and ordinarily if the reservoir capacity is to be maintained, the cheapest method of removing the deposits is by dredging.

If the detritus moves in sand waves and in relatively small amounts, an auxiliary dam can be constructed at the upper end of the reservoir which will retain the sediment above it for a limited period; and by connecting the upper pool thus formed by large conduits to the portion of the stream below the main dam, the deposits can be transported around the reservoir through the conduits by repeated flushings. The deposition extends over the entire reservoir bed when a large percentage of the material is carried in suspension, and to attain the same object the conduits must be located in the vicinity of the main dam. In a canalized river, the entire pool is periodically flushed by manipulating movable dams which can be quickly lowered; but such a procedure destroys the reservoir capacity, and is therefore inapplicable when the reservoir is required to store water. No system of sluice gates would be effective for scour which did not create a greater velocity through the reservoir than existed in the river channel before the dam was erected, because it requires a greater velocity to put in motion material deposited, than it does to transport it when in suspension.

Theoretically a series of conduits could be constructed in the bed of a reservoir with numerous openings, and by allowing these conduits successively to discharge below the dams during high stages, a local scour could be created in the vicinity of each which would remove the material surrounding it without materially lowering the water level of the reservoir. The scour is limited, however, to a short distance from the opening unless it is very large. Practically, in such a system of conduits, the openings would be so large and numerous that the conduits would become choked with sediment during deposition in the reservoir and fail to work when needed, just as a sewer pipe clogs when it receives an intermittent flow without a sufficiently constant discharge to prevent the deposition of sewerage.

It is practicable to largely reduce the deposition, where only a limited portion of the river discharge is utilized and the reservoir can be constructed in a portion of the valley outside the stream bed. By building a weir of sufficient height in its intake the sand waves rolling along the river bed can be entirely prevented from entering the reservoir. By means of sluice gates on the weir which are opened only when the river carries little material in suspension, this cause of deposition can be greatly reduced. By such means, however, only a small percentage of the river discharge can be utilized. If the water is to be taken from the river at all stages, a settling basin must be constructed above the weir, which will cause a partial settlement of material in suspension before it approaches the intake.

While frequently the degree of saturation of water carrying material in suspension diminishes from the bed of a river to its surface, this is not an invariable rule. In discussing the critical stage in Chapter III, attention was invited to the effect of sand waves on the flow of water during floods, and the boils and eddies which they produced at the water surface. Velocities then are generated capable of carrying gravel in suspension, as is shown by the deposits of gravel at high stages along the banks of alluvial streams. When such boils appear, the upper portions of the river are carrying a greater load of sediment than the waters at greater depths. This heavy material, however, is deposited readily and a settling basin of limited extent will cause a clarification of the surface waters. Even though a sufficient time has not elapsed to cause the material to be deposited on the river bed, the sediment deposited in the reservoir will be reduced to a minimum, if a weir of great length is constructed and its gates are so manipulated that only a thin sheet of surface water flows over it. This principle is utilized in clarifying the water supply of cities, and reducing the amount of deposits requiring removal from filtration basins.

On the Great Lakes, the bacteriological condition of the water supply of cities is greatly improved by the proper manipulation of valves in their intake towers (8). While the flow of sediment in the deep water at the intakes is insignificant, a considerable amount of sewerage empties into the lakes and pollutes their waters. With a wind blowing from the shore, this sewerage flows on the water surface and the pure lake waters flow along the lake bed. When the direction of the wind is reversed, the sewerage flows along the bed and pure water on the surface. The intake gates to the water supply tunnels can be manipulated accordingly.

The most extensive application of these principles has been made, however, in the irrigation ditches which derive their waters from the rivers of India, carrying an abnormal amount of silt. The Sirhind Canal (9), which derives its waters from the Sutlej River at Rupar, is a conspicuous example. The Sirhind Canal has a width of 200 feet and a depth of 10 feet and was designed for a discharge of 7,000 second-feet. To maintain the water of the Sutlej River at a proper height, a dam was constructed across the river below the inlet to the canal. The unregulated waters from the river soon filled the upper portions of the canal with sediment to such an extent as to seriously reduce its discharge. It was first attempted to reduce the deposit by increasing the velocity in the canal by permitting a discharge through sluices situated about twelve miles from the intake. It is stated (9) that this did some good, but that there seldom was water to spare for the purpose. A regulating sill was then raised to 7 feet above the canal bed on which shutters were constructed which could further increase the elevation three feet. Material in suspension passed over the sill, and it was necessary to keep the canal closed during heavy floods. A divide wall 710 feet long was then constructed perpendicularly to the river dam so as to create a pool between it and the regulator. A rapid deposit of sediment occurred in this pool which could, however, be flushed out frequently through sluices in the dam. With a proper flushing of this pool, the period in which water could be introduced into the canal was increased, but the supply to the canal was usually suspended while the pool was being flushed.

Three methods of raising or lowering a boat to enable it to overcome the difference in elevation above and below a dam have been devised (10). The *incline*, the *lift*, and the *lock*. With the incline the boat enters a water-tight caisson which is supported on a carriage mounted on wheels. This carriage moves on rails which frequently are built with a slope of 1 to 10. Usually two caissons and carriages are constructed, which with their loads counterbalance one another. They are connected by a cable, and one ascends as the other descends, the power necessary to overcome frictional resistance is supplied by an engine driven by steam, water power, or electricity.

With the lift, the caisson is raised vertically, usually by means of hydraulic rams, though in some of the earlier designs caissons counterbalancing one another and connected by cables were employed as in inclines.

Except where large differences of elevation are to be overcome, the lock is employed universally to pass from one elevation to the other. A lock consists of a chamber in which the elevation of the water surface can be changed from that of the upper pool to that of the lower one, and vice versa. There are upper and lower gates, which when opened permit the boat to enter and depart from the chamber. When the gates are closed, sluices regulated by valves allow a flow of water into or out of the chamber, so that the water surface can be raised or lowered as desired. The invert of the lock-chamber and the sills of the lower gates must have such a depth of water over them that vessels can pass from the lower pool into and out of the lock, and the elevation of the top of the chamber walls must exceed that of the upper pool. In canal locks, the upper gates are supported by a lift-wall which extends from the elevation of the bed of the lower pool to that of the upper one. In locks closing tidal basins, the upper and lower gates are usually of the same dimensions.

As much ingenuity has been expended in building lock-gates as in constructing movable dams. In fact, many of the types of movable dams have been employed also as lock-gates. The tumble-gates of the locks of the Old Erie Canal work on the same principle as shutters, which rotate around a horizontal axis and rest on the lock floor when open. The gates of the Elbe-Trave Canal in Germany have hollow chambers. When air is forced into the chambers in a gate it rotates about its axis in a manner similar to the modified Brunot shutter. The latter is moved by hydraulic pressure under the caisson, however, instead of by compressed air. The Chittenden drum weir has been reproduced as a gate in a lock on the Mississippi River at St. Paul. Bear-trap gates have been constructed at several localities. A roller-lift gate has been constructed for the lock on the New York Barge Canal at Little Falls, which is raised to such a height that boats can pass under it. Roller gates, which slide horizontally into recesses in the lock walls, have also been built, particularly in locks on the Ohio River.

The gates most often employed are those which rotate about a vertical axis. For narrow locks, a single leaf is employed which rotates around a *quoin post* located in a recess of the lock-wall made to fit it, and called the *hollow quoin.* The leaf is balanced by a timber arm on the land side of the quoin. This arm is used also to open and to close the leaf. When closed the gate abuts against a sill along its lower edge and against shoulders of the lock-wall. This system is used extensively in the canal locks of France. For larger locks in the United States, two gates are employed, each of which has a greater width than one-half the lock, so that the gates when closed incline upstream and abut against one another along what are termed *mitering posts.* Since the strains to which the gates are subjected vary with the inclination between them and with their form, whether straight or curved, the inventive genius of the country has produced numerous varieties of mitered gates whose advantages have been elaborately discussed (11).

Lock-gates are subject not only to ordinary wear and tear, but also to injury from a vessel's striking them as it enters the lock, and some device is necessary to retain the water of the upper pool at its proper level while an upper gate is being repaired. For repairs to the lock-chamber, a similar device is required to exclude the waters of the lower pool. For narrow locks stop-planks placed in grooves in an extension of the lock-walls usually are employed for this purpose. The floating caisson employed in dry docks is better adapted to wide locks. In the first American canal constructed at Sault Ste. Marie, two gates abutting against a mid-channel pier were first employed to maintain the upper level, while the lock was being repaired, but the frequency of collisions by boats with the lock gates led the Canadian Government, when it constructed its lock and canal, to substitute for the gates an emergency dam operated from a swing-bridge, so that even if a gate is destroyed by a collision, the flow of water can be stopped. The United States Government has constructed a similar structure on the pier between the two protective gates. The wisdom of this policy was demonstrated when one of the gates of the Canadian lock was carried away by a collision, and the flow through the lock had to be checked. In the third and fourth locks of the American canal at Sault Ste. Marie (12), two sets of upper and lower gates have been substituted for the emergency dam. These are made so strong that the momentum of the boat will be checked by the destruction of one gate, and both the upper or the lower sets are always mitered before a boat is permitted to approach the lock. An emergency swing-bridge dam has been constructed to protect the locks of the Panama Canal (13). The gates are further protected by heavy chains which are swung across the channel to receive the impact of a boat not under proper control and to reduce its momentum.

Locks are filled and emptied either through valves in the gates, or through conduits located in the walls or under the lock floor and controlled by valves. The valves are of numerous types. Those most often used are (a) balanced or butterfly valves rotating about a horizontal axis or about a vertical axis, (b) sliding-valves which when large are moved on rollers as are Stoney gates, and (c) drum-valves. In small locks that are filled slowly the location of the filling and emptying conduits is of minor importance; but in large locks which require the sudden addition or removal of large amounts of water, conduits under the lock-floor with numerous openings into the locks produce the least surging of the vessels locking through them. The discharge of a large lock may be sufficient to require a concrete apron to prevent scour for a considerable distance below the lock. The discharge capacity of the third and fourth locks (14) at the Sault Ste. Marie at maximum head and with the gates fully opened, exceeds 5000 second-feet, or over twice the low-water discharge of the Mississippi River at St. Paul. The Poe lock at Sault Ste. Marie can be emptied or filled in nine minutes, giving an average discharge during the entire operation of about 3000 second-feet. When both the Weitzel and Poe locks are being filled simultaneously, a current averaging over one foot per second is created in the upper pool of the American Canal, and a series of oscillating waves are produced which have received careful study and which necessitate special care in mooring boats waiting their turn to pass through the locks.

The width to be given a lock depends on the character of the boats which are to pass through it. When single vessels are employed, the length and width of the lock should readily accommodate the largest vessel, and where a ship-building industry is situated above a lock, it may be necessary to provide for vessels larger than those which ordinarily navigate the river. When tows of barges are employed, it is desirable to pass an entire tow at a single lockage. On the Ohio River the locks are given a width of 100 feet and a length of 600 feet in order to pass tow-fleets.

It is also necessary to take into consideration the future growth of commerce, as is illustrated by lock-construction at Sault Ste. Marie (15). The Weitzel lock completed in 1881 was designed for vessels of a draft of 16 feet. It was 60 feet wide at the gates and 80 feet wide in the chamber, 515 feet long, and 17 feet deep. The Canadian lock, completed in 1895, was also made 60 feet wide, but it was made 900 feet long to accommodate a vessel and its tow, with the depth on the miter sills of 22 feet. The Poe lock, which was designed prior to 1887 and completed in

1896, was intended to accommodate four vessels at a time. It was made 100 feet wide, 800 feet long, and 22 feet deep on the miter sills. When it was designed, the largest vessels navigating the lakes had a length of 350 feet and a beam of 45 feet. The increase in depth of the Poe and the Canadian locks over the Weitzel lock led to a rapid enlargement of the dimensions of vessels. In 1903 there were 97 vessels navigating the lakes having a length exceeding 400 feet and a beam from 45 to 53 feet. In 1918 there were 42 vessels of a length exceeding 600 feet and a beam from 58 to 64 feet, and both the Poe and Canadian locks became of uneconomical dimensions, even for the average vessel that navigated the lakes. The third and fourth American locks were made 80 feet wide, 1350 feet long, and 24½ feet deep on the miter sills, so as to accommodate two of the largest vessels, or three of average size, at one lockage.

CHAPTER IX

DREDGING—REMOVAL OF OBSTRUCTIONS—BUOYS AND LIGHTS

DREDGING

It frequently happens in valleys formed wholly or in part of glacial drift, that bars exist in rivers that have such a resistance to erosion that they cannot be removed by river currents even when the channel is contracted. If they are composed of gravel, clay or boulders, a channel can be excavated through such obstructions by dredging. If they are composed of rock, it is usually necessary to resort to blasting. Such channels are usually permanent, since the rivers flowing in such valleys transport little sediment as sand waves, and the cuts are made through a material incapable of being scoured by the gentle currents that exist.

The rivers which empty into the Great Lakes (1) and their connecting waters, have been very generally improved in this manner, but it must be borne always in mind that the tendency of such excavations is to lower the level of the pool above the cut. The mouths of many rivers emptying into the Great Lakes have been dredged to depths of from 12 to 23 feet, and the natural low-water river slopes have been completely destroyed thereby, the depth in the river becoming dependent on the rise and fall of the lake level.

The excavation of the Neebish Channels in the St. Mary's River produced a lowering of the water surface below the locks at Sault Ste. Marie, so as to materially diminish the draft of vessels which could pass through the locks, on account of the reduced depth over their lower miter sills. In constructing the Livingston Channel in the Detroit River (2), this lowering of the upper pool was prevented by depositing the excavated material across other portions of the river channel so as to limit the flow through shoal sections of the river sufficiently to compensate for the increased flow through the navigable cut. The channels excavated in the Rock Island rapids (3) of the Mississippi River exhibited the same tendency toward a lowering of the water surface of the upper pools, and it was necessary to construct not only a series of long spur-dikes to maintain the pool levels, but also a series of submerged sills across the navigable channel.

When a river is canalized, dredging becomes necessary to maintain the channel through the deposits of material carried in suspension or rolled along the river bed, which form below the dams. Under the conditions described above, the advantages of dredging are self-evident.

It has been proposed also to substitute dredging for canalization, or for regulation in alluvial rivers carrying large amounts of sediment. The limitations of dredging under such circumstances require explanation. A dredged channel is subject to the same laws governing the flow of sediment as is one produced by natural scour. In the straight reaches below every bend there is a movement of sand waves and an elevation of their crests on a rising river. Hence there is a tendency for a dredged cut in an alluvial river to fill on every rise, requiring re-dredging as the river falls. In most of the tributaries whose combined flow creates the main stream, these fluctuations of stage are frequent, and the cut must be re-dredged so often during a season of navigation that it becomes more economical to direct the river currents by means of dikes in such a way that they will perform the same work.

The fluctuations of the tributaries may combine in the main stream, however, in such a way as to produce a long gradual rise succeeded by a slow fall, and one or two dredgings of the bars of the main river may be sufficient to maintain a channel during an entire year. In the main stream the cost of dike construction largely exceeds that in the tributaries and in such a case the interest on the investment in dike construction may exceed the cost of maintenance by dredging. The tributaries also have a much smaller low-water discharge than the main stream and their slopes are usually steeper.

The dimensions of the channel to be dredged are often considered a function of the size of the vessels which it is proposed to employ for navigation, rather than of the discharge and the slope of the river. This frequently requires in a tributary a channel of such width and depth that there is not a sufficient discharge to fill it during low water; and if the width of channel is reduced to overcome this difficulty, the space occupied by a vessel ascending the channel becomes so great as to interfere seriously with the river flow, and the boat has not sufficient power to propel itself against the current without being cordelled.[1]

As an illustration, let us assume that the main stream has a low-water discharge of 70,000 second-feet, and a slope over its bars of 0.4 foot per mile, while a tributary has a low-water discharge of 1000 second-feet and a local slope over its bars of 1.5 feet per mile. In the main river a channel 200 feet wide and 9 feet deep will have a cross-section whose area is 1800 square feet, and will discharge about 5400 second-feet, which is less than eight per cent of the flow of the river. In the tributary a navigable channel 6 feet deep will require a width of at least 70 feet to enable boats to pass one another. The area of its cross-section will therefore be at least 420 square feet, and its discharge will exceed 1400 second-feet so long as the pool above can supply the water, but when the water supply has become exhausted the depth of the water in the channel diminishes. Because a satisfactory navigable channel can be economically dredged on the lower Mississippi River, it by no means follows that a similar channel can be maintained in the creeks that empty into it, as many advocate.

When it is attempted to straighten a river by regulation, the dredge becomes a necessary adjunct to the improvement during the long period during which the river is readjusting its slopes, since channels must be dredged annually through the sand-bars which form until the new equilibrium is established.

The principles governing dredge construction (4) belong to mechanical engineering, and attention will be invited here only to the adaptability of certain varieties of dredges to various kinds of work.

The dipper dredge, which is the ordinary steam-shovel mounted on a barge, is the best machine for miscellaneous dredging. It can excavate either hard or soft material; and when its dipper is armed with steel teeth, it affords the most economical means of removing subaqueous boulders and blasted rock. For deep channels, the clam shell dredge is more economical when the material is sufficiently soft to be excavated by its bucket and is of sufficient consistency to remain in it when raised to the surface.

The elevator dredge, though rarely employed in the United States, is used extensively in Europe for deep channels. When the chain of buckets is made particularly strong, it can excavate

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[1] **A method of propulsion by a vessel's capstans through ropes attached to trees on the bank.**

stratified rock. It was employed for this purpose in the St. Lawrence River near Montreal.

All these types of dredges require dump-scows to receive the dredged material, and to transport it to the designated dumping grounds. Occasionally the elevator dredge delivers its soil by gravity through side chutes.

In alluvial rivers, the hydraulic-suction dredge has been used extensively to excavate channels through the bars. The maintenance of a river channel by dredging requires the prompt removal of a large amount of material, so as to rapidly concentrate the flow along the line selected. If the excavation is made slowly, the natural forces may scour a channel at some other place and the tendency to fill on the line to be dredged may become so great as to cause a more rapid deposit than the dredge can remove. Dredges of large capacity operated continuously are therefore required, and the material removed must be deposited at such a distance from the channel that it cannot obstruct it. The hydraulic-suction dredge (5) discharging through a pipe line best fulfills these conditions. It is particularly effective if the spoil can be deposited between dikes, as is usually the case in rivers which are being regulated. If the material to be removed is sand, water forced through jets against the sand-bank affords the best means of dislodging it and moving it to the mouth of the suction pipe. If the material is clay, some form of cutter is necessary. Whether a dredge should be self-propelling or should be towed from place to place by a towboat, depends on the frequency with which it has to be moved and the distance it has to travel. A tender is necessary to furnish fuel and other supplies, and can be utilized for towing. On the lower Mississippi river, a small tender suitable also for surveying and a self-propelling dredge makes the most economical combination.

On bars at the mouths of rivers, the hopper dredge (4) is substituted because the pipe-line cannot resist wave action successfully. This is a self-propelling suction dredge with bins in which the spoil is deposited. When filled, the dredge is moved to deep water where the hoppers are emptied. There are several types of hopper dredges depending on the form of the suction head. Their relative economy is a function of the kind of material to be removed.

Numerous substitutes for the hydraulic dredge have been proposed. While most of them are so visionary as not to merit mention, a few of them can be utilized in cases of emergency, though they are uneconomical as a regular means of channel improvement. The increased velocity which the paddle wheels or the propeller of a steamboat imparts to the water can be utilized to form a narrow channel of the width of the boat across a bar, and the stern wheels of western river packets have frequently been used for this purpose. On the upper Rhine a washing dredge has been devised based on this principle. The material removed, however, is deposited in the channel a short distance below and has to be rehandled several times, while a suction dredge removes it from the channel in one operation.

The Long scraper (3) was used quite extensively on the upper Mississippi River to temporarily deepen the channels over bars before dredges were available. It consisted of a triangular frame of oak timber with buckets or cutters of boiler iron bolted to the lower side. It was attached by bolts to the sides of the boat, and was raised and lowered by ropes controlled by steam capstans. The method of operating the scraper was to move the boat to the head of the bar to be removed, and to lower the scraper. The wheels of the steamer were then backed so as to drag the scraper over the bar, the boat floating with its stern downstream. The scraper was then raised and the boat returned to the initial point, and the operation was repeated until the desired depth was obtained. The buckets cut up and loosened the material on the bar and then conveyed it to deep water, being assisted in the movement of material by the river currents. The amount of material the drag could remove at each operation was quite limited, and the time occupied by the boat in returning for its load was quite long. It can be readily appreciated that a dredge working continuously will excavate a channel more economically.

It also has been proposed to utilize the river currents to scour through the bars, by constructing temporary spur-dikes either by sinking barges on the line proposed which can afterwards be pumped out, or by anchoring them by spuds and cutting off the flow under them by shutters, which can be raised after they have accomplished the work for which they were intended. Devices of this class can be constructed which will be effective, but an analysis of the cost usually will show that either a permanent dike or dredging is more economical.

ROCK EXCAVATIONS

When a large area of rock of considerable thickness is to be removed, the cheapest method of doing it is to surround the area by a cofferdam, pump out the inclosure, and excavate the rock in the dry, provided the cofferdam does not interfere seriously with existing navigation. This method has been employed extensively for the rock excavation of the Rock Island Rapids (3) of the Mississippi River, of the West Neebish cut of St. Mary's river, and of the Livingston Channel of the Detroit River (2). The rock is broken up by the ordinary methods of rock excavation employed on land, and is removed by steam shovel and dump cars, or by cableways. The relative economy of the different methods is discussed in the report upon the excavation of the Chicago Drainage Canal (6), which is one of the largest works of this character ever undertaken.

When the rock obstruction is of less extent, or when the interests of navigation prevent the construction of a cofferdam, several methods of rock removal have been employed. When the rock projects above the river bed in small patches, or is stratified so as to be broken into pieces of considerable size, the Lobnitz rock crusher is an economical machine for rock removal. It consists of a heavy steel plunger which is allowed to fall from a considerable height and breaks up the rock by impact. It has been used extensively for that purpose in the rapids of the Rhine (7), and in those of the Danube (8). When the rock is homogeneous, this method is not so successful. The first blow of the crusher breaks up a certain amount of material which remains in place and the succeeding blows merely pulverize the broken fragments.

On the upper Rhine (7) the diving bell was used extensively in drilling the holes and in inserting the charges for blasting the rock. In the United States, it has been found more economical to place the drills on barges which are held securely in position over the rock to be excavated by means of spuds. Such drill barges have been employed on portions of the Rock Island rapids (3), the Middle Neebish Channel of St. Mary's River, and the Amherstburg Channel of the Detroit River. On the Danube also drills were mounted on barges.

In the Hell Gate (9) of the East River of New York Harbor, the method of rock removal was to sink a shaft on the land adjoining the section of channel to be improved and run a tunnel under the channel. An amount of rock was then removed from the tunnel and numerous branches, so that when the roof of the tunnel was allowed to fall into the space excavated, a sufficient channel depth would be created. The blasting of the roof, however, caused an irregular settlement of the mass, and considerable rock had to be removed by operations from the water surface before the required depth was obtained over the entire area. The later removal of Blossom Rock (10) from San Francisco Harbor by similar means was more successful.

