FLOW GAUGING ON THE RIVER THAMES - THE FIRST 100 YEARS

The United Kingdom has a relatively dense network of flow-measurement stations. However, the average length of flow record is rather limited being of the order of twenty years. Since a river flow record tends to increase in value in proportion to its length, the few available long records are of particular importance. In 1983 the gauging station at Teddington, on the River Thames, became the first to register one hundred years of data on the surface water archive. The following article celebrates this milestone.

Catchment Description

The River Thames rises in several headstreams in the Cotswold Hills. Its traditional source is at Thames Head near Cirencester some 382 kilometres from the effective lower limit of the non-tidal Thames at Teddington weir. The Thames, together with all its tributaries, drains a topographical catchment above Teddington of 9950 km^2. However, the true area which contributes to the groundwater component in the Thames flow is less than that indicated by the topographical divide. This is because some of the infiltrate reaching aquifers within the catchment is lost by sub-surface drainage to adjoining river basins. For instance, in the regions where the Chalk outcrops, there are areas, mainly within Hampshire and Wiltshire, where the ground water divide is significantly offset from the surface water divide. There is also a substantial natural transfer of water from the upper Colne sub-catchment eastwards into the basin of the River Lee. Evidence of significant underground flow out of the Thames catchment may also be found in the Cotswolds where drainage from the Oolitic Limestone aquifer enhances runoff in the Wessex and Severn Trent Water Authority areas.

The oldest rocks cropping out in the Thames catchment are of Lower Jurassic age, consisting of clay, shales and occasional limestones of the Lias Series. The geological succession passes up through the Inferior and Great Oolite Series (mainly limestone), the Oxford Clay, the limestones of the Corallian (absent in the east of the catchment) and the Kimmeridge Clay of the Upper Jurassic. The topmost beds of the Jurassic, the Portland and the Purbeck, are seen only as attentuated remnants in the Oxford area. Throughout much of the catchment the Jurassic rocks are overlain by Cretaceous strata, commencing with the mainly clayey Wealden Beds and passing up into the more arenaceous Lower Greensand; although well developed in the Weald dome, the Wealden beds are absent in the north and the outcrop of the Lower Greensand is discontinuous. Strata of upper Cretaceous age commence with the Gault Clay followed by the Upper Greensand and then by the dominant geological horizon of the region, the Chalk. The Chalk outcrop extends across the Thames basin from the south-west to the north-east giving rise to the characteristic downland scenery which contrasts with the relatively flat expanses of the clay vale to the north-west. Strata of Tertiary age (Eocene) are also found in the catchment with some sandy developments in the otherwise clayey Reading formation below and the almost wholly argillaceous London Clay above; sandy Bagshot Beds overlie the London Clay. Along the valleys of the Thames itself and the lower reaches of the main tributaries the Jurassic, Cretaceous and Tertiary formations are overlain by extensive tracts of river gravels and alluvial silt and clay.

The strata in southern England have a regional dip to the south east. In the lower Thames Valley this simple structure is markedly modified by the London Basin, an asymmetrical syncline, with a steeper southern limb, striking west to east and plunging beneath London itself. The Chalk outcrop along the southern limb of the syncline is narrow with a well defined escarpment east of the Hog's Back near Guildford; further west the Hampshire Downs have no consistent scarp and generally merge with the extensive tract of chalk upland of Salisbury Plain.

In its headwaters the Thames receives a significant proportion of its flow from both the Inferior Oolite and Great Oolite strata which form the Cotswold Hills. The river then flows east and then south across the Vale of Oxford, passing over the relatively impermeable beds of the Oxford clay and taking a minor groundwater contribution from the Corallian. Leaving the Jurassic strata, the Thames passes through the Chalk escarpment at Goring Gap. From here, the river flows approximately along the axis of the London Basin, first over the Chalk and then over Tertiary rocks receiving substantial baseflow support from the former.

The outcrops of the major aquifers (the Inferior and Great Oolite, the Lower Greensand and the Chalk) amount to some 47% of the Thames catchment. On average, about half of the total river flow at Teddington is derived from the natural groundwater discharge from the aquifers.

Outside London, agricultural land accounts for about 65% of the catchment area. Over the last 50 years or so Ministry of Agriculture statistics show that the proportion of agricultural land has decreased steadily, overall by about 9% with a consequent increase in land for other uses. The land devoted to agriculture has become more intensively managed with a steady increase in the area given over to arable farming at the expense of pasture land. A particularly dramatic decrease in permanent grassland also occurred during the Second World War when large areas were brought into arable cultivation.

