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The Tidal Regime of the River Thames; Long-Term Trends and their Possible Causes

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The tidal régime of the River Thames; long-term trends and their possible causes

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Some of the processes responsible for the observed changes in the tidal régime of the River Thames are fairly well established, for example, the general sinking of southeastern England. However, the reason for the relatively large increase in the mean tidal range in the upper estuary is not obvious. Although definitive evidence is lacking, it seems probable that this increase is largely man-made and results primarily from the continual processes of embanking and bank raising.

Introduction

'In 1799 the range of springs at London Bridge, as ascertained by Russell and Gream for the Trinity Corporation, was only 15 feet; so that, in the last three-quarters of a century, the increased oscillation is 5 feet 9 inches. Of the increased range of 4 feet 7 inches as compared with Sheerness, 3 feet 10 inches are due to the elevation of the surface at high water, and 9 inches to the depression at low water' (J. B. Redman 1877).

Despite the uncertainty associated with tidal measurement in the 19th century, it is clear that the tidal régime of the River Thames has undergone major changes in the past. Redman naturally discussed these changes in terms of the civil engineering work in the river as a most obvious alteration in the tidal régime had followed the removal of Old London Bridge in the early 1830s. The consequent lowering of the river bed had resulted in the failure of the foundations of the neighbouring bridges, Mylne's bridge at Blackfriars in 1836 and Old Westminster Bridge shortly afterwards; by 1846 the river bed had been lowered by 2 m at Blackfriars and both bridges were eventually removed. These alterations allied with a substantial dredging programme produced a continuous change in the tidal régime between 1843 and 1877, the result being an earlier and a longer flood with increased tidal height and a shorter, lower ebb (Redman 1877).

The major survey of the river by Commander F. Bullock was made in the years 1830–9 coincident with the time of major change. More recent surveys in 1939–40 show the river is now a few metres deeper throughout much of its length (Inglis & Allen 1957). Clearly a substantial proportion of the change in the upper river may well have taken place during or shortly after Bullock's survey. This illustrates a fundamental problem in studying the long-term trends; spot readings give little indication of the type of changes taking place. In the absence of a reasonable physical understanding of the important processes, one must rely as far as possible on continuous series of reliable data.

Previous studies

Scattered tidal data exist from the early years of the 19th century. In his paper, Redman (1877) used various observations made between 1843 and 1877. Unfortunately, this data cannot be tied in with the more recent data to provide a coherent picture of the changes in the tidal régime over a period of more than 100 years. The old data, both observations and predictions, contain inconsistencies of which Redman, himself, was aware.

In addition, the lack of a stable datum not only prevents the linking of old and modern data, but prevented Redman from noticing the secular increase in sea level which should have been significantly larger than the nominal accuracy of the observations he discussed.

There seems to be no doubt that mean sea level was rising at approximately its present rate during the nineteenth century; Longfield (1932), using historical information on the levels of Roman and Neolithic occupation in southeast England, has suggested that this relative sinking of the land has been continuing for many centuries.

The secular trend in mean sea level has been examined using relatively recent tidal data (Valentin 1953; Rossiter 1967) and a rise in sea level at Southend of 25–35 cm/century determined. In addition to the general sinking of southeast England, Wilson & Grace (1942) suggested that the centre of London was sinking locally into the underlying clay at a rate of about 10 cm/century. In studying the trends in mean sea level the semi-diurnal and other relatively short period tides are regarded as a noise to be filtered from the record and discarded. Consequently, information about the long-term trends in the tidal régime itself was sparse.

TABLE 1. TRENDS IN THE TIDAL PARAMETERS (AFTER ROSSITER 1969*a*)

	Southend cm/century	Tower Pier cm/century
mean high water	36.3 ± 7.6	77.5 ± 11.6
mean low water	24.9 ± 7.9	9.2 ± 8.9
mean amplitude	5.2 ± 6.1	34.5 ± 7.0
mean level	31.1 ± 4.6	43.4 ± 8.2
	min/century	min/century
high-water interval	0.2 ± 3.4	−6.4 ± 4.7
low-water interval	−4.4 ± 5.7	−25.1 ± 5.6

However, a detailed examination of the data from the tide gauges at Southend and Tower Pier was made by Rossiter (1969*a*) using the records from the years 1934–66 which had been processed by the Port of London Authority to extract the annual mean values of high-water height (h.h.), low-water height (l.h.), high-water interval and low-water interval. The time intervals represent the mean time lag of high, or low, water relative to the corresponding transit of the moon.