REMOVAL OF SNAGS

On account of the caving of banks, numerous trees fall into a river and lodge on sand bars, where they form snags dangerous to navigation. For their removal a snag-boat is required.

On the lower Mississippi, the snag-boats are powerful machines, capable of removing not only snags, but also the wrecks of vessels. Not infrequently they have had to replace on the bank, railway locomotives that have fallen into the river at the inclines to car ferries. On the smaller tributaries, a strong pair of shears placed on a barge is utilized for snagging purposes. Early in the season it is towed to the upper limits of the snagging district, and then is allowed to float downstream with the current as the work progresses. A motor boat usually accompanies such a barge as a tender.

An important function of the snag-boat is the cutting of trees on the edges of caving banks and thus preventing them from becoming snags. It is used also for the removal of other obstructions, such as wrecks and boulders.

In certain rivers of the United States snags have been deposited in such quantities as not only to endanger navigation but also to interfere seriously with the discharge of the rivers. On the Red and Atchafalaya rivers these accumulations of snags, termed rafts, obstructed the channel for many miles, and the improvement of these rivers has consisted in the removal of these rafts. Their removal in the Atchafalaya, which is an outlet to the Mississippi, has increased its flood discharge from less than 100,000 second-feet to over 400,000 second-feet, and has rendered necessary the construction of submerged sills near its junction with the Mississippi to prevent a further enlargement.

On the Red River (11) the removal of the rafts has been accompanied by a marked lowering of the river bed, in some places of about 25 feet. When the rafts existed, they acted as dams and caused an immense deposit of sediment, which affected the river slopes for many miles above them. The river discharge, unable to follow the main channel, escaped through numerous sloughs excavated through the river banks, some of which afforded a precarious navigation during high stages. When the rafts were removed, these sloughs were closed and the river flow concentrated in a single channel, which has adjusted its slope to the changed conditions. The concentrated flow also has increased bank caving in certain sections of the river, and numerous cut-offs have resulted. Above these sections the bed of the river has been lowered about five feet. Below them it has been raised about 3½ feet. Levees have also been constructed along the river banks, and these changes in the regimen of the river have sometimes been ascribed erroneously to the levee construction.

BUOYS, LIGHTS AND BEACONS

An important aid to navigation consists in so marking the channel that the pilot can follow it readily by day or night. Buoys, beacons and lights are used for this purpose. In the United States the Bureau of Lighthouses has charge of their maintenance, but an intimate coöperation is necessary between this bureau and those engaged in channel improvement. On the western rivers this coöperation is insured by assigning the duties of Lighthouse Superintendent to a Division or District Engineer. While performing this function, he reports directly to the Chief of the Lighthouse Bureau. An engineer officer is detailed also for consultation or to superintend the construction and repair of any aids to navigation authorized by Congress, in the other lighthouse districts.

One method of marking the channel is by means of buoys showing its limits; another is by a system of ranges which locate its center line. These two methods are frequently combined. On the Mississippi River the limits of a dredged channel are usually marked by four buoys placed by the dredge employees when the cut is made, and the center line is marked by two white posts on the opposite banks of the river on which lanterns are maintained at night by the lighthouse establishment. Lights are also maintained in the river bends at such distances that at least one is always in view in advance of the boat, whether moving upstream or downstream. As the channel is frequently changing and the banks are unstable, a cheap structure that can be readily moved is necessary.

Since the channels connecting the Great Lakes are stable, the range lights are placed in lighthouses. Two lights are placed on the same side of the river, on the prolongation of the center line, and frequently one of them — a low structure — is located in shoal water, while the rear light is on the river bank at a greater elevation. When the boat is in the channel, the two lights appear one vertically above the other. On channels of considerable length, range lights may be established at both extremities. Lights frequently are placed on the buoys; the New York State Barge Canal, recently completed, is thus lighted.

On the seacoast and on the Great Lakes, lighthouses (12) are established at frequent intervals to warn the mariner of the proximity of land or of dangerous shoals. The general project contemplates ultimately surrounding the United States with a system of lighthouses whose areas of visibility intersect, so that the light from at least one will be visible on a clear night before the vessel arrives within dangerous proximity to the shore. The mariner can also determine his location with considerable accuracy, when the light first appears above the horizon, as every lighthouse has its characteristic light, and the height of the light above sea level is published. The lights usually are differentiated by means of revolving shutters which obscure the light for a certain length of time. By varying the length of the eclipses and flashes, a large variety of clearly distinguishable characteristics can be obtained for the different lights.

The form of lens and reflector for lighthouses and lanterns which will throw the maximum volume of light in the direction desired, has been studied carefully. The construction of lighthouses in exposed localities is one of the most difficult of engineering feats. Other auxiliary aids are fog sirens and whistling buoys, to warn the mariner of danger during fogs. They are rarely employed on rivers except at their mouths (13).

CHAPTER X

RESERVOIRS AND LEVEES AS A MEANS OF IMPROVING NAVIGATION

RESERVOIRS

The advocates of the improvement of the low-water navigation of rivers by means of reservoirs (1) usually assume that a river's depth has the same relation to its discharge as that which exists in a conduit or sewer, and that by increasing the discharge there will be a similar increase in the depth of the navigable channel. This can be true only when the bed is immobile.

As explained in preceding chapters, during extreme low stages the velocity is small in the pools and in the upper reaches of a river, and is insufficient to cause bank caving. As the discharge is increased the velocity in the pools increases more rapidly than over the bars and it soon has sufficient force to scour its bed. The material thus removed from a pool is deposited to a great extent on the bar below, raising its crest. It was pointed out also that in a river similar to the Mississippi, under certain conditions the rise in bar height may equal one-half the increase in stage, but it does not follow therefrom that a permanent increase in the low-water discharge would be accompanied by an increase in depth over the bars of one-half that usually computed. The reason that the crest of a bar on a rising river does not attain a greater height is that the elevation of the river bed is a much slower process than the change in stage. The crest of a flood passes before it has had an opportunity to produce its maximum effect, and a falling river causes a scour.

If the discharge remains constant at a given stage, the elevation of the bar continues until a dam is formed at the lower end of the pool. This reduces the velocity over it sufficiently to prevent caving, or the ratio of the velocities in the pool and over the bar becomes such that the material scoured in the pool can be transported across the bar as fast as it tends to deposit. The effect of permanently increasing the low-water discharge in a river therefore is to increase largely the depth in the pools and to improve but slightly the channels over the bars. For example, the natural low-water discharge of the Mississippi River at St. Paul is about 2500 second-feet, its extreme flood discharge is about 100,000 second-feet, and its slope is about 0.4 foot per mile. At low stages the depth of the river unimproved by regulation was about 10 feet in pools, and about 1 foot on some of the bars. As the low-water discharge of the river increases by the inflow of tributaries, the channel depths progressively increase. When a low-water discharge equal to the extreme flood discharge at St. Paul is attained by natural causes with the same slope of 0.4 foot per mile, the depth in pools becomes approximately 100 feet, but the natural channel depths over some bars is about 4 feet at low stages. A channel depth of 9 feet, which is exceeded on the upper river during floods, can be maintained on the lower river for the same discharge only by dredging. On the other hand, variations in discharge in an immobile bed produce variations in depths which correspond to those computed for conduits. This occurs in the rock cuts of the Neebish channels in the St. Mary's River, where the variations are caused by the fluctuations of Lake Superior.

The attempt has been made to improve the navigation of the Mississippi by reservoirs (1). Six reservoirs have been constructed at its headwaters capable of impounding about 97,000,000,000 cubic feet of water, which it was estimated would maintain a low-water discharge of 5000 second-feet at St. Paul. The original project contemplated the construction of 41 reservoirs on the tributaries of the river in the states of Minnesota and Wisconsin, but the results attained by those built have not justified a further extension of the system.

It is estimated that the increase in the low-water discharge which the reservoirs are capable of producing will cause an increase in low-water navigable depths at St. Paul of 2 feet, and an appreciable increase in depth from St. Paul to Lake Pepin, a distance of 52 miles. This portion of the river has been improved by regulation, however, its banks have been protected from caving, and the channel across bars has been given such a direction as to convert bad crossings into good ones. The increased discharge is therefore confined to a channel in which its injurious effects have been limited.

Below Lake Pepin, where the improvement is not so far advanced, the increase in the low-water discharge has produced no appreciable increase in navigable depths. This is due to a more potent cause than that mentioned above. The reservoir capacity of Lake Pepin is as efficient a regulator of the low-water discharge of the river as are the artificial reservoirs constructed at its headwaters; and before their construction it caused a minimum discharge below it equal to that which they are now capable of maintaining at St. Paul.

When the channel has been improved by regulation and it is necessary to obtain greater navigation depths than this method of improvement will afford, the result can be attained by increasing the low-water discharge by means of reservoirs. As a substitute for regulation, however, the results attained do not justify the construction of these reservoirs, even under such favorable conditions as those which exist at the headwaters of the Mississippi, where large volumes of water were impounded at an exceedingly low cost for the dams (2).

The practical manipulation of the reservoirs at the headwaters of the Mississippi presents difficulties which, while not insurmountable, mitigate against their use for the purpose intended. The original act of Congress authorizing their construction stated that the purpose was to improve the navigation of the river below St. Paul. There are numerous other interests than the navigation of the lower river which have to be considered. The fall in the river between the headwaters and St. Paul has been utilized in several localities for the production of water power, and the water power companies desire to preserve a uniform flow at all times. The closing of the gates in the dams to conserve the water at certain seasons causes a fluctuation in flow detrimental to their interests. The logging companies require a certain amount of water to float their logs in the tributaries which are the outlets to the reservoirs. If too little water is allowed to pass the dams the logs ground on the river bars. If too much water is released, the bottom lands are overflowed and many of the logs lodge upon them. Also, the farmer who utilizes the bottom lands to produce crops of hay strenuously objects to any manipulation of the gates which will flood the land, particularly at a time when he is harvesting his crop. This is usually the time when the greatest discharge from the reservoirs is required to maintain the proper river heights.

The navigation interests above St. Paul have also to be considered, and there is a demand for the utilization of the reservoirs to reduce flood heights, but those living below the dams desire the closure of the gates during floods, while those above them protest against the flooding of the land by back-water caused by filling the lakes. In addition to the difficulties arising from human agencies, nature adds to the complexity of the problem by the variations in rainfall. In some years not only does a drought tax the reservoirs to their capacity, but there is not enough rain during the flood season to fill them again, and a second low-water season occurs without a sufficient amount of water stored for their proper functioning.

A period of about a month formerly elapsed before the water allowed to escape from Lake Winnibigoshish produced an appreciable effect on the river heights at St. Paul, and it has sometimes happened that in attempting to harmonize the conflicting interests there has been too great a delay in opening the valves at the dams, and the reservoirs, instead of increasing the extreme low-water discharge at St. Paul by the amount proposed, have materially reduced it. The gage at St. Paul quite frequently has had a reading lower by about one foot since the reservoirs have been built than was on record prior to their construction, but the manipulation of the dams is now so regulated that it is exceptional for these low readings to occur during the period of navigation.

By straightening the upper river, the time required for the transmission of the discharge has been diminished and the following general rules are now observed in operating the reservoirs:

"(a) The discharge must not, by operation of the reservoirs, be reduced below the normal low-water flow of the streams affected. This rule is necessary in the interest of manufacturers.

"(b) When logs arrive in the reservoirs, they must be sluiced through. Transportation of logs by floating is a form of commerce, and the main form of commerce on the streams affected by the reservoirs. It is dangerous to the dams to allow accumulations of logs, so that they must be sluiced through even in times of flood.

"(c) The winter flow is so regulated as to make room for 39 billion cubic feet of water at the end of winter. This is the amount ordinarily to be expected in the spring floods.

"(d) From the spring thaw until the dry season of summer (ordinarily until about July 10) as much water is retained in the reservoirs as possible, subject to rules (a) and (b).

"(e) When the gage at St. Paul has fallen nearly to 3 feet, water is released so as to keep the gage at this reading. If there is not enough water for this purpose, then the greatest constant depth possible is maintained.

"(f) When during the low-water stage, there is not sufficient depth for the steamer plying between Aitken and Grand Rapids, and the quantity of water in the reservoirs is sufficient, enough water is released on request to make the trip possible. This use of the reservoirs is occasional"(3).

There are numerous other localities where reservoirs have been constructed and where the water has been used incidentally to increase the flow during low water. With the exception of those at the headwaters of the Volga, their primary purpose has been either to create water power or to reduce the dangers from floods. One of the greatest enterprises of this kind is the reservoir construction being undertaken on the Ottawa River and its tributaries in Canada.

IMPROVING THE LOW-WATER CHANNEL BY CONFINING THE FLOOD DISCHARGE BETWEEN LEVEES

The question of the influence of levees on the low-water channel of a river has been a subject of discussion for many years, particularly in the Mississippi Valley (4). During floods a river usually has a discharge from twenty to fifty times that of low water, and the water moves in the channel with at least twice the low-stage velocity. Hence its energy, which is a measure of its scouring effect, is from eighty to two hundred times as great during floods as during low stages.

A great deal of this energy is dissipated in the water which flows over the banks and floods the alluvial valley. It is claimed that if this water is prevented from escaping from the river bed by the construction of levees, the force acting during floods will be greatly augmented, and that it will produce a powerful scouring effect on the low-water channel.

That levees largely increase the force acting during floods is unquestionable. On the lower Mississippi from Cairo to Vicksburg a confined flood of 2,000,000 second-feet can now be carried, while prior to the construction of levees, the maximum discharge at Vicksburg was about 1,000,000 second-feet. It is a serious question, however, whether or not this confined force is producing useful work. For such a purpose it is necessary not only to increase the force but also to give it the proper direction. By increasing the intensity of the fire under a steam boiler a greater force is generated, but unless a proper direction is given to it through a steam pipe leading to a steam engine, the increased force, instead of producing useful work, may become one of destruction, and burst the boiler shell. While not conclusive, there is presumptive evidence that levee construction has enlarged the bed of the Mississippi (5). If the river followed the same channel during high and low stages, as explained in the discussion of the effect of reservoirs on channel depths, an increase in the discharge would cause an increased caving in the bends and a raising of the crests of bars, deepening the river in the pools to the detriment of the crossings.

It is impossible, however, to construct levees so as to force the flood discharge to follow the low-water channel. If levees were constructed with this object in view they would have to be placed so close to the banks as to be destroyed by caving. When located from half a mile to ten miles from the river bank, as is the case on the lower Mississippi, the river during flood stages follows a course far different from that which it has during low water. While at some localities the scour during high and low water may coincide, at others the scour during floods may be on bars above low water and a deposit may occur in the low-water channel.

Whether the resultant combination of scour and fill during flood stages increases or diminishes the amount of work which it is necessary for the low-water discharge to do in order to produce a certain channel-depth is a question of fact difficult to determine. On the lower Mississippi, a certain amount of dredging is required to provide a channel depth of nine feet at low water; but whether or not the amount of dredging required to obtain that result has been increased or diminished by levee construction is unknown.

The low-water channel can be maintained readily by dredging, however, and since Congress has authorized the construction of levees for flood protection, for which purpose they are essential, their employment for improving low-water conditions has ceased to be a question of practical importance on this river, and it may be relegated to the zone of academic discussion.

The theory that levees would improve navigation was the natural sequence to the theory formerly held by many advocates of river regulation that the proper method for improving a river was to straighten it and give it a uniform slope and depth. If it were practicable to so improve the low-water channel of a river, it logically follows that an increase in discharge would produce an enlargement of the low-water section. But when it has been demonstrated that it is impossible to eradicate the curves from the low-water channel, that the slopes in pools and on crossings must be preserved, and that a variable depth in bends and bars must exist, the corollary suffers the same fate as the proposition on which it is founded.

The present practice in European rivers is to ignore the high-water discharge in improving the low-water channel except to prevent its injurious effects, and to allow it to escape with as great freedom as possible. For this purpose, even the works of improvement in the river bed are given as low an elevation as practicable.

The original project for the improvement of the Danube (6), adopted in 1882, contemplated restraining its floods by means of levees and concentrating its flow in a single channel between two fixed banks, relying on flood control to ameliorate low-water conditions. The cut in front of the city of Vienna executed from 1870 to 1875 illustrates the application of the general principles. The river was confined here to a single channel, nearly straight, 484.5 meters wide at mid-stage (Nullwasser), and 760 meters wide at flood stage. The enlargement of the low-water bed was on the bank opposite the city and at an elevation of 1.5 meters above Nullwasser. From this section all trees and shrubbery were removed. The low-water bed had a discharge of 1700 cubic meters at a zero stage and only 600 to 700 cubic meters at low water, which produced a winding and variable channel along the Vienna water front, where it was desirable to permit access to the banks for the greatest possible length.

A further contraction of the low-water channel then became necessary. This was accomplished by means of a system of spur-dikes extending 98 meters from the left bank, with an elevation of 2.5 meters below Nullwasser at the bank, and a slope of about 1.5 per cent. These dikes incline upstream, making an angle of about 75° with the axis of the bed, and they are generally about

100 meters apart. At some places their outer ends have been connected by submerged longitudinal dikes.

Notwithstanding this work the channel is still sinuous, but a depth of 4 meters below the zero of the gage has been realized at those portions of the Vienna front used as quays, and a navigable channel of 2.0 meters has been obtained at extreme low water except during periods of freezing weather, when all navigation is interrupted.

On other portions of the river excessive dredging was required to maintain the low-water channel, and a similar method of contraction was attempted at first. In 1899 a new project was adopted, which contemplated a low-water channel of a uniform width of 210 meters and a depth of 3.5 meters. This channel is limited by means of spur-dikes inclined upstream at an angle of 70° with the axis of the bed. They have an elevation of mid-stage at the bank and a slope of from 5° to 10° to low water and are there extended by submerged dikes with a slope of 3°.

All attempts to straighten the river have now been abandoned, and the channel follows a series of curves, so that the centrifugal force of the water tends to secure the stability of the bed. At certain localities longitudinal dikes have been constructed on the concave banks.

In a comparison of the improvement of the Danube with that of the Rhône, M. Armand, Chief Engineer of the Ponts et Chaussées, makes the following remarks (6):

> "It is known that works of improvement of rivers with a mobile bed, undertaken by the method of contraction, have often led to mistakes. The contraction of the bed across a shoal increases the erosive force of the water, the shoal is deepened, but the water plane is lowered in the pool above, and the upper shoal is aggravated.
>
> "That is what occurred in the Rhône following the first works of improvement executed before 1882, and that is what led the engineers charged with the improvement of that river to adopt a different plan, based on the preservation of the natural forms of the bed, and its division into successive pools, which it is sought to modify as little as possible, except when it is necessary in order to realize at low water the draft of water desired.
>
> "The dangers of the method of contraction have not escaped

the Engineers of the Danube Commission. While limiting the river, they have studied a judicious tracé of the low-water bed which respects the natural sinuosities of the river as far as possible, and by the use of submerged works avoids too great a depth at some points of the low-water bed. The method which they have employed is in the main intermediate between simple contraction and the method of preservation of the natural forms applied on the Rhône.

"The results obtained at this time appear to show that they have been right; and these results have been obtained by works of an execution assuredly less delicate than the works of direction necessary on the Rhône.

"Moreover, the conditions of the two rivers were appreciably different. On the Danube the slope is less, the low-water discharge is two or three times as great, and there is little uneasiness that extreme low-water will be produced by great freezing when navigation is interrupted by ice.

"It is probable that the bed of the Danube is less subject to scour than that of the Rhône, or that it presents at certain points rocky shoals which do not scour; this appears to result from the fact that the great cut at Vienna, straightening the river for a great length, has produced only a very small lowering of the low-water plane above."

CHAPTER XI

FLOOD PROTECTION

In discussing the protection of land from the ravages of flood waters, it is necessary to bear in mind the divisions of a river basin into an area of erosion, one of deposition, and one where the forces of erosion and deposition are in unstable equilibrium. The problem of flood protection differs materially in the three sections.

On the hillside where the precipitation tends to remove the soil, the best protection is a forest growth, as the roots of the trees bind the soil together and offer a great resistance to the flow of water where any local scour starts an incipient gulley. The removal of the forest in itself is not necessarily destructive, as the stumps and roots that remain resist decay for a long period and a second growth of timber can replace the one removed before serious erosion results. But if the land is cleared for cultivation great damage may be caused. The water flowing down the hillside then removes the humus which has been deposited on it by the leaves falling from the trees through ages and which gives it the fertility necessary for the growth of vegetation.

The best substitute for the forest is a growth of grass, particularly of those varieties whose roots tend to grow in a horizontal direction near the surface of the ground. When not exposed to freezing weather, Bermuda grass is particularly adapted for this purpose and is used extensively in southern latitudes for the protection of the slopes of levees and other embankments. It requires considerable time, however, to form a good bond by the interlacing of the roots, and in sandy soils there is a liability of wash from heavy rains scouring the bank and even carrying away the tufts of grass before the sod is formed.

The plowing of furrows at right angles to the slope is of service during light rains, but it is of little use during the heavy storms, which are the great cause of the damage wrought.

The scour can largely be prevented by terracing the hillside and guiding the rain water by drains across the terraces, but this method is applicable only in special cases on account of its excessive cost. It has been employed, however, in thickly settled countries where land has a great value, and particularly where irrigation is necessary for agriculture, the formation of level areas being essential to the proper use of the irrigating waters for crops.

In the area of deposition the problem which confronts the engineer is usually to prevent the detritus which is washed down from the hills from spreading over the bottom lands and destroying their fertility. For this purpose levees have frequently been constructed which limit the flow to a narrow channel and thus preserve the remainder of the bottom lands from the action of the stream. When levees are thus employed a fill invariably occurs by deposition at the point where the steep slope down the hillside changes to a gentle slope across the bottom lands; and, to maintain the channel within the limits prescribed, the levees must be raised from time to time, or the material deposited must be removed. Around Lake Biwa in Japan, where levees have been used for this purpose for generations, they are of inordinate height on insignificant streams whose discharge is limited to the water flowing during storms. The deposit, however, is frequently a mixture of small cobble stones and gravel which would make a good material for road construction, and in a country where macadam roads prevail, the annual removal of the detritus may be an economical solution of the problem.

Another method of protecting the bottom lands is by the construction of dams across the ravines in which the stream flows, above its entrance into the valley, thus forming pockets in which the detritus is deposited. These pockets rapidly fill, necessitating a periodic raising of the dams or the building of additional ones. This method of construction has been employed extensively on the tributaries of the Sacramento River (1) to prevent injury to the Sacramento Valley by material washed from the hillsides in the hydraulic mining of gold.

In hydraulic mining, the material of a hillside is washed into sluices by jets of water directed against it under heavy pressure, and the waste material is allowed to flow into the neighboring streams after the gold has been extracted. This detritus flowed into the tributaries of the Sacramento River and rapidly destroyed the equilibrium between scour and fill which nature had established through the work of geological ages. Large sand waves which contained none of the elements necessary to cause the growth of vegetation, and which destroyed the fertility of the land over which they spread, were placed in motion down the main river.

These sand waves have a motion of about 4 miles per year, and not only injure the agricultural interests by killing vegetation as they pass over the land, but their crests fill the river bed and cause increased flood height at the localities they successively occupy in their passage downstream. They also affect navigation injuriously. By this motion of sand, nature is attempting to readjust the relations between scour and fill which man has disturbed.

