HR Wallingford

THE HYDRAULIC ROUGHNESS OF VEGETATED CHANNELS

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COMMISSION

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ABSTRACT

Vegetation in and around watercourses provides both benefits and problems. Floodplain vegetation, especially grass, has been comprehensively studied but aquatic weeds have received less concentrated attention, partly due to the greater diversity of plants and the difficulty of defining the physical parameters. This study relates the overall hydraulic retardance to the physical dimensions for the common shallow water weeds, ranunculus and calitriche.

CONTENTS page

1. INTRODUCTION 1

2. PREVIOUS WORK 1

3. FIELD SITES 5

3.1 General description 5
3.2 Locations 6

4. TEST PROGRAMME 8

5. SITE MEASUREMENTS 8

6. ANALYSIS 10

7. CONCLUSIONS 17

8. REFERENCES 19

FIGURES

1. Proportion of overall Mannings n value attributable to channel blockage
2. Vegetation volume ratio related to vegetation surface area ratio
3. Overall Mannings n related to V*R and vegetation surface area ratio
4. Overall Mannings n related to V*R and vegetation volume ratio
5. Overall Mannings n related to vegetation surface area ratio divided by V*R
6. Application of results to Powells data
7. Comparison of results with Peppers data

1. INTRODUCTION

The growth of vegetation in rivers and canals is an ever present problem. In many existing waterways, the consequences of the vegetation growth will have been learned by experience. However, there are a number of situations where a prediction of the effect of vegetation growth is required. Examples of such situations are:

Design of new drainage channels

A change of flow conditions in an existing waterway eg: increased run-off from bankside developments; use as a feeder from storage ponds or pumped aquifers.

Assessment of the benefits of vegetation control programmes

Intermittent flow over grassed surfaces has been widely studied in the field and in the laboratory but comparable information on aquatic plants, which are more varied in form, is not generally available for general application. This study is intended to obtain a better understanding of the effects of aquatic vegetation.

2. PREVIOUS WORK

Numerous studies have been made of flow over grass surfaces since vegetation in this form is a naturally occurring protection for flood plains and river banks. Grass is also used deliberately as a low cost and environmentally acceptable protection for flood bypass channels and emergency spillways that will only operate intermittently and for short periods. On the other hand, aquatic plants that live permanently in water have received less concentrated attention.

Hydraulically, aquatic plants cause problems with few balancing benefits. However, such plants are valuable indicators of water quality and as such are studied extensively by botanists. This type of work and the work on grass give useful pointers for studies of the hydraulic effects of aquatic plants and are broadly summarised below.

The most extensive series of tests on grass covers was carried out by the US Soil Conservation Service, beginning at the Spartanburg Hydraulics Laboratory in 1936 (Ref 1). From 1940 onwards related testing was carried on at Stillwater, Oklahoma in co-operation with the Oklahoma Agricultural Experimental Station (Refs 2 & 3). Testing continued at Stillwater (Refs 4, 5 & 6) until a Handbook of Channel Design was produced in 1954 (Ref 7). The analysis was based on the widely used Manning flow equation and the general conclusions were that:

a) Mannings coefficient n varied with a flow parameter that was the product of the velocity V and flow depth D. For application to all shapes of channel D could be replaced with the hydraulic mean depth R.

b) Mannings coefficient n varied with a vegetation parameter that was the length of the grass and to a lesser extent the "stand". The latter was classified as "fair" or "good" and represented a broad measure of vegetation density.

The coefficient n was referred to in this context as a "retardance coefficient" since it includes the effect of all factors tending to retard the flow and the effects of the channel area blocked by vegetation.

Field tests by Eastgate (Ref 8), Yong & Stone (Ref 9) and others broadly supported the use of VR as the flow parameter. Experiments carried out by Larsen, Frier & Vestergaard (Ref 10) also showed a close relationship between Mannings n and the parameter VR for the aquatic plant Sparganium.

