Shallow-Water Effects on Diurnal River Tides: The West Pascagoula River, Mississippi

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

In order to understand better the diurnal tidal regime in a shallow river, an investigation of tides of the West Pascagoula River, Mississippi, is presented.

When applied to coastal stations, the traditional specification of the astronomical tides using harmonic analysis produces acceptable results. When applied to the distorted regime of shallow water, this harmonic method can become inadequate. One difficulty in dealing with shallow-water tides arises from the proliferation of higher harmonics when the tide curve is distorted by changes in the wave propagation speed and frictional attenuation. A second difficulty arises because some of these constituents are spectrally close and thus become difficult to resolve. Compound tides, which are hydrodynamic in nature, arise from the interaction between astronomical tidal constituents (Franco, 1956). Their significance depends on the amplitude of the interacting terms, water depth, and distance the tide has progressed.

Many researchers have addressed the problem of better defining shallow-water harmonic constituents. Doodson, who published the historical approach to analysis and prediction of tides in 1921, also developed a method of improved prediction of high and low waters called the Harmonic Shallow Water Correction (HSWC) in 1957. He found it necessary to include shallow-water harmonics of a much higher order than had previously been considered. A problem with his method was due to the limitations of manual harmonic analysis and a mechanical tide predicting machine. Rossiter and Lennon (1968) approached the problem of defining the shallow-water tide using harmonic analysis to describe the spectrum of the tidal residuals. Their method, the extended harmonic method (EHM), included 114 constituents. Zetler and Cummings (1967), working independently, applied their version of the EHM to Anchorage, Alaska, tide data and agreed with the number of constituents, finding a greater reliability when predicting tides. Cartwright and Rossiter (1972) updated Munk and Cartwright's 1966 response analysis approach to tidal prediction with the improved response method (IRM). Amin (1977) compared the EHM, the HWSC, and the IRM and concluded that use of these shallow-water corrections methods has reached its practical limits. He found that the main problem affecting shallow-water tidal analysis is the nontidal effects in observed data arising from meteorology, fresh water flow, radiation effects, and flooding at high tides.

The traditional principles of harmonic analysis used by the National Ocean Service have remained largely unchanged with the advent of computer analysis replacing mechanical analysis (Zetler, 1982). However, the least squares analysis was extended to a larger set of constituents using a version of the EHM.

Tides in the West Pascagoula River are predominantly diurnal, and a literature search reveals previous shallow-water tide research has been done mostly in areas with predominantly semidiurnal tides. Consequently, this presentation is first a description of the observed effects of shallow water (and river flow) on the diurnal tide curve using hourly height plots and tidal means. Second, it is a description using harmonic analyses of the changes in various tidal constituents as the tide travels up a shallow estuary.

II. DESCRIPTION OF THE AREA

The West Pascagoula River is one of the largest rivers in the State of Mississippi. Having its origin from several rivers to the north, the West Pascagoula empties into Pascagoula Bay, an arm of the Mississippi Sound (Figure 1). The tide in this region is diurnal, with the moon's declination as the major astronomical influence. Being small in range, the tide is easily masked by meteorological effects. This is especially true when the moon is over the equator and the astronomical diurnal tide signal is at a minimum, as shown by days 5-8 and 19-22, August 1981 (Figure 2).

The surrounding area is marshy and flat; topographical maps indicate little slope to the river basin. Preliminary datums have been completed for the tide stations on the West Pascagoula River. However, they have not been connected by levels to the National Geodetic Vertical Datum (NGVD) and bottom slope cannot be accurately determined. The mouth of the West Pascagoula River is about 3 miles wide and contains several alluvial islands. The river width constricts to about 1/3 mile where it branches near Bayou Chemise. From the branching until Graham Ferry, the river is about 1/8 mile wide. On the delta near Graveline Bayou Entrance, the West Pascagoula has a depth running from 1/2 to 20 feet; some dredging has occurred. Further upstream, no depth figures are available. The West Pascagoula is a major river north of Graham Ferry and has large seasonal variations due primarily to runoff.

Data collected by the U.S. Geological Service at Merrill, Mississippi, which is north of the tidal zone, indicate monthly and yearly differences in river flow (Figure 3). From 1931 to 1982, yearly mean flow has varied from 3718 cubic feet per second (cfs) to 19410 cfs. For the year being studied, 1981, there was a relatively low mean flow of 6475 cfs. March and April usually have the highest runoff values for any given year; March had a value of 11930 cfs. The other 2 months of interest were August, with a value of 1849 cfs and September, with a value of 2910 cfs. Both months had rather low flow figures, September being larger. Naturally, the more southern sections of the river are more influenced by the tidal pulse.

Further north, the tidal pulse is gradually weakened and river flow takes over as a major influence. Table 1 lists the stations, coordinates, and approximate distances from Mississippi Sound. The first four tide stations are located on the West Pascagoula River and the remaining two northernmost stations are located on the Pascagoula River proper. For this report, the term West Pascagoula River includes both sections of the river.

III. METHODS OF HARMONIC ANALYSIS

Two methods of harmonic analysis were used to analyze hourly height tidal data from the stations listed. For stations having a record length of 180-369 days, a least-squares harmonic analysis (LSQHA) using a computer program based on Harris, Pore, and Cummings (1963) was used. For stations having less than a year's data, a 29-day Fourier harmonic analysis program (an updated version of Dennis and Long (1971) based on Schureman (1958)) was used. Data from stations 1 through 6 were analyzed using the Fourier 29-day method for the months of August and September 1981. Data from March 1981 were also used for three stations.

Three of these stations have at least 365 days of data available and were also analyzed using the LSQHA method. With a 29-day analysis, the constituents which can be analyzed or directly calculated with the Dennis-Long program are K_1, O_1, M_2, M_4, M_6, M_8, S_2, S_4, S_6, and N_2. With an LSQHA, the following additional constituents are calculated: the diurnal constituents P_1, S_1, M_1, J_1, OO_1, ρ_1, Q_1, $2Q_1$; the semidiurnal constituents μ_2, ν_2, $2N_2$, λ_2, T_2, R_2, L_2, K_2; and the long-period constituents Ssa, Sa, Msf, Mf, and Mm. In addition to calculating the amplitude and phase of the constituents, the Harris, et. al., program also provides an analysis of total explained variance. Each component is listed in its order of contribution to the total explained variance and the percentage that each constituent contributes can be estimated. The long-period constituents Ssa, Sa, Msf, Mf, and Mm are determined, in practice, using special analyses of several years of record.

IV. EFFECTS OF THE RIVER BASIN UPON THE TIDE

A river is too small to be significantly influenced directly by the gravitational forces of the sun and moon. The tide of the West Pascagoula River is forced by the tide entering the river mouth from the Mississippi Sound. Changes and distortions to this tide are mainly caused by the shallow depth, friction, narrowing river width, topography, partial or total wave reflections, and river flow. Together, these cause interaction between astronomical forces. In his research on the Santana River, Franco (1980) found that friction is not the main agent in the generation of shallow-water constituents, but Parker (1984) has shown that friction plays an important and sometimes dominant role. River basin friction and friction due to runoff may be major factors affecting the tidal dynamics in the West Pascagoula River.

In many deep estuaries, a nearly standing tidal wave oscillation frequently occurs and is caused by reflection of the entering progressive tide wave at the closed end. In shallow-water estuaries, friction attenuates progression and reflection of the tidal wave (Doodson and Warburg, 1941). The reflected wave, having traveled further, is always smaller than the incident wave, the difference being greater moving down the estuary toward the entrance. (Sverdrup et al, 1942). The result is a tide wave approaching the characteristics of a progressive wave with a gradual phase change and no nodal point. The lack of a closed end where the tidal wave can reflect will also result in a near progressive situation. The West Pascagoula River tide appears as a damped progressive wave traveling upriver; times of high waters and low waters are later as the distance upstream increases. There is no apparent node or quasinode present in this system.

The tidal curve shape is increasingly distorted upriver because high waters travel faster than low waters. Low waters are retarded, causing the tidal curve slope to be steeper from low to high water. In contrast, the tidal curve slope from high to low water is more gradual, indicating a rapid rise and slow fall in time. Figure 4 shows the typically distorted sinusoidal shape of the tide curve at Graham Ferry (station 6).

A second aspect to note is the characteristic of tropic intervals. These are the lunitidal intervals pertaining to higher high and lower low waters at the time of the tropic tides, e.g., when the effect of the moon's semimonthly maximum declination is greatest. Tropic higher high water and lower low water intervals differ from each other proceeding upstream. Figure 5 shows the time interval differences (relative to the entrance) as the wave travels upriver. High water interval differences are larger than low water interval differences up to station 4. After station 4, this pattern is reversed, with low waters delayed more than high waters.

As the tide travels upriver, the variance in observed water level attributed to the tide becomes a smaller percentage of the total explained variance in observed water level. At the coast, about 51 percent of the total observed variance in the record is tidal. At station 4, only 17 percent can be attributed to the tide. In this case, Sa and Ssa frequencies are not considered tidal, but are seasonal meteorological constituents. Thus, river effects are stronger upriver as the tide is being attenuated by friction. This tidal attenuation is illustrated by changes in tidal range (Figure 6). At station 1, the diurnal range of the tide is nearly 1.5 feet, a typical range on the northern Gulf of Mexico. As the tide progresses upriver to station 2, there is an initial slight decrease in range. This may be due to a major branching in the river just south of station 2. Constriction of the tidal pulse caused by convergence of the estuary results in a small increase in range to a maximum near Martins Bluff (station 3). The range then decreases slightly to station 4. By station 6, there is a rapid decrease to less than half of the range at the coast.

Changes in wave speed and frictional attenuation cause the tidal amplitude ratio $(K_1+O_1)/(M_2+S_2)$ to change. This is the traditional ratio describing the type of tide; the higher the ratio, the more diurnal the station. Figure 7 shows that from station 1 to station 4, the tide is slowly becoming more semidiurnal in nature, although it is still predominantly diurnal. After station 4, the tide becomes increasingly diurnal and at station 6, the ratio is larger than at the coast.

V. EFFECTS OF RIVER FLOW UPON THE TIDE

Because of the shallow depths, friction has a major effect on the tidal characteristics of the West Pascagoula River. River flow can also have an important effect on the tide via friction. The river flow varies seasonally; so does its influence.

Below is a comparison between August 1981 data—a month with lower flow values, and September 1981 and March 1981 data—months with higher flow values.