Even if no further deterioration of the river channel by the mining interests is permitted, it will require a long period of time for the river to so reform its bed and to so adjust its slopes as to restore normal conditions. In the meantime, the regulation of the river presents novel and difficult engineering problems, which will be discussed later. It has been assumed by many that human agencies in the destruction of forests, in the drainage of fields, and in the building of levees, are causing a similar deterioration of other rivers, beyond the ordinary area of deposition, though not to the same extent, and careful investigations have been made in Europe and the United States to determine if any such tendency could be observed.

The problem is a difficult one, due to the mobility of the river bed and the irregularity of the rainfall. As the area of the cross section of the river is constantly changing, due to the movement of sand waves, a series of observations extending over a long period of time is necessary to determine whether an observed scour or fill is due to a permanent cause, or is the accidental result of the location of the sand wave at the time of the observations. As the mean rainfall for even ten-year averages differs materially at the same stations, there is an uncertainty as to whether a river's height at any time has been due to a variation in rainfall or to changes in the river section, for it is only exceptional that sufficient discharge observations are of record to establish any change of relation between gage and discharge.

M. Proney, many years ago, claimed that the bed of the Po had risen to such an extent through levee construction as to render necessary the construction of a new river channel, to preserve the valley from serious injury. His statement was questioned by contemporary Italian engineers (2) and has been disproved by recent Italian investigators. It was accepted by Cuvier and has been transmitted to the present day by compilers who, while familiar with Cuvier, are ignorant of the investigations which have resulted from the statement.

Herr Gustav Wex (3), in a series of papers published from 1873 to 1879, asserted that the cutting of the forests of Hungary and Austria had caused a rise of the river beds of that country, which assertion was denied by Hagen and other German engineers, who claimed that the evidence submitted not only did not justify the assertion, but that the little change in the river beds which had occurred, could be more logically accounted for by the works of river regulation than by deforestation or levee construction.

Recent investigations have developed a similar difference of opinion among engineers (4), which when analyzed indicates that those who study large river systems find no evidence of a deterioration from deforestation or from the drainage of marsh lands, while those who investigate the flow of mountain streams of steep declivity find a resultant fill. These discrepancies can be explained by the fact that one set of investigators is discussing the portion of a river where the scour and fill are in unstable equilibrium, while the other group is considering the area of deposition. The best example is afforded by the valley of the Po, where a fill of the bed has been observed in some of the tributaries rising in the Alps, while the main stream affords no evidence of such action (5).

As stated in the chapter on the laws of the flow of sediment, the area of deposition acts as a large reservoir in which the detritus is retained for a certain period and reduced to a fineness that enables it to be transported down the river, without disturbing the relations which geological eons have established. Man's destructive work is ordinarily so puny when compared with the gigantic forces of nature, that while it may increase slightly the rate at which the area of deposition moves from natural causes down a valley, its effect below that area is incapable of measurement. In the United States the engineers who have studied the large river systems have arrived at the same conclusions as those of the engineers of Germany and Russia, while those engaged in forestry and those whose observations are confined to mountainous tributary streams give illustrations of river fill. In Germany, the influence of forestation even on small streams is questioned. (Appendix B.)

It recently has been claimed that the Yellow River (6) of China afforded evidences of the raising of its bed from levee construction, due to the fact that when for any cause the river changes its location, the old river bed is found at a higher elevation than the one newly formed. This is not an unusual occurrence in any alluvial river. As was stated in explaining the formation of rivers, such streams rapidly build up their banks from deposits, which have a higher elevation than the land at a greater distance from the channel. Their deltas also encroach on the sea by deposits of material carried down them. In the course of geological ages they may so increase their length that even with the gentle slopes that usually exist toward the river's mouth, the river bed may be higher at the upper end of a delta than the original land level.

Levee construction, by retaining in the river channel a large amount of material which otherwise would be deposited on the banks, may increase the deposits in the sea and thus accelerate the lengthening of a river, but a change of slope due to this cause is so gradual as to be a subject of geological discussion rather than of practical river engineering. But if a channel is opened to the low areas distant from the river, by a caving of the high river banks, the new channel will flow over land lower than the river bed, until it has been adjusted to the new conditions.

Moreover, the diversion of the great part of the discharge from the main stream would cause such a reduction in velocity of the flow of the remainder, as to cause a rapid fill of the old bed, and might even raise the crests of its bars above the low-water surface, so that a traveler visiting the region a few years after the diversion occurred, and unfamiliar with the conditions, would conclude that there had been a greater lowering of the water surface than actually had been created.

When a river excavates a channel across a narrow neck of land, forming what is called on western rivers a *cut-off*, a similar lowering of the river bed occurs at its upper end, and the retardation of the current around the bend causes a large deposit there. At the Napoleon cut-off on the Missouri River which was made during the flood of 1916, such a fill resulted as to raise a great part of the upper end of the old channel by 1919 above the mean river stage.

Such changes modify the slope of a river, and its discharge will seek to regain the original regimen by a scour at some places and a fill at others, as is illustrated by the Red River, and explained on page 96. There is a possibility, however, that the conditions which exist in the streams emptying into Lake Biwa, Japan, as stated on page 108, may obtain at Honan on the Yellow River, since the latter also debouches from a mountainous region into a plain at that locality. River slopes are more productive of changes in a river bed than are levees.

The necessity for protection against the destructive action of floods is the greatest, however, in those portions of the river valley where the forces causing deposition and fill are in an unstable equilibrium. The soil created by the deposit from alluvial rivers in such localities is usually very fertile and invites agricultural development. Hence these localities tend to become thickly inhabited, and a flood not only destroys the growing crops but endangers the lives of the inhabitants and of their live stock.

Numerous methods have been employed or suggested for preventing floods or for ameliorating their effects. The first primitive method employed was to build a mound of earth, on which the settler and his stock could take refuge from the flood and remain until it subsided. When floods occur at such seasons of the year that they do not interfere with the raising of crops, this method has certain advantages. It is not only an economical method of affording relief from floods, but also the land is enriched by the annual deposits from the flood waters, and the fertility of the soil is maintained without recourse to fertilizers, which soon become necessary in the richest alluvial valley, when all overflow is prevented. The Nile is an example of a river which is annually permitted to overflow its banks with most beneficial results, and works have been constructed to insure an adequate amount of water for this purpose (7).

While a portion of the land on certain rivers is protected from overflow from the highest floods, another portion has only limited protection, the levees being given such a height as to permit overflow above a certain stage. Certain portions of the Rhine have been thus protected, and the increased area over which the flood is allowed to spread has reduced its height to a certain extent. On rivers where the greatest floods are liable to occur during the growth of vegetation, however, the agricultural interests usually demand complete protection at all stages.

The reduction of floods by forest growth has so many advocates in the United States (8) that it merits critical analysis. It is an unquestioned fact that a large amount of the rain that falls during the period of the growth of vegetation is absorbed by the plants and produces their growth. If that amount of water could be abstracted from the discharge at the crest of a flood, it would cause a perceptible reduction in its height. It also is claimed that a forest during its growth creates a humus over the soil, from the decay of leaves and mosses, which will absorb a large amount of rainfall; that the roots of trees also loosen the soil and render it more porous to the water that falls on the surface; that it retards the surface flow; that it delays the melting of snow by shielding it from the sun's rays, thus diminishing the danger of the production of floods by the snow suddenly adding its volume of water to that of a rainfall; and that it causes a more uniform distribution of the rainfall, reducing the intense rains which produce floods and diminishing the period of drought during summer. As an example Asia Minor is cited, which has been converted from a fertile region in ancient times to almost a desert at the present day, the change being accompanied by a destruction of forest growth.

An analysis of the causes which create floods does not sustain these contentions. The moisture which is absorbed in the growth of plants is derived principally from the soil through their roots. It therefore is abstracted not from the water which flows on the surface but from that which has already percolated into the ground, and instead of reducing the flood discharge it lessens the flow from springs, *i.e.*, the low-water stage. Moreover, on many of the rivers of the United States, the great floods occur in late winter or early spring, when the deciduous trees are bereft of foliage, and the flow of sap has ceased even in the evergreen varieties.

While the humus absorbs proportionately more water than ordinary soil, it forms a reservoir of very limited depth, and its capacity is exceeded by even moderate rains. It therefore acts during the light rains which produce low-river stages, but fails during the great storms which produce floods.

The theory that the roots of trees loosen the soil is contrary to fact. A field whose soil has been loosened by plowing absorbs more rainfall than the ground under any variety of forest growth, and the roots of trees not only compact the earth through which they force their way, but themselves retard the flow of water which has been absorbed by the soil. The retarding action of the forest on the surface flow may be beneficial or injurious, depending upon the superposition of the flow from one hillside on that from another. In a prolonged rain it will probably have little effect in increasing or diminishing floods.

The influence of the forest on snow is extremely variable (9). One year it may retard its melting or even accelerate it so as to prevent the junction of its water with that of a heavy rainfall, while the next year it may reverse this action and cause a superposition of one on the other, depending on climatic conditions during the late winter and early spring. The melting of the snow by the sun's rays alone is so slow a process that the discharge it creates in a river does not produce floods. If the sun's rays melt the snow before a heavy rain occurs, the retarding action of the forest is injurious rather than beneficial. However, it is by no means a universal law that the snow in forests remains longer than on areas bereft of trees. The snow that falls in a forest is spread uniformly over the surface of the ground, while the action of winds on a barren hillside tends to cause the snow to collect in immense drifts which often remain of considerable size after the snow of the forest has disappeared. On the other hand, a fall of sleet which will create on the exposed hillside an impermeable covering of the soil, may be caught by the leaves and branches of trees and the underlying soil be thus protected and rendered more permeable to subsequent rainfalls.

The effect of forests on rainfall has not been determined accurately, but there is considerable evidence that there is a difference in precipitation over forests and over other areas, as for example a city. But the great storms which produce floods have their origin in cyclonic atmospheric action which brings large amounts of moisture from the ocean to the land. Such storms have a path of maximum precipitation which is independent of the character of the vegetation over which they pass. The location of the mountain ranges has then a great influence on the amount of rainfall, the hillside whether barren or covered with vegetation receiving more than the valley.

That Syria has become unproductive in recent years is ascribed by many to the destruction of irrigation works, rather than to destruction of forests. But even admitting for the sake of argument the extreme claims of the advocates of reforestation, the reduction of the volume of floods by forest growth to such dimensions as would prevent overflow would require such a conversion of existing agricultural lands into a sylvan wilderness, that the country could not sustain its existing population, and the deer, bear, wolf, and other denizens of the forest would replace the inhabitants of our cities and farms. It should be borne in mind that when the forest is removed other vegetation takes its place; the fruit tree in its growth absorbs a corresponding amount of water to the oak, and it is even possible that the amount of water absorbed per acre by a field of wheat or corn in producing annually the stalk and seed may exceed that of a pine forest, whose growth is limited to the area of its upper branches.

A second method of preventing floods that has been proposed is by the construction of large reservoirs (9) to retain the excess water during storms and to feed it gradually to the river during low stages. Nature affords numerous examples of this method of reducing flood heights, of which the most noted is the regulation of the floods of the St. Lawrence River by the Great Lakes. There are, however, certain practical difficulties in this method of flood prevention which require consideration. The most effective location for such reservoirs is in the bed of the main river, but its alluvial valley is usually very fertile and a reservoir of the size necessary to regulate the floods efficiently would necessitate the condemnation of a rich farming region, so that economical considerations require the location of the reservoirs at the headwaters of the various tributaries of the river, where the land is less adapted to agriculture and therefore cheaper. This leads to a multiplicity of reservoirs, and an increase in the volume of water which must be stored, due to the irregularity of the rainfall in the basin. In one year the heaviest precipitation may be in the areas drained by one tributary; in another year the rainfall may be light in that basin and intense in another; and provision must be made for the storing of the maximum flow of each. A centrally located reservoir with less capacity than the two combined could provide storage for both years.

In a large river basin the limitation that the reservoirs shall be located at the headwaters of the tributaries on land not useful for farming, leaves a large area whose flood waters are unrestricted. The construction of an enormous number of reservoirs in areas where land is valuable for agricultural purposes is the only other alternative.

The basin of the Mississippi River affords an extreme example. Its mountainous tributaries rise in the Rocky Mountains, the Appalachian range, and the Ozarks, from 1000 miles to 3000 miles from its mouth; and if the entire rainfall of its mountain ranges were withdrawn from its flood discharge, there would still remain a vast region (whose extent can be appreciated by a glance at a map of the United States) that would contribute its precipitation to the floods of the lower river.

When a reservoir is built even in mountainous regions, economical considerations limit its capacity. It is exceptional that the discharge for an entire year or even during an entire rainy season can be stored without constructing dams of inordinate height. Ordinarily the reservoir must be emptied after every great storm to supply space for the flow of one which succeeds it.

This necessity is a serious objection to the combined employment of reservoirs to reduce flood heights and also to store water for the production of power. The two purposes are antagonistic. The production of water power demands a conservation of the water until low stages so as to preserve as constant a head as practicable. When once filled the reservoir should remain so until low water and the surplus from subsequent precipitations should be allowed to escape, which would interfere seriously with its utilization for flood protection. If it is emptied, the anticipated storm may not materialize and the reservoir may be useless for power purposes for the remainder of the season.

Where a system of reservoirs only partially controls the discharge of a basin, due to the irregularity of the rainfall, there is danger of the discharge from the reservoir arriving in the lower valleys of a river, when the unregulated floods from the other tributaries are at their highest stage, thus increasing their height. If the flood in the mountains had been uncontrolled by reservoirs, its flood waters might have passed down the main stream prior to the arrival of the floods of the tributaries from prairie regions.

Employing the Mississippi River basin again as an extreme example, a series of reservoirs can be constructed at the headwaters of the Missouri River, which would retain all the water derived from a heavy precipitation and could deliver it after all danger from that rainfall had subsided within a bank-full stage. But it would require about 40 days for the water after it had been released to flow to the Mississippi. If heavy rains should occur in Nebraska, Kansas, Iowa, and Missouri which would cause the lower tributaries of the Missouri to have a maximum discharge when the reservoirs were producing a bank-full stage in the main river, a great flood would result which would have been avoided if the original flood from the mountains had been permitted to escape without restraint, and if the main river was again at a low stage when the lower tributaries were in flood.

Such a combination on the Missouri, however, would be exceptional, as the floods of the lower tributaries usually precede those of the mountain streams, and the discharge of the latter is small compared to that of the former. It would be more liable to occur in the Ohio Valley, although the flood-wave moves from Pittsburgh to Cairo in about ten days, and a delayed flood from the Ohio whose crest corresponded at Cairo with that of the Missouri River, which usually arrives at that point at a later date, would produce most disastrous results in the lower Mississippi Valley, since the combined maximum discharges of the two rivers far exceed any discharge recorded on the lower river.

Nor is it a proper reply to the criticism that such a combination would be exceptional. It cannot be too strongly emphasized that average conditions produce average stages and that great floods always arise from exceptional conditions.

When the entire basin is regulated by reservoirs, the engineer in charge of the system has a most complicated problem to solve. (In a project for regulating the Kaw Valley, Kansas, over 70 reservoirs are proposed.) After every storm he must reduce the level of all the reservoirs to a predetermined elevation before the arrival of the next rainfall, and he must not permit the discharge from each reservoir to overflow the banks of the tributary on which it is situated, and the combined flow of the various tributaries must not exceed that of the bank-full stage of the main river. As the time of the arrival of the next storm and its intensity are unknown, he does not possess the requisite data on which to base his computations. In the United States the retarding basin has therefore been substituted recently for the retention reservoir.

The retarding basin (10) is formed by the construction of a barrier across a valley which does not interfere with the low-water discharge of the stream, but limits the flood discharge to a predetermined amount. One of the first examples of this type of construction is afforded by the Pinay dam across the valley of the Loire River in France. When a flood occurs, the portion of the valley selected for the retarding basin is overflowed to a higher stage than otherwise would exist. Since the flow through the barrier is reduced, the flood heights in the lower portions of the valley are diminished, but as the river is permitted to return to its normal condition during low stages, the lands in the upper reaches of the river are overflowed only temporarily during high stages, and they still can be utilized for such agricultural purposes as raising a crop of hay or for pasturage. The cost of land condemnation is therefore less than when a reservoir of corresponding dimensions is constructed, since only a temporary use of the lands affected by the increased heights of the restrained flood over ordinary overflow has to be obtained, instead of a purchase of the entire area flooded.

It also has been attempted to reduce flood heights by enlarging the low-water section of the river. The success of this method is dependent largely upon the amount of sediment the river carries in suspension. In alluvial rivers the low-water bed is the result of a conflict between the forces that cause deposition and those that cause scour. If the equilibrium which these forces have created is destroyed by artificial means, there is a tendency to return to normal conditions, and periodic dredging is required to maintain the enlargement. In a valley formed of glacial drift, however, an enlarged section may afford considerable relief.

Another method proposed for reducing flood heights is by straightening the river (11). This method of flood reduction is successful only when the excavated channel extends to a tidal bay or a lake. If it connects one portion of a river with another it causes merely a local lowering of the water surface at the upper end of the cut, and a corresponding raising of flood heights at the lower end, similar to that which is caused in the low-water channel by analogous means. There is also the same tendency to excessive caving in alluvial soils. In fact the deterioration of the low-water channel usually occurs during floods, including the movement of a large amount of sediment into the channel below the cut, the reduction of slope through it, and the increase of slope above. Humphreys and Abbot, in their *Physics and Hydraulics of the Mississippi River*, estimate the increased height of the flood below the straightened channel to be equal to half the fall in a straight portion equal in length to the shortening of the channel.

The reduction of flood heights by means of outlets (12) and waste weirs also has been proposed. Since an outlet reduces the discharge of the river at all stages, it is injurious to the regimen of the river at low water when as great a discharge as practicable is required to maintain the low-water channel. The water flowing through the outlet has also to be prevented from overflowing the country, and usually the cost of levee construction along its banks will exceed the extra cost of making the levees along the main stream of sufficient height to carry the entire river discharge. A system of lakes through which the outlet flows may reduce flood heights in the outlet, however, to such an extent that the combined levee system is more economical than a single one.

There is a fundamental principle, moreover, which condemns the use of outlets on alluvial rivers, with but few exceptions. When a river's flow is divided between two channels, there is a difference of velocity in the two branches, and there is a tendency to the deposition of sediment in the one that has the least velocity. The latter channel thereby contracts and the other channel tends to enlarge. An outlet therefore will fill or scour, according as its velocity is less than or greater than that of the main stream. If it tends to fill, it can be kept open only by dredging. If it scours, there is danger that it will become the main channel, and that the old river bed will be abandoned. In the lower Mississippi Valley, the outlets have all shown a tendency to fill and close themselves, though in some instances this tendency has been accelerated by the construction of levees across their heads. Even the Atchafalaya outlet, which is required for the navigation of the Red River, can be maintained at low water only by dredging. As a precautionary measure, however, submerged dams of brush and stone have been constructed across its head to prevent undue enlargement during floods.

A waste weir or spillway is a structure in a levee line which permits the discharge of water above a bank-full stage and does not produce as injurious effects on the low-water channel as an outlet. The water which escapes through a waste weir has also to be prevented from overflowing the adjoining land, and its channel has to be limited by levees. There is also the same tendency to a deposit of sediment as in an outlet, and periodic dredging is required to maintain its efficiency.

In the Sacramento Valley (13) waste weirs have been employed extensively to reduce flood heights, which had become excessive on account of the passage down the valley of sand waves caused by hydraulic mining. The river is in a state of transition from the old equilibrium which existed prior to the introduction of hydraulic mining to a new one which it is now attempting to create, and its local slopes are constantly changing. These waste weirs lead to broad-passes on the opposite side of the valley to that in which the river channel is located. These by-passes unquestionably will afford places of deposit for large masses of the detritus moving down the river, but it is considered probable that sufficient sand will continue to move in the river bed so that extensive dredging to maintain the low-water channel will be required for many years until the new equilibrium is established.

If dredging were suspended at the juncture of the Mississippi, Red, and Atchafalaya rivers, natural causes would soon convert this outlet of the Mississippi River into a waste weir. To maintain navigation between the Mississippi and the Red rivers (14) would then require the construction of an expensive lock and a short canal. The flow through the dredged connecting channel is small when compared with the low-water discharge of the Mississippi, and the shoaling of the main river resulting from the small low-water diversion through the outlet is slight. The advisability of converting the outlet into a waste weir therefore becomes a question of the relative cost of maintaining a dredged channel, and of the interest on the construction and maintenance of a lock and canal.

The method of flood protection that is employed most universally is the construction of levees. This method has stood the test of practical application for ages. The principal objection to its use is the increase in flood heights that is caused by the confinement of the overflow to the river channel. Many engineers claim that the concentration of the flood discharge in the river bed will produce its enlargement so as ultimately to remove this objection, but observations over long periods on leveed rivers have demonstrated that the increase in the cross-sections of the river channel is so gradual from this cause as not to merit practical consideration. The levees must be built to the maximum height to produce the scouring effect desired or they will be overflowed and destroyed before it is effected. Any subsequent enlargement of river section merely adds a factor of safety to a levee line already constructed.

While a levee performs the same function as a reservoir embankment, it differs from an ordinary earthen dam both in form and in method of construction. For economical reasons it must be built from the soil in the vicinity, and there is rarely available material to form the puddled core so essential in reservoir construction. Moreover, it usually rests on a permeable foundation through which water would percolate even if the embankment were made impermeable. The necessary seepage must be reduced to such an extent that the embankment is not endangered by planes of saturation through its having such slopes that the superincumbent dry material will tend to slide. Moreover, the water passing through or under the levee must not be permitted to flow with sufficient force to move particles of the material of which the levee is composed or that on which it rests. This requires gentler slopes on the land side than usually are formed in reservoir dams. The exact dimensions depend on the character of the alluvium of the valley to be protected.

On the lower Mississippi (15), levees usually are given a height of three feet above the estimated highest flood, a width of crown of eight feet and a land slope of one on three, for levees less than 12 feet in height. For levees of a greater height, it is necessary to increase the width of the base, generally by the addition of a banquette, which extends from a point on the land slope with an elevation eight feet below that of the crown. Its width varies from 20 to 40 feet, depending on the height of the levee. Its upper slope is about 1 on 10 to provide for a proper drainage of rain water, and its land slope is 1 to 4.

This arrangement provides a width of base exceeding 10 times the head under which the water flows through the subsoil. This is somewhat less than is allowable in a dam founded on permeable soil in a river bed. Since the river is at an extreme flood stage for a comparatively short time, however, so large a factor of safety is not requisite. In exceptional cases sand boils have developed behind the levee line during floods, rendering necessary a further extension of the banquette.

The river slope is usually one to three, which is sufficiently gentle to afford protection from erosion from rains and river currents when the slope is well sodded with Bermuda grass. However, if the levee is exposed to wave action during storms or from passing vessels, either a gentler slope or a more effective protection must be provided. In such locations a facing of concrete is frequently employed. The crown and land slopes of the levee are protected by Bermuda sod.

In European countries, the levees have approximately the same width of base as those on the Mississippi River, but they have a much wider crown and much steeper slopes. This is on account of the common use of the levees as roadways, for which purpose the crowns of the levees are paved. The American form of levee secures protection from floods with less earth than those of Europe, and when road construction has advanced to the stage of substituting some form of pavement for the dirt road, the banquette will afford a proper place for its location with far less expenditure than if it were placed on the top of the levee.

