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DEPARTMENT OF NATURAL RESOURCES
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Information Circular No. 82

FLOW AND CHEMICAL CHARACTERISTICS OF
THE ST. JOHNS RIVER AT JACKSONVILLE, FLORIDA

By
Warren Anderson and D. A. Goolsby

Prepared by the
UNITED STATES GEOLOGICAL SURVEY
in cooperation with the
BUREAU OF GEOLOGY
FLORIDA DEPARTMENT OF NATURAL RESOURCES
and the
CONSOLIDATED CITY OF JACKSONVILLE

TALLAHASSEE
1973
Bureau of Geology
Tallahassee
August 24, 1973

Honorable Reubin O’D. Askew, Chairman
Department of Natural Resources
Tallahassee, Florida

Dear Governor Askew:

The Bureau of Geology of the Division of Interior Resources is printing as its Information Circular No. 82 a report prepared by Warren Anderson and D. A. Goolsby of the U. S. Geological Survey entitled, “Flow and Chemical Characteristics of the St. Johns River at Jacksonville, Florida”.

This report will be of substantial value to water managers in developing the St. Johns River as a multiple resource. Evaluation of the capacity of the river to accept pollutants without adversely affecting other uses requires detailed data of flow and chemical characteristics and an understanding of how they interact.

Respectfully yours,

Charles W. Hendry, Jr., Chief
Bureau of Geology
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FLOW AND CHEMICAL CHARACTERISTICS OF THE ST. JOHNS RIVER AT JACKSONVILLE, FLORIDA

by

Warren Anderson and D. A. Goolsby

ABSTRACT

The St. Johns River at Jacksonville, which is 21 miles upstream from the ocean, is part of a tidal estuary that for practical purposes may be considered to end at Lake George, 106 miles upstream from the ocean. Occasionally, tidal effects are noted 161 miles upstream.

The channel of the estuary above Jacksonville is capable of storing huge amounts of water, and rising ocean tides at the mouth of the river force large amounts of water up the river past Jacksonville. Most of this water subsequently flows back past Jacksonville as the ocean tide falls. These tidal flows average 87,000 cubic feet per second at Jacksonville, and peak flows exceeding 150,000 cubic feet per second are common. The average tidal flows are more than seven times as large as the average net or fresh-water flow.

Fresh water draining from the estuary increases the volume and duration of ebb tidal flows (downstream) and diminishes the volume and duration of flood tidal flows (upstream). About a quarter of the fresh water that flows into the estuary from April through September is released to the ocean from October through March. When evapotranspiration from the estuary above Jacksonville exceeds rainfall and fresh-water inflow into the estuary, the net loss of water tends to cause the volume and duration of the upstream flows to exceed those of the downstream flows.

The net flow of the St. Johns River at Main Street Bridge in Jacksonville was downstream about 70 percent of the days of record and upstream about 30 percent of the days of record. Zero net flow occurred on 13 of the 4,597 days of record, or 0.3 percent of the time. The greatest number of consecutive days that the net flow was zero or upstream was 14 days.

Sea water moving upstream from the mouth of the St. Johns River mixes with the fresher water already in the river channel to form a zone of transition. The chloride concentration in this zone varies from that of sea water to that of the fresh-water input. When the zone of transition extends upstream from Jacksonville, the chloride concentration in the river at Jacksonville increases with upstream flow and decreases with downstream flow. During a particular tidal cycle, the magnitude and range in chloride concentration in the river at
Jacksonville depends on the length and gradient of the zone of transition and on the volumes of the tidal flows. About 80 percent of the time the chloride concentration at Main Street Bridge exceeds 250 milligrams per liter.

Between Jacksonville and the ocean the river shows some stratification between the sea water and overlying river water. However, stratification tends to weaken or disappear in the vicinity of Jacksonville, probably because of increased turbulence caused by channel constriction and bridge piers. The temperature of the river averages less than 15° C (Celsius) (59° F) in January and February and more than 28° C (82° F) in summer.

INTRODUCTION

The St. Johns River, which flows through the city of Jacksonville, discharges about one tenth of the 40-billion-gallon average daily surface runoff from the State of Florida -- a generous share of the 150-billion-gallon average daily rainfall on the State. This prodigious and continually renewed resource can be used for diverse and, in some instances, conflicting purposes such as water supply, waste disposal, transportation, heat disposal, fisheries, and recreation. In the Jacksonville area, the river (a tidal estuary) is used for all these purposes except water supply.

There is continuing concern about the effect that the rapidly growing population and economy in the St. Johns River basin will have on the potential for pollution of the river by industrial and domestic waste. Evaluation of the capacity of the river to accept pollutants without adversely affecting other uses requires detailed data on flow and chemical characteristics and an understanding of how they interact.

PURPOSE AND SCOPE

This report was prepared to present and interpret information on the flow and chemical characteristics of the lower St. Johns River in the vicinity of Jacksonville (figs. 1 and 2). It is intended that the report (1) describe the flow and chemical characteristics with respect to variations with time, frequency of occurrence, and magnitude of tidal flows; (2) indicate the factors that affect flow and portray the manner in which they interact to produce characteristic flow patterns; and (3) relate the chemical quality of the river to the flow regime.

Flow records computed through September 30, 1966 for the lower St. Johns River and chemical quality data obtained through May 1967 were
analyzed during preparation of this report. The procedures used in the procurement and computation of the flow data are described in the following section. Field reconnaissance trips and special observation of water quality and flow characteristics were also necessary to this analysis.

This report is one of several to result from a comprehensive investigation of the water resources of Duval County by the U. S. Geological Survey in cooperation with the Consolidated City of Jacksonville and the Bureau of Geology, Florida Department of Natural Resources.

The report was prepared under the direct supervision of L. J. Snell, former Subdistrict Chief, Joel O. Kimrey, Subdistrict Chief, and B. F. Joyner, District Laboratory Chief, Ocala, and under the general supervision of C. S. Conover, District Chief, Tallahassee, all of the U. S. Geological Survey.

DATA COLLECTION AND COMPUTATION OF FLOW RECORDS

Stage data used in the computation of flow records for the St. Johns River at Jacksonville are obtained at Main Street Bridge, at the Naval Air Station 8.2 miles upstream from Main Street Bridge and at the U. S. Corps of Engineers Dredge Depot 4.8 miles downstream from Main Street Bridge. The upstream and downstream gages are set at datums 10.00 feet below mean sea level and the base gage is set at a datum 9.99 feet below mean sea level. The stage record collected at Main Street Bridge is only used for flow computation if record is lost at one of the other two gages.

Discharge measurements and point-velocity measurements are made from the downstream (east) side of Main Street Bridge. Point-velocity measurements are made at station 1,300, which is 1,005 feet from the south bank of the river. The point velocity consists of the average of current-meter readings taken at 0.2 and 0.8 of the depth at station 1,300. Rapid discharge measurements, which include velocity determinations at station 1,300 are occasionally made with four current meters. The discharges and point velocities thus obtained are plotted against each other for both upstream and downstream flow as shown in figure 3. These relations, though they differ slightly, are linear. The discharge during a tidal cycle is determined from frequent point-velocity readings (see fig. 6) by use of these curves of relation. The volume of flow during the tidal cycle, both upstream and downstream, is computed from the area under the discharge graph thus obtained. As shown by figure 4, the volumes of flow are then plotted against the area between the superimposed stage graphs (see fig. 5) obtained by the gages at the Naval Air Station and the Dredge Depot. The volume of each upstream and downstream flow is then determined from the stage record using this latter curve of relation.
Figure 1. Map of northeastern Florida showing major elements of the St. Johns River system.
Flow records computed for February 10, 1954, to September 30, 1966, were used in this analysis. A year of record beginning on October 1 and ending the following September 30 is called a water year. For example, the 1955 water year began on October 1, 1954 and ended on September 30, 1955.
Figure 3. Relation of point velocity at Station 1300 to discharge of the St. Johns River at Main Street Bridge.
Figure 4. Relation of area between superimposed stage graphs to volume of tidal flow at Main Street Bridge.