Since the War the population of the region has been fairly steady but there has been a significant change in its distribution with rapid expansion of provincial centres such as Swindon, Oxford, Reading, Basingstoke and Bracknell and the decline in London's population.

Water Usage

The River Thames is a major source of water for public supply as well as for industry and agriculture. Of all the water currently put into supply in the Thames Water Authority area, the Thames itself contributes just over 50%. This includes some 70% of London's needs. In the lower reaches between Windsor and Teddington there are nine points where water is abstracted by Thames Water and by its agent water companies, for the supply of London and its environs. All of the water abstracted from the lower Thames by Thames Water is pumped into raw water storage reservoirs; a proportion is transferred to reservoirs in the Lee Valley via the Thames-Lee tunnel. The large storage capacity of these reservoirs provides a considerable buffer against drought. They also provide an important stage in the treatment process because of the significant improvement in water quality which occurs during retention in the reservoirs. In addition to the licensing regulations the major abstractions are also constrained by a statutory requirement to maintain a residual discharge over Teddington weir. In times of drought the prescribed residual flow can be reduced in steps to a statutory minimum flow according to a rather complex set of rules which take account of the actual volume of water in the reservoirs, its rate of depletion and the time of year. Thames Water is currently seeking a modification of these statutory restrictions; the aim is to make better use of the available water resources whilst at the same time safeguarding the interests of other users of the river.

Virtually all of the water taken for public supply from surface water resources in the lower reaches of the Thames is returned as effluent below Teddington weir. In 1883 these abstractions amounted to less than 4 $m^3\ s^{-1}$, on average. The succeeding one hundred years witnessed considerable variation in the relative proportions of London's water needs met from surface water and groundwater sources. Nevertheless the demand for water continued to grow and, now, almost 20 $m^3\ s^{-1}$ is taken from the Thames for supply purposes.

History of Teddington Weir

The first recorded weir at Teddington was constructed in 1812. It consisted of an overfall with a central rymer[1] weir controlled by hand paddles. It was not, however, until 1883 that the daily hydrometric record began when headwater and tailwater readings were first established, although for the previous thirty years the total monthly discharges at nearby Thames Ditton had been assessed routinely[2]. By 1883 the capacity of Teddington weir had been considerably increased with the addition of deep sill sluices. Over the next fifteen years the weir was further enlarged with the addition of overfalls and hand paddles. In 1923 a sharp-crested weir was constructed on part of the original overfall specifically to measure low flows. In 1931 the low flow thin-plate weir was reconstructed on a new line adjacent to the left bank and, at the same time, two additional deep sill roller sluices were added (Plate 1). The whole sill of the gauge weir which consists of a 21.34 m wide sharp crested plate, can be moved manually up or down within a limited range in order to discharge a quantity of water whilst maintaining a desired level in the reach. Finally in 1950, the remaining sections of the overfall and rymer type weir, dating from 1883 were replaced by radial-type gates. At the present time, the weir consists of 34 radial gates, 37 sluice gates (including the two large roller sluices) and the sharp crested weir and has an overall effective width of about 222 metres.

1. A 'rymer' weir is a simple form of variable geometry weir consisting of fixed horizontal beams which support vertical timber posts to form a series of rectangular openings. The openings may be partially or totally closed by means of timber gates fixed to the end of long poles – the combined gate and pole is referred to as a 'paddle' – which may be inserted or removed by hand.
2. John Taylor. 1876. "The Flow of the River Thames". Min. Proc. Instn. Civ. Engrs, vols: xlv pt iii, p.102, and lxiv pt ii(1881), p.328.

Measurement of Discharge

Records of the upstream and downstream water levels at Teddington read from staff gauges located at the head and tail of the lock system, have been logged at fixed times between 09.00 and 18.00 hours every day and at times of high and low water. Autographic records of water level have been maintained since about 1891. In order to compute discharge it is also essential to have a knowledge of all the individual weir gate settings. A log of all tackle movements and lock operations is maintained