An important item of levee construction which is too often neglected is a drainage ditch on the land side of the levee to prevent the seepage water from injuriously affecting the crops in the adjoining fields.

The methods employed in levee construction vary from the laborer with his spade and wheelbarrow to elaborate steam levee machines (16) and the hydraulic dredge. The principal economic factor in the problem is the height of the levee. In a small levee of short length, manual labor may be the cheaper, due to overhead charges for plant; as the levee increases in size, animal traction is profitably substituted; for the large levees on the lower Mississippi the levee machines become the most economical means of construction.

The hydraulic dredge which derives the material for the levee from the river bed is economical when the lift from the low-water surface to the crown of the levee is relatively small and the levee is located close to the river bank. It has been employed extensively for levee construction on the Sacramento and on the upper Mississippi.

The flood protection of the Miami River, Ohio, (17), is an example of a judicious application of the principles enumerated above. It is estimated that the maximum flood discharge of the Miami River if uncontrolled may equal 350,000 second-feet at

Dayton and 490,000 second-feet at Hamilton. By retarding basins the crest of the flood is reduced to 125,000 second-feet at Dayton and 200,000 second-feet at Hamilton, a discharge about one-third greater than the natural channel capacity of the river at either locality. This is provided for by an enlargement of the low-water bed and by levee construction.

The estimated cost of the work was $25,000,000, while the cost of detention basins which would have reduced flood heights to the existing channel capacity of the river was estimated at $96,000,000.

The Miami River carries relatively little sediment in suspension, and a large amount of the material that moves along the river bed during floods will be retained in the detention basins. Hence the danger of refilling the enlarged channel is not so great as it is in an alluvial river heavily charged with sediment.

The preceding analysis leads to the following conclusions regarding the proper method of treatment of the flood waters of a large river basin.

On steep mountain slopes, the destruction of forest growth should be prevented in order to preserve the soil from excessive erosion, just as the steep slopes of a levee are protected from rain wash. It is not necessary to prevent the cutting of trees to attain this object, as the stumps and roots are the protective agencies. Until they decay they will prevent scour as effectively as the live tree. The cut over land, however, must be protected from forest fires, the removal of the stumps and roots prohibited, and a second growth of timber encouraged.

The mountainous valleys within the area of deposition usually contain relatively little land suitable for agriculture, and are frequently of such shape that dams can be constructed readily which will create reservoirs of large capacity. Under such conditions power development should become the controlling factor. Private capital is prepared to construct the dams if granted a franchise. The general public, however, is entitled to some return for permitting such construction, and the power company equitably can be required to build dams of such height that larger volumes of water can be stored than are required for power purposes. The excess water can be employed to regulate stream flow. As the valleys increase in width and in fertility, the retarding basin affords an economical method of reducing flood heights. It converts the flood wave as shown on the river's hydrograph from a series of sharp peaks with intervening depressions to a smoother curve, diminishing the height of the flood but increasing its duration. When, however, by the superposition of the flow of many tributaries, the river's hydrograph has been flattened by natural flow, a further lowering of the flood crest requires the storage of such a volume of water as to require the occupancy of too much agricultural land by the storage basin for the economical protection of the remainder of the valley. In that case, a levee system becomes the cheapest method of flood protection. It may be that the reduced floods from numerous tributaries, controlled by retarding basins, will occasionally so combine as to increase the resultant flood on the lower river. If so, it is a penalty the lower valley incurs from its location, and the increased size of its levees becomes necessary as the result of insuring protection to the lowlands of the tributaries.

CHAPTER XII

ESTUARIES

When a river empties into the ocean, it is exposed to the influence of the tides, which frequently exert a greater force than the discharge. In mid-ocean the tidal wave causes a relatively small rise and fall of the water surface, but as the wave approaches a coast the oscillations increase in size and extend up estuaries for long distances. At the mouths of rivers the slope due to the river flow is gentle, frequently less than 0.1 foot per mile. The river encounters a fluctuation in sea-level which varies from 14 inches in the Gulf of Mexico to 28 feet in some localities around the British Islands, and in extreme cases, as in the Bay of Fundy, the fluctuation may exceed 50 feet. At low tides the natural flow of the river is greatly accelerated, while at high tides, not only is the outflow of the river water prevented, but there is often a large inflow of water from the ocean. Since salt water has a greater density than fresh water, the inflowing tide of salt water at certain stages moves along the river bed with an outflow of river water above it.

In the St. Lawrence River (1) the tidal wave is propagated up the river a distance of 350 miles at the rate of 83 miles per hour. Even the relatively small tides of the Gulf of Mexico produce during low water an appreciable effect on the flow of the Mississippi River at Red River Landing, 300 miles from its mouth.

The height of the tidal wave in a river is a function not only of the height of the ocean tide, but also of the form of the estuary. If a river empties into a sea through a wide funnel-shaped mouth, the height of its tides is greatly increased. In the Gulf of St. Lawrence the tidal range is from 3 to 4 feet, while at Quebec it varies from 9 to 18 feet. In the Thames the level of high water at London Bridge is nearly 4 feet higher than at its mouth (2). If the river outlet is contracted from any cause, the height of the tidal wave is diminished. Thus the contracted entrance to Chesapeake Bay reduces the height of the tides of the rivers emptying into it, but the funnel-shaped mouths of the Potomac

River and the James River cause higher tides at the head of navigation of these rivers than exist in the bay.

The rate of propagation of the tidal wave is a function of the depth. In mid-ocean it has a motion of about 600 miles per hour. As it approaches a coast not only is the oscillation increased but the rate of propagation is diminished. The speed does not exceed 100 miles per hour in depths of 100 feet. In rivers it is still further reduced by shoals. At the mouth of the Seine, when the depth was 5.9 feet, the rate of propagation up the river was 9.8 miles per hour. Increasing the depth of 17.7 feet increased the rate of propagation to 16.4 miles per hour (3).

The tidal wave is caused primarily by water pressure. It is transmitted in the same manner that the flood wave is propagated in non-tidal rivers. It is not dependent on the velocity of the river flow, which is a function of the slope of its surface and the energy imparted to the water. Even where tidal oscillations are large, the velocity of the tidal currents rarely exceeds five miles per hour. Excessive velocities result from obstructions to the transmission of the tidal oscillation. Where a shallow bar is formed at the mouth of a river, the tide rises much more rapidly in the sea than in the river, producing a steep slope over the bar. At certain periods of the tide, the tidal oscillation may break over the bar as a wave breaks on the seashore instead of moving up the river as a wave. This produces what is termed a tidal bore and causes a supplemental surface wave to flow up the river with great velocity. Among the most noted bores is that found at the mouth of the Tsien-Tang-Kiang River (4) in China. At certain tidal stages this bore creates a slope of 1 foot to the mile for a distance of 20 miles and a surface velocity of 20 feet per second. In the Petit Codiac River emptying into the Bay of Fundy, a bore wave 5 feet 4 inches high, moving at the rate of 8.47 miles per hour, has been observed. Bores are created at the mouths of numerous other rivers, particularly during spring tides, and it has also been observed that if a deep channel is formed across the obstructive bar, the bore may be eliminated.

As the result of the tidal oscillation the flow of rivers within tidal influence is constantly changing. As the tide rises, the outflow is checked and is succeeded by a period during which the water ceases to flow. This is followed by an inflow from the sea which is reduced to zero at high tide, and is succeeded by an outflow as the tide falls. During both flood and ebb tides the velocity of the flow is greatest at half tide.

As the flood tide enters a river it encounters in the low-water tidal basin the fresh water, which is increased by the river's discharge. The tide has to force this water upstream in advance of its flow. Hence the inflow from the sea would ascend a river a relatively short distance if it were not for the difference in density of salt and fresh water, which causes the river water to rise to the surface and the ocean water to flow along the river bed until they have become mixed. While the inflow of sea water is limited, the motion it imparts to the water that it backs up extends to a point where the river's discharge cannot be overcome. The discharge of the Mississippi River is so great during floods that not only is the tidal flow unable to enter the river, but its discharge displaces the waters of the Gulf of Mexico for a considerable distance from its mouth. Since the flood tide impounds the river discharge while the ebb tide flows with it, more water is discharged during the ebb than enters during the flood. The durations of the flood and ebb tides also differ. At the mouths of large estuaries the duration of the flood tide is about 5½ hours and of the ebb tide about 6½ hours. The difference in the duration increases with the distance from the mouth, and with the frictional resistance to the progress of the tidal wave due to the shoaling of the water and to the narrowing of the channel (5).

As a result of this tidal action, a river's discharge moves intermittently through its tidal estuary, with its velocity increased during the ebb tides and reduced during the flood tides. When the flow is checked, there is a tendency to deposit the sediment it carries, which is again moved along the river bed when the current is accelerated. Moreover, the inflow from the sea brings silty material into the river from the sand waves which are moving along the coast, and this silt has also an intermittent motion up and down the tidal basin.

There is a marked difference in the method by which the silt is transported in the non-tidal sections of a river and in its estuary. In the upper portions of a river the great mass of the material either is carried in permanent suspension, or moves as sand waves in contact with its bed associated with a small amount temporarily in suspension. In a tidal basin, on account of the greater specific gravity of sea water and its tendency to flow along the river bed, the material eroded is mixed more intimately with the water. A much larger percentage is placed intermittently in suspension and a comparatively small amount moves as sand waves. The material which has been carried in permanent suspension in the upper portions of the river is deposited during slack water and thereafter also moves intermittently in suspension. This silt moves back and forth with the tides along the river bed, and where for any cause there is an obstruction to the free propagation of the tidal wave, it tends to accumulate and form a shoal.

The curved tracé with its pools in bends and its crossings over bars between the pools, which is so essential to the regulation of the non-tidal portions of a river, as explained in Chapter VI, is inapplicable to the improvement of its estuary. In the upper reaches of a river the formation of a bar in the crossing, with the resultant slope over it, is necessary to preserve the depths in the pools, and to prevent an injurious increase of slope on the bars above and below it. In the tidal section, however, the formation of a permanent shoal not only limits navigation over it but reduces the tidal flow and therefore affects channel depths in other localities. With the constant fluctuation of the tides, there can be no permanency of river slope in any portion of the estuary. A bar steepens the slope locally during certain portions of the tide, with a corresponding reduction of slope at other localities. A bend not only tends to form a bar below it, but it also offers a resistance to the flow of water by forcing it to change its direction, thus interfering with the tidal flow. In a curved channel there is also a tendency for the flood tide and the ebb tide to follow different paths, causing a long period of slack water in each path, during which silt is deposited. This action produces cross-currents injurious to the main channel.

In the improvement of an estuary, the channel should therefore be made as straight as possible, and any bends that it is necessary to introduce should be of gentle curvature. When the tidal inflow largely exceeds the river's discharge, it becomes the controlling factor in determining channel depths and should be restricted as little as practicable. This necessitates a gradual enlargement of the channel of the estuary from the head of the tidal flow to the river's mouth, proportioned to the tidal discharge.

Where it has been attempted to reverse the process and prevent the entrance of the flood tide, as at the port of Boston, England, where the river Witham was closed by a sluice-gate, a disastrous shoaling has occurred (6). In such cases the incoming tide has its velocity checked by the barrier and a long period of slack water is created. During this period any material held in suspension is deposited, and the ebb flow has not sufficient force to remove it. Moreover, the effect of the barrier extends for long distances below it and may even have an injurious action on the bar at the river's mouth. There results as a corollary another principle in improving estuaries: *The tidal flow should be admitted as far up a river as possible and all barriers to its progress removed so that the period of slack water may be reduced to a minimum* (6).

In Chapter II attention was called to the influence of the geological formation of non-tidal rivers on the flow of sediment. This is still more evident in their tidal estuaries. A river that empties into the ocean between two rocky promontories or into a bay similarly protected, is exposed to the movement of comparatively little material along the ocean bed, and will have a deep mouth. If the river empties into the ocean along a sandy coast, however, a bar is formed across its outlet. For example, the rocky coasts of Labrador, Newfoundland, and Cape Breton Island protect the outlets of the St. Lawrence River and its gulf from the formation of such a bar as that which forms across the Columbia River. Nature sometimes provides a trumpet-shaped channel with its cross-section proportioned to the tidal flow, of which the St. Lawrence is an example.

If the estuary is wide and its banks are irregular, the main river channel may be tortuous and shifting, with depths on shoals insufficient for navigation. Under such conditions a system of longitudinal dikes, with the distance between dikes reduced in proportion to the flow of the tide, will reduce the periods of slack water and will prevent inequalities of flow in different sections of the estuary. This is of benefit to navigation, although it reduces the volume of the tidal prism. The increase in channel depths and in tidal oscillation will compensate in great measure, however, for the resulting reduction in widths. Since the flow at mid-tide is the greatest and diminishes at both high and low water, regulating dikes directing and concentrating the lower part of the ebb tide may be sufficient to attain the depths required for navigation, and the upper portion of the flood tide may be permitted to fill the portion of the estuary behind the dikes and thus prevent the reduction in the volume of the tidal prism. But if the channel is very tortuous and shifting, high dikes are necessary.

The reduction of the volume of the tidal prism is objectionable where an obstructive bar forms across the river's mouth, and to make the diminution as little as practicable it has been proposed to supplement the channel formed by dikes rising to mid-tide by a wider channel limited by dikes rising above high tide. There is a practical difficulty of construction, however. The space between the two systems of dikes must be given a gradual upward slope from the low-water dikes to the high-water dikes or there will be a sudden lateral expansion of the incoming tide above mid-stage, accompanied by eddy action detrimental to the direct tidal flow.

The spur-dike which is employed extensively for the regulation of non-tidal rivers is not so well adapted to the improvement of estuaries, since it creates eddies and also a retardation or acceleration of the tidal flow which tends to deposit material temporarily in suspension. There is, moreover, a possibility that the tidal flow may follow the eddy current around the end of such a dike and adopt a tortuous path difficult to navigate instead of preserving the straight course desired, besides leaving a shoal in mid-channel. In the early attempts to improve the navigation of the Appomattox River in Virginia, its channel was contracted by a system of spur-dikes inclining upstream in accordance with the German system of improving non-tidal rivers. A sinuous channel resulted, with deep water between the dikes first on one side of the river and then on the other, with mid-channel depths less than those that formerly existed. By connecting the ends of the dikes by training walls, satisfactory mid-channel depths were obtained.

The material deposited in shoals becomes compacted and requires a greater force to place it in motion again than the force which originally transported it. Hence the regulation of an estuary is greatly facilitated by dredging. In a non-tidal river the force which creates a bar recurs at every river rise, but in an estuary when the channel across a bar is once enlarged, the cause of the deposition is removed and the material carried in suspension has no greater tendency to deposit at that locality than at any other, provided the dredged channel coincides with the natural direction of flow of the tidal currents.

It is not unusual for a dredged channel to enlarge its section without the aid of training walls. This occurred in a channel excavated by hydraulic dredges in the St. Lawrence River below Montreal. During a falling river the dredged channels of the Mississippi frequently increase their cross-section, but this enlargement is accompanied by a fill during rising stages.

When a channel is so designed that its cross-section increases in proportion to the increase in the tidal flow, the river discharge aids the ebb tide in maintaining channel depths. However, the necessities of navigation frequently require a channel of such depth and width at the head of the estuary that its progressive widening toward its mouth is impracticable, due to the topographical features of its banks. Thus it may happen that a channel of uniform width must be constructed because a widening of the channel could be attained only by the removal of high or rocky bluffs at great expense. In such cases the duration of slack water is increased at the head of the estuary, the river discharge tends to deposit its sediment there, and periodic dredging is then required to remove the bars which form.

The river Clyde (7) is a conspicuous example of the successful application of proper principles to the improvement of tidal rivers. In its natural state the Clyde was an insignificant stream connecting Glasgow with the Firth of Clyde, the distance from Glasgow to the mouth of the Clyde at Greenock being 21 miles. Its low-water depth was about 1½ feet at Glasgow and at spring tides 3½ feet, notwithstanding the fact that the range of spring tides in the Firth of Clyde is about 11 feet.

The original project for its improvement contemplated obtaining 7 feet of water up to Glasgow at high water of neap tides and was to be obtained by contracting the river by jetties at the worst bars. At the beginning of the nineteenth century the systematic construction of low rubble training walls was undertaken with a channel width between them of 180 feet just below the harbor of Glasgow and gradually increasing to a width of 696 feet. In a report submitted in 1835 it was stated that the depth at low water in the harbor at that time was from 7 to 8 feet, and 15 feet at high water of spring tides.

The growth of commerce demanding greater channel capacity, the river was given a width of 450 feet in Glasgow harbor, 370 feet just below it, and gradually increased in width to 1000 feet within

6 miles of its mouth. The effect has been to depress the low water at Glasgow 8 feet and increase the depth at spring tides to 30 feet. The first improvement lowered the high water at ordinary spring tides about 6 inches, but a further enlargement of the channel has raised it about 9 inches so that at present it is from 2 to 3 inches higher than it was in 1758 (8).

CHAPTER XIII

THE MOUTHS OF RIVERS

At the mouths of rivers, ocean waves and currents are encountered which are caused not only by the tides but also by winds. In mid-ocean, while the height of the wave produced by tidal action has been computed to vary from 0.73 foot to 1.95 feet (1), waves over 40 feet high have been observed during storms. As the water shoals in the vicinity of a coast, the tidal wave increases in height and the storm wave diminishes, but the tidal wave along the shore is also markedly increased or diminished both at high water and low water by the action of the wind, depending on the direction in which it is blowing. It is to be noted, however, that while the storm wave breaks in shallow water, it can also greatly increase in height in deep, trumpet-shaped bays in a manner similar to the tidal wave.

While the height that waves attain is of importance in the determination of the amount of the tidal flow entering estuaries and harbors and the elevation to be given works of improvement, the vital elements in determining the stability of structures exposed to wave action are their oscillation and the force generated thereby.

When a wind blows over a body of water, it imparts to the particles on its surface an oscillatory motion. Where the depth is great, the particles of water at the surface thus set in motion move in circular orbits, whose diameter is equal to the height of the wave. Hence a water particle moves in the direction of the wind in the upper portion of its path, and has a reverse motion below. The particles below the surface acquire a similar motion but the diameter of their orbits rapidly diminishes through frictional resistance, and the motion becomes inappreciable at a depth below the trough of the wave equal to its height. The form assumed by the water surface under such circumstances is trochoidal, and this trochoid is advancing constantly in the direction of the wind.

When such a wave is created in shoal water, the bed obstructs the reverse motion of the particles and their orbit becomes elliptic. The form of the wave becomes more nearly cycloidal and there is a certain depth at which the crest of the wave assumes the cusp shape of the cycloid instead of the rounded form of the trochoid.

In still shoaler water, the frictional resistance of the bed retards the reverse flow of the particles to such an extent that the particles moving in the upper portions of their orbits cannot adjust themselves to the changed conditions. Then the wave breaks, and the upper portion flows as an auxiliary wave over the lower part.

While the relation of the height to the length of a wave is a function of the duration and the intensity of the wind, it can be assumed for purposes of illustration that a wave has a length of about 25 times its height. The velocity with which the wave is transmitted varies from 2 feet per second to over 100 feet per second, depending on the intensity of the wind. It is evident that a body such as a breakwater, opposing such a moving mass, is exposed to great pressure. If the wave breaks just before it reaches the obstacle, the pressure is transformed into a blow of great force, since water is incompressible. Since the particles of water are free to slide over one another when their velocity is checked, even a breaking wave converts some of the energy of its blow into friction losses, and the force of the blow cannot be accurately computed. If the wave breaks at a considerable distance from the obstacle, as on an outer bar, its force is dissipated and the bar acts as a protection to the breakwater. Dynamometer pressures of over 6000 lbs. per square foot have been recorded on structures exposed to breaking waves. The accuracy of the records has been questioned, however.

A more vivid realization of the force of waves is obtained from the damage they have caused to breakwaters. At Peterhead (2), blocks of concrete weighing 40 tons have been displaced at levels of 17 to 36 feet below low water. During the construction of the Plymouth breakwater blocks of stone weighing from 7 to 9 tons were removed from the sea slope at the level of low water and carried over the top a distance of 138 feet and deposited on the inside. At Wick, two stones weighing 8 and 10 tons, respectively, were thrown over the parapet of the breakwater, the top of which was 21 feet above high water, and blocks of concrete weighing respectively 1350 and 2500 tons were displaced. At the Ymuiden breakwater a block of concrete weighing 20 tons was lifted vertically by a wave to a height of 12 feet and landed on the top of the pier which was five feet above high water. At Bilboa a solid block of the breakwater weighing 1700 tons was overturned (2).

As a further illustration of the power of waves, Mr. Shields gives examples of their destructive effect on rocky cliffs. Thus at Wick, at a height of from 70 to 80 feet above sea-level, blocks of stone weighing 15 tons have been detached from their stratified beds, lifted over ledges 7 feet in height, and driven uphill for a distance of fully 100 feet from the edge of the cliff. At Holburn Head on the coast of Scotland, at an elevation of 130 feet above sea-level, a similar degradation of the cliff is occurring, the debris being moved over 80 feet and consisting of stones weighing up to half a ton.

From these illustrations it will be noted that when a wave dashes against a vertical obstruction, a column of water is projected into the air to a great height, and this mass falls with destructive energy not only on the obstacle which formed it but also on the water, producing a blow which is transmitted to the foundation of the structure, sometimes with disastrous results.

When a wave breaks perpendicularly on a sloping beach, its upper portion is driven up the beach until its energy is exhausted. The water then recedes with increasing velocity until it is met by a succeeding wave, when it continues its course as an undertow, the incoming waters flowing over it. This motion acts on the material of which the beach is composed, the incoming wave moving material inland and the outgoing flow carrying it toward the sea, where it comes to rest when the impetus of the undertow is exhausted. It results that with waves of a certain height and frequency, the beach is being scoured at a given elevation by both the inflow and outflow, the material scoured by the inflow being deposited at the upper limits of the water's motion, while that moved by the outflow forms an outer shoal. The portion of the beach thus acted upon will assume a steep slope.

With a lowering of the tide or a reduction in wave height, this shoal may be scoured by the incoming wave and its material driven toward the beach, so that erosion and fill are alternately occurring along an exposed coast. With a strong onshore wind the beach is being destroyed, while an offshore wind tends to rebuild it.

When the waves approach the coast obliquely, their crests after they break run along the beach and their waters return to the sea by different paths than their paths of approach. This produces a movement of the material scoured along the shore in the direction the wind is blowing, which is increased by the current which is at the same time created in the water. If there is an obstacle along the beach, the moving sand is checked by it, and piles up on its windward side. Beyond it erosion still continues, and as the obstacle prevents the replacement of the material excavated by that moving along the shore, the beach caves more rapidly beyond an obstacle than when it is unobstructed.

When the material thus transported encounters the currents at the mouth of a river it is carried up the estuary during certain portions of the flood tide and out to sea during a part of the ebb, but during certain periods of high and low water the material is deposited, forming a bar across the river's mouth, which also may be increased by material transported by the river's discharge. The tidal ebb and flow scours a channel through this bar, but as it is constantly being increased by material moved along the shore, there is a tendency to force the channel from its normal path by continued accretions on its windward side. This lateral movement of the channel continues until, during some violent storm on the ocean or a flood in the river, the river currents have sufficient force to scour through the bar along the lines of natural flow. The old channel then tends to fill and the lateral channel movement is again repeated.

