BANK PROTECTION USING EMERGENT PLANTS AGAINST BOAT WASH IN RIVERS AND CANALS

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SYNOPSIS Field test results are presented of the boat wash from recreational motor boats in the summer on the River Thames near Wallingford. A speed limit of two metres per second if successfully imposed would substantially eliminate boat wash that exceeded wind waves in height on this reach of the River Thames.

Field test results are presented of the attenuation of the ship waves from motor boat wash in beds of:- Phragmites australis (syn. P communis) common or Norfolk reed; Schoenoplectus lacustris (syn. Scirpus lacustris) common clubrush, greater rush or bulrush; Typha angustifolia, lesser or narrow leaved reed mace; and Acorus calamus, sweet flag. Under suitable conditions of depth, vegetation density, and a bed slope of one in four, two metres of width of bed of any of these species will dissipate almost two thirds of the shipwave energy.

Bank protection is proposed against boat wash for gravel and mixed bed rivers and also for fen and Broadland rivers with high motor boat usage. The submerged toe protection utilises old tyres, with the advantage of fend off effect. The beds may then be shaped and re-established with mixed species of emergent river plants to give bank protection and to provide a scarce natural habitat.

This report was prepared by Mr A J Bonham during his temporary attachment to the Hydraulics Research Station. The views expressed and the conclusions drawn are those of the author; they do not necessarily reflect the official views of the Station.

SYMBOLS

b	subscript, breaking depth
C	wave velocity (celerity)
E	total energy in one wave length per unit of crest width
E_n	energy density per unit surface area in a wave profile
$\overline{E}$	total average energy per unit of surface area
f	wave frequency
g	gravitational acceleration
h	ship wave height
$\overline{h}$	mean of five highest ship waves
h^{max}	maximum ship wave height
H	wave height
H^{max}	maximum wave height
I	shock impulse
I	inner count zone or probe
k	constant
L	wave length
L_s	boat hull waterline length
n	ratio of group velocity to individual wave velocity
O	outer count zone or probe
p	probe
T	wave period
U	forward momentum per unit of wave crest
V_s	boat speed
ϱ	mass density of water

CONTENTS PAGE

TABLE

FIGURES

CONTENTS (Cont'd)

PLATES (see Fig 3 for locations on River Thames)

INTRODUCTION 1

Rivers and canals are a magnificent recreational resource for people providing opportunities for angling, boating, ornithology, bank side rambling and many other pastimes. They are also required to efficiently discharge flood water, to preserve drainage levels, to provide convey and store water supplies, to dilute effluents, to support fisheries and sometimes to carry freight.

These watercourses are also a most significant and scarce part of the natural ecology supporting very rich plant and animal communities. A great responsibility exists to preserve the environment in the bed and banks of channels as a habitat and a refuge.

In recent years the recreational use of rivers and canals has increased and the wash from motor boats is eroding the banks. Where the waterway system is sufficiently extensive to support numerous holiday motor cruisers the high traffic density and long seasonal duration has led to a significant river widening in some locations or expensive bank protection. Examples of waterways under stress are the River Thames, the Norfolk Broadland rivers and some of the rivers and canals controlled by the British Waterways Board.

In rivers and canals the relationship is profound between motor boat usage, river plant survival and bank protection. Where the usage of motor boats is small plant growth may be excessive and will require weed control by cutting or herbicides or dredging. However, as the usage of motor boats increases their propellers cut plants and if the boat traffic is dense their wash is sufficient to sweep away the bank vegetation(1). The effect of very frequent wash from recreational motor boats is the scour of soil from the roots of emergent river plants close to the bank and the undermining and battering of natural vegetation in the bank area. Generally once vegetation is lost the rate of erosion increases and regeneration is inhibited. Where extensive damage has been permitted to occur, bank protection or restoration may be carried out as detailed in the "Report on Bank Protection on Rivers and Canals"(2). It may be necessary to use piling which will have the unfortunate effect of reflecting boat wash whereas the original emergent river plants and natural bank vegetation would have absorbed and dissipated the wave energy. A chop will persist longer in the piled channel which will increase the damage to unprotected banks nearby and the consequent erosion may outflank the ends of the piling works themselves. A process may be set in train resulting eventually in very extensive and expensive continuous lengths of protection on both banks of the channel as may be seen on some Broadland rivers and canals.

The purpose of this report is to show examples, and a methodology, of how channels may be managed a little better for the essential and recreational purposes outlined above and at the same time the banks and margins may also be protected to support a natural environment using engineering techniques which make the greatest possible use of the intrinsic engineering properties of the natural plant communities themselves.

THE RIVER THAMES AND THE NORFOLK BROADLAND RIVERS, EXAMPLES OF RIVERS WITH BANK EROSION FROM BOAT WASH 2

The River Thames

The River Thames near Wallingford was selected for study. This reach of 10.5km from Benson lock to Cleeve lock is the longest reach between locks on the River Thames, and is shown in Figure 3.

One hundred years ago Henry Taunt travelled through Oxfordshire often by punt on the River Thames taking superb photographs, many of which show extensive beds of emergent river plants and large areas of floating leaved rooted plants. Thirty-six old photographs were found of this reach, many by Taunt[3], and comparative modern photographs of this reach show a gradual loss of emergent vegetation after the second world war followed more recently by a rapid elimination of emergent and floating leaved rooted plants until the present day when only a few beds exist in favoured locations. It will be shown that the larger beds of surviving emergent species are well suited to withstand some boat wash and they are located on beds profiled to help the plants to withstand the impact of wave energy.

The marginal beds of emergent river plants in this reach have recently been under stress from the following causes:

1) The river was dredged in the early 1960s which steepened the bank slopes and damaged the outer edge of the beds.
2) River levels are kept lower in winter by weir regulation to assist land drainage by rapid removal of flood water. The lower stage discharge relationship results in greater scour at the edge of beds during floods and between floods the rhizomes are unprotected from frost.
3) The heavy seasonal load of recreational motor boats has increased in recent years resulting in scour from boat wash turbulence around the stems and rhizomes of emergent river plants.
4) The ends of marginal beds are under increasing attack from behind from boat wash which is reflected from smooth steep banks.
5) Propeller action from the heavy summer seasonal load of motor boats has decimated the floating leaved rooted river plants, thereby reducing channel roughness and at high flows reducing stage and increasing scour velocity at the outer edge of the beds. (The drag effect of submerged river plants is not always appreciated[4, 5]).
6) The mooring of boats against the outer edge of beds has produced mechanical damage.
7) Fishermen still cut swathes through the remaining marginal beds of emergent river plants and steps in the banks.
8) Wild fowl graze a higher proportion of the beds than when the beds were more extensive.

Sectional diagrams of a typical river bank before high motor boat usage and also of present erosion are shown in Figure 1. The boat wash erosion mechanism is as follows:

Soil is washed from the roots of any emergent plants in shallow beds close to the banks and from the roots of marginal bank vegetation. In areas where the banks contain clay the rate of attrition is very slow and herbage may recover the receeding upper bank but at water level the bank will remain generally steep, bare, smooth and wave reflective except under trees where roots may form mat-like protections; trees may be outflanked by erosion and fall into the river. In areas where clay is absent from the subsoil then erosion is rapid once the vegetative cover disappears. A wave cut platform extends into the bank until a spending beach bay develops at a slope and width adequate to dissipate boat wash wave energy. Coarser sediment tends to remain on the bank and finer sediment is removed to a shoal or offshore bar. Flood discharges remove or redistribute these shoals and subsequently the beach erosion will continue. The eroded banks tend to collapse with the rapid drawdown of river level caused by flood recession or weir regulation.

If the present level of boat wash continues into the future there are several long term management techniques available as follows:

1) Allow the process of bank erosion to continue until the river becomes much wider and shallower with wide beaches as on many navigated rivers such as the Rhone and Rhine[6]. Extensive permanent shoals will develop which may eventually be colonised and stabilized by river plants, such as sweet flag, when the channel has developed and changed sufficiently to produce a suitable habitat.
2) Sheet pile the river banks on their present line. This will eliminate the rich bank habitat.

3) Develop a technique to protect and reinforce the boat wash absorbing beds of emergent river plants as detailed in Section 5.

4) Impose and enforce a speed limit as detailed in Section 3.

Broadland rivers

The Norfolk Broadland rivers and particularly the Rivers Bure, Thurne and Ant near Horning were selected for study. The numerous old photographs[7] available show that before the onset of heavy holiday motor cruiser traffic the rivers were much narrower, were flanked by continuous thick stands of emergent river plants and contained extensive areas of floating leaved rooted plants. See Plates 1 to 4.

The diurnal tidal influence is small in the rivers near Horning but river levels are influenced by surge levels in the North Sea, fluvial flood discharges and fluvial seasonal discharges; the typical range of normal summer levels is 300 or 400mm.

The bank soil structure consists of soft peat often overlaid by a post glacial deposition of clay. The clay may be deep on the bed and the banks of the larger rivers downstream but generally diminishes inland and on smaller streams. The clay may peter out towards the landward edge of the marshes, where the peat subsoil may be soft enough for a man to sink in if the grass root mat is disturbed.

The land has been slowly sinking in relation to the sea level for many centuries. Ancient peat workings became flooded in medieval times and lakes known as broads were formed. In order to make agricultural use of the marshes it has been necessary to raise clay flood walls and clay is excavated from the marsh drainage channels for this purpose. These channels are known as soke dykes in Norfolk, delphs in Suffolk and rhynes in Somerset. The purpose of the dyke system is to drain the marsh and to lower the water table on the marsh as required by the farmers. The weight of the clay wall gradually consolidates the underlying peat and clay strata and the wall continues to sink. Before equilibrium is reached it will generally be necessary to raise the wall again after a few years to higher levels. It is an expensive continuing process.

The bank between the river edge and the clay wall is called the rond. Erosion of the rond is now generally taking place, often rapidly. When the rond becomes very narrow the stability of the clay wall becomes endangered and it becomes necessary to close pile the bank using steel sheet piling or a composite piling system using steel king piles and close timber sheet piling or some other system such as asbestos sheet piling or all timber piling. The piling systems may require to be tied back and anchored into the firm clay behind the wall. It is generally not economic to rebuild the clay wall back on a new retirement line because of the very considerable time required to consolidate and thereby increase the structural strength of the peat sub strata or the great cost of removing it. Reed beds seem to prosper behind very old timber piling which has rotted down some 100 to 400mm below low water level, and colonise to the edge of the protection.

The rapid erosion of the unprotected rond has several causes shown diagramatically in Figure 2. Generally the causes of bank erosion are as follows:-

1) Deterioration in the vigour of Phragmites australis, Norfolk reed, in Norfolk. George[8] considers that the Norfolk reed may be senescent in some places, that there is significant attack by the fen wainscot moth, and that there is dieback which may be caused by changes in water quality. The writer has noticed that some Phragmites australis in Norfolk is much less vigorous than some in Australia, Africa, North America, Somerset and the River Thames.

2) Overgrazing. George also considers that grazing of the outer edge of the reeds may now be excessive from swans, coot, greylags and Canada geese.

3) Undermining. Payne[9] has examined the wash of boats, the effect of burrowing into the clay on the edge of the rond by voles, water rats and shrimps, etc. and the boat wash pumping action under the reed rhizome and root mat of fine sediment in fluid suspension which is sucked out with drawdown. The reed mats soon break off and float away.

4) Turbulence. Payne and Garrard are also examining the erosion by propeller turbulence of the soft peat river banks and Garrard is also looking at the effect of turbulence caused by propellers on the river bed.

5) End attack. The ends of marginal beds are under attack from behind where boat wash is reflected from smooth steep clay banks and from piling.

6) Mechanical effects. The mooring of boats against the outer edge of the rond produces mechanical damage.

7) Fishing. Fishermen cut swathes through the remaining marginal beds of emergent water plants.

If the present level of boat wash continues into the future there are several long term management techniques available as follows:

1) Allow the process of bank erosion to continue until the river becomes much wider, the flood walls become endangered, and eventually sheet pile continuously on both banks.
2) Develop techniques to protect and reinforce and replant the boat wash absorbing beds of emergent river plants as detailed in Section 5.
3) Impose and enforce a speed limit as detailed in Section 3.

BOAT WASH ON THE RIVER THAMES AT WALLINGFORD 3

The wash of motor boats was investigated on a straight reach of the River Thames upstream of Wallingford Bridge on the left bank at a location on the river frontage of the Hydraulics Research Station.

The seasonal use of recreational motor boats is at its peak during August and for several days the boats and boat wash were monitored at the HRS boathouse during wind free periods of very low flow.

Boat speed was obtained from the speed of the boat's wave train which triggered two capacitance sensors located 20 metres apart and mounted on heavy planks floating parallel to and close to the river bank. The sensors were elevated 50mm above mean water level to be clear of the more frequent wind waves. Boats producing wash below this level were ignored.

Boat length and sailing line were obtained from polaroid photographs taken from a high fixed position and using a transparent overlay calibrated for waterline length and sailing line.

A continuous record of wave height was obtained from a twin wire probe[10] set one metre out from the bank in deep water, see Fig 12. Some banks near the wave recorder were devoid of vegetation at the waterline, were cohesive, smooth and steep and were therefore reflective.