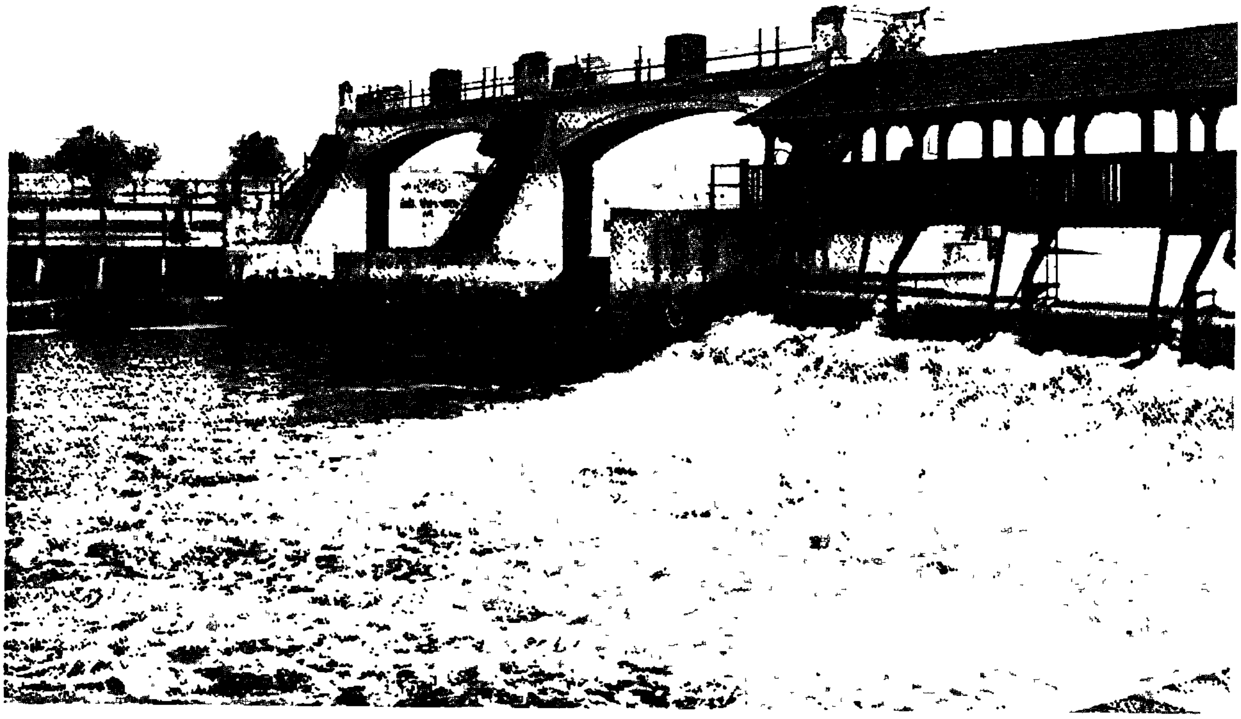

Plate 1. Roller sluices and part of the sharp-crested gauging weir at Teddington (1947).
Photograph: Thames Water

for this and other purposes. Discharge over or through the weir is computed by applying standard formulae to each individual gate. Discharge calculation for most of the flow ranges date from formulae adopted in 1883. They were further developed in 1893 and refined as a result of special investigations carried out by Nathaniel Beardmore and Sir John Hawkshaw. Over the years the coefficients and dimensions have been revised to take account of the changes which have been made to the weir system. Current meter gaugings have been made periodically to check the validity of the ratings.

Quite apart from the inherent difficulties in calculating discharge through such a complex weir system, the situation is further complicated by the tidal effects downstream. When the discharge exceeds about 85 $m^3 s^{-1}$, it is not possible to obtain a reliable estimate of discharge from a knowledge of head and tail water levels and gate settings. Instead a tailwater rating is used. However, even this is not straightforward. About 5 kilometres downstream from Teddington is Richmond weir. This weir, under normal operating conditions, is opened on the flood tide to allow the passage of water upstream, and closed on the ebb to retain the level for navigation purposes. Because of the variable tidal backwater effects it is only possible to estimate discharge by this method twice each day at low tide. When Richmond weir is permanently open, under high flows or for other operational reasons, a different tailwater stage-discharge curve is employed.

Although Teddington is normally regarded as the upstream tidal limit, high spring tides can raise the head water level in the reach above Teddington and can reduce, or on occasions even reverse, the flow for a short period. In these circumstances, tidal effects are observed upstream as far as Molesey weir. In addition to the influence of tides, the other factors which affect the computation of discharge are leakage and locking. With any weir system as complex as that at Teddington, there will always be a certain amount of leakage through gate seals and under gate bottoms. At low flows with all the gates closed, the leakage will tend to be a maximum both in absolute terms and as a proportion of total discharge. There will generally also be some leakage past closed lock gates, but in addition there will also be the quantity which is passed through the lock each time the gates are opened.