On sandy shores where the winds have a prevailing component moving the sand in one direction, this lateral channel movement occurs in more or less regular cycles at an unimproved river mouth, and two or more channels will be in existence across the bar, one enlarging as the others are filling. The energy of the tidal flow will be dissipated among these channels.

A knowledge of the direction of the prevailing winds is of great importance in planning works for the improvement of the mouths of rivers and harbors, but it should be borne in mind that the wind bloweth where it listeth, and that for considerable periods the water currents may flow in the direction opposite to that of the prevailing winds, and that these currents carry their load of material, but in less amounts, which is also deposited across the mouth. The character of the shore, whether rocky or sandy, and its exposure, which determines the intensity of the waves, are frequently of more importance than the direction of the prevailing winds. Waves with a long fetch which impinge on a sandy shore, though caused by only an occasional wind, may move more material than those produced by prevailing winds of even greater intensity which strike a rocky coast or whose dimensions are reduced by outlying islands or other obstructions. The ground swell is an illustration of a wave of great force which is independent of local winds. It is created by storms in mid-ocean and is propagated to great distances as a long, low wave of great depth. Local winds merely produce on it a choppy sea.

In the improvement of the mouths of rivers three cases arise. First, the river's discharge may be the determining force in forming the bar. Second, the movement of material along the shore may be the important element. Third, both the river's sediment and the littoral drift may combine to form the bar. When a river with a large discharge flows directly into a sea where the rise and fall of the tide is small, the sediment which it carries is deposited at its mouth and a bar is formed which gradually extends outward, through which the river forces its way in several channels. During flood stages the discharge of the river deposits sediment on these bars above the sea-level and each channel becomes a mouth. This deposit of sediment is termed a delta, as at the mouths of the Mississippi, the Nile, the Danube, and the Rhône.

But there may exist, also, some distance in front of the mouth of the river, a drifting sand bar parallel to the coast which rises at places above sea-level. In that case, the river deposits its sediment in the lagoon thus formed and its discharge enters the sea through one or more channels across this bar. The rivers of Texas and North Carolina have mouths of this character. Formerly some of the rivers of the valley of the Po discharged into the Lagoon of Venice in a similar manner.

Even where the normal fluctuation of the tide is small, as in the Gulf of Mexico and in the Adriatic Sea, the tidal flow may be so increased by the action of winds that the area of these lagoons becomes an important element in determining the depths across the bars at their outlets. This tidal basin may, however, extend inland with its greatest length in the direction of the river discharge, forming a tidal estuary, and the bar may be the result of the deposition of the material carried along the coast and of that discharged by the river.

When a river discharges through several mouths its energy is dissipated, and it is incapable of maintaining a deep channel through any of them. This suggests as a method of improvement the concentration of the flow in one mouth by closing the side channels. Such a method would be temporarily successful, but it would concentrate all the sediment carried by the river in the same channel, with the result that a second delta would begin to form at this new outlet, similar to the one nature has already created. The new delta would have numerous mouths which in the process of time also would require regulation.

Even when the tidal fluctuations are small, the winds along the sea coast produce currents of considerable force and capable of moving large amounts of the light silt brought down by a river. If the prevailing winds have a decided component in one direction along the coast, a littoral current is produced, which creates a steeper seaward slope in the deposits from the mouths that discharge at right angles to its flow than in those which enter the sea in an oblique direction. Hence, if that mouth is selected whose deposits have the steepest sea slope and only enough discharge is concentrated in it to insure an adequate depth of water across the bar, the littoral current will remove a large amount of the deposit and will reduce the rate of progress of the bar seaward, while the remaining mouths will discharge the great mass of water and sediment so far from the one being improved that its bar will not be increased by littoral drift.

For these reasons, in improving the mouth of the Danube (3), the Salina Pass was selected, although it discharged less than 8 per cent of the river flow, and at the mouth of the Mississippi (4) the South Pass was chosen originally, which also had a discharge of about 8 per cent. In its original condition Salina Pass was about 300 feet wide. South Pass was about 600 feet wide. The adopted projects contemplated a depth across the bar at the mouth of the Danube River of 20 feet, and at the mouth of the Mississippi of 30 feet. To concentrate the river flow across the bar, the banks of the pass were extended by means of parallel jetties to water of the depth desired beyond it. The distance between jetties at the Salina Pass is 600 feet. The jetties at the

South Pass are 1000 feet apart, but the width is contracted to 600 feet by spur-dikes 200 feet long built at right angles to them on both sides of the channel. In both instances the projected depths have been obtained and the movement of the bar seaward is so gradual that the cost of the periodic extension of the jetties necessary to maintain the required depths is not excessive. At the South Pass occasional storms may so interfere with the littoral current as to cause a temporary shoaling, and dredging is employed to restore the channel and to obviate the delay which would result from relying on the river current to reëstablish it.

The improvement of the channel across the bar has been accompanied by the enlargement of the South Pass its entire length and an increase in its discharge to about 14 per cent of that of the entire river. Although dredging was necessary originally at the head of the pass to maintain a channel thirty feet deep, at the present time a submerged sill and contraction works are necessary to limit the flow into it.

The improvement at the mouth of the Mississippi has caused a rapid increase in the commerce of New Orleans, and there is a resultant demand for a channel of 35 feet depth to the Gulf. While the South Pass could be enlarged readily so as to obtain the increased discharge necessary to scour such a channel across the bar, the soil which forms the banks is an alluvium readily scoured by river currents and gulf waves and there was danger that its further enlargement would be accompanied during floods by breaks through the narrow necks of land which separate it from the waters of the Gulf. To prevent such a catastrophe it would have been necessary to revet this pass along its entire length. The Southwest Pass (5), which originally carried about one-third of the discharge of the river, therefore was selected in the project of 1902 for obtaining a depth of 35 feet across the bar. For economic reasons converging dikes about 5600 feet apart at their land-ends and 2800 feet apart at the bar were substituted for the parallel jetties constructed at the South Pass, and dredging was relied upon to maintain the channel between them. This dredging was found to be excessive, and in 1916 the project was modified by limiting the channel width uniformly to 2400 feet by two parallel interior jetties. This modified project is now in process of execution.

Whether the channel will maintain itself without excessive dredging when thus contracted, can be determined only when the work is completed. Investigations have demonstrated that the much-discussed Gulf Stream is non-existent at the mouths of the Mississippi River (6), but that the winds produce strong littoral currents which are capable of moving large amounts of silt at both outlets. The silt which flows in the Southwest Pass is also a large percentage of that of the main stream.

Due to the difference in length of the two passes, it is feared that there will be difficulty in maintaining the proper proportions of the river discharge in them, since there are changes of slope caused by floods in the river and by tides and winds in the gulf, with a tendency to deposit sediment in one or the other. The improvement of two mouths of a river is an experiment without precedent in engineering practice.

At the mouth of the Rhône (7), where the whole discharge was confined to a single outlet, the growth of the bar has been so rapid that the extension of the jetties necessitates an excessive expenditure for maintenance, and a lateral canal connecting the river with some harbor beyond the zone of the river's deposits has become necessary to afford a navigable outlet. Such a canal usually requires a lock at its junction with the river to provide for variations in flood heights, with the consequent delays to navigation.

Where the river approaches the sea through an estuary with a pronounced tidal flow in the direction of the river's discharge and gradually enlarges its section so as to facilitate the tidal flow, the tides assume a direction and force that will maintain a deep channel at the river's mouth. The Thames, the Potomac, and the James rivers are of this class. Their outlets maintain themselves without auxiliary works. In outlets of this character, local currents sometimes form bars which can be permanently removed by dredging, as at the entrance to New York Bay. The coasts of New Jersey and Long Island form the trumpet-shaped outlet considered so essential to create an ample tidal flow in an estuary, but the littoral and tidal currents meeting between Sandy Hook and Coney Island create a complicated local flow which produces a bar extending across the estuary between them, with several channels across it. One of these near the Long Island shore has been dredged to a depth of 20 feet and a width of 600 feet, a second one near Sandy Hook to a depth of 30 feet and a width of

1000 feet, and an intermediate channel, called the Ambrose Channel, to a depth of 40 feet and a width of 2000 feet. The two deeper channels have been maintained with little dredging, and the Ambrose Channel has enlarged its section materially since it has been excavated. The conditions which permit the maintenance of two deep channels at this harbor are exceptional and are probably due to a natural diversion of the tidal currents, one of which passes from the lower bay into the upper bay and thence to the Hudson and East rivers, while a second passes east of Staten Island to Newark Bay and the rivers that empty into it (8).

It frequently happens that topographical features prevent the gradual enlargement of the section of the estuary, and that there is a littoral drift of material through which the tidal currents are unable under natural conditions to create and maintain a channel of suitable depth for navigation. It then becomes necessary to contract the outlet and concentrate the tidal flow in a single channel of reduced width, which will maintain the required depth across the bar.

Parallel jetties have been used extensively for this purpose, as at Calais, Dunkirk, and Ostende (9). Since these harbors have been maintained for several hundred years they afford good illustrations of the ultimate effect of such structures on the movement of littoral drift. These harbors were located originally near the outlets of small streams, with tidal basins not proportioned to the discharge of the river. The outlets were obstructed by bars with insignificant channels over them at low tide. With the growth of commerce deeper channels were required, and parallel jetties were constructed across the bar for the purpose of inducing tidal scour. A deeper channel was created by this means, but in process of time the littoral drift piled the sand against these jetties and the entire shore line was built out to their ends. The bar then reformed in advance of its original position and the inflowing tides also brought material into the harbors which gradually filled them. This action frequently was accelerated by the reclamation by the inhabitants of land covered at low tides.

The reduction of the tidal area diminished the force of the outflowing tides, and a further extension of the jetties was unable to maintain a satisfactory channel across the bar. To increase the tidal outflow sluicing-basins were then constructed, which consisted of reservoirs which were filled by the inflowing tide, the water retained by gates, and then suddenly released when it would have the greatest scouring effect. By these means a narrow channel has been maintained at these ports, which can be utilized by small channel vessels, but is inadequate for the large modern steamships.

At the Malamocca entrance (10) to the Lagoon of Venice parallel jetties have successfully maintained a channel of 30 feet depth at low tides. The littoral drift is small and the effect of the jetties is to concentrate the outflow from the lagoon and prevent its conflict with the littoral current until deep water is attained. The range of tides in the Adriatic Sea only slightly exceeds that of the Gulf of Mexico, but the Lagoon has been gradually filling, both from material carried in from the sea and from that deposited by the discharge of the rivers of the Po Valley that formerly flowed into it. To reduce this fill, the waters of the Brenta River have been diverted from the Lagoon.

A more successful means of concentrating the tidal flow across the bar is by means of converging dikes, as at Charleston and Galveston (11). As their name implies, such dikes starting from the shore, gradually reduce the width of the waterway toward the crest of the bar. They add the area of the bar which they enclose to the natural tidal capacity of the basin, thus forming a sluicing basin properly located to increase the flow at their extremities. The littoral drift, instead of causing an advance of the foreshore, is guided by the outer surface of these dikes into deep water, where a littoral current can carry it beyond the entrance or the tidal inflow and outflow can hold it in suspension until it is deposited in deep water. For the successful accomplishment of works of this character, a rapid construction is necessary and a channel should be opened through the bar by dredging so that the tidal flow can operate at full depth, since tidal action extends to the river's bed while wave action frequently is of limited depth. If reliance is placed on the dikes alone to scour the channel across the bar, there is a tendency to push the bar further out to sea without attaining sufficient depth over it to insure a proper tidal flow.

Occasionally the littoral drift is so pronounced in one direction, that only a single jetty is required to maintain the channel. At the mouth of the Cape Fear River (12), the southern trend of the drift has formed a long bar which creates a sheltered bay behind it. There is only a small flow of sand in a northerly direction along the coast. By closing the channel across this bar called the New Inlet and preventing others from forming, the outlet into the bay is successfully maintained by dredging.

On Lake Erie, the entrance to Sandusky Bay has been improved by a single jetty, but under very exceptional conditions. The tidal flow of the Great Lakes is insignificant, but their level is affected by winds. The prevailing winds of Lake Erie have a westerly component which raises the water level at the eastern extremity of the lake and similarly depresses it at the western end. The axis of Sandusky Bay is parallel to that of the Lake and its outlet is at its eastern end, while the bay is located near the western extremity of the lake. A westerly wind, therefore, depresses the water in the lake at the outlet of the bay while it raises the water of the bay at the same locality, thus creating a head which generates a strong current along the directing jetty. When the wind subsides, the return flow into the bay is spread over a large area and has little scouring effect. Moreover, the littoral drift is small.

It also has been proposed to improve the outlets of tidal estuaries and bays, by means of a single detached jetty called a *reaction breakwater* (13), and in addition to make the jetty concave to the tidal flow so as to increase the deepening of the bar by the centrifugal force generated when water is forced into a curved path. Such a jetty would prevent the lateral movement of the channel, but it would largely increase the flow of sand into the harbor instead of reducing it. If located on the opposite side of the harbor from that along which the great mass of littoral drift is moving, as at Sandusky Bay, the only resistance to the inflow of the littoral drift is the tidal flow. During a large part of the flood tide there would be a flow of sediment across the windward bar into the harbor, which would be removed only partially by the flow concentrated along the concave dike during the last half of the ebb tide. If located on the windward side, there is a movement of sand into the harbor between the detached breakwater and the beach, sometimes sufficient to scour an auxiliary channel.

The concave form of the dike also would have an injurious effect on the tidal flow. As explained in Chapter III, whenever water is forced to follow a curved path, there is generated a centrifugal force, which causes the filaments of water to move in helicoidal lines. This creates a local scouring effect that tends to undermine the structure which opposes the rectilinear flow and produces a deep narrow channel close to the dike. When the water passes beyond the curved obstruction, this helicoidal flow diminishes, and the additional sediment which it has caused the water to carry is deposited in a bar extending obliquely across the channel, this action creating a shoaling above the dike during the flood tide and beyond the dike during the ebb. The curvilinear path thus started has a tendency to propagate itself along the estuary, first impinging on one bank and then on the other, and creating a shoal at every crossing by the change from helicoidal to rectilinear motion.

The structures constructed at the mouths of rivers are not usually exposed to the intense wave action which harbor breakwaters have to resist, since the littoral drift forms a sloping beach on which the waves break and exhaust their force before reaching the dikes. Sand sometimes is piled against a jetty to the height of high water (14) and becomes a deciding factor in determining the elevation to be given the structure.

At the mouths of non-tidal rivers, the deposit is frequently a fine silt. If rip-rap is deposited directly on this silt, there will be an excessive settlement. To prevent this action heavy willow mats are sunk as foundation courses for the jetties, the rip-rap structures being placed thereon. At the outer ends of the jetties, which are exposed to a stronger wave action, large concrete blocks usually are substituted for the rip-rap, as in breakwater construction described in the following chapter.

In the United States, mattresses are frequently employed as foundation courses on bars formed by littoral drift. This has been done at Charleston and at Galveston. In such cases, however, it is necessary to cover the mats rapidly with a layer of rip-rap in order to induce a deposit of sand and thus to protect the mats from the ravages of the teredo.

CHAPTER XIV

HARBORS

Many harbors are located near the mouths of rivers, and their entrances and the protection afforded to shipping within them are dependent on the works necessary to maintain the river's outlet. When harbors are on bays or on slight indentations in the coast line, however, breakwaters can be constructed to afford additional protection. The Standard Dictionary defines a harbor as "a sheltered place where ships can find protection from storms," which definition indicates the two most essential elements of harbor construction: first, protection of vessels within it, and second, a safe entrance during storms. Where a harbor is not merely one of refuge, but is also used for commercial purposes, a third element consists of suitable arrangements for loading and unloading the cargoes which seek the port.

To afford protection, the breakwaters should intercept the waves formed in the open sea over an area which will accommodate the vessels seeking shelter during storms; and to insure a safe entrance, a vessel fleeing before a gale must be able to enter the harbor before she turns. If a ship has to maneuver in the open sea, there is danger of capsizing or drifting on to the piers which limit the width of the entrance. The entrance therefore should face in the direction of the greatest storms. While this allows a vessel to enter the harbor readily, a wave can follow the same path, so that a considerable space is required inside the entrance in which the wave can expand and reduce its height before reaching the portion of the harbor in which shipping is moored.

Stevenson's formula (1) for the heights of waves in harbors is

$$X = H\sqrt{\frac{b}{B}} - \frac{(H + H\sqrt{b/B})\sqrt[4]{D}}{50}$$

in which X is the height of wave at any observed point in the harbor, H is the height of the wave at the entrance, b is the width of entrance, D is the distance of point of observation from entrance, and B is the width of the harbor at the observed point, all given in feet. It is apparent from this formula that the height of a wave in a harbor is a function of the width of the entrance, and of the angle which the two arms of the breakwater which form it make with each other.

In a discussion of the proper form to be given to harbors on the Great Lakes to give the greatest tranquillity, a board of Engineer Officers (2) says: "The breakwaters should, theoretically, in order to afford the greatest protection for the least length, be given a direction perpendicular to the line of approach of the waves caused by the heaviest and most objectionable storms, *i.e.* parallel to the waves of such storms, but they should also fulfill the condition that the entrance between them be in a depth of water which will allow the largest storm waves to pass without breaking. They should make with each other an angle large enough to permit sufficient expansion of the entering wave, and they should be far enough apart to allow a vessel to enter in the worst weather without danger of striking on either side."

The first consideration in determining the width of the entrance is the contraction necessary to give the desired depth, where the tidal basin is small. Where there is a large estuary, the first consideration is the necessity of permitting as large a tidal inflow as possible for the improvement of the upper sections of the estuary. The next consideration is the size of the vessels using the harbor. Finally, the disturbance caused by the inflowing wave must be reduced to a minimum.

A small tidal basin whose bar has been deepened by parallel jetties cannot be entered safely during on-shore winds, nor is there adequate protection unless interior basins are constructed to afford additional shelter. When the harbor has been improved by converging dikes, the area thus added to its basin frequently renders an interior basin unnecessary.

On the Great Lakes most of the harbors originally were formed by deepening the outlet of a river or of a lake by means of parallel jetties, and to prevent the destructive inflow of waves during storms and to reduce their force, it has been necessary to construct breakwaters in the lake in front of the jetties. Frequently, as at Buffalo (3), Cleveland (4), and Chicago (5), the growth of commerce has been so great that these breakwaters have been developed into outer harbors. At many of the minor ports the breakwaters have been constructed for the purpose of creating a basin in which the waves can flatten out before reaching the jetties, and of enabling a vessel to enter the harbor with greater safety during storms. They also permit a wider entrance to be built in a turbulent sea. Moreover, a channel which affords ample depth for navigation in calm weather has its depth greatly reduced as the trough of a large wave is propelled along it. In shallow entrances the wave may break.

On the Great Lakes, harbor entrances designed for vessels of 19 feet draft have a minimum width of 400 feet in water over 30 feet deep. After entering the outer basin, the wave is reduced sufficiently so that the boat is usually able to continue its course in a channel 21 feet deep and 200 feet wide.

For vessels of 30 feet draft the writer has recommended an entrance at least 600 feet wide (6). With a properly proportioned harbor of 350 acres, the incoming wave soon dissipates its force, so that a ten-foot wave at the entrance will not injuriously affect shipping moored at wharves directly in front of it. When the area of the enclosed harbor is greater, the width of entrance can be safely increased to 800 or 1000 feet, and it is rarely necessary to limit the tidal inflow of rivers to insure a quiet harbor. Sometimes in large harbors two entrances facing in different directions can be provided so as to afford additional security to vessels entering them. This has been done at Colombo and at Boulogne. At Citte an outer breakwater has been constructed opposite the entrance and facility of entrance has been sacrificed for the tranquillity in the harbor.

Experience has demonstrated that if the harbor expands symmetrically on both sides of the entrance, Stevenson's formula for the height of waves gives satisfactory results, but in a harbor where the main channel follows one of the dikes while the other merely prevents an inflow of sediment, a wave that enters can strike the channel dike obliquely and follow along it with little diminution of force. If, however, there is a break in the continuity of the dike and if a small basin with a sloping beach is formed behind it, the restrained wave expands into the basin, and its height is greatly reduced. Such stilling basins have been constructed at Dieppe (7) and at Havre (8).

In Chapter XIII illustrations were given of the force generated by wave action. Since the breakwaters employed in harbor construction frequently are located so as to receive the full force of the greatest wave created in the sea to which they are exposed, their construction is extremely difficult. The difficulty is increased by the great depths in which it is sometimes necessary to place them.

Two methods of resisting the force of the waves have been employed: by a rubble mound, and by a vertical wall. These two methods also have been combined by erecting a vertical wall as a superstructure on a foundation of rip-rap. In the rubble mound breakwater, the rubble or concrete blocks of which it is composed are deposited on the site of the work, and are permitted to assume such slopes as the waves create. These slopes are functions of the intensity of the wave action and of the dimensions of the rubble. Under ordinary conditions, wave action extends only to a depth below the trough of the wave, equal to the height of the wave. Hence the mound assumes a natural slope not exceeding 1 to 1½ at from ten to twenty-five feet below low water, dependent on the exposure. In the breakwaters of this class which were first constructed, the rubble deposited was the run of the quarry in sizes up to five tons in weight, and above the level of no disturbance the slope assumed by the mound at exposed sites was about 1 to 10. Such was the case at Cherbourg, France, and at Table Bay, Cape of Good Hope (7). Even where there was partial protection, as at Portland (7), slopes of 1 to 6 were obtained.

Two methods have been employed to increase the sea slope and thus diminish the dimensions of the breakwater. The first method consists in paving the exposed face. At Plymouth (7), England, the breakwater above low water was given a sea slope of 1 on 5 and was paved with granite blocks set in cement. At Kingstown (7), a pavement of granite blocks placed on edge covers the entire surface exposed to the action of the waves. Portions of the breakwater at Buffalo, N. Y., were constructed in this manner.

A second method of protecting the sea slope is by increasing the dimensions of the rubble deposited on the sea face. When rubble of sufficient size is not readily obtained, concrete blocks are substituted. Large rubble was adopted at the Delaware Breakwater (8), at San Pedro, Cal., at Cleveland, O., and at numerous other harbors on the Great Lakes. At Port Said, Algiers, and Alexandria in the Mediterranean Sea, and at Osaka in Japan, concrete blocks have been substituted for rubble. At Port Said (7) the main portion of the breakwater consists of 20-ton concrete blocks, deposited at the slope they naturally assume. At Osaka (9), the body of the breakwater consists of small rubble overlaid with concrete blocks weighing about 4 tons each, on a sea slope of about 1 to 2. This harbor is exposed only to moderate seas, however.

In the United States, the width of the crowns of breakwaters is from 8 to 14 feet on the Great Lakes, and 15 to 20 feet when exposed to ocean storms. The sea slopes are 1 to 3 to a depth of from 12 to 25 feet below low water, and below those depths the natural slope, which the mound assumes. On the harbor face a slope of 1 to 1.33 is usually adopted. The elevation of the breakwater on the Great Lakes rarely exceeds six feet above high water. At the Delaware breakwater it is 14 feet above low water, at Sandy Bay 22 feet above low water.

