SALT-WATER MOVEMENT IN THE LOWER WITHLACOOCHEE RIVER - CROSS-FLORIDA BARGE CANAL COMPLEX

U. S. GEOLOGICAL SURVEY

Water-Resources Investigations 5-72

Prepared in cooperation with

U. S. DEPARTMENT OF THE ARMY

CORPS OF ENGINEERS

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GEOLOGICAL SURVEY

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January 1973

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SALT-WATER MOVEMENT IN THE LOWER WITHLACOOCHEE RIVER - CROSS-FLORIDA BARGE CANAL COMPLEX

By
Peter W. Bush

CONCLUSIONS

Salt-water movement in the Lower Withlacoochee River - Cross-Florida Barge Canal Complex depends on fresh-water discharge and tidal flow. In the river below the bypass channel, salt water moves inland as a wedge beneath the fresh water with upstream tidal flows and back toward the Gulf with downstream tidal flows. The salt front (toe of the wedge) in the river tends to move farthest upstream near times of relatively high higher high water (HHW), or HHW preceded by relatively high higher low water (HLW), especially during or after several days of rising mean tide level (MTL).

Fresh-water discharge during the investigation ranged from 500 to 1,500 cfs (cubic feet per second). The only time that fresh-water discharge clearly showed an effect on upstream salt-water movement was the 4-day period when discharge was reduced to about 500 cfs. Tides seem to have a stronger influence on upstream movement of the salt front than discharge in the 500- to 1,500-cfs range. For instance, the estimated farthest upstream movement of the salt front during the investigation occurred when discharge was 1,320 cfs.

The point of maximum intrusion on this occasion was estimated to be 4.8 miles upstream from the river entrance. If salt water did, in fact, penetrate that far upstream, the event must be uncommon, as salt water was present on the bottom at station W4A, 3.3 miles from the river entrance, only 1.7 percent of the total time during the year of record.

Discharge from the Withlacoochee Backwater to the lower Withlacoochee River over the long term before the barge-canal complex was built was less than 1,600 cfs about half the time. In the future, all inflow to the Withlacoochee Backwater below about 1,600 cfs (the approximate capacity of the bypass channel with a high stage elevation in the backwater) will be discharged through the bypass channel. Thus, the future discharge regimen in the lower Withlacoochee River should be about the same as the discharge regimen that occurred approximately half the time before construction of the barge canal complex. Since seasonal high discharges to the lower river can no longer occur because of the small capacity of the bypass channel, the long-term average discharge before construction of the barge-canal complex, 1,899 cfs, cannot be maintained. The future long-term average discharge to the lower river through the bypass channel is estimated to be 1,430 cfs.

Because low flows (that is, discharges less than about 1,600 cfs) are essentially unchanged from the pre-bypass channel period, and tides are the controlling factor in determining the position of the salt front under low flow conditions, it is concluded that the farthest upstream position of the salt front for comparable low-flow-tide conditions has not changed since the opening of the bypass channel.

The future mean tide level in the lower river during periods of discharge less than about 1,600 cfs should be about the same as before the bypass channel was opened. Lower low water levels should be about 0.1 foot lower than they would have been during periods of comparable discharge and Gulf tides before the bypass channel was opened, and higher high water levels should increase 0.1 to 0.2 foot over pre-bypass channel higher high water levels during periods of comparable discharge and tides. The slight increase in the range of tidal elevations is probably the result of shortening the lower tidal-affected reach of the river.

Salt water in concentrations varying from near fresh water to near sea water was present on the bottom of the canal near the U.S. 19 bridge about 99 percent of the time during the investigation. Salt water in substantial concentrations occurred most of the time in the canal to Inglis Lock. No consistent relation was detectable between the generally cyclic pattern of salt-water concentration in the canal and tidal patterns. In general, the salinity of water in the canal decreases as the amount of water discharged increases. However, near the U.S. 19 bridge, a marked decrease in salinity of the bottom water occurs only when the flows become appreciably greater than 1,500 cfs; increasing the flow from an amount well below 1,500 cfs to about 1,500 cfs produces only a slight decrease in salinity.

Salt water moves upstream in the stretch of river between Inglis Dam and the canal with upstream tidal flows and back toward the canal with downstream tidal flows in a manner similar to salt-water movement in the river below the bypass channel. Upstream salt-water movement is more sensitive to discharge changes in the river below Inglis Dam than in other parts of the river-canal complex and decreases as the discharge increases.

The chance of salt water reaching the Withlacoochee Backwater is very low, as long as there is discharge in the bypass channel. The concentration of salt water locked to the upper pool area via Inglis Lock is rarely, if ever, above 1,000 mg/l (milligrams per liter); and the bypass channel effectively transports this locked-up salt water away from the upper pool area.

A theoretical analysis of sediment conditions in the river below the bypass channel indicates that a discharge on the order of 6,800 cfs would be needed to remove accumulated sediment from the rocks forming the banks of the river.

INTRODUCTION

The Lower Withlacoochee River - Cross-Florida Barge Canal Complex is the name given to the Withlacoochee River between Inglis Dam and the Gulf of Mexico, the west end of the Cross-Florida Barge Canal from the Withlacoochee Backwater to the Gulf, including Inglis Lock, and the Inglis Lock

Bypass Channel (fig. 1). Construction of the canal changed the regimen of the lower Withlacoochee River, giving rise to certain questions regarding the movement of water in the river-canal complex. In September 1970, the U. S. Geological Survey began an investigation to answer these questions.

Purpose and Scope

The intent of the investigation was to determine how salt water from the Gulf moves in the river-canal complex under the influence of various combinations of fresh-water discharge and ocean tide. Information about the extent of inland movement, concentration, frequency of occurrence, and residence times of salt water in the river and canal was sought, particularly during times of farthest upstream movement of the salt water. Emphasis was placed on learning how factors that affect upstream movement of the "salt front" (the point farthest upstream where specific conductance near the bottom of the river is higher than the undisturbed fresh-water specific conductance in the river) have changed since the opening of the bypass channel, on determining the combination of controlling factors that allows the farthest upstream movement of the salt front, and on locating the salt front under conditions favorable to upstream movement of the salt front.

The purpose of the investigation was also to document the extent to which salt water is conveyed to the upper pool area by operation of Inglis Lock under various salinity and tidal conditions in the canal below the lock and to evaluate the effectiveness of the bypass channel in removing this locked-up salt water from the upper pool area.

A data-collection and investigative program was begun in September 1970 to accomplish these objectives. Specific conductance and chloride data obtained from water samples collected monthly at various places in the river-canal complex provided knowledge of salinity under varying seasonal, tidal, and fresh-water-discharge conditions. Several conductance recorders at various places in the river and canal indicated salt-water concentration, frequency of occurrence, and duration with changing seasons, tides, and fresh-water discharge. When patterns of salt-water movement became better understood, the lock area and the part of the river where maximum upstream salt-water penetration was anticipated, were subjected to intensive conductance surveys.

An objective not related to salt-water movement was to determine the minimum discharge needed to remove sediment from near-shore rocks along the banks of the river. The minimum velocities required to initiate particle movement were determined from theoretical relationships. These velocities were then compared to measured velocities in a representative channel section and the results related to a minimum discharge needed to scour sediment.

Acknowledgments

This investigation was made by the U. S. Geological Survey in cooperation with the U. S. Department of the Army, Corps of Engineers. The cooperation of local landowners in permitting construction of hydrologic instru-

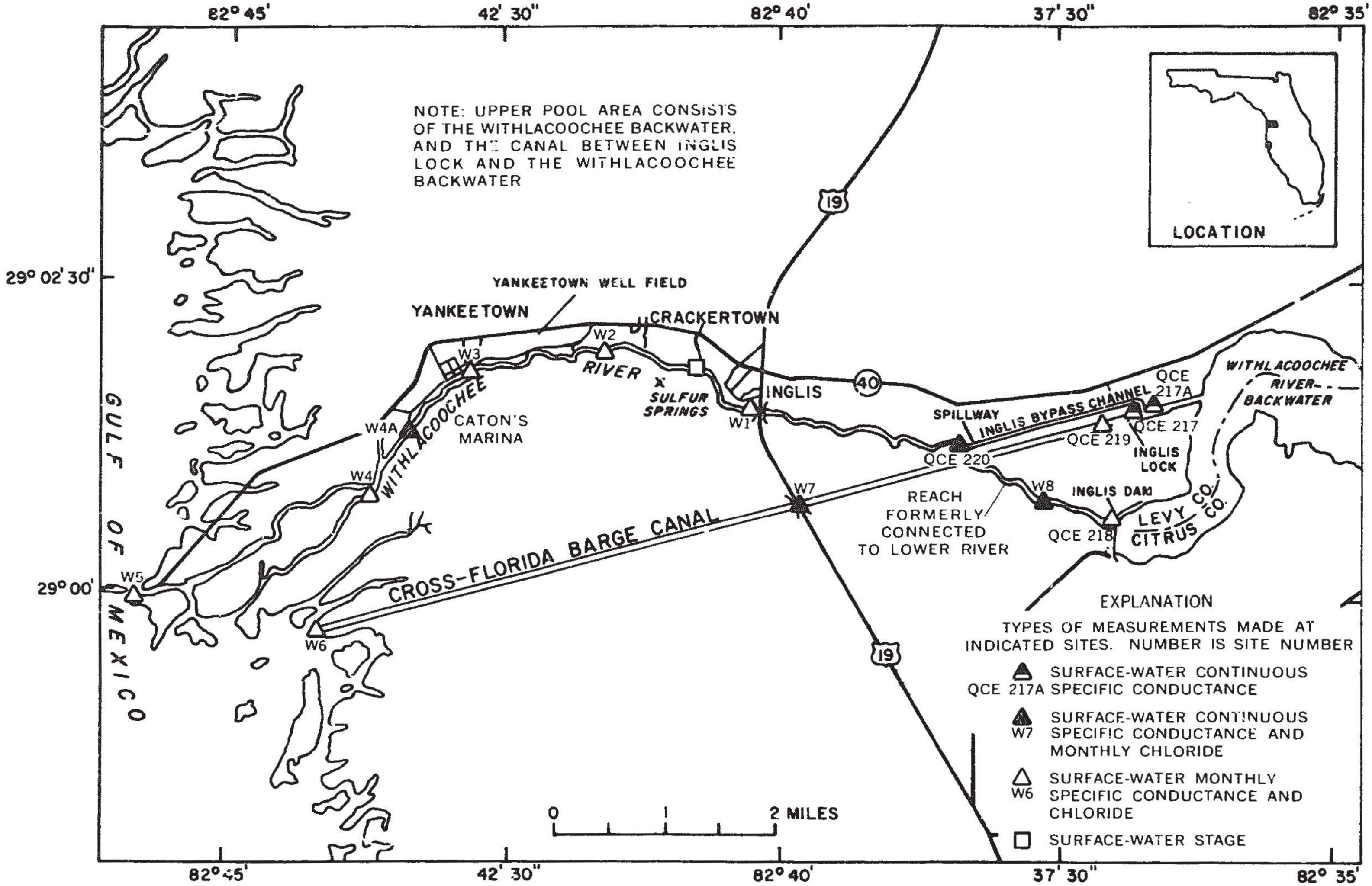


Figure 1. Map of lower Withlacoochee River-Cross-Florida Barge Canal

ment shelters is gratefully acknowledged. The investigation was made and the report prepared under the direct supervision of Joel Kimrey, Subdistrict Chief, Winter Park, and under the general supervision of C. S. Conover, District Chief, Tallahassee.

FACTORS AFFECTING SALT-WATER MOVEMENT BEFORE AND AFTER CANAL CONSTRUCTION

Figure 1 shows the present river-canal relationship, in which the Withlacoochee River between Inglis Dam and the Gulf is divided into two reaches by the canal. This configuation has existed since December 1969, when the Inglis Lock bypass channel was completed to provide fresh-water discharge in the river reach between the canal and the Gulf. Previously, the river was continuous between Inglis Dam and the Gulf. During construction of the canal and bypass channel, an earthen plug in the canal prevented diversion of the river flow to the Gulf through the canal. Before the bypass channel was opened, Inglis Dam was the only point of outflow from the Withlacoochee Backwater. Discharge through the dam before construction of the lock and bypass channel was regulated to maintain desirable stage levels in the Backwater.

Discharge

Within practicable limits, flow into the Withlacoochee Backwater from the Withlacoochee River drainage basin is equal to outflow (Rabon, 1966). Inflow and, therefore, outflow through the dam can be determined with fair accuracy by summing the discharges from Rainbow Springs (16 miles upstream from upper pool area) and the Withlacoochee River at Holder (22 miles upstream from upper pool area). The average discharge into the lower Withlacoochee River thus determined for 38 years, from October 1931 through September 1969, is 1,899 cfs, with a maximum monthly average of 7,937 cfs and a minimum monthly average of 645 cfs. Monthly average discharge for the period of record is cyclic in response to variations in rainfall in the basin; flows usually are highest in late summer and early fall and lowest in late spring and early summer.

The average discharge of the bypass channel from January 1970 through December 1971 was 1,215 cfs; the maximum monthly average was 1,435 cfs and the minimum monthly average, 795 cfs. Runoff from the drainage basin from January 1970 through December 1971, discharged from the backwater through both Inglis Dam and the bypass channel, averaged 1,870 cfs, differing little from the long-term average runoff from the basin of 1,899 cfs. This implies that hydrologic conditions in the basin during those 24 months were similar to the long-term hydrologic conditions in the basin. Thus, if future releases at Inglis Dam were to average about the same as they did during this 24-month period (655 cfs), the average discharge through the bypass channel during the period (1,215 cfs) is about what the long-term average would be. Since the bypass channel was opened, fresh-water discharge from Inglis Dam has been continuous, although at times minimal. However, in the future, the Corps of Engineers plan that all inflow to the Withlacoochee Backwater below about 1,600 cfs (the approximate capacity of the bypass channel with a high stage elevation in the backwater) will be discharged through the bypass channel. If this had been the policy during the 2-year period of record of bypass-channel discharge, the average would have been about 1,430 cfs, rather than the actual 1,215 cfs.