The variety of vegetation and its wide ranging, constantly changing characteristics under the influence of climate and water quality make field experiments an essential part of any study. However, independent variation of the various parameters involved is rarely possible on a field site and a number of laboratory studies have been carried out so that the effect of individual parameters can be more closely investigated. Most of these investigations have related to grass or grass-like vegetation with uniform cover and flow over and through the vegetation. Some investigators have used real vegetation set into a flume, for example Larsen et al (Ref 10) and van Ieperen & Herfst (Ref 11). Others have simulated the vegetation with flexible fronds or steel rods. Examples of the former approach are Kouwen, Unny and Hill (Ref 12) and Murota et al (Ref 13). The latter approach was used by Li & Shen (Ref 14) and Lal & Pandya (Ref 15) and made a more detailed study of the vegetation parameters such as plant width, plant spacing and plant drag coefficients than can be achieved in the field. In relation to aquatic plants this is particularly relevant to situations where the flow is entirely through the vegetation as can often happen in small drainage ditches.

Information on aquatic plants that form randomly distributed beds, such as Ranunculus, is notable for its scarcity.

Powell (Ref 16) collected valuable data over a long period on the effects of aquatic plants on the hydraulic conditions in the River Bain where the main plant present was Potamogeton. However, detailed measurement of the weed was not undertaken. A particular feature of the study is that measurements of water levels and discharge were recorded at 15 minute intervals. Discharge variations as much as five-fold and the consequent variations in Mannings n were therefore picked up over short time periods when vegetation cover would to all intents and purposes be constant.

The major problem with this type of plant is to devise a vegetation parameter that relates to the observed changes in the hydraulic regime.

Efforts have been made to relate flow resistance to plant biomass (Dawson (Ref 17), Brooker et al (Ref 18)) but no clear cut relationship has been found.

Pepper (Ref 19) measured Mannings n values on the River Ousel over a period of a year and also made a measure of the weed growth. The results showed a strong correlation between Mannings n and the ratio of weed volume to water volume in the test reach. In this instance, discharge during the period of highest weed growth did not vary greatly.

An extensive bibliography of papers relating to the botany and hydraulics of vegetated watercourses has been published by the Freshwater Biological Association (Ref 20).

3. FIELD SITES

3.1 General description

The sites originally chosen were the River Anton near Romsey and the River Wey near Farnham. The R Anton was a relatively large river with an uneven bed and difficulty was experienced in inspecting and measuring in some areas because of the depth of the water. Early in the programme, study of the R Anton was discontinued and a site at Candover Brook on the east side of Winchester was adopted.

All these sites were of the same type; gravel bed streams with relatively high width to depth ratio and moderate to high flow velocities throughout the year. In these circumstances the principal mainstream plants were Ranunculus and Calitriche. Both of these are streaming plants that have no inherent stiffness in individual plants but, in bulk, form large beds with an elastic consistency that respond to the hydraulic forces by expanding and contracting. The shallows were populated by varieties of weed that have more innate stiffness but do not thrive in the velocities encountered in the mainstream. As silt was deposited by the slow flow through these plants, there was a gradual encroachment of the banks of silt and their weed population into the mainstream until the plants died off and the banks of silt were eroded away. The advance and retraction of the bank lines took place in a yearly cycle.

An essential requirement of a research site and a major limitation on availability of suitable sites is a means of accurately measuring discharge. Each of these sites was close to a measuring structure.

Other factors looked for in a site were:

1. A history of strong weed growth
2. Unrestricted weed growth ie: little or no management
3. Absence of pollutants in the flow

3.2 Locations

1. The principal source of data was Candover Brook at Itchen Stoke near Winchester. This stream, running mainly through private property, is spring fed and exceptionally clear. The weed grows naturally and is not managed in any way. One bank was lined with substantial tree growth and, while in some reaches the shading tree growth appeared to inhibit weed growth, in others weed growth was very extensive.

The Brook has an average width of 7m and typical water depth in the centre of the stream of 0.5m. The section chosen for testing was straight for a distance of approximately 120m but, to avoid side streams and cattle drinking places the test length was limited to 40m. It was intended to use this as a single section but under some flow conditions it was possible to measure the water surface slope with sufficient accuracy to allow analysis of subdivisions of the test length.