In breakwater construction the character of the quarry affects to a great extent the methods employed. If the rock on blasting naturally breaks into masses more or less rectangular, the body of the breakwater can be composed of the quarry refuse, and the larger pieces can be laid with their longer dimensions at right angles to its surface, thus forming a pavement of great resisting power to wave action. If the rock breaks in irregular fragments, however, they cannot be bonded together, and reliance must be placed on the weight of the individual pieces to hold them in place. Such breakwaters have not the finished appearance of those which are paved, but possess the advantage that they break more effectively the wave which impinges against them.

If the pavement is smooth, a considerable amount of water will roll up its surface and may enter the harbor over the top of the breakwater in sufficient amounts to affect its tranquillity, and undermine the harbor face of the breakwater. If the sea slope is rough, the crest of the wave is converted into spray, covering the breakwater with a foam, but having little effect on the harbor.[1] To prevent their displacement the individual stones must be of greater size for the same slope than where the surface is paved.

[1] This was forcibly illustrated during a typhoon at Manila, where one of the old monitors with a low free-board moored behind the detached breakwater, which is of the rough rubble mound type, with an elevation of its crest of but five feet above high water. The spray created by the waves dashing against the breakwater was sufficient to obscure the view of the monitor from shore, but the writer was informed by the Commander of the vessel that the water in which she floated had only a slight wave motion from the waves passing through the harbor entrance.

Where the depth is great, the area of the cross-section of a rubble mound breakwater is large, and a considerable reduction in its dimensions and therefore of the quantity of material required in its construction can be obtained by the substitution of a breakwater with vertical masonry walls. When the area of the harbor is limited, such a substitution may be necessary, but it is rarely economical compared with the use of large facing stones for the rubble mound, on account of the excessive cost of underwater masonry construction. In the United States, the vertical type of breakwater has been employed only in the Great Lakes, where the absence of the teredo and other sea worms has permitted the substitution of timber cribs for masonry walls.

The vertical breakwaters first built consisted of two masonry walls with a hearting of rubble. Below water the joints were usually not filled with mortar. The oscillation of the water surface caused by the impinging waves transmitted a pressure through the interstices of the walls to the water in the hearting, and as the wave receded, a sufficient interior pressure would be created to force some of the stone from the face of the wall. The breach thus formed would rapidly enlarge, and the hearting would escape through it.

This interior pressure was sometimes sufficient to disrupt a pavement placed on top of a breakwater to protect it from the blow caused by the water flowing over it during storms. The overflowing water at the Wicks breakwater had sufficient force to undermine and overturn the harbor wall, the rubble hearting was then washed away, and the sea wall collapsed (10).

By replacing the rubble hearting by masonry so that the breakwater is practically a monolith, these sources of danger can be avoided. In recent breakwater construction, concrete has been generally substituted for rubble masonry. The portion below low water is formed of concrete deposited in bags to form a monolith; between high and low water, the breakwater is built of concrete blocks mortised and toggled so as to form a compact mass; and above high water the concrete is deposited in mass. The north breakwater at Aberdeen is composed of concrete deposited in bags to low water, and of mass concrete above low water (7).

The pressure which is exerted horizontally on the face of a breakwater also is transmitted vertically to the sea bed. If the face is vertical, a heavy rip-rap protection is required to prevent scour even at great depths. With a rubble mound the waves expend a considerable portion of their force running up and down the slope as on a beach, and the blows they can deliver on the inclined surface tend to consolidate the mass, particularly if it is paved. Against a vertical face in deep water the force exerted is one of pressure. However, if a vertical superstructure is superimposed on a rubble mound which is high enough to break the waves, the pressure is converted into a blow of great magnitude, which will hurl a column of water into the air to great heights. Such a force is very difficult to control.

The Alderney Breakwater is an example of this type which has failed (11). At the Sandy Beach Harbor of Refuge (12), Cape Ann, Mass., the superstructure was composed of stone blocks laid in steps to a slope of 1 on 2, the height of the steps varying from 3½ to 5 feet, but with the same result as at Alderney. The suction which accompanies the receding waves scoured the rubble mound to great depths, undermined the superstructure, and so loosened the stone forming it that masses weighing 20 tons were carried on to the sea slope of the mound.

When it is necessary to place a superstructure on a rubble mound, to insure permanency the mound should be extended above high water by large blocks of stone or concrete to form a wave breaker, as at Ymuiden at the entrance to the Amsterdam Ship Canal.

In many European harbors, the vertical type of breakwater is required, so that the harbor side of the structure can be used as a quay for loading and unloading vessels. A high parapet is then necessary on the sea wall to enable operations to be carried on during storms. Such a parapet increases the force of the wave against the structure and tends to cause an unequal settlement of the foundations. In the United States, vessels rarely moor along breakwaters except at certain harbors of refuge on the Great Lakes. On this account as well as on account of the smaller height of tides, breakwaters having a lower elevation than those of Europe prevail.

When breakwater construction was first undertaken on the Great Lakes, timber was cheap and a very economical vertical type of breakwater (13) was evolved, consisting of timber cribs filled with small rip-rap, which was covered by a timber flooring. In the fresh waters of the lakes, timber is preserved from decay and destruction from boring insects and worms, so that below low water, when properly built, the structure proved permanent, and above water it could be replaced economically as it decayed. Masses of ice striking against the timber would crush it, however, and it was found necessary to face the timber on the lake side with sheet iron along the low water line to prevent such action. The cross braces originally were dovetailed into the main timbers, but if the dovetail was not perfect, water would find its way through any imperfection as the waves rose and fell, and in process of time so erode the joint as to destroy the connection. Long iron rods with washers and bolts were then added to the structure. In recent years the high price of lumber has rendered a concrete superstructure more economical. At Milwaukee (14), cribs of reinforced concrete have been substituted for timber cribs in the substructure.

In the arrangements for loading and unloading vessels, there is a radical difference between European practice and that in the United States. The great heights which the tides attain around the British Islands and in the North Sea originally were utilized by the vessels in entering harbors, the depths being insufficient during low water for them to cross the bars, and as the banks of a river have a gradual slope, the vessel would ground at low water if moored close to the bank, or would require lighters to transfer its cargo to the bank if anchored in midstream.

To overcome this difficulty basins are constructed in which the vessels can enter at high tide. Their entrances can be closed during low water by means of gates so as to maintain the water level within them at that of high tide. These tidal basins enable vessels to be moored along the quay walls which formed them, and their cargoes to be removed by the ship's tackle, without recourse to lightering.

In the harbors along the Mediterranean Sea, the tidal oscillation is not sufficient to necessitate such basins, but the harbors originally designed were of small area, and the disturbance caused by incoming waves during storms was therefore so great that inner basins without gates were required to protect the vessels while discharging cargo. In the United States, the moderate tidal range permits vessels to cross the harbor bars during a much longer period than at corresponding ports in the north of Europe, and tidal basins, open only at high tides, would delay the departure of vessels. A sufficient depth for the vessels to float at low tide while being unloaded usually can be obtained more economically by constructing piers into deep water than by excavating basins of sufficient depth in the banks, so that in the United States pier construction or a quay wall parallel to the channel very generally replaces the tidal basin of northern Europe or the enclosed basins of the Mediterranean Sea.

Since the piers extend from the bank into the channel, the space at which vessels can moor along a given frontage is largely increased. The water area of the harbor is correspondingly reduced, however, and the tidal flow is obstructed. Some relief is afforded by supporting the superstructure of the piers on piles which permit a restricted flow between them. In rivers carrying a large amount of sediment in suspension, the piles have an effect similar to permeable dikes, and cause a deposit not only under the piers, but also in the slips between them. Such deposits are so great in the Mississippi River at New Orleans, that not only is dredging required annually, but also sluicing devices have to be maintained to remove the deposits under the piers. Unless such deposits are flushed out before low stages occur in the river, large masses have a tendency to slide into the channel carrying the supporting piles of the dock with them, and thus destroying it.

The piers in New York harbor have been lengthened, as the dimensions of vessels have increased during recent years, and thereby the space in the river channel of the Hudson River frontage, which is required for maneuvering boats, has become so restricted that the Federal government has intervened and limited the length of piers.

Harbor and dock lines also are imposed at numerous other localities.

CHAPTER XV

THE ECONOMIES OF WATER TRANSPORTATION

One of the most important problems that has to be solved by an engineer in charge of the improvement of rivers and harbors is the determination of whether a given project is worthy of being undertaken.

While this question in the United States is one for Congressional action rather than executive decision, Congress has delegated its powers on this question to a certain extent to the Corps of Engineers of the Army. It requires a report from Engineers of the Corps on the worthiness of a project for river or harbor improvement, before it takes final legislative action. A knowledge of the relative economies of transportation by land and by water is therefore requisite for all officers in charge of river and harbor districts.

Before the employment of steam to replace animal traction as a means of propulsion, the river afforded such economies in the transportation of products as to eliminate competition by land vehicles. A team of horses can haul 200 tons of freight in a canal boat with the same exertion it requires to move ten tons on a railroad track or one ton on an ordinary dirt road. As a result, in Europe the early centers of trade and manufacture were invariably located on rivers, and the growth and development of the country has been along its waterways.

The invention of the locomotive, however, disturbed this relation. While it requires the same tractive force to move the 200-ton canal boat, the 10-ton car, or the 1-ton wagon at two miles per hour whether obtained from a team of horses or from a steam engine, when the speed is increased to 20 miles an hour, the resistance of the boat to motion through the water enormously increases, as compared with the friction on the rail. This is particularly the case in contracted waterways.

The boat in its motion is continually displacing a mass of water equal to that of its weight, and the amount of water displaced per hour is proportional to the velocity. By giving a proper shape to the boat, the force necessary to displace the water can be reduced, but it is also necessary to have a sufficient space around it to permit the water to flow readily from in front of the boat to the vacuum created behind it. In a shoal, narrow channel this space becomes so contracted that there is created a rising of the water surface in advance of the boat and a lowering behind it. The water cannot flow with sufficient velocity around the boat to maintain the water level and the boat is compelled to move not only the water it displaces, but a large percentage of the contents of the channel in front of it, in the form of a wave of considerable height, and the water surface may be so lowered at the boat's stern as to cause it to rub the river bed.

A limit is soon attained, therefore, beyond which it is uneconomical to increase the speed. This limit varies with the width and the depth of the channel, the form of the barge, and the methods employed in combining the barges in tows. For purposes of the present argument let the limit be assumed to be five miles per hour for such rivers as the Ohio and the Mississippi. For small canals it will be less, and for vessels navigating the Great Lakes or the ocean it may reach twelve or fifteen miles per hour.

The resistance to be overcome in moving a car over a railroad track is also a variable function of the speed, the curvature, and the grades. For a boat, a small increase in speed above the economic limit necessitates so large an increment of power as to make the consumption of fuel prohibitive. The same increase in the speed of a railroad car will increase only slightly the fuel bill for the locomotive. Since it requires the same crew to handle a freight train whether the average speed is 5 miles per hour or 20 miles per hour, the saving in the men's wages resulting from a quicker trip may compensate for the extra coal consumed, and the cost per ton-mile for hauling freight in a train which travels at an average speed of 20 miles per hour may be less than the cost when it moves at a smaller average speed. Hence the steam locomotive, by increasing the speed with which cars are moved, has rendered the cost of transportation on land more nearly equal to that by water than it was when animals were the chief means of traction.

It has been found also that the force required to move a ton of freight and the work expended per ton-mile are diminished as the load in the car is increased. The substitution of a car which carries 50 tons of freight for one whose load is 20 tons, reduces the traction per ton of car and contents on a level track approximately from 7.6 pounds to 3 pounds for a velocity of 5 miles per hour (1). Thus four freight cars carrying fifty tons each require much less force to propel them than twenty cars containing ten tons each. The increase in the size of the freight car has enabled the locomotive to haul 200 tons of freight at the rate of 5 miles per hour with the same application of force that was required on the canal boat also carrying 200 tons and moving in the contracted waters of a canal at the rate of 2 miles per hour. By increasing the capacity of the locomotive, a large number of cars can be hauled in the same train, and train loads of from 2500 tons to 3000 tons are regularly hauled at the present time by one locomotive and a train crew of five men, thereby producing great economies in the labor cost per ton-mile of freight carried. Where no progress has been made in the methods of transportation by water, the locomotive has forced the old-fashioned canal boat to suspend business.

By enlarging the boat, however, equally great economies can be introduced into water transportation as the enlarged car has produced for the railroads, and wherever water transportation successfully competes with transportation by rail it will be found that there has been a large increase in the dimensions of the vessels employed. Thus on the Great Lakes the freighters of from 12,000 to 15,000 tons capacity have been substituted for those of 2000 tons, and on the Rhine barges of a capacity of 1500 to 2000 tons are now used in place of the former 200-ton canal boats. The enlarged boat, however, requires a channel of greater area, to reduce the resistance to motion through the water. If it is necessary to construct a canal for the water transportation, it has been found that the necessary enlargement of section will increase its cost so much that the interest on the investment and the cost of maintenance will exceed the saving produced by the increase in size of the boats, unless a very large traffic is created (2).

In an improved river this is not the case, as the width of the cross-section is usually very large compared with that of the boat.

On the ocean, a vessel is exposed to severe strains due to wave action during storms and must be constructed with sufficient structural strength to resist them. This requires certain relations between the length, width, and draft of the vessel. The ocean freighter with a carrying capacity of about 12,000 tons has a draft of about 30 feet. On the Great Lakes, the intensity of the wave action is not so great, and sufficient structural strength can be obtained for a vessel of 12,000 tons capacity if it has a draft of 21 feet. On a river, wave action during storms is insignificant, and a satisfactory barge of 2000 tons capacity can be constructed with a draft of but 8 feet. By uniting six such barges in a tow, a carrying capacity of 12,000 tons is readily attained.

In the economical production of steam power, the compound or triple-expansion condensing marine engine has a great advantage over the high-pressure non-condensing locomotive. Theoretically, therefore, it would seem that transportation by water still should be more economical than by rail, provided the improvements which have been made in boat construction are utilized properly.

A comparison of the records of the latest types of locomotives when hauling heavy trains on the standard railroads of the country with those of steamboats and barges on the Great Lakes and on the rivers of the United States confirms this expectation (3). The fuel economy of the modern freighter on the Great Lakes far exceeds that of the railroad locomotive even with the most level track and with the least curves. On rivers that have a navigable depth at low water of 6 feet, by assembling a number of barges in tows, similar economic results are attained. The amount of human labor per ton-mile of freight carried is also less for the lake boat or the tow of barges than for the train. However, where navigation is limited to the river packet, which was the prevailing method of river transportation forty years ago, the recent improvements in the locomotive and car, and the reduction of grades and curves in the track, have rendered rail transportation cheaper in both the elements of fuel consumption and of expenditure of human labor per ton-mile of freight carried.

These, however, are frequently minor factors in the total cost of transportation. The annual interest on the cost of constructing the rail bed, or of deepening the river, of constructing the requisite number of locomotives and cars, or boats, the annual outlay for maintenance, the overhead charges for supervision, insurance, etc., may largely exceed the cost of fuel and labor when the traffic is relatively small.

In many of these items the waterway has an advantage over the railroad. It is pertinent therefore to inquire why the water-borne commerce on certain rivers has diminished in recent years, while rail transportation has enjoyed an enormous growth.

It is often assumed that the decline in water transportation has been caused by underhand methods on the part of railroad administrations, but it is unquestionable that there are certain fundamental principles (neglected by those engaged in water transportation) which have enabled the railroad managements successfully to meet water competition. The owners of steamboats have failed to give the regularity of service which commerce demands. During the period of the year when the business of a town was not active they have neglected it and sought traffic elsewhere. A train runs on a regular schedule. The railroad official could therefore make a contract with a shipper in which he guaranteed regularity of service on condition that the railroad would also be used when the boats returned to the regular routes. The rebate formerly could be used to insure the execution of the contract.

Another great advantage which the railroad formerly possessed was due to through bills of lading. A steamboat can deliver freight only at water points, and its transportation to localities inland must be completed by rail or wagon. The railroad running from the river town nearest to the point of ultimate destination honored only a local bill of lading from the river town when merchandise was shipped by water, while it accepted a through bill of lading from the origin of shipment to the point of ultimate destination from a connecting railroad. The shipper naturally selected a rail route instead of a water route under such conditions. Rates for short distances which were relatively higher than through rates afforded merely an additional reason for this preference.

The fact that the steamboat is confined to a waterway also compels the loading or unloading of its cargo on the river bank. When a warehouse or a factory is located inland, the truck which transports the merchandise to and from the river also charges local rates for short distances which are relatively higher than through rates. A track can be laid wherever a road bed of suitable grades and curvature can be constructed. The railroad official by constructing a switch into the warehouse or factory eliminates not only this expensive truck haul, but also the expenditure of labor which is necessary in order to transfer the freight between the dock and the vessel.

However, when the ship owner and the railroad manager work in harmony and there is a large traffic, the terminal charges can be reduced to a minimum by the introduction of mechanical appliances. Cheap terminal facilities have been as large a factor in developing the commerce of the Great Lakes and reducing the freight rates as the improvement of the vessels which are employed in transporting the cargoes. When a railroad owns the boat line, it can substitute a car-ferry for an ordinary freighter, transporting both the car and its contents together. Then terminal charges are eliminated, and the cost per ton mile of revenue-producing freight transported is greatly reduced, notwithstanding the non-revenue-producing weight of the car which is transported by the boat.

Car-ferries are extensively used as substitutes for bridges and tunnels in transporting rail freight across rivers, lakes, and bays. Moreover, in New York, they afford an economical method of distributing freight to different sections of the harbor. The Pennsylvania Railroad and the Hudson and Manhattan tunnels have affected only passenger travel, and the car-ferry is still used by rail lines for distributing freight to the different boroughs of the city as well as to some of the ocean steamship terminals.

The most vital principle which has led to the growth of rail traffic, and which has hindered transportation by water is one, however, that the vessel owner cannot control. It is the necessity of finding a market at the point of ultimate destination in which the freight can be sold at a profit. The United States owes its expansion to its railroads, and its development has been across its rivers instead of in the direction of their flow. The western farmer or miner seeks a market for his products in an eastern city and the wholesale merchant in New York or Boston finds his best customers in the west. Most of the rivers of the country cross the lines of traffic thus created, instead of running parallel to them. On many rivers of the United States, the boat is relegated, therefore, to the minor function of collecting the products of agriculture and mining along the banks, and transporting them to a railroad, whose terminal is a large city. The cost of the transfer of freight by manual labor between car and boat is so great, moreover, that a waterway that extends along a main line of commerce must exceed at least 200 miles in length to permit its economical utilization for through freight, if the boat cargoes are received from cars and delivered to them. The difference in cost between the transportation over the rail or in the waterway is exceeded by the terminal charges when the boats travel only a short distance.

There is also a certain density of traffic necessary for the successful operation of a line of transportation. If a river flows through a thinly settled country, with no mines along its bank, and few factories, there exists comparatively little traffic from which to build up a large system of transportation.

The ability of railroads to divert traffic from the waterways has been greatly restricted recently. By the decisions of the Interstate Commerce Commission, discriminations between shippers have been prohibited. By recent Congressional enactments the railroads are required to grant not only the same through bills of lading to steamboat lines as to railroads, but also to similarly prorate the revenues from through freight. Hence, a waterway extending along a natural line of communication is not limited to local freight, but can compete for through traffic. The cities and towns on the river banks have awakened also to the value of efficient terminal facilities, and economical methods of loading and unloading boats have been introduced in many localities. The southern ports, especially New Orleans and Galveston, are rapidly increasing both their exports and imports. This should create a greater north and south movement of freight by water. While the influence of the Panama Canal possibly has been exaggerated, it should give an additional tendency to a north and south transportation of products, and the movement of the center of population of the country westward increases the cost of rail transportation to and from the Atlantic Coast. Moreover, there has been a remarkable manufacturing development in the southern states in recent years which should affect the movement of freight and increase the density of traffic.

In determining the worthiness of a waterway project, the engineer is required to take into consideration not only existing commerce but also reasonably prospective commerce. While he should not permit himself to be unduly influenced by visionary schemes of the future development of the country, he should be aware of the natural tendencies of its growth, and should give due weight to those which will expedite it.

A cheap north and south line of transportation across the United States is rapidly becoming an economic necessity. It is self-evident that the Mississippi Valley affords the cheapest line.

Its natural terminals are at Chicago on the Great Lakes, which is the center of manufacture and trade of the western portion of the United States, and at New Orleans on the Gulf of Mexico, which is the natural port for the importation and exportation of the products required and raised in the Middle West. The tributaries of the Mississippi River afford numerous auxiliary feeders for such a route, some of which could readily become main lines of transportation. For example, Minneapolis and Kansas City are as important centers of the grain trade as is Chicago, and the Pittsburgh district far exceeds it as a center of iron and steel production.

Inadequate terminal facilities also largely increase the cost of water transportation on account of the delays in loading and in unloading the boats. With the exception of the bill for fuel, the expenses of operating a vessel are the same whether she is in motion or tied to a dock, but her receipts are a function of the number of trips she can make in a season with a full cargo. If she spends a large portion of her time in port, the wages of her crew, the interest on the investment, insurance and deterioration, continue, while the revenues received diminish. Moreover, there is a large saving, if there is a well-balanced shipment of freight, so that she can transport full cargoes in both directions.

M. Galliot in a recent paper, in the ANNALES DES PONTS ET CHAUSSÉES (2), analyzes the various elements that enter into the cost of transportation, and deduces mathematical equations which express the relations between them. The deduction can be made from his analysis that in a canal the dimensions of a boat are limited economically by the cost of the enlargement of the waterway; that in a river the dimensions of the units of a tow are determined economically by the depth of the river channel; that in the ocean there are theoretically no limits; the greater the carrying capacity of the vessel, the more economical is the transportation per ton of capacity, as long as the vessel remains at sea. As soon as a vessel enters a harbor, however, the savings resulting *en voyage* are diminished by delays due to the lack of port facilities.

The 12,000-ton freighter of the Great Lakes is economical, not only on account of her size, but also because the time which she spends in port has been reduced to a minimum. Mechanical appliances enable the vessel to be loaded with coal or iron ore in a few hours, and unloaded in less than a day. The distance of approximately 900 miles between harbors on Lake Superior and on Lake Erie permits her to remain in port only a small percentage of her time.

If a similar vessel is employed in transporting freight between minor ports on the Atlantic Ocean, in which the terminal facilities are such that as many days are expended in transferring freight between boat and dock as hours are required for the same purpose on the Great Lakes, the time in port becomes excessive. If three vessels of 4000-ton capacity are substituted for the 12,000-ton freighter, they can be loaded and unloaded at separate docks simultaneously and the port delays reduced thereby.

During a certain period in the development of lake traffic, the whaleback and its consorts were employed very generally; but a cargo can be propelled through water of ample depth more rapidly and more economically in a single vessel than in a tow; and coincident with the enlargement of unloading devices at the various lake ports, large single vessels have replaced barge navigation, while barge tows still prevail along the Atlantic coast. In river navigation, an advantage in employing barges of moderate capacity results from the facility with which cargoes destined for different city landings can be loaded in separate barges, and the proper barge can be left at each port to be unloaded and loaded, while the remainder of the tow continues its voyage, as a car is switched out of a freight train at a way station of a railroad.

Density of traffic has also an important influence on port development. In order to be profitable, the 2500-ton train requires a large movement of freight, and such trains are operated only between important terminals in large railway systems. On the branch lines trains of less capacity must be employed. The same principle applies to water transportation. The 25,000-ton freighter cannot be operated profitably when the sources from which its cargo is derived permit the economic use of only a 500-ton freight train. The port delays are too long. Such an inherent defect in harbor location can be corrected neither by improvement in loading facilities, nor by an increase in harbor depth.