The annual values for high- and low-water heights at these gauges showed both a small secular change and a noticeable oscillation of 18.6 years period associated with the precession of the Moon's node. Regression coefficients for the secular trend for all four variables plus those of the mean tide level and mean amplitude are shown in table 1. The steady increase in the mean water level at Southend is in good agreement with the previous estimates, while the slightly larger value at Tower Pier, although not very different statistically, could be due to the differential sinking of London suggested by Wilson & Grace. However, there is a marked increase in amplitude at Tower Pier which is not observed at Southend. As a result, the high-water height at Tower Pier appears to be rising at more than twice the rate of increase in the mean level.

The trends for the high- and low-water intervals at Southend are barely significant. However, the trend in mean low-water intervals at Tower Pier suggests that low tides tend to arrive earlier, the change being 16 min/century, and that the mean duration of the falling tide is decreasing by almost 20 min/century. The tides are therefore becoming larger, earlier, and less asymmetric; the same type of change as that observed by Redman.

A further investigation (Rossiter 1969*b*), including data from additional tide gauges in the river, confirmed the previous results. Similar trends in the mean high-water heights were found at North Woolwich and Chelsea eliminating the possibility of spurious results due to a serious gauge or datum error at Tower Pier. In addition, a multiple regression analysis of the data, designed to eliminate the nodal oscillation, resulted in an even higher estimate of 85 cm/century for the rate of rise of mean high water at Tower Bridge.

Regression analyses

Since Rossiter's papers, considerable attention has been given to the implications of such large increases in high-water level, particularly to their importance in determining flood-defence levels. Rossiter's results strictly apply only to the period of analysis, i.e. 1934–66, and extrapolation into the future is reliable only if the physical mechanism producing the change is reasonably well understood. This is the case for the secular trend, where the additional evidence suggests a long period of steady sinking.

However, the additional increase in the high waters at Tower Pier has no obvious explanation. A more detailed analysis using all the data currently available is therefore indicated.

The basic data for the annual mean high-water heights (h.h.) is shown in figure 1; also included is the annual mean freshwater flow over Teddington Weir. The variations in levels are coherent from station to station along the river with the magnitude of the annual perturbations increasing markedly up river. This seems primarily due to the increasing effect of the freshwater discharge which is well correlated with the variations in high-water heights. However, the dependence on flow does not conceal completely the importance of the nodal tide of 18.6 year period, producing high-water levels in 1941 and 1959/60, and lows in 1950 and 1968/69 at all stations. The secular trend is less obvious but can be seen in comparison with the freshwater flow which has zero trend over this period.

Multiple regression analyses using the maximum spans of data available have been performed on the data for all the stations except Richmond where there are serious gaps in the data. The independent variables used were the year, the two components of the nodal tide, cos N and sin N, and the mean annual freshwater flow at Teddington. The regression coefficients and their standard errors are shown in table 2, which also indicates the years of data available from each location.

The increase in h.h. at Southend is in good agreement with the previous estimates and also with the value for rise of mean sea level obtained by Rossiter (1967) of 34.2 ± 1.2 cm/century. The estimate for the rise of h.h. at Tower Pier is reduced slightly from the values in table 1. This is partly due to the elimination of a bad datum point, partly due to the inclusion of the other independent variables but mostly due to the inclusion of the most recent data which are rather low and weight the estimate accordingly. The estimate of mean low-water height at Tower Pier is also somewhat reduced.

The primary effect of the introduction of the other variables is to substantially reduce the standard error of the estimates. Statistically there is no contradiction, the new estimates lie within even the 70 % confidence limits of those given in table 1. For the number of degrees of freedom involved in these analyses the distribution of error, nominally a *t* distribution, is very closely Gaussian so that the 70 % confidence limits are given by ± the standard error and the 95 % confidence limits by ± twice the standard error. One modification, however, is that the original difference between the secular increase in mean level at Tower Pier and Southend is now by no means as noticeable. The results from Chelsea even suggest an increase of less than 30 cm/century in the upper river. There remains little evidence for the differential sinking of central London suggested by Wilson & Grace (1942).