An analysis of the distribution of monthly mean inflows to the Withlacoochee Backwater from October 1931 through September 1969 indicates that monthly mean inflows were less than 1,600 cfs about 50 percent of the time. Thus, assuming the future policy regarding discharge from the Backwater to be as stated, flow in the lower Wighlacoochee River will, over the long term, be similar to flow that occurred about half the time before the canal complex was built. Since hydrologic conditions (that is, runoff from the Withlacoochee River basin) during the two-year period of record of bypass channel discharge were similar to long-term hydrologic conditions (runoff) in the basin, the long-term average discharge through the bypass channel is inferred to be about 1,430 cfs. The reduction in average discharge to the lower river results from the diversion of seasonal flood discharges into the barge canal at Inglis Dam that formerly passed through the lower river.

Tides

Tides in the river-canal complex are generally semidiurnal. On most days the two high tides are unequal, and the two low tides are unequal. The characteristic tidal cycle is a higher high water (HHW), followed by a lower low water (LLW), followed by a lower high water (LHW), followed by a higher low water (HLW), as shown in figure 2. Tides also vary monthly with the phases of the moon, and seasonally, being slightly higher on the average in summer and fall than in winter and spring.

Since May 1967, a water-stage recorder has been maintained in the river at Crackertown about 6.5 miles upstream from the Gulf. The record provides tidal data both before and after December 1969, when the bypass channel was opened and flow was diverted from Inglis Dam. Figure 3 shows the monthly mean HHW and LLW and the difference in the monthly mean HHW and LLW in the river at Crackertown. Freshwater discharge through Inglis Dam before December 1969 and through the bypass channel after December 1969 is also shown on figure 3.

The decrease in average discharge through the lower reach of the river after the opening of the bypass channel necessarily caused some lowering of the mean level of water in that reach. A comparison of water levels at Crackertown (fig. 3) indicates that the mean tide level (MTL) (average of monthly mean HHW and LLW) averaged 0.27 feet lower during the 24 months of record after the opening of the bypass channel than during the preceding 31 months. The lowering of the MTL resulted from a change in mean LLW, which averaged 0.58 foot lower during the 24 months after the opening of the bypass channel than during the preceding 31 months. Mean HHW averaged 0.05 foot higher since the bypass channel opened.

The lowering of the mean LLW was caused by the diversion of seasonal flood discharges into the barge canal. When comparable discharges occurred

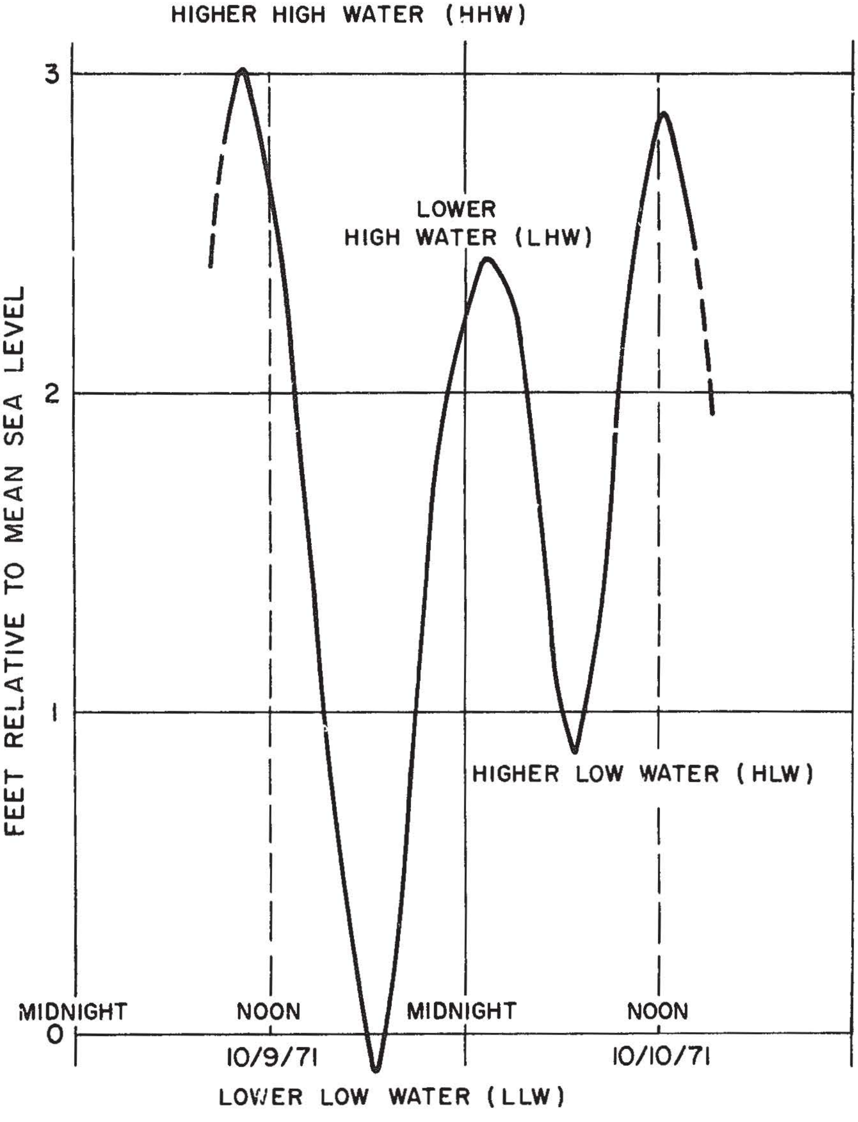


Figure 2. Representative tidal cycle in Lower Withlacoochee River at Crackertown.

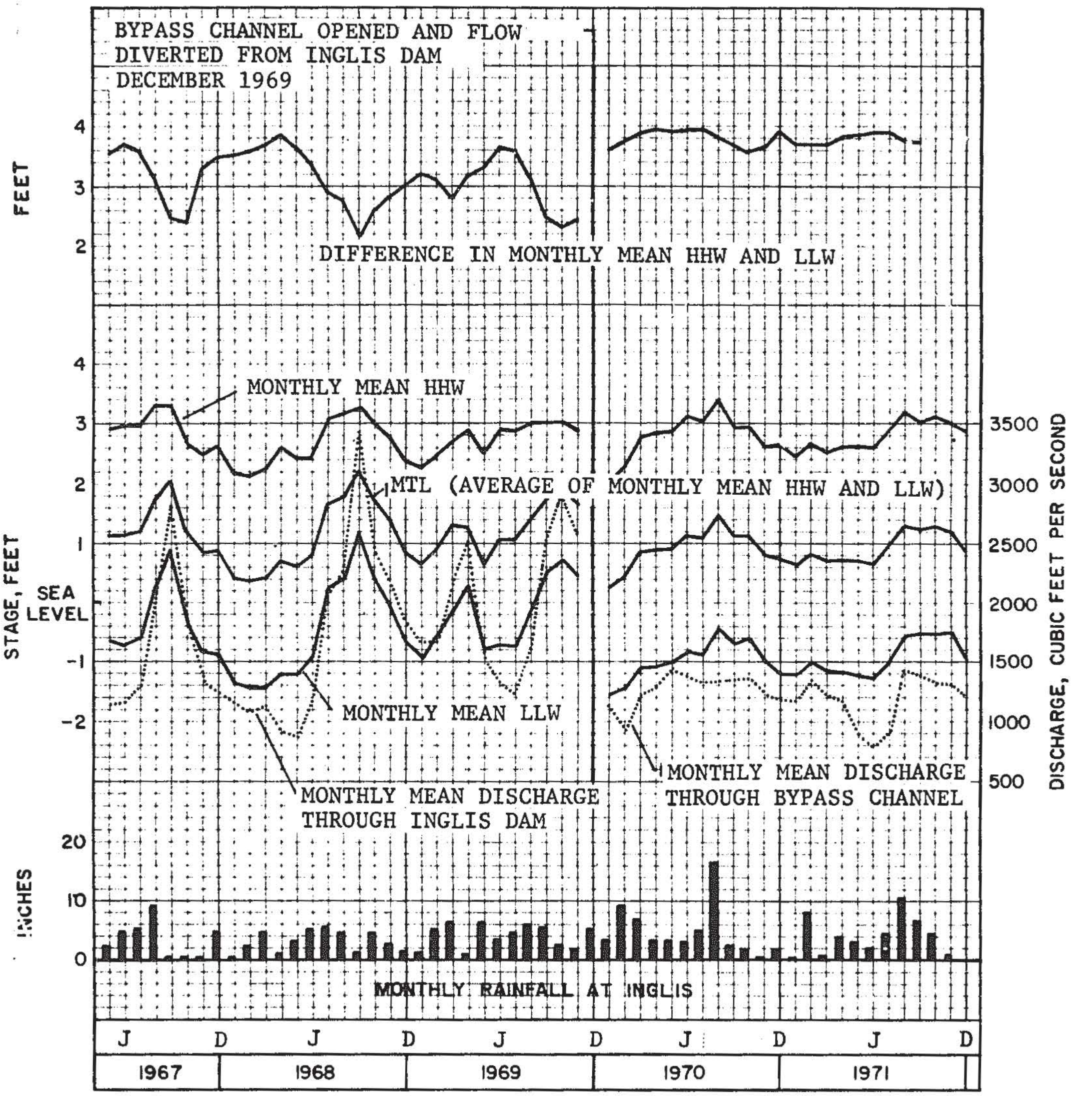


Figure 3. Graph of stage of the Withlacoochee River at Crackertown, discharge in the lower Withlacoochee River, and rainfall at Inglis, May 1967 - December 1971.

during the same months before and after the bypass channel was opened, mean tide levels in the lower reach of the river were about the same. For example, the mean discharge to the lower river in December 1967 was about the same as in December 1970, and the mean discharge in May 1968 nearly equaled the mean discharge of May 1971; mean discharges were similar in June 1969 and June 1970 and also in July 1967 and July 1970. For any given month, the tidal effect is assumed to be about the same each year.

As figure 3 shows, the MTL of the river at Crackertown was about the same for these months, respectively, as would be expected, but some slight differences in LLW and HHW are noted. For the same months before and after the opening of the bypass channel, when monthly mean discharges were comparable (differed by less than 5 percent), monthly mean LLW levels averaged 0.1 foot lower, and mean monthly HHW levels averaged nearly 0.2 foot higher after the bypass channel was opened. The apparent increase in the range of tides is probably the result of shortening the lower river by cutting off the 1.5 mile reach between the canal and Inglis Dam from the lowermost 9-mile reach below the bypass channel. Before the lower river was shortened, tidal effects extended upstream all the way to Inglis Dam. Shortening the tidal reach apparently causes more water to be stored in the reach below the bypass channel and slightly higher maximum stages during upstream tidal flows. Conversely, less water is stored in that reach during downstream tidal flows, resulting in slightly lower minimum stages.

The increase in HHW was partly compensated by the lowering of the HHW that resulted from the diversion of flood discharges into the barge canal. Consequently, the mean HHW for the periods of record before and after the opening of the bypass channel were about the same, at least within 0.2 foot.

Comparison of stages during the entire periods of record before and after the bypass channel was opened indicates the average frequency of LLW elevations more than 1 foot below mean sea level increased 75 percent after the bypass channel was opened. However, comparison of stages during the same months before and after opening of the bypass channel in which discharges were about equal shows an increase of 19 percent in the average frequency of LLW elevations more than 1 foot below mean sea level.

The average of the lowest LLW elevation of each month during the 24-month post-bypass channel period was 0.39 foot less than the average of the lowest LLW elevation of each month during the 31 months of record before the opening of the bypass channel; but comparison of the averages of the lowest LLW elevations of each month occurring on days of comparable discharge (disregarding tidal differences) before and after the opening of the bypass channel shows the average of the lowest LLW elevations to be only 0.11 foot lower than on days of comparable discharge before the bypass channel was opened.

The future MTL in the lower reach of the river must necessarily be lower, on the average, than the MTL prior to the opening of the bypass channel, because the prior long-term average discharge of 1,899 cfs to the lower river cannot be maintained in the bypass channel in its present configuration. However, the future discharge regimen in the lower river should be the same as the discharge regimen that occurred about half the time (flow less than 1,600 cfs) before the canal complex was built. Thus, the MTL should be about the same as during periods of flow less than about 1,600 cfs prior to the opening of the bypass channel. LLW levels should be about 0.1 foot lower than they would have been during periods of comparable discharge and tides before the bypass channel was opened, and HHW levels should increase 0.1 to 0.2 foot over pre-bypass channel HHW elevations during periods of comparable discharge and tides.

Other Factors

The rainfall record at Inglis (fig. 3) shows the influence of local (at Inglis) rainfall on river stage. Only the heavy rains of August 1970 and February 1971 seem to have affected river stage immediately.