The most obvious difference between August and September data is the distance the tide travels upstream before being masked. The tide advances further upstream during low runoff months. Station 6 has daily tides for the month of August. During the month of September, however, station 6 is tidal only part of the month. Figure 8 compares Graveline Bayou (station 1) with Graham Ferry (station 6) for September 1981. Several observations can be made from this figure. First, the water level change due to river flow is greater than the amplitude of the tide at Graham Ferry from September 1 - 9. Instead of dominant tides, there are minimal tides (less than .1 foot range) superimposed on a changing river stage. The water level increases until September 6, then decreases until September 15. The effect of runoff is to diminish both the diurnal and semidiurnal tides; semidiurnal tides are diminished to flattened areas when runoff is greatest. Later, between September 13 - 19, the water level at Graham Ferry is at a minimum when Graveline Bayou Entrance has a small diurnal range.

A second difference between high and low runoff months is the relative increase in mean sea level (MSL) for high runoff months. Figure 9 shows that MSL is similar during August and September up to station 4; further upriver during September, MSL decreases but less dramatically than during August. For March, the highest runoff month, MSL actually increases upriver. This increase in MSL is due to more fresh water flowing downstream, which may be a frictional effect on the mean river flow. When river discharge increases, MSL also increases due to frictional momentum loss from the main flow (Parker, 1984).

MSL increases, but upstream diurnal range (Gt) decreases with larger runoff values. Figure 9 shows that March, with the largest runoff, has the smallest tidal range at station 4. September also has a decreased range upstream of station 3, due to runoff. This is another indication of river flow friction damping the tidal signal.

Time intervals also are influenced by increased runoff. Up to station 4, both high water and low water intervals are smaller during September. Upstream from station 4, September high and low water intervals are larger than August (Figure 10). So, the effects noted for August data are apparently amplified in September due to runoff friction.

Finally, high runoff influences the $(K_1+O_1)/(M_2+S_2)$ ratio. For August, March, and September, the ratio decreases to station 4. Further upriver, September data become more diurnal, but less dramatically than August data (Figure 11). Runoff seems to increase semidiurnal influences after station 4. This is analogous to the increase in M_4/M_2 ratios seen in the Delaware River during high river runoff (Parker, 1984).

In summary, larger runoff enhances the frictional effect of the river basin, and in reality, runoff and frictional effects cannot be separated. Runoff decreases the distance upriver of tidal influences, it influences time intervals by advancing the downstream values and delaying the upstream values, it increases mean sea level, and it decreases diurnal range.

VI. HARMONIC DESCRIPTION OF DIURNAL TIDES IN THE WEST PASCAGOULA RIVER

The major astronomical constituents for diurnal tides are K_1 and O_1, which represent the declinational motions of the sun and moon. In the case of diurnal tides, when K_1 and O_1 are in phase at maximum lunar declination, the tide has a large range and has little evidence of higher harmonics. When K_1 and O_1 are out of phase at lunar equatorial, the range is small. During this time, the tide is mainly semidiurnal.

At coastal station Graveline Bayou, approximately 51 percent of the total explained variance in observed water level can be attributed to tidal components, with Sa and Ssa not considered tidal constituents. The major components here are K_1 and O_1, accounting for about 47 percent of the total signal. At Portico Landing, the tidal contribution to the total water level fluctuation has decreased to about 17 percent, and K_1 and O_1 are much smaller, less than 10 percent of the total signal.

A combination of shallow water and increased river flow effects on these diurnal constituents appears to decrease their amplitudes. Using an LSQHA analysis to illustrate this, K_1 decreases in amplitude from .54 to .44 foot, from Graveline Bayou (station 1) to Portico Landing (station 4). O_1 decreases from .50 to .41 foot, Q_1 decreases from .11 to .08 foot, while P_1 remains the same. J_1 decreases from .03 to .01 foot and S_1 decreases from .05 to .02 foot. Care must be taken when speaking of constituents that are very small since the amplitudes may be within the noise level of the harmonic analyses methods used.

P_1 represents the sun's declination, while Q_1 and J_1 modulate K_1 and O_1 to represent the moon's elliptical orbit. S_1 is a meteorological constituent reflecting daily land/sea breezes. All of these diurnal constituents decrease upriver, apparently due to frictional attenuation. Parker (1984) found that the lost momentum contributes to the amplification of higher frequency constituents and compound constituents.

Constituents that are terrestrially, rather than astronomically, generated are called shallow-water constituents. These constituents represent the non-linear interaction between two or more astronomical constituents, or between the tide interacting with nontidal effects. Shallow-water constituents are numerous; Defant (1961) calls their number in many estuaries "unmanageable." This is because the successive species of shallow-water tides do not diminish in importance as rapidly as once thought. This study is limited to the constituents that are calculated by the two harmonic analysis methods used.

Shallow-water constituents are also known as overtides and compound tides. Overtides have a speed that is an exact multiple of one of the major astronomical constituents; compound tides have a speed that is the sum or difference of two major astronomical constituents. Compound shallow-water constituents can have the same period or speed as astronomical constituents. Harmonic analyses cannot separate such compound constituents from those astronomical constituents with the same speed. For example, although energy at the 1/12.42-hour frequency is generally thought of as resulting only from astronomical constituent M_2, it can also result from the compound shallow-water tide KO_2, in a shallow estuary with a dominant diurnal tide. Other compound tides, resulting from the interaction of diurnal constituents, are given in Table 2, along with the astronomical constituents that have the same speed (period).

The constituents are divided into two major groups: semidiurnal and long period. Rates of change are used as percentages when comparing amplitude changes as the tide progresses upriver (the amplitude of the constituent at the river location divided by the amplitude at the entrance). This provides a more meaningful comparison than using absolute amplitudes since the entire tidal signal becomes attenuated.

Semidiurnal Constituents

Results of 29-day analyses of August 1981 (Table 3) indicate that while the diurnal constituent amplitudes remain approximately the same upriver to station 4, the semidiurnal constituents increase. Using station 1 amplitudes as 100 percent, Figure 12 shows that relative to the changes in K_1, the major component of the tide, the semidiurnal amplitude ratios increase up to station 4. Up to Portico Landing (station 4), M_2 (or KO_2) increases 19 percent, S_2 (or KP_2) increases 52 percent, and N_2 (or KQ_2) increases 41 percent. After station 4 the tide is, as a whole, noticeably attenuated. Upriver from station 4, K_1 is less attenuated than the semidiurnal constituents.

Using 365-day LSQHA harmonic analyses from station 1 to station 4, M_2, S_2, and N_2 amplitudes stay approximately the same and K_2 decreases slightly. As seen previously, diurnal constituents are decreasing from station 1 to station 4, as is total tidal energy. K_1 decreases 18 percent, O_1 decreases 18 percent, S_1 decreases 64 percent, and P_1 stays the same. While total tidal energy and diurnal energy are decreasing upriver, semidiurnal energy is not changing.

Parker (1984) found on the Delaware River that the main tidal constituent (M_2) has a frictional effect on other constituents, or is modulated by nontidal effects causing an exchange of energy to the next harmonic. A similar process may be happening in the West Pascagoula River where the main tidal constituents, K_1 and O_1, which are decreasing, are transferring energy to the next harmonics which are semidiurnal in frequency. If there is any significant reflected tidal wave at all, one would also expect more amplification of semidiurnal constituents than diurnal constituents because of the shorter wave lengths. However, the differences in amplification among the semidiurnal constituents imply that at least some of this amplification is due to shallow-water generation. It thus appears that the semidiurnal constituents may include a shallow-water generated part. However, when the tide is dominated by nontidal effects, as at stations 5 and 6, the higher frequency semidiurnal constituents disappear more rapidly.

Results of LSQHA analyses indicate that the semidiurnal constituents remain about the same or increase upriver to station 4. The largest semidiurnal constituents have already been discussed as shallow-water constituents. Other semidiurnal constituents have amplitudes that are too small to make a noteworthy contribution to the tide.

One major difference between shallow-water constituents for diurnal tides and shallow-water constituents for semidiurnal tides is speed. The only shallow-water tides taken into account in most tidal investigations are the higher harmonics (overtides) of the fundamental tides. The speeds of these overtides are multiples of the principal lunar and solar semidiurnal constituents, M_2 and S_2. A literature search shows that authors deal predominantly with semidiurnal tides. In the case of diurnal tides, however, the major shallow-water constituents would be semidiurnal in speed.

Quarter-diurnal M_4 decreases upriver on the West Pascagoula River. All other quarter-diurnal and sixth-diurnal constituents are too small on the coast and upriver to be of consequence.

In summary, diurnal constituents generally remain unchanged upriver to station 4, and semidiurnal constituents generally increase. After station 4, the semidiurnal constituents are attenuated faster than the diurnal constituents.

Long-Period Constituents

Investigation of three river stations by 365-day analyses indicates a large increase in amplitudes for many long-period constituents up to station 4. This is due to the monthly and seasonal variations in river discharge. Table 5 lists the twelve largest constituents at these three locations along with their total contribution to the tidal signal.

On the coast, K_1 and O_1 are the largest contributors to the tide with Sa and Ssa being third and fourth, respectively. Sa and Ssa are solar long-period constituents, reflecting periodic seasonal variations in weather conditions that influence sea level. Sa has a period of one year and Ssa a period of one half year. They are commonly known as meteorological constituents, which inland, include river discharge effects. NOS generally computes Sa and Ssa constants from several years of monthly mean sea levels for tidal predictions. However, for this study, we are using the constants from LSQHA analyses for simultaneous comparisons between stations.

There are several possible reasons why Sa and Ssa have fairly large amplitudes at the river entrance. First, wind effects are significant in this area of low tidal signal. Smith (1979) found that in the northern rim area of the Gulf of Mexico, wind stress processes and meteorologically driven estuarine shelf exchanges are comparable in magnitude to tidal processes. Because there are noticeable seasonal variations in wind direction in the Mississippi Sound area (Eleuterius, 1979), with generally prevailing southerly winds in summer and northerly winds in winter, Sa and Ssa may reflect this annual cycle.

Another cause of large meteorological Sa and Ssa constituents is runoff, a seasonal phenomenon on the West Pascagoula River. For this closely related and inter-connected river system, 13 years of mean river flow data show strong seasonal effects. The winter mean river flow is many times larger than the summer mean flow (Eleuterius, 1979). This increased flow greatly influences mean sea level (MSL) and mean range. Using 4 years of monthly mean data at station 2, a 180-day annual variation in both MSL and range can be seen; when range is large, MSL is small, and when range is small, MSL is large. The Ssa period is similar to this 180-day annual variation. Figure 13 shows this seasonal variation of MSL and range.

Upriver, the tidal signal is getting smaller while the river signal is getting larger. The river signal shows up in Sa, Ssa, Mm, and other long-period constituents, and at station 4, it must be the predominant source of energy at the Sa, Ssa, and Mm frequencies.