Figure 5. Superimposed stage graphs for the St. Johns River at Jacksonville.
ACKNOWLEDGMENTS

The authors express their appreciation to the following employees of the city of Jacksonville: Tom Ard, Director, Air and Water Pollution Control, Department of Health, Welfare and Bioenvironmental Services; E. T. Owens, Engineer, and S. Hay, Assistant Engineer, City Engineering Department; who provided valuable data and assisted in tests; and to Messrs. James English, Director of Public Works and Robert B. Nord, Director, Water and Sewer Department, whose valuable assistance enhanced the collection of basic data. The contribution of E. T. Owens is especially appreciated, as it was he who fostered the data-collection program from its inception.

PREVIOUS INVESTIGATIONS

The earliest investigation to yield data applicable to the present physical conditions in the St. Johns River estuary was led by E. F. Hicks in the winter of 1933-34. The results of this investigation were reported by F. J. Haight in 1938. Measurements of the stage, velocity, and discharge of the river at Jacksonville were made by the U. S. Geological Survey on May 10, 1945. The U. S. Geological Survey investigated the river August 16-24, 1945, to determine the change in position from Main Street Bridge of a particle of river water during the course of a tidal cycle. E. E. Pyatt investigated the distribution of pollutants in the river in 1959.

DESCRIPTION OF THE SYSTEM

The source of the St. Johns River is a marsh near Fort Pierce, Florida, 312 miles from its mouth near Mayport. The river flows on a generally northward course to Jacksonville and then eastward to the ocean. The topographic drainage area of the St. Johns River is 9,430 square miles, nearly one-sixth of the land area of Florida.

From the ocean to Jacksonville, the river ranges in width from about 1,250 feet at Main Street Bridge to more than 2 miles at Mill Cove, and in the reach from Jacksonville to Palatka the width ranges from 1 to 3 miles. From just south of Palatka to Lake George, the river narrows to generally less than half a mile and in one place to only about 600 feet. Lake George, the largest expansion in width (nearly 7 miles) along the entire river, is about 70 square miles in area and normally shows no tidal fluctuation. South of Lake George, the river channel is generally much narrower than to the north, although several large lakes or widenings of the river exist. The shore line of the river north of Palatka is indented by many coves and enlarged mouths of tributaries.
The Corps of Engineers, U. S. Army, maintains a navigation channel in the river. The channel is 34 feet deep and 400 to 900 feet wide between the ocean and Jacksonville, 13 feet deep and 200 feet wide between Jacksonville and Palatka, 12 feet deep and 100 feet wide between Palatka and Sanford, and 5 feet deep and 100 feet wide between Sanford and Lake Harney.

At low water, the flood plain of the St. Johns River contains openwater areas totaling more than 300 square miles. Lake George, Crescent Lake, and the river between Lake George and the ocean occupy about two-thirds of this area.

At the mouth of the St. Johns River the tidal range averages 4.9 feet. The ocean tide generates a progressive tidal wave that moves up the river with gradually diminishing amplitude until at Orange Park the range is only 0.7 foot. From Orange Park southward; the amplitude of the wave increases until at Palatka the range is 1.2 feet, the same as that at Main Street Bridge in Jacksonville. From Palatka to Lake George, the amplitude again decreases and becomes practically zero at the outlet of Lake George, 106 miles upstream from the mouth of the river (Haight, 1938).

Occasionally, during severe droughts, high tide and northeasterly winds combine to cause upstream flow at the outlet of Lake Monroe 161 miles upstream from the mouth of the river. During the drought in 1945, a river stage of 0.42 foot below mean sea level was recorded south of Lake Harney, 191 miles upstream from the mouth of the river.

FACTORS AFFECTING THE RIVER FLOW AND QUALITY

The flow of the St. Johns River at Jacksonville is affected by the ocean tide, wind, runoff from the land in the river basin, rainfall, and evapotranspiration. The extent to which these factors can affect the flow is controlled by the channel geometry and available storage capacity upstream from Jacksonville. Therefore, the interaction of these factors cause wide variations in the volume of flow at Jacksonville.

Normally, tides are the dominant flow-producing factor at Jacksonville, but winds as strong as those associated with Hurricane Dora in September 1964 can completely offset or significantly accentuate the effect of tide. The factors that affect the flow of the river also affect the chemical characteristics of the water and cause it to range from relatively fresh water to a mixture of fresh and marine water consisting of more than 60 percent sea water.
The gravitational interaction of the earth, moon, and sun cause a vertical motion of the ocean surface, called tide, and a horizontal motion of the water, called tidal current. The amount of vertical motion of the surface is called range of tide, and the limits of the motion are called high water and low water. Tidal heights are referenced by the NOS (National Ocean Survey) (formerly the U. S. Coast and Geodetic Survey) to mean low water, which at Jacksonville is 0.6 foot below mean sea level. In an estuary such as the lower St. Johns River, the current flows both upstream and downstream. The current first increases in one direction from zero velocity (called slack water) to a maximum velocity (called strength of the current), then decreases to slack water. The process is then repeated in the opposite direction.

In a progressive tidal wave the time of slack water comes, theoretically, exactly midway between high and low tide. Also, maximum upstream current velocity (flood strength) occurs, theoretically, at high water; and maximum downstream current velocity (ebb strength) occurs, theoretically, at low water (Haight, 1938). The range of tide and strength of current resulting solely from gravitational tide-producing forces are closely but not precisely related. The relation is not precise because forces involving the angular distances of the sun and moon from the equator (declination) affect the range of tide about twice as much as they affect the strength of current.

Yearly tables, which give the predicted times of occurrence and heights of high and low tides, are published by the NOS. The NOS also publishes yearly tidal current tables, which give the predicted times of occurrence of slack water, flood strength, and ebb strength and the magnitudes of the flood and ebb strengths. Tables from the tide at Mayport and the tidal current at St. Johns Entrance are included in these publications. The tide tables and tidal current tables published by the NOS for 1954-66 were used extensively in this analysis.

THE TIDAL CYCLE

A graphic representation of the rise and fall of the tide, in which time is represented by the abscissas and the height of the tide by ordinates, is called a tide curve. A graphic representation of a reversing type of current, in which time is represented by the abscissas and the velocity by the ordinates, is called a current curve. In general, these curves approximate a cosine curve (Schureman, 1963).
The NOS designates flood velocity (upstream velocity) positive and ebb velocity (downstream velocity) negative so that tide curves and current curves will be in phase. However, designating the signs in this manner results in the average net current -- and, therefore the average net discharge -- being negative. In this report, upstream flow is considered negative, and downstream flow is considered positive, and therefore, the current and discharge curves are theoretically $180^\circ$ out of phase with the tide curve.

The current or velocity curve and the corresponding discharge curve for a tidal cycle measured August 5, 1955, is shown by figure 6. The tide curve for this tidal cycle is also shown on figure 6, with height of tide given as gage height above a datum 9.99 feet below mean sea level rather than heights above MLW (mean low water), which is the datum used for tide predictions by the NOS. The datum of 9.99 feet below mean sea level is used to avoid negative water-level readings. The tidal cycle measured August 5, 1955, was used to illustrate flow and stage relations because the volumes of flow measured during this tidal cycle more nearly approximate those of an average tidal cycle than any other cycle measured from February 1954 to September 1966. Also, determinations of the chloride concentration in the river at Main Street Bridge were made while this tidal cycle was being measured.

The curves in figure 6 show that the actual time relationships of the tidal cycle do not conform to the previously discussed theoretical time relationships for a progressive tidal wave. Instead, the current curves, represented by the point-velocity and discharge curves, lag the tide curve, represented by the gage-height curve, by 20 to 60 minutes during this particular cycle.

**RELATION OF CHLORIDE CONCENTRATION TO THE TIDAL CYCLE**

Curves of the cumulative volume of flow and the variation in the chloride concentration near the bottom of the river at the Main Street Bridge during the tidal cycle measured August 5, 1955, are also shown on figure 6. As shown, the chloride concentration increased with increasing upstream flow volume and reached a maximum when upstream flow stopped. The concentration subsequently decreased as the water stored during upstream flow moved back out during the downstream flow. When the volumes of downstream and upstream flow were equal the chloride concentration was about the same as that at the beginning of upstream flow. Subsequently, the concentration continued to decline because the volume of the downstream flow exceeded that of the upstream flow. Therefore, the curve of the chloride concentration for the ensuing cycle began at a lower base concentration. Had the volume of the downstream flow been less than that of the upstream flow, the ensuing cycle
showing variations of point velocity, discharge, gage height, cumulative flow volume, and chloride concentration with time and gage heights and times of mean tidal levels.

would have begun at a higher base chloride concentration. Changing of the base chloride concentrations as a result of unequal volumes during consecutive tidal flows is the cause of the wide variation in the chloride concentration in the river.