Both the lower Withlacoochee River channel and the barge canal cut into the limestone of the Floridan Aquifer to depths below the water table. The canal is excavated to 13 feet below mean sea level from the Gulf all the way to Inglis Lock. The bottom elevation of the river slopes upward with distance upstream, from about 15 feet below mean sea level near the Gulf to about 6 feet below mean sea level below the bypass channel. The top of the Floridan Aquifer, which is the principal aquifer in the river-canal area, lies close to land surface, and in most places it is covered by a thin layer of sand. The elevation of the water table at the river and at the canal is assumed to be near the mean stage of these watercourses. Therefore, at low tide, the stages in the river and canal are lower than the water table, and ground water flows into both watercourses. At high tide, the stage of the river and canal are higher than the water table, and water from both channels flows into the ground. Because the gradient is generally toward the river and canal, there is some net movement of ground water to the river and canal. G. L. Faulkner (1972) shows that the total ground-water inflow to the river and canal is small and that the decrease in ground-water inflow to the river caused by the construction of the canal is about 7 cfs, or less than 0.5 percent of the mean annual discharge of the river.

PROGRAM TO MONITOR SALT-WATER MOVEMENT

Figure 1 shows the locations of 12 water-sampling stations, four of which supplied a continuous record of the specific conductance of the bottom water at different points in the river-canal complex. These stations provide most of the record that documents salt-water movement in the river-canal complex. From September 1970 to June 1971, water samples were collected each month near the surface, at mid-depth, and near the bottom of the canal or river at each of the stations and analyzed for specific conductance and chloride content. Specific conductance and chloride content of the first four sets of samples were determined by laboratory analysis. From these data, a relation between chloride content and specific conductance was established; thereafter, chloride content was determined from specific-conductance measurements.

Samples were collected under a variety of tidal and discharge conditions, with special emphasis on conditions favorable to upstream movement of the salt-front; as discharge into the river through the bypass channel and into the canal through Inglis Dam and Inglis Lock could not be predicted in advance, sampling days and times were selected on the basis of predicted tides at the Withlacoochee River entrance.

Additional information about movement of the salt-front in the river below the bypass channel was obtained by tracing the movement of the salt front with a portable conductance meter under various discharge and tidal conditions.

SALT-WATER MOVEMENT IN THE RIVER BELOW THE BYPASS CHANNEL

Nature of Movement

Salt-water movement in the river below the bypass channel is in phase with tidal movement. When the tidal flow is upstream, salt water from the Gulf moves upstream; when the tidal flow is downstream, salt water moves back toward the Gulf. The denser salt water moves inland as a wedge beneath the fresh water. The wedge becomes thinner and less saline with distance upstream from the river entrance, so that near the upper limit of movement of the salt front, the chloride content is only slightly above that of the fresh-water discharge. When salt water is moving upstream, the interface between the salt-water wedge and fresh water above it tends to be move distinct than when salt water is moving downstream.

The interrelations of factors influencing the distance that the salt front will move upstream with upstream tidal flows are so complex that the most inland point of salt-water intrusion cannot be predicted exactly for a particular tidal event. In general, when a series of tidal events occurs so that the total volume of upstream tidal flow exceeds the total volume of downstream tidal flow, the salt front will be farther upstream at the end of the series of tidal events than it was at the beginning of the series, if fresh-water discharge remains constant. In general, tidal flow increases as the ranges of tides increase and decreases as the ranges of tides decrease. Thus, during periods when the ranges between low tides and high tides exceed the ranges between high tides and low tides, an accumulation of upstream flow is likely. An increase in MTL is therefore an indication of a net upstream movement of the salt front, and conversely, a decrease in MTL is an indication of net downstream movement of the salt front.

The location of the salt front at the end of a given series of tidal events depends partly on the location of the front at the beginning of the series. A slight increase in MTL might result in a relatively high upstream movement of the salt front if the salt front was well upstream to begin with, whereas the effect of a larger increase in MTL might be less than in the first instance if the salt front were initially at a point farther downstream.

Wind and barometric changes strongly influence tides in the area. Comparison of the daily stage record at Crackertown to a plot of predicted tides showed that actual tides often differed considerably from corresponding predicted tides.

Analysis of tidal flows in relation to salt-water movement was beyond the scope of the investigation. Emphasis was placed instead on correlating tide levels and fresh-water discharge with the position of the salt front.

An observation made early in the investigation was that high upstream movement of the salt front tended to correlate with high HHW or when the HHW was preceded by relatively high HLW. High upstream movement of the salt front in the river below the bypass channel was documented by the conductance recorder at station W4A, Caton's Marina, 3.3 miles upstream from the river entrance. Figure 4 shows, by means of the conductance record from October 1970 to October 1971, the number of times that the salt front intruded at least as far upstream as station W4A. Also included on the figure are plots of daily HHW at Crackertown, the HLW which preceded each HHW, and the MTL. Most occurrences of salt water at station W4A were preceded by day-to-day rises in the MTL, indicating an accumulation of upstream tidal flow and, therefore, a probable net upstream movement of the salt front.

Test results suggest that significant reductions in discharge cause increased upstream movement of the salt front. Figure 4 shows the provisional daily discharge through the bypass channel during the investigation and also the frequency of occurrence and conductance of salt water at station W4A. The only time that the fresh-water-discharge rate clearly shows an effect on frequency of occurrence of salt water at station W4A is the period June 22-25, 1971, when discharge was purposely reduced to approximately 500 cfs so that tests could be made to determine salt-front locations under low-flow conditions.

Reducing the discharge to 700 cfs for 10 days in mid-May 1971 might have enhanced upstream salt-water movement. At station W4A salt water was present on three occasions during that period; however, figure 4 also shows that on these three occasions tidal conditions were optimum for high upstream movement and, therefore, may have been at least as important a factor as reduced discharge in causing salt water to move past station W4A.

Figure 4 also shows that varying the discharge in the 800-1,500 cfs range does not noticeably affect upstream intrusion of the salt front; but reducing discharge to the order of 500 cfs, as in June 1971, increases the frequency with which salt water appears at station W4A.

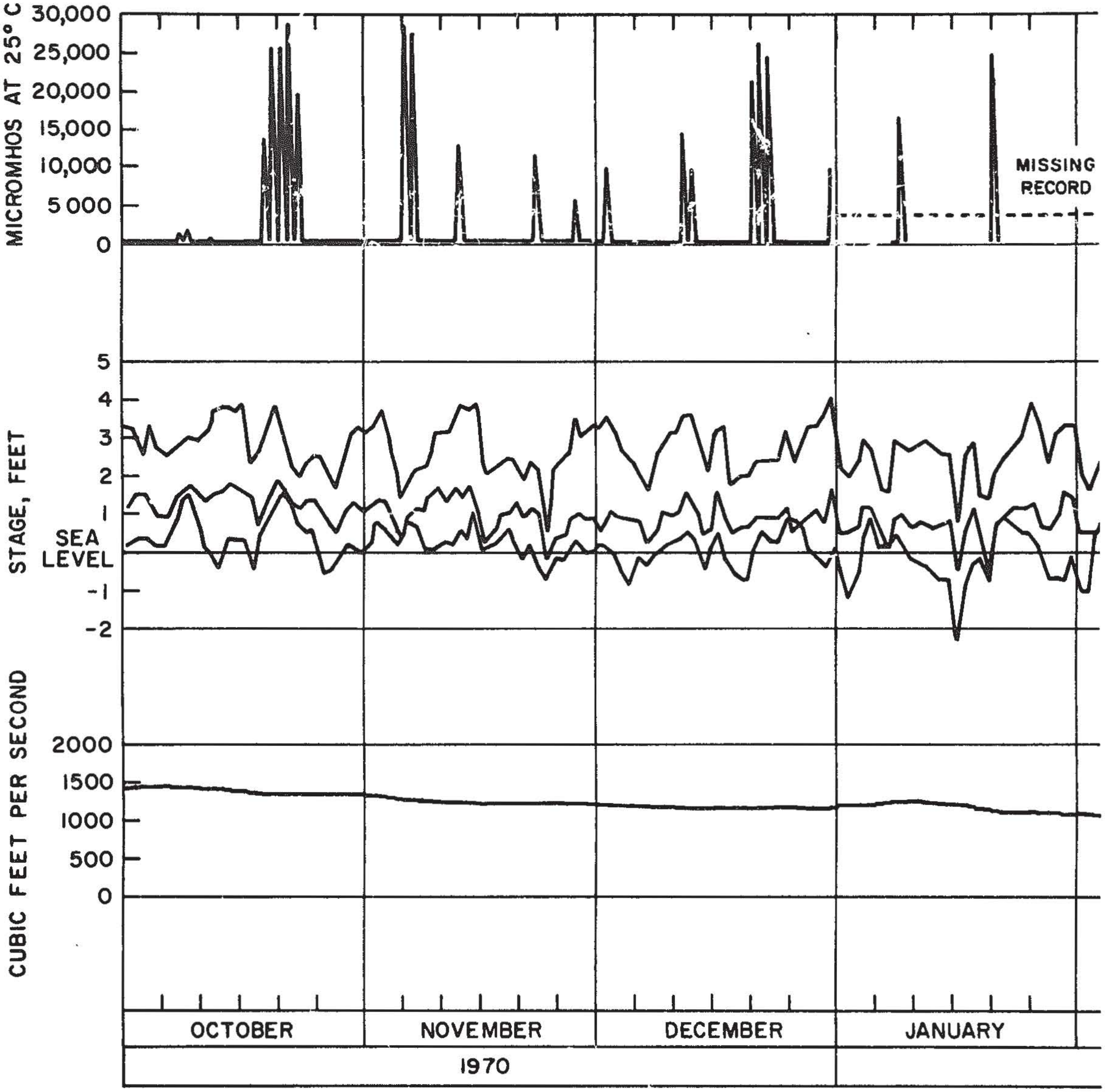
Extent of Movement

The inland extent of the salt front in the lower reach of the river after the opening of the bypass channel has probably changed little from pre-bypass channel periods of comparable discharge and Gulf tides. This conclusion is based on the premise, documented in this report, that a combination of low discharge and high tide most likely will produce a condition favorable for relatively great inland (upriver) incursion of the salt front. Because low flows--those less than about 1,600 cfs--are essentially unchanged from

FIGURE 4. GRAPH OF SPECIFIC CONDUCTANCE AT STATION W4A (CATON'S MARINA), STAGE AT CRACKERTOWN, AND BYPASS CHANNEL DISCHARGE, SEPTEMBER 1970-SEPTEMBER 1971.