It is very difficult to estimate reliably on a day by day basis the amount of leakage and locking. It has, therefore, been the practice to add a nominal quantity to the calculated daily mean flow to make an allowance for the unmeasured discharge. Over the years at least three different allowances appear to have been used to adjust the calculated discharge corresponding to different stages of the weir development.

The daily mean discharge is the basic unit of derived data. During the currency of Teddington weir as a gauging structure, the mean discharge for the day commencing at 09.00 hours, was derived from the average of the discharges calculated regularly or irregularly throughout the subsequent 24 hours. Even in more recent years with recorders of greater sensitivity, this was never done more frequently than every hour. Considerable smoothing and interpolation of recorded traces was often necessary to take account of the short term fluctuations due to lockings and tidal effects described earlier. When the tailwater rating had to be used the mean discharge was based on only two estimates of discharge when the tide was at its lowest ebb.

For many purposes a discharge record which represents the flow as it would have been but for artificial effects, is desirable. Therefore, a so-called "naturalised" flow series is produced for Teddington which consists of the gauged flow plus the non-returning abstractions. No attempt is made to allow for any other man-made influences such as upstream abstractions and returns or the effect of groundwater abstractions, because it is almost impossible to assess the effects with any accuracy. For a similar reason no attempt is made to allow for the progressive modifications to the flow regime resulting from land-use changes.

The Ultrasonic Gauging Station

It is evident from the foregoing that the calculation of an accurate estimate of discharge at Teddington is no easy matter. In order to improve the accuracy of flow measurement a single-path ultrasonic gauging station was commissioned in 1974 at Kingston some 2 kilometres upstream of Teddington weir. Kingston is now regarded as the primary flow gauging station, although measurements still continue to be made at Teddington as a back-up to the ultrasonic station.

With the advent of Kingston ultrasonic gauging station, discharge is computed automatically every 15 minutes. The data are logged on site and telemetered, by radio, to a control centre to assist with the operational management of the lower Thames system. Examination of these short time interval data reveals clearly the effect of high spring tides, referred to earlier, including the complete reversal of the flow and the oscillations resulting from lock operation at either end of the reach. The estimation of daily mean discharge is thus now based on a much greater sample which automatically takes account of transient phenomena. It also removes much of the labour intensive manual effort involved in abstracting and computing the data.

On the basis that the ultrasonic gauging station provided an accurate reference, comparisons were made between the daily mean discharges derived from Kingston with those calculated from Teddington weir. It was found that at low flows Teddington was significantly underestimating the discharge (possibly indicating an inadequate allowance for locking and leakage). At higher flows, Teddington tended to overestimate although in certain ranges differences of 1 per cent or less were found.

As a result of these findings the archived daily mean discharges which had been calculated for Teddington from 1950 were adjusted in accordance with the derived relationships. No adjustments to the record prior to 1950 were made because the weir structure then was different and direct comparisons were therefore not valid.

The single-path ultrasonic gauge was replaced during 1986 with a multi-path ultrasonic gauge at the same site to allow better representation of the vertical velocity profile in the measuring section.

Runoff Trends

Long river flow records tend to display significant variations about the mean flow. Oscillations in runoff amounts may be associated with climatic perturbations but the distribution of rainfall within the year will also influence total runoff amounts. For instance, an increase in the proportion of rainfall falling in the winter, when evaporation is minimal, will result in enhanced runoff totals.

The average naturalised flow of the River Thames at Teddington is 78 $m^3 s^{-1}$ corresponding to an annual average runoff of 249 mm; by comparison the 1941–70 annual average rainfall over the catchment is 720 mm. A marked seasonality characterises the normal runoff pattern of the Thames, the average August flows being approximately 25 per cent of the mean January flow. Year by year variation in flow rates can also be substantial and, additionally, certain rather more persistent features in the runoff pattern may be recognised.

During the 100 years of the Teddington/Kingston gauging station there appear to have been at least three distinct phases in the pattern of runoff. This is illustrated in Figure 13 which shows both the annual runoff and annual rainfall plotted as accumulated departures from their respective 100 year means. The slope of the rainfall and runoff traces provides a guide to the relationship between hydrological conditions in a particular year, or over a period of years, and the long term average; the steeper the trace, the more marked is the departure from average conditions. For about the first 30 years runoff was generally below average whereas for the subsequent 30 year period this situation was reversed with runoff predominately above average. For the last 40 years or so there were some minor trends but they were much less pronounced than the earlier ones