Boats sailing in the wake of other boats for instance in convoy from lock to lock were ignored because of lack of independence of data. Boats sailing in periods of significant stream flow or wind waves were also ignored.

Five distinct categories of boat hull form were recognised (Plates 5, 6 and 7) as follows:

A) Narrow boats. Traditional bluff barge shaped narrow boats with beams 2060 to 2185mm, designed to sail through narrow canals.
B) Wide boats. Bluff barge shaped boats similar to narrow boats but with beams in the range of 3000 to 4000mm.
C) Modern chine. Modern displacement multi chine hull forms with fine entry and flaring capable of use in a seaway.

D) Planing hull. Modern planing forms but operated at sub-planing speeds in the Thames.

E) Full curved. Streamlined full curved low frictions forms as in displacement yachts and some fishing boats.

F) Miscellaneous.

Additional data was obtained separately using a small boat which fell roughly into category D above.

Comprehensive data was obtained for some 75 boats which represented about half of the boats which sailed by during the limited times the investigations were taking place in August 1980.

Three types of boat wash were identified from the record; 1) surge waves, 2) ship waves and 3) a wake of transverse and reflected waves.

1) Surge waves. Twelve boats produced surge waves resulting from draw down effects, nine of which were heavy displacement wide boats sailing on a line close into shore. The river width is 36m, with a cross sectional area of $62.2m^2$. The blockage factor for these craft was approximately 0.048. Only two boats out of the 75 produced a surge height exceeding 100mm and the mean period of surge waves was 6.2 seconds.

2) A vee shaped train of ship waves. The train was propagated at an angle of approximately 20 degrees from the sailing line. The train usually consisted of five or six curved short crested waves but sometimes as few as one or as many as 10 waves were recorded. The wave period was in the range of one to two seconds with a mean period of 1.3 seconds. The wave angle of propagation of individual ship waves varied between 20° and 70° from the sailing line.

3) A wake of transverse waves and reflected waves. After a boat producing ship waves had passed a gradually decaying train of following waves then ensued.

The three types of waves described above were generally generated at differing angles to the bank and these angles also changed continuously as the boat sailed by.

Figures 4 to 7 show for each vessel a plot of the mean of the five highest ship waves and the highest ship waves against boat speed. Parameters which vary from boat to boat and contribute to the wide scatter of the results include sailing line distance from the probe, displacement, hull form, boat length, beam and attitude.

Although no speed limit exists on the Thames, boats are required to sail with an acceptable low wash. It was observed that some of the worst examples of high boat wash were generated by boats proceeding in convoy from lock to lock with an element of competitive jockeying for position to enter the next lock.

Boats may find it difficult to comply with a speed limit since few are equipped with reliable speedometer instrumentation. However, a speed limit of two metres per second if successfully imposed would substantially eliminate boat wash that exceeded wind waves in height on this reach of the River Thames.

BOAT WASH ENERGY REDUCTION THROUGH BEDS OF EMERGENT RIVER PLANTS 4

Tests on the River Thames at Wallingford

The river near Wallingford was chosen for study. The marginal beds of emergent river plants have been under severe stress in recent times. Only the fittest to survive have survived these stresses that have been brought about by a valiant attempt to manage the river to satisfy many uses and users. The recent stresses placed on beds of emergent river plants are listed in detail in Section 2. The outer edge of the beds erode because of flood scour, dredging and mechanical damage from boats. The stems and rhizomes are scoured by boat wash, both directly and reflected from the banks at the ends of the beds. Fishermen cut swathes and wild fowl graze the edges of the beds of emergent river plants.

The remnant marginal beds of emergent river plants are therefore very capable surviving communities worthy of performance evaluation. They are essentially low cost low maintenance spending beaches capable of absorbing boat wash wave energy and protecting the river bank. At the same time they are a scarce natural wild life habitat and refuge.

There are four dominant surviving species as follows:-

1) Phragmites australis (syn. P. communis), common or Norfolk reed
2) Shoenoplectus lacustris (syn. Scirpus lacustris), common clubrush, greater rush or bulrush
3) Typha angustifolia, lesser or narrow leaved reed mace
4) Acorus calamus, sweet flag, a medieval introduction.

These are the only emergent plants in the reach in beds of single or dominant species. However, smaller mixed beds also occur with a small proportion of Carex sp., sedges: Phalaris, reed canary grass; and Sparganium erectum, bur-reed[11].

The four species listed above are of special interest because of wide geographical distribution.

Figure 9 contains details of the four plant species drawn on a substrate slope of one in four and showing details of the lower stems, rhizomes and roots viewed as structures which have proved capable of:

1) absorbing boat wash wave energy
2) maintaining vigour and stability
3) preventing substrate scour
4) encouraging sediment deposition.

Phragmites australis, common or Norfolk reed, forms dense intertwining mats of long rhizomes on the bed with deeply anchored thin root stems and tough thin stems which are flexible and able to withstand wave action. The outer edge of the bed is subject to scour.

Shoenoplectus lacustris, common clubrush or bulrush forms short rhizomes below the bed with very close intertwining mats of fine roots above and below the rhizomes, very resistant to wave action. The outer edge of beds is also subject to current and propeller scour. The plant density is high.

Typha angustifolia, lesser or narrow leaved reed mace, forms mats of rhizomes and systems of fine roots eminating from the base of every stem. The stiff thick stems are subject to high stress at the base and loosening or uprooting may occur after high levels of boat wash; nevertheless a well surviving species.

Acorus calamus, sweet flag and a medieval introduction. Sweet flag has rhizomes which can float above the bed anchored down by long thin, tough flexible root systems. Sweet flag is capable of withstanding breaking waves from boat wash in shallow water. The foliage is of low form on the River Thames and will withstand floods. Sweet flag is successfully colonising stable shoals of sediment in the River Thames.

Four beds, one of each species, were selected for study and a fifth beach of similar bank slope and with no vegetation as a control. The four beds were selected for the strength and vigour of the plant communities and the test section was located in the bed well away from end effects, and in a part of the bed of most uniform width and most uniform plant density. The sections are shown in Figure 8. The most common bank slope was one in four. Figure 8 and Plate 8 also shows an unvegetated control beach section which has an offshore bank slope of one in four and also has a sandy inshore spending beach at a slope of one in ten.

A scaffolding was set up on the section to be tested supporting two twin wire probes, one over deep water beyond the vegetation and one inside the mass of vegetation but outside the zone of breaking waves. It was observed that the vegetation inhibited or even prevented breaking waves.

When a boat sails by the boat wash waves are propagated into the beds firstly as surge waves, followed by vee shaped trains of curved short crested ship waves followed by a gradual decaying wake of transverse and reflected waves. Wave crests range in angle to the sailing line from 20° to 70° and generally the three types of waves are generated at quite different and changing angles which vary from boat to boat. Consequently the inner wave record was sometimes markedly different in form from the outer record because some wave energy might be propagating in a direction at 20° to the bank through as much as 10 metres width of vegetation, whereas some other wave energy might be propagating at 70° to the bank through only 3 metres width of vegetation.

Notes on parameters affecting shoaling wave energy

In the River Thames the ship waves are almost deep-water waves. It was observed that it is the ship waves that produce the most significant plant stem movement and any breaking waves that should occur.

In deep water the total average wave energy, $\overline{E}$ per unit of surface area for a small amplitude wave component is

$$\overline{E} = \frac{\varrho g H^2}{8} \tag{12}$$

Once the waves reach shallow water in the reed bed the multidirectional boat wash wave components come under the influence of refraction, friction and vegetation form drag. The vegetation form drag slows up the wave crest and inhibits wave breaking. The wave heights are also reduced by the reed bed as compared with a similar wash reaching the unvegetated control beach.

On a shallow unvegetated beach Das[13] concluded that for ship waves the energy density per unit surface area in a wave profile is $E_n = \frac{1}{2}\varrho g C^2$. This indicates the contribution at each frequency f given by n/T to the total energy density or energy per unit of surface area, and this quantity is also proportional to the mean square height $\overline{H}^2$. In shallow water Das plotted $(H^{max})^2$ as a suitable function of energy density. Das also found little contribution to energy density at the low frequency range using Fourier analysis. Sorenson[14] also used $(H^{max})^2$ as a plotting parameter. Denny[15] concluded that for breaking waves considering them to be represented by the highest solitary wave, the forward momentum per unit of wave crest is $U_b = 4.5\varrho H^2 C$ where

$C = \sqrt{gH(1 + I/0.78)}$ and shock impulse I is $\frac{1}{2}\varrho g^{\frac{1}{2}} H^{5/2}$

Carr[16] in laboratory studies for beaches of 1:3, 1:10 and 1:30 and a 30° bulkhead on a beach of 1:10 slope found that the momentum of a solitary breaking wave is $U_b = 55.5 H_b^{5/2}$.

and $\dfrac{H_b}{H_o} = \dfrac{1}{33.3\ \sqrt[3]{H_o/L_o}}$

Kajura[17] found the rate of energy dissipation per unit area of unvegetated bottom per unit of time is

$$\frac{\pi k \varrho g H^2}{4L \cosh^2 (2\pi h/L)}$$

The most commonly observed parameter of energy propagation in shallow water, as also in deep water is the square of wave height.

Boat wash energy reduction

The progress of boat wash was observed through the four beds of emergent river plants fringing the River Thames near Wallingford, and a continuous synchronous plot of wave height against time was obtained for the inner and outer wave probes. For the bed of Shoenoplectus lacustris, common clubrush or bulrush, records were also obtained for wave probes in middle and outer locations as shown on Figure 4.

Wash from all boats sailing by during the period of observation was included and supplementary wash was made using a small motor boat.

Figure 10 shows the mean of five highest ship waves at the outer probe and the ratio of the square of the mean of the five highest ship waves at inner and outer probes, which is the energy reduction.

Figure 11 shows the maximum of highest ship waves at the outer probe and the ratio of the square of the highest ship waves at the inner and outer probes, which is the energy reduction.

Vegetation density surveys made on the section lines and mean energy reductions are shown in Table 1. The vegetation density varied considerably through the beds of emergent river plants from very small clear pools to very dense clumps. No doubt the ratio of energy dissipation will vary for alternative sections, but nevertheless the results were consistent. 60% of the shipwave energy was dissipated by a stand of emergent Phragmites two metres wide; 70% by clubrush or bulrush 2.5 metres wide; 66% by lesser reed mace 2.3 metres wide and 75% by sweet flag 2.4 metres wide. There was no evidence of any reflected wave from the bank and no evidence of bank damage behind any of the four species. Wave breaking was inhibited by the four species and sweet flag is able to withstand an environment of breaking waves in shallow water and may even extend its area of colonisation over shallow shoals. Very roughly, under suitable conditions of depth, vegetaiton density, and a bed slope of one in four, two metres of width of bed of any of these species will dissipate almost two thirds of the boat wash ship wave energy.

PROPOSED PROTECTION AGAINST BOAT WASH 5

Figures 1 and 2 show the proposed bank protection using marginal beds of emergent river plants at a bank slope of one in four or less. The least slope gives the best energy dissipation. In the Netherlands the bed is sometimes graded flat[18]. However a slope of one in four probably uses least width for maximum bank protection.

Submerged toe protection is required generally in rivers with high motor boat usage if only to provide a fend off against mechanical damage from boats. However, there are locations of strong lateral accretion as for example below point bars or in rivers without flood scour where piling may be omitted; it may be constructed later if necessary. Submerged toe piling will be required everywhere generally in rivers with peat banks.

The use of old tyres will give adequate fend off effects to prevent navigation hazard. Twenty three million old tyres are discarded from vehicles each year in Britain[18]. Indications are that the garage industry will helpfully assist with the supply of old unwanted tyres for schemes intended to improve the natural environment.

Tyres must be organised into sets of uniform wheel size and may be threaded over wire mesh cylinders. The tyre size governs pile spacing. Piles are driven to a level some 500mm above the waling level to support temporary distant paling and the cylinders of tyres are then placed. A traditional tie and anchor system will be required in Broadland rivers for one pile in every three or four.

The submerged waling should be at a depth of from 100 to 400mm below low summer water level in Broadland rivers near to Ant mouth and Thurne mouth. The precise level will depend on the summer range of levels, the hazards and costs of working below water level, navigation requirements and rond width.

The bank, or rond is then backfilled with selected fill and regraded to a slope not exceeding one in four. A filter membrane must be used if the backfill is of low strength or if the tyres tend to be openly spaced to prevent loss of backfill by pumping due to boat wash. A filter membrane is essential in Broadland rivers.

Emergent river plants must be planted either by heeling in rhizomes as proposed by Brooks(19), Eaton and Pearce(20), George(8), Haslam(21), Kite(22), Raven(23) and Seibert(24), or by spreading drain dredgings as proposed by Brooks(19), Pearce(20) and Robson(11), or by spreading reed 'feathers' in shallow water for May germination as proposed by Ellis(25) and Kite(22) or reed turf may have to be placed as suggested by Haslam(21). Mixed species are generally proposed, perhaps on a detailed planting plan as proposed by George(8). A very successful planting of mixed species behind chestnut paling was made by Pearce(20) at a slope of one in four in an area of high motor boat usage in the River Dee above Chester. The planting should take place in early spring. The palings may be removed and piles cut down to waling level when the bed is established.

