REPORT OF EVERGLADES ENGINEERING BOARD OF REVIEW.

MAY, 1927

PART II.

TECHNICAL DISCUSSIONS OF RECOMMENDATIONS

We have presented our recommendations, findings and conclusions on Everglades drainage engineering problems in Part I of the report, formally arranged and stated in summary terms. We now present in Part II a detailed technical discussion of the reasons for our recommendations.

LAKE CONTROL

The orderly control of Lake Okeechobee within prescribed limits of area, below a predetermined maximum elevation and, so far as may be practicable, above a predetermined minimum stage, may properly be considered a first essential to the reclamation of the Everglades.

Lake Okeechobee is the down stream terminus of Kissimmee River, Fisheating Creek, Taylor Creek and other streams of relatively minor importance. The waters flowing off from a total of approximately 4,176 square miles of land are delivered into the lake by those streams. Under existing conditions the lake also receives the flood time discharge from approximately 300 square miles of Everglades lands adjacent to the southern half of the lake.

The tributary watershed is shown by Figure 5.

The lake may be considered as lying almost completely across, and near the upper end of a broad slough which, confined by higher sand lands on either side, slopes gently as to surface elevation in a southerly direction to tide water, at the southern end of the State. A relatively narrow arm of that slough, known as Loxahatchee Marsh, extends easterly from the main slough to tide water at the coast near Jupiter. The rock bed of the slough is overlaid with an accumulation of muck and peat soils, varying in thickness from 12 feet to 2 feet or less.

That slough, which varies from 35 to 50 miles in width and which is approximately 102 miles in length below the lake, is the natural outlet of Lake Okeechobee and is known as the Everglades of Florida. Its location is indicated by Figure 1.

Adjacent to the south end of the lake the original surface of the muck lands stood at a general elevation approximately twenty-one feet above sea level, corresponding with the normal high water stage of the lake. Under such conditions a normal lake stage resulted in complete saturation of the muck lands and any rise of the lake above normal resulted in the discharge of waters onto those lands, there to remain until it would gradually work its way to the sea, or pass off by plant transpiration, evaporation, or deep percolation. The settlement of the muck which has occurred since the beginning of drainage operations has aggravated that condition, and the protection of the Everglades lands against such saturation or overflow by the waters of Lake Okeechobee is essential to their reclamation. With that protection provided by proper control of the lake, the problem of the reclamation of those lands may be considered as largely freed of external physical influences.

The planning of a system for the control of the lake requires consideration of certain general features, including:

The demands of the forces of nature, such as rain fall and wind storm, which the system should be designed to meet.

The limits of area and elevation within which it is desirable that control be maintained, and

Existing physical conditions affecting a choice of alternate possible methods of control.

The selection of a system of control may properly be made after consideration of those features to the extent possible with available data.

The basis of our consideration of the several features noted above is set out hereafter.

NATURAL FORCES AFFECTING LAKE CONTROL.

(1) *Recorded Storms.*

Rainfall upon the lake and upon its tributary drainage area, evaporation from the lake surface, wind storms, and resultant wind tides such as those accompanying the hurricane of September, 1926, are natural forces which must be considered in the selection and design of a system of lake control.

Rainfall upon the surface of the lake directly affects the lake elevation and, excepting as that effect is controlled by evaporation or by the discharge of water through outlets from the lake, a rain of given amount over the entire lake surface would raise the elevation of the lake by a like amount.

Rainfall over the drainage area tributary to the lake determines the discharges into the lake from such areas, but the volume and period of run-off varies widely under varying storm conditions.

The rate and duration of run-off from drainage areas such as those tributary to Lake Okeechobee, under varying conditions of distribution and intensity of rainfall, can be accurately determined only by long continued measurements of stream flow and precipitation. Such records are not available for the area in which we are concerned.

Fortunately there are available records of precipitation at certain points on Lake Okeechobee, which have been maintained almost continuously since May, 1915. Daily readings of lake stages and of the discharges from various canals leading out of the lake are also available since the same date. Those records may be used in determining the effect of different storms upon the elevation of the lake. The time covered by those records embraces three major storm periods which, for purpose of reference, we will designate as those of 1922, 1924 and 1926, respectively, and which are of particular interest in this study.

From an examination of rainfall records extending back to 1894, it appears doubtful that any storm period has occurred in that time, with the possible exception of one in 1901, which would have taxed a system of lake control as severely as those of 1922, 1924 and 1926. While the nature and extent of available records necessitate offering that statement as one of probability, rather than of fact, it is apparent that each of those was of extreme severity and, in its particular effect, generally on a par with or actually in excess of the most severe other storms of the past 33 years.

While there can be no assurance that the effect of the maximum storm recorded in any given period of years may not be exceeded at any time in the future, there appears to be a general rate of frequency through long periods of years for storms of comparative intensity, which may be employed as one of the most satisfactory available basis for determining the comparative frequency with which storm periods of given intensities may be reasonably expected in the future, and the degree of protective works which would appear to be reasonably justified.

In determining the relative demands of various storm periods upon a system of lake control such as that under consideration, it will be found generally that extreme conditions of rainfall for any particular day are less important than the combined conditions of the entire storm as evidenced by the daily and total catchment of the lake. The nature and dimensions of the facilities for lake control will usually be determined by the maximum volumes of water reaching the lake in various periods of time. An exception to that principle is found in the conditions resulting from severe wind storms, such as the hurricane of 1926. Under the influence of a high wind, water already in the lake and otherwise retained at harmless elevation may be moved by the wind and accumulated upon limited areas at stages resulting in great damage, unless proper provision is made against such a contingency.

The severity and the distinctive character of the storm periods of 1922, 1924 and 1926 makes the record of the effect each of them had upon Lake Okeechobee of particular value in planning a system for the control of the lake.