In addition to meteorological influences, Sa and Ssa may also have a component resulting from the shallow-water interaction of the diurnal tides (Table 2). The speeds of these long-period constituents are the same as K_1-P_1 and K_1-S_1. Ssa reflects the annual variation of the sun's declination.

The amplitudes of three long-period lunar constituents, Mf, Mm, and Msf are larger in the West Pascagoula River than those found in semidiurnal regimes. The two constituents Mf and Msf have periods related to the moon's position. Mf has a period of 13.6608 days, which is half a cycle of the moon's declination. Mm has a period of 27.5546 days, which is the period from perigee to perigee. Msf reflects the interaction between the sun and moon, and has a period of 14.7653 days. At Graveline Bayou, Mf, Mm, and Msf are all within the top 13 contributors to the explained tide. Because these constituents have the combination of long periods and relatively small amplitudes, in practice they cannot be distinguished from meteorological effects and river effects (Doodson & Warburg, 1941).

Upriver, Mf, Mm, and Msf increase dramatically. From Graveline Bayou (station 1) to Portico Landing (station 4), Mf increases in amplitude from .051 foot to .192 foot, a fourfold increase. Mm increases in amplitude from .034 foot to .352 foot, a tenfold increase. Msf increases from .033 foot to .062 foot, a twofold increase. Mf, Msf, and Mm may include effects of shallow-water constituents from the interaction of astronomical diurnal constituents K_1, O_1, P_1, and Q_1. The Admiralty Manual of Tides states, "In some places, Mf and Mm are affected by shallow-water constituents with identical speeds" (Doodson & Warburg, 1941). The increase in these long-period constituents moving upriver (while the tidal constituents are decreasing) implies that they must be predominantly representing the river flow effects on the water levels.

In summary, sea level changes represented by long-period constituents are important contributors to overall changes in water level in this river, and increase in importance upriver. At Portico Landing, three of the top four contributors to the tide are long-period constituents and make up 66 percent of the tidal signal.

VII. EFFECTS OF RIVER FLOW ON DIURNAL AND SEMIDIURNAL CONSTITUENTS

Results of 29-day harmonic analyses for August 1981 are similar to those of the 365-day analyses, both for diurnal and semidiurnal constituents up to station 4. Further upstream, river flow decreases the amplitudes of the constituents K_1, O_1, P_1, Q_1, M_2, S_2, and N_2. The effects of increased river flow become noticeable when comparing results of August 1981 with September 1981—a period characterized by increased runoff and mean sea level.

Comparing the diurnal constituent K_1 for August and September (Figure 14), upriver to Portico Landing, the ratio of the K_1 amplitude at the upstream station to the K_1 amplitude at station 1 slowly decreases. An increased river flow in September has little effect on this diurnal component up to station 4. However, further upriver, the rate of change for K_1 is greater in September than in August. For August, the K_1 amplitude is .475 foot at station 1 compared with .460 foot for September. At station 4, the K_1 amplitude decreases from .456 to .423 foot; at station 5, the K_1 amplitude decreases from .352 to .260 foot; and at station 6, the K_1 amplitude decreases from .193 to .130 foot. Increased friction upriver attenuates the K_1 amplitude more in September than in August. Other diurnal components O_1, P_1, and Q_1 behave in a similar way.

Figure 15 compares the semidiurnal constituents for August and September. The S_2 ratio is more affected by runoff than the M_2 ratio. The S_2 ratio increases up to station 4 and decreases after station 4 for both August and September. However, the increased runoff in September dampens the S_2 ratio, making the month less semidiurnal in character than August. However, for M_2 the increased runoff in September has little effect.

Figure 16 illustrates the S_2/K_1 and M_2/K_1 ratios for August and September. The S_2/K_1 ratio increases up to station 4 and decreases after station 4 for both August and September. However, the increased runoff in September has little effect on the S_2/K_1 ratio. Like S_2/K_1, M_2/K_1 increases up to station 4 and decreases after station 4 for both August and September. However, the increased runoff in September increases semidiurnal effects after station 3.

In general, the increased friction through runoff enhances shallow-water constituents by transferring energy to the next harmonic. This was demonstrated by Parker (1984) in the upper Delaware River, where the M_4/M_2 ratio increased with increasing river discharge.

CONCLUSIONS

The diurnal tide on the West Pascagoula River changes greatly as it travels from the river entrance to Graham Ferry, 36 miles upriver. The diurnal tide behaves as a damped progressive wave, with time of the tide occurrence increasing as distance from the entrance increases. High waters and low waters travel at different rates; high waters slower than low waters up to Portico Landing, high waters faster than low waters upriver from Portico Landing. The range of tide remains nearly constant to Portico Landing, then decreases by half near Graham Ferry. The tide becomes slightly more semidiurnal up to Portico Landing, then becomes increasingly diurnal further upriver.

Semidiurnal constituents increase more rapidly than diurnal constituents up to Portico Landing. Further upriver, the tide decreases in energy, with semidiurnal constituents decreasing more rapidly than diurnal constituents.

River runoff has numerous effects—decreasing or limiting the distance the tidal influences will reach upriver, delaying time intervals, increasing MSL, decreasing diurnal tide range, and enhancing shallow-water effects.

In the West Pascagoula River, semidiurnal constituents are still predominantly astronomical in origin, but there is evidence for some shallow-water generated semidiurnal energy from the diurnal tide. A part of this semidiurnal energy results from the effect of river flow. Finally, diurnal river tides become more difficult to predict due to a lessening of tidal influences and a strengthening of nontidal effects upriver.

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Table 1. Tide stations on the West Pascagoula and Pascagoula Rivers.

Station Number	NOS Number	Station Name	Latitude	Longitude	Distance Upstream (miles)
1	874 2205	Graveline Bayou Entrance	30°21.7'N	88°39.8'W	0
2	874 1798	Gautier	30°23.0'N	88°36.6'W	2.5
3	874 1941	Martin Bluff	30°26.9'N	88°37.5'W	8.4
4	874 1863	Portico Landing	30°30.7'N	88°37.1'W	17.1
5	874 1489	JCPA	30°35.0'N	88°34.2'W	26.5
6	874 2187	Graham Ferry	30°36.8'N	88°38.5'W	36.3

Table 2. Shallow-water constituents.

Astronomical Constituent Name				
Semidiurnal	Long Period	Speed °/hr.	Shallow Water Interaction of	Compound Tide (Interaction) Name
K_2		30.0821	$2 \times K_1$	K_2
M_2		28.9841	$K_1 + O_1$	KO_2
S_2		30.0000	$K_1 + P_1$	KP_2
N_2		28.4397	$K_1 + Q_1$	KQ_2
	Ssa	.0821	$K_1 - P_1$	KP
	Mf	1.0980	$K_1 - O_1$	KO
	Sa	.0411	$K_1 - S_1$	KS
	Mm	.5444	$O_1 - Q_1$	OQ
	Msf	1.0159	$P_1 - O_1$	PO

Table 3. 29-day harmonic analyses.

	K_1		O_1		M_2		N_2		S_2		K_2 *	
	H	K'	H	K'	H	K'	H	K'	H	K'	H	K'
8742205												
August	.475	308.5	.468	302.9	.124	334.7	.034	341.1	.077	2.7	.021	2.2
September	.460	307.9	.475	306.6	.116	332.6	.030	16.7	.085	340.3	.023	339.8
8741798												
August	.463	314.7	.458	309.3	.122	351.1	.032	4.4	.080	13.5	.022	13.0
September	.449	313.2	.467	311.7	.119	348.0	.029	24.1	.084	351.1	.023	350.6
8741941												
August	.462	324.4	.469	317.9	.150	14.2	.045	40.8	.104	38.3	.028	37.8
September	.447	321.1	.482	318.8	.144	7.9	.017	45.3	.100	10.4	.027	9.9
8741863												
August	.456	337.2	.469	329.6	.148	38.5	.048	65.6	.117	59.5	.032	59.0
September	.423	335.0	.469	330.1	.143	30.4	.017	52.7	.102	30.7	.028	30.2
8741489												
August	.352	3.9	.375	354.7	.084	70.7	.029	92.2	.076	99.2	.021	98.7
September	.260	15.9	.318	357.3	.075	70.9	.017	60.9	.060	73.8	.016	73.3
8742187												
August	.193	48.9	.216	33.5	.036	116.8	.007	139.8	.028	160.0	.008	159.5
September	.130	85.4	.153	26.8	.035	152.3	.020	68.9	.023	173.0	.006	172.5

* inferred values

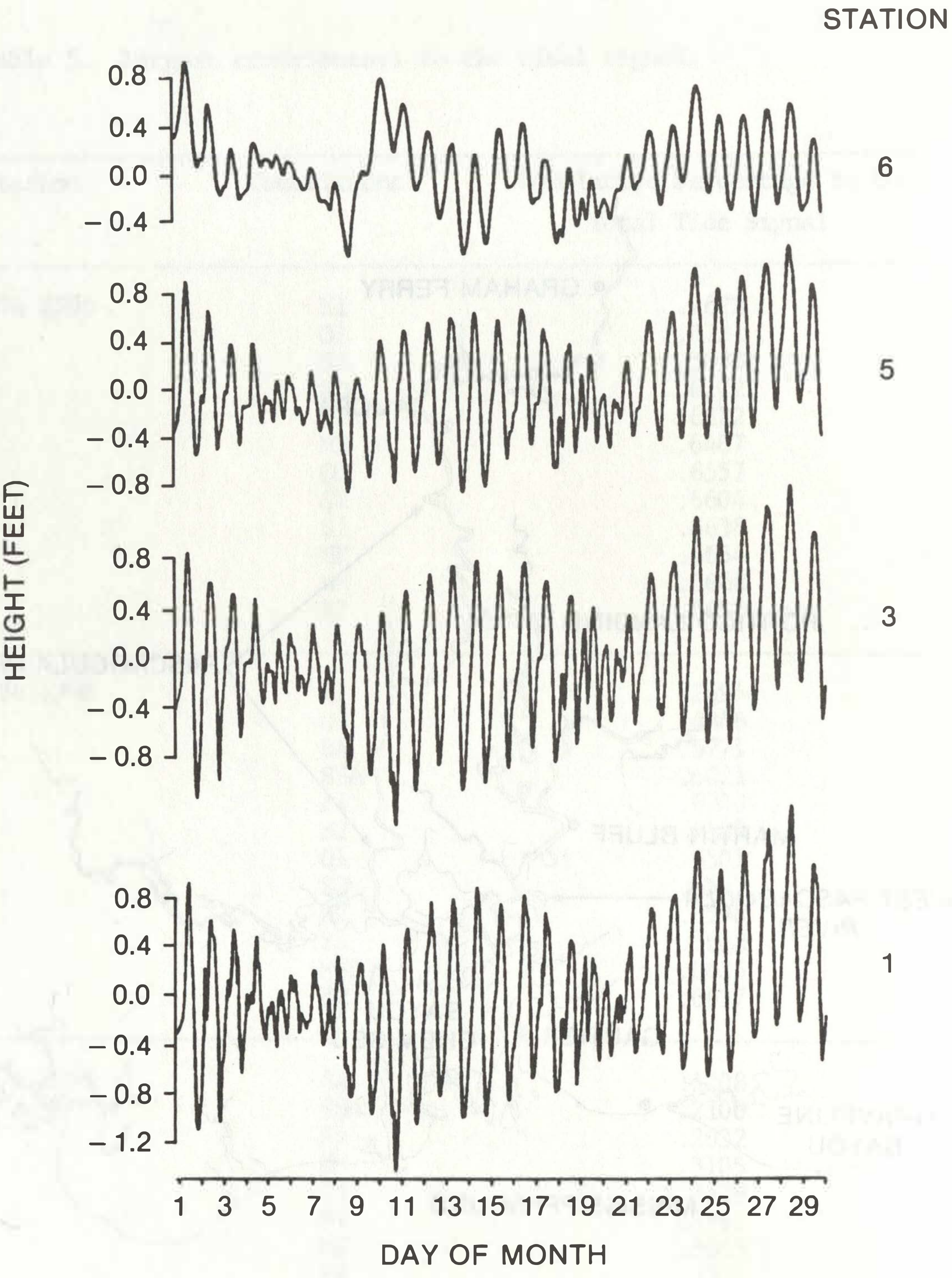
Table 4. 365-day harmonic analyses, 1980-1981.