The chemical characteristics of the lower St. Johns River vary from that of sea water near the ocean to that of the fresh-water input farther inland. Fresh-water input consists of a mixture of rainfall directly into the river, direct runoff from the land, and ground-water inflow. The reach of river in which sea water and fresh water are mixed is called the zone of transition in this report. This zone of transition shifts bodily toward the ocean and thus shortens with each downstream flow. The opposite occurs with each upstream flow.

The length and gradient of the zone of transition varies with changes in the general level of the ocean and fresh-water runoff as these factors affect the individual tidal flows. The length of the zone of transition is reduced, and its average gradient is increased by downstream movement of the terrestrial end of the zone, which results from a series of cycles having predominantly excessive downstream flow volumes. After a prolonged period of high fresh-water runoff,
the zone of transition sometimes becomes so short that the entire zone remains downstream from the Main Street Bridge. During such periods, the chloride concentration at Main Street Bridge is nearly constant at the level of the fresh-water runoff.

When the balance between the ocean level and runoff favors upstream flow, the zone of transition lengthens in increments proportional to the excess in volume of the upstream flows over the downstream flows. The terrestrial end of the zone of transition does not migrate upstream as the result of a continuous series of tidal cycles during which all the upstream flows are excessive. Instead, it migrates upstream as the result of a series of cycles, some of which have excessive downstream flows but most of which have excessive upstream flows. Sometimes, especially during droughts, predominance of excessive upstream flows causes the zone of transition to extend a considerable distance upstream from Jacksonville.

After each incremental increase in the length of the zone of transition, the river at Main Street Bridge is more saline, and the magnitude of the chloride concentration depends on how far upstream the zone of transition extends. Conceivably, the chloride concentration at Main Street Bridge could approach that of sea water diluted only by local inflow if the entire zone of transition moved upstream from the bridge, but this condition has not been observed.

NON-TIDAL FACTORS

Although tide exerts the greatest influence on the flow regime of the St. Johns River at Jacksonville, the regime is continually affected by other factors, which are non-tidal in origin. These factors, which include wind, runoff, channel storage, rainfall, and evapotranspiration may interact in any number of combinations to superimpose their combined effect on the tidal flow regime. It is thus not possible to distinguish the proportionate effect of the individual factors on a single tidal event. However, the net effect can be shown by comparing characteristics of observed tidal events with those of the theoretical event. Both the time of occurrence and the magnitude of flood and ebb strengths caused by the gravitational tide-producing forces are theoretically fixed and predictable. The predicted times and maximum velocities of the tidal currents at St. Johns River Entrance and at Jacksonville near the Main Street Bridge are published by the NOS. A constant relation exists between the times that maximum velocity occurs at these two sites and also between the maximum velocities attained.

The scatter of the points in figure 7A around the line of agreement between predicted and observed data shows the net effect of non-tidal factors on the time of occurrence of maximum velocity in the St. Johns River during 28 tidal cycles for which the actual times of ebb and flood strength were observed. A small part of the departures from the line may be owing to difficulty in determining the exact time of maximum velocity by observation.
Figure 7A. Relation of the observed times of occurrence of maximum velocities to the predicted times of occurrence.

Figure 7B. Relation of the observed maximum discharges at Jacksonville to the predicted maximum current velocities at St. Johns River Entrance during 28 tidal cycles observed in 1954, 1955, 1956, 1963 and 1964.
Comparisons of the maximum upstream and downstream discharges at Main Street Bridge with the concurrent predicted maximum velocities at St. Johns River Entrance during the 28 observed tidal cycles are shown on figure 7B. The peak discharges at Main Street Bridge may be compared directly with the current strengths at St. Johns Entrance because the peak discharge is directly proportional to the maximum velocity at Jacksonville (fig. 3), and the maximum velocity at Jacksonville has a fixed relation to the maximum velocity at St. Johns River Entrance. (See annual tidal current tables.) The linear curves, representing unaltered tidal flow, pass through the average maximum upstream and downstream discharges at Main Street Bridge and the average maximum upstream and downstream velocities of St. Johns River Entrance. The departures from the curves represent the influence of non-tidal factors.

**WIND**

In general, winds from the northern quadrants increase the upstream flow and decrease the downstream flow; whereas winds from the southern quadrants have the opposite effect. The greatest effects from winds of comparable speed are those caused by winds blowing from the northeast or southwest. Winds that add energy to the system elsewhere can affect the flow at Jacksonville. As stated earlier, occasionally wind effect is greater than the tidal effect.

**FRESH-WATER INPUT**

Fresh water enters the estuary as direct runoff, spring flow and ground-water seepage, and direct rainfall; the total from these sources minus the evapotranspiration from the estuary is the fresh-water input. When the input is positive, that is when evapotranspiration is exceeded by the total of the other elements of input, it tends to increase the duration and volume of downstream flows and to decrease the duration and volume of upstream flows. However, especially during droughts, evapotranspiration sometimes exceeds the total of the other elements of input, and fresh-water input is negative. During such periods, if insufficient water is stored in the estuary to keep its level higher than the level of the ocean, ocean water will flow upstream. When this happens, the duration and volume of the upstream flows tend to be greater than those of the downstream flows and the zone of transition moves upstream relatively fast.

The effect of fresh-water inflow to the estuary on the volumes of both the upstream and downstream flows is shown by figure 8. The average volume of the downstream flows during the water years 1955 to 1966 was computed to be 2,076 mcf (million cubic feet) and that of upstream flows 1,806 mcf. Thus, the computed average net (fresh-water) flow, was 270 mcf per tidal cycle in the downstream direction. Had the net, or fresh-water flow, not been superimposed on the tidal flow during this period, the average volume of a tidal flow would have been the average of the computed upstream and downstream volumes or, 1,941 mcf. Thus, the average relation of the computed tidal flow volumes to the computed net fresh-water volumes is as shown by the two linear curves in figure 8.
The data for the individual water years would be expected to plot on these curves if the average range of tide for the individual years were the same as that for the 12-year period. However, the average ranges of tide determined from the tide tables for Mayport were not the same for the individual years. Therefore, the average tidal volumes for the individual years were adjusted to allow for these differences. These adjustments were based on the linear curve of relation shown on figure 9. This curve passes through the average range of tide (4.57 feet) at Mayport and the average volume of tidal flow (1,941 mcf) at Jacksonville. The curve is nearly parallel to the plot of average volume of flow against range of tide shown by the solid circles on figure 9, especially in the
The plot of solid circles on figure 9 was obtained by matching each range of tide on rising tide at Mayport with the volume of the ensuing upstream tidal flow at Jacksonville and each range of tide on falling tide with the volume of the ensuing downstream tidal flow at Jacksonville. Thus, each time the range of tide was a specific value, the corresponding volume of tidal flow was listed under that value. The volumes of tidal flow plotted on figure 9 are the averages of these lists of volumes.

The linear relation through the average volume of tidal flow and the average range of tide indicates a volume adjustment of 425 mcf per foot of departure of the yearly average range of tide from the 12-year average range of tide. Thus, if the average range of tide during a year were 0.1 foot less than the 12-year average, 42.5 mcf were added to the volumes of tidal flow for that year.
The adjusted yearly average volumes of downstream tidal flow are plotted against the corresponding average net flow per tidal cycle on the upper curve, and those of the upstream tidal flows, on the lower curve, in figure 8. The departures from the curves for the 12-year period are probably caused mostly by errors in determining the volumes of tidal flow. The maximum departure is 5.7 percent and the average departure is 2.7 percent.

**STORAGE**

Water enters the reach of the St. Johns River estuary that lies between Jacksonville and De Land as downstream flow at De Land, upstream flow at Jacksonville, inflow from the intervening tributaries, ground-water inflow, and rainfall directly onto the estuary. Water leaves this reach of the estuary as upstream flow at De Land, downstream flow at Jacksonville, and evapotranspiration from the estuary. These eight factors can interact in any number of combinations to change the amount of water stored in the estuary. If these factors interact to increase storage, the effect is to decrease the volumes and durations of downstream flows and to increase the volumes and durations of upstream flows at Jacksonville. If they interact to reduce storage, the effect is to increase downstream flows and decrease upstream flows. Most of the time storage in the estuary -- and, therefore, the flow at Jacksonville -- is affected more by fresh-water inflow and outflow than by rainfall and evapotranspiration.