The 1922 storm period was one of long continued and relatively uniform heavy rainfall. Its effect upon the stage of Lake Okeechobee became apparent about the middle of August. On the 16th of that month the lake stood at elevation 14.47. Through the next 95 days, or by November 19th, it rose 4.33 feet to a maximum elevation of 18.8, indicating a net accumulation of 88.2 billion cubic feet of water in that period. The gross accumulation, representing the combined inflow from the tributary drainage area and rainfall upon the lake surface during that period, would be increased by the addition of 10.32 billion cubic feet as the estimated coincident loss by evaporation from the lake surface. As there was no other appreciable recorded loss from the lake during the period in question, the 1922 storm apparently delivered a total of 98.52 billion cubic feet of water to the lake through a period of 95 days. Figures 6 and 7 respectively, present daily records of lake stages and accumulations resulting from the storm.

The 1924 storm period was shorter but of greater intensity. The important rise of the lake resulting from that storm developed through a period of 51 days extending from September 11th to November 15th. During that time the lake rose 3.2 feet, from elevation 16.1 to elevation 19.3. Allowing for the volume of water removed from the lake by outlet canals, it appears that the total delivery of water to the lake in that time, exclusive of the loss by evaporation, was 67 billion cubic feet. If the estimated evaporation loss of 7.57 billion cubic feet is added, the figure for gross delivery of water in the 51 days period is established at 74.57 billion cubic feet. Figures 9 and 10, respectively, present daily records of lake stages and accumulations resulting from the 1924 storm.

The storm of 1926 included a period of heavy rainfall, accompanied by two severe wind storms; one occurring early in the storm period and the other near its close. The noticeable rise of the lake due to rains began on June 5th, when the lake stood at elevation 17.0. In the next 90 days, or by October 2nd, the lake rose 2.5 feet, to an elevation of 19.5. Allowing for the volume of water removed from the lake by outlet canals during that period, it appears that the total delivery of water into the lake, exclusive of the loss by evaporation, was 69.9 billion cubic feet. The addition of 21.3 billion cubic feet as the estimated evaporation loss established the figure of 91.2 billion cubic feet as the total delivery to the lake from all sources in the 90-day period. Figures 12 and 13 respectively present daily records of average lake stages and of accumulations resulting from the 1926 storm period.

The temporary effect of wind storms on the elevation of water in the lake was clearly demonstrated on two separate occasions. On July 27th, the lake was subjected to the effects of a high wind, blowing from the north. While no records are available as to the wind velocity attained in the lake section, it was sufficient to damage roofs of buildings and similar structures. That wind developed a tide which reached a maximum of 4.9 feet rise at the head of the Hillsboro Canal, decreasing in height at other points along the lake.

Again, on September 18th, when the lake stood at elevation 19.2, it was subjected to the full force of the hurricane of that date. Wind velocities of that hurricane, which was by far the most severe recorded as ever striking the State of Florida, reached an apparent maximum of 132 miles per hour at Miami. The velocities had probably decreased somewhat by the time the storm reached Lake Okeechobee, but there is no record available as to what they actually were at that point. The effect of the wind, which blew across the lake almost directly toward Moore Haven, located on its southwestern shore, was to raise the water, at that point, up to a recorded elevation of 26.0, at which stage it stood for sufficient time to establish definite water marks on trees and buildings. The rise in lake level at that point due to the wind amounted to 6.8 feet, decreasing from that amount at other points along the lake in either direction from Moore Haven.

Figures 15 and 16, respectively, present diagrams of the wind tides developed at different points along the lake by the July and September hurricane.

Figure 17 permits a further comparison of the three storms discussed above, by presentation of principal characteristics of each.

The areas of Lake Okeechobee at various stages and the increments of storage included between different stages are shown by Figure 18.

(2) *Possible Storms.*

While the storms of 1922, 1924 and 1926 appear to have exceeded in severity any other recorded for many years, it is possible that they may be surpassed at any future time. With that thought we have made studies to determine the effect on the lake that would result from storms which would represent hypothetical increases in intensity over those described above.

Figures 7 and 8 present respectively a record of daily accumulations and lake stages, which would be expected from a storm delivering into the lake each day, through a period equal to that of the 1922 storm, fifty per cent more water than was actually delivered by that storm.

Figures 10 and 11 present respectively a record of daily accumulations and lake stages, which would be expected from a storm equal to that of 1924 but with the daily delivery from the drainage area tributary to the lake increased fifty percent over the delivery received in the 1924 storm. Such an increase of runoff might be approached as the result of either an increase in the severity of the conditions of rainfall, or by drainage improvements in the tributary area.

Figures 13 and 14 present respectively a record of daily accumulations and lake stages, which might be expected from a storm equal to the 1926 storm in duration, but producing daily discharges into the lake fifty per cent greater than those of the 1926 storm.

DESIRABLE LIMITS FOR LAKE CONTROL.

Determination of the maximum and minimum elevation between which it would be desirable to control the lake involves consideration of the interests of drainage, irrigation, fire protection, navigation, and the effects of wind tides. To some extent those interests are conflicting. While control between a range of high levels would aid irrigation, fire protection and navigation, and would decrease costs of outlet canals through the increase of available head, a control between a range of low levels would provide the maximum degree of drainage and would decrease the required height and the cost of levees to provide protection against wind tides. A wide range between permissible high and low water stages would decrease outlet canal costs through the provision of added storage in the lake, while a narrow range would have the opposite effect.

After careful consideration of the different factors involved and after discussion of the matter with residents within the affected area, we have reached the conclusion that the lake may be permitted to rise to a maximum elevation of approximately 17.0 without objectionable results, and that the minimum elevation should be kept as nearly as practicable at 14.0. By supplementing existing facilities for navigation by the construction of artificial channels from point to point about the lake as might be necessary, such a range of control would appear to be most satisfactory from all regards, under existing conditions. The limits of area within which the lake should be controlled are already substantially established by natural conditions and existing levee construction.