Some advantages of the proposed toe protection systems are as follows:

1) The piling and chestnut palings will make excellent protection against boat wash for a long time if the reed bed is slow to get established.
2) All timbers will finally be almost permanently submerged and will therefore be resistant to rot. In the brackish Broadland rivers the timber from nearby alders may be used for piles with long life expectancy.
3) Deep level wave reflection will be dispersed by the rough profile of the tyres.
4) The hydraulic roughness of the tyres will inhibit toe scours.
5) The toe structure is flexible.
6) Additional fend off tyres may be fixed to the walings to further reduce the hazard to navigation.
7) A complex habitat and refuge is provided in the vicinity of the walings and tyres.
8) When the reed bed is fully grown the visual effect will be natural rather than man made.

The proposals shown in Figures 1 and 2 refer to Broadland rivers in the vicinity of Ant Mouth and Thurne Mouth and certain banks of the River Thames. The locations under consideration have flood level variations, seasonal level regulation and seasonal motor boat usage patterns which suit the systems of toe protection proposed in this report. There are many other rivers and canals subject to heavy motor boat usage but with different patterns of level variation for which these models of toe protection are unsuitable. For these other channels, the methodology proposed in this report should be used but alternative models of toe protection may have to be devised.

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TABLE

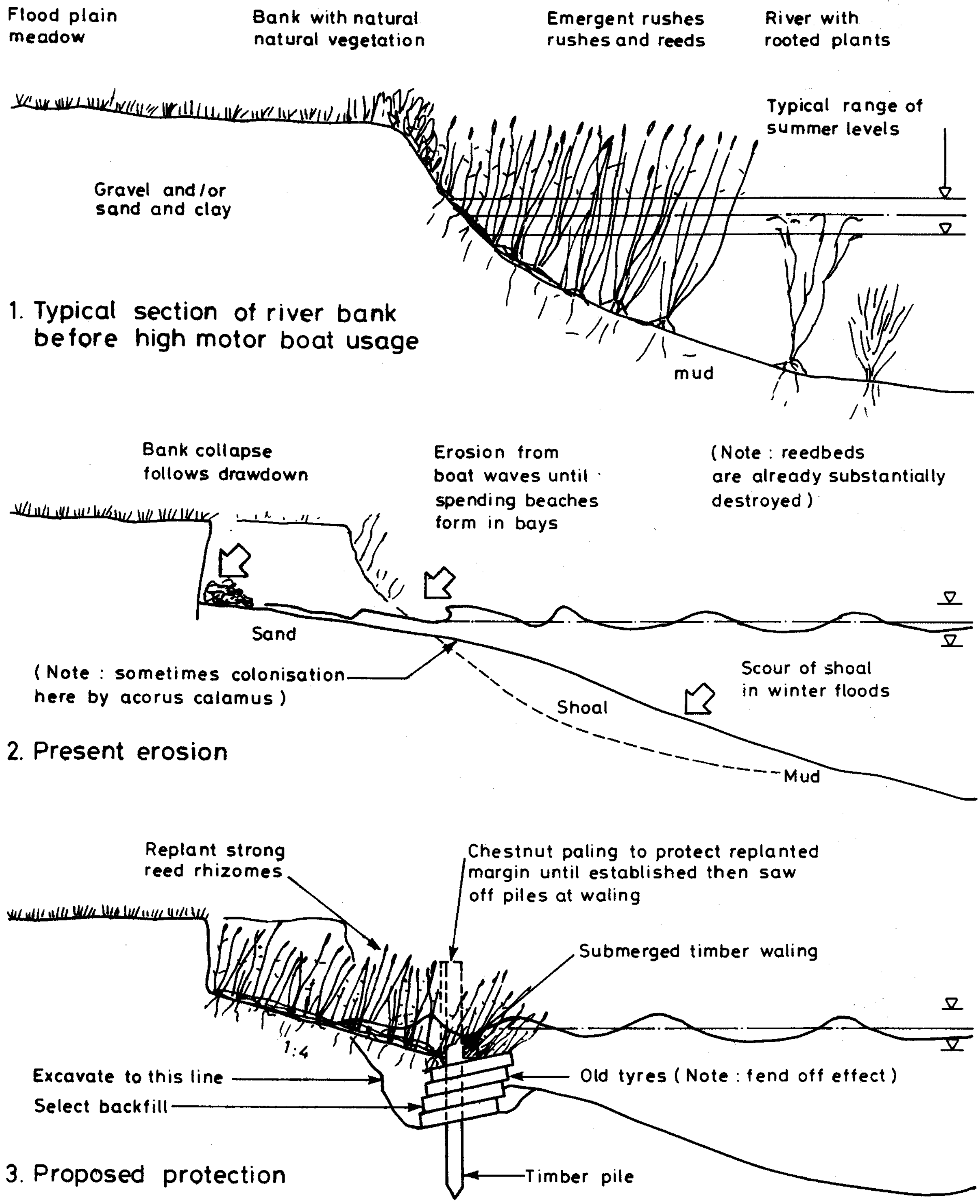
TABLE 1 BOAT WASH ENERGY REDUCTION THROUGH BEDS OF WELL SURVIVING EMERGENT RIVER PLANTS IN THE RIVER THAMES NEAR WALLINGFORD

Cross section no. and species of river plants	Note	No. of stems or leaves per square metre	Mean stem dia. or principle axes (mm)	Mean reed leaf width (mm)	Twin wire probe spacing (m)	Depth at inner probe (mm)	$\frac{\bar{h}_I}{\bar{h}_O}$	$\frac{h_I^{max}}{h_O^{max}}$
1) Phragmites australis (syn P communis) common or Norfolk reed	Inner count zone	216	3.3	nil	2.15	80	0.42	0.38
	Outer count zone	100	2.6	nil				
2) Schoenoplectus lacustris (syn Scirpus lacustris) common clubrush or bulrush	Inner count zone	112	13.3	nil	3.10*	170	0.31	0.22
	Outer count zone	408	11.8	nil	1.65**	300	0.52	0.48
3) Typha angustifolia lesser or narrow leaved reed mace (reed)	Oval leaf	56	21 x 33	nil	2.97	360	0.36	0.32
	Flat leaf	80	nil	11.2				
4) Acorus calamus sweet flag (reed, medieval introduction)	Diamond section leaf	248	nil	13.2	2.60	140	0.27	0.24
5) Control section, sandy beach without vegetation	Breaking waves	nil	nil	nil	2.90	90	1.38	1.15

* Outer probe to inner probe

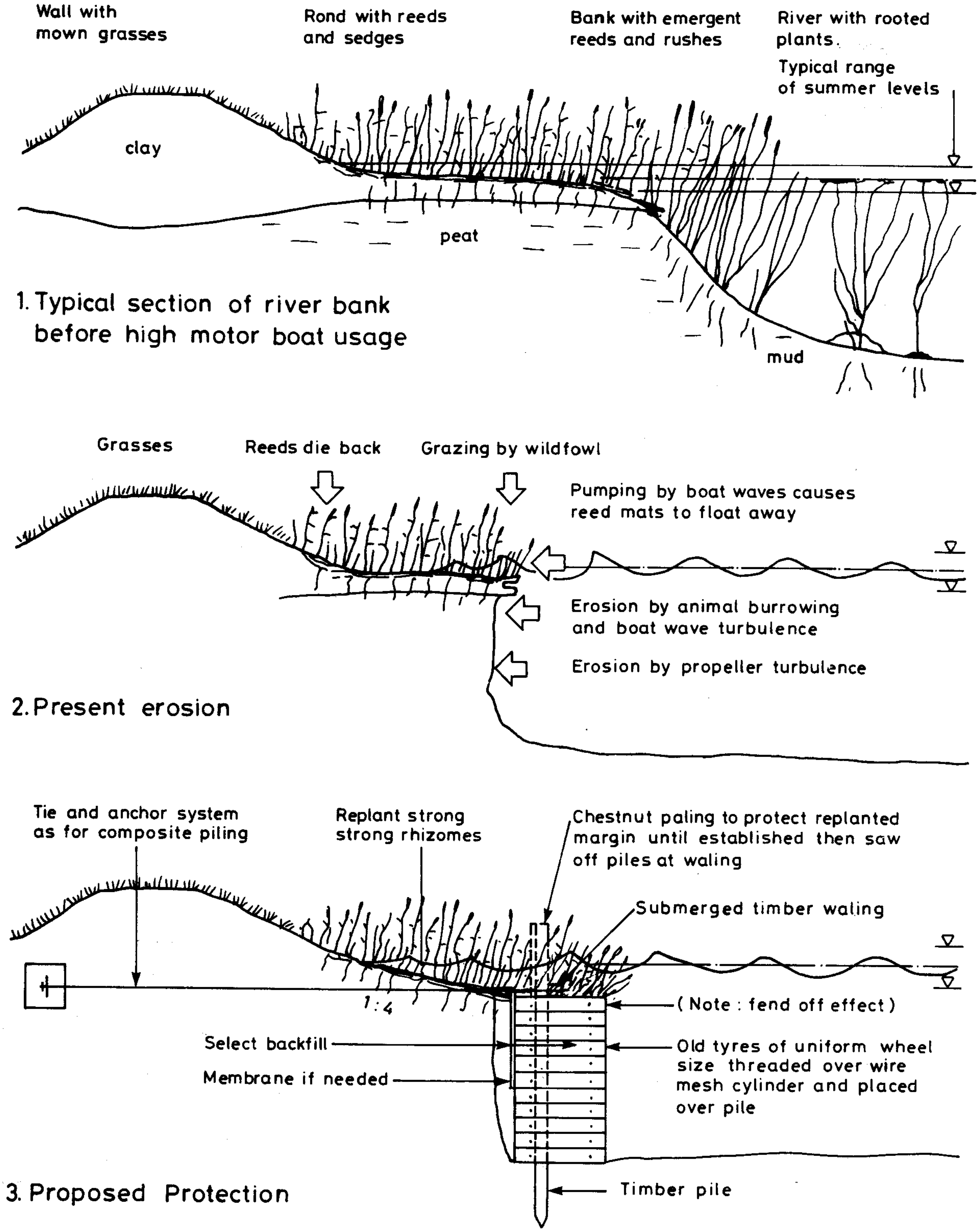
** Outer probe to middle probe

Figures



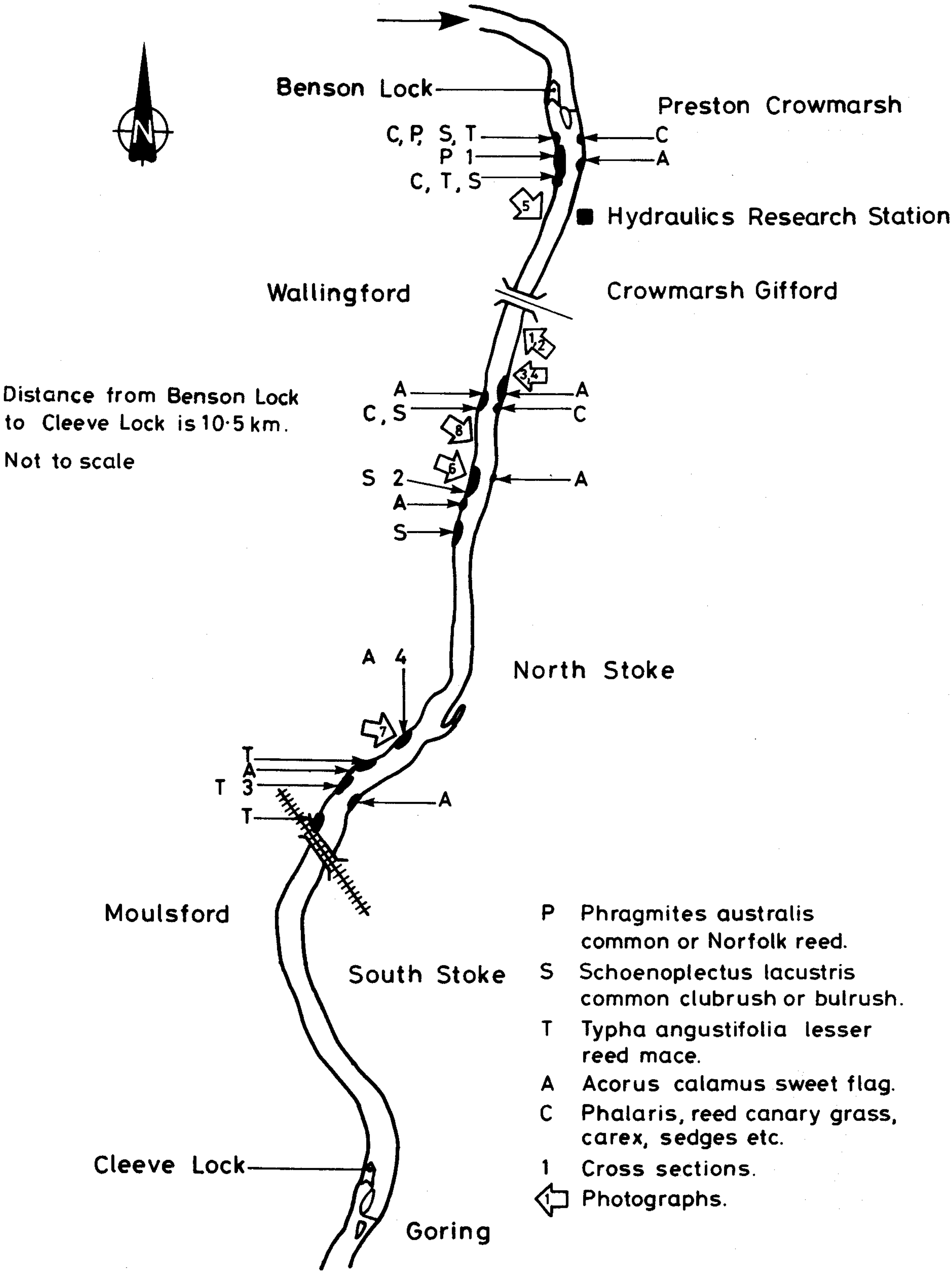
Bank protection against boat wash for gravel and mixed bed rivers with high motor boat usage