	8742205		8741798		8741863	
	H	K'	H	K'	H	K'
K_1	.536	308.9	.514	314.0	.442	338.7
O_1	.501	304.0	.485	312.1	.413	331.6
P_1	.142	304.9	.138	316.5	.144	337.7
Q_1	.106	299.6	.111	308.4	.076	341.3
S_1	.055	60.5	.043	76.9	.020	96.8
M_2	.112	339.9	.109	353.2	.113	44.3
S_2	.066	359.1	.063	12.0	.065	64.4
N_2	.022	356.1	.022	19.9	.026	84.9
K_2	.043	344.7	.038	344.8	.037	0.2
M_4	.026	117.5	.019	134.8	.016	238.5
Ssa	.159	57.6	.148	44.6	.524	356.2
Sa	.319	121.8	.284	117.5	.608	8.5
Mf	.051	228.2	.081	219.8	.192	181.5
Mm	.034	292.6	.022	127.8	.352	60.1
Msf	.033	351.6	.034	14.3	.062	215.4

Table 5. Largest contributors to the tidal signal.

Station	Constituent	Cumulative Percentage to the Total Tide Signal
874 2205	K1	.2622
	O1	.4721
	SA	.5830
	SSA	.6102
	P1	.6322
	M2	.6467
	Q1	.6557
	S2	.6604
	S1	.6638
	MF	.6654
	MM	.6668
	K2	.6682
874 1798	K1	.2694
	O1	.4846
	SA	.5771
	SSA	.6021
	P1	.6243
	M2	.6389
	Q1	.6501
	S2	.6547
	MF	.6590
	S1	.6612
	MSF	.6625
	K2	.6637
874 1863	SA	.1208
	SSA	.2100
	K1	.2632
	MM	.3105
	O1	.3529
	P1	.3597
	MF	.3663
	M2	.3707
	S2	.3721
	Q1	.3735
	MSF	.3748
	M1	.3755

Figure 1. Locations of tide stations.



Note: The moon was over the equator on 8/5 and 8/19, and at maximum declination on 8/12 and 8/25.

Figure 2. Hourly heights for August 1981, for stations 1, 3, 5, 6.

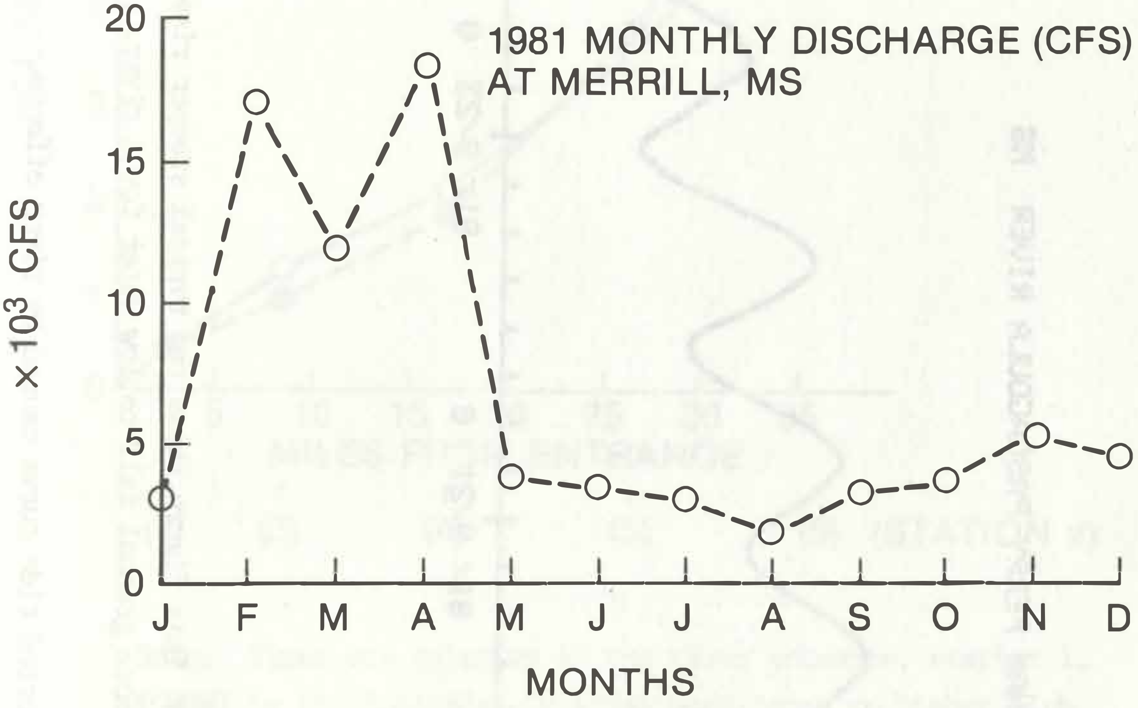
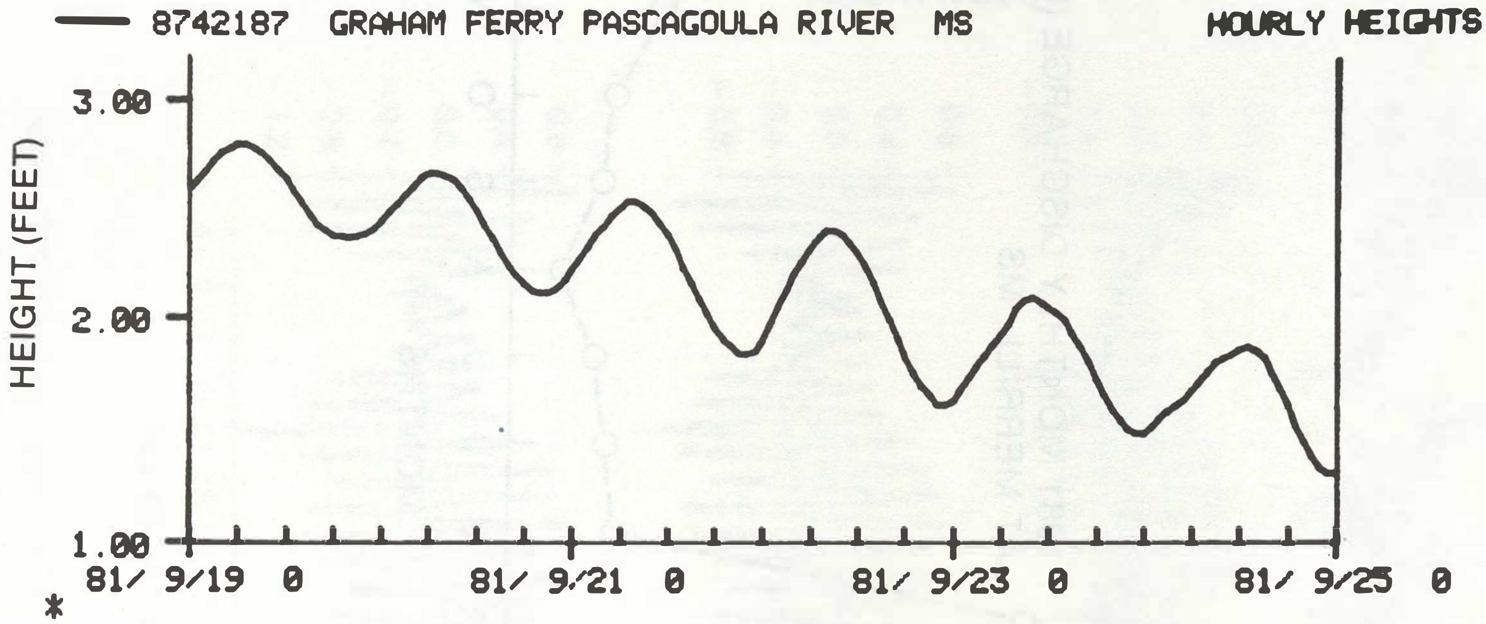
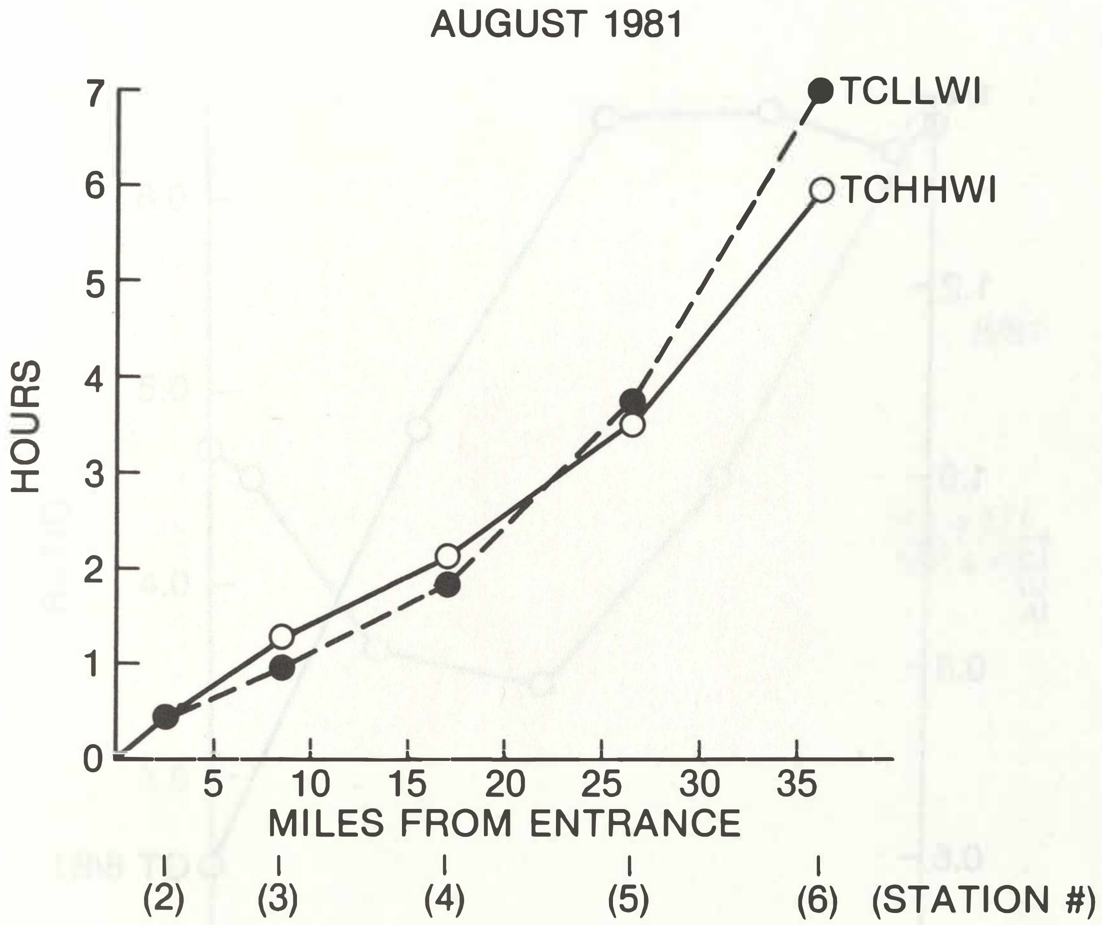