Extensive development in the Everglades in the future may indicate the desirability of varying those limits of maximum and minimum elevation. The expense of constructing a levee completely around the lake, of height and dimension sufficient to permit development of maximum stages well above 17.0 with safety, may be justified by the value of added facilities for irrigation through dry seasons resulting from such an increased accumulation of wet season storage. It is our opinion that such extended provisions are not justified at the present time.

REQUIRED CAPACITIES OF CONTROL SYSTEM

Our studies lead us to the belief that provision should be made for a system of lake control which will regulate the lake approximately within the ranges set out above when subjected to a storm equal in period to that of the storm of 1924, but exceeding it in delivery to the lake by 50 per cent of the daily discharge from the tributary drainage area.

The demands of such a storm upon a system of lake control would exceed those of one 50 per cent greater than the storm of 1926, but would be less than those of a storm 50 per cent greater than that of 1922.

We believe that provision should be made against a wind tide of seven feet occurring while the lake is at maximum stage.

A system of control built to the capacities outlined above should, so far as available records of the past permit accurate judgment, be overtaxed only at rare and infrequent intervals. No storms have occurred in the past thirty-three years which would not have been handled within a substantial margin of safety by a system built to such capacities.

RECOMMENDED FEATURES FOR CONTROL SYSTEM

Such a system of control would include the following essential provisions:

(1) *Levee.*

The construction of a continuous levee extending around the south end of the lake, beginning at the sand ridge approximately three miles northwest of Moore Haven and extending to Bacom Point, north of the Hillsboro Canal, for a total length of 47.6 miles. The levee should be built to a top elevation of 27.0, and the front face should be riprapped with local dredged rock for a thickness of three feet. At points of intersection with existing or proposed canals, the effect of the levee must be continued across the canals by the construction of storm tide gates with top elevations at 27.0. The gates would be similar to the upper gates of the existing locks, and supported between concrete piers constructed for the purpose. The piers on either side of the canal opening would be joined into the levee. Such gates could be constructed to provide openings of standard dimensions, and built in successive units across any particular canal, to provide from time to time the dimensions of waterway opening required as the canal itself was enlarged under a program of progressive development.

The existing lock structures can be adapted to the above requirement, to the limit of their cross sectional capacity, by the provision of facilities for raising the top elevation of the upper lock gates or of the movable dam to 27.0

by the installation of flash boards upon receiving hurricane warnings.

We have prepared alternate designs for the levee, as presented by Figures 3 and 4. Both contemplate the incorporation of the existing levee into the new section. The first presents the section which we recommend as the minimum necessary to provide proper protection against possible wind tides. The second is a modification of the design recommended by the Chief Engineer of Everglades Drainage District in his biennial report of January 1, 1927. The advantages of the latter design in providing available sites for home construction are manifest, but as those advantages are apart from the requirements of drainage and flood protection, we feel that final decision as to which of the two types should be constructed may properly be determined as a matter of administrative policy.

The construction of the levee to either section will provide a channel along the entire length of the levee which should permit navigation at even minimum lake stages.

Our estimates indicate the cost of the levee built to the first design to be $725,000.00. The estimated cost of the levee built to the second design is $1,600,000.00, but participation by the trustees of the Internal Improvement Fund to the extent suggested in the current Biennial Report of the Chief Engineer would reduce the estimated cost to Everglades Drainage District to $1,018,000.00. To the Figures presented above, as the estimated cost of levee construction to either section, should be added the sum of $80,000.00 as the estimated cost of the necessary storm gates.

(2) *Outlet Canals.*

The completion of the St. Lucie Canal to the present plan, at an estimated cost of $723.880.00 should be continued without interruption.

The early provision of an increase of outlet canal capacity for the control of Lake Okeechobee, from 5000 cubic feet per second at elevation 17.0 of the lake as provided by the present plans for the St. Lucie Canal, to 7500 cubic feet per second at the same lake stage, is indicated as a necessity. Such an increase in outlet canal capacity may be provided by an increase in the depth of the St. Lucie Canal at an estimated cost of $1,224,000.00, or it may be provided by an improvement of the Caloosahatchee River by Everglades Drainage District from the lake to Ft. Thompson at an estimated cost of $872,560.00. The availability of the latter route is, however, dependent upon the improvement of Caloosahatchee River down stream from Ft. Thompson by Caloosahatchee Improvement District, the Federal Government, or some other agency, to the extent necessary to permit the discharge of lake waters into the river without flooding the river valley lands. The end of the current year will undoubtedly determine whether or not the improvement of the river below Ft. Thompson will be undertaken by such independent agencies and, accordingly, whether or not improvement of the Caloosahatchee by Everglades Drainage District as an outlet for lake control will be justified.

The possibility of enlarging Canal B (Figure 2) and extending it west along the township line to the lake to permit its use as an outlet canal to carry 2500 second feet from the lake has been investigated. It is entirely feasable to construct such a canal, but the required capacity can be secured more economically by improvement of either the St. Lucie or the Caloosahatchee River.

We have made studies to determine the feasibility of diverting the water of Kissimmee River east to the Atlantic Ocean from a point upstream from the entrance of the river into Lake Okeechobee. The unfavorable topography and physical conditions that would be encountered by any such diversion canal would result in costs which make such a project financially impracticable.

We have also studied the possibility of a floodway extending to tide water from the south end of the lake, and find that the costs of levee construction, of right of way, and of necessary excavation, under the conditions of the long distances and the flat slope to tide water, make the cost of additional outlet facilities by such a method far more expensive than their provision by way of either the St. Lucie Canal or the Caloosahatchee River. We do not consider either Kissimmee River diversion or floodway construction to be practicable projects.