Fig 1



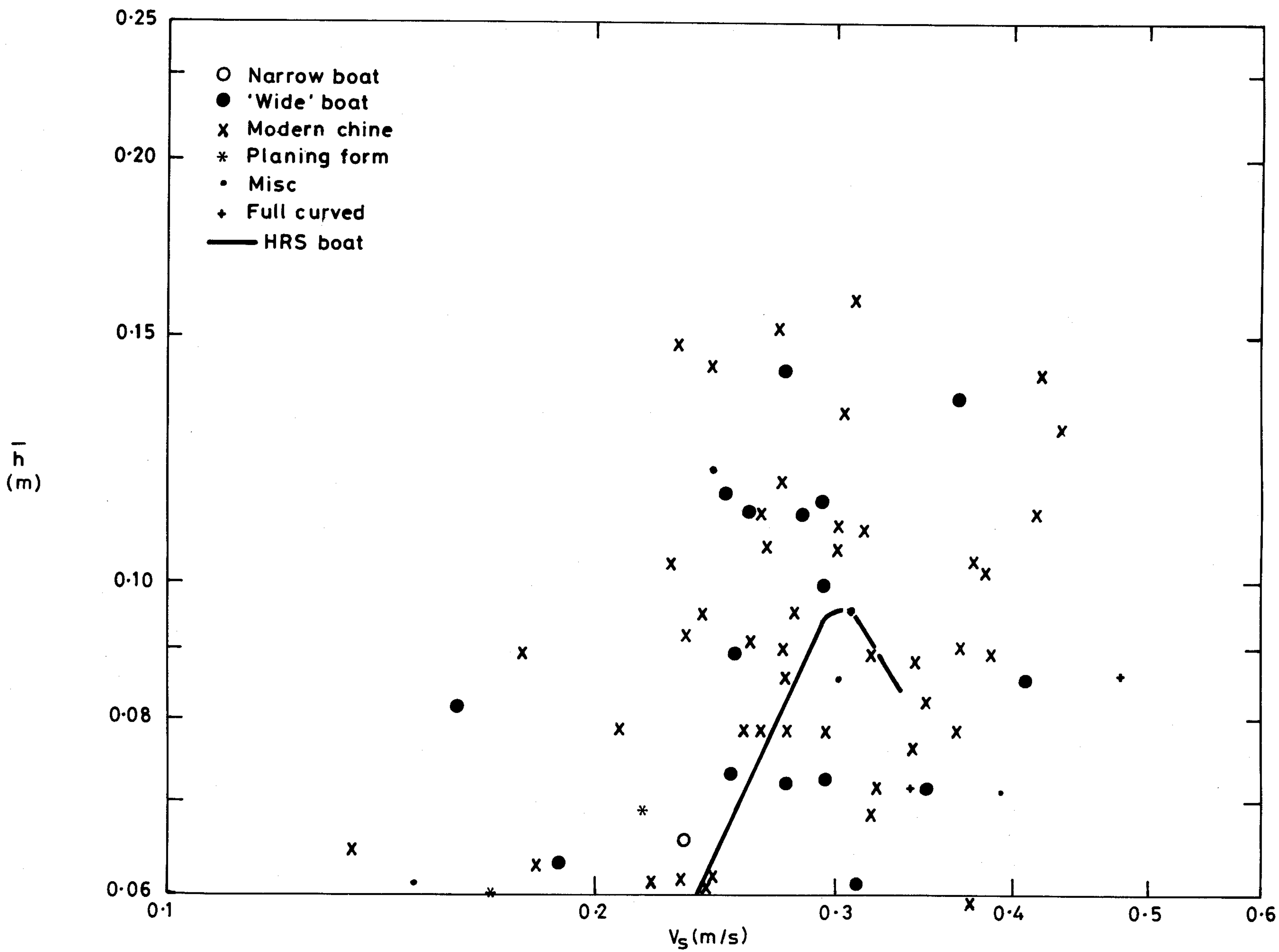
Bank protection against boat wash for Fen and Broadland rivers with high motor boat usage

Fig 2



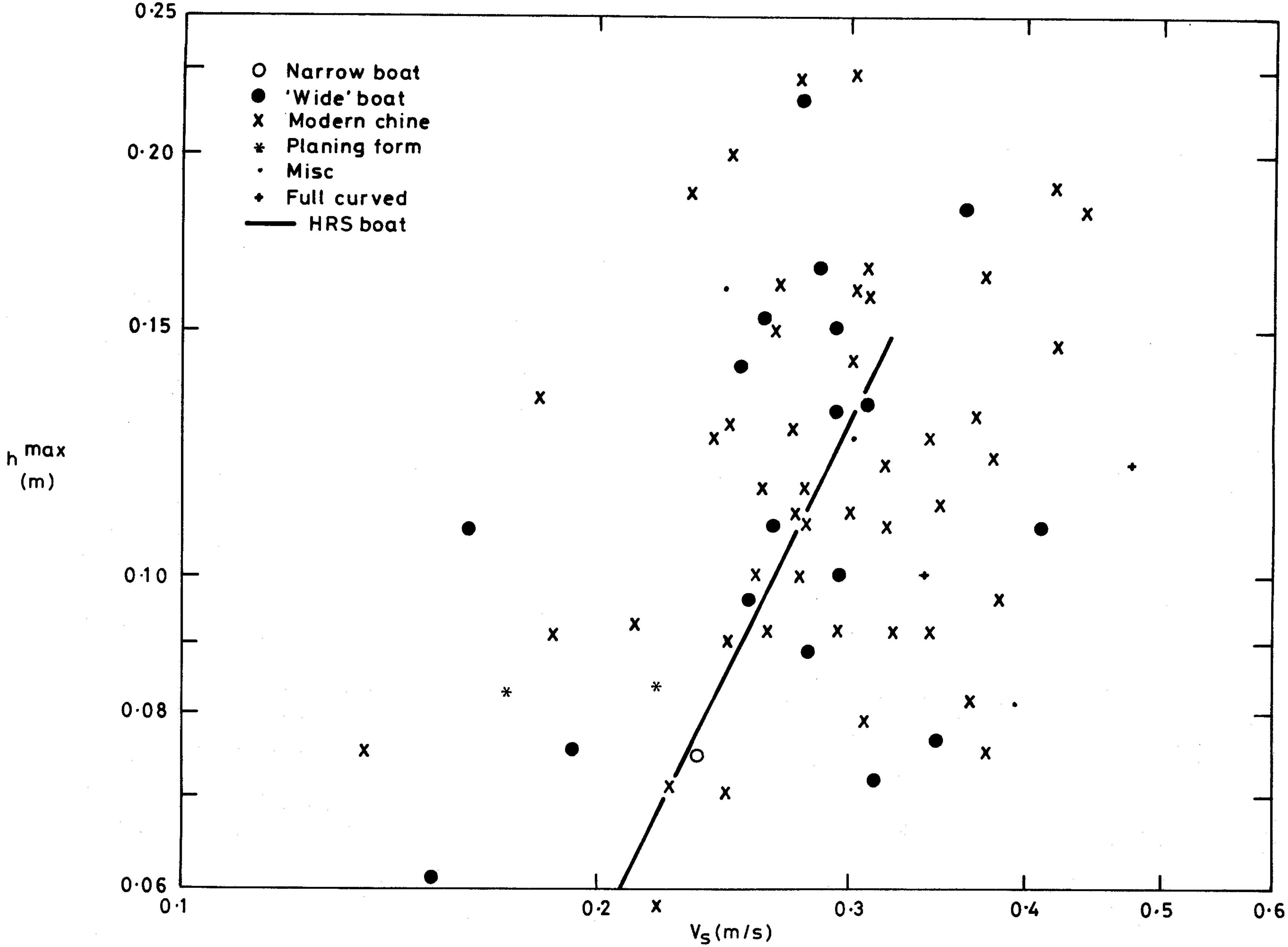
Plan of River Thames at Wallingford

Fig 3



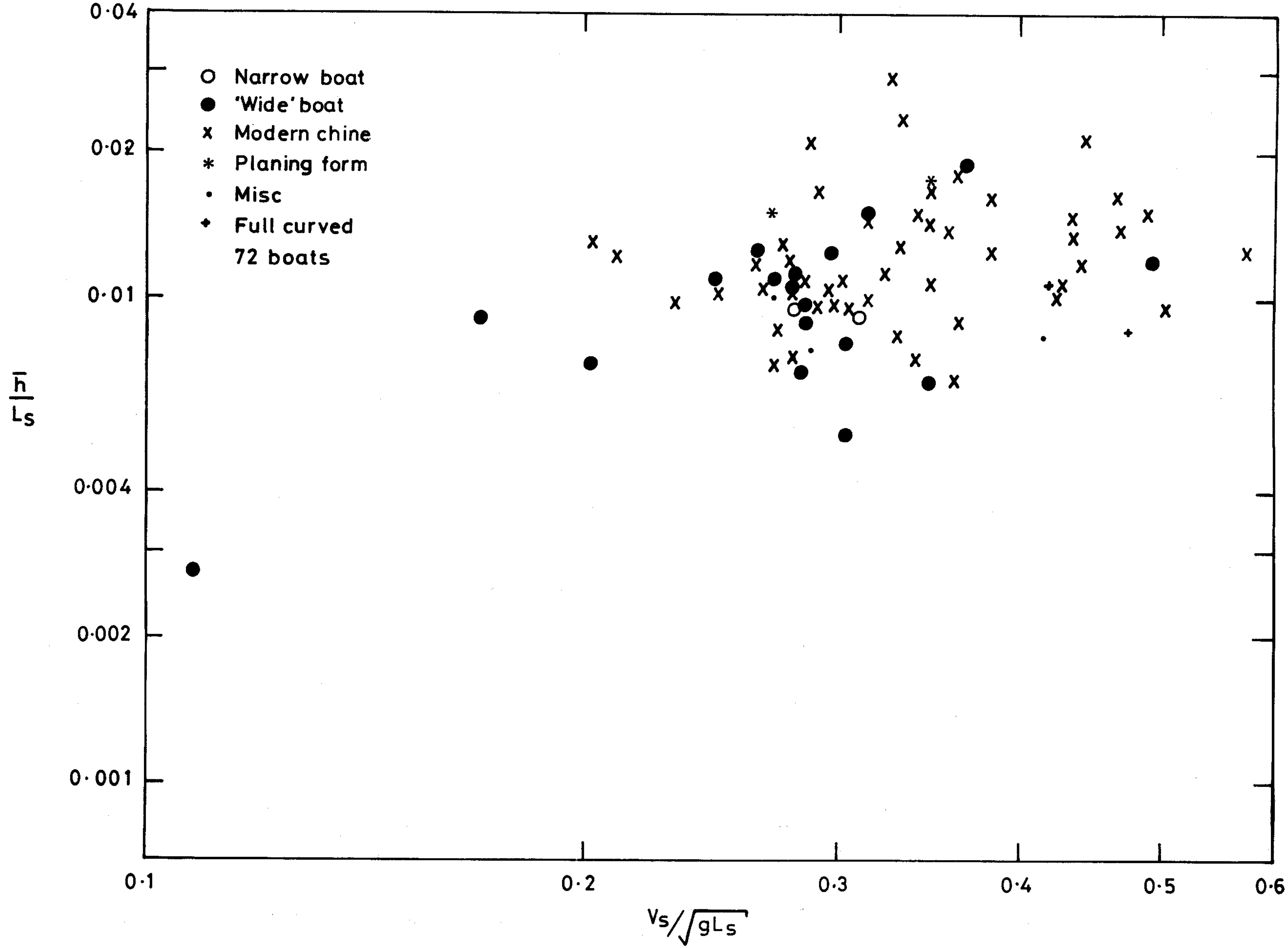
Mean of five highest ship waves (1)