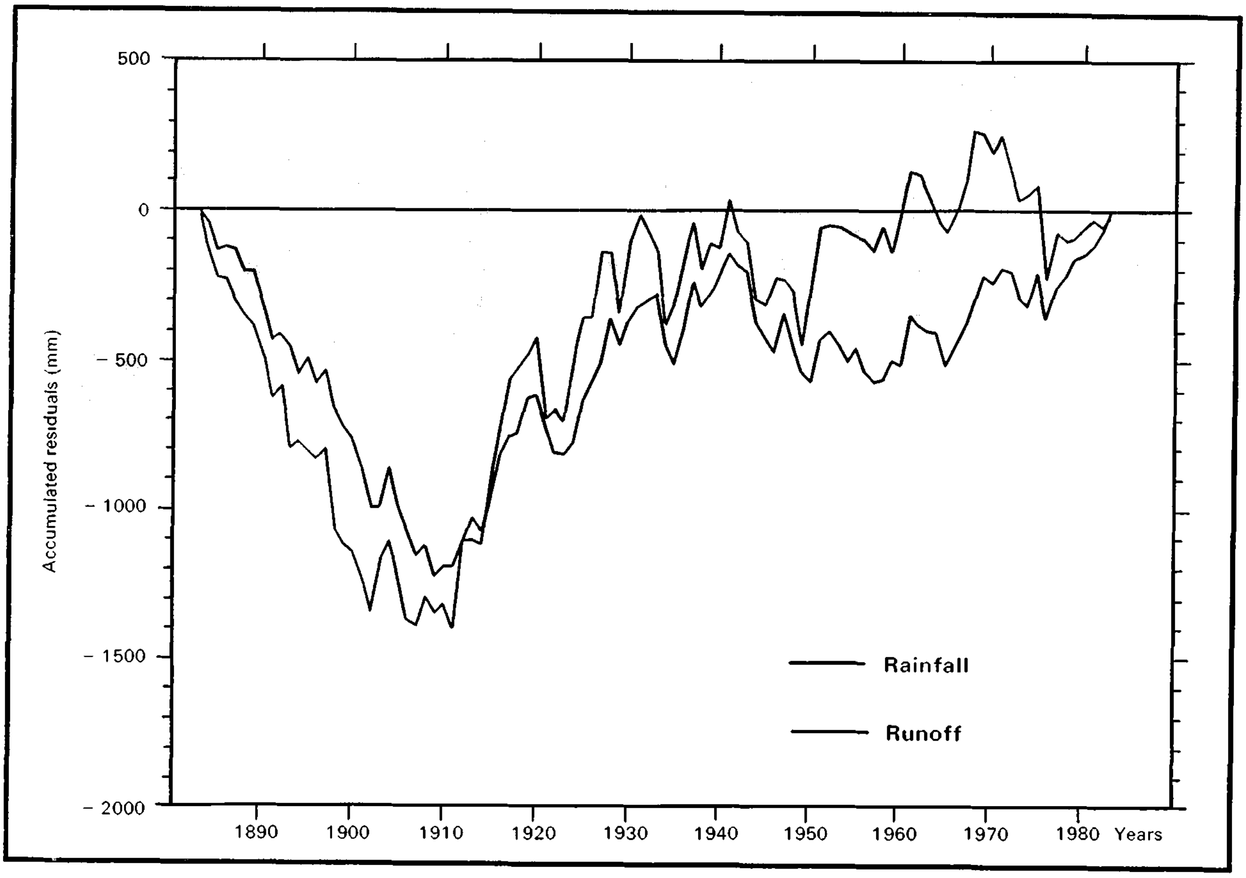

Figure 13. Accumulated departures of annual rainfall and runoff totals from the period of record average for the River Thames catchment above Teddington.

and generally runoff was closer to the long term average.

Allowing for the phase difference, the residual mass curve of annual rainfall exhibits a form very similar to the runoff and so it would appear that the trends in runoff can be attributed generally to climatic perturbations rather than other changes.

The double-mass curve is a classic technique for examining annual flow series for inconsistencies in the gauging method or for trends in runoff. Figure 14 shows such a curve of cumulative rainfall against cumulative runoff on which is also marked the dates of significant changes or improvements to Teddington weir. There are a number of small changes in the slope of the curve, but none of these appear to coincide with the development of the weir. A much better correlation would appear to exist with the runoff trends indicated in Figure 13 which tend to confirm the view that oscillations in the climate may be the most significant factor.