Certain of the Canals recommended in a subsequent section of this report as necessary to the reclamation of the Everglades lands will be available, in part at least, for use in controlling the lake after they have first carried off the excess waters originating within the territory they are primarily designed to serve. However, we feel that the outlet canals in themselves should be designed to furnish all capacities reasonably to be required for lake control, and that the use of the drainage canals as mentioned above should be considered only as a possibility of emergency reserve.

It is possible that future development of the Everglades will justify the provision of a total of 10,000 cubic feet per second outlet canal capacity. Such an ultimate capacity, which could be obtained by carrying out both the enlargement of the St. Lucie Canal and the improvement of the Caloosahatchee, or Canal B, as described above, might be desired as a means of accommodating a large increase in runoff from the tributary drainage area resulting from extensive drainage operations in that area, or it might be desired as a means of controlling the lake between somewhat narrower ranges of elevation than those recommended above. However, we feel that the early provision of 7,500 cubic feet per second as recommended above will meet all demands which can be reasonably foreseen or which should be reasonably provided against at this time.

(3) *Operation of Outlet Canals.*

With the provision of the levees and of 7,500 cubic feet per second outlet capacity as recommended above, the control of the lake would be accomplished by opening the outlet canals to full capacity whenever the lake rose above elevation 14.5 at the beginning of the rainy season and maintaining their discharge at full capacity throughout the rainy season at all times during which the elevation of the lake stood at 15.0 or higher. They would be closed and the water in the lake at elevation 15.0, supplemented by the dry weather flow from the tributary drainage area, would be used to carry the lake through the dry period.

EFFECT OF CONTROL ON LAKE STAGES.

It is quite possible that extended periods of drought might result in evaporation losses and demands for water for use in irrigation which would lower the lake below the desirable minimum of 14.0 before the rains of the next rainy season would replenish the supply of water in the lake. However, it appears that the inconvenience resulting from any such deficient stage must be accepted if the value of storage in the lake in controlling it against destructive stages is to be employed as the only means of accomplishing such control within reasonable limits of cost. That value does not appear to be generally recognized. In the instance of a storm such as that of 1924, the storage afforded by the lake between elevations 14.5 and 17.0 would be equivalent, in protecting the Everglades lands against overflow, to the results that would be furnished for a period of twelve consecutive days by ten canals equal in capacity to the present St. Lucie Canal.

In considering the contingency of lake stages below 14.0 it would seem that the interests of navigation should be subordinated to those of reclamation and of possible destruction of lives and property, and met so far as practicable by the construction of artificial channels from point to point about the lake as the means of providing navigation at such times.

The curves of daily lake stages and storage accumulations and the tabulation of the characteristics of the 1922, 1924 and 1926 storms and of the various hypothetical storms previously presented in this report indicate the stages of maximum lake elevation that would be expected under a system of lake control providing 7,500 second feet of outlet capacity as outlined above. It appears that storms equal to those of 1922 and 1924 would produce maximum stages of 17.0 and 16.54 respectively, while a storm such as that of 1926 would be controlled at a still lower maximum elevation. A storm 50 per cent greater than that of 1922 would apparently produce a maximum stage of 18.7; one resulting in a run-off from the tributary area 50 per cent greater than that of the storm of 1924 would produce a maximum stage of 17.45, and the maximum stage resulting from a storm 50 per cent more severe than that of 1926 is indicated as 16.93.

The apparent adequacy of the system of control recommended above is indicated by those figures.

As information, the same curves and tabulations also indicate the effect in controlling the lake under typical storms that would result from outlet canal capacities of 5,000 and 10,000 cubic feet per second.

PROTECTION OF ST. LUCIE CANAL

The heavy rains of the 1924 storm accumulated water against the outside of the spoil banks on both sides of the St. Lucie Canal. That water finally broke through the spoil banks in some twenty-five different places, washing large amounts of eroded material into the canal, and leaving a gully-like opening into the canal at each point.

While the general process of natural adjustment has probably been sufficient to insure against a recurrence of that condition to as great a degree, we believe the importance of maintaining the full capacity of St. Lucie Canal available at all times justifies the early provision of works necessary to protect it against such deterioration.

Such protection would be provided by deepening the present inlets into the canal, to a depth of three to six feet below low water stage in the canal, for a length of one to two hundred feet. From that point, the bottom of the inlet should be carried up at a grade generally not greater than five per cent to meet the present grade of the inlet. The sloping grade should be riprapped to a thickness of at least two feet. At the intersection with the present grade, a substantial notch should be constructed across the inlet, with the bottom of the notch at the grade of the inlet and its width sufficient to accommodate the expected discharge. The notch should be built of steel piling or concrete, and its sides should be built into the earth embankment to prevent water washing around them.

In some instances it will be found practicable to combine two or more of the present inlets, and thus reduce the number of openings into the canal. Any inlets so eliminated should be closed up by filling with selected material in a manner to assure against their washing out again, and the spoil banks on both sides of the canal should be improved and maintained as a continuous levee with no opening excepting the inlets described.

The dimensions for each of the inlets will depend upon its present condition and the amount of water which investigation will indicate it may be called upon to pass.

We estimate that such protective works can be constructed at a cost of $175,000.00.

ESTIMATES OF COST.

We are presenting, on the following page, a tabulation showing the quantities and costs included in the lake control system described above.