Figure 10 shows for the period of record, March 1, 1954 to September 30, 1966, the average monthly change in storage in the estuary and the estimated average monthly difference in rainfall and evapotranspiration. The average annual variation in sea level is also shown in figure 10 because it has a pronounced effect on the flow at Jacksonville and, therefore, the storage in the estuary.

Storage changes in the reach of the estuary between De Land and Jacksonville, which are shown by figure 10, were computed as follows:

1. The average discharge at Jacksonville was computed for the entire period of record and for the individual months by subtracting the computed upstream flow from the computed downstream flow.
2. Rainfall and evapotranspiration were assumed equal for the 12-year period, and change in storage over the period relative to the total flow during the period was considered negligible, so that total average inflow equals average discharge at Jacksonville.
3. The average gaged inflow to the estuary upstream from Jacksonville during the 12-year period was computed for the individual months, and the percentage of the total average gaged inflow occurring in each month was determined.
4. The average discharge at Jacksonville was multiplied by the percentage of gaged inflow determined for the individual months to obtain the total average monthly inflow.
5. The average monthly discharges at Jacksonville were subtracted algebraically from the total average monthly inflow to obtain the average monthly change in storage.
Average monthly rainfall and evapotranspiration were estimated on the basis of Weather Bureau record at various places in the St. Johns River basin.

The results of these procedures indicate that, on the average, storage increases about 1,250 cfs in April and May, even though evapotranspiration exceeds rainfall by about 700 cfs (fig. 10). This is because backwater from rising sea level during these months holds back the outflow, so that the average inflow exceeds the average outflow by about 1,950 cfs. Even in very dry years storage increases during April and May, because, if fresh-water input is insufficient to hold the estuary at a level at least as high as that of the ocean, sea water flows...
upstream into the estuary, where it is stored until the level of the estuary becomes higher than the level of the ocean.

The tendency for sea water to move upstream, when the amount of water stored in the estuary is low in March and fresh-water inflow is small during the subsequent period of rising sea level, is illustrated by the period March to September 1956. Inflow to the estuary for this period was estimated to be 3,720 cfs. Fresh-water input accounted for 2,160 cfs of this inflow, and upstream flow of sea water accounted for the other 1,560 cfs. Evaporation from the surface of the estuary was estimated to have exceeded rainfall onto the surface during the period by only 300 cfs. This indicates that the long periods of average net upstream flow at Jacksonville result more from the coincidence of low storage in the estuary at the start of the annual general rise in sea level than from an excess in evaporation over rainfall. In fact, May 1962 was the only month during the period March 1954 to September 1966 that the inflow of fresh water was estimated to be less than the excess of evaporation over rainfall.

Figure 10 shows, further, that storage in the estuary on the average continues to increase from June through September. Average input is greater than average output during this period because of increasing backwater from rising sea level during much of the period and because average rainfall exceeds average evaporation throughout the period. On the average, fresh-water inflow in July increases so rapidly that storage in the estuary increases despite a small decline in sea level.

Figure 10 also shows that from October through March fresh-water input shows a general decline in concert with the annual decline in sea level, which results in the release of the water stored from April through September. On the average, only about three quarters of the water that enters the estuary from April through September is discharged at Jacksonville during that period. The rest is stored and released from October through March.

Figure 11 compares average discharge at Jacksonville during each water year with the proportional yearly average inflow to the estuary from 1954 to 1966. The departures of the individual years from the equal-flow line represent the changes in storage in the estuary during the individual water years. The average yearly discharge at Jacksonville was computed by subtracting the upstream flow from the downstream flow for each year. The proportional yearly average inflow was computed by totaling the yearly average discharges at the gaging stations contributing to the estuary, computing the ratio of these totals to the total of the 12-year average discharges at these stations, and multiplying the 12-year average discharge at Jacksonville by these ratios. This procedure presupposes that rainfall on the estuary and evapotranspiration from the estuary
during the 12-year period were equal and that the change in storage over the 12-year period was insignificant.

The years that fall to the right of the equal flow line in figure 11 are those during which storage in the estuary increased, and those that fall to the left are those during which storage decreased. The amount of water in the estuary at the onset of rising sea level in the years to the right was relatively small, and, therefore, much capacity was available for added storage. In fact, the water level in the estuary was so low in each of these years that the net flow at Jacksonville was upstream for at least 1 month. In the years to the left, high water levels at
the onset of rising sea level coupled with exceptionally high rates of outflow during the period of falling sea level resulted in decreases in storage comparable to the increases during the years that fall to the right. Parts of the storage changes resulted from the imbalance in the yearly rainfall and evapotranspiration totals, but, as indicated earlier, these imbalances play a minor role in the storage regime.

FLOW STATISTICS

Flow statistics for the St. Johns River at Jacksonville, based on the records computed for the period March 1, 1954 to September 30, 1966 are given in table 1. This period covers 4,597 days, during which 8,883 tidal cycles occurred. Therefore, the average duration of a tidal cycle during the period was, 0.5175 day, or 12.42 hours.

Table 1. Selected flow statistics for the St. Johns River at Jacksonville.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Direction of Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Downstream</td>
</tr>
<tr>
<td>Average discharge, cfs</td>
<td>46,419</td>
</tr>
<tr>
<td>Average net discharge, cfs</td>
<td>5,883</td>
</tr>
<tr>
<td>Maximum daily net flow, cfs</td>
<td>87,000</td>
</tr>
<tr>
<td>Minimum daily net flow, cfs</td>
<td>-</td>
</tr>
<tr>
<td>Average volume per tidal cycle, mcf</td>
<td>2,075.5</td>
</tr>
<tr>
<td>Average net volume per tidal cycle, mcf</td>
<td>263.1</td>
</tr>
<tr>
<td>Maximum volume per tidal cycle, mcf</td>
<td>5,280</td>
</tr>
<tr>
<td>Minimum volume per tidal cycle, mcf</td>
<td>0</td>
</tr>
</tbody>
</table>
The monthly mean upstream and downstream volumes of flow per tidal event for the period indicated are shown by graph A on figure 12. This graph is the composite of the flow caused by both tidal and non-tidal factors. Graph B on figure 12 shows the averages of the upstream and downstream volumes of flow shown in graph A. These volumes represent the part of the composite flow caused by the tide because non-tidal factors that tend to increase flow in one direction also tend to decrease flow in the other direction, so that averaging the flow in both directions cancels the non-tidal influences. As indicated previously, the flow is approximately proportional to the range of tide, and over the period of a month it is very nearly proportional, as the effects of lunar declination are largely self cancelling. Therefore, the distribution of the values in graph B about the mean value should be similar to the distribution of the monthly average predicted ranges of tide about the mean of the predicted range of tide during the
same period as shown by graph C on figure 12. However, a comparison of graphs B and C shows that the distributions about the means are not similar. For example, in October 1958, when the indicated flow caused by tide was the smallest during the period of record, the mean predicted range of tide was 0.9 foot above the average value. Conversely, in January 1964, when the indicated tidal flow was the greatest during the period of record, the mean predicted range of tide was 0.6 foot below the average value. Some of this nonconformity may be caused by errors in the computation of the flow values.

Graph D on figure 12 shows the monthly mean net flow per tidal cycle in the St. Johns River at Jacksonville. The monthly mean net volume of flow per tidal cycle for each month is the algebraic difference in the monthly mean volume of downstream flows and the monthly mean volume of upstream flows, shown by graph A, for the corresponding month. The mean net volume of flow per tidal cycle for each month is equal to the average fresh-water inflow into the estuary per tidal cycle, plus the average rainfall on the estuary per tidal cycle, minus the average evapotranspiration from the estuary per tidal cycle, plus or minus the average change in storage per tidal cycle during the month. If the sum of fresh-water inflow and rainfall is greater than evapotranspiration plus or minus the change in storage in a month, the average net flow per tidal cycle will be downstream. If the sum of fresh-water inflow and rainfall is less than evapotranspiration plus or minus the change in storage in a month, the average net flow per tidal cycle will be upstream.