Figure 3. 1981 monthly discharge (cfs) at Merrill, MS.



Note: This figure shows the typical steeper rise to high water and more gradual fall to low water for a river.

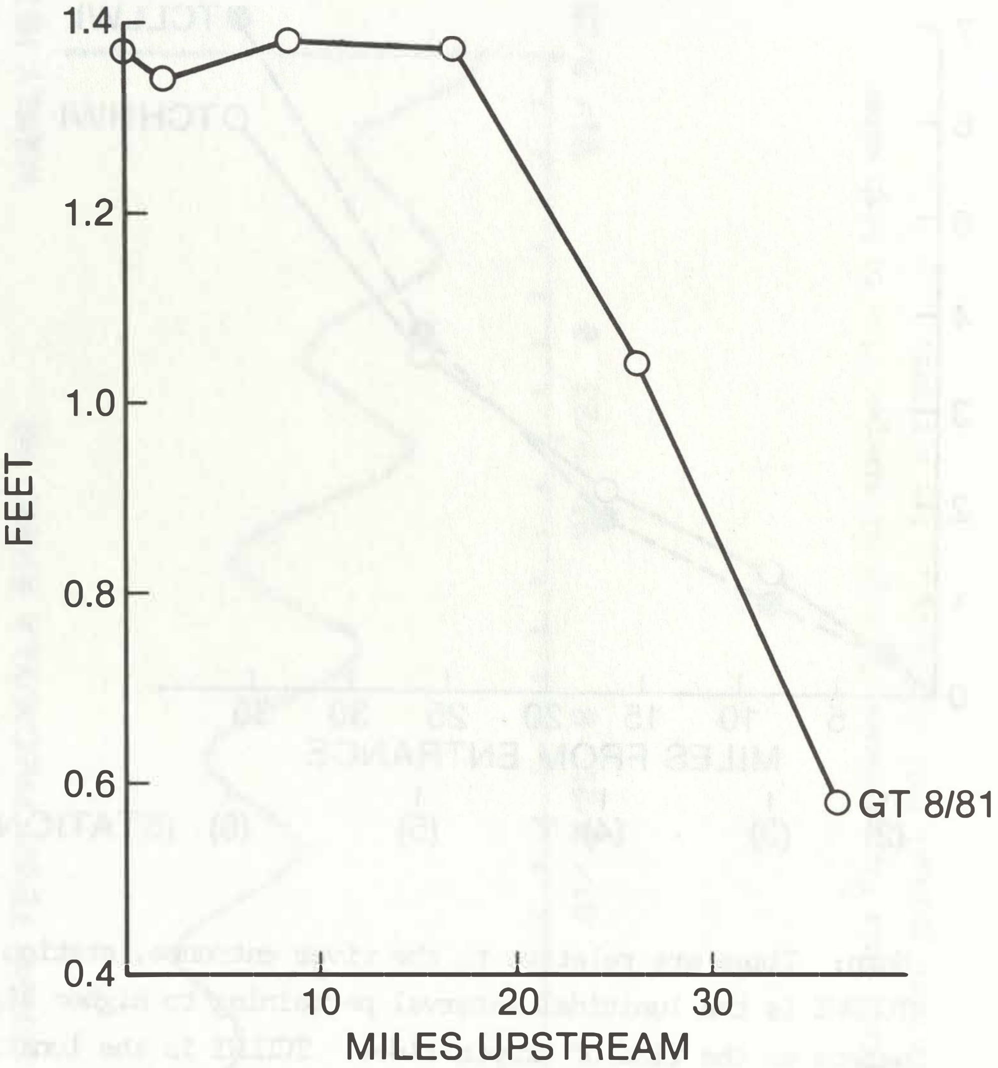
Figure 4. Distorted tide curve caused by river effects.



Note: Times are relative to the river entrance, station 1. TCHHWI is the lunitidal interval pertaining to higher high waters at the time of tropic tides. TCLLWI is the lunitidal interval pertaining to lower low waters at the time of tropic tides. Upstream from station 4, low waters are more delayed than high waters.

STATION	1	2	3	4	5	6
TCHHWI	3.131	3.599	4.420	5.257	6.660	9.137
TCLLWI	13.700	14.157	14.671	15.517	17.472	20.750

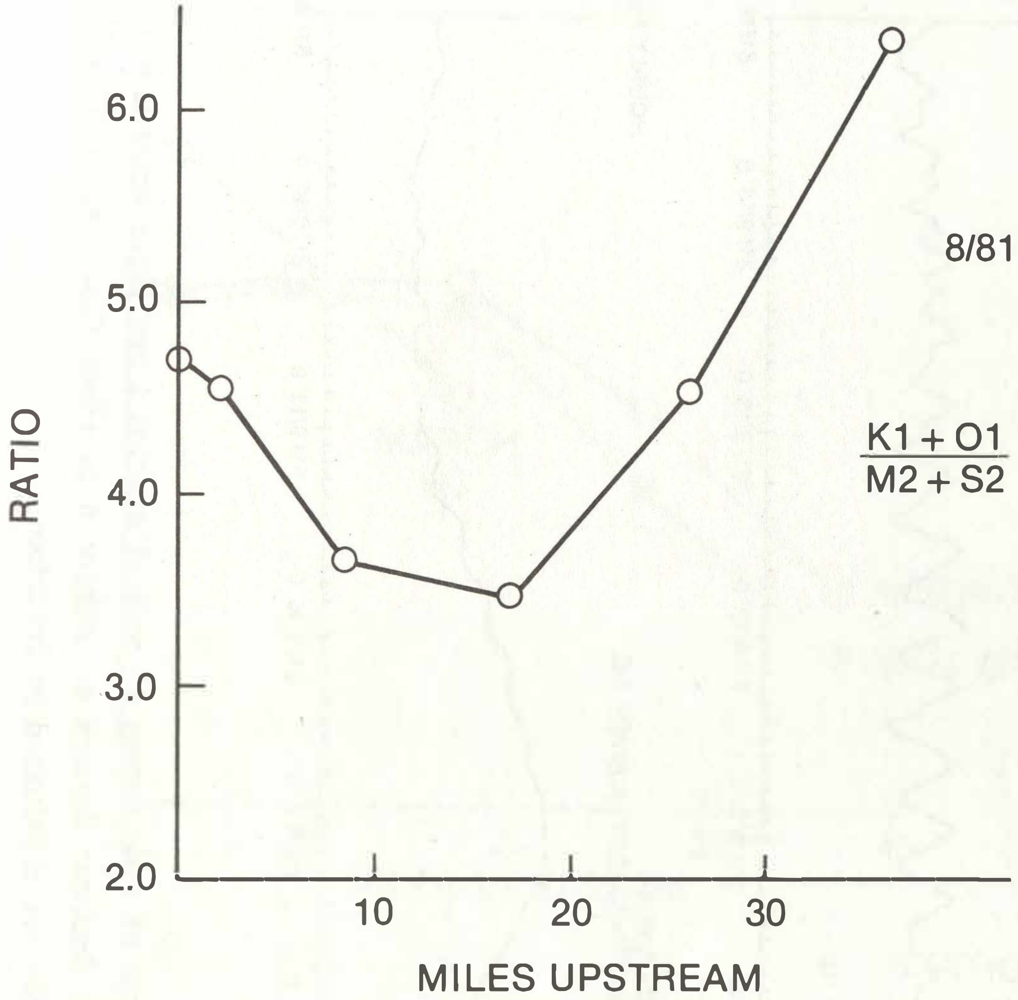
Figure 5. Elapsed time between tropic intervals.



Note: Diurnal range (GT) reaches its maximum near station 3. Upriver from station 4, the range rapidly decreases to less than half that at the entrance.