Item	Units	Unit Price	Total Cost
Completion of St. Lucie Canal to 5,000 *c. f. s.*			
Total excavation	1,809,700 cu, yds..	$ .40	$ 723,880.00
Lake Levee (figure 3 design).			
Earth excavation			
net amount ...	1,900,000 cu. yds.	.13	247,000.00

Item	Units	Unit Price	Total Cost
Adjacent rock riprap	708,000 cu. yds.	.40	283,000.00
Hauled rock riprap	122,000 cu. yds.	1.60	195,000.00
Storm tide gates..	(Lump sum)		80,000.00
Total			$ 805,000.00
Lake Levee (figure 4 design).			
Earth excavation	9,350,000 cu. yds.	.12	$1,122,000.00
Adjacent rock riprap	708,000 cu. yds.	.40	283,000.00
Hauled rock riprap	122,000 cu. yds.	1.60	195,000.00
Storm tide gates .	(Lump sum)		80,000.00
Total			$1,680,000.00
Protection of St. Lucie Canal Against Erosion.			
Protective works .	(Lump sum)		$ 175,000.00
Improvement of Caloosahatchee to 2500 c. f. s.			
Earth excavation	2,820,696 cu. yds.	..	....
Rock excavation	536,126 cu. yds.	..	....
Total excavation	3,356,800 cu. yds.	.26	$ 872,560.00
Enlargement of St. Lucie Canal to 7500 c. f. s.			
Earth excavation	1,214,044 cu. yds.	..	....
Rock excavation	1,234,194 cu. yds	..	....
Total excavation	2,448,000 cu. yds.	.50	$1,224,000.00

The estimated prices presented above all include an allowance which we believe sufficient to cover engineering and administrative costs to be reasonably expected in connection with the work.

RESUME

(a) We recommended the immediate completion of the St. Lucie Canal to 5,000 c. f. s. capacity at an estimated cost of $723,880, and the early increase of outlet capacity to a total of 7,500 cubic feet per second at lake elevation 17.0. Such additional capacity may be provided by an improvement of either Caloosahatchee river, at an estimated cost of $872,560, or of St. Lucie canal, at an estimated cost of $1,224,000.00. The availability of the former outlet depends upon improvement of the lower river by agencies other than Everglades Drainage District.

(b) We recommend the early construction of protective works, at an estimated cost of $175,000.00 as a means of assuring against destructive erosion into the St. Lucie Canal.

(c) We recommend the immediate construction of a levee around the southern shore of the lake from the sand ridge north of Moore Haven to Bacom Point, as a means of assuring against destruction by wind tides and as a means of controlling the lake within prescribed limits of area. The levee to be built to either of the alternate sections presented, at estimated costs of $725,000.00, or $1,018,000.00, dependent upon the section selected.

(d) We recommend the construction of storm tide gates across the existing canals intersected by the levee, at an estimated cost of $80,000.00, as a means of continuing the effect of the levee across the canals.

(e) Upon the completion of the works described, we recommend a program of operation of the works which should generally result in the control of the lake below a maximum elevation of 17.0, and which will recognize elevation 14.0 as the desirable minimum stage, to be adhered to so far as natural conditions will permit.

(f) The provision and operation of the facilities as described are entirely practicable and, in our judgment, will provide adequate control of the lake under all conditions and through the period of time that can now be reasonably anticipated.

(g) It is possible that future development in the Everglades may justify provisions for outlet capacity as great as 10,000 cubic feet per second, or for safely controlling the lake at maximum elevation substantially above 17.0 as the means of conserving for irrigation a greater portion of the wet weather accumulation in the lake. Such provisions are, in our judgment, neither necessary nor justified at this time, but should be considered as a possible requirement developing from future extensive use of the Everglades lands.

(h) As a guide to the operation of the lake control works, we believe the value of complete hydrographic data as to flow of streams into and out from the lake justifies its collection.

MAIN DRAINAGE OR ARTERIAL CANALS.

Assuming the proper control of Lake Okeechobee and the consequent relief of the lands of the Everglades from inundation by waters from the lake, the second major problem of the reclamation of those lands is the development of a system of arterial drainage canals which will be so located and of such capacities as to provide adequate outlets for the detail drainage of all of the lands they serve.

In the design of such a system of canals, consideration may be given to the possibility of their use in supplying water for the maintenance of a satisfactory ground water table and for irrigation in dry periods. The adaptability of the system to such service would be a desirable feature if it can be accomplished within limits of cost justified by the value of the results.

The canals will have certain value as waterways for navigation, but that value will be entirely incidental to their main purpose.

We understand that the provision of such an arterial canal system is a responsibility assumed by Everglades Drainage District, and that the detail drainage of the lands will be carried out by individuals or sub-drainage districts.

RUN-OFF ALLOWANCES.

A word essential to the design of such a system is a determination of the amount of excess water that may be reasonably expected to originate upon different areas to be served, for the required capacities of the different canals will be determined by that consideration.

The principles affecting run-off or storm-water discharge from various areas of lands of different types and of various conditions of topography have been so commonly discussed as not to require repetition here. The run-off diagrams appearing as Figure 19 of this report are those which, after careful consideration of all available data, we rcommend for use in the design of a system of arterial canals such as that under consideration. They indicate a run-off of one inch of water in 24 hours from tracts of 16 square miles, decreasing to one-half inch in 24 hours from tracts of 324 square miles. The use of those diagrams contemplates that in the design of canals the flow line will not be raised above the elevation of the ground surface after the further subsidence discussed in the following paragraph has developed. It also contemplates that in the operation of the canals the ground water table in lands served by the system will be reduced from two to four feet below the surface in advance of the rainy season, in order that the benefit of the ground storage may be secured.

We recommend that the arterial canal system be designed to the capacities indicated as necessary by those diagrams and subject to the regulation of flow line described in the belief that such capacities will not be overtaxed by the demands of any but storms of exceptional severity and infrequent occurrence. Such storms are to be expected only at intervals so great that wise economy forbids providing canals large enough to prevent the overflow they will produce.