Fig 4



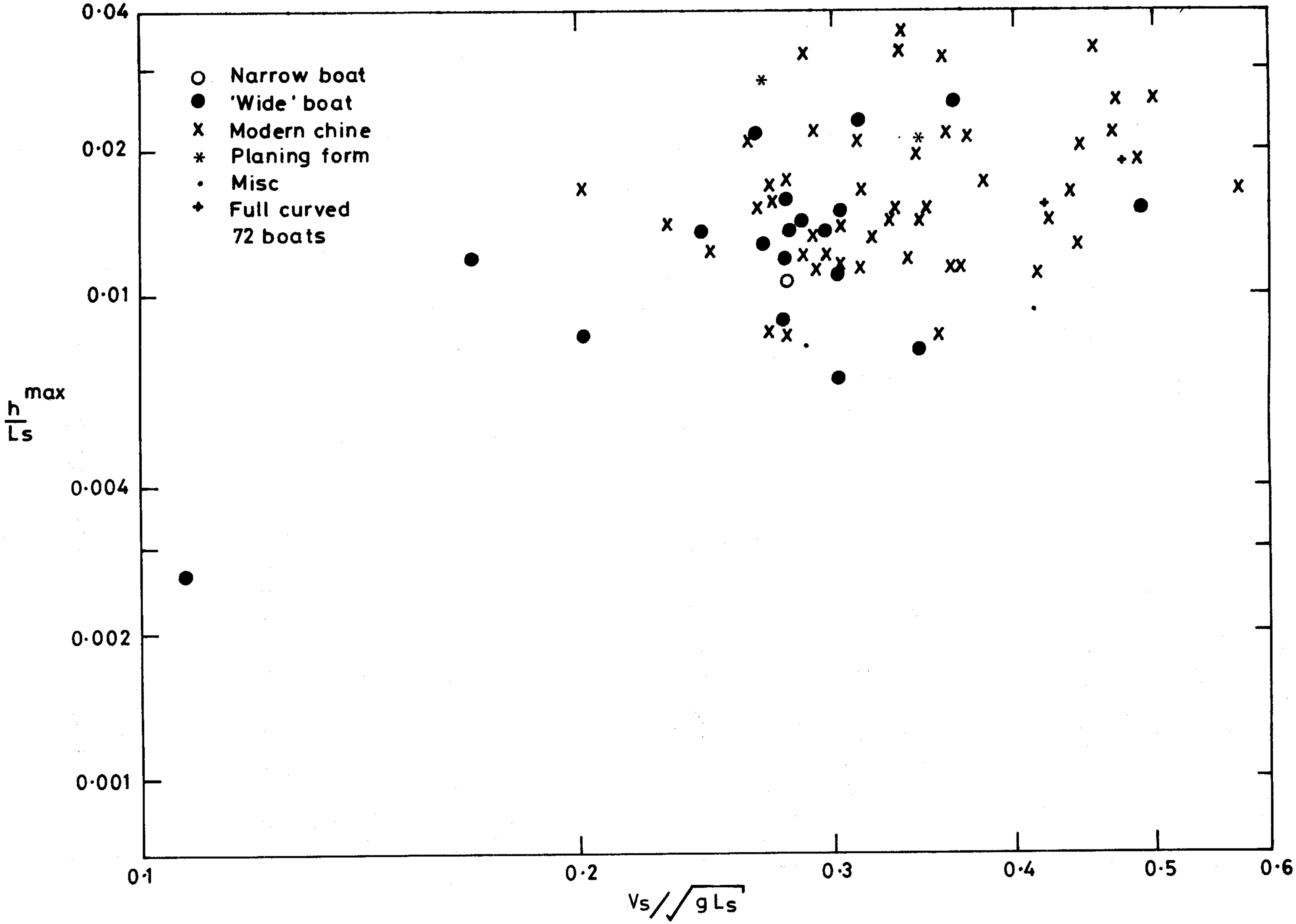
Maximum height of ship waves (1)

Fig 5



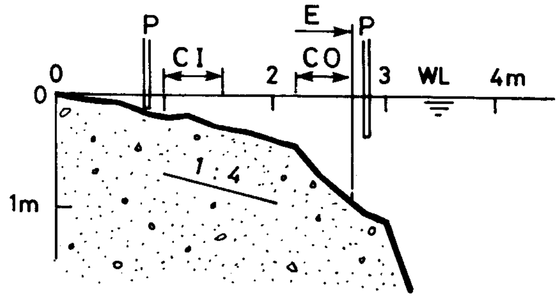
Mean of five highest ship waves (2)

Fig 6

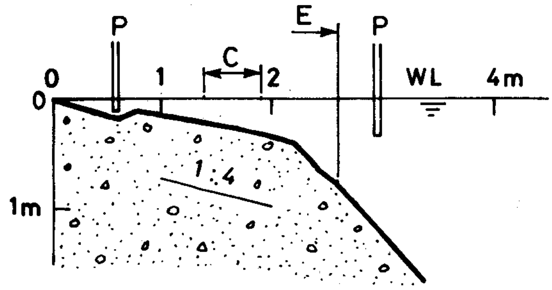


Maximum height of ship waves (2)

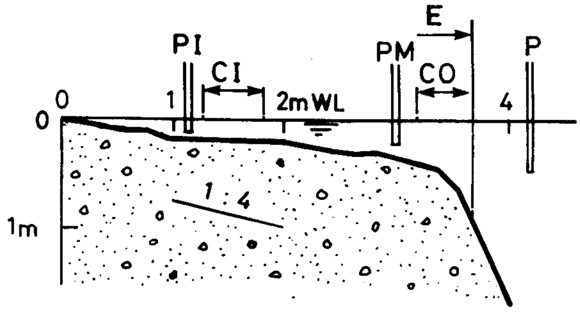
Fig 7



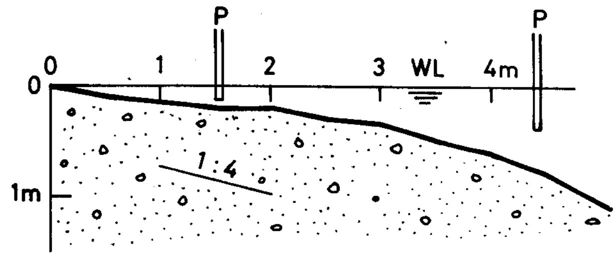
C.S.1 Phragmites australis
common or Norfolk reed



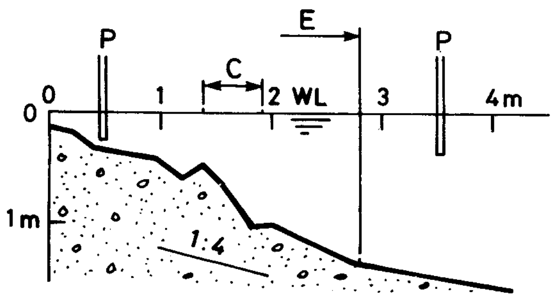
C.S.4 Acorus calamus
sweet flag (reed)



C.S.2 Schoenoplectus lacustris
common clubrush or bulrush



C.S.5 Control section
with no vegetation

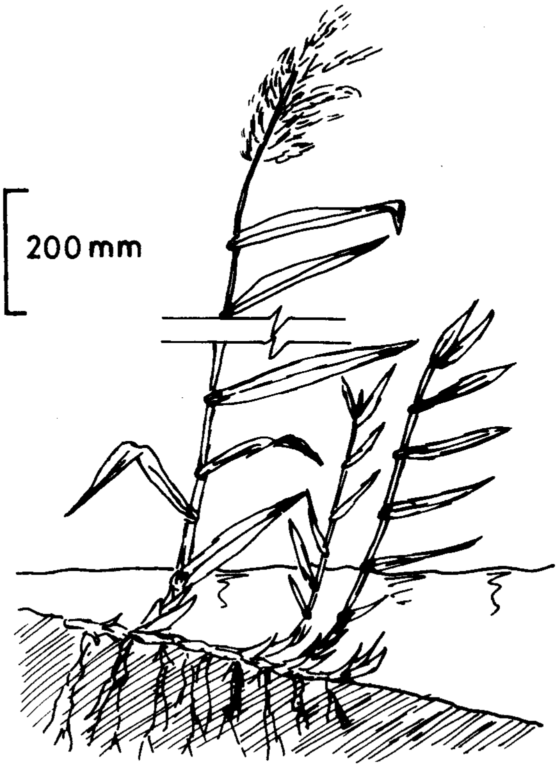


C.S.3 Typha angustifolia lesser
or narrow leaved reed mace

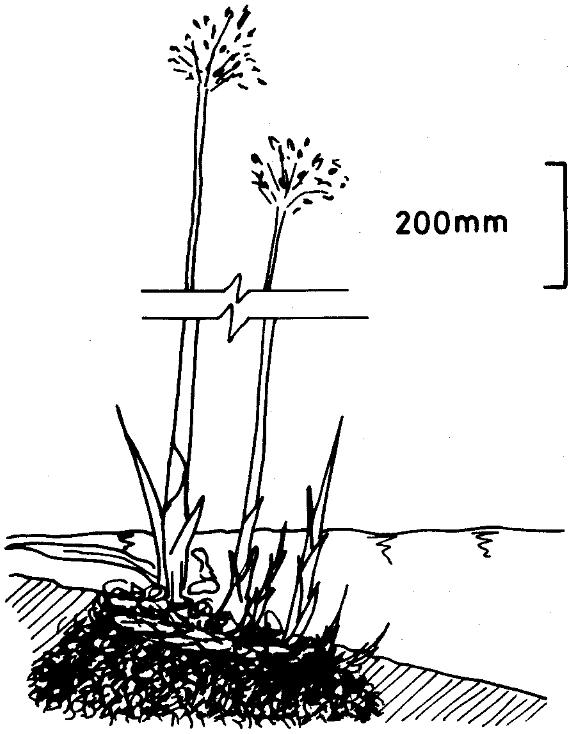
C = stem and leaf count zone
I = inner
O = outer
E = outer edge of bed
P = probe
M = middle

Cross sections of marginal beds of river plants

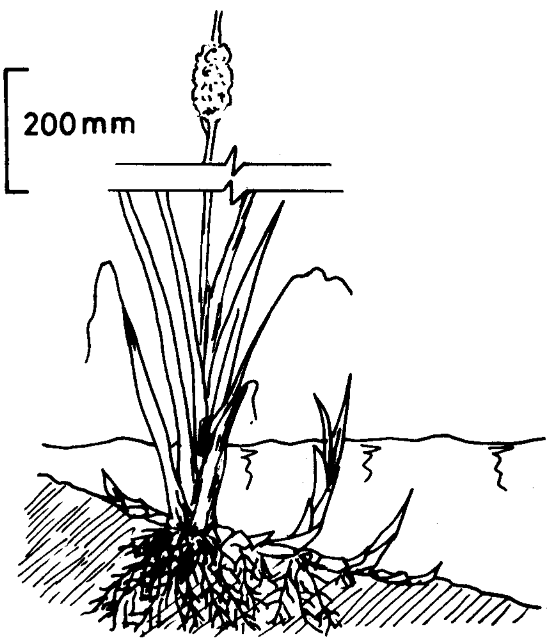
Fig 8



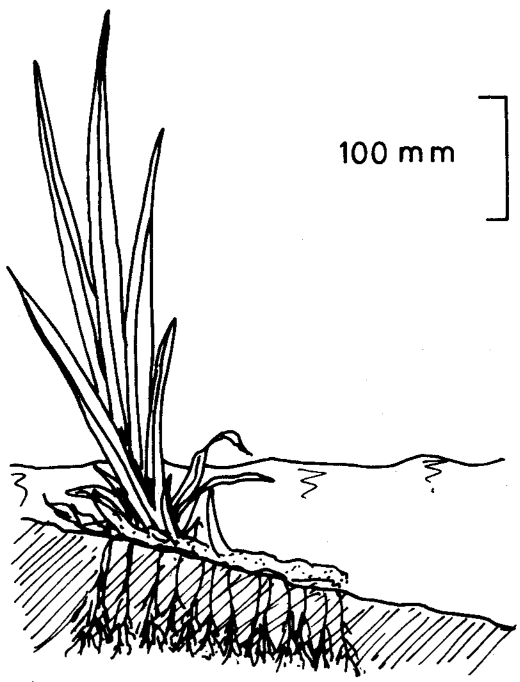
1. Phragmites australis
common or Norfolk reed