STATION	1	2	3	4	5	6
FEET	1.37	1.34	1.38	1.37	1.04	0.58

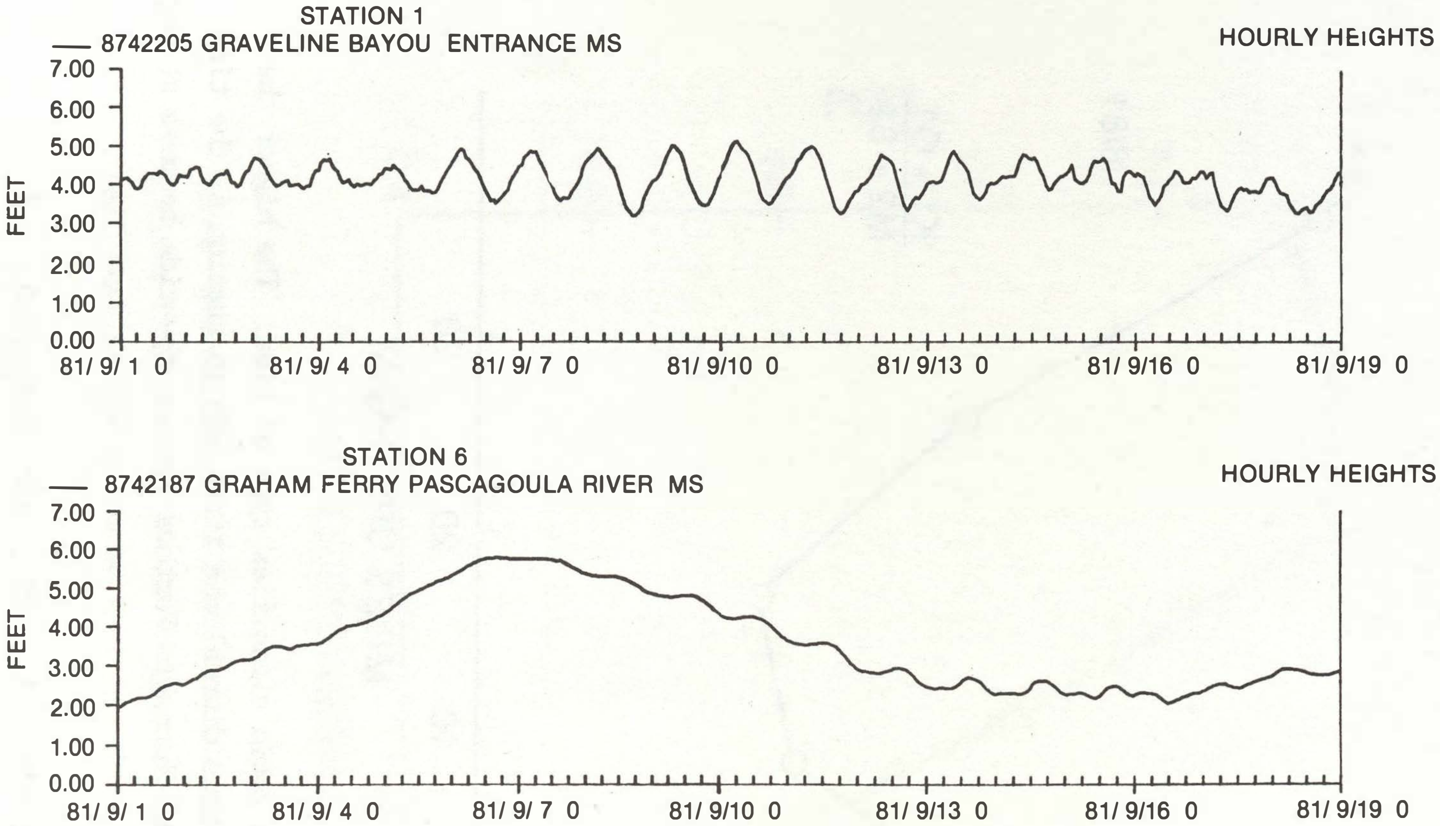
Figure 6. Diurnal range variation.



Note: This ratio classifies type of tide. The higher the ratio, the more diurnal the tide. Up to station 4, the tide becomes less diurnal. Further upriver the tide becomes strongly diurnal.

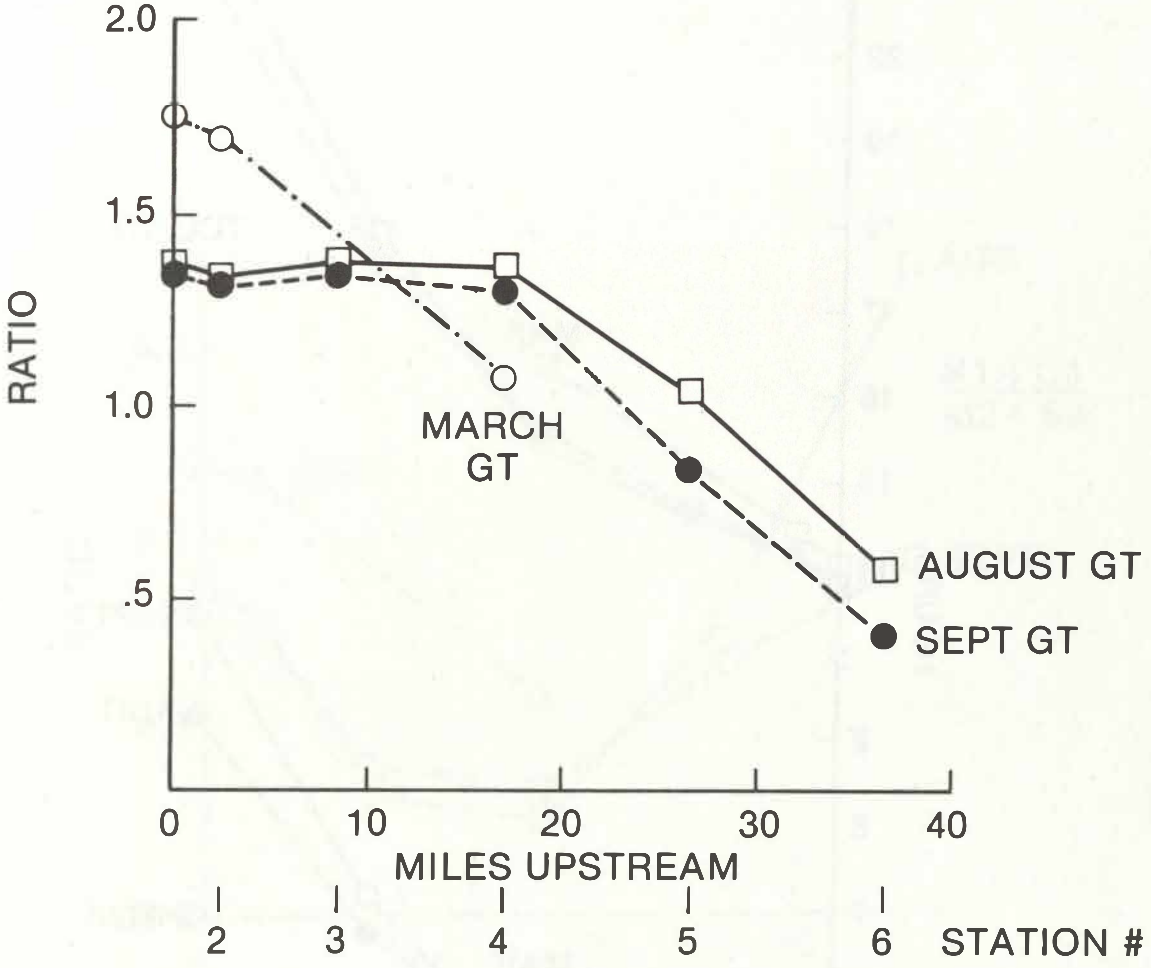
STATION	1	2	3	4	5	6
RATIO	4.71	4.56	3.66	3.49	4.56	6.42

Figure 7. $(K_1+O_1)/(M_2+S_2)$ variations caused by river effects.



Note: Comparison of tide curves at coastal station 1 and river station 6. Before 9/10 the dominant feature at station 6 is river flow. After 9/10 semidiurnal tides are eliminated by friction.

Figure 8. Effects of runoff on tide curve shape.



Note: As runoff increases, range decreases.

MONTHLY MEAN SEA LEVELS (FEET)

STATION	1	2	3	4	5	6
MARCH	3.49	3.66		4.43		
AUGUST	4.02	4.15	4.21	3.97	3.04	1.99
SEPTEMBER	3.94	4.07	4.15	3.91	3.25	2.82

Figure 9. Influence of runoff on mean sea level and diurnal range.