13.1	13.2	13.3

Index showing page numbers of each component of figure 4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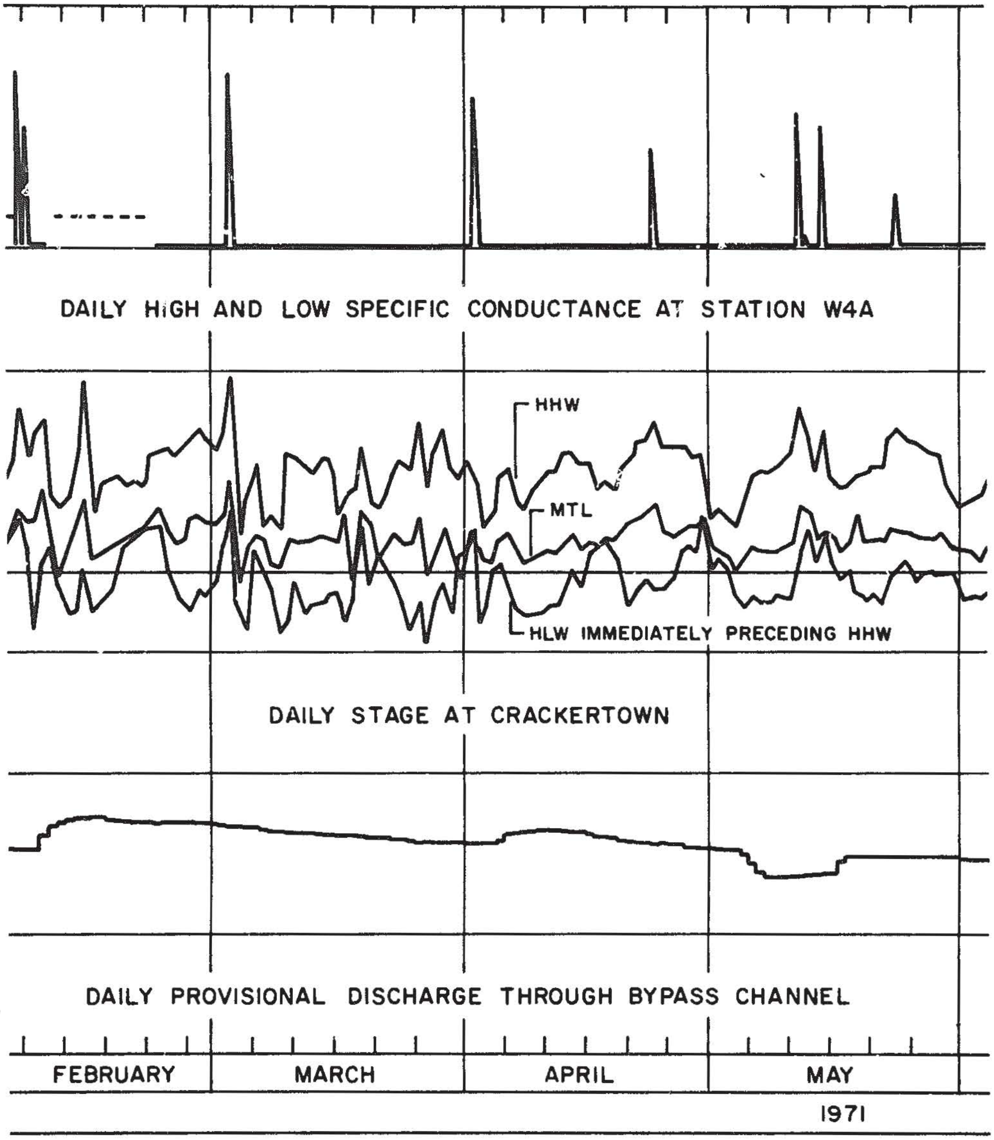
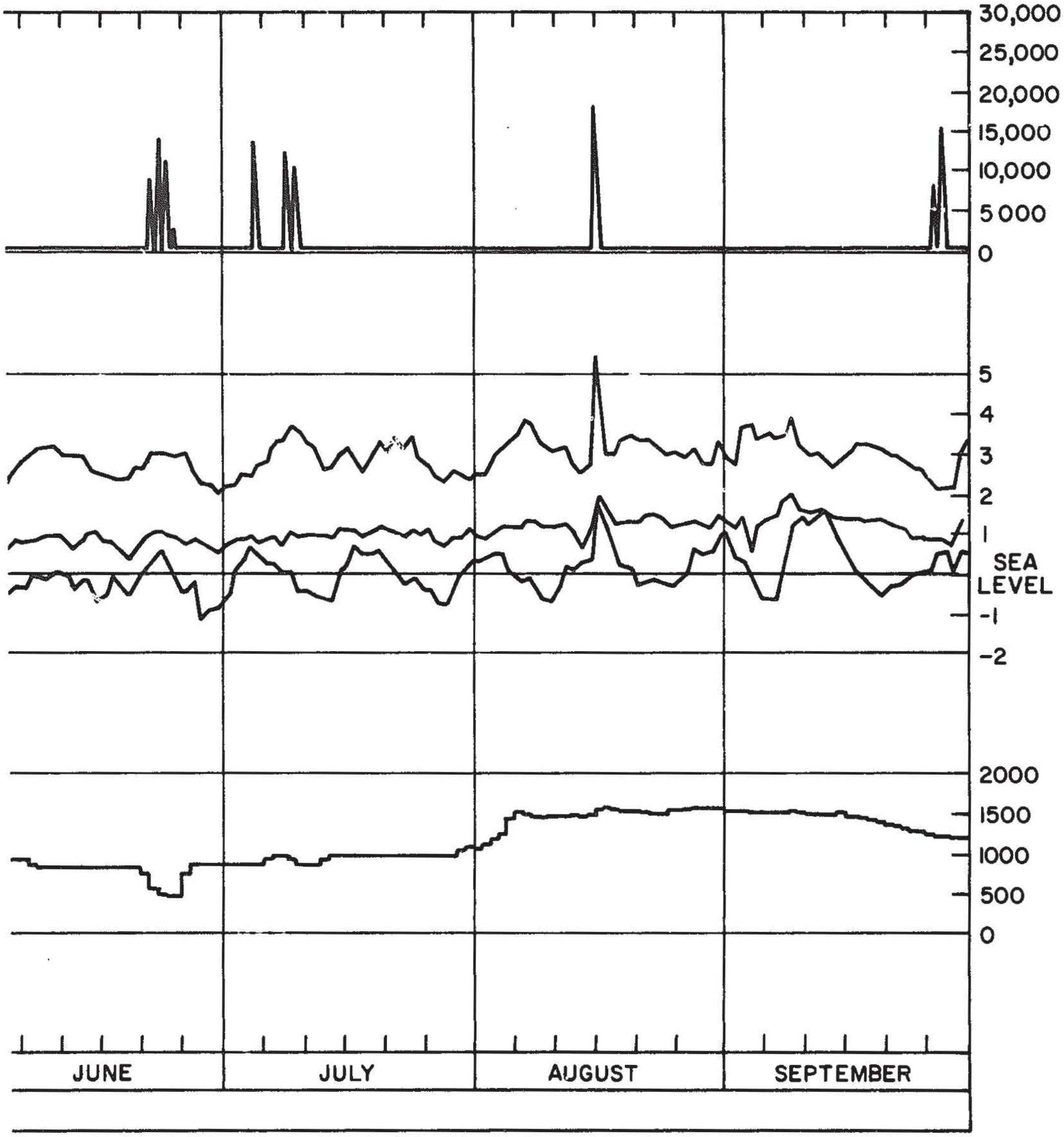

DAILY HIGH AND LOW SPECIFIC CONDUCTANCE AT STATION W4A
HHW
MTL
HLW IMMEDIATELY PRECEDING HHW
DAILY STAGE AT CRACKERTOWN
DAILY PROVISIONAL DISCHARGE THROUGH BYPASS CHANNEL
FEBRUARY
MARCH
APRIL
MAY
1971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AUGUST
SEPTEMBER

the time before the bypass channel came into existence, the effect of the bypass channel on the inland extent of the salt front, seemingly, is minimal. However, because of the bypass channel, the salt front is farther upstream more of the time--discharges less than about 1,600 cfs now occur all the time rather than about half the time, as before.

Samples of water were collected monthly from 12 stations (fig. 1) for analysis of conductance and chloride (table 1). Samples were collected near times of HHW, when predicted tidal conditions seemed favorable for high upstream movement of the salt front on 8 of the 10 sampling days. At the beginning of the investigation, when little was known about conditions conducive to high upstream salt-water movement, water samples were collected on those days when the predicted HHW was highest for each month. Later, the HLW and MTL were also considered in the selection of monthly sampling days. In December 1970, samples were collected near one of the lowest predicted tides. Samples in January 1971 were collected between a predicted LHW and a predicted HLW differing by only 0.1 foot, a time span representative of midrange tide level.

Table 1 shows that no salt water was detected at times of sampling upstream from station W4A. Only on June 25, 1971, was salt water present at the time of sampling at station W4A. On that day, bypass-channel discharge was about 500 cfs, having been lowered earlier that week for salt-front-location tests (fig. 4). At station W4, 2.6 miles upstream fron the river entrance, salt water was present 6 of the 8 times samples were collected under conditions favorable to high upstream movement. The samples collected December 30, 1970, at station W5, the river entrance, taken near the time of a very low LLW, contained less than 300 mg/l chloride; salt water can be flushed almost completely from the river channel if the tide falls low enough and fresh-water discharge is large enough to displace the salt water from the channel. Fresh-water discharge on December 30, 1970, was 1,160 cfs (fig. 4).

The month-to-month variation in fresh-water conductance at the river stations inland from the salt front probably reflects the variation in the ratio of ground-water inflow to surface-water flow. Although the ground-water contribution to discharge in the lower river is small, ground water in the river canal complex area commonly has a conductance 200 micromhos or more greater than the surface water (G. L. Faulkner, oral commun., 1971).

As previously mentioned, salt water moves as a wedge along the river bed, becoming thinner and less saline with distance upstream. Spot checks of the conductance at varying depths downstream from the salt front (that is, the toe of the wedge) confirmed the wedge shape. Near the point of maximum upstream movement of the salt front, conductances higher than fresh-water levels are likely to occur only in the bottom few feet of the channel. For example, on April 23, 1971, near the point of maximum upstream movement of the salt front, conductance measured 5,700 micromhos in the bottom 3 to 4 feet of water at a stream depth of 21 feet. Proceeding toward the surface in the overlying 17 feet of water, conductance dropped sharply at first, then steadily toward the surface, where the conductance of the water was 260 micromhos. On June 10, 1971, when the salt front was about 2,200 feet upstream from station W4 and moving inland, the conductance at station W4 was

Table 1.--Specific Conductance and Chloride Concentration from monthly water samples.

Station	W1				W2				W3			
Date	Sp Con mmho @ 25°C	Chlor mg/1	Depth ft	Temp °C	Sp Con mmho @ 25°C	Chlor mg/1	Depth ft	Temp °C	Sp Con mmho @ 25°C	Chlor mg/1	Depth ft	Temp °C
9-25-70												
surface	249	6.8	1	27.0	248	5.4	1	27.5	255	6.2	1	28.0
middle	251	7.2	18	27.0	251	6.4	8	27.5	252	6.2	10	28.0
bottom	252	7.2	35	27.0	252	6.8	15	27.5	253	8.8	19	26.0
10-15-70												
surface	253	6.6	1	26.5	254	6.8	1	27.0	257	6.4	1	27.0
middle	254	5.8	18	26.5	254	6.6	9	27.0	257	7.6	9	27.0
bottom	254	6.6	37	26.5	254	6.0	17	27.0	257	6.8	18	26.5
11-12-70												
surface	255	6.2	1	19.5	253	6.4	1	19.5	254	7.0	1	20.0
middle	255	6.4	18	19.5	253	6.6	8	19.5	253	7.0	9	19.5
bottom	255	6.6	36	19.5	252	7.2	16	19.5	253	7.0	18	19.5
12-30-70												
surface	262	6.4	1	15.5	261	7.0	1	15.5	261	6.6	1	15.5
middle	261	6.6	17	15.5	262	7.0	7	15.5	261	6.6	8	15.8
bottom	261	6.6	35	15.5	261	7.2	14	15.5	262	6.6	15	15.5
1-21-71												
surface	274	<20	1	13.5	277	<20	1	14.0	275	<20	1	14.5
middle	274	<20	16	13.5	274	<20	8	14.0	274	<20	8	14.5
bottom	275	<20	32	13.5	275	<20	15	14.0	276	<20	17	14.5
2-25-71												
surface	280	<20	1	19.5	281	<20	1	19.5	284	<20	1	19.5
middle	279	<20	18	19.5	280	7.6	8	19.5	284	<20	10	19.5
bottom	280	<20	37	19.5	282	<20	16	19.5	284	<20	19	19.5
3-18-71												
surface	252	<20	1	20.5	263	<20	1	20.5	263	<20	1	20.5
middle	262	<20	18	20.0	260	<20	7	20.5	261	<20	9	20.5
bottom	262	<20	35	20.0	260	<20	15	20.0	260	6.4	17	20.5
4-16-71												
surface	254	<20	1	23.0	251	<20	1	23.0	255	<20	1	23.5
middle	253	<20	17	23.0	251	<20	8	23.0	254	<20	10	23.5
bottom	250	<20	34	23.0	252	<20	16	23.0	255	<20	20	23.5
5-26-71												
surface	181	<20	1	27.0	180	<20	1	27.0	176	<20	1	27.5
middle	181	<20	18	27.0	180	<20	9	27.0	178	<20	10	27.0
bottom	180	<20	35	27.0	185	<20	17	27.0	178	<20	20	27.0
6-25-71												
surface	202	<20	1	29.0	210	<20	1	32.5	205	<20	1	30.5
middle	204	<20	17	29.0	214	<20	8	30.0	205	<20	8	29.5
bottom	210	<20	33	28.5	220	<20	16	29.5	205	<20	16	29.5

Notes: 1) Underlined chlorides determined by lab analysis; others determined from chloride vs. specific conductance curve.
2) Symbol "<" read as "less than".

Table 1.--(continued)

Station / Date	QCE 218				QCE 219				QCE 220			
	Sp Con mmho @ 25°C	Chlor mg/1	Depth ft	Temp °C	Sp Con mmho @ 25°C	Chlor mg/1	Depth ft	Temp °C	Sp Con mmho @ 25°C	Chlor mg/1	Depth ft	Temp °C
9-25-70												
surface	229	5.2	1	28.0	36300	12790	1	28.5	249	5.8	1	27.0
middle	230	5.4	4	28.0	37700	13500	8	29.0	251	5.8	4	27.0
bottom	229	5.0	7	28.0	39900	14310	15	29.0	255	5.0	7	27.0
10-15-70												
surface	220	7.4	1	27.0	12900	4000	1	28.0	254	7.0	1	27.0
middle	225	5.0	6	27.0	29500	10180	9	26.0	254	6.4	4	26.5
bottom	232	7.8	12	27.0	31500	10980	17	26.0	258	6.8	8	26.5
11-12-70												
surface	221	6.4	1	20.0	4330	1210	1	19.0	255	7.6	1	20.0
middle	218	6.4	6	20.0	22600	7590	9	19.0	255	7.0	5	19.5
bottom	219	6.4	11	20.0	30100	10400	17	19.0	258	7.8	9	19.5
12-30-70												
surface	238	6.2	1	15.5	18500	6000	1	18.0	261	5.6	1	15.5
middle	238	6.2	2	15.5	20000	6580	5	18.5	261	5.6	4	15.5
bottom	239	6.0	4	15.0	21700	7200	10	18.5	261	5.4	7	15.5
1-21-71												
surface	250	20	1	14.0	19100	6300	1	12.5	275	<20	1	13.5
middle	252	20	3	14.0	21700	7200	8	16.5	275	<20	5	13.5
bottom	251	20	6	14.0	26200	8980	16	17.0	274	<20	9	14.0
2-25-71												
surface	275	20	1	18.5	3200	900	1	17.0	279	<20	1	19.5
middle	275	7.2	4	18.5	11200	3500	8	17.0	280	<20	4	19.5
bottom	276	20	8	18.5	19800	6520	16	17.0	280	<20	9	19.5
3-18-71												
surface	256	<20	1	20.0	3000	840	1	21.0	260	<20	1	20.5
middle	256	<20	5	19.5	9300	2850	8	19.0	260	<20	5	20.0
bottom	256	<20	10	19.5	12700	4000	16	18.5	260	<20	9	20.0
4-16-71												
surface	200	<20	1	22.5	2040	520	1	22.5	261	<20	1	23.5
middle	203	<20	5	22.5	3480	950	8	21.0	255	<20	5	23.5
bottom	211	<20	11	22.5	11000	3410	17	21.0	257	<20	10	23.5
5-26-71												
surface	202	<20	1	27.0	8100	2450	1	29.5	183	<20	1	27.0
middle	200	<20	4	26.5	8700	2650	5	28.5	184	<20	3	27.0
bottom	201	<20	8	27.0	10500	3250	10	28.0	184	<20	6	27.0
6-25-71												
surface	240	<20	1	30.0	1180	295	1	29.0	202	<20	1	29.0
middle	238	<20	5	28.0	3280	920	8	28.5	203	<20	4	29.0
bottom	240	<20	10	28.0	12400	3900	17	27.5	203	<20	8	28.5

Notes: 1) Underlined chlorides determined by lab analysis; others determined from chloride vs. specific conductance curve.
2) Symbol "<" read as "less than".