Flow was measured a short distance downstream of the test section by a triangular profile weir of British Standard specification. There were no significant flow inputs between the test section and the weir.

2. The second site was the River Wey at Farnham. The test section was near the town centre with houses backing onto one bank and open ground with public access on the other.

The river is 8 to 9m wide and typical water depth in the centre was 0.6m. The total test length was approximately 100m comprising two 50m lengths of distinctly different slope.

Flow was measured by a non-standard full width weir immediately upstream of the test section. The accuracy of the rating could not be established.

In practise, the results from this site were of poor quality. The weed growth was low and died off early; one observer took the view that the weed was being affected by pollutants. This could not be confirmed but only limited data was obtained and the value of the site was in doubt.

4. TEST PROGRAMME

The most rapid changes in vegetation volume occurred between April and August and visits to the sites were normally made at a rate of one a month during this period. During the remainder of the year, visits were made occasionally to establish the natural roughness of the channel without weed and to observe the movement of the silt beds which are often retained by the weed roots after the top growth has died away. Two full years of readings were obtained and one part year.

5. SITE MEASUREMENTS

The only permanent work at the sites was the installation of bench marks to locate sections and provide reference levels. The marks were round-head bolts set in a concrete block. In soft ground the block was cast around a steel angle iron driven into the ground. Straight lines between the marks formed the base line for horizontal measurements.

On arrival on-site, the head over the weir was recorded. A river cross section was then surveyed at each of the markers. Water level was established with a tripod mounted point gauge standing in the river. The level was then related to the bench mark with an optical level. Water depths, weed height and silt depths were then measured relative to the water surface. A marked rope stretched across the river located measuring positions relative to the baseline.

Vegetation growth was surveyed by wading in the stream and marking the outline of large beds with a ranging rod. Each time a position was marked, it was triangulated to the baseline with theodolites mounted over the two bench marks that spanned the section being surveyed. Small clumps were surveyed by locating the centre and measuring the length and width. For each bed, depths were measured from the water surface at several points to the top of the vegetation, to the silt within the bed and to the channel bed. The bank lines were plotted by the same method.

Experiments were made to survey vegetation growth by aerial photography from a helicopter or model plane. This method was weather dependent, reflections or wind-ripples on the water surface leading to poor resolution. Lack of contrast was also a problem particularly if algae was present. Since it was still necessary to enter the river if vertical measurements were required, this method offered little advantage and was discontinued but may have application to weed surveys of extended lengths of a waterway.

When the survey was complete, the water level at the gauging weir was again recorded.

6. ANALYSIS

The principal macrophytes in the Candover Brook which yielded most of the data were Ranunculus, Calitriche Berula and Rorippa. Botanical surveys by the then Southern Water Authority during the 1970s showed Calitriche to be the dominant species but during the hydraulic experiments, Ranunculus accounted for 75 percent of the aquatic cover during periods of high weed growth. During the summer Rorippa was found growing more as a bankside emergent than as part of the stream flora.

The Manning equation was used for analysis in the manner of the Stillwater Laboratory tests:

$$Q/A = 1/n * R^{(2/3)} * s^{(0.5)} \qquad (1)$$

Q	=	discharge
A	=	cross sectional area of channel without vegetation
R	=	hydraulic mean radius of channel without vegetation
s	=	energy slope
n	=	Manning coefficient referred to as the retardance coefficient since it includes all losses other than friction.

Calculated in this way the retardance coefficient varied from 0.04 during the winter to a maximum of approximately 0.3 during the summer. This very wide range is typical of that recorded by other investigators.

One approach to analysing the flow in a general way would be to replace A, R and n in Equation (1) with the true values occurring when vegetation is present.

Consider the cross sectional area A. The resistance to flow of plant beds is very high even when the vegetation is relatively open. Consequently, if there is a parallel unvegetated zone of flow over or around the weed beds, the proportion of total flow through the weed rapidly decreases as the 'bypass' area increases. In many circumstances, the low velocities within the weed bed will deposit silt, further restricting the flow path. In the present tests, when plant growth was at its height, the beds were heavily silted and velocity measurements showed stagnant water immediately downstream of the beds; that is, there was virtually no flow through the beds.