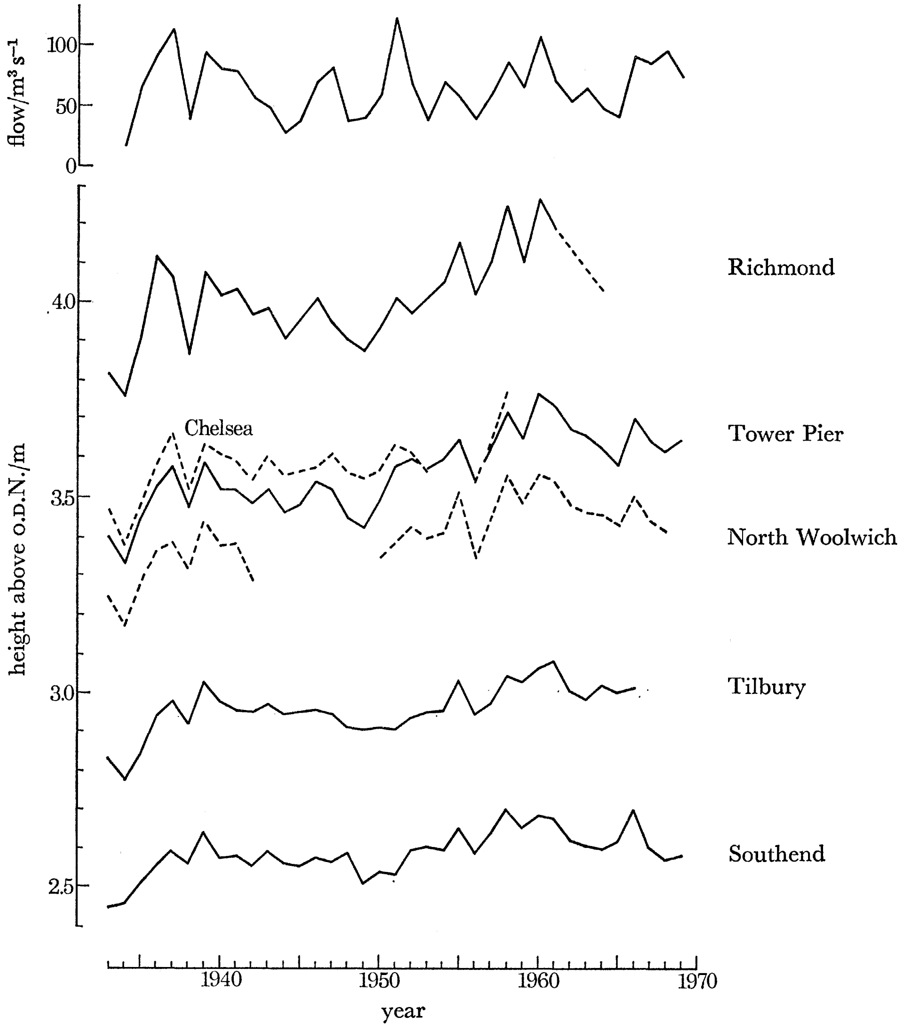

FIGURE 1. Mean annual high-water heights at tide gauges in the River Thames and the annual mean freshwater flow at Teddington Weir.

The regression coefficients for the freshwater flow decrease seawards as might be expected from figure 1. With the exception of Chelsea, the values for high and low water are very similar, the flow affecting only the mean level. Upstream, where the freshwater flow becomes relatively more important, some more complex interaction may occur. It is likely that low waters are more strongly influenced by the freshwater flow than high levels and there is some indication of this in the results for Chelsea. An analysis of a shorter period of data including Richmond and Teddington (table 3), shows the general effect of freshwater flow on the mean high-water heights throughout the river. The coefficients obtained are in good agreement with those derived from the longer spans of data. Again the decreasing influence of the flow in the seaward direction is well illustrated.

A more detailed examination of the Tower Pier data in terms of the mean spring and mean neap high and low waters is shown in figure 2. The difference between the nodal modulation of high and low waters is apparent. The nodal effect being primarily an amplitude modulation raising high-water and lowering low-water (Rossiter 1969*b*), the regression coefficients for the primary variable, cos *N*, have different signs for high and low water.

Table 2. Regression analysis of the annual mean high and low waters

data available	mean high water	mean low water
Southend	1931–69	1934–68
Tilbury	1933–66, 1968	1950–66, 1968
North Woolwich	1933–42, 1950–68	1951–68
Tower Pier	1933–69	1934–68
Chelsea	1931–53, 1956–8	1931–53, 1956–8

Regression coefficients with standard errors.

	station	year cm/century	cos *N* cm	sin *N* cm	flow cm per 100 m³/s
mean high-water heights	Southend	35.1 ± 4.3	−4.3 ± 0.6	−0.9 ± 0.7	4.3 ± 2.0
	Tilbury	38.1 ± 5.8	−3.6 ± 0.8	0.8 ± 0.8	7.8 ± 2.3
	North Woolwich	63.0 ± 8.2	−4.9 ± 1.0	−2.2 ± 1.4	11.8 ± 3.0
	Tower Pier	68.0 ± 4.9	−4.9 ± 0.7	−1.5 ± 0.7	15.2 ± 2.1
	Chelsea	58.8 ± 8.5	−4.0 ± 0.9	1.0 ± 1.0	16.1 ± 2.7
mean low-water heights	Southend	25.0 ± 4.6	5.0 ± 0.6	−0.9 ± 0.6	3.8 ± 1.8
	Tilbury	27.7 ± 17.4	4.5 ± 0.9	1.4 ± 1.2	5.9 ± 2.6
	North Woolwich	−5.2 ± 13.4	2.9 ± 0.6	2.3 ± 1.0	12.3 ± 1.8
	Tower Pier	4.3 ± 4.0	4.5 ± 0.5	1.0 ± 0.5	14.9 ± 1.6
	Chelsea	−8.8 ± 8.2	—	—	26.3 ± 2.6