The 21 months during which the average net flow was upstream all occurred during the dry season in exceptionally dry years except, possibly, February 1966, which followed the very dry year 1965. During these months, storage in the estuary was relatively small, and this condition coupled with high losses by evapotranspiration permitted more water to flow upstream into the estuary than flowed out. In 1962, the excess of upstream flow was so great that enough sea water entered the estuary to cause the chloride concentration to exceed 2,000 mg/l (milligrams per liter) at Green Cover Springs, where the chloride concentration is ordinarily less than 400 mg/l.

FLOW DISTRIBUTION AND FREQUENCY

The distribution of the volumes of tidal flows in the St. Johns River at Main Street Bridge in Jacksonville is shown in figures 13 and 14. The distribution of flow volumes during tidal flows in increments of 100 million cubic feet is shown as percentages of the total number of tidal flows.
A cumulation of a flow-distribution curve of data for flow occurring continuously in time is called a flow-duration curve. Tidal flow is not continuous in one direction, and, therefore, the duration of flow in any one duration can be described only in terms of percentage of the total number of tidal flows during which the flow was in that direction. The volume of a tidal flow is a function of both the duration of and the average discharge during the tidal flow. The relation between these three parameters is not constant, and, therefore, the volume of an individual tidal flow does not determine its duration. Therefore, in this report, the cumulation of flow-distribution curves.

Cumulative flow-distribution curves that show the percentage of the total number of tidal flows during which specific volumes were equaled or exceeded during tidal flows are defined by the open circles on figures 13 and 14. Cumulative flow-distribution curves that show the percentage of the total number of days of record during which specific total daily volumes of downstream or upstream flow were equaled or exceeded are defined by the solid circles in figures 13 and 14. Values for equal percentages in figures 13 and 14 cannot be subtracted to obtain the net flow for that percentage because it is necessary to take the algebraic sum of consecutive downstream and upstream flows to obtain the net flow for a tidal cycle. Figure 15 is a cumulative flow-distribution curve of the daily net flow in the St. Johns River at Main Street Bridge. The curve was computed using the algebraic sum of the daily downstream and upstream volumes of flow. The volumes of downstream and upstream flows are increasingly large in comparison with the net flow volume as the net flow volume approaches zero, and, therefore, the computed net flow volume is subject to increasingly greater percentage error as the net flow volume approaches zero. However, the smooth transition of the cumulative flow distribution curve from positive to negative net flow indicates that, although values for individual days may be grossly erroneous, the errors may be mutually compensating, and the curve may be approximately correct.

The average recurrence intervals in months and years of specific monthly and yearly extremes in volumes of tidal flow are shown by figures 16 through 21. The curves are based on data obtained between March 1954 and September 1966. The following discussions of the figures presuppose that conditions during the period of record are representative of long-term conditions.

Figure 16 shows the average recurrence intervals in months and years of downstream tidal flow volumes that occur as monthly and yearly maximums. For example, the average recurrence interval of monthly maximum downstream tidal flows of 4,000 mcf or more is 60 months. Likewise, the average recurrence interval of yearly maximum downstream tidal flows of 4,000 mcf or more is 6.7 years.
Figure 13. Flow distribution and cumulative flow-distribution curves for downstream flow at Main Street Bridge.

Figure 17 shows the same information for upstream flows that figure 16 shows for downstream flows. For example, the average recurrence interval of monthly maximum upstream tidal flows of 3,400 mcf or more is 60 months. The average recurrence interval of yearly maximum upstream tidal flows of 3,400 mcf or more is 4.2 years.

Figure 18 shows the average recurrence intervals in months and years of downstream tidal flow volumes that occur as monthly and yearly minimums. For example, the average recurrence interval of monthly minimum downstream tidal flows of 1,000 mcf or less is 5 months, and the average recurrence interval of yearly minimum downstream tidal flows of 1,000 mcf or less is 1.18 years.

Figure 19 shows the same information for upstream flows that figure 18 shows for downstream flows. For example, the average recurrence interval of monthly minimum upstream tidal flows of zero flow is about 86 months, and the average recurrence interval of yearly minimum upstream tidal flows of zero flow is 7.2 years.
Figure 14. Flow distribution and cumulative flow-distribution curves for upstream flow at Main Street Bridge.
Figure 15. Cumulative flow-distribution curve of daily net flow of the St. Johns River at Main Street Bridge.
Figure 16. Frequency of monthly and annual maximum downstream flows in the St. Johns River at Main Street Bridge.
Figure 17. Frequency of monthly and annual maximum upstream flows in [missing text].
Figure 18. Frequency of monthly and annual minimum downstream flows in the St. Johns River at Main Street Bridge.
Figure 19. Frequency of monthly and annual minimum upstream flows in the St. Johns River at Main Street Bridge.
Figure 20. Frequency of monthly and annual maximum daily net flow in the St. Johns River at Main Street Bridge.
Figure 20 shows the average recurrence intervals in months and years of daily net flows that occur as monthly and yearly maximums. For example, the average recurrence interval of monthly maximum net flows of 5,000 mcf or more is 120 months, and the average recurrence interval of yearly maximum net flows of 5,000 mcf or more is 10.3 years.

Figure 21 shows the average recurrence intervals in months and years of daily net flows that occur as monthly and yearly minimums. For example, the average recurrence interval of monthly minimum net flows of minus 3,000 mcf or less is about 74 months, and the average recurrence interval of yearly minimum net flows of minus 3,000 mcf or less is 6.3 years.

The extremes caused by Hurricane Dora do not fit these relations except, possibly, the minimum upstream flow. This is probably because the conditions that caused the extremes are unlikely to occur frequently. The minimum upstream flow, however, is more likely to occur than the other extremes because the conditions required to cause small upstream flows occur much more frequently than the conditions required to cause the other extremes. In fact, the volumes of four upstream flows during the period of record were less than 100 million cubic feet.

MAXIMUM PERIODS OF FLOW DEFICIENCY

Figure 22 shows the maximum number of consecutive days that the daily net flow was less than specified amounts between October 1954 and September 1966. However, the figure does not indicate how much less than a specific amount the daily net flow was for any specific number of days. The number of consecutive days that the flow remains below a specific volume has no relation to the total amount of net flow during those days. For example, even though the net flow was upstream in excess of 518 million cubic feet per day for 7 consecutive days in both 1963 and 1966, during the 1963 period the average net flow was only 8,660 cfs upstream, whereas during the 1966 period the average net flow was 22,720 cfs upstream.

Between March 3 and October 15, 1956, the cumulative net upstream flow was 34 billion cubic feet, an average of 150 million cubic feet per day. Between January 26 and August 14, 1962, the cumulative net upstream flow was 39 billion cubic feet, an average of about 200 million cubic feet per day. Most of this flow was sea water moving in to replace water lost by evaporation or to provide the normal increase in channel storage that results from the annual rise in sea level from March to October. In wet years this water is provided by fresh-water inflow.
Figure 21. Frequency of monthly and annual minimum daily net flow in the St. Johns River at Main Street Bridge.
Figure 22. Maximum periods of deficient daily net flow in the St. Johns River at Jacksonville.
CHEMICAL CHARACTERISTICS

Variation in the flow of the St. Johns River at Jacksonville is accompanied by variations in the chemical characteristics of the water in the river. Ocean water advances up the lower St. Johns River during each upstream flow and recedes from the river during each downstream flow. While it is in the river, some of the ocean water mixes with fresh water within a zone in which a transition from water having the chemical characteristics of ocean water at its downstream end to water having the chemical characteristics of the fresh water at its upstream end takes place. This zone of transition was discussed in the section of this report on the relation of chloride concentration in the river to the tidal cycle.

Reliable estimates of the concentration of dissolved chemical constituents in the St. Johns River can be made quickly and conveniently by use of the curves of relation shown in figure 23 between the concentration of the chemical constituents and the specific conductance of the water in the river (specific conductance is a measure of the ability of water to conduct electricity, and it is reported in micromhos per centimeter at 25°C).

Chemical analyses of samples of water from the St. Johns River at Main Street Bridge, obtained from April 1966 through May 1967, are given in table 2. The curves shown in figure 23 are based primarily on the data given in table 2.