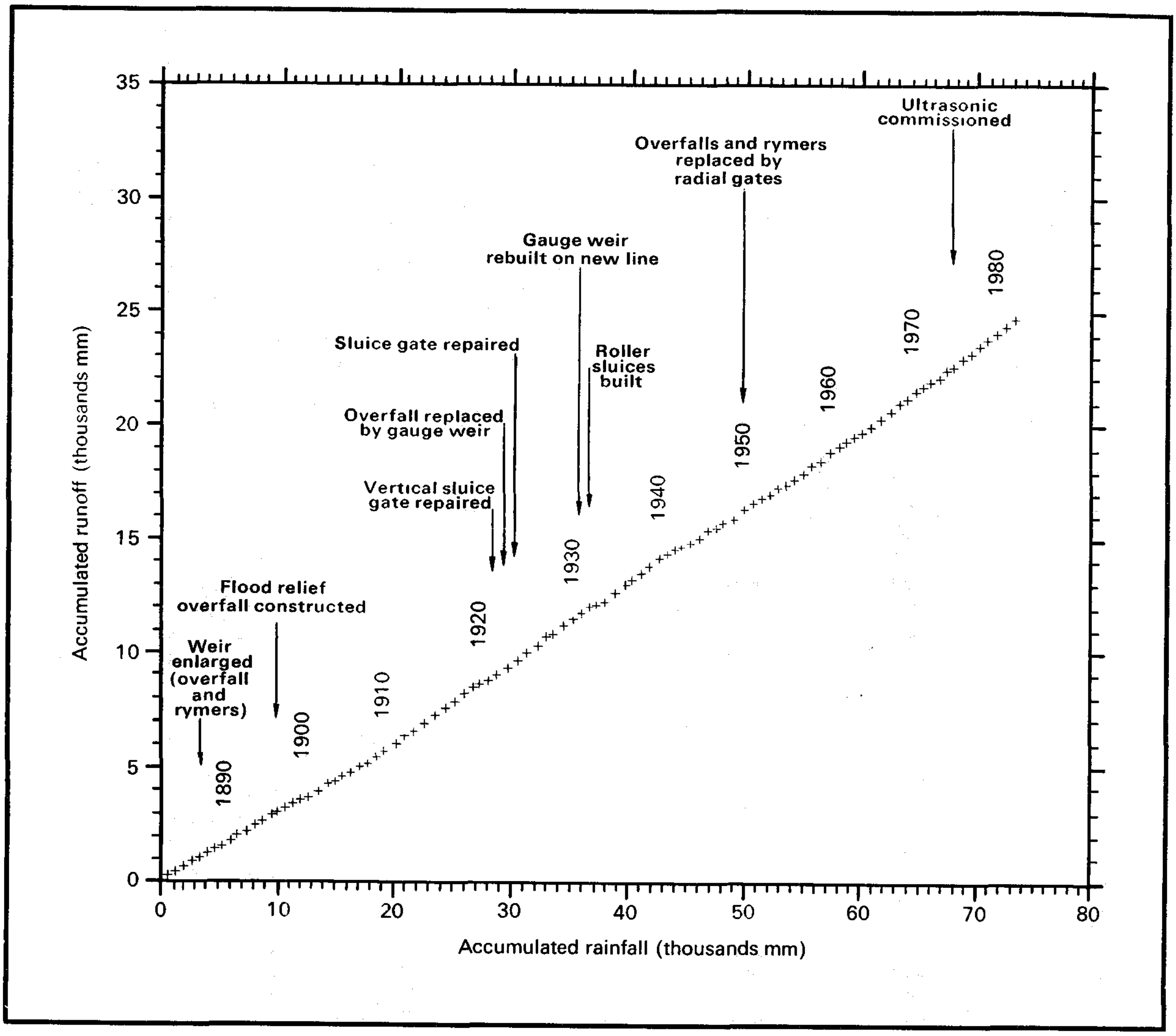

Figure 14. Accumulated annual runoff totals plotted against accumulated annual catchment rainfall totals for the River Thames at Teddington.

Floods and Droughts

On average, flows in the River Thames reach bank-full two or three times a year. Substantial inundation of the flood plain is uncommon and channel improvements have increased the carrying capacity of the river system significantly since the nineteenth century. On rare occasions, however, a combination of meteorological and catchment conditions give rise to flood events of notable magnitude. The three highest floods during the 100 year record occurred in November 1894, March 1947 and September 1968. Each one was brought about by different antecedent conditions.

The recorded peak daily mean flow in the 1894 flood was 1059 $m^3 s^{-1}$ on the 18 November. Although subsequent investigation suggested the true figure was probably lower, there was insufficient evidence to justify amending the record. Throughout the length of the Thames, flood levels were generally the highest ever recorded and flooding was widespread throughout the catchment. Plate 2 shows a rare photograph of the 1894 flood at Teddington lock.