Table 3. Influence of freshwater flow on mean high-water level (data 1933–53)

station	correlation water level/flow	regression coefficient cm per 100 m³/s
Southend	0.282	2.9 ± 2.3
Tilbury	0.376	7.0 ± 2.9
Tower Pier	0.682	14.1 ± 2.5
Chelsea	0.665	14.7 ± 2.3
Richmond	0.735	20.1 ± 3.6
Teddington	0.872	29.6 ± 2.7

Table 4 gives the results of a multiple regression analysis using this data. Mean annual spring high-water height is defined as the average of all high tides higher than the mean and mean neap high-water height as the average of those lower than the mean. Low waters are similarly derived. The effect of freshwater flow is seen to be concentrated in the mean levels and shows no preferential effect on the low water. This can be seen in figure 2 where the perturbations in the annual mean values seem to be very similar for both the high and low waters. The difference between the rate of increase of h.h. springs and neaps, while not statistically very significant, is physically interesting as the rate of increase in amplitude of each tide is proportional to its amplitude. The difference between the rates of increase in mean levels could be partly dynamic, higher mean levels could reasonably be associated with the spring tides, again the statistical significance of the difference is small. There is little suggestion of local sinking but this result is based on essentially the same data as that used to derive the coefficients in table 3.

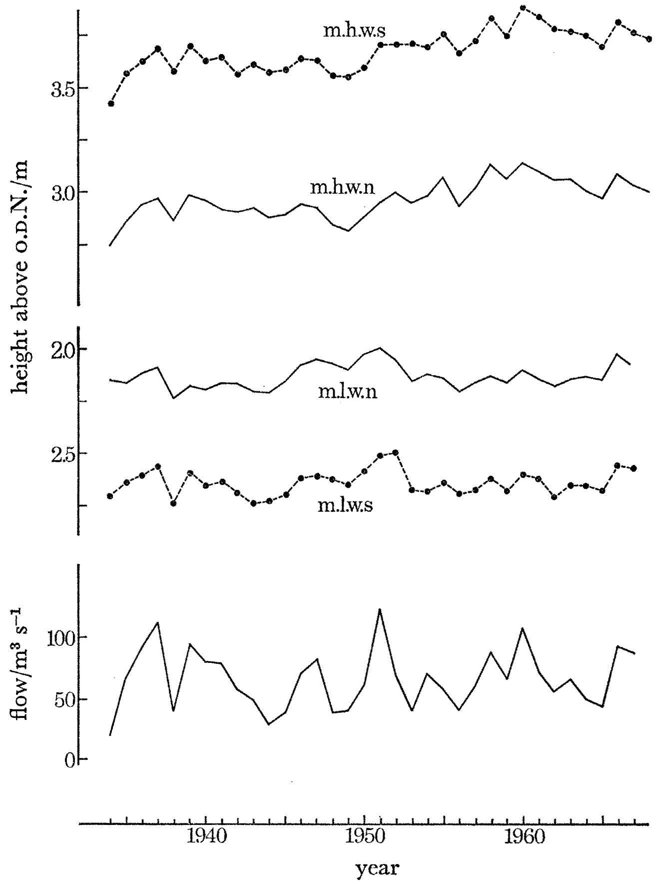

FIGURE 2. The mean spring and neap high-water (m.h.w.s., m.h.w.n.) and low-water (m.l.w.s., m.l.w.n.) heights at Tower Pier.

TABLE 4. REGRESSION COEFFICIENTS, MEAN SPRING AND NEAP TIDES AT TOWER PIER

	year cm/century	cos N cm	sin N cm	flow cm per 100 m³/s	years used
mean high-water springs	75.8 ± 6.1	−4.8 ± 0.8	−2.0 ± 0.9	15.6 ± 2.4	1934–68
mean high-water neaps	65.1 ± 6.4	−5.5 ± 0.9	−1.7 ± 0.9	14.2 ± 2.5	1934–68
mean low-water neaps	3.4 ± 4.3	6.1 ± 0.6	1.6 ± 0.6	14.3 ± 1.7	1934–67
mean low-water springs	2.4 ± 5.5	4.2 ± 0.7	1.0 ± 0.7	18.6 ± 2.1	1934–67
amplitude, springs	38.7 ± 3.4	−4.3 ± 0.5	−1.1 ± 0.5	—	1934–67
amplitude, neaps	32.6 ± 3.4	−5.6 ± 0.5	−1.6 ± 0.5	—	1934–67
mean level, springs	41.1 ± 4.6	−0.1 ± 0.6	−0.9 + 0.6	18.0 ± 1.7	1934–67
mean level, neaps	36.0 ± 4.3	+0.5 ± 0.5	−0.1 ± 0.5	14.7 ± 1.6	1934–67