VARIATIONS IN CHEMICAL CHARACTERISTICS AT MAIN STREET BRIDGE

The relation of specific conductance to the concentration of chemical constituents was used in evaluating the variations in chemical characteristics of the St. Johns River at Main Street Bridge.

In 1966, an instrument was installed at Main Street Bridge to obtain a continuous record of the specific conductance of the river. The daily maximum specific conductance near the surface of the river recorded by this instrument from October 1, 1966, to April 21, 1967, is shown in figure 24. The extreme variability in chemical quality is indicated by the changes in specific conductance from November 19-28, 1966. The specific conductance increased from about 8,000 micromhos on the 19th to more than 30,000 micromhos on the 23rd and then decreased to about 8,000 micromhos by the 28th. Changes in specific conductance of as much as 12,000 micromhos during a single tidal cycle are common. (See fig. 15).
Figure 23. Relation of specific conductance to concentration of major chemical constituents in the St. Johns River at Main Street Bridge.

Figure 24. Daily maximum specific conductance near the surface of the St. Johns River at Main Street Bridge, October 1966 to April 1967.
Table 2. Chemical analyses of the St. Johns River at Jacksonville, Florida - (samples collected at Main Street Bridge).

| Date of Collection | Silica (SiO₂) (mg) | Iron (Fe) (mg) | Calcium (Ca) (mg) | Magnesium (Mg) (mg) | Sodium (Na) (mg) | Potassium (K) (mg) | Bicarbonate (HCO₃⁻) (mg) | Sulfate (SO₄²⁻) (mg) | Chloride (Cl⁻) (mg) | Fluoride (F⁻) (mg) | Nitrate (NO₃⁻) (mg) | Phosphate (PO₄³⁻) (mg) | Dissolved solids (mg) | Hardness as CaCO₃ (mg) | Calcium, Magnesium, Non-carbonate (mg) | Residue on evaporation at 180°C (mg) | pH | Special conductance (micromhos at 25°C) |
|--------------------|-------------------|----------------|------------------|-------------------|----------------|------------------|------------------------|---------------------|-------------------|------------------|-------------------|---------------------|----------------------|----------------------|------------------------------------------|------------------|------------------------|
| 1966               |                   |                |                  |                   |               |                  |                        |                     |                   |                  |                   |                     |                      |                      |                                           |                  |                        |
| b Apr. 26          | 0.7               | 0.01           | 41               | 26                | 201            | 7.3              | 66                     | 88                  | 359               | 0.3              | 0.1               | 0.00               | 765                   | 820                  | 210                   | 156                      | 1470             | 7.3                    |                      |
| t Oct. 5           | 4.7               | 0.05           | 1.04             | 10.04             | 274            | 2320             | 84                     | 571                 | 4090              | 0.5              | 2.1               | 0.16               | 7490                  | 7830                 | 1390                  | 1320                      | 1300             | 7.0                    | 100                   |
| b Oct. 5           | 2.4               | 0.00           | 1.00             | 100                | 377            | 3240             | 119                    | 84                  | 750               | 0.6              | 3.3               | 0.20               | 10400                 | 10500                | 1900                  | 1830                      | 17500            | 7.1                    | 80                    |
| t Oct. 10          | 3.6               | 0.05           | 0.05             | 0.05              | 29             | 14                | 95                     | 64                  | 42                | 176              | 0.3              | 0.15               | 396                   | 459                  | 130                   | 78                         | 790              | 7.0                    | 100                   |
| b Oct. 10          | 3.9               | 0.05           | 0.05             | 0.05              | 28             | 14                | 96                     | 60                  | 43                | 174              | 0.3              | 0.26               | 394                   | 462                 | 128                   | 79                         | 790              | 6.8                    | 100                   |
| t Nov. 3           | 4.6               | 0.04           | 0.04             | 0.04              | 27             | 10                | 71                     | 40                  | 34                | 136              | 0.3              | 0.11               | 306                   | 360                 | 109                   | 76                         | 618              | 6.9                    | 120                   |
| b Nov. 3           | 2.6               | 0.13           | 0.13             | 0.13              | 27             | 10                | 72                     | 78                  | 28                | 128              | 0.3              | 0.10               | 310                   | 363                 | 109                   | 45                         | 770              | 6.8                    | 110                   |
| t Nov. 16          | 5.2               | 0.08           | 0.08             | 0.08              | 211            | 608               | 5340                    | 85                  | 1240              | 9470             | 0.9              | 1.5                | 17100                 | 18200                | 3030                  | 2960                       | 28000            | 7.0                    | 40                    |
| b Nov. 16          | 2.5               | 0.05           | 0.05             | 0.05              | 225            | 633               | 5520                    | 200                 | 109               | 1320             | 0.9              | 1.1                | 17700                 | 18700                | 3170                  | 3080                       | 30000            | 7.1                    | 60                    |
| t Nov. 21          | 4.6               | 0.11           | 0.11             | 0.11              | 104            | 263               | 2310                    | 82                  | 84                | 563              | 0.6              | 1.2                | 7460                   | 7560                 | 1340                  | 1270                       | 12500            | 7.1                    | 120                   |
| b Nov. 21          | 3.4               | 0.10           | 0.10             | 0.10              | 131            | 351               | 3110                    | 122                 | 112               | 756              | 0.6              | 6.3               | 10100                  | 10600                | 1770                  | 1680                       | 18000            | 7.0                    | 100                   |
| t Dec. 22          | 3.4               | 0.12           | 0.12             | 0.12              | 72             | 141               | 1180                    | 46                  | 78                | 304              | 0.3              | 1.1               | 3890                   | 4150                 | 760                   | 696                        | 6700             | 7.1                    | 100                   |
| 1967               |                   |                |                  |                   |               |                  |                        |                     |                   |                  |                  |                     |                      |                      |                                           |                  |                        |
| t May 10           | 3.6               | 0.05           | 0.05             | 0.05              | 215            | 448               | 3690                    | 143                 | 95                | 933              | 0.7              | 5.7               | 12300                  | —                    | 2380                  | 2310                       | 20800            | 6.9                    | 45                    |

(t) top sample  
(b) bottom sample
Figure 25. Cumulative discharge and specific conductance at the end of each tidal flow beginning December 12, 1966 and ending January 31, 1967.

The specific conductance at the end of each tidal flow and the cumulative discharge at Main Street Bridge is shown by figure 25 for the period December 12, 1966, to January 31, 1967. The scale on the cumulative discharge graph is inverted so that the graphs may be more easily compared. The graphs show that as long as the zone of transition extends upstream from Main Street Bridge the specific conductance of the river at Main Street Bridge decreases with increasing discharge accumulation and increases with decreasing discharge accumulation. Discharge accumulation increases with downstream flow and decreases with upstream flow.

The amount of change in the specific conductance of the river is not always the same for a specific change in cumulative discharge because the rate of change in specific conductance is dependent on the gradient of the zone of
transition. If the zone of transition is entirely downstream from the Main Street Bridge when cumulative downstream flow begins, little or no change in specific conductance occurs at Main Street Bridge as a result of tidal action. The specific conductance would be that of the fresh-water input. Conversely, if enough cumulative upstream flow were to occur, the specific conductance of the river at Main Street Bridge could approximate that of sea water; however, this condition has not been observed. The specific conductance near the surface of the river also tends to increase during periods of non-accumulating flow because of mixing in of water with higher conductance from greater depth. It follows that the specific conductance at greater depth decreases during such periods. However, this hypothesis has not been verified.

From October 1954 to September 1966, the Jacksonville Department of Public Health obtained water-quality data at the Main Street Bridge at about 2-month intervals in each year except 1956. These data were collected throughout a total of 63 complete tidal cycles. The chloride concentration was determined by chemical analysis of samples collected hourly during each of the tidal cycles. Concentrations of sulfate, sodium, hardness and dissolved solids during these cycles were calculated from their relation to the chloride concentration using figure 23. Duration curves of these chemical constituents in the river during the 63 tidal cycles sampled are shown in figure 26. Although in a strict sense the data apply only to the cycles sampled, they are considered fairly representative of the long-term duration because the sampling was done at uniform intervals. However, had continuous data been available for the period, the durations, especially the extremes, probably would differ some from those shown in figure 26. The curves show the percentage of time that the concentration of any of the major constituents is equal to or more than any specified amount. For example, the curve for duration of chloride concentration shows that the chloride concentration equals or exceeds 250 mg/l 82 percent of the time.