Table 1.--(continued)

Station	W4A				W4				W5			
Date	Sp Con mmho @ 25°C	Chlor mg/1	Depth ft	Temp °C	Sp Con mmho @ 25°C	Chlor mg/1	Depth ft	Temp °C	Sp Con mmho @ 25°C	Chlor mg/1	Depth ft	Temp °C
9-25-70												
surface	252	5.8	1	28.0	345	33	1	28.0	22300	7350	1	28.5
middle	252	6.0	19	28.0	1360	328	8	28.0	40100	14400	7	28.5
bottom	257	6.4	10	28.0	29200	10030	15	28.0	41200	15010	13	28.5
10-15-70												
surface	263	7.6	1	27.0	367	38	1	27.0	29700	10290	1	28.0
middle	263	5.8	11	26.5	7680	2270	8	27.0	32400	11480	8	28.0
bottom	265	7.2	21	27.0	14300	4590	15	27.0	34400	12060	15	28.0
11-12-70												
surface	257	7.4	1	20.0	284	14	1	20.0	27500	9400	1	20.0
middle	254	7.2	12	20.0	3350	894	8	19.5	30600	10500	7	20.0
bottom	254	7.0	24	20.0	10400	3150	16	19.5	32600	11300	14	19.5
12-30-70												
surface	264	6.8	1	15.5	277	12	1	15.5	1150	258	1	15.0
middle	264	7.0	8	15.5	277	12	6	15.5	1150	260	5	15.0
bottom	264	6.8	16	15.5	283	11	12	15.5	1160	260	10	15.0
1-21-71												
surface	275	<20	1	14.5	289	<20	1	14.5	4030	1150	1	14.0
middle	277	<20	7	14.5	286	<20	7	14.0	33100	11700	7	10.0
bottom	275	<20	15	14.5	298	<25	14	14.0	35600	12700	13	10.0
2-25-71												
surface	285	<20	1	19.5	298	<25	1	19.5	22000	7260	1	17.5
middle	286	<20	10	19.5	294	<25	8	19.5	22100	7360	6	17.5
bottom	286	<20	20	19.5	312	<25	15	19.5	24100	8150	12	17.5
3-18-71												
surface	262	<20	1	21.0	268	<20	1	21.0	11800	3690	1	20.5
middle	262	<20	9	21.0	268	<20	8	20.5	22000	7250	7	19.0
bottom	262	<20	17	21.0	270	<20	15	20.5	23100	7750	14	18.5
4-16-71												
surface	254	<20	1	24.0	271	<20	1	24.0	23200	7780	1	24.5
middle	254	<20	10	23.5	2700	775	8	22.5	25700	8710	7	24.0
bottom	260	<20	19	23.5	19700	6500	17	22.0	30500	10600	14	23.0
5-26-71												
surface	187	<20	1	27.0	493	62	1	27.0	24000	8100	1	27.5
middle	185	<20	9	27.0	8550	2600	8	27.0	25800	8770	8	27.5
bottom	187	<20	18	27.0	17000	5500	16	27.0	26700	9080	15	27.0
6-25-71												
surface	286	<20	1	29.5	2810	740	1	30.0	27500	9400	1	29.5
middle	304	<25	10	29.5	10500	3250	8	29.5	29100	10340	7	29.0
bottom	3900	1100	20	29.0	17100	5550	16	29.5	31800	10480	15	29.0

Notes: 1) Underlined chlorides determined by lab analysis; others determined from chloride vs. specific conductance curve.
2) Symbol "<" read as "less than".

Table 1.--(continued)

Station	W6				W7				W8			
Date	Sp Con mmho @ 25°C	Chlor mg/l	Depth ft	Temp °C	Sp Con mmho @ 25°C	Chlor mg/l	Depth ft	Temp °C	Sp Con mmho @ 25°C	Chlor mg/l	Depth ft	Temp °C
9-25-70												
surface	28900	10130	1	28.0	10800	3700	1	28.0	289	24	1	28.0
middle	43900	16010	8	29.0	38800	14000	8	29.0	860	225	4	28.0
bottom	44100	16250	15	29.0	42500	15590	16	29.0	1830	465	7	28.0
10-15-70												
surface	31300	10900	1	28.0	8200	2425	1	27.5	226	6.6	1	27.0
middle	37200	13200	9	27.0	31700	11040	10	27.0	227	7.6	4	27.0
bottom	37800	13520	17	27.0	34300	12060	20	27.0	233	7.4	9	27.0
11-12-70												
surface	26500	9100	1	20.0	4440	1240	1	20.0	224	6.4	1	20.0
middle	32600	11500	8	19.5	22200	7410	9	19.0	229	6.2	5	20.0
bottom	33000	11700	17	19.0	34500	12230	17	18.0	227	7.0	9	20.0
12-30-70												
surface	15200	4950	1	15.0	8980	2700	1	16.0	253	6.8	1	15.5
middle	19300	6300	6	14.5	17200	5540	5	16.5	245	6.6	3	15.5
bottom	23400	7850	12	15.0	24500	8300	10	16.5	248	6.6	5	15.5
1-21-71												
surface	5790	1670	1	13.5	8450	2570	1	13.0	252	<20	1	14.0
middle	37200	13300	7	11.5	22900	7700	7	15.0	253	<20	4	14.0
bottom	38000	13550	14	11.0	30000	10500	14	15.0	254	<20	7	14.5
2-25-71												
surface	9440	2900	1	17.5	5540	1660	1	18.0	275	<20	1	18.5
middle	24100	8150	8	17.5	15000	4820	8	18.0	275	<20	4	18.5
bottom	25400	8650	15	17.5	19300	6350	16	16.5	280	<20	8	18.5
3-18-71												
surface	5600	1650	1	20.5	1290	300	1	20.0	260	<20	1	20.0
middle	26000	8820	8	18.0	3720	1040	8	19.5	260	<20	4	20.0
bottom	28800	9910	15	17.5	17200	5600	16	18.5	261	<20	8	20.0
4-16-71												
surface	19800	6520	1	24.0	3500	980	1	23.0	223	<20	1	22.5
middle	29500	10200	8	22.0	14300	4500	8	23.0	208	<20	5	22.5
bottom	32000	11200	16	21.5	26500	9100	17	21.5	208	<20	11	22.5
5-26-71												
surface	25000	8480	1	27.5	9150	2800	1	27.5	270	<20	1	28.0
middle	30000	10380	8	26.5	9000	2730	7	27.0	9800	3000	5	27.0
bottom	30500	10400	16	26.0	21000	6980	15	26.0	13050	4100	10	27.0
6-25-71												
surface	7600	2290	1	30.5	1230	310	1	29.0	222	<20	1	29.5
middle	30100	10380	8	28.0	11500	3600	8	28.5	223	<20	5	29.5
bottom	31000	10450	17	28.0	22700	7600	17	28.0	225	<20	9	28.5

Notes: 1) Underlined chlorides determined by lab analysis; others determined from chloride vs. specific conductance curve.
2) Symbol "<" read as "less than".

15,200 micromhos at the bottom, 3,820 at mid-depth, and 930 at the surface. The conductance of the water at the salt front was 1,450 micromhos.

In April 1971, a series of tests was started to locate the point of farthest upstream movement of the salt front under conditions most favorable to inland movement. For comparison, tests were also run when the salt front was not expected to reach its limit of inland penetration. Figure 5 shows the location of farthest upstream movement of the salt front on the days of tests and also the lag time between the predicted time of high tide at the river entrance and the time when the salt front was the farthest upstream. The rate of fresh-water discharge and tide elevation during each test are shown in Figure 4.

In April 1971, tidal conditions seemed to be optimum for high upstream salt-water movement (at least to station W4A) on the 1st and 23rd. The predicted HLW preceding the HHW on April 1 was relatively high. On the 23rd, the predicted HHW was among the highest for the month, and the MTL had been rising. However, on neither day did the salt front reach station W4A; the salt front reached station W4A on April 2 and April 24.

The next series of salt-front-location tests was made on June 9, 10, and 11, 1971. Predicted tidal conditions again seemed favorable for upstream movement. Discharge was about 300 cfs less than when the tests were run in April; but maximum salt-front penetration on all 3 days was about the same as in April, downstream from station W4A.

The third series of tests was made on June 17 and 18, 1971, chosen for tests because predicted HLW and HHW on those days were not particularly high. As expected, on neither day was the salt front carried as far inland as station W4A.

Bypass-channel discharge was reduced to approximately 500 cfs on June 22-25, 1971, so that salt-front-location tests under low-flow conditions could be made. Both HLW and HHW were predicted to be relatively high during the period, and the MTL had been rising. On June 21, before discharge was reduced, the point of maximum upstream movement of the salt front was 2.8 miles upstream from the river entrance. Because predicted tides on that day were similar to those predicted later in the week, the position of the salt-front on June 21 provided a basis for isolating the effect of a sizeable discharge reduction on movement of the salt front. As the Crackertown record shows, however (fig. 4), actual tidal conditions were more conducive to upstream movement of the salt front on June 22-25 than on the 21st. With the aid of the slightly higher tides, reducing the discharge to 500 cfs allowed the salt front to move 0.8 to 1.2 miles farther upstream on June 22-24 than on June 21. During the 4-day low-flow period, the farthest upstream penetration of the salt front occurred on June 23, the same day that marked the highest HLW of that period. The recorder at station W4A also registered the presence of salt water at LHW levels during that 4-day period, although conductance recorded at LHW was considerably less than that recorded at HHW.

Although tide and discharge conditions on June 22-24 seemed ideal for maximum salt-water intrusion, the conductance record from station W4A (fig. 4) indicates that salt water does, on occasion, move farther upstream than the maximum upstream location attained on June 23, 1971. This is indicated in the following way: On June 22, 23, and 24, the 3 test days when the salt front moved upstream from station W4A, the bottom conductance recorded at station W4A was greatest on June 23, the day that salt water made its greatest upstream penetration of the test period. On June 24, when upstream penetration of the salt front was less, bottom conductance at station W4A was less than on June 23. Similarly, on June 22, when upstream penetration was the least of the 3-day period, bottom conductance at station W4A was least. This suggests a possible relationship between conductance measured near the bottom at a reference point downstream from the salt front and the distance upstream from the reference point that the salt front moves. If such a relationship exists, when the conductance of bottom water at station W4A is greater than on June 22-25, the salt front is farther upstream also. On figure 6, this hypothetical relationship is portrayed graphically. It provides the means to estimate the possible farthest upstream distance that salt water moved in the river during the investigation. Conductances of bottom water at a reference point are scaled on the ordinate of figure 6. The abscissa of figure 6 is the ratio of the distance of the salt front from the river entrance to the distance of the reference point from the river entrance. A straight line has been fitted through the six data points. For the 3 test days, when the salt front moved upstream from station W4A, station W4A is the reference point. For 3 more test days, when salt water did not reach station W4A, station W4 is the reference point. There was no recorder at station W4, but conductance was measured at that station near the time of farthest upstream movement of the salt front on the 3 test days. From figure 4, the highest conductance recorded at station W4A during the investigation was 29,000 micromhos on October 22, 1971. On figure 6, the salt front-reference point ratio corresponding to 29,000 micromhos is 1.45; that is, the farthest point upstream to which the salt front moved during the investigation is estimated to be 1.45 times the distance from the river entrance to station W4A. This point of maximum intrusion is 4.8 miles from the river entrance, as shown in figure 5.

As previously mentioned, near the upper limit of movement of the salt front, the chloride content is only slightly above that of the fresh-water discharge. The upper limit for chloride in potable water as defined by the U. S. Public Health Service is 250 milligrams per liter (Hem, 1959). Thus, if the point of farthest upstream movement of the salt front during the investigation was 4.8 miles, the point farthest upstream where the quality of water was less than that of potable water due to chloride content was slightly less than 4.8 miles. The 250 milligram per liter point is estimated to be 4.7 miles upstream if the salt front is 4.8 miles upstream.

The fact that the farthest upstream movement of the salt front during the investigation apparently did not occur during the period when discharge was about 500 cfs, but instead, when the discharge was about 1,320 cfs, is significant. This indicates that tides have a stronger influence on the upstream movement of the salt front than fresh-water discharge in the 500-1,500 cfs range.