Possible causes of the increased tidal amplitude

Although the analyses show several factors are important in determining the value of the mean annual levels in the River Thames, these are reasonably well understood and the regression coefficients obtained express the most important in quantative terms. The secular trend, the effect of the nodal tide and the influence of the freshwater flow are satisfactorily explained. There remains the increase in tidal amplitude in the upper river; this is so large an effect it seems that its cause must be obvious. It is not. It is therefore necessary to consider all the possible reasons for such an increase. These fall essentially into two categories, natural and artificial:

(*a*) natural

(i) A dynamic effect of the secular change in mean level.
(ii) A change in the tidal input, perhaps due to secular change.
(iii) An indirect effect of secular change, for example on temperature or salinity.
(iv) A change in the mean weather; temperature, rainfall, wind.

(*b*) artificial

(i) A change in river geometry; dredging, bridges and piers, embankments.
(ii) A change in the river temperature.
(iii) Pollution.

(*a*) *Natural causes*

(i) Perhaps the most physically satisfying explanation for the increase in amplitude would be an association with the other major change, the secular trend. This was considered by Rossiter (1969*a*) and the direct effect of deepening the river was examined using the existing numerical model of the estuary (Rossiter & Lennon 1965). The results showed that the increase in depth largely explains the alteration in the timing of the tide. However, the increases in amplitude observed in the model were quite small. The differences between the present tidal levels and those obtained by lowering the mean sea-level by 30 cm are shown by the solid line in figure 3. The tide used was a mean spring tide. The deepening of the water does reduce the friction term and produce a small increase in tidal amplitude in the upper river, but accounts only for a small part of the observed change.

The difference in both high- and low-tide levels at Woolwich is exactly the 30 cm subtracted from the present mean levels to try to reproduce the conditions of 1870. The data from table 2 also shown with 95 % confidence limits of the estimates indicated. There is no suggestion of an effect which could produce the observations.

(ii) One possible criticism of this approach is that a modern tide was used as input at Southend; the general deepening of the Southern North Sea may well have an effect on the tidal input to the Thames Estuary. As the observed tide at Southend is almost purely progressive, the reflexion from the upper river being very small, this provides a convenient position to examine this possibility. As is the case in the river, itself, the deepening of the sea would tend to give an increased tidal amplitude. The results given in both tables 1 and 2 suggest an increase of amplitude of 5 cm/century at Southend. In view of the standard errors, little statistical significance can be attached to this particular value, but there is certainly a suggestion that this mechanism could provide another small contribution to the total increase.

In figure 4, the maximum water-level observed at Tower Pier is plotted as a function of the

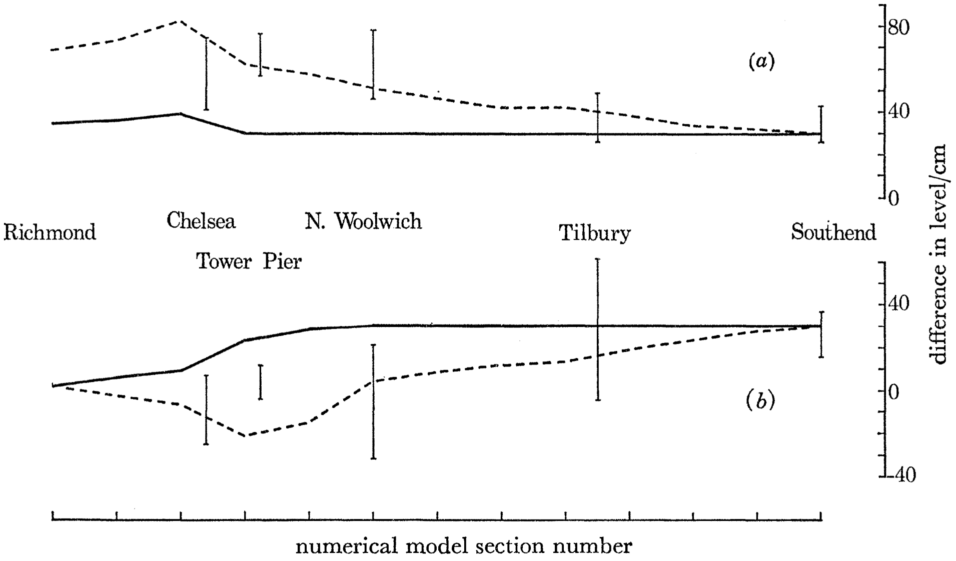

FIGURE 3. The change in (*a*) the mean high-water height and (*b*) the low-water heights in 100 years. The estimated changes from table 2 are illustrated by the 95 % confidence limits. —, effect of an increase in depth of 30 cm; ----, difference between a modern tide and a tide 30 cm lower with a 70 % increase in the frictional term.