SUBSIDENCE OF MUCK

The muck lands of the Everglades are of a type in which a substantial subsidence below the original natural surface elevation may be expected to develop as a natural process under the conditions of drainage and reclamation. The amount of ultimate subsidence and the period of time that must elapse before it will be accomplished are problematical. The principal causes of such subsidence appear to be the removal of the supporting value of the ground water when the water table is lowered, the physical compaction due to occupancy and agricultural use of the land, and gradual escape of certain volatile constituents of the original soil. The maximum recorded subsidence of muck of which we have knowledge is that of a tract in the Fens of England, where a subsidence of ten feet has developed through a period of 87 years, in muck originally 18 feet in depth. Numerous observations have been made of subsidence in the Everglades by the engineers of the District, by the U. S. Department of Agriculture, and by individuals. It is known that a general subsidence to elevations varying from 1.5 to 4.6 feet below the original surface elevation has already occurred throughout the peat or muck area. Probably as valuable a local record as any is that of a tract near to Moore Haven. The soil is typical sawgrass peat or muck, originally from 10 to 11 feet deep and with an original surface elevation of 21.4. The tract has been under general cultivation since 1914, and the normal ground water table has been held below the surface since about the same date. The following tabulation presents a record of the progressive subsidence recorded since that time.

Year	Elevation of Surface	Subsidence
1912	21.4	0 Ft.
1917	19.6	1.8 Ft.
1921	18.0	3.4 Ft.
1927	16.8	4.6 Ft.

The above data indicates that the rate of subsidence decreases through a period of years, and that in fifteen years it has amounted to 4.6 feet or, in that particular tract, to approximately 45 per cent of the original depth of the soil.

We believe that a further general subsidence of three feet below the present ground surface for present depths of 6 feet or more of muck may be expected in any tract of the Everglades lands within a period of five to fifteen years following the construction of the arterial canals through the tract, and we recommend that the arterial canals be designed in anticipation of such subsidence. The rate of subsidence will depend upon the degree of drainage furnished the lands, the extent of occupancy and agricultural use, the control of the ground water table, and the control of fires. In areas where the present depth of muck is approximately 6 feet or less, the total subsidence will be proportionately less than the figure stated above.

LOCATION OF MAIN DRAINAGE CANALS.

The location of the various canals to be included in the system of arterial drainage is subject to many influences. As a means of furnishing available outlets permitting detail drainage of all lands, a parallel arrangement at intervals of six to eight miles would appear desirable, as being best suited to the development of unit or sub-district improvements of the most efficent size. The efficient use of the available fall from the Everglades lands to tide water outlet indicates the desirability of a system of canals running east and west rather than a continuation in future work of the southeast and northwest system already constructed. The nature of the materials to be encountered in alternate locations and the comparative costs of such excavation have great importance in the determination of the economical location of a canal system, and the data as to sub-surface conditions in the Everglades and the comparative hardness of rock in different sections of the area, all of which are set out in detail in the Biennial Report of the Chief Drainage Engineer of Everglades Drainage

District, dated January 1, 1927, indicate clearly the comparative advantage and economics which will result from an east and west canal system from those considerations.

The availability of outlets through the east coast ridge must also be considered in the location of such a canal system.

SUGGESTED SYSTEM OF MAIN DRAINAGE CANALS.

After consideration of the factors discussed above, and all other available data bearing on the subject, we have outlined a system of arterial or main drainage canals, the construction of which would in our opinion make possible complete and satisfactory drainage of the area of the Everglades which they serve. That system of canals is indicated, each with a designating letter for purpose of future reference, by Figure 2, which presents suggested locations for the several canals, for the control works of various types necessary to their operation, and for the Miami Canal Levee.

The last mentioned unit of the work will be a continuous levee extending along the west bank of the Miami Canal from a connection with the south and of the west spoil bank of Canal H to a connection with the south spoil bank of Canal P. The purpose of this levee is to keep the water from the southwestern Everglades from flowing east into the area served by the canals shown on Figure 2. The levee is to be built of material excavated from the Miami Canal along side to a section with side sloped 1-1/2 to 1; a 10 foot width of crown, and to a top elevation 5 feet above the present ground surface. If the excavation resulting from the minimum section required to pass the dredge is not sufficient to build the levee specified, the width of crown may be reduced to not less than six feet. Our estimates indicate that the construction of the levee will involve the excavation of 787,000 yards of rock and 49,000 yards of muck, at a total estimated cost of $525,000.00.

All of the canals of the system presented by Figure 2 provide the capacity and elevation of flow line previously discussed, excepting canals G and H, which discharge into Lake Okeechobee. In the design of those canals, the elevation of the flow line at the lake end is established at 17.0 as the anticipated high water stage in the lake, and a hydraulic slope of 0.132 feet per mile is allowed from the lake to the upper end of each canal.

It will be noted that the new canals, in many instances, intercept the canals which have already been constructed. Except where indicated on Figure 2, the proposed system does not contemplate the improvement of the existing canals beyond their present condition, as it appears that the required provision of drainage can be furnished more economically by the proposed east and west canals than by the further improvement of those already built.

The suggested basis of operation of the system proposed is presented hereafter.

OPERATION OF MAIN DRAINAGE CANAL SYSTEM

An arterial canal system located as indicated by Figure 2 and designed to the capacities provided in the preceding sections of this report will be available as a means of accomplishing the detail drainage of the entire area it serves.

Our studies have convinced us that such detail drainage will necessarily be supplied to the greater area of the Everglades by the process of pumping. Unit areas will be selected, surrounded by levees, and equipped with pumps as the means of transferring into the available arterial canals the excess of water which may develop within the tracts. Along the lower reaches of the arterial canals the flow lines at times of maximum discharge will, in many instances, be sufficiently below the ground surface to permit gravity drainage from tracts located along such sections of the canals. The area to which gravity drainage will be available will decrease as the anticipated subsidence of the muck lands develops. Areas to which gravity drainage will be permanently available will, however, be the exception and wet season drainage by pumping will be the rule.