2. Schoenoplectus lacustris
common clubrush or bulrush



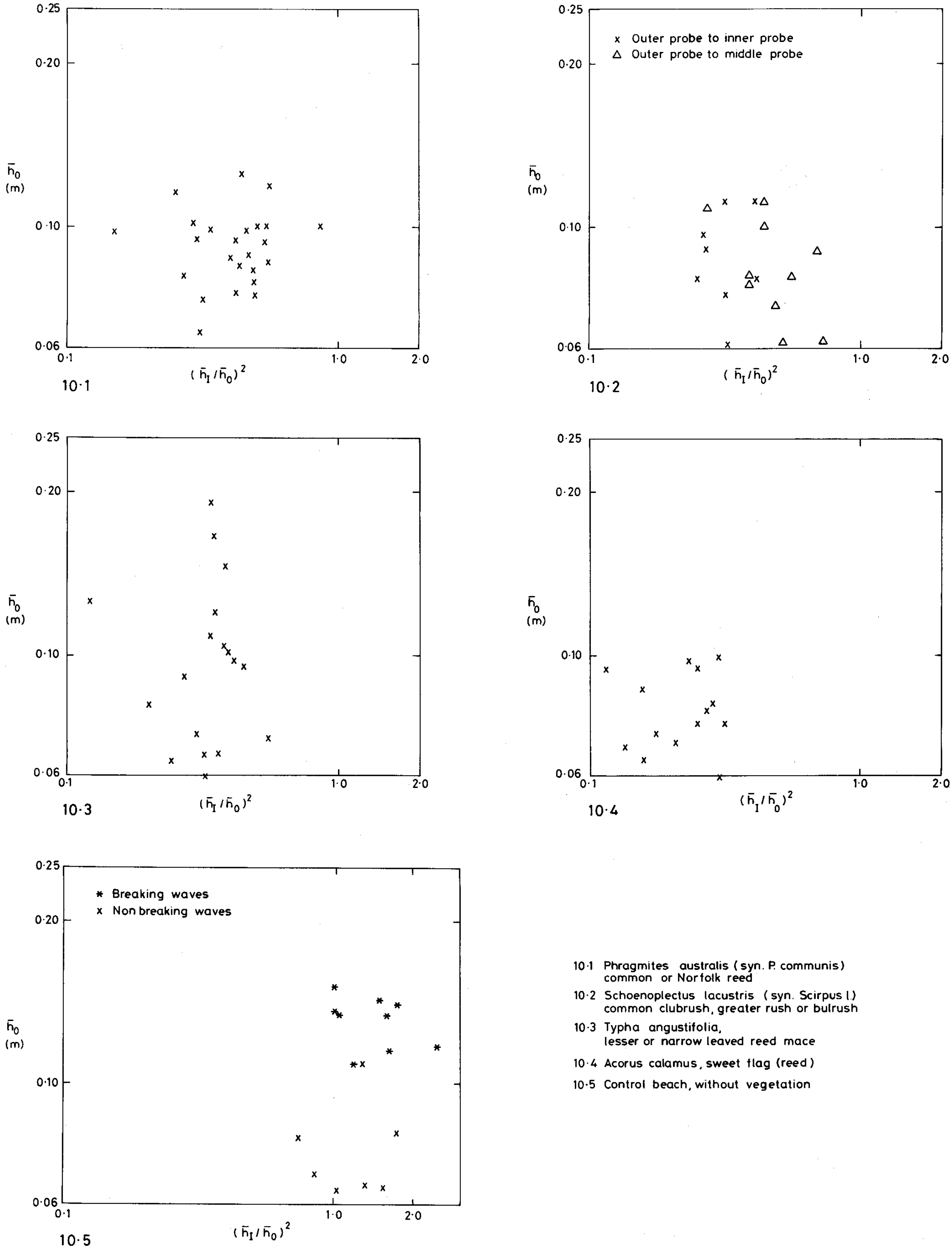
3. Typha angustifolia
lesser reed mace



4. Acorus calamus
sweet flag (reed)

Details of river plants

Fig 9



10·1 Phragmites australis (syn. P. communis) common or Norfolk reed

10·2 Schoenoplectus lacustris (syn. Scirpus l.) common clubrush, greater rush or bulrush

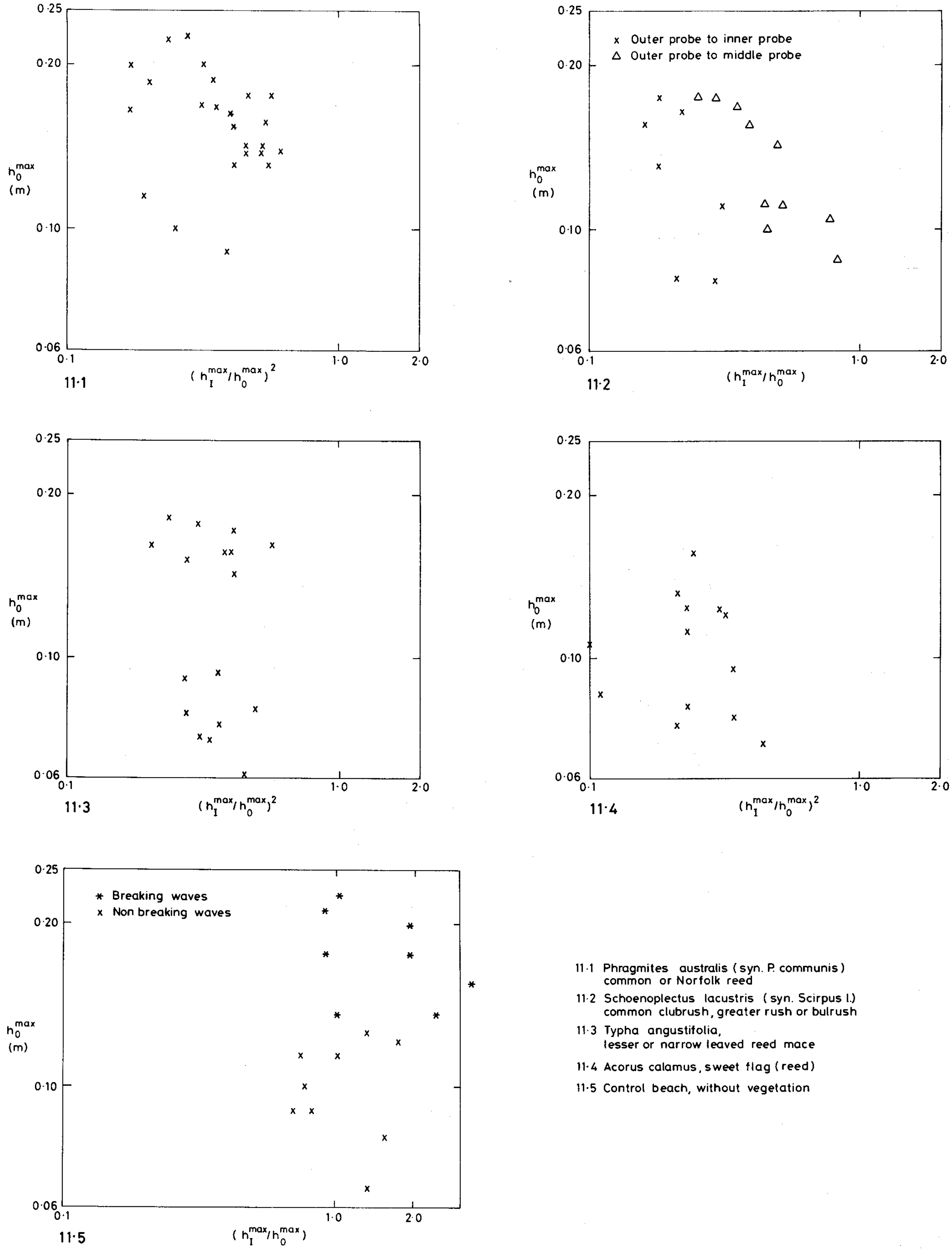
10·3 Typha angustifolia, lesser or narrow leaved reed mace

10·4 Acorus calamus, sweet flag (reed)

10·5 Control beach, without vegetation

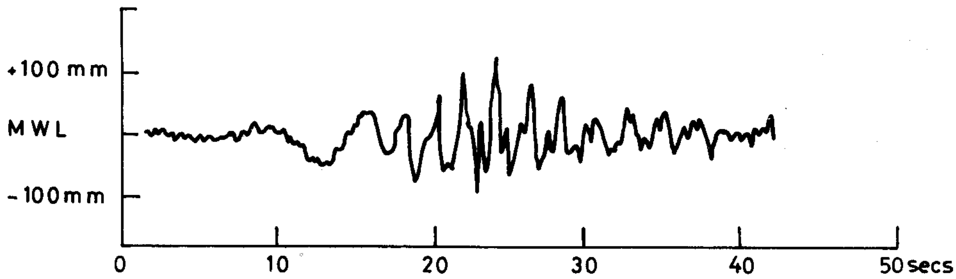
Energy reduction, mean of five highest ship waves

Fig 10



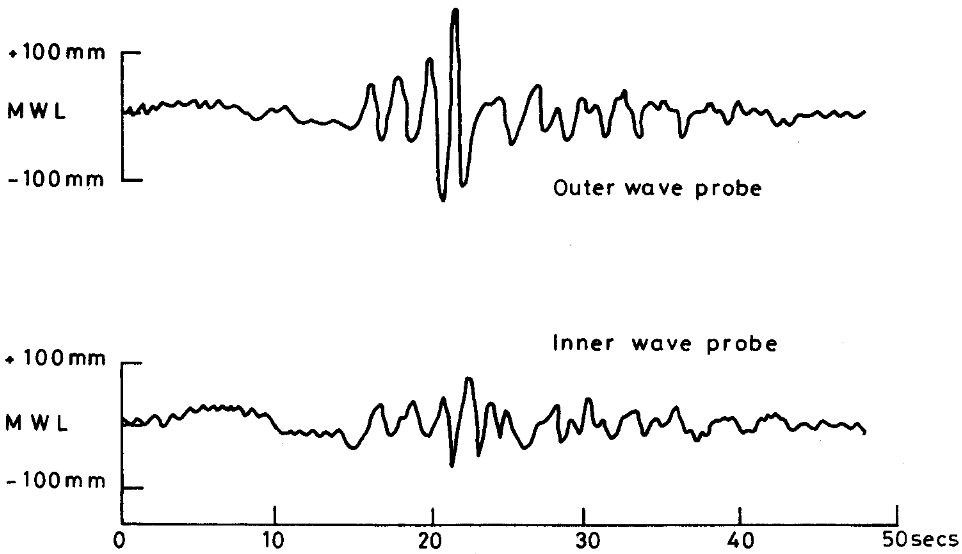
Energy reduction, maximum height of ship waves

Fig 11



Boat speed = 2·74 m/s
Boat waterline length = 10·5 m
For a 'wide' boat hull form, similar to Plate 5

A. Boat wash at HRS



For a modern multichine hull form
Phragmites australis, common or Norfolk reed

B. Boat wash at C.S.1.

Wave profile of boat wash

Fig 12

PLATES

See Fig 3 for locations on River Thames

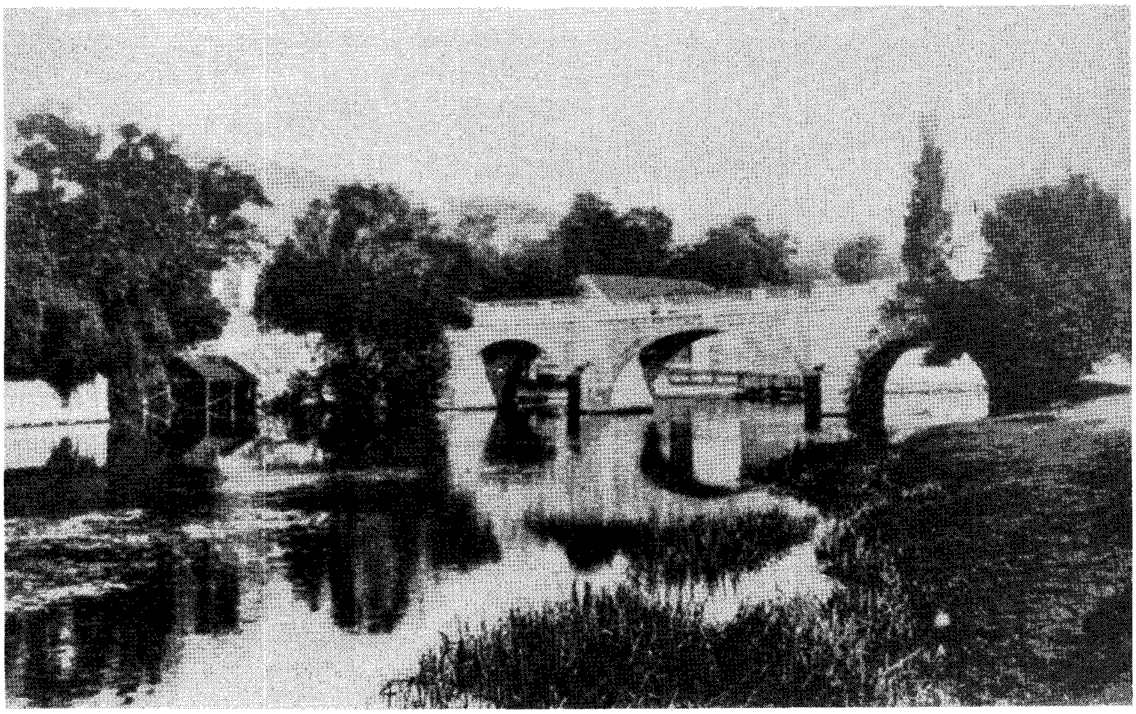


PLATE 1 Right bank below Wallingford Bridge in 1910, showing emergent and floating leaved rooted river plants