The flood was brought about by the persistence and volume of rainfall which fell over an extended period. Heavy rainfall at the end of October, and in early November, totalling some 95 mm, caused the river to rise rapidly. The subsequent flood flows apparently passed without undue damage and began to recede. However, further heavy rainfall, in excess of 100 mm, fell between the 7th and the 14th of November on a thoroughly saturated catchment with the rivers still in spate. Flow rates in the Thames increased again attaining the peak discharge four days later; there had been very little rainfall over this four-day period. When considering the 1894 event in relation to more recent flood events it should be appreciated that land drainage and flood alleviation schemes together with regular channel maintenance work have significantly changed the character of the flow regime. In the nineteenth century only limited channel improvement had taken place; as a consequence times of concentration and times of travel for flood discharges would have been longer with

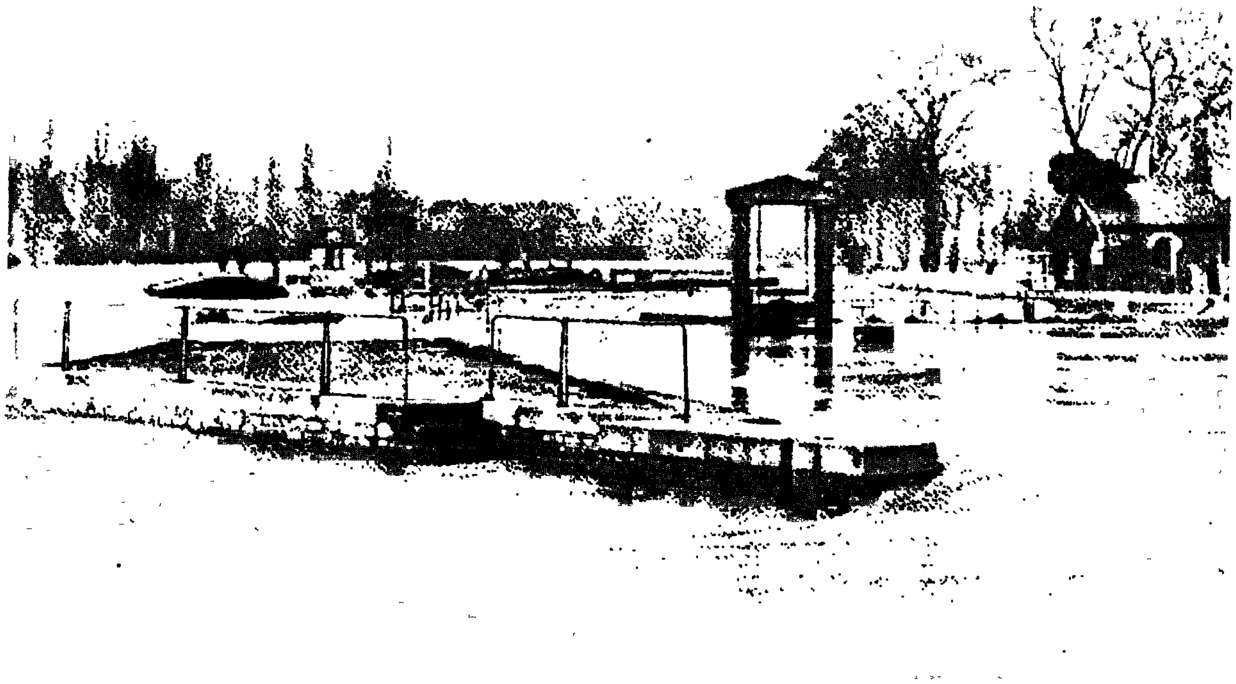

Plate 2. Teddington weir during the 1894 flood.
Photograph: Thames Water

inundations of the Thames flood plain occurring with greater frequency and lasting for longer periods.

The flood in March 1947, which attained a peak daily discharge of 714 $m^3 s^{-1}$, came about for a totally different reason. In this case the catchment was frozen and thickly covered with snow. A rapid thaw set in accompanied by rainfall. Although the rainfall was not exceptionally high (74 mm in the 11 days preceding the peak), the compressed lower layers of snow and the frozen ground caused the catchment to behave as though it was much less pervious than normal and, with the melting snow, the percentage runoff was remarkably high. Flooding was widespread throughout the catchment, as it was throughout most of England, and the duration of flow in excess of 500 $m^3 s^{-1}$ was the greatest yet recorded.