Our plans contemplate the contruction of control dams at the discharge ends of the arterial canals where such works are indicated by Figure 2. Such dams, of the general type now in use in Everglades Drainage District, would permit the opening up of the full discharge capacity of the canals in wet periods, and would be closed to assist in maintaining the ground water table at a desirable minimum stage in dry seasons.

Such dams will not afford means for through navigation from tide water into the canals. We feel if such facilities for navigation are desired, the cost of the lock structures and other necessary works that would be required should be borne by the interests desiring them, and should not be considered as a part of or charged against the reclamation of the Everglades lands.

By reference to Figure 2, it will be noted that none of the canals suggested for the arterial system, excepting Canal D (the West Palm Beach Canal), is provided with a direct connection to Lake Okeechobee. It will also be noted that the through connections with the lake by means of the existing canals which the proposed canals intersect are broken by the provision of solid earth and rock dams across the existing canals at the points indicated on the Figure.

Such dams will destroy whatever degree of through navigation is now afforded by the existing canals, but there too we believe in the application of the principle that the cost of additional works necessary to provide or maintain navigation should be borne by the interest desiring navigation.

The system of arterial canals indicated by Figure 2 does not provide facilities for delivering Lake Okeechobee waters to the lands for irrigation in dry season excepting in the case of Canal D (The West Palm Beach Canal). If such facilities should be ultimately determined as desirable, we estimate that they can be provided by the construction of control gates through the earth dams and by the enlargement of the Miami, the North New River and the Hillsboro Canal to capacities sufficient to permit delivery of the required water to the arterial canals. Such works, we estimate, can be provided at a total cost of approximately one million dollars.

We are unable to convince ourselves that such provisions should be made until actual experience has indicated whether or not the results they will produce will justify their cost. The plan of lake control previously recommended in this report contemplates the lowering of the lake to elevation 15.0 as soon as practicable after the end of a rainy season, as necessary to insure against the development of dangerously high stages in the succeeding wet period. Under such conditions, normal evaporation may be expected to lower the lake to at least elevation 14.0 before the end of the dry period. Should it be determined that the needs of irrigation would justify drawing the lake down to elevation 13.0, one foot of lake storage would be released for use in irrigation. As the average area of the lake between elevation 13.0 and 14.0 is approximately 571 square miles, and the area served by the proposed system of arterial drainage is approximately 2,805 square miles, it is apparent that under a system of uniform distribution over all of the lands, which would be required when the area is generally developed, one foot of lake storage would provide only 2.4 inches of water over the area, even though no allowance is made for the losses by seepage and evaporation that will ensue during transportation from the lake before the water is actually distributed over the lands. We doubt that the value of that small amount of water would justify the cost of making it available. Control of the ground water table as to minimum elevations will, in our opinion, best be accomplished through the period now reasonably to be anticipated by proper operation of the control dams at the outlet ends of the arterial canals and by retaining upon all undeveloped lands as fully as practicable their wet weather accumulation of water. The latter provision would be accomplished by constructing and maintaining the spoil banks of the arterial canals as continuous levees, built to a top elevation not less than 5 feet above the theoretical flow line, and preventing the flow of water into the canals from all adjacent lands excepting those tracts subjected to actual development.

Such a provision will be of definite importance in preventing fires, in checking both subsidence of undeveloped lands and their growing up with objectionable vegetation, in the general maintenance of a satisfactory dry weather ground water table, and in the provision of a substantial increase in canal capacity for emergency use by raising the flow line above the theoretical grade and confining the flow between the spoil bank levees.

We recommend the adoption of such a policy as one of those to govern development in the Everglades Drainage District.

ESTIMATES OF COST

We are presenting, on the following page, a tabulation showing the quantities and costs of the works included in the arterial drainage system described above.

Item	Estimated Excavation Cu. Yds.	Estimated Unit Price	Estimated Cost
Canal B	4,825,000	.15	$ 723,750.00
Canal C	3,013,000	.15	451,950.00
Canal D	3,660,000	.15	549,000.00
Canal E	10,191,000	.18	1,834,380.00
Canal F	5,332,000	.20	1,066,400.00
Canal G	1,268,000	.50	634,000.00
Canal H	3,248,000	.50	1,624,000.00
Canal J	1,135,000	.20	227,000.00
Canal K	11,565,000	.35	4,047,750.00
Canal L	7,001,000	.35	2,450,000.00
Canal M	7,701,000	.35	2,695,350.00
Canal N	1,075,000	.25	268,750.00
Canal O	4,107,000	.40	1,642,800.00
Canal P	2,907,000	.40	1,162,800.00
Canal Q	4,267,000	.35	1,493,450.00
Canal R	4,350,000	(Being built by Dade Drainage District)	
Canal S	300,000	.30	90,000.00
Canal T	933,000	.25	233,250.00
Canal U	1,728,000	.25	432,000.00
Miami Canal Levee—			
Rock	787,000	.65	
Earth	49,000	.27½	525,000.00
Control works (Lump sum allowance).....			560,000.00
Totals	79,442,000		$22,711,630.00

The figures presented above indicate the estimated cost of the arterial drainage system to be $22,711,630.00. The unit prices employed include an allowance which, in our judgment, should be sufficient to provide for engineering and administrative costs to be reasonably expected on the work.

DEVELOPMENT OF FINAL DESIGN.

In the preceding paragraphs of the report, we have presented definite conclusions and have made definite recommendations as to the principles which should be observed in the design of the arterial main drainage canal system. Those recommendations cover such features as the provision of east and west canals at intervals of six to eight miles; the basis for the determination of the capacities to be provided in all canals; the further subsidence of muck soils to be expected, and the maximum elevation of flow lines to be provided in design. Subject to those and the other specific recommendations previously presented, the various canals included in the system of arterial drainage presented in this report should be redesigned before actual construction in the expectation that such redesign, made in the light of complete physical data, will indicate economies to be accomplished by adjustment of location, grades and dimensions.