VARIATIONS IN CHLORIDE CONCENTRATION IN THE LOWER ST. JOHNS RIVER

Chloride concentrations in the lower St. Johns River were investigated by measuring the specific conductance of the water in mid-channel at selected points on May 18, October 18, and December 12, 1966. Figure 27 shows the results of these measurements for the reach of the river from 12 to 31 miles upstream from its mouth. The measurements were made near both the bottom and surface of the river at each of the points indicated. On May 18 and October 18, 1966, measurements were made at slack water before both downstream and upstream flow, but on December 12, 1966, measurements were made at slack water before the downstream flow only. The average daily net flow was 3,120
Figure 26. Duration curves of major chemical constituents in the St. Johns River at Jacksonville.
cfs upstream on May 18, 9,370 cfs downstream on October 18, and 5,320 cfs upstream on December 12. Although the general level of the specific conductance and chloride concentration do not depend wholly on the net flow of the river for any single day but rather on the cumulative flow over many days, the specific conductance was higher on May 18 and December 12, when the net flow was upstream, than it was on October 18, when the net flow was downstream. Further, both the specific conductance and the rate of increase in specific conductance with river mileage were higher on December 12, when the average net flow was 5,320 cfs upstream, than on May 18, when the average net flow was only 3,120 cfs upstream. Also, at slack water before downstream flow on October 18, the specific conductance near the surface was lower at river miles 12.2 and 15 than at some points farther upstream. This was probably caused by high fresh-water inflow to the St. Johns River from Trout River and other nearby tributaries, as indicated by high discharges recorded on nearby Ortega River. At slack water before upstream flow on October 18, virtually fresh water was observed as far downstream as the mouth of Trout River.

Figure 27. Longitudinal and vertical variation in specific conductance of the water in the lower St. Johns River from river mile 12 to river mile 31 at slack water on selected days.
A vertical gradient in chloride concentration tends to exist in estuaries such as the St. Johns River because the lighter fresh water tends to override the denser sea water. In a straight and uniform river channel, sea water enters and recedes from the channel as a wedge of salt water between the river bottom and the overlying fresh water and mixing is caused primarily by turbulence at the salt-water-fresh-water interface. However, the channel of the St. Johns River is neither straight nor uniform. Instead, it bends and varies in both width and depth, so that a well defined interface between salt water and fresh water does not exist in the river in the Jacksonville area. Thus, the river either has no vertical gradient in chloride concentration or has a uniform increase in chloride concentration with depth.

The change with time in specific conductance, which is indicative of the chloride concentrations near the surface and the bottom of the river, is shown in figure 28 for four of the points measured May 18, 1966. The amount of vertical variation in specific conductance is indicated by the shaded areas. The data show that vertical variation in specific conductance increases with distance downstream from the river constriction and bridge piers near Main Street Bridge (river mile 21) but changes little with distance upstream from the constriction. This indicates that the vertical variation in chloride concentration, which tends to decrease gradually between the ocean and Main Street Bridge during upstream flows, is almost eliminated by the turbulence and eddies created by the constriction and bridge piers. At the beginning of the measurement period (figure 28), flow was upstream, and the major change in the vertical variation in chloride concentration took place between Commodore Point and Acosta Bridge, showing the great effect of the constriction and piers on the vertical variation in chloride concentration. Near the end of the measurement period, however, the major change in the vertical variation in chloride concentration took place between Commodore Point and Dredge Depot. By this time, the flow had been downstream for more than 6 hours and then upstream for about 2 hours, and the shift in the reach of major change in variation represents the displacement of the zone of transition by the downstream flow. The greater vertical variation in chloride concentration at Dredge Depot at the end of the measurement period than at the beginning is probably related to the tendency for sea water to flow upstream beneath the fresh water late in the downstream part of the tidal cycle. This results in greater vertical variation in chloride concentration in the early stages than in later stages of the upstream part of the cycle.

Data from the survey shown in figure 27 and from pollution surveys by the Jacksonville Department of Public Health indicate that there is no fixed relation between chloride concentrations at different sampling points along the river. However, a fair relation was indicated between the maximum chloride
Figure 28. Variations with time in the specific conductance of the St. Johns River near the surface and bottom at selected points in the Jacksonville area.

Concentrations at different sampling points at slack before the downstream flow of common tidal cycles. Figure 29 shows the relation between the maximum chloride concentration at the Main Street Bridge and those upstream at Orange Park and downstream at Drummond Point for the same tidal cycle. The figure shows that, with increasing chloride concentration at Main Street Bridge, the chloride concentration at Orange Park at first increases less rapidly but later on increases more rapidly than at Main Street Bridge. The opposite relation prevails between the chloride concentrations at Drummond Point and Main Street Bridge.

The maximum chloride concentration observed at the Main Street Bridge from October 1954 to October 1966 was 12,700 mg/l on February 12, 1962. Extrapolation of the relation in figure 29 indicates that the maximum chloride concentrations at Orange Park and Drummond Point on February 12, 1962, may have been about 10,000 and 17,000 mg/l, respectively.

The longitudinal variation in the chloride concentration at slack water before the downstream flows of common tidal cycles in the St. Johns River between its mouth and Palatka, which would be exceeded as the daily maximum less than 7 percent of the days, is shown in figure 30. The longitudinal variation
in chloride concentration which would be exceeded as the daily maximum 50 percent of the days is similarly shown for the reach between Drummond Point and Orange Park. The chloride concentrations for all points shown in the figure other than at Main Street Bridge were derived from relations like those shown in Figure 29.

SEASONAL VARIATION IN FLOW AND CHLORIDE CONCENTRATION

The average monthly mean tidal flow at Jacksonville during the period of record from March, 1954, to September, 1966, should be about the same for every month. Thus, there should be no seasonal variation in the tide induced flow. This is because the tidal flow is approximately proportional to the range of tide (Haight, 1938) and the monthly mean ranges of tide as determined from the tide tables for the period of record were almost the same for every month. The difference between the highest and lowest monthly mean range of tide was 0.027 foot. The record shows a difference of 235 mcf between the highest and lowest monthly mean tidal flow which ranged from 7.4 less than to 4.7 percent more than the mean tidal flow.
Figure 30. Approximate longitudinal variation in the daily maximum chloride concentration which will be exceeded less than 7 percent of the days and 50 percent of the days in the lower St. Johns River.
Because, as indicated by the foregoing discussion, all average monthly mean tidal flows should be almost the same, any seasonal variation in the flow of the river is manifested by the net flow. Determination of the net flow of the river can be no more accurate than that of the tidal flow and on a percentage basis, it must be considerably poorer. This is especially true for periods when the net flow is small. The inaccuracy of the record is indicated by the computed average net flow of only 5,883 cfs whereas the average net flow based on the gaged inflow and estimated inflow from ungaged areas is about 8,100 cfs. Nevertheless, the average and extreme monthly mean discharges based on the records for the river at Jacksonville are shown by figure 31. The distribution pattern, if not the values, is probably valid as is the departure from average conditions indicated by the extremes.

Figure 31 shows the seasonal net flow regime of the St. Johns River at Jacksonville to consist of four periods, which result from the interplay of the rainy season from June through October, the dry season from November through May, the period of increasing storage from April through September, and the period of decreasing storage from October through March. The four periods are that of low net discharge in May and June, that of increasing net discharge from July through September, that of high net discharge from October through January, and that of decreasing net discharge from February through April.

Some insight into the seasonal variation in chloride concentration was obtained from the bimonthly chloride data collected by the Jacksonville Department of Public Health. A generalized comparison between the average of extremes in chloride concentration and average net outflow at Jacksonville for the same months is shown in figure 32. As would be expected, there is an inverse relation between chloride concentration and net discharge. The range between the average maximum and average minimum chloride concentration at Jacksonville is greatest when net outflow is low because the gradient of the zone of transition is steeper at Jacksonville under these conditions than when net outflow is high. That is, low net outflow places Main Street Bridge closer to the sea-water end of the zone of transition, where the gradient is steep; whereas, high net outflow places Main Street Bridge near the fresh-water end of the zone, where the gradient is gentle.