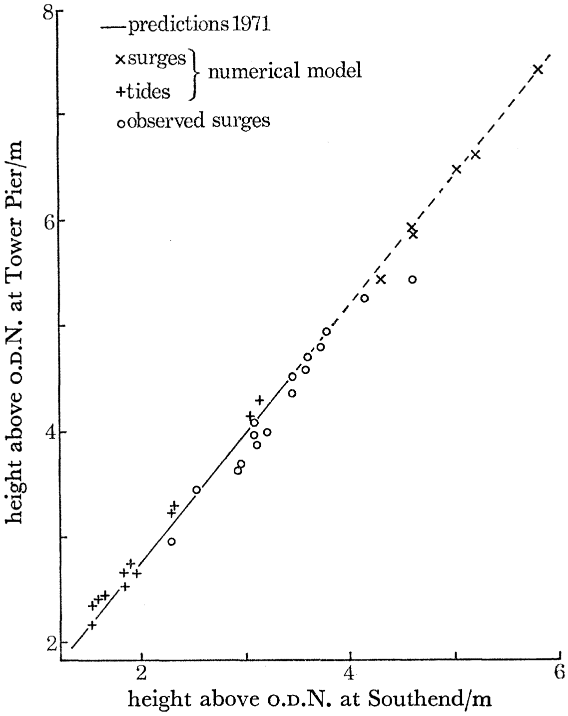

FIGURE 4. The relationship between the maximum height of a tide or tide plus surge at Southend and its maximum height at Tower Pier.

height of the same tide, or tide plus surge at Southend. A very consistent relationship is observed for predicted tides, observed tides and surges, and for tides or surges calculated with the numerical model of the river. A rise of 1.0 m at Southend produces an increase of 1.2 m in the maximum level at Tower Pier. This is true for a wide variety of tidal profiles. The one point that falls distinctly below the line is the 1953 surge with a value of +4.75 m at Southend. In this case the level reached at Tower Pier was substantially reduced by the disastrous flooding in the lower estuary particularly around Canvey Island.

(iii) The indirect effects of the increase in mean sea-level are difficult to assess. The balance between fresh and salt water in the estuary must slowly change and in a completely natural estuary the whole régime, including the depth and the sedimentary pattern would be continually adjusting to the change. No major changes seem to have been reported, certainly none that would affect the water level significantly. The artificial changes taking place may well obscure any tendency for a natural adjustment.

(iv) The weather influences the water level in several important ways. However, considering the effects of a whole year, the average changes are small. For example, the wind stress is the most important factor in generating a storm surge during which there may be changes in sea level of several metres. However, even apart from the tendency for both positive and negative surges, such major surges are rare (Suthons 1963) and their effect on the mean annual tidal height is small. There is no evidence that changes in wind, pressure or temperature have been sufficiently larger or sufficiently steady to contribute to the apparently continuous increase in tidal amplitude.

The rainfall effectively determines the freshwater flow of the river. A regression analysis showed no correlation between the year and the annual freshwater flow at Teddington.

(*b*) *Artificial causes*

(i) Redman ascribed the changes in the tidal régime that he observed to structural works, or the destruction of structures, and continuous dredging. The type of change taking place today is similar and may well have a similar cause. The major engineering work is of three distinct sorts: (1) maintenance and capital dredging, (2) building or removal of bridges and piers, (3) embanking.

There seems to be no evidence that maintenance dredging influences water levels, rather the reverse if nominal depths were accurately determined as one could allow the bed to accrete at 0.3 m/century. However, the line between maintenance and capital dredging is a thin one and with the increase in the size of ships there has been a general requirement for deeper channels in the outer estuary. In fact, a major capital dredging programme between 1909 and 1928 deepened the channel upstream from Tilbury. The consequence was an increase in the rate of tidal propagation and increase of range in the upper reaches. 'At London Bridge low water was lowered by about 6 inches and high water raised about 2 inches' (Inglis & Allen 1957). As can be seen from figures 2 and 3 the annual perturbations in mean sea level are not small compared with these suggested values for the permanent effects of the dredging. Again the statistical significance of the estimate cannot be assessed. Although this capital dredging was completed before the beginning of the data used in this study, the rate of readjustment of the river to a major change may well be quite slow. Redman suggests changes were continuing in 1846 as a result of the removal of Old London Bridge a dozen years before. One cannot entirely reject the possibility that dredging may have some affect on the tidal amplitude, particularly on the earliest years used in the analysis.