It should be noted that the estimates, which we submit for the construction of the arterial drainage system, are based on incomplete data as to both surface and sub-surface conditions. Neither is definite information available at this time as to the exact points and conditions of the delivery of water into the arterial canals. That must be left to final determination as the several sub-drainage districts develop.

The allowances which we have made in our estimates, in view of the lack of such data, are further justification for the expectation that savings will be indicated by redesign based on complete physical information.

RESUME.

(a) We recommend the provision of a system of arterial drainage canals, running east and west, and spaced at intervals of six to eight miles, as necessary for the most economical provision of proper outlets for the development of the Everglades lands.

(b) Such outlet canals should, in all instances, provide the capacities indicated by the run-off diagrams appearing as Figure 19 of this report, whether such canals are built to ultimate dimension or to partial section.

(c) A further subsidence of three feet may be expected in from five to fifteen years after development in all muck lands now over six feet in depth, with proportionately less subsidence in lands of less than that depth. The flow lines of canals should, at all times, be designed to be not higher than the ground surface after such subsidence has developed, except in the instances specifically set out in the report.

(d) The typical detail drainage development of the muck lands of the Everglades will include pumping of excess waters.

(e) In the design of canals and control works, navigation should be regarded as incidental, and the works designed to provide only the requirements of reclamation. If added facilities are required for navigation, the expense of such additional works should be borne by the interests desiring navigation.

(f) The expense of making lake water generally available for irrigation of lands along the arterial canals does not appear to be justified under present conditions. Ground water control for the present should be accomplished as fully as possible by the operation of the control works at the lower ends of the arterial canals.

(g) The arterial canals should be built with spoil banks operating as continuous levees, to prevent the free draining off of wet weather accumulations of water from all excepting lands under actual development, and to make possible an increase in canal capacity for emergency use.

(h) A system of arterial drainage built to the requirements stated can be constructed at an estimated cost of $22,711,630.00. Detail design should be made in the light of complete physical data and subject to the basic requirements outlined, for the purpose of effecting all possible savings from the estimate of cost presented above.

(i) Such a system of arterial drainage is practicable and, by affording the necessary outlets, will make possible and practicable complete drainage of the Everglades lands served by the system.

PROGRESSIVE DRAINAGE.

The system of arterial drainage canals previously outlined may be readily adapted to a program of progressive development of the Everglades lands.

Wherever it is found practicable to concentrate development along the lower reaches of any particular canal, it will be necessary to construct only the portion of its total length required to serve the developed area, leaving the construction of the remainder of its length until such time as development of the areas it will serve makes its provision necessary.

Under the policy of maintaining spoil banks as continuous levees the ultimate dimensions and capacities of any canal will not be required until all of the lands finally to be served by it are brought into development. Under such conditions, as development of any particular tract is begun, it will be necessary to provide in the arterial canal serving that tract only the portion of its ultimate capacity required to accommodate the calculated flood discharge from the developed tract, plus a proper allowance for the additional water that will find its way into the canal by seepage from the lands through which it will pass even though the spoil banks are maintained through them as levees.

From time to time, as further development may require, the capacities may be increased; the amount of increase in each instance corresponding to that needed for additional outlet capacity as closely as economical machine movement and excavation will permit.

Such a program will permit the rate of construction work and the capital investment therein conforming as closely as possible to the progress of actual development and use of the land. It will frequently make possible the development of units of the total area to be ultimately served by any particular canal without the expenditure of the amount necessary to complete the canal to full dimension. The economic advantages of maintaining expenditures as nearly as possible on a par with actual land development are apparent, and the development of the proposed canal system by progressive stages will contribute to that end.

RESUME.

(a) A program of unit or progressive development is desirable, and the system of arterial canals previously outlined is adaptable to such a program.

GENERAL RESUME.

In the preceding pages, we have set out in detail our conclusions and recommendations covering a system of lake control and of main canals for the provision of arterial drainage to a large area of the Everglades lands, the construction of which we consider to be a practicable undertaking. We believe that the completion of those improvements, under the conditions previously outlined, will make available the engineering works and facilities necessary to the general successful agricultural development of that portion of the Everglades which the improvements will serve: i. e.: the territory lying north and east of the designating line on Figure 2.

The plans for improvements previously recommended in this report include alternate routes for the securing of additional outlet capacity from Lake Okeechobee, by the further enlargement of the St. Lucie Canal and by an improvement of the Caloosahatchee River respectively.

They also include alternate designs for the section of the levee recommended to be built around the southern portion of Lake Okeechobee, presented by Figures 3 and 4 respectively; the first being the minimum section recommended as adequate for the proper provision of protection against possible wind tides, and the second being a modification of the levee section recommended by the Chief Drainage Engineer of Everglades Drainage District in his Biennial Report of January 1, 1927.

The total estimated cost of the improvements recommended for the provision of lake control and of arterial drainage for the Everglades lands will depend upon the final selection made from the alternates mentioned.

Depending upon that selection, the total costs for the complete project appear as follows:

(a) For a complete system utilizing the Caloosahatchee River as the route for increased lake outlet, and employing the minimum levee section indicated by Figure 3, the total estimated cost is $25,288,070,00.

(b) If the Caloosahatchee route and the modified levee section are adopted, the total estimated cost is $25,581,-070.00

(c) If the increased outlet capacity is provided by an enlargement of the St. Lucie Canal, and the minimum levee section is adopted, the total estimated cost is $25,639,510.00.

(d) If the increased outlet capacity is provided by an enlargement of the St. Lucie Canal, and the modified levee section is adopted, the total estimated cost is $25,-932,510.00.

The carrying out of the improvements described will afford a varying degree of benefit to approximately 2,800,-000 acres of the Everglades Drainage District, of which approximately 2,000,000 acres will be provided with either arterial canal service or a favorable outlet into Lake Okeechobee.