In complete contrast the flood of September 1968 was caused by very heavy rainfall falling in a short period over a fairly localised area. The summer of 1968 was unsettled in most of southern England with the usual west to east passage of depressions following a more southerly course than normal. On 14 September a trough of low pressure moved northwards from France into south-east England to meet an almost stationary cold front and an exceptionally severe two-day storm began. In the Thames catchment, the storm was primarily concentrated over the Mole and Wey catchments in the south of the region. Most of the rainfall fell in a period of about 17 hours with two-day totals generally in excess of 130 mm over much of the area. There was extensive flooding in the Mole and Wey valleys and in the lower reaches of the Thames. The peak daily mean flow at Teddington was 600 $m^3 s^{-1}$.

At the other end of the spectrum there have also been some notable droughts during the 100 year period. Droughts are generally more difficult to classify than floods because for many purposes the duration of a low flow event can be equally, if not more, important than the absolute minimum. It is generally accepted that the four classic droughts this century are those which occurred in 1921, 1934, 1944 and 1976 although the first thirty years of the Teddington record also featured several periods of sustained low discharges.

In the case of the Thames at Teddington, which derives a large proportion of its flow from groundwater, lack of summer rainfall alone is not usually sufficient to cause very low flows. The seeds of a drought are usually sown by a lack of aquifer replenishment in the previous winter; the dry winter may be preceded by a summer characterised by low flows so that the drought is a two year event. That was the case with three of the droughts mentioned above. The exception was 1921 where the previous summer's rainfall was above average. Table 5 shows, as a percentage of the long term mean, the rainfall which preceded the classic droughts.

TABLE 5. RAINFALL AMOUNTS PRECEDING SUMMER DROUGHTS IN THE THAMES CATCHMENT

Period	Long term mean (mm)	% of mean 1921	1934	1944	1976
Preceding Apr–Sep	346	125	75	81	81
Preceding Oct–Mar	400	69	54	60	45
Preceding Apr–Mar	746	95	64	70	62

In terms of duration, the drought of 1921 was the longest with no significant recovery of flow until the following January. Plate 3 shows Teddington weir in July 1921 when the river level was at its lowest. However, the 1934 drought has been found to be the most severe in relation to assessments of the reliability of the water resources system for London, which is in part dependent on the Thames.

In more recent years the 1976 drought was remarkable because the gauged flow at Teddington was reduced to virtually zero. This unprecedented situation arose when temporary pumps were installed below Molesey weir in order to pump water back over the weir to make the flow of the Rivers Mole and Hogsmill available for abstraction. Steps were taken to seal weir gates and restricted locking was introduced to conserve water in the lower reaches. Water was also pumped back over Teddington weir in order to recirculate leakage. Despite these severe measures, use of the river for water supply and all other purposes continued throughout the drought. Water levels were generally maintained and navigation was not severely restricted.

Table 6 summarises the periods of low "naturalised" flows during the four droughts.

TABLE 6. LENGTH OF PERIOD FOR WHICH FLOWS AT TEDDINGTON FELL BELOW SELECTED THRESHOLDS DURING THE DROUGHTS OF 1921, 1934, 1944 AND 1976

Flow ($m^3 s^{-1}$)	No. of days flow less than value indicated 1921	1934	1944	1976
10	15	7	9	11
13	79	60	56	53
16	130	138	120	88
20	186	183	160	116
25	218	215	183	157

The Value of the Discharge Record

In addition to providing the basic evidence that has allowed increasing rates of abstraction to be supported by the Thames, river flow data are required for many operational and planning purposes by

Plate 3. Downstream of Teddington weir during July 1921.

Photograph: Thames Water

Thames Water in fulfilling its various functions. These can include the setting of discharge consent conditions, the design of land drainage and flood alleviation schemes, the planning of the integrated development of water resources, pollution control and other aspects of environmental management. The long Teddington flow record has been particularly valuable in assessing the reliability of the water resources system in relation to London's water requirements.

As greater demands are placed upon the Thames, not only for water supply and effluent disposal but also for recreational activities, the accurate monitoring of levels and flow becomes increasingly important. During drought conditions, in particular, river management requires the control to be carried out to finer limits.

In order to achieve this, Thames Water has a comprehensive plan of improved monitoring of the lower Thames. This includes the installation of telemetry to monitor remotely the water level at the head and tail of each weir and the quantities of water being abstracted at the intakes. Further ultrasonic gauging stations on the lower Thames and its tributaries are also being planned. The recently modernised Kingston ultrasonic gauging station is an integral part of this plan and will continue to be the cornerstone of flow measurement on the Thames for many years to come.