The effect of bridges and piers is rather difficult to determine particularly in a numerical model in which their influence is lumped together with other frictional effects. While there have been changes since 1931, no obvious decrease in the number of structures has occurred. There is no evidence of changes that would give a more or less steady change in the tidal régime.

Embanking, however, is itself a more or less continuous process. This was of particular interest to Redman as it was clearly a matter of lively controversy in the late 19th century.

'Respecting the effect of the Thames embankments... there is, even among those having the best opportunity of forming a judgement, a very diverse opinion. The Royal Commission gave a guarded opinion as to the results to be anticipated...' (Redman 1877). This caution seems to extend to the present day as little scientific consideration seems to have been given to the problem. However, one expects that the continual reclamation and the straightening, smoothing and raising of the banks would tend to reduce both the effective viscosity of the estuary and the total tidal prism.

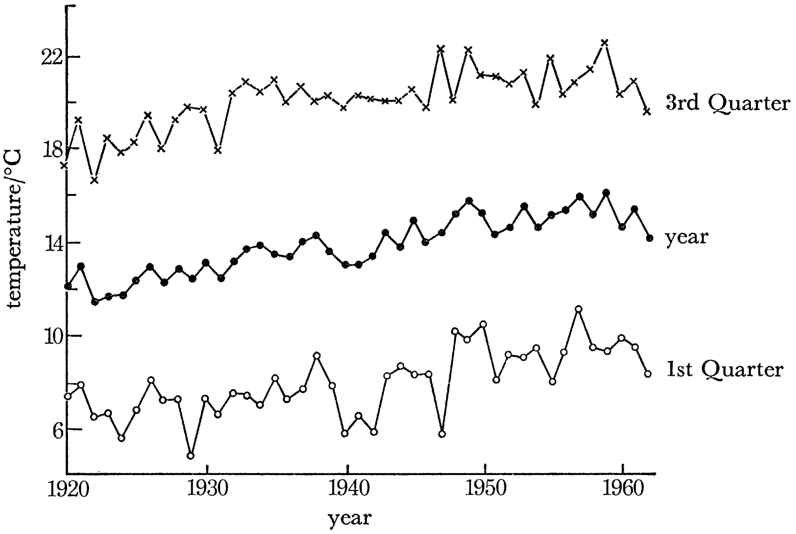

FIGURE 5. Average water temperature at half-tide in the reach extending 40 km seawards from London Bridge (after W.P.R.B. 1964).

(ii) The temperature of the river is slowly increasing, primarily due to the increased use of water for cooling at the power stations along the banks. Again the tendency will be to reduce viscosity and therefore increase the range. However, as can be seen in figure 5 the secular trend is quite small compared with the seasonal variation in water temperature. Long-term changes due to the temperature increase are expected to be small compared with the seasonal variation in the tidal régime.

(iii) The direct effects of pollution, as measured by the oxygen saturation for example, are similar in action to the temperature, having large seasonal variations in comparison with their long term trend. The more insidious effects of pollution depend on the type of pollutant emitted rather than the total quantity. Figure 6 shows the annual flow through a major sewage works. The trend is small compared with the variation, particularly that of 1940–6. There is no obvious correlation with observed water levels. However, types of pollution are continually changing and a pollutant, either by itself or in interaction with the bottom sediment, might affect the viscous behaviour of the river.

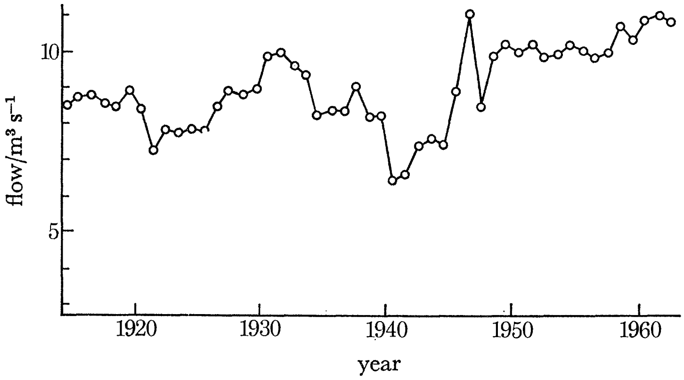

Figure 6. Annual average rate of flow through the Northern Outfall Sewage Works (after W.P.R.B. 1964).

Conclusions

Naturally, nearly all the mechanisms considered would tend to increase the tidal amplitude at Tower Pier. However, few seem capable of producing a change of the observed magnitude.