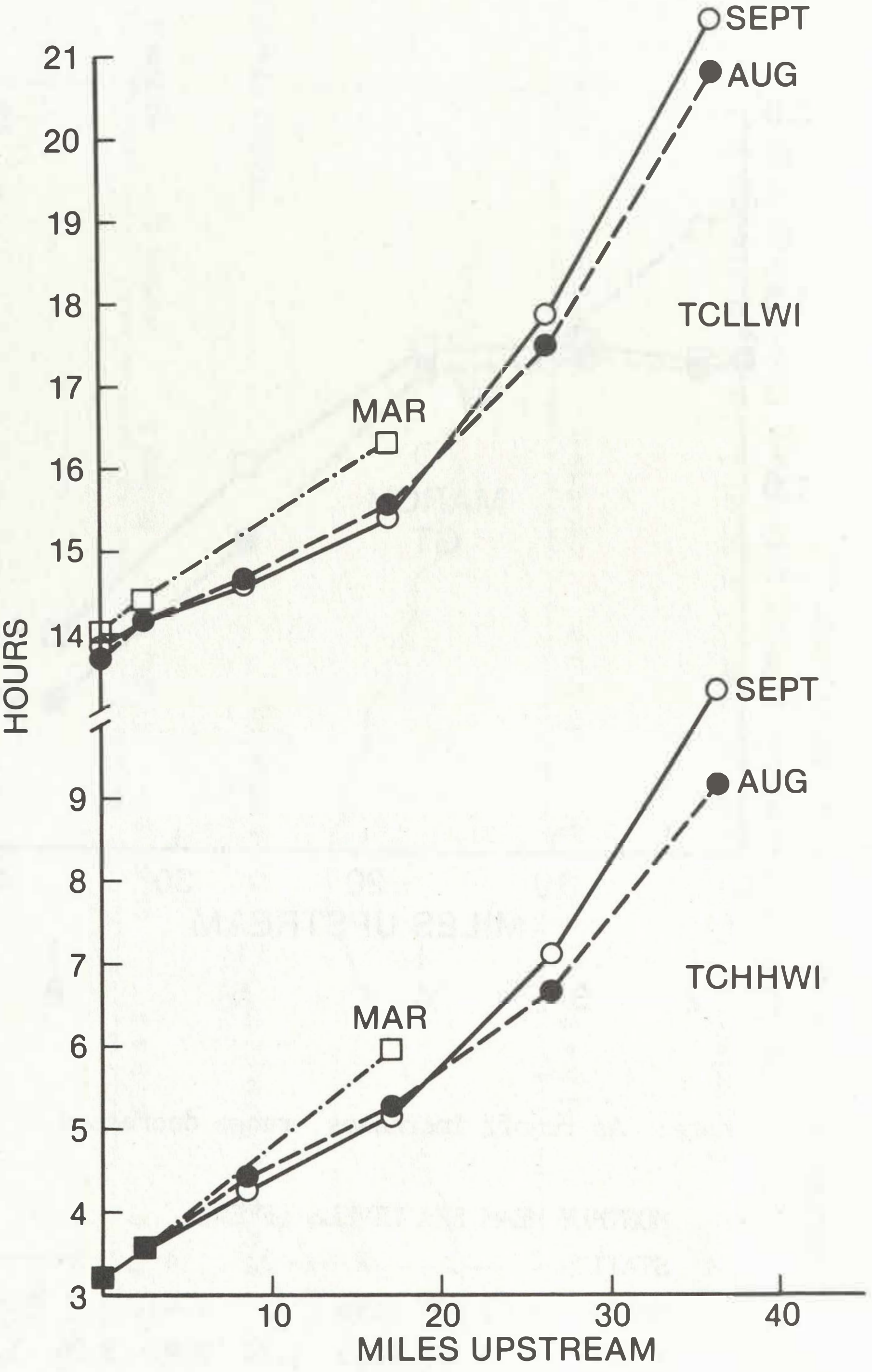
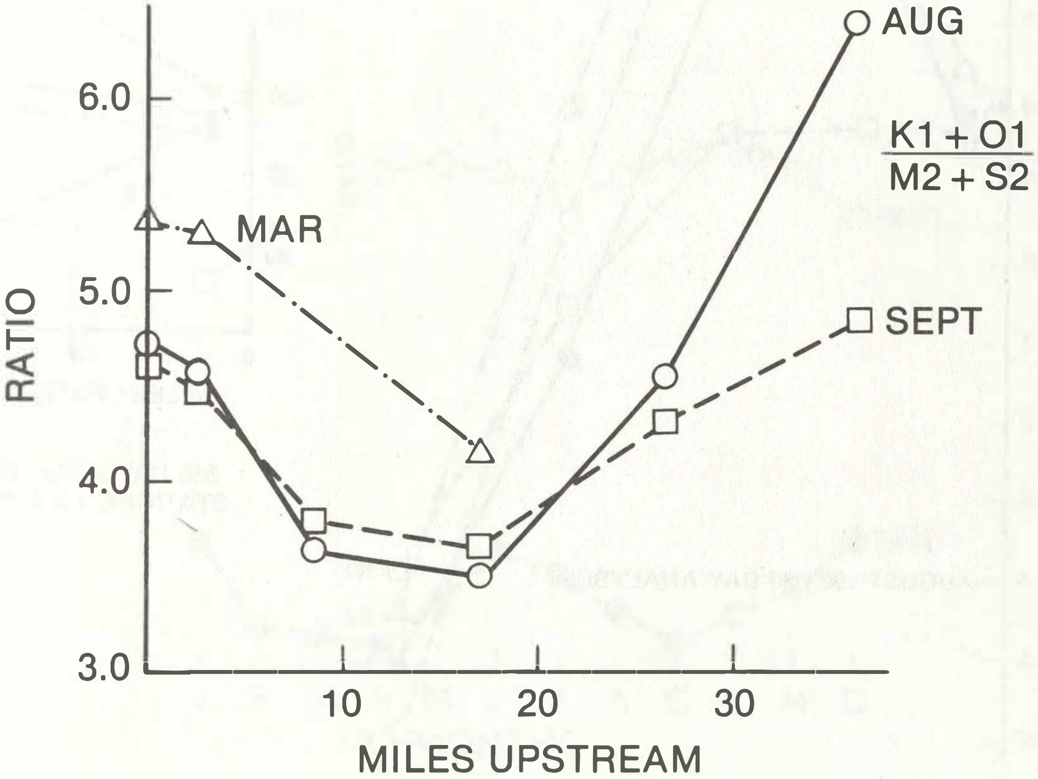
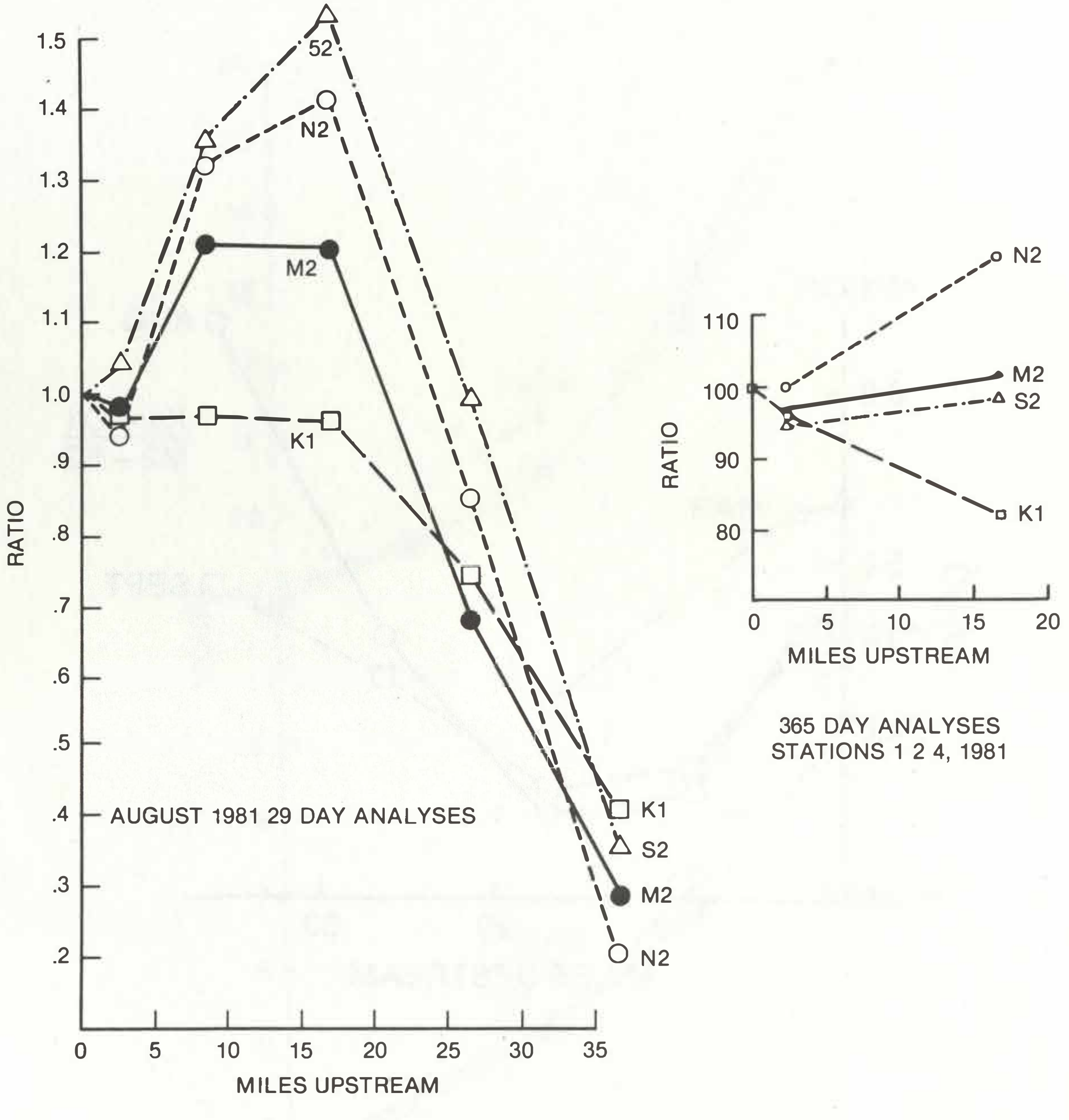


Figure 10. Influence of runoff on time intervals.



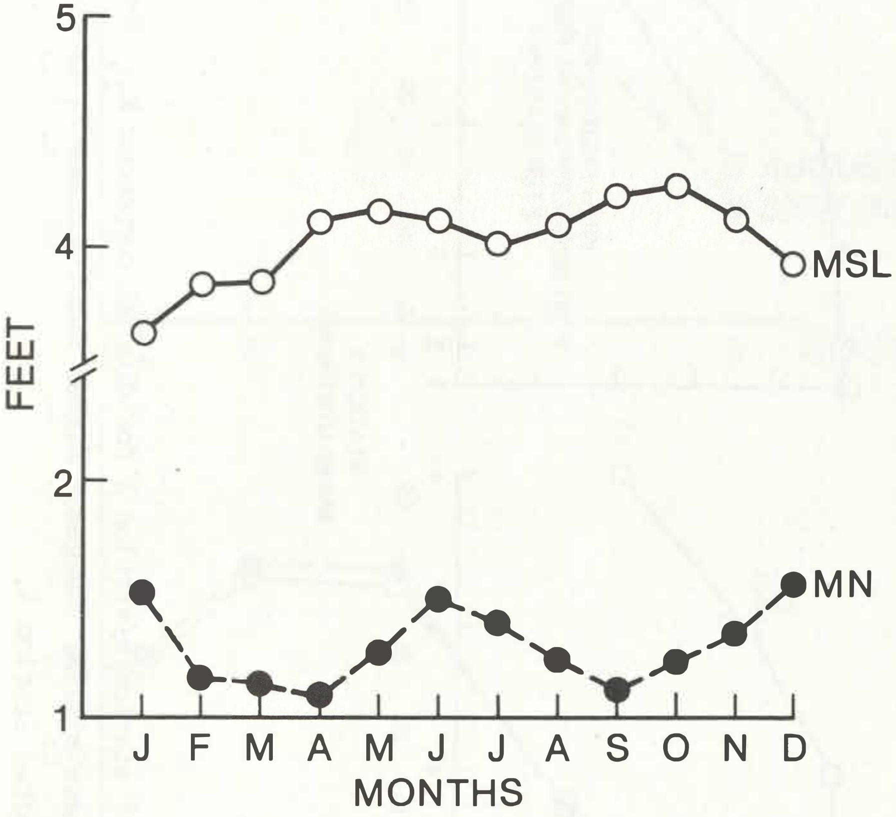
Note: Increased runoff in September increases semidiurnal constituents or decreases diurnal constituents.

Figure 11. $(K_1+O_1)/(M_2+S_2)$ variations caused by runoff.