**TEMPERATURE**

In 1966, about 180 million gallons of water per day was withdrawn from aquifers in the Jacksonville area (Leve, 1969). Perhaps 30 to 50 mgd (million gallons per day) of this water was used for cooling in various processes. If
Figure 31. Graphs showing the highest, lowest, and average monthly mean net discharge of the St. Johns River at Jacksonville.
surface-water sources such as the St. Johns River could be substituted for ground-water sources to provide this cooling water, all the projected increase in water demand from 1966 to 1980 could be met without increasing the rate of withdrawal of water from the aquifers.

Water-temperature measurements of the St. Johns River taken at random over a period of several years and temperature of ground water at different depths in the area are portrayed by figure 33. Water temperatures in the artesian
Figure 33. Approximate average daily water temperatures of the St. Johns River at Main Street Bridge and ground-water at specified depths.

The temperature of water from wells 500 to 800 feet deep averages about 24°C (75°F) and that of water from wells greater than 1,000 feet deep about 27°C (81°F).

Figure 33 shows that the water in the St. Johns River has a lower temperature, and, therefore, a greater cooling capacity than any water from the artesian aquifer from November through April. In January and February, the temperature of the river water averages less than 15°C (59°F). The temperature of the river water is higher than that of all water now being withdrawn from the artesian aquifer only from June through mid September when the temperature of the river water averages more than 28°C (82°F). Thus, use of ground water in the Jacksonville area could be reduced if installations now perennially using ground water for cooling were to use river water from November through April, with the realization of some gain in efficiency of the installations.

RELATION OF FLOW AND QUALITY CHARACTERISTICS TO USE OF THE RIVER

Most uses of the St. Johns River at Jacksonville depend on the chemical and biological quality of the river. The water quality of the river is controlled by the flow of the river. The flow characteristics of the river are such that the river at Jacksonville can become saline, as a result of upstream flow, or severely
polluted with wastes as a result of low net flow. High chloride concentrations restrict use of the river for public water supply and industrial processes. High concentrations of wastes in the river, which can persist after the resumption of net upstream or downstream flow, adversely affect the esthetic and recreational value of the river.

SUMMARY AND CONCLUSIONS

The St. Johns River drains about one-sixth of the State of Florida and in its lower reaches is a tidal estuary in which about 1 in every 10 gallons of water that drains from Florida passes beneath the Main Street Bridge at Jacksonville. Daily tidal effects are evident as far upstream as Lake George, and, during droughts, the higher tides aided by northeasterly winds sometimes cause tidal fluctuations as far upstream as Lake Monroe. River levels below mean sea level have been observed near the southern end of Lake Harney.

The tide generates progressive tidal waves, which move up the river in cycles accompanied by tidal currents. When the tide at Jacksonville is about midrange, the current is slack. When the tide rises above about midrange, the current sets inland as upstream flow and reaches a maximum velocity at near high tide. When the tide falls below about midrange, the current sets seaward as downstream flow and reaches a maximum velocity at about low tide. Slack water does not occur at exactly midrange nor do the maximum velocities occur at exactly high and low tides. Instead, the tidal currents slightly lag the tides because of inertia and channel friction.

The main variable factors controlling the amounts of water flowing back and forth at Jacksonville are the height of the tides, the tidal range, and wind. The height of the tides varies annually and over even longer periods. The tidal range varies more rapidly, reaching a maximum and a minimum once in each lunar month. Both the tidal height and range are uniformly periodic in response to gravitational forces. The effect of wind on the flow of the St. Johns River at Jacksonville ranges from none at all to more than that of the tide.

Tidal and wind effects can work in concert or in opposition and thereby increase the variation in their net effect on the flow. The long-term effect of both tide and wind on the net downstream flow at Jacksonville is negligible, although, when evapotranspiration exceeds fresh-water input, tidal effect causes a small net upstream flow, which eventually is approximately offset by rainfall on the estuary.
Fresh-water input affects the tidal flow appreciably during very wet periods, but it is unlikely that its effect is ever sufficient to offset even the lesser tidal effects. When fresh-water input is equal to or less than evapotranspiration from the estuary, it cannot cause net downstream flow at Jacksonville. The average net or fresh-water flow at Jacksonville is about 14 percent of the average tide-induced flow.

Volumes of flow induced by tide average 1,944 mcf and range from about 1,250 mcf to about 2,750 mcf per tidal event. Average fresh-water flow computed from the flow records is 264 mcf per tidal cycle. The maximum effect of fresh-water flow and wind on tidal flow cannot be determined, but their minimum effect is zero.

Evapotranspiration from the river surface exceeds the sum of the rainfall on the river and the fresh-water inflow to the river during some droughts. When these conditions prevail at a time when storage in the estuary is low, they may work in concert with the annual rise in sea level to cause a cumulative net inflow of as much as 40 billion cubic feet of sea water over a period of months. The river becomes salty for many miles upstream from Jacksonville when this happens.

Frequency analysis of the flow records indicate that extremes in flow volume such as those caused by Hurricane Dora in September 1964 are rare, except for the minimum upstream flow volume, which was zero. The analysis indicates that the minimum upstream flow will be zero on an average of once in 7 years, whereas occurrences of the maximum and minimum downstream flow volumes of record and the maximum upstream flow volume of record are much less frequent.

The average seasonal flow regime of the St. Johns River can be divided into four periods, that of low net outflow in May and June, that of increasing net outflow from July through September, that of high net outflow from October through January, and that of decreasing net outflow from February through April. Wide departures from the average seasonal net flow regime can and often do occur as a result of abnormal rainfall.

The seasonal variation in chemical quality on the St. Johns River, as indicated by the chloride concentration in the water, is inversely related to the seasonal net outflow. The chloride concentration is generally lowest and varies the least as a result of tidal flow during the high net-flow period and is generally highest and varies the most as a result of tidal flow during the low net-flow period. The chloride concentration in the river generally increases during the period of decreasing flow and decreases during the period of increasing flow.
The quality and chemical composition of water in the St. Johns River is highly variable in the vicinity of Jacksonville. The chloride concentration may increase or decrease more than fourfold in a matter of a few hours and more than tenfold in several days. Variations in quality are controlled by the flow characteristics of the river. Chloride concentration in the river sometimes shows considerable vertical variation, which seems to be greatest at the time the river begins to flow downstream. There is some correlation between maximum chloride concentrations at Main Street Bridge and at other points on the river.

From November to April, water in the St. Johns River is cooler than ground-water at any depth, and, from October to May, river water is cooler than ground water at depths greater than 1,000 feet. Use of river water for industrial cooling would reduce the demand for ground-water supplies.

The flow and chemical characteristics of the St. Johns River at Jacksonville are dominated by tide, on a tide-to-tide, monthly, and annual basis. Fresh-water drainage from the river basin is the only factor that has a significant cumulative long-term effect on the flow of the river. All other factors, which include wind, rainfall, and evapotranspiration along with tide, are virtually self cancelling and have no cumulative effect on the flow of the river. The seasonal and short-term interaction of the factors that affect the flow of river are greatly modified by the availability of huge storage capacity in the tidal estuary upstream from Jacksonville.

The chemical characteristics and esthetic condition of the river are controlled by the flow characteristics of the river, which cause high concentrations of chemical constituents to occur at Jacksonville as a result of excessive upstream flow and, possibly, high concentrations of wastes in the river as a result of periods of little or no net river movement.

CONTINUING AND FUTURE STUDIES

One of the concerns for the future of the St. Johns River is the potential for pollution from industrial and domestic wastes. In addition to knowledge about the flow and chemical and temperature variations in the river, knowledge about the variations in dissolved oxygen, coliform populations, and eddy and turbulence regimes is essential in attaching the problems of pollution evaluation and control. Further, knowledge of the movements of the water and its contents, both areally and chronologically, is necessary to determine where wastes enter the river at Jacksonville, where they subsequently go, and how long they reside at a particular locale.
To help meet the need for information, continuous records of the stage, flow, conductivity, dissolved oxygen content, temperature, and pH of the river are being collected.

Study of the tidal parts of tributaries to the St. Johns River in and near Jacksonville by the U. S. Geological Survey show that very poor quality conditions sometimes exist in the tributaries. However, more definitive studies of the water quality in the tributaries are needed to determine the magnitude and duration of this problem.
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