There is certainly a suggestion that the change can be regarded as a substantial decrease in the effective viscosity of the estuary. The change in tidal amplitude increases steadily with distance upstream from Southend. In addition there is the suggestion that at Tower Pier the spring and neap tides have an amplitude increase proportional to the amplitude itself. The numerical model of the Thames was used to test this idea. Again a tide representing 1870 conditions was input, mean sea-level being lowered by 30 cm, in addition the frictional coefficient was increased by 70 % throughout the model. In figure 3, the dashed line represents the difference between the modern tide and the somewhat synthetic tide of 100 years ago. The changes are very much of the observed order. Of course, minor changes could be made in the distribution of the frictional term to further improve the fit.

Some general data on the frictional coefficients of river and canals is available in terms of the Manning coefficient, n (Chow 1959). The coefficient for a natural river, similar to the Thames above Teddington is

$$n = 0.035 \quad \text{or} \quad n^2 = 1.2\times 10^{-3}.$$

Rossiter & Lennon found in proving the Thames model a value of n of 0.022 throughout much of the estuary, or

$$n^2 = 4.84\times 10^{-4}.$$

As the coefficient enters the frictional term in the equations of motion in the form n^2, increases of 70 % of the present value are not inconceivable. Henderson (1966), discussing the difference in friction between a canal having cohesive or non-cohesive banks, finds that the non-cohesive banks give a 65 % greater frictional term than cohesive banks.

A further, slightly puzzling, result is shown in figure 7.

If the maximum height reached at Tower Pier during the major storm surges is plotted against the year of occurrence, a rate of increase of 73 cm/century is obtained. Superficially this would seem to be in excellent agreement with the increase in the tidal height at Tower Pier. However, after almost every disastrous surge the bank levels along long sections of the river have been raised to prevent the danger from reoccurring. For example, since 1953 the bank levels in the

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lower estuary have been substantially raised and were the 1953 surge to reoccur it would consequently reach a higher level in central London; figure 4 suggests about 23 cm higher in the absence of significant flooding. The embankments therefore seem to play an important role in determining the height of major surges.

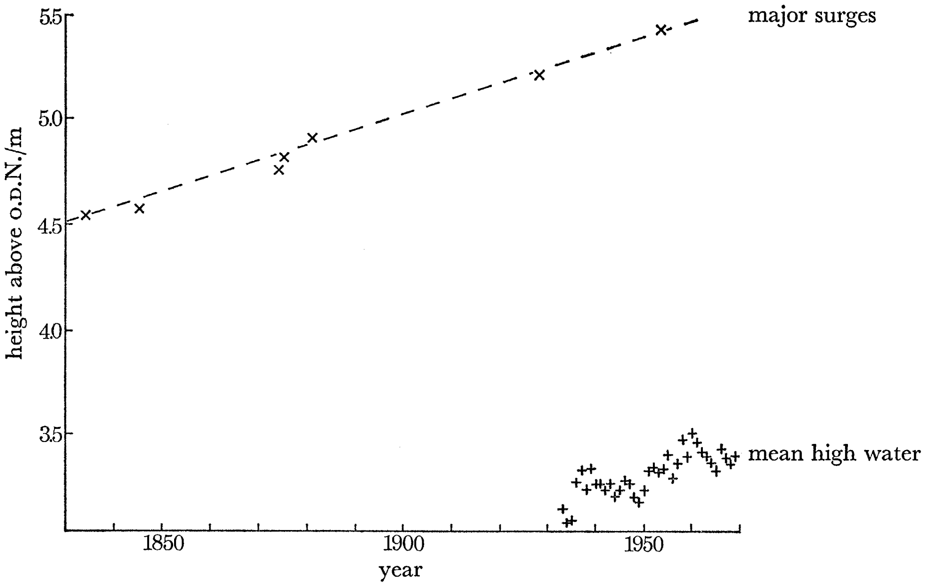

FIGURE 7. The maximum height at Tower Pier of major surges. For comparison the mean annual high-water heights are shown.

Although the mechanism is somewhat different, being a combination of frictional effects and the reduction in the tidal prism, particularly that part of the tidal prism associated with the higher tidal levels, embankments are also the most likely major cause of the increase in tidal amplitude in the river.

Before the construction of extensive sea defences much of the water coming up the river spread laterally to cover mud flats and marshes. Towards high tide an increasing area had to be filled to raise the actual level of the river. This had a limiting effect on the maximum tidal height reached which is not unlike the limitation imposed on the height of a surge by the loss of water from the river by overflowing and breaching the banks.

Although embanking undoubtedly smooths the banks and decreases the effective frictional dissipation it is quite likely that this effect is not as important as that due to the loss of the storage volume at the higher water levels. Both, however, work in the same direction increasing the tidal range.

Unless it can be shown that pollution has a substantial effect, there is no real alternative to the conclusion that the more or less continuous process of raising, widening and improving the river banks is canalizing the river and this process can adequately account for the observed changes in the tidal amplitude.

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