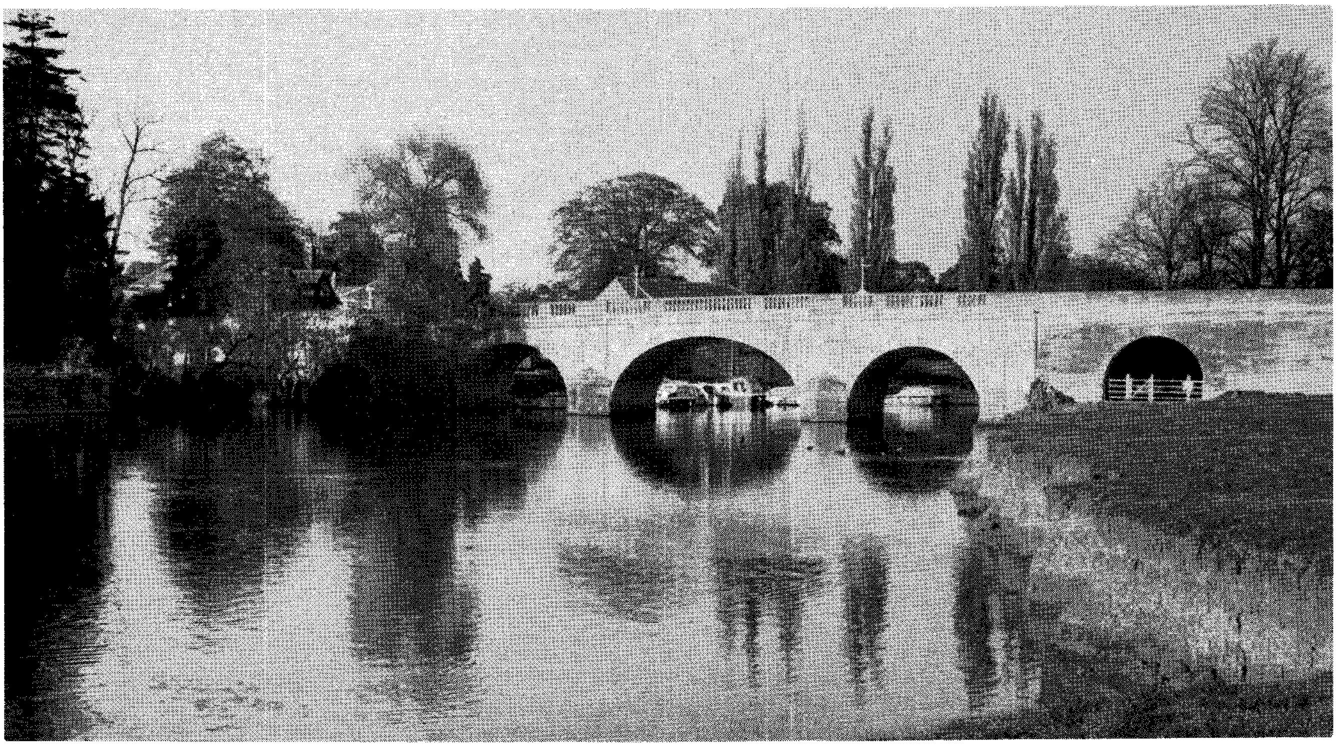


PLATE 2 Right bank below Wallingford Bridge in 1980 showing extensive bank erosion

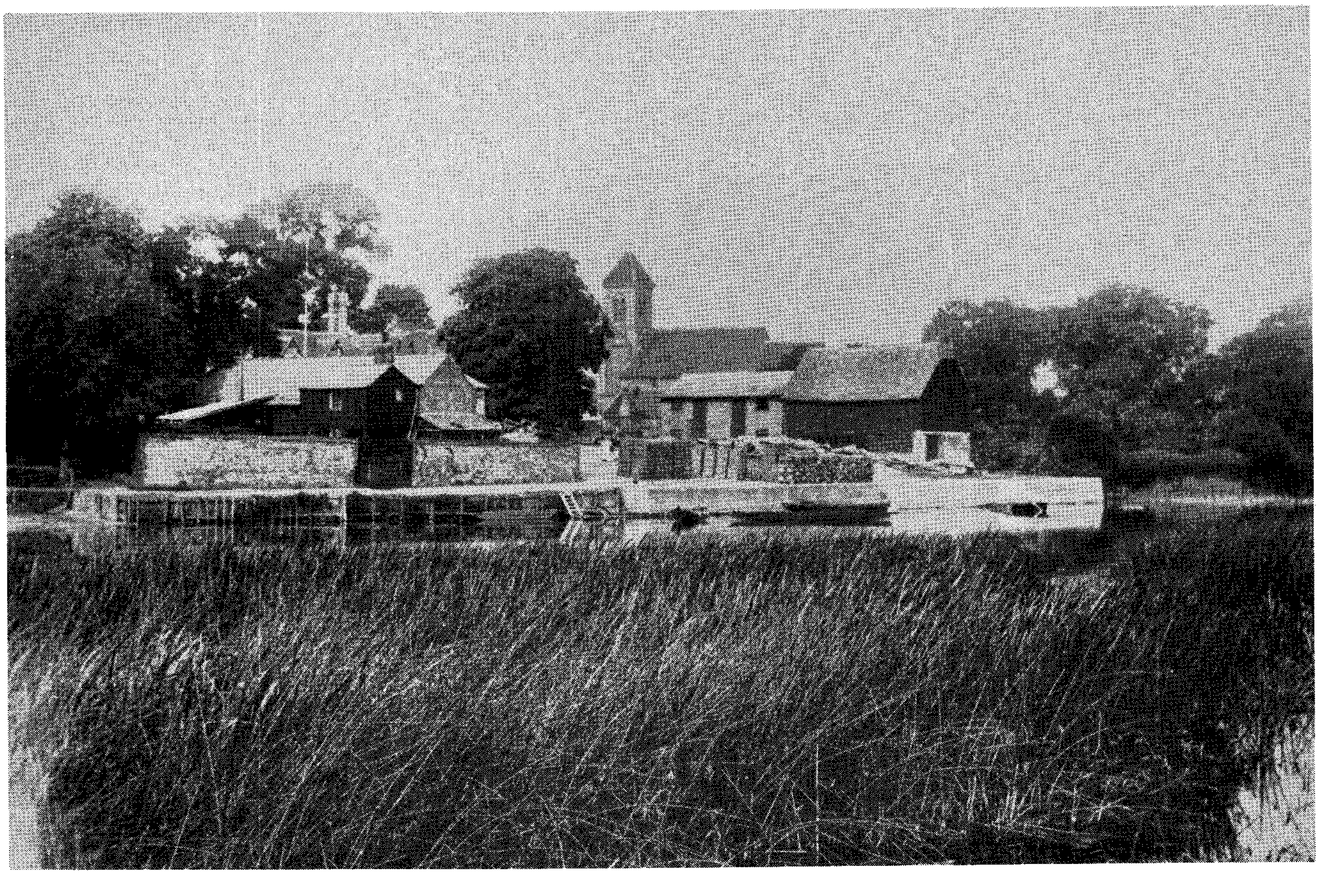


PLATE 3 Right bank below Wallingford Bridge in 1890 showing thick stands of emergent river plants

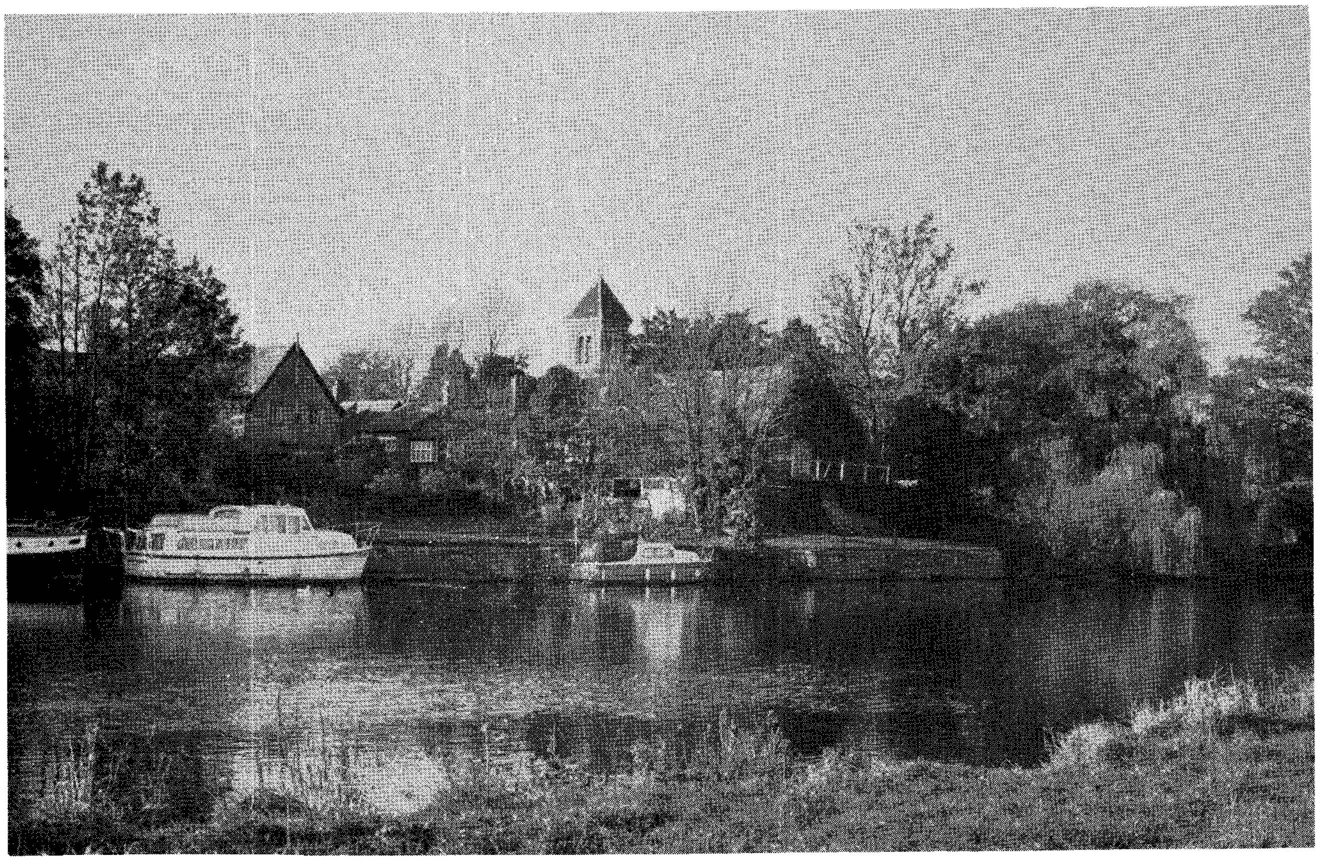


PLATE 4 Right bank below Wallingford Bridge in 1980 without river plants

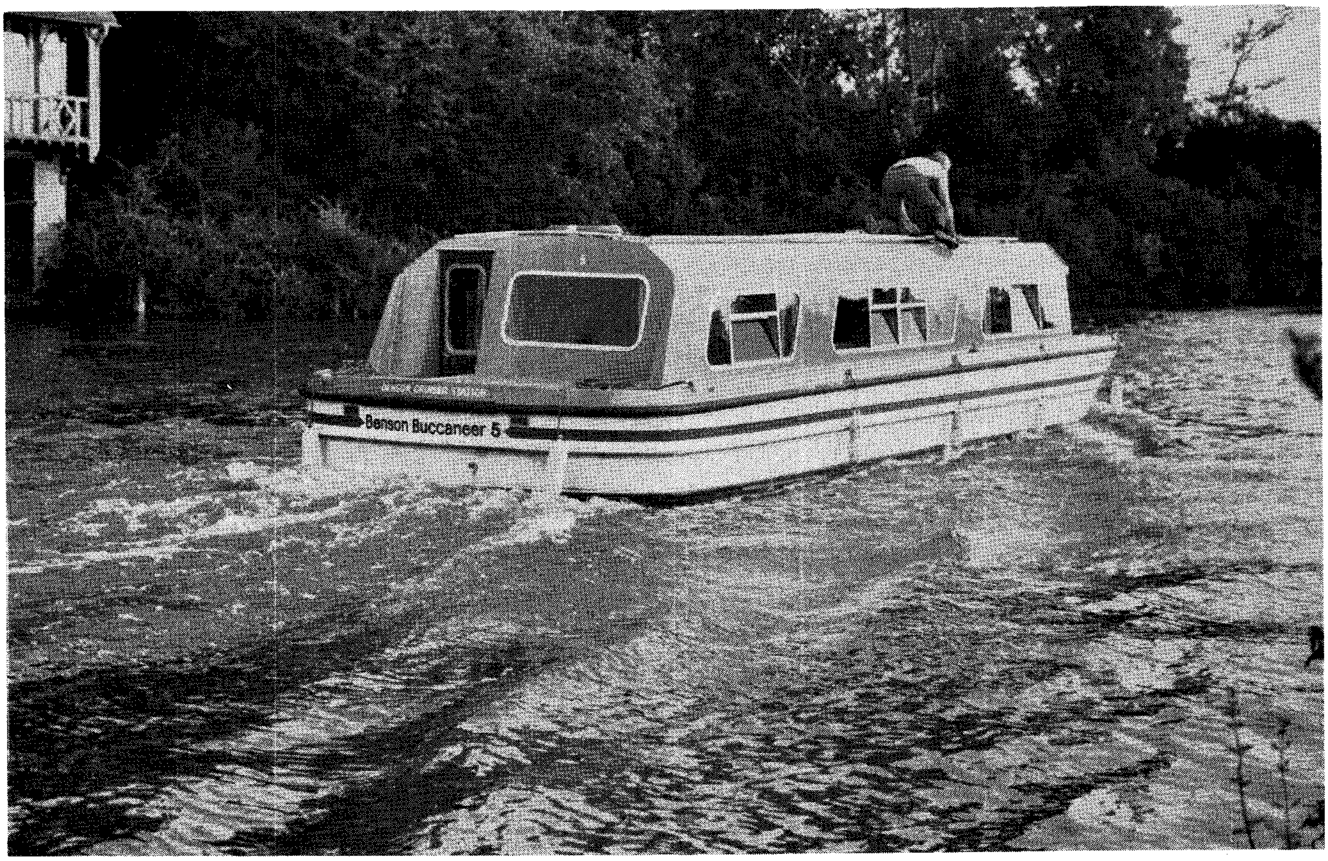


PLATE 5 'Wide' recreational motor boat on the River Thames passing the Hydraulics Research Station wave recorder