Density of traffic forces the large freighter to large centers of population where factories exist which import fuel and raw material and export manufactured articles; and where a wholesale trade is created which stores products received and retails them to smaller towns; or to localities where an extensive *hinterland* readily supplies an abundance of agricultural or mineral products. The important ports of a country are found when a rich *hinterland* is coincident with a large manufacturing population. A traffic of great density then is combined with a well-balanced shipment of exports and imports, and the large freighter produces economies in transoceanic shipments that are impossible when operating to minor ports. Hence, there is also an economic limitation to the dimensions of vessels navigating the ocean; but it varies with the traffic density of the ports between which they sail. The cheapest transportation for a minor port is by a small coast vessel, which transfers a cargo destined for export to the larger vessel in the first great harbor. The economies which result from the construction of the large transatlantic steamships insure the commercial supremacy of a few large harbors. If two harbors in close proximity compete for transoceanic trade, the law of density of traffic insures the survival of the fittest and the relegation of the unsuccessful rival to the position of a minor port. An appropriation by the Federal Government for deepening a harbor may aid the action of natural laws, but it cannot overthrow them.

The same reasoning applies not only to the coast trade but also to the navigation of rivers. The large ocean steamship seeks the port which has the greatest density of traffic, and it leaves to river and harbor craft the collection and distribution of its cargo at other towns. In river navigation, however, other principles also are involved. The ocean vessel has to be given sufficient strength to resist the shocks which it sustains during storms on the high seas. Wave action in rivers is relatively insignificant. A boat can be constructed for river navigation, therefore, much cheaper than for ocean navigation, so that the annual interest on the investment and the cost of maintenance are much less for river craft, and this compensates in large measure for the cost of transferring the freight from one class of boats to the other. The discharge and the tidal flow in rivers produce currents in their narrow and sinuous channels, which are a serious menace to navigation by large vessels. Insurance rates then become prohibitive. Ocean vessels, therefore, seek the city situated near the mouth of the river, and barge navigation connects this port to the interior towns on the river bank.

The economy of mechanical appliances for transferring a cargo between boat and dock is dependent on the character of the freight which is moved. Iron ore, coal, grain, and other products transported in bulk can be handled much cheaper by devices like Hewlett Machines and Gantry Cranes, than by manual labor. Package freight, when the elements are of uniform size, also permits economic movement by machinery adapted to the purpose. The vessel must be constructed, however, with numerous wide hatches to enable such appliances to be utilized to their maximum capacity. With narrow hatches and with the miscellaneous cargoes which usually are carried on vessels, the ship's tackle frequently affords the quickest means of transferring merchandise between the dock and boat, and the port economies consist in measures for rapid movement of freight to and from the ship's side.

The wharf frontage, the width of wharves, and the water space between them are important factors in port development. A sufficient frontage should be afforded so that a vessel is not delayed unnecessarily in obtaining a berth at which it can load or unload its cargo. In a harbor where lighterage is extensively employed, vessels can moor in mid-channel and discharge their contents without access to wharves, and in such harbors only a limited wharf frontage may be necessary. Thus at Manila, P. I., the *go-downs* which receive the freight usually are located on the numerous *esteroes* which intersect the city, and the native *casco* is a much cheaper method of transportation than a caribou and cart or the auto truck, so that the deposit of a cargo on a dock adds to the cost of its distribution.

When there is an extensive hinterland which can be reached by river transportation, as at Hamburg, Germany, the transfer of goods destined to inland ports also can be more economically made direct from ship to barge, and in such cases a wide water space between piers is required so that the barge can be loaded at the ship side, simultaneously with the placing on the pier of those products which are required for local delivery. In New York harbor there is a large coast and river traffic and an enormous local distribution by lighter.

The width to be given a wharf is primarily a function of the rapidity with which freight can be delivered to it by the shipper or removed from it by the receiver. For example, on the Great Lakes, the shipping coal docks require merely a width which will contain two railroad tracks, one for the loaded car whose contents are dumped into the vessel, and a return track for the empties, while the receiving dock has an abnormal width to provide storage for the coal received.

Federal officials are strongly in favor of wide docks, for the purpose of storing goods for custom appraisement, but there results an increased cost of original construction, and of moving the freight where it is received on piers. The narrow wharves of Hong Kong which have an efficient tramway system that deposits the cargo promptly in neighboring go-downs on land is much more economical in first cost and in operation than the large government pier at Manila.

Where there is not an efficient rail or tramway system which insures a prompt removal from the ship's side, sheds must be erected on the dock to receive both the incoming and outgoing freight and to protect it from the inclemency of the weather. The width of the shed becomes a function of the dimensions of the vessels seeking the port and varies with the cube of their length (4). Where the vessels moor against a quay wall and the sheds are erected on land, they can readily be given an ample width, but when vessels moor at piers, the problem presents many difficulties. Thus at New York harbor many of the piers were constructed when the draught of the largest ocean vessel did not exceed 26 feet, and traffic becomes congested when vessels of a draught of 35 to 40 feet attempt to use them. Moreover, to widen the piers so as to obtain adequate width of shed would diminish unduly the width of slip between them, which is an important consideration in pier construction, particularly at this harbor.

To minimize the congestion, some sheds are made two stories in height, the upper story for outgoing freight and the lower for incoming freight. In Europe, the usual practice is to utilize one shed for the incoming freight and another for the outgoing freight. When the cargo is discharged, the vessel is moved from its berth in front of one to that in front of the other.

While facilities for moving freight by rail or by truck can be provided readily when the shed is on the mainland, when it is located on piers the question becomes a complicated one, since as much space as practical must be devoted to piling the merchandise in order to avoid congestion. There is a popular error that congestion can be avoided by a multiplicity of rail tracks on a pier.

This is true only when a great mass of freight is in transit to the hinterland, as in handling coal and iron ore at the docks of the Great Lakes. In New York harbor a large percentage of miscellaneous cargo requires local receipts and deliveries, and both the truck and lighter are more important factors than freight cars.

On estuaries the tidal fluctuations, and on non-tidal rivers the height of floods, affect the economies of loading and unloading. With the large tidal fluctuations in the North Sea, tidal basins with their resultant delays in entering and in departing are necessary. Where there is a difference of elevation of over fifty feet between flood and low water stages, as at some localities on the Mississippi River, a flexible means must be devised for overcoming the differences in elevation between the top of the bank and deck of the vessel. The usual method adopted is a floating wharf boat to receive the cargo, with a sloping bank over which the freight is hauled by animal traction. The substitution of machinery for the horse or mule as a means of raising the freight to the level of the bank is economical only when large amounts are handled.

APPENDIX A

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APPENDIX B

EXAMPLES OF FLOOD PREDICTION

Cairo at Junction of Ohio and Mississippi Rivers

The problem can be stated as follows: When the crest of a flood passes Cincinnati on the Ohio River, what height will be recorded on the gage at Cairo, at the mouth of the Ohio, six days thereafter? The data available for its solution are the gage readings at Cincinnati, 498 miles above Cairo on the Ohio River, at Chattanooga, 509 miles above Cairo on the Tennessee, at Nashville, 246 miles above Cairo on the Cumberland, and at St. Louis, 191 miles above Cairo on the Mississippi, on the date the crest of the flood passes Cincinnati. Gage records at these places are available for a period of over forty years.

If there are plotted the gage heights of the flood at Cairo six days after the flood-wave passes Cincinnati, using the height at Cincinnati as abscissæ, a curve can be drawn giving the mean gage relation between the two localities, as shown in Fig. 4. This curve shows merely that the mean of all the floods that have passed Cincinnati at a given height has attained a height at Cairo as shown by the curve. Thus a flood of fifty feet at Cincinnati will produce a mean flood height at Cairo of 41.9 feet. But in order that the flood at Cairo shall actually attain that height, average conditions must obtain, not only in the slope of the Ohio River, but in the discharge of the tributaries.

Similarly, by plotting the heights which the Cairo gage recorded the day the crest of the flood passed Cincinnati, a curve is obtained which indicates the mean difference in gage heights between Cairo and Cincinnati on that date. On the Ohio River this curve is parallel to the curve of mean gage relations and about 5 feet below it, *i.e.*, if on the day the crest of the flood passes Cincinnati, the Cairo gage reads 5 feet less than that shown by the curve of mean gage relations, the river slope is normal and the crest of the flood at Cairo six days thereafter will conform to that shown by the curve if there are no perturbations from the tributaries. If,

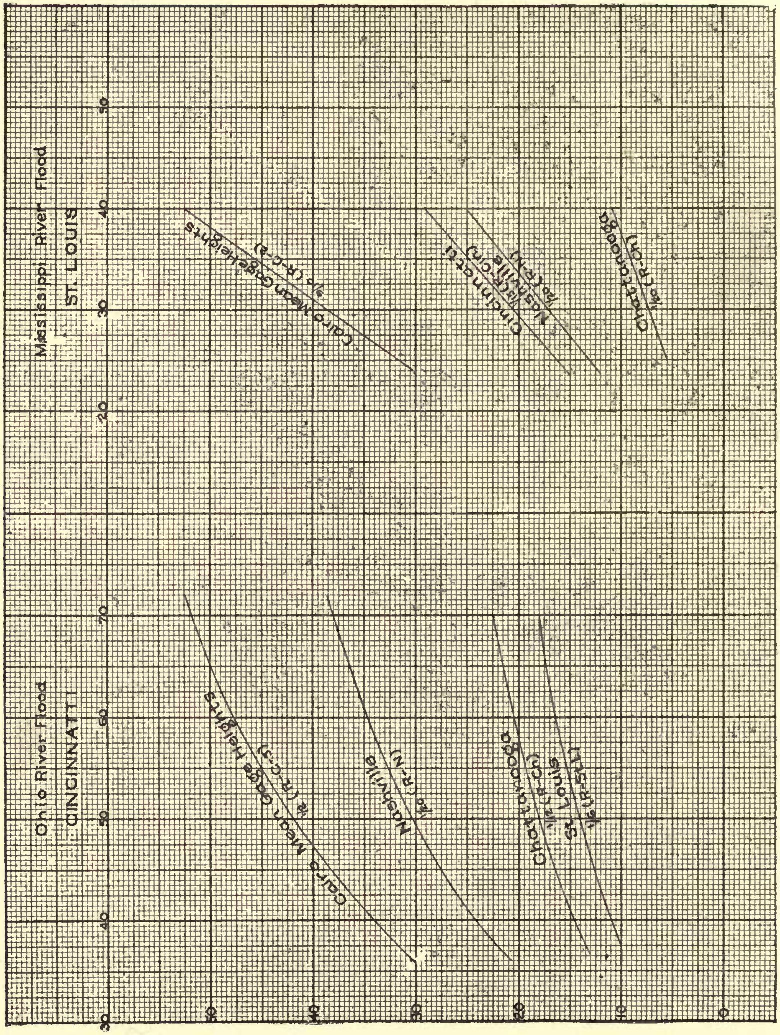
Mississippi River Flood
ST. LOUIS
Ohio River Flood
CINCINNATI
Cairo Mean Gage Heights
1/10 (R-C-S)
Cincinnati
1/3 (R-Ci)
Nashville
1/20 (R-N)
Chattanooga
1/10 (R-Ch)
Cairo Mean Gage Heights
1/4 (R-C-S)
Nashville
1/10 (R-N)
Chattanooga
1/2 (R-Ch)
St. Louis
1/6 (R-St.L)
50
40
30
20
70
60
50
40
30
50
40
30
20
10
0

FIG. 4

however, on the day the crest of the flood passes Cincinnati, the reading of the Cairo gage is higher or lower than 5 feet below that indicated by the curve of mean gage relations, the crest of the flood will exceed or be less than the height shown by the curve and by an amount in this particular case found to be equal to one-half the difference.

The tributaries will also have a disturbing influence unless they also conform to average conditions, and similar curves have been constructed also for each tributary giving the average height it has attained when the crest of the flood passed Cincinnati. If the actual heights differ from the mean, corrections have to be applied, which for the upper Mississippi River at St. Louis are found to be ± 1/6 the difference, for the Tennessee River at Chattanooga ± 1/15, and for the Cumberland River at Nashville ± 1/20.

There remains, however, a large area of country (over 50,000 square miles) drained by the numerous rivers emptying into the Ohio between Cincinnati and the mouths of the Cumberland and Tennessee rivers which affects the computations. The Wabash is the largest of these rivers. Employing its flow as an indicator for the others as M. Belgrand utilized certain tributaries of the Seine in his flood predictions for Paris, it is found that when the Wabash River at Mt. Carmel, 221 miles from Cairo, is rising or falling more than six inches a day, the height of the Cairo flood is increased or diminished about one foot. The data for the Wabash River have been published by the Mississippi River Commission during the past twenty years only, so that the correction can be but partially applied in the tables.

As it requires only from two to three days for the flood-wave to be transmitted from St. Louis and Nashville to Cairo, and about five days for it to be transmitted from Chattanooga, the readings of the gages on the day the crest of the flood passes Cincinnati are not those which produce the crest of the flood at Cairo. They should be increased or diminished by the rise or fall during the interval which must elapse before their waters will be in conjunction with the crest of the Ohio River flood. To obtain accurate results at Cairo a flood prediction therefore is required at these localities, and the rise or fall during the preceding day for this reason is added to or subtracted from their readings. This ordinarily gives, within a few feet, the height of the wave in the river which affects the flood crest at Cairo, but occasionally an error of from 5 to 10 feet in the gage readings occurs from the resulting faulty predictions, causing an error from 0.5 foot to one foot in the flood height at Cairo, as is shown in the last column on Table 1.

There is, however, an exception to the rule which must be carefully guarded against. If the river is falling at Cairo, while it is rising at Cincinnati, it usually indicates that a flood from some of the other rivers is passing Cairo, on which that of the Ohio River is merely a perturbation. If the flood originates in the upper Mississippi River, which is normally the case, its height at Cairo can be determined by a similar set of curves shown in Fig. 4 with St. Louis the controlling gage. The prediction can be made only three days in advance, and the heights of the gages at Cincinnati and Chattanooga used are those recorded three days prior to the crest of the flood at St. Louis. Theoretically the readings of the gages at Evansville on the Ohio River, 179 miles from Cairo, and at Johnsonville on the Tennessee, 141 miles from Cairo, on the day the flood passes St. Louis, are preferable to the ones employed on those rivers, but the records of these gages were not available when the computations were first made and have been published only recently in the daily bulletins of the Weather Bureau.

The gage at Cairo also may fall while that at Cincinnati is rising, due to an ice gorge in the Ohio River, as in January, 1918. Such irregularities are incapable of computation.

If the main flood-wave passing Cincinnati begins to fall, and within two or three days a perturbation from one of the upper tributaries causes a second slight rise, the computations should be based on the main rise. Before the flood reaches Cairo the perturbation will be absorbed in the general flood and merely prolong its duration.

St. Louis at the Junction of the Mississippi and Missouri Rivers

A similar set of curves has been deduced (shown in Fig. 5) for determining the height of a flood at St. Louis three days after its crest passes Kansas City, 388 miles above the mouth of the Missouri River, with perturbations of the upper Mississippi computed from the gage at Hannibal, and of the Illinois River from that at Peoria.

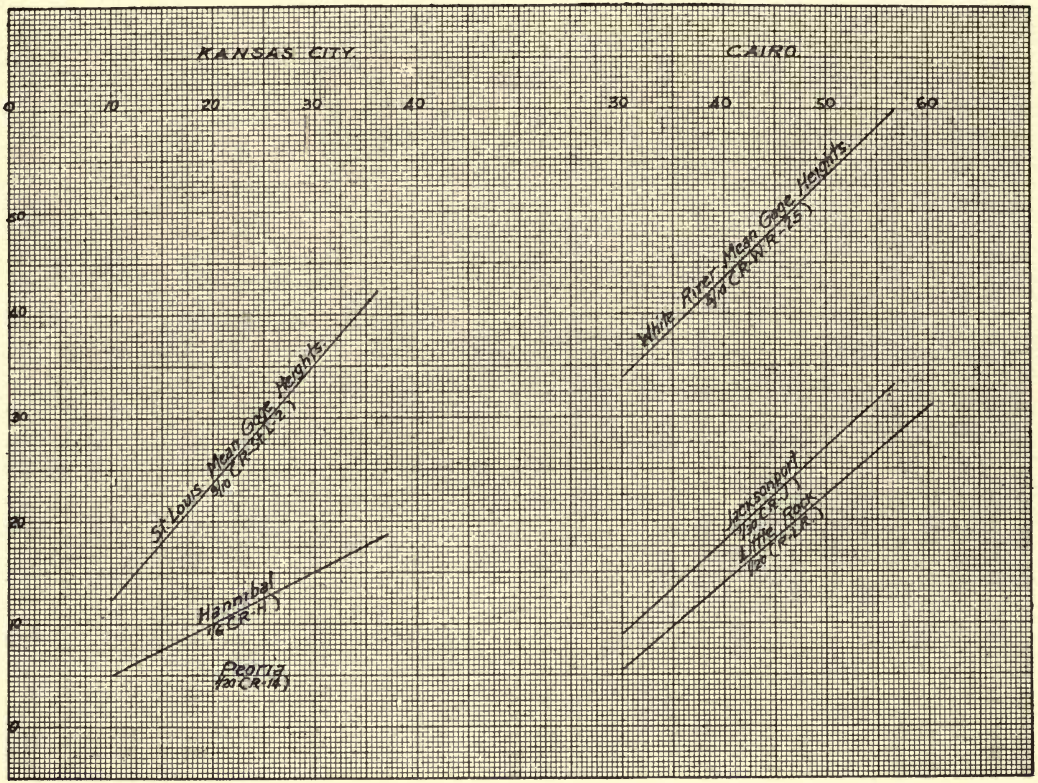
KANSAS CITY
CAIRO
0
10
20
30
40
30
40
50
60
50
40
30
20
10
0
St. Louis Mean Gage Heights
9/10 (CR-ST.L-2)
Hannibal
1/6 (CR-H)
Peoria
1/20 (CR-14)
White River Mean Gage Heights
4/10 (CR-W.R.-25)
Jacksonport
7/10 (CR-J)
Little Rock
1/20 (CR-L.R.)

FIG. 5

There are, however, three important tributaries of the Missouri River, between Kansas City and its mouth, on which regular gage stations should be established and maintained for a number of years, to enable accurate predictions of the floods at St. Louis to be made; *i.e.*, the Grande River, draining 7185 square miles, the Osage, draining 15,375 square miles, and the Gasconade, 3553 square miles. The floods in these rivers are sometimes very violent, the rivers rising twenty feet in a day, and with a moderate flood in the Missouri River, their effect singly or combined may be large. There is no satisfactory indicator of their combined action. Hermann on the Missouri River, 103 miles from its mouth, gives an invariable warning that there is an abnormal flow in the Missouri River, by a rise of over two feet on the day the crest of the flood passes Kansas City, and it also measures the extent of the rise, but on the same day the flood passes St. Louis and therefore too late to be of value in predicting floods. During the years 1915, '16, and '17, the Weather Bureau published the gage readings at Chillicothe on the Grande River, 62 miles from its mouth, and at Arlington on the Gasconade, 108 miles from its mouth. It has also occasionally published the readings at Bagnelle, 70 miles from the mouth of the Osage River. These limited observations clearly indicate that if continuous records were published for a number of years at the *same stations* on these rivers, a satisfactory flood prediction could be made for St. Louis for lower stages than those indicated in Table 3.

Mississippi Floods at the Mouth of White River

An application of the same principles has been made at the mouth of White River, as shown in Table 4, with Cairo as the origin of floods, 393 miles above it, and for the tributaries using the gages at Little Rock on the Arkansas River, 174 miles from its mouth, and Jacksonport on the White River, 264 miles from its mouth. In this case the time of transmission of the flood is variable, — it is about 5 days for floods in the Mississippi less than 40 feet in height, about 10 days for those over 45 feet. If a crevasse occurs in the levee line in the St. Francis Basin it may be increased to two weeks. In the table, the computations are based on the transmission of the flood from Cairo to the mouth of White River in 5 days, for floods not exceeding 42 feet in height, and in 10 days for those exceeding 46 feet. Between 42 feet and 46 feet, the results for a movement of the flood wave in both 5 and 10 days are given. On account of the frequency of breaks in the levee line, prior to 1910, the computations are confined to the past ten years.

APPENDIX C

INFLUENCE OF FORESTS UPON STREAMS

Verbal Note

Foreign Office
No. II S 7540
81331

Referring to the Verbal Note of the 27th ult., the Foreign Office begs to transmit to the Embassy of the United States of America the enclosed copy of an expert opinion on the influence of forests upon streams, rendered by the instructor in the Academy at Eberswalde, Professor Dr. Schubert.

The Royal Prussian Minister of Agriculture, at whose instigation the above-mentioned opinion was given, has no further material on hand. But more detailed information on the subject may be found in a paper on the drainage from forests, read by Professor Dr. Vater of Tharandt, a separate impression of which, from the report of the 49th meeting of the Sächsischen Forstverein in Marienberg i. S. 1905, was published in Freiberg i. S. 1905 by Craz & Gerlach (Sch. Stettner), and in the report by Mr. Hermann in the "Förstliche Rundschau" of 1906, p. 45, published by S. Neumann in Neudamm.

Berlin, November 7th, 1908

To the Embassy of the
United States of America.

Copy from S 7540.
Meteorological Section of the
Experimental Department of Forestry.

Discussions about the influence of the destruction of forests and the drainage of swamps upon the course and the water-supply of streams, for which the representatives of the different countries had submitted reports, took place at the Congress on navigation at Milan in 1905. The views in regard to the action of forests were rather divided, and the members finally contented themselves with the following joint resolution:

"The Congress expresses the wish that those Governments which have not done so before, may now issue distinct and rigorous instructions about the conservation of the forests still extant, about the protection of the mountain districts and about the afforestation of waste lands, so as to avoid the damage to navigable water-courses, resulting from the formation and the movement of alluvial detritus."

Interesting numerical results were embodied in the report by M. E. Lauda, Director of Public Works and Chief of the Hydrographical Central Bureau in Vienna, containing measurements as to precipitation and drainage of the Bistritzka and the Seniza creek-basins. Both these valleys show great similarity in regard to area, shape of surface, and permeability of soil, the last named of which they possess only in a moderate degree. There is also no marked difference in the angle of their banks and in their elevation above sea-level. The two localities are about 20 kilometers distant from one another. The Bistritzka creek flows in a direction from east to west, the Seniza creek from south to north. In both valleys meadows and pastures are in preponderance of the tilled ground. But while these conditions are fairly similar, the area of forest in the district of the Bistritzka is about 1.8 times greater than that in the district of the Seniza. The annual precipitation is nearly equal for both valleys, that of the Bistritzka basin being a trifle heavier in summer.

	Highest elevation above sea-level (in meters)	Area of district in square kilometers	Area of forest, per cent	Drainage, per cent
Bistritzka . .	912	63.8	48	28
Seniza . . .	923	74.0	27	42

The drainage, in proportion to the precipitation, from the heavier timbered district is considerably smaller, amounting to only two-thirds of that of the other valley.

In wide districts, during the dry period of summer, the proportion of drainage was of the same inconsiderable quantity of about 5 per cent.