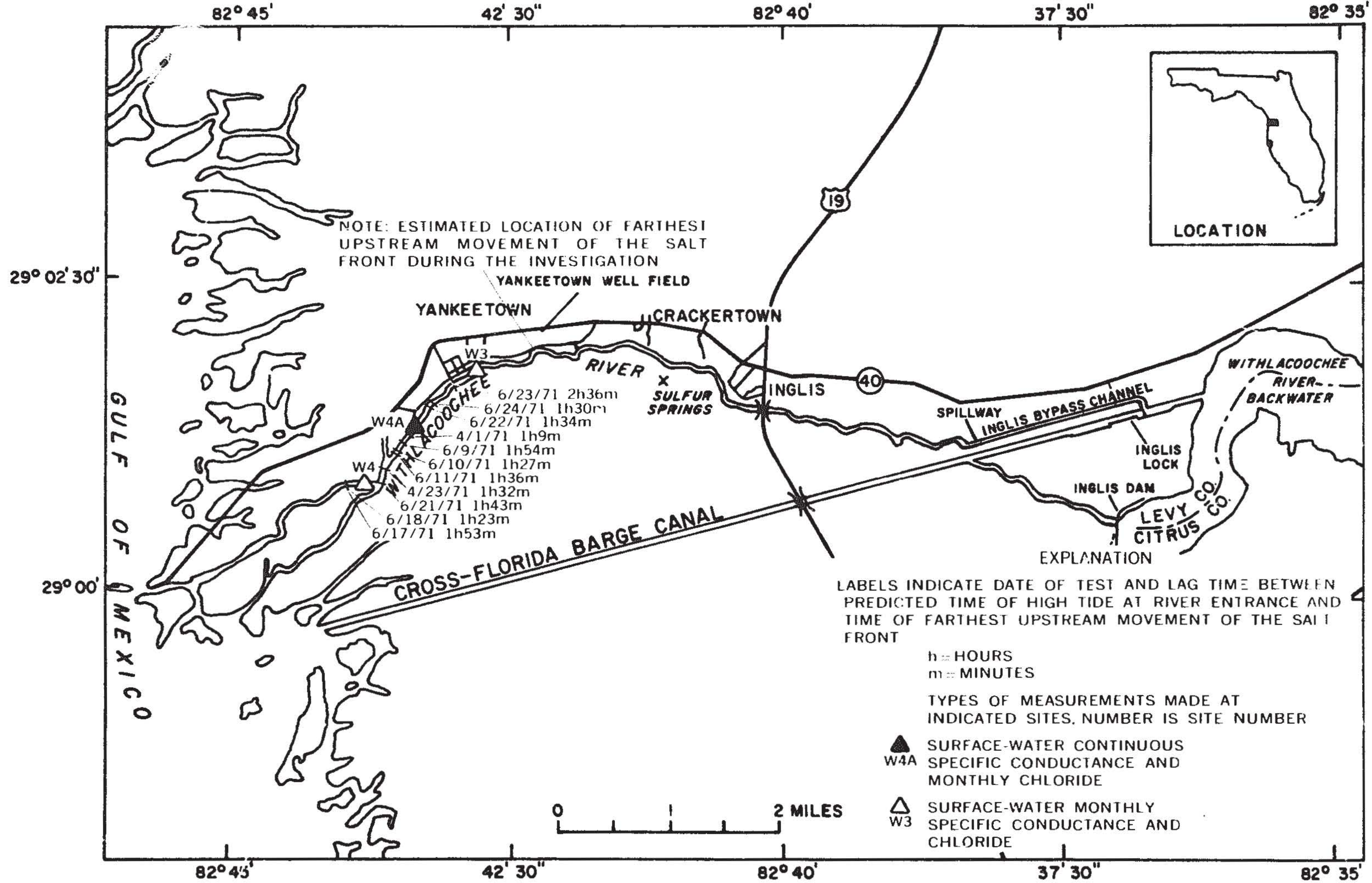


Figure 5. Map showing farthest movement of the salt front on days of tests; Lower Withlacoochee River.

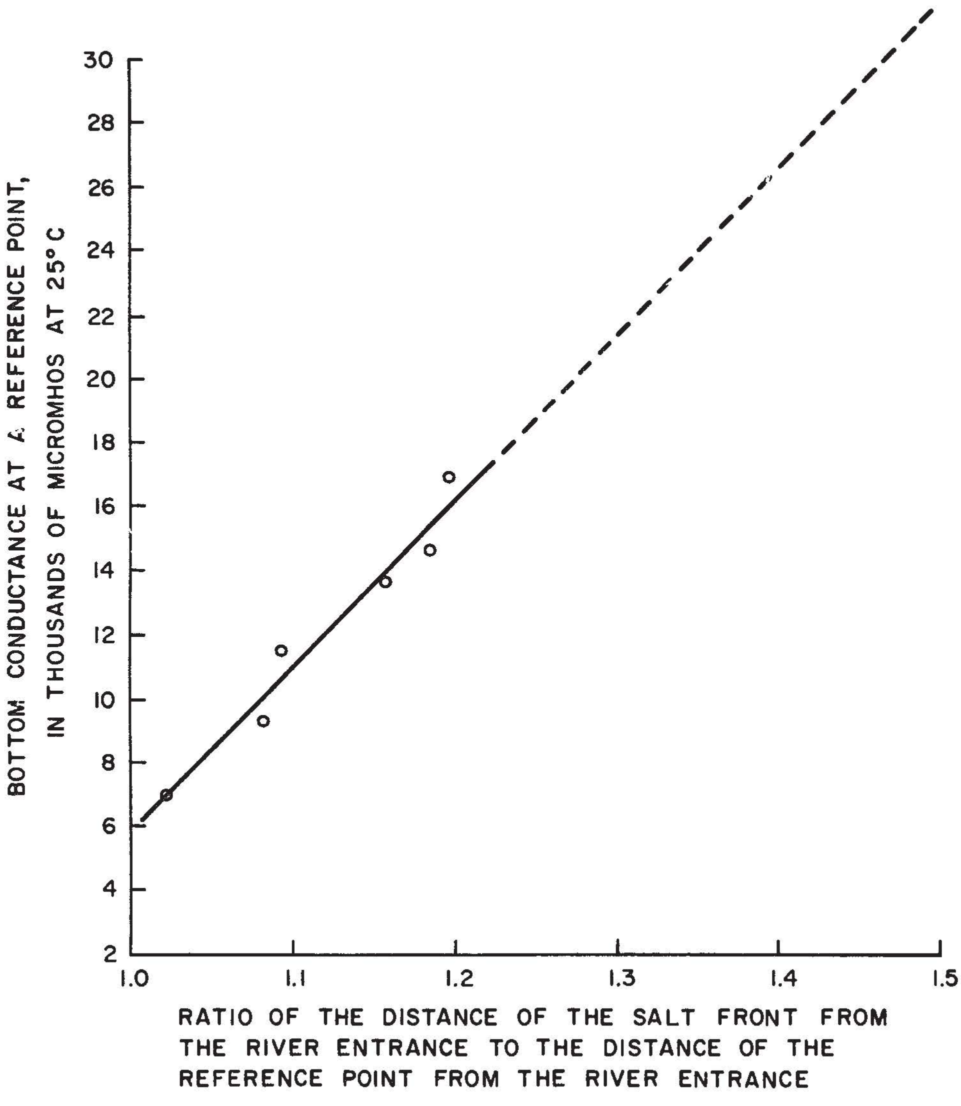


Figure 6. Graph showing relationship between specific conductance at a reference point and distance upstream from that reference point to which salt water moves; lower Withlacoochee River.

As salt water moves in and out of the river with tidal flows, the length of time that salt water is present at a particular location depends on the nature of the tidal flow. When salt water reaches station W4A, conductance of the bottom water in the river remains greater than conductance of the overlying fresh-water from a fraction of an hour to about 6 hours. The average length of time that salt water remained at the station during the investigation was 3.2 hours. Of the 320 days of conductance record from station W4A, salt water reached the station with high tides on 41 of those days. Assuming a duration time of 3.2 hours for each occurrence, salt water was present at station W4A about 1.7 percent of the total time of record.

Also of interest is salt-water movement in the two canals branching off the river just downstream from station W4A (fig. 1). On May 18, 1971, when the salt front in the river was several thousand feet downstream from station W4, water ssmples were collected near the bottom at the entrance, mid-point, and end of each canal. The conductance of samples from the canal closest to station W4A were 280, 600, and 730 micromhos, respectively, and for the second canal, 280, 3,500, and 665 respectively. Salt water brought in by high tides can apparently become trapped in the canals when the salt front recedes toward the Gulf at low tides. Tidal flushing of salt water may be hampered by adverse bottom slopes in the canals.

SALT-WATER MOVEMENT IN THE CANAL AND IN THE RIVER BETWEEN THE CANAL AND INGLIS DAM

Salt water in varying concentrations was present near the bottom of the barge canal at station W7, the U. S. 19 bridge, about 99 percent of the time during the investigation. Conductance near the bottom at times of sampling at stations W7 and QCE 219 (below Inglis Lock) in the early months of the investigation approached that of near-shore Gulf salt water (45,000-50,000 micromhos). Figure 7 shows that the pattern of salt-water concentration at station W7 is generally cyclic, but that small variations occur frequently, superimposed on the cyclic pattern. Comparison of the conductance graph from station W7 with the stage record from Crackertown presented in figure 7 shows no consistent correlation between tidal patterns and the cyclic conductance pattern. At times (for example, February 18-22, April 15-20, July 30-August 5, August 14-17) high HLW tends to coincide with high specific conductance at station W7. Occasionally, daily conductance variations coincide with individual tidal events, as do conductance variations at station W4A on the river; often the variations appear erratic.

No close relation was observed between the rate at which water was discharged through Inglis Dam and conductance variation at station W7 as long as discharge remained below about 1,000 cfs. When discharge rose as high as 1,500 cfs, as during September 1971, conductance at station W7 dropped markedly to about 800 micromhos, the lowest level during the investigation.

On the river between Inglis Dam and the canal, salt water frequently reaches station W8. The movement of salt water is similar to that in the river below the bypass channel. Salt water from the canal moves upstream when the tidal flow is upstream. When the tidal flow reverses, salt water moves back toward the canal. Most occurrences of salt water at station W8 coincided with HHW, but LHW also brought salt water to the station, although less frequently. The peak salt-water concentrations at station W8 sometimes remained nearly 24 hours.

Discharge through Inglis Dam has an appreciable effect on salt-water movement in the river below the dam. The effect of increased discharge through the dam is shown best in Figure 7 during the 4-day period July 6-9, 1971. Except for leakage estimated at 10 cfs, the dam discharged no water in May, June, and July except during the 4 days. Salt water reached station W8 every day in July except those 4 days, when the discharge was about 100, 900, 550, and 200 cfs, respectively.

The frequency of occurrence and concentration of salt water at station W8 was, on the average, greater during May, June, and July, when no discharge was allowed, than during other months of the investigation. However, maximum conductance at station W8, in one instance as high as 26,000 micromhos, occurred when discharge was not zero but in the 150-300 cfs range, probably because of tides that were very conducive to high upstream salt-water movement.

At station QCE 218, below Inglis Dam, salt water was not present at any sampling time during the investigation.

EVALUATION OF BYPASS-CHANNEL ABILITY TO FLUSH LOCKED-UP SALT WATER FROM THE UPPER POOL AREA

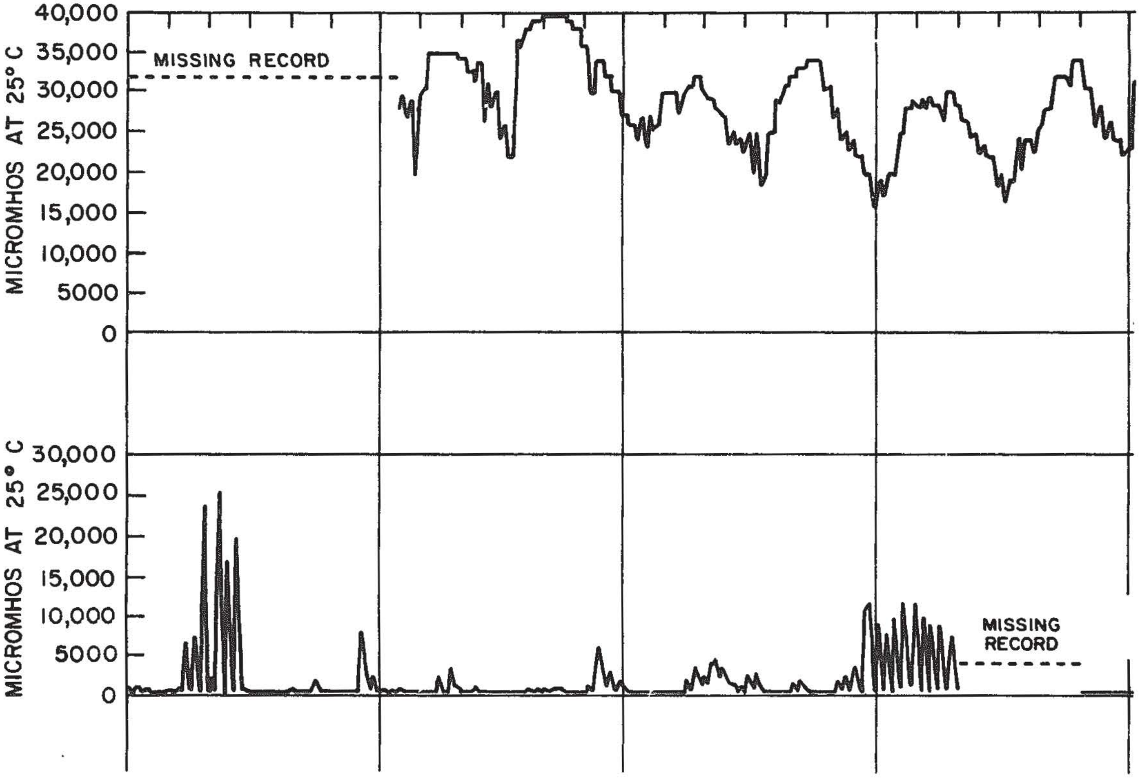
Depending on the manner in which Inglis Lock is operated and on the salt-water concentration below the west lock gates, varying quantities of salt water can be locked to the upper pool area. During the investigation, conductance of the water was monitored continuously near the bottom of the channel at station QCE 217 (fig. 1), about 50 feet out in the canal immediately west of the bypass-channel entrance, and near the bottom at station QCE 220 in the center of the river below the bypass-channel spillway. The records from these stations show that salt water locked to the upper pool area moves down the bypass channel. Sharp increases in conductance over the prevailing fresh-water conductance, lasting from several minutes to several hours before falling rapidly back to the prevailing fresh-water level, were often noted at station QCE 217 after lock operations. The increases recorded since September 1970 ranged from about 10 micromhos to over 3,000 micromhos. At station QCE 217, increases in conductance of several hundred micromhos were usually followed 4 to 6 hours later by conductance increases of lesser magnitude at station QCE 220. Increases in conductance at station QCE 220 commonly ranged from 10 to 60 micromhos and lasted from 5 to more than 20 hours. Most of the increases at station QCE 220 usually occurred abruptly and subsided gradually.