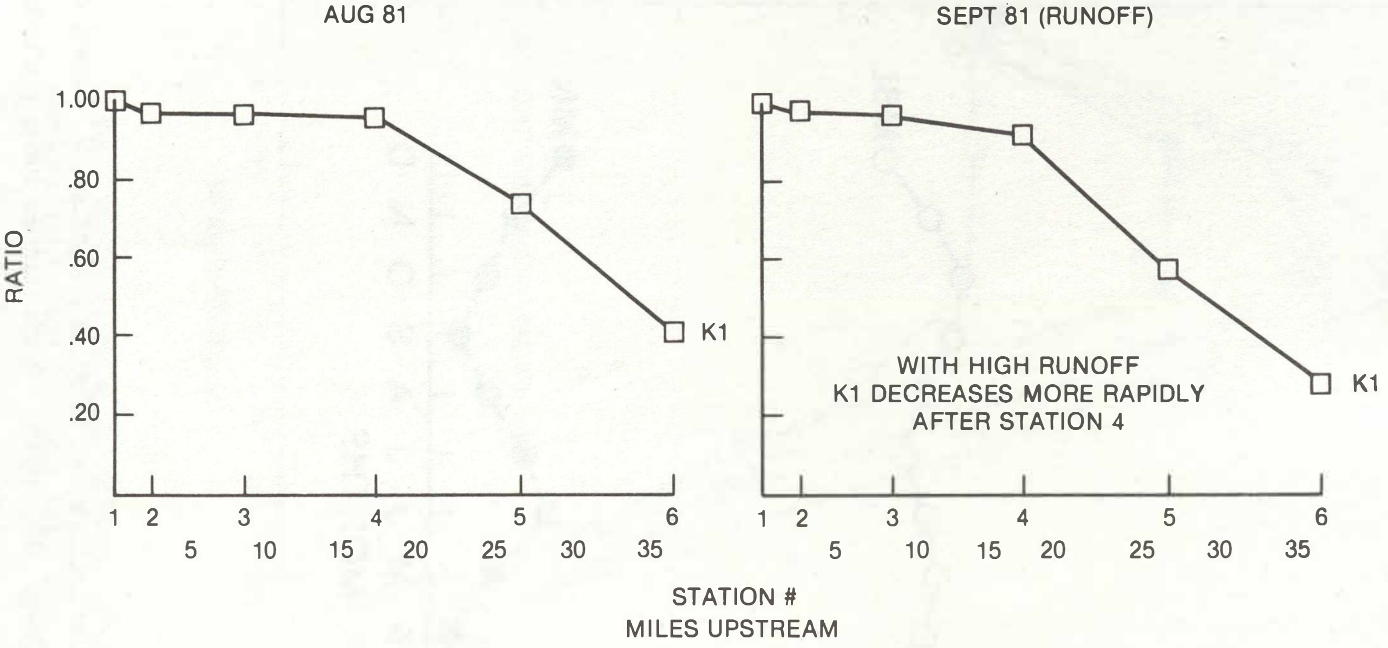
Note: Up to station 4, diurnal constituent K_1 decreases while semidiurnal constituents increase. Further upriver all constituents decrease, with semidiurnal constituents decreasing more rapidly. (Ratio = ratio of station x/station 1).

Figure 12. Harmonic changes in the tide.



Note: Annual variations at Gautier, station 2, based on monthly means from 1981-1984. Both curves have periods of about 6 months.

Figure 13. Annual variation in range and sea level.



Note: Ratio of station x/station 1 for diurnal component K_1. Other diurnal constitients have similar changes. Higher runoff causes K_1 to decrease more rapidly after station 4.

Figure 14. Effect of runoff on K_1.

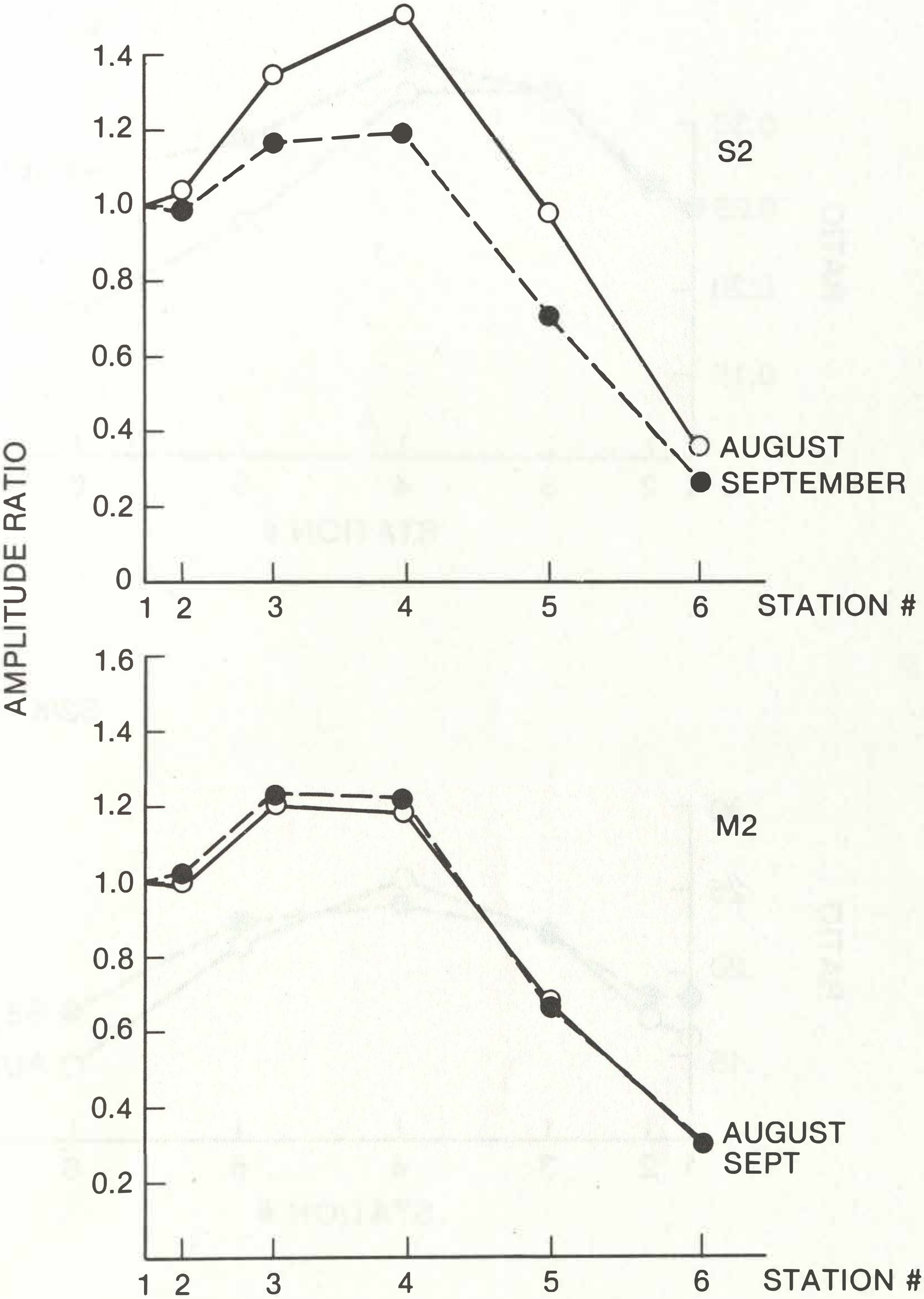


Figure 15. Effect of runoff on semidiurnal constituents.

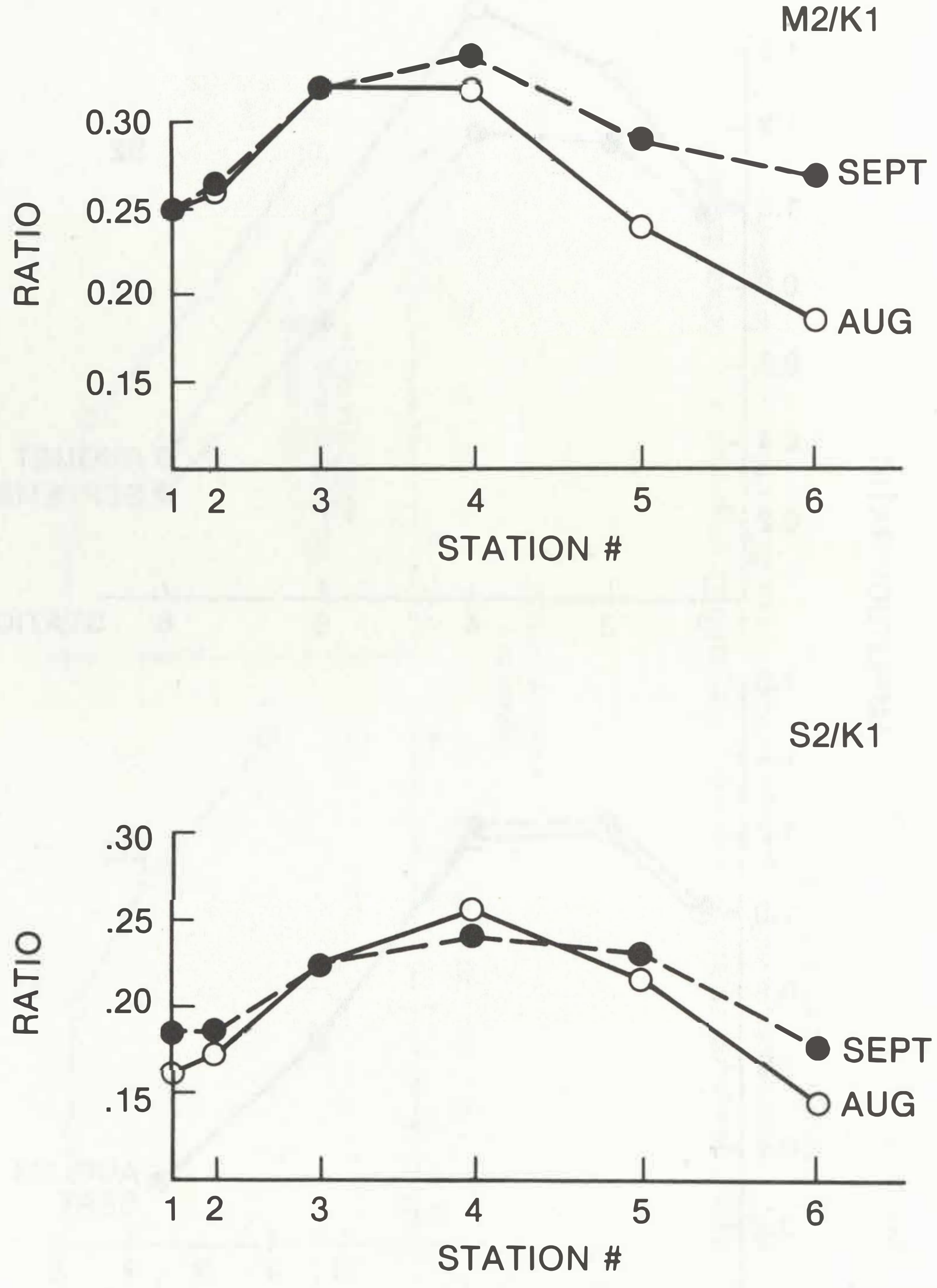


Figure 16. Effect of runoff on semidiurnal constituents divided by K_1.