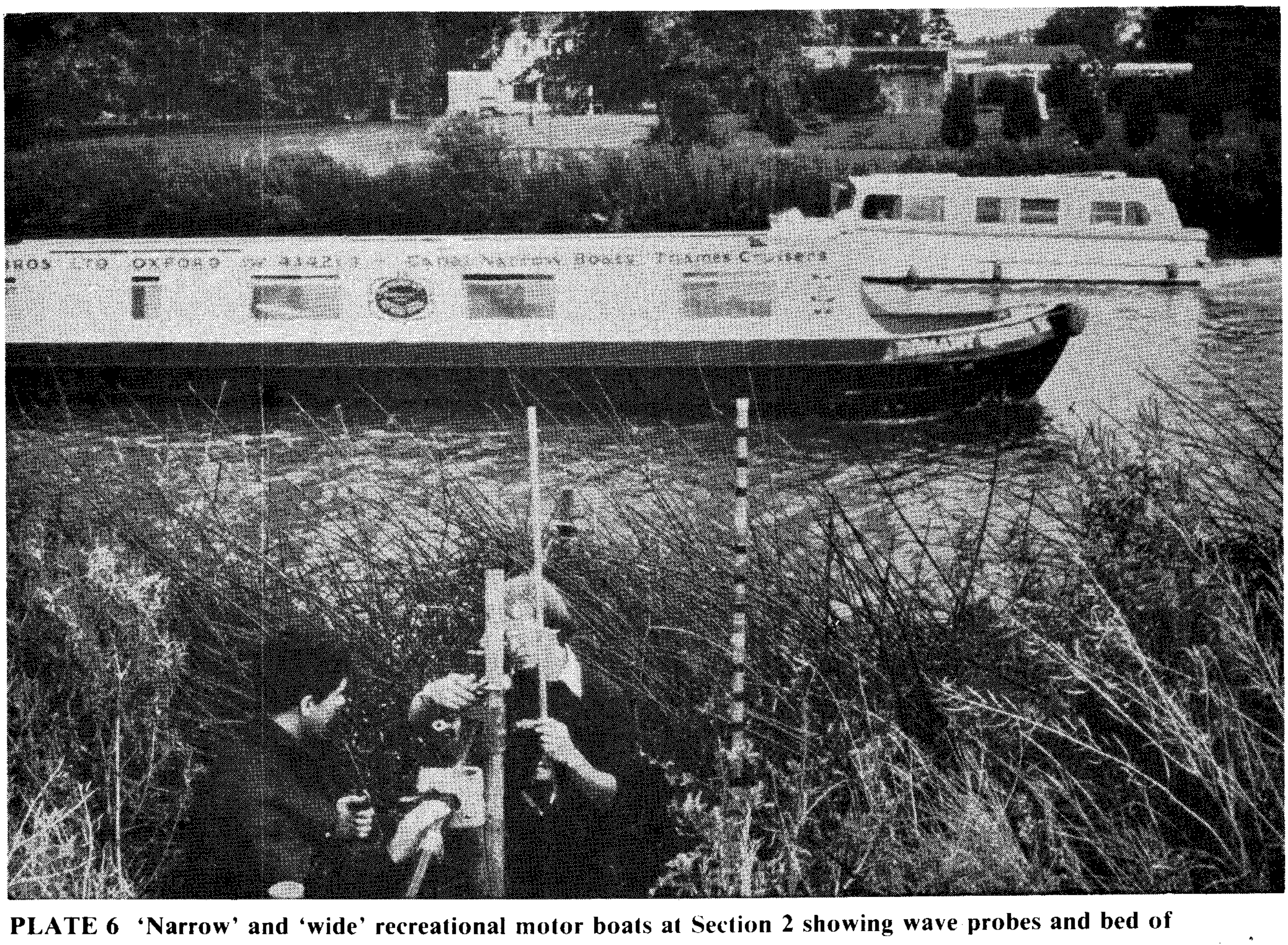


PLATE 6 'Narrow' and 'wide' recreational motor boats at Section 2 showing wave probes and bed of Schoenoplectus lacustris, common clubrush or bulrush

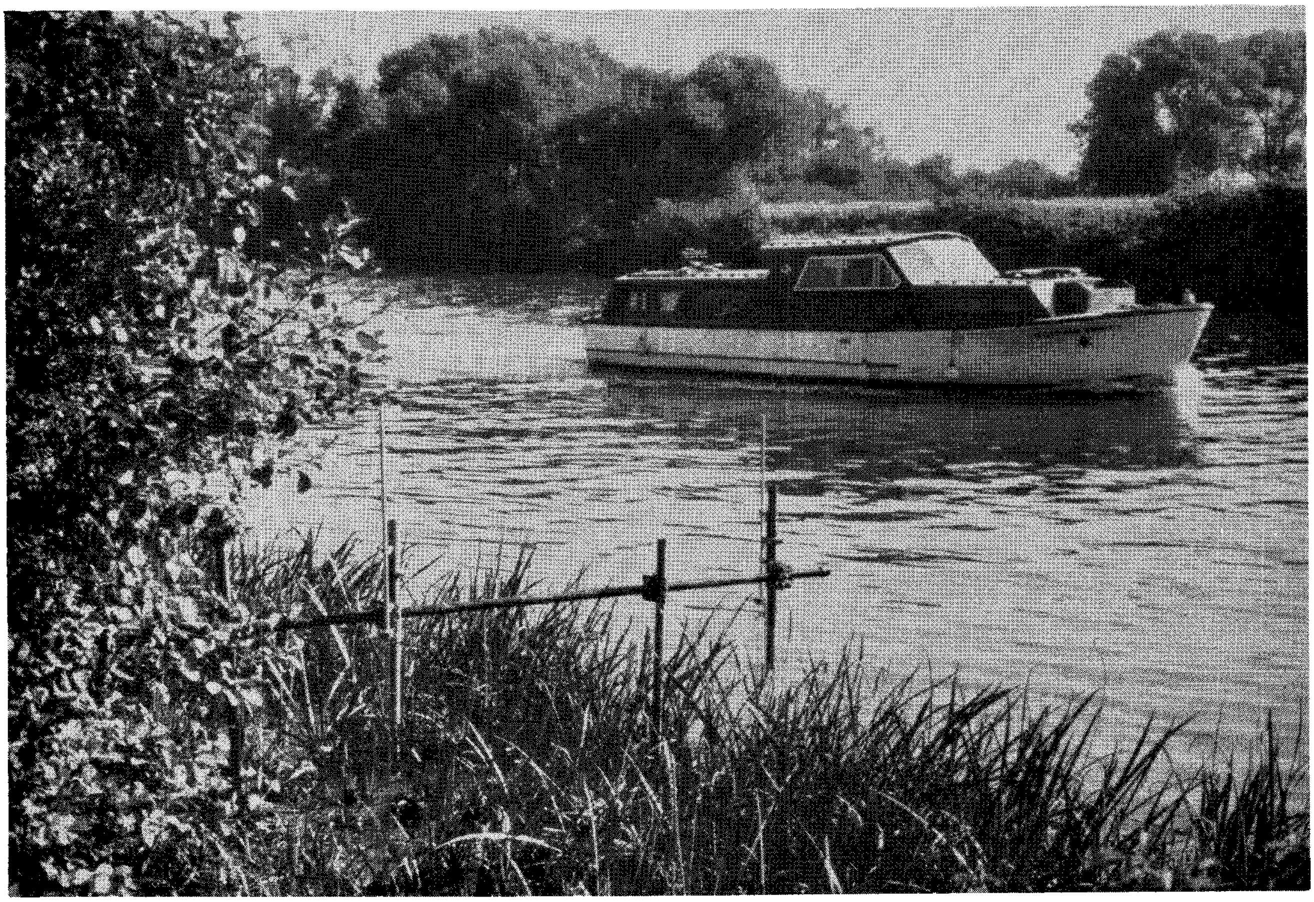


PLATE 7 Recreational motor boat at Section 4 showing wave probes and bed of Acorus calamus, sweet flag

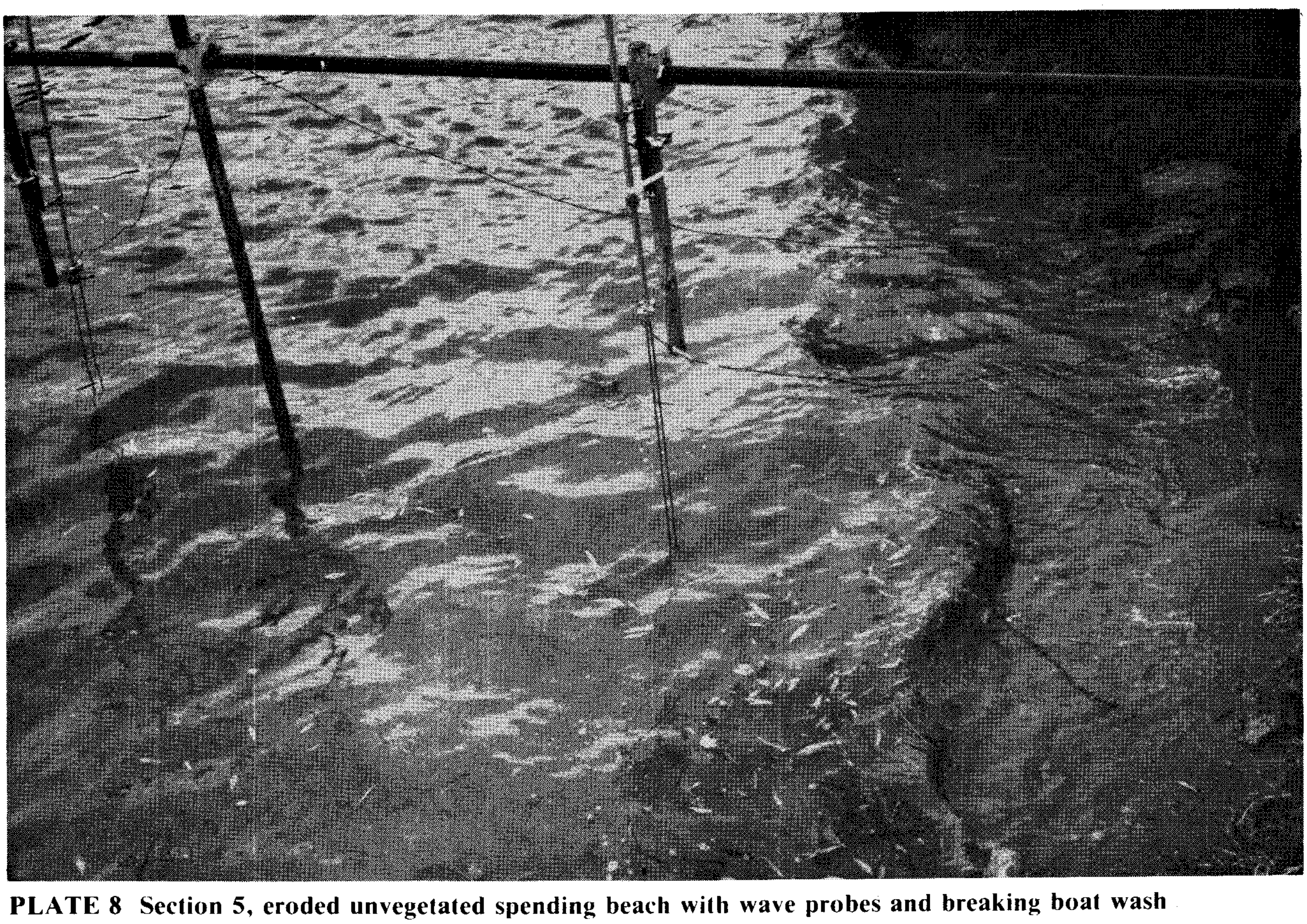


PLATE 8 Section 5, eroded unvegetated spending beach with wave probes and breaking boat wash