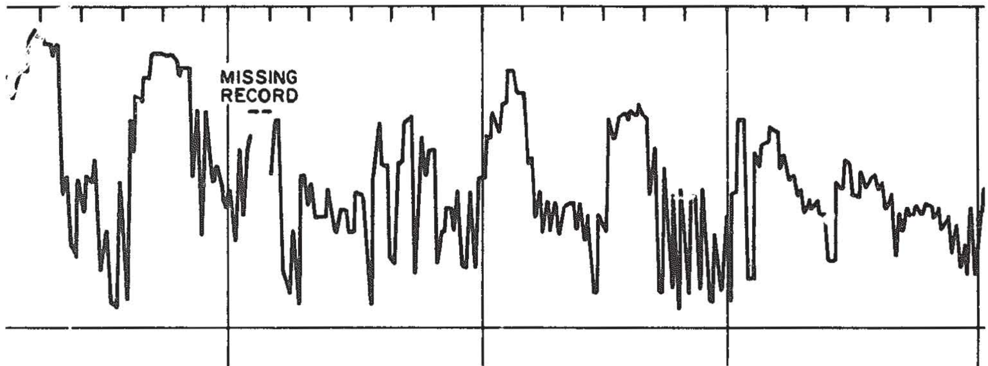
In April 1971, two tests were made to determine whether salt water moves up the canal east of the bypass-channel entrance. Before the tests,

FIGURE 7. GRAPH OF SPECIFIC CONDUCTANCE AT STATIONS W7 (BARGE CANAL AT U.S. 19 BRIDGE) AND W8 (BETWEEN BARGE CANAL AND INGLIS DAM), STAGE AT CRACKERTOWN, AND DISCHARGE FROM INGLIS DAM, SEPTEMBER 1970-SEPTEMBER 1971.

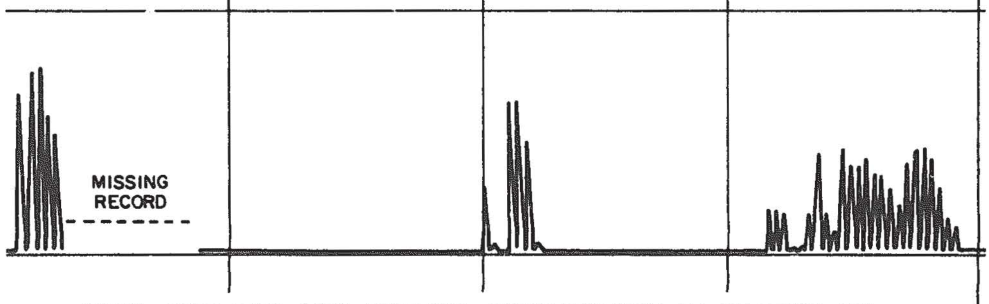
25.1	25.2	25.3
25.4	25.5	25.6

Index showing page numbers of each component of figure 7

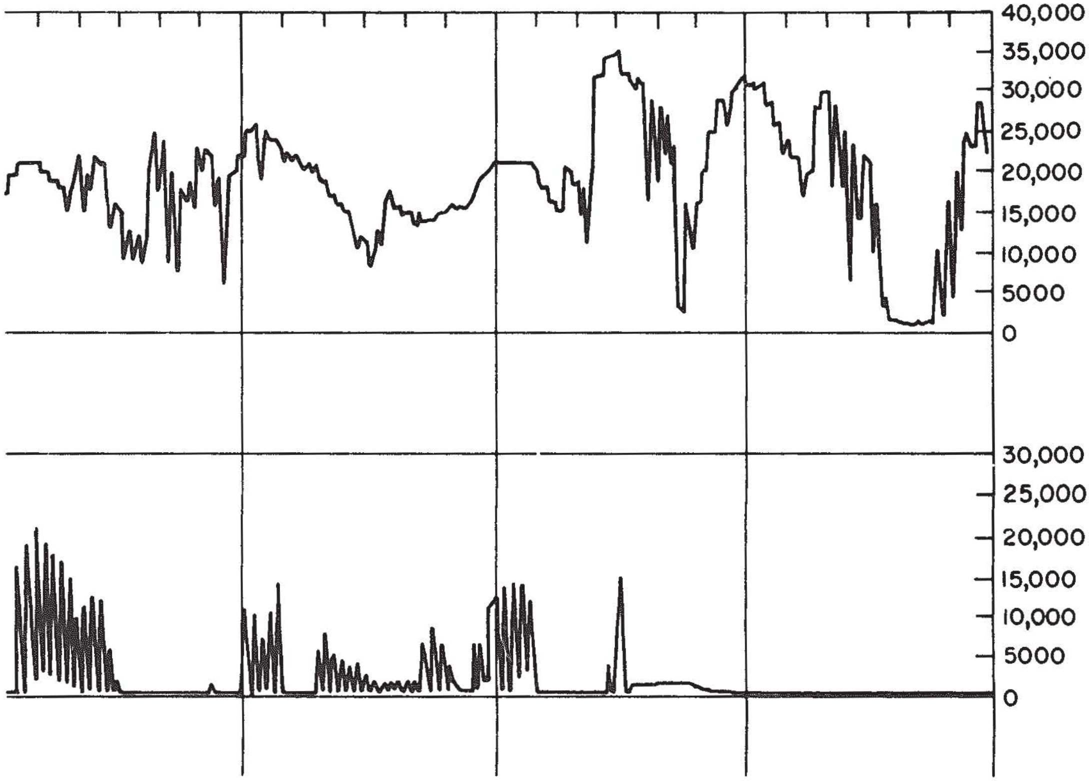

40,000
35,000
30,000
25,000
20,000
15,000
10,000
5000
0
MICROMHOS AT 25° C
MISSING RECORD
30,000
25,000
20,000
15,000
10,000
5000
0
MICROMHOS AT 25° C
MISSING
RECORD



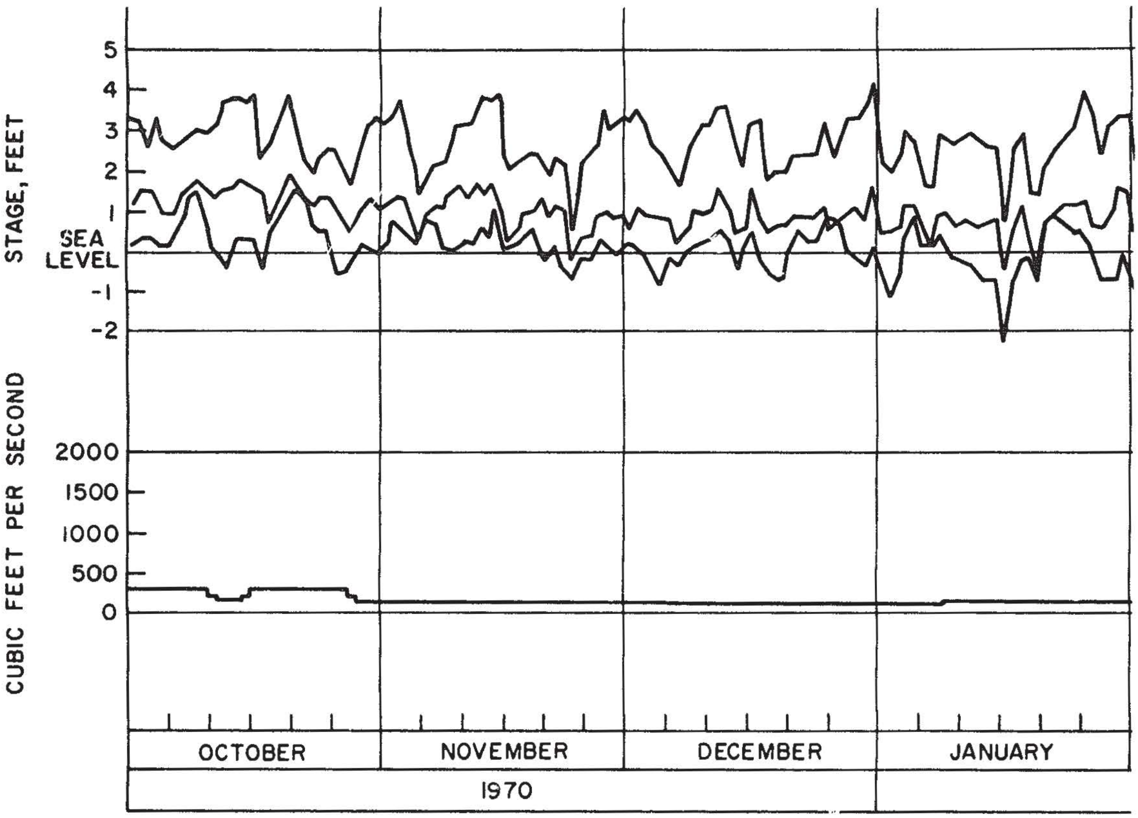
DAILY HIGH AND LOW SPECIFIC CONDUCTANCE AT STATION W7