An article by F. Umfahrer, on the report cited above and on the transactions of the congress on navigation, is to be found in the

"Oesterreichische Wochenschrift für den offentlichen Baudienst" (Austrian Weekly Magazine for Public Works), XII, 1906, p. 176.

According to the measurements, taken by the Prussian State-institution for Hydrology (Prussische Landesanstalt für Gewässerkunde), it appears that in a number of river basins in Northern Germany the proportion of drainage for the heavier timbered districts is generally larger than that for those poorer in forests.

From a comparison of several affluents of the Vistula the following values are derived:

	Precipitation in millimeters	Forest, per cent	Drainage, per cent
Ferse, Dreweuz	540	17.5	27.0
Brahe, Schwarzwasser . .	555	30.1	34.1

There the permeability of the ground plays an essential part, being greater in wooded localities possessing a more sandy soil, and naturally increasing the amount of drainage.

The forests in the lowlands of Northern Germany alter the drainage in a sense exactly opposite to that of the results of the Austrian experiments and so we shall have to agree to the opinion of G. Keller that the influence of the forests on the drainage proceedings is being hidden by other causes more powerful in their effects.

EBERSWALDE, 1908.

Signed:

PROF. DR. T. SCHUBERT.

TABLES

TABLE I — OHIO RIVER FLOODS AT CAIRO, ILL.

		Cincinnati, O.	Cairo, Ill.					St. Louis, Mo.	Chattanooga, Tenn.	Nashville, Tenn.	Corrections	Mount Carmel, Ill.	Computed gauge height Cairo, Ill.	Error	Corrections for errors in heights of tributaries
1884	2/14	71.1	48.2	2/21	51.8			14.3− 0	31.0−3.0	46.4+2.1	52.0+ .6− .6+ .4+ .5		52.9	+1.1	
1913	4/1	69.8	53.3	4/7	54.7			23.0− .7	26.9−6.9	44.8+ .5	51.6+3.3+ .7− .1+ .4	−1.0	54.9	+4.2	
1883	2/15	66.3	43.3	2/27	52.2	2/21	51.8	10.3+*10.0*	13.1− .5	41.5− .1	50.4−1.0+ .8− .7+ .4		49.9	−1.9	+.7
1907	1/21	65.1	44.9	1/27	50.3			25.5+ 3.2	5.6+ .5	21.5+6.3	50.0− 0+1.8−1.3− .5		50.0	− .3	
1907	3/19	62.1	43.6	3/24	46.1			16.7− .2	10.6− .9	31.3− *.3*	48.7− 0− 0−1.0− 0	+1.0	48.7	+2.6	−.6
1913	1/14	61.9	40.8	1/26	48.8	1/20	45.8	-1.4− 0	12.0− .0	48.4− 0	48.4−1.3−3.0− .7+ .7	+1.0	45.1	− .7	
1897	2/26	61.1	37.3	3/11	48.6	3/4	44.1	15.1− .3	34.8+3.2	35.7− .9	48.0−2.8− .3+1.4− 0	−1.0	45.3	+1.2	
1898	3/28	61.1	45.6	4/6	49.8			22.6− .1	4.5+ .1	13.8+ .9	48.0+1.3+1.0−1.3−1.0		48.0	−1.8	
1901	4/26	59.6	40.5	5/1	43.2			17.1− .6	17.1−1.9	37.4− *.4*	47.1− .8− 0− .4+ .1	−1.0	45.0	+1.8	−.5
1890	3/25	58.9	46.7	4/3	48.6			12.1− .1	27.0− 0	41.5− .1	47.0+2.3− .7+ .4+ .3		49.3	+ .7	
1882	2/21	58.6	47.4	2/26	51.9			27.5+ 9.3	15.5−1.1	38.0+1.2	46.7+2.9+3.3− .4+ .3		52.8	+ .9	−1.4
1891	2/25	57.3	44.3	3/4	46.2			11.0+ .8	29.0− 0	25.9+3.9	46.3+1.6− .7+ .8− .2		47.7	+1.5	
1899	3/8	57.3	42.4	3/24	46.0	3/14	44.4	11.5− 1.0	27.6+1.4	36.1+1.5	46.2+ .6− .9+ .7+ .2	−1.0	45.8	+1.4	
1887	2/5	56.2	38.8	2/11	43.6			5.4− .3	19.0+4.9	39.7+1.2	45.7− .9−1.8+ .3+ .3		43.6	0	
1887	2/28	54.5	47.0	3/9	48.5	3/6	47.3	15.1− .5	27.3+ .5	43.7+ .8	44.5+3.7− .1+ .7+ .5		49.3	+ .8	
1917	3/17	56.1	45.7	4/4	50.0	3/23	48.7	11.7+ .4	21.5− .8	34.8+4.6	45.6+2.6− .6− 0+ .3	+1.0	48.6	− .1	
1915	2/7	55.8	43.7	2/12	45.6			16.5+ .2	22.7−2.8	36.5−1.5	45.3+1.7+ .2− 0+ .1		47.3	+1.7	
1886	4/9	55.7	47.8	4/19	51.0			21.3− .3	38.2−1.1	48.9+ .4	45.3+3.7+ .9+1.4+ .8		52.1	+1.1	
1893	2/21	54.6	41.3	2/28	44.9			9.8− 0	32.8−1.0	40.4+ .8	44.5+ .9− .8+1.0+ .4		46.0	+1.1	
1909	2/28	54.6	44.0	3/16	47.3	3/6	46.8	15.8− .3	16.3−1.4	40.0+ .4	44.5+2.3− 0− .2+ .3		46.9	+ .1	
1916	4/1	53.5	38.8	4/9	44.5			26.2+ 1.7	13.7+ .7	19.8− 0	44.0− 0+2.1− .4− .6		45.1	+ .6	
1877	1/20	53.2	28.6	1/28	37.0			9.9− .1	22.1+ 0	38.4+ .8	43.8−5.1− .9− .1+ .3		38.0	+1.0	
1880	2/17	53.2	35.7	2/24	43.3			10.1+ .5	26.8− 0	43.9+ .2	43.8−1.5− .7+ .6+ .6		42.8	− .5	
1903	3/5	53.2	42.8	3/16	50.6	3/11	48.9	17.9+ *.8*	16.5−7.1	37.1+ *.7*	43.8+2.0+ .6− .7+ .3	+1.0	47.0	−1.9	+.4
1912	3/27	53.2	49.8	4/6	53.9	4/2	53.5	25.3+ *.7*	13.7−1.8	29.2+1.6	43.8+5.5+1.8− .6+ .1	+1.0	51.4	−2.1	+.4
1908	3/11	53.2	42.0	3/19	45.5			21.0− .1	8.4−1.4	18.3− .7	43.8+1.6+1.0−1.0− .7		44.7	− .8	
1916	1/14	53.1	48.4	2/4	53.2	1/20	49.5	18.4− 0	19.9+ .9	36.6− .3	43.8+4.8+ .6+ .1+ .2		49.5	0	
1898	1/26	52.2	42.7	1/31	44.3			6.8+ .1	15.2+3.1	38.2− 0	43.1+2.3−1.3+ 0+ .3		44.4	+ .1	
1910	3/7	51.8	39.6	3/15	42.1			11.3+ .2	8.6−1.3	16.1−1.4	42.8+ .9− .5− .9− .8		41.5	− .6	
1876	1/29	51.7	41.1	2/5	45.2			11.6+ .7	10.6− 0	34.4+1.6	42.8+1.6− .4− .4+ .2		43.8	−1.4	

1899	3/31	51.5	46.2	4/15	46.2			12.8−	.3	22.6+	.9	36.5+	.7	42.7+	4.3−	.3+	.4+	.3		47.4	+1.2	
1893	5/2	50.6	46.1	5/8	49.3			31.4+	.6	9.6+	1.4	14.0+	1.0	42.1+	4.5+	2.8−	.6−	.8		48.0	−1.3	
1881	2/16	50.5	38.7	2/25	42.4	2/22	41.7	13.6−	.7	14.7+	3.4	13.8+	.4	42.0+	.9−	.1−	0−	.8		41.6	− .1	
1902	3/5	50.9	29.7	3/17	42.1	3/11	39.1	6.2+	.1	35.9−	2.1	23.7+	2.0	42.2−	3.7−	2.0+	1.3−	.3	+1.0	38.5	− .6	
1906	4/2	50.2	44.3	4/9	46.9			25.0−	.5	12.4−	2.4	33.4+	1.4	42.0+	3.6+	1.7−	.7+	.2		46.8	− .1	
1884	3/17	49.6	42.1	3/30	48.5	3/23	47.1	10.4+	*.5*	24.9−	5.2	47.8−	.5	41.5+	2.8−	.5+	.2+	.9		44.9	−2.2	+.6
1887	4/25	49.3	30.3	5/2	39.4			19.0−	.5	18.0+	3.2	16.1+	1.1	41.2−	2.5+	.8+	.3−	.6		39.2	− .2	
1903	2/8	49.4	36.9	2/14	41.6			14.4−	1.0	18.0+	.5	30.2+	.7	41.4+	.3−	.1+	0−	0		41.6	0	
1911	2/3	49.1	27.3	2/14	37.7	2/9	34.4	6.8−	.2	9.7+	2.3	19.9+	.8	41.1−	4.4−	1.2−	.6−	.5		34.4	0	
1891	1/6	48.4	28.6	1/12	32.2			4.7+	0	15.2−	.3	23.4−	0	40.4−	3.5−	1.5−	.3−	.4		34.7	+2.5	
1882	1/16	48.5	42.2	1/30	47.6	1/22	46.0	13.1−	0	30.2−	.1	49.2+	.2	40.5+	3.3−	0+	1.4+	1.0		46.2	+ .2	
1905	3/13	48.3	35.4	3/18	38.4			16.4−	.2	15.4−	1.9	30.5+	2.1	40.4−	0+	.4−	.3+	.2	−1.0	39.1	+1.4	
1895	1/14	48.4	23.7	1/21	33.0			−0.1+	.3	28.3−	2.9	27.8+	.8	40.4−	5.8−	2.3+	.7−	0		33.0	0	
1905	5/16	48.2	26.3	5/24	38.6	5/22	38.0	16.2+	2.2	7.2+	2.4	10.0+	.3	40.3−	4.5+	.8−	.7−	.9	+1.0	36.0	−2.0	+.4
1910	1/24	47.9	38.0	1/29	38.9			15.3−	1.2	9.4−	.2	23.6−	1.1	40.1+	1.5+	.1−	.7−	.4		40.6	+1.7	
1896	4/4	47.7	34.0	4/13	39.1			6.7−	.3	38.8+	4.2	39.9+	1.7	40.0−	.5−	1.1+	1.3+	.6		40.6	+1.2	
1915	12/22	47.3	36.8	12/30	42.0			5.8−	.4	32.3−	2.0	39.5+	.9	40.0+	.9−	1.4+	1.3+	.5		41.3	− .7	
1891	2/5	47.7	34.6	2/11	39.3			4.5+	.1	22.6−	0	36.6+	1.3	40.0−	.2−	1.5+	.4+	.5		39.2	− .1	
1902	12/18	47.0	34.1	12/26	39.0			9.0−	0	7.4+	.4	31.2+	.8	39.8−	.3−	.7−	.7+	.2	+1.0	39.3	+ .3	
1909	5/6	47.0	40.1	5/13	42.6			20.0−	.1	14.5−	5.5	25.0−	1.7	39.8+	2.6+	1.2−	.7−	.3		42.6	0	
1914	4/4	47.2	37.5	4/10	41.3			18.9−	.2	20.2−	1.2	35.9+	.7	40.0+	1.2+	.9+	.1+	.4		42.6	+1.3	
1885	1/20	46.0	36.8	1/26	39.0			12.3−	.5	18.4−	6.1	37.4+	1.7	39.0+	1.4−	.2−	.4+	.5		40.3	+1.3	
1904	3/9	45.9	26.2	3/17	36.3	3/15	35.6	9.9+	.7	11.0+	3.0	15.9+	1.4	38.9−	3.8−	.4−	.4−	.5	+1.0	34.8	− .8	
1917	1/26	45.9	31.6	1/31	36.5			1.6−	.1	20.7−	.6	32.8+	.3	38.9−	1.1−	1.9+	.3+	.2		36.4	− .1	
1904	3/27	45.7	40.7	4/5	49.1	4/2	48.2	21.0+	*1.1*	19.1−	1.8	37.6−	0	48.8+	3.5+	1.6−	0+	.5	+1.0	45.4	−2.8	+ .5
1880	3/11	45.1	40.5	3/22	44.6	3/17	43.9	10.5+	.3	28.0+	3.5	36.8+	.5	38.2+	3.6−	.4+	1.4+	.5		43.3	− .6	
1892	4/25	43.9	47.8	4/28	48.3			25.4−	.6	13.5−	1.3	38.5+	.7	37.2+	7.8+	2.1−	.3+	.6		47.4	− .9	
1907	6/17	43.1	38.3	6/18	38.4			22.7−	1.0	15.3+	0	13.3−	3.8	36.0+	3.7+	1.6−	0−	1.1	−1.0	39.2	+ .8	
1879	12/27	42.7	31.2	1/3/80	37.0			4.0+	.5	21.6−	.3	34.6+	2.0	36.0+	.1−	1.2+	.5+	.6		36.0	−1.0	
1881	4/17	42.6	44.7	4/20	45.8			27.8−	.1	16.0−	1.9	31.5−	.3	36.0+	6.9+	2.8−	.1+	.2		45.8	0	
1875	3/2	42.6	29.9	3/8	39.7			9.2+	.5	51.0−	3.0	41.5+	1.0	36.0−	.5−	.3+	2.7+	1.3		39.2	− .5	
1892	1/18	41.6	18.4	1/24	30.3			8.3+	.5	35.2−	2.7	29.4+	.6	35.2−	5.8−	.5+	1.4+	.3		30.6	− .3	
1900	11/30	40.0	28.7	12/4	32.6			10.8−	.6	13.2−	2.4	33.2+	1.6	34.0−	0−	.1−	.3+	.5		33.9	+1.3	
1890	5/24	40.5	30.1	5/30	33.8			12.4+	0	11.6−	.3	28.4−	0	34.2+	.4−	0−	.3+	.1		34.4	+ .6	
1879	2/2	40.2	30.7	2/9	34.1			10.1+	.2	11.5−	.1	15.5+	1.2	34.2+	.9−	.2−	.3−	.4		34.2	+ .1	

TABLE II — MISSISSIPPI RIVER FLOODS AT CAIRO, ILL.

		St. Louis, Mo.	Cairo, Ill.			Cincinnati, O.	Chattanooga, Tenn.	Nashville, Tenn.	Corrections	Computed gauge height, Cairo, Ill.	Error
1875	8/3	29.8	43.4	8/7	45.1	34.7	5.9	13.1	38.0+ 6.6+1.0−.1−.1	45.4	+ .3
1876	5/10	32.0	39.2	5/14	42.2	18.2	10.0	14.3	41.6− .4− .3+.1−.1	40.9	−1.3
1881	5/6	33.6	41.7	5/9	42.6	19.2	7.5	14.6	43.8− 0− .4−.1−.2	43.1	+ .5
1882	7/5	32.2	37.0	5/9	38.8	23.8	6.0	9.8	42.0− 2.7+ .1−.1−.5	38.8	0
1888	6/4	29.3	32.3	6/6	32.5	15.4	8.3	5.2	37.5− 2.9− .3−.1−.6	33.2	+ .7
1892	5/19	36.0	43.1	5/22	45.1	22.0	5.2	11.8	47.2− 1.9− .2−.2−.5	44.4	− .7
1893	5/3	31.6	46.9	5/6	48.9	42.8	10.4	14.0	41.0+ 7.1+1.0+.1−.2	49.0	+ .1
1903	6/10	38.0	42.7	6/13	43.4	14.5	9.8	16.7	51.0− 5.7−1.0− 0−.3	44.0	+ .6
1904	4/29	33.6	38.0	5/2	40.6	16.4	3.8	8.0	43.8− 3.4− .5−.2−.5	39.2	−1.4
1905	9/21	30.2	26.1	9/24	30.0	13.2	2.3	8.3	39.0− 9.0− .5−.2−.5	28.8	−1.2
1907	7/25	28.0	31.0	7/29	32.7	23.8	4.5	7.8	37.0− 3.6+ .4−.1−.4	33.3	+ .6
1908	6/20	34.9	35.3	6/21	35.5	9.6	5.5	8.1	45.5− 7.4−1.4−.2−.7	35.8	+ .3
1909	7/16	35.2	42.2	7/19	43.4	14.8	11.6	16.0	46.0− 1.6− .8− 0−.2	43.6	− .2
1915	6/24	31.6	36.0	6/27	37.4	18.5	9.3	11.7	40.8− 2.5− .3− 0−.3	37.7	+ .3
1916	1/31	31.4	51.3	2/4	53.2	30.7	16.0	15.7	40.6+11.4+ .6+.3−.2	52.7	− .5
1917	6/14	32.9	44.1	6/17	44.5	25.8	11.5	10.8	42.9+ 2.0+ .2+.1−.3	45.8	−1.3

TABLE III — MISSOURI RIVER FLOODS AT ST. LOUIS, MO.

		Kansas City, Kan.	St. Louis, Mo.					Hannibal, Mo.	Peoria, Ill.	Computed gauge height	Error
1903	6/1	35.0	27.8	6/10	38.0	6/4	32.2	15.7	11.2	30.6	−1.6
1908	6/15	30.3	32.4	6/20	34.9			16.3	15.4	34.7	− .2
1915	7/21	29.0	30.6	7/23	31.3			11.5	15.2	32.2	+1.0
1915	6/21	27.0	28.7	6/24	31.6			12.5	13.6	30.8	− .8
1909	7/13	27.0	33.2	7/15	35.2			13.4	12.7	34.7	− .5
1917	6/9	26.5	27.8	6/14	32.9			18.1	14.8	30.7	−1.2
1915	5/30	25.2	27.3	6/4	31.3			13.1	12.2	30.0	−1.3
1907	7/20	23.5	25.4	7/25	28.0			13.2	15.2	27.9	− .1
1912	4/17	23.2	28.2	4/15	28.9			12.7	17.4	30.2	+1.3
1912	4/2	23.1	29.8	4/5	30.8			14.8	19.6	32.3	+1.5
1905	7/12	23.0	24.1	7/15	25.4			12.3	10.4	26.3	+ .9
1898	6/12	21.5	21.2	6/19	25.0	6/15	23.0	5.5	14.5	22.8	− .2
1913	4/16	21.9	27.2	4/16	27.2			12.5	20.7	29.4	+2.2
1917	4/20	21.6	21.5	4/24	22.9			12.7	14.2	23.9	+1.0
1915	4/15	21.3	20.8	4/16	20.9			8.9	10.5	22.5	+1.6
1914	6/17	21.2	16.0	6/21	20.5			8.5	12.0	18.3	−2.2
1907	7/8	20.3	20.2	7/10	20.4			7.9	11.8	21.9	+1.4
1910	3/24	20.2	19.6	3/27	22.5			10.8	15.9	22.1	− .4
1909	6/11	20.0	22.4	6/14	26.2			14.2	14.2	25.1	−1.1
1916	7/15	19.8	18.4	7/18	19.0			8.8	13.6	20.6	+1.6
1906	6/21	19.7	19.7	6/25	22.0			10.2	8.5	21.7	− .3

TABLE IV — MISSISSIPPI RIVER FLOODS AT THE MOUTH OF WHITE RIVER

		Cairo	White River					Little Rock	Jacksonport	Computed gauge height	Error
1918	2/25	39.8	40.3	3/3	41.5	3/5	41.7	2.5	9.0	41.8	+ .1
	3/25	33.9	34.3	3/30	35.9			1.1	2.7	36.4	+ .5
	5/19	34.9	37.2	5/26	39.8			11.4	28.5	39.8	0
1917	1/14	38.4	37.9	1/19	39.7			4.2	9.7	40.2	+ .5
	4/4	49.9	49.4	4/9	50.7	4/15	51.5	8.0	25.9	51.6	+ .1
	6/16	44.5	44.4	6/21	46.2	6/25	46.9	10.4	17.5	46.7	− .2
1916	2/4	53.2	54.8	2/10	56.5			27.9	32.6	56.5	0
	4/9	44.5	44.2	4/14	46.6	4/18	47.4	18.9	21.9	47.2	− .2
	6/3	34.0	34.8	6/8	37.6	6/10	38.2	7.5	4.5	37.0	− .6
	6/14	36.2	39.4	6/19	41.6	6/22	42.4	16.0	9.5	40.8	− .8
1915	1/26	32.4	32.8	1/31	34.3			5.1	3.7	34.9	+ .6
	2/12	45.5	42.6	2/17	45.3	2/23	46.9	6.3	14.6	45.8	+ .5 (−1.1)
	6/6	39.9	41.6	6/11	44.8	6/15	45.8	22.8	16.5	44.0	− .8
	6/26	37.4	43.2	7/1	43.8			18.5	10.5	43.3	− .5
	7/20	37.7	41.4	7/27	42.0			9.7	4.0	41.7	− .3
	8/26	39.0	40.4	8/31	44.2	9/2	44.8	23.2	32.0	43.4	− .8
1914	2/26	32.3	31.4	3/4	35.4			12.7	21.4	35.4	0
	4/10	41.3	41.1	4/20	44.5			11.9	16.0	43.7	− .8
1913	1/26	45.0	46.7	1/31	49.1	4/6	50.4	14.6	27.1	49.1	0 (−1.3)
	4/8	49.3	50.4	4/13	53.7	4/24	55.3	9.6	21.9	51.8	−3.5 (Crevasse in levee line)
1912	1/5	39.0	40.6	1/10	42.0			7.4	9.5	42.1	+ .1
	3/4	41.8	38.1	3/9	43.2	3/15	45.8	12.5	21.0	42.7	− .5
	4/6	53.9	53.7	3/11	55.6	3/16	56.3	23.4	28.0	56.1	− .2
1911	2/14	37.7	35.4	2/20	38.3			1.9	1.5	38.3	0
	3/16	34.1	31.6	3/21	35.6			26.3	6.0	35.3	+ .3
	4/21	45.4	44.8	4/26	47.2	5/1	48.3	14.6	23.5	47.7	+ .5 (−.6)
1910	1/29	38.9	39.0	2/3	40.3	2/5	40.6	8.0	3.1	41.0	+ .4
	3/15	42.1	43.0	3/20	44.2	3/23	44.4	5.5	11.2	44.7	+ .5 (+.3)
	5/12	30.7	29.6	5/17	34.4	5/21	35.6	3.4	4.6	33.1	−1.3
	5/28	31.4	35.7	6/1	37.0			13.5	16.8	37.0	0
	6/16	36.4	34.6	6/21	39.2			10.3	16.6	38.3	− .9

TABLE IV — Continued

		Cairo	White River					Little Rock	Jacksonport	Computed gauge height	Error
1909	3/16	47.3	48.3	3/21	49.3	3/28	49.9	10.4	24.8	49.9	0
	4/27	40.8	40.8	5/2	43.2			9.6	24.4	43.9	+ .7
	5/13	42.6	44.8	5/18	45.8	5/21	46.2	7.2	18.2	45.9	+ .1 (−.3)
	6/17	37.7	41.1	6/24	42.4			9.2	6.6	41.8	− .6
	7/18	43.4	40.0	7/23	43.2	7/28	44.8	11.2	9.2	43.7	+ .5 (−1.1)