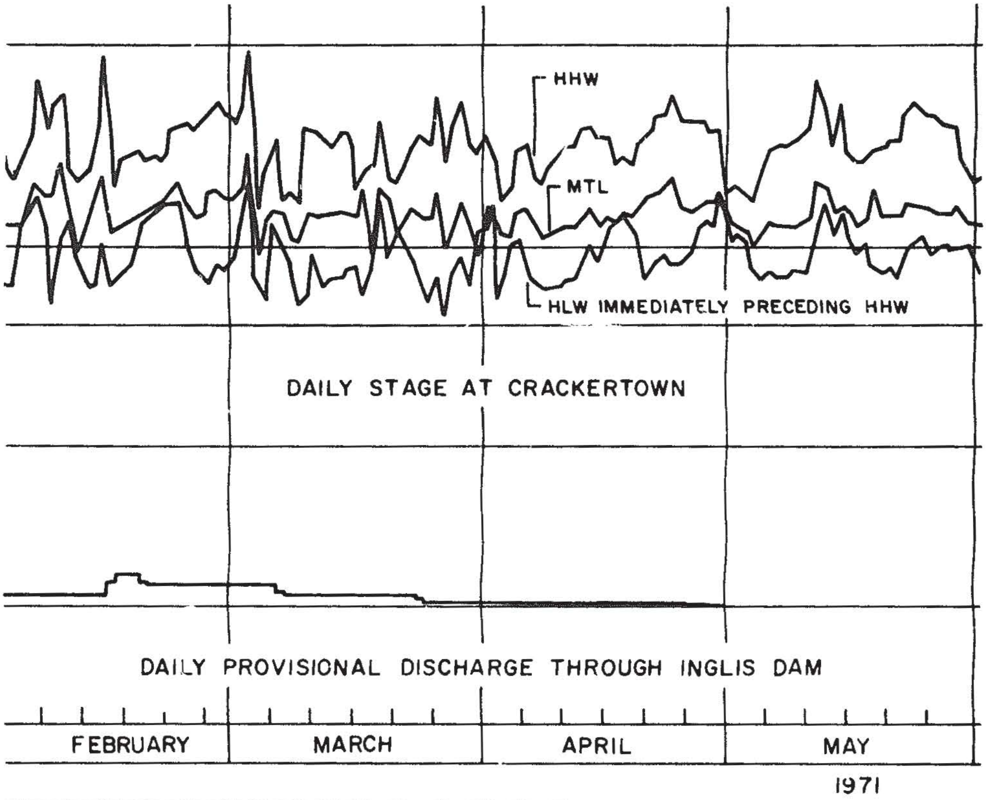


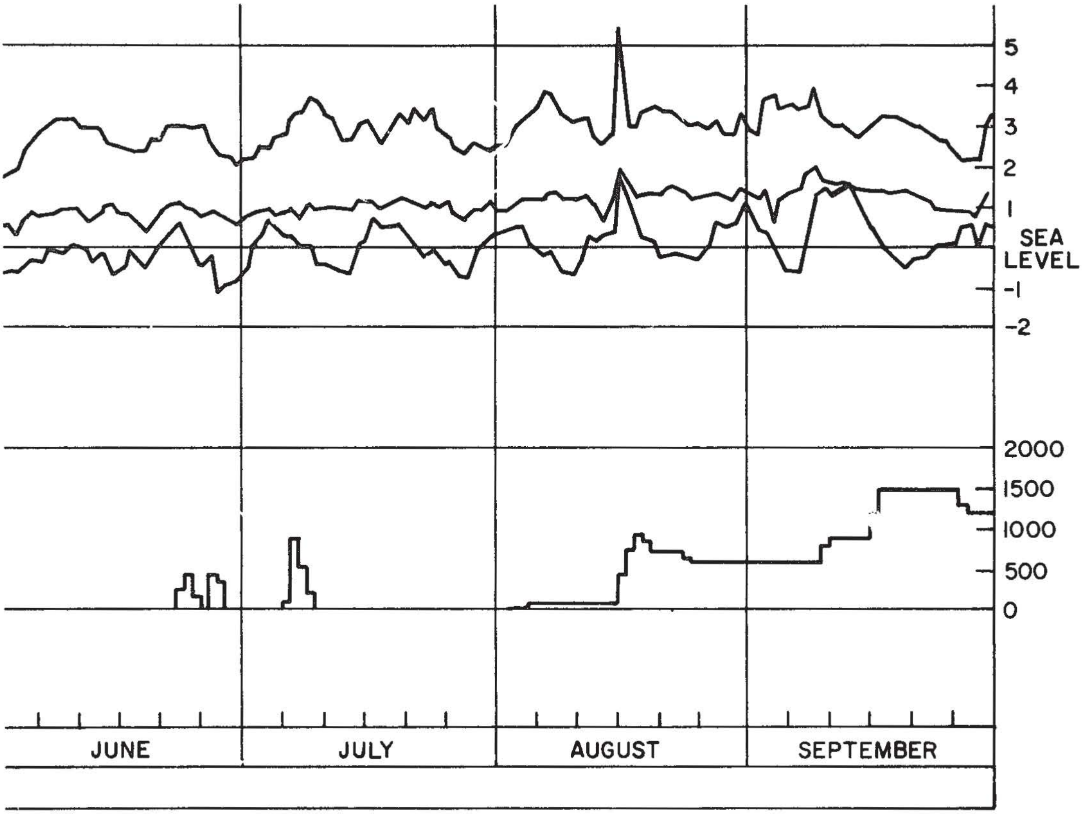
DAILY HIGH AND LOW SPECIFIC CONDUCTANCE AT STATION W8


40,000
35,000
30,000
25,000
20,000
15,000
10,000
5000
0
30,000
25,000
20,000
15,000
10,000
5000
0

25.3


STAGE, FEET
5
4
3
2
1
SEA LEVEL
-1
-2
CUBIC FEET PER SECOND
2000
1500
1000
500
0
OCTOBER
NOVEMBER
DECEMBER
JANUARY
1970


HHW
MTL
HLW IMMEDIATELY PRECEDING HHW
DAILY STAGE AT CRACKERTOWN
DAILY PROVISIONAL DISCHARGE THROUGH INGLIS DAM
FEBRUARY
MARCH
APRIL
MAY
1971


5
4
3
2
1
SEA
LEVEL
-1
-2
2000
1500
1000
500
0
JUNE
JULY
AUGUST
SEPTEMBER

detailed bottom profiles were made in the canal between the east lock gates and the Withlacoochee Backwater to locate any channels in the bed that could collect and transport the denser salt water toward the Backwater; none were located.

Before the gates were opened for the first test, conductance near the bottom in the canal outside the gates was 9,750 micromhos. Near the time of a high tide, the west gates were opened for approximately 2 hours, and the conductance of water stabilized at about 8,500 micromhos near the bottom of the lock chamber and 375 micromhos at the surface. The west gates were then closed and the chamber filled. When full, conductance near the bottom of the chamber decreased to about 3,000 micromhos. The east gates were opened and left open while the movement of salt water out of the lock chamber was monitored. Numerous water samples were collected both east and west of the bypass entrance and at the entrance for about 4 hours after the east gates were opened. The samples were field tested for conductance. No increase in conductance from the fresh-water level of 235 micromhos was detected in the water anywhere east of the bypass-channel entrance. At station QCE 217, conductance of the water reached a peak of 1,300 micromhos after the east gates had been open about 2 1/2 hours. In the canal opposite the bypass entrance, conductance of water ranged from 235 to 1,130 micromhos. The conductance of water in the river at station QCE 220 increased 25 micromhos about 5 hours after the east gates were opened; the rise lasted about 7 hours.

The next day, a similar test was made except that the lock was operated normally, as if a barge were being locked through to the Backwater. The conductance of water near the bottom outside the west gates before opening was 7,300 micromhos. The west gates were open only 10 minutes, then shut. Before refilling the chamber, conductance of water near the bottom of the chamber was 3,250 micromhos. After the chamber was filled, conductance near its bottom decreased to 510 micromhos. The east gates were then opened for 8 minutes. Again, the canal area between the east gates and the Withlacoochee Backwater was sampled extensively. No rise in conductance was noted in the water within the canal anywhere east of the bypass channel entrance. At station QCE 217, the conductance of the water reached a maximum of 300 micromhos about 1 1/2 hours after the east gates were shut. At station QCE 220, the conductance did not increase after this test.

The conductance of water in the canal below the west gates was not as high when these tests were made as at other times earlier in the investigation. At station QCE 217, just west of the bypass-channel entrance, however, the conductance increase to 1,300 micromhos during the first test was the highest until July 1971, when the lockmaster began locking large masses of water hyacinths from the Backwater to the lower part of the canal. The operation necessitated leaving both the east and west gates open for several hours at a time to allow wind to move the hyacinths into the lock chamber at the upper level and out at the lower level. Hyacinth masses were locked several times each week from July through October 1971. At times, the conductance of water at station QCE 217 was greater than 3,000 micromhos (the upper limit of the particular sensing element). The most pronounced increases in conductance of water at station QCE 220 in the river also occurred during the hyacinth lockages, and correlation was good between conductance peaks at stations QCE 217 and the peaks at QCE 220. Occasionally during this 4-month period, salt water moving down the bypass channel was detected at station W4A. Six to ten hours after the water at station QCE 220 increased in conductance, the water at station W4A increased 10 to 30 micromhos in conductance for short periods of time. These increases at station W4A were not related to tidal flow.

To verify the conclusion drawn from the tests in April, that no salt water moves east of the bypass-channel entrance, conductance was monitored continuously east of the bypass-channel entrance near the bottom of the canal about 50 feet out from the north bank (station QCE 217A on fig. 1) for several weeks during the period of hyacinth lockages. When the conductance of the water at QCE 217 increased to less than about 2,000 micromhos as a result of lockage, the conductance of water in the canal at QCE 217A was unaffected. When the conductance of the water at QCE 217 increased to more than about 2,000 micromhos as a result of lockage, the conductance of water in the canal at station QCE 217A increased, usually from 5 to 20 micromhos, several hours later. These slight increases at QCE 217A, east of the bypass entrance, occurred less abruptly, lasted longer, and subsided slower than the larger increases west of the bypass entrance.

The evidence from this and previous tests indicate that the salinity of the salt water locked to the upper pool area is relatively low. For example, a conductance of 3,000 micromhos in the river-canal complex corresponds to a chloride content of about 840 mg/l. In general, water must have a chloride content of at least 1,000 mg/l to be considered saline by the U. S. Geological Survey. The bypass channel seems to be effective in flushing locked-up salt water from the upper pool area.

DISCHARGE REQUIREMENT FOR REMOVAL OF SEDIMENT FROM ROCKS ALONG THE BANKS OF THE LOWER WITHLACOOCHEE RIVER

Outcrops of limestone that form the banks of the lower Withlacoochee River are coated with a layer of sediment from a fraction of an inch to several inches thick. The layer consists mainly of fine sand and small particles of decayed organic matter. According to several residents of the area, shoreline rocks exposed at low water and those visible along the banks to several feet below the surface appeared clean and free of sediment before the canal complex was built. They feel that when Inglis Dam was the discharge control, the occasional discharges of several thousand cubic feet per second of water scoured the accumulated sediment off the rocks. They conclude that, since these periodic high discharges no longer can occur with the bypass channel controlling the flow, the shoreline rocks will continue to be coated with sediment.

The river and near-shore rocks were inspected regularly during the investigation. Although the rocks were covered with sediment, no suspended load was evident in the river except in early fall 1970, when the bypass channel was being dredged. Probably some of the sediment coating the river's banks was deposited within a short time during upstream construction operations, and additional sedimentation is not likely as long as the river remains free of sediment.

The question still arises, however, as to what minimum discharge would be required to remove sediment from these rocks. For several reasons, velocities associated with a given discharge and capable of removing sediment may occur in one part of the river, while in another part the same discharge would not produce velocities sufficient to remove sediment. As the river is tidal below the bypass, velocities vary with location and time, although the discharge in the bypass may be constant. Varying stages cause some sediment-covered rocks to be inundated at high tides and exposed at low tides. Irregularities in channel geometry produce local velocity variations. Also the variation in size, shape, arrangement, and surface roughness of the individual rocks, which together form the river banks, cause changes and differences in velocity.

A theoretical approach was taken to arrive at an estimate of discharge sufficient to scour sediment from shoreline rocks. The method involved determing critical mean velocities in verticals, where critical mean velocity is the mean velocity in a vertical at which particle movement begins. Critical mean velocities in verticals were compared to measured mean velocities in verticals at a representative channel section, and the results related to a critical discharge. A brief explanation of the method and results are discussed.

Velocities in the river are highest when tidal flow is downstream. Velocities are assumed to decrease as channel cross section increases. Therefore, a theoretical minimum discharge sufficient to remove all sediment from near-shore rocks in all sections of the river is one that, during downstream tidal flows, would produce critical mean velocities in verticals over near-shore sediment-covered rocks in the largest sections of the river. As large a section as could be located in the vicinity of the Crackertown stage recorder was chosen for measurement, not on or near a curve, and where the banks are covered with sediment. In this section a series of five discharge measurements was made between a HHW and a LLW. Emphasis was placed on obtaining mean velocities in verticals of less than 6 feet during the discharge measurements.

Theoretical critical mean velocities in verticals were determined by assuming that Shields' equation describing the velocity profile in turbulent flow applies (Raudkivi, 1967). This equation expresses velocity as a function of depth, bed surface roughness, and shear velocity. Shear velocity is a function of average bed shear stress, which is the average horizontal force exerted by a flowing fluid on one unit area of the channel bed (in this instance, one unit area of sediment-covered rocks). Using Shields' entrainment function (Henderson, 1966), a critical value of average bed shear stress, that is the average bed shear stress when there is beginning of particle movement, was calculated, based on the unit weight and grain size of

Withlacoochee River sediment samples. A corresponding critical shear velocity was calculated. With the critical shear velocity and estimates of the height of bed-surface-roughness projections in the areas of interest, a series of critical mean velocities in verticals to total depths of 1 to 6 feet were computed, as shown in Table 2.

Critical mean velocities in verticals were then compared with measured mean velocities in verticals for corresponding depths below 6 feet. Of the 18 measured mean velocities in verticals less than 6 feet deep determined during the five discharge measurements, 16 were less than corresponding critical mean velocities in these verticals. The average of the 18 measured mean velocities, 0.44 fps (feet per second), needed to be increased by a factor of 1.64 to equal the average of the 18 critical mean velocities, 0.72 fps. In the worst instance, the measured mean velocity, 0.16 fps, needed to be increased by a factor of 4.56 to equal the corresponding critical velocity, 0.73 fps.

To increase the mean velocity in a vertical along the shallow edges of the river, the mean velocities in verticals across the entire section must be increased. Just how much mean velocities near the center of the river at a particular section and time must be increased to produce a desired increase in near-shore mean velocities depends on such factors as the geometry of the section, the tide height at the section at the given time, and the slope of the water surface at the section at the given time. When the five discharge measurements were made between a HHW and LLW, mean velocities across the section were expected to increase with each measurement as the tide dropped and the effect of the downstream tidal flow advanced upstream, thus providing an indication of how velocities near the center of the watercourse change relative to velocities near the edges. Although the tide dropped 2.5 feet between the first and the last discharge measurements, mean velocities changed very little and not enough to reveal any trends when plotted against the width of the water surface at the measuring section. The five discharge measurements were 1,520, 1,570, 1,440, 1,440, and 1,490 cfs, respectively.

To obtain an estimate of critical discharge, the assumption was made, arbitrarily, that, if the shallow-water mean velocities in verticals over sediment-covered rocks are increased by a certain factor, that factor also should be applied to measured mean velocities in verticals throughout the section. The largest factor necessary to bring a measured shallow-water mean velocity in a vertical up to the corresponding critical mean velocity in a vertical was 4.56. Both the mean velocities in verticals and corresponding depths across the section from the five discharge measurements were averaged and the resulting velocities increased by a factor of 4.56. Based on these data, 6,800 cfs was calculated to be the minimum discharge sufficient to remove accumulated sediment from all but the shallowest of submerged rocks. However, a discharge of 6,800 cfs, depending on tidal and wind conditions, probably would raise the river stage sso high that all sediment-covered rocks would be under several feet of wwater.

Table 2.--Critical mean velocities in verticals of specified depth.

Depth ft	Critical mean velocity fps
1	0.59
2	0.67
3	0.72
4	0.75
5	0.77
6	0.79

Table 2 shows that critical mean velocities in verticals of varying depth do not vary greatly. In contrast, measurements indicate that actual mean velocities in verticals drop significantly with decreasing depth. Consequently, critical mean velocities are less likely to be attained as the depth decreases.

The critical discharge of 6,88800 cfs determined by this analysis is subject to large errors, but it probably represents the order of magnitude of the discharge required to remove the sediment. A more reliable estimate might be determined experimentally by releases of water into the reach of the river below Inglis Dam, where similar conditions exist. The discharge capacity of Inglis Dam is considerably larger than the capacity of the bypass channel.

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