Assuming for the moment a friction-only value of n equal to the basic channel value of 0.04 and dividing by the fraction of the channel cross section that is clear of vegetation (raised to the power 5/3) gives a value of n equivalent to the overall n of Equation (1). The result is shown in Figure 1. This suggests that it is not blockage alone that leads to the high retardance coefficients. The unexplained gap could be closed by varying the friction n and the wetted perimeter P. Wetted perimeter undoubtedly varies with the presence of the vegetation but not in any simple way. When the vegetation is dense and reaches the surface, there is no significant flow over the top and effective wetted perimeter would drop but if the plants were not fully developed, or a rise in discharge inundated the beds, the effective wetted perimeter could rise. Integrating these effects over a river reach with variable weed growth and relating it to some measurable weed parameter (eg: volume or biomass) borders on the impossible.

A value could be assigned to the roughness of the vegetation and combined with the roughness of the channel using one of the common formulae for combined roughness to give a more precise value of the friction-only value of n. This would be the surface roughness of a bed rather than its internal roughness and there is little or no available information on this subject. However, on the evidence of the present tests, the friction value of n for the weed would have to be very high (0.08) to bring the calculated value of the retardance coefficient into line with the measured values. This does not appear likely since an aquatic plant might be expected to have evolved a drag equivalence much less than this as a matter of survival.

A third possibility exists, that the excess retardance when weed beds are present is due to form loss. This could arise as the flow turns, contracts and expands between the beds of vegetation. This is not just a consequence of the beds of aquatic plants but also of the emergent plants along the banks. It was noticed that as the emergent plants trapped silt and advanced into the stream, the vegetation line could become very irregular creating extensive pools of dead water along the bank. The emergent plants trapped floating debris as well as silt so that compensating flow through the plants soon became negligible.

In view of the impossibility of separating the effects of the various variables, this approach was not pursued. The results were therefore assessed along the more empirical lines of a number of previous investigations using broad measures for the biological and hydraulic parameters.

The biological parameter could be biomass, volume, cross-sectional area or surface area. Biomass is not easy to assess comprehensively for other than short reaches but may be one of the few practical methods for choked drainage ditches where all the flow is through the vegetation. In this instance, with the type of vegetation that forms beds and channels and flow through the beds is negligible, or is conservatively assumed to be, a dimensional parameter is preferred. Mean cross sectional area and volume of weed are directly related by the length of the reach but surface area and weed volume will not have so simple a relationship. Figure 2 shows a plot of the ratio vegetation volume/water volume to the ratio vegetation surface area/water surface area. This indicates that volume relates to the square of the surface area which implies that the average thickness of a bed is proportional to the area. The multiplying factor of 2.5 would make the vegetation depth/water depth ratio equal to 1 with a 40 percent area cover after which the relationship would not hold.

Most of the available evidence supports the conclusion of the Stillwater Laboratory that the resistance offered by vegetation is inversely proportional to the product of velocity and hydraulic mean depth (V*R). Figure 3 shows the retardance coefficient plotted against V*R with the related vegetation surface area ratio separated into 10 percent bands. Figure 4 shows the same plot but with the results separated into 10 percent volume ratio bands. Both plots are similar in form to that produced originally by the Stillwater Laboratory and supported by later researchers. Of the two, vegetation surface area ratio gives a more distinct pattern than vegetation volume ratio.

From a practical point of view, vegetation surface area is an easier measure to obtain than vegetation volume either by aerial photography or visual estimation and would therefore be the more preferable one of the two even had the correlation been worse.

In these tests it was not possible to observe the effect of significant changes in discharge while the vegetation cover remained constant and the surface area/volume ratio relationships in Figures 3 and 4 are shown only as estimated bands. Plotting the retardance coefficient against a single factor of weed surface area ratio divided by V*R without any weighting gave a single line relationship shown in Figure 5. A best fit straight line gave the equation for retardance coefficient n as:

$$n = 0.0337 + 0.0239*(\text{factor}) \qquad (2)$$

Where (factor) = vegetation surface area ratio/V*R and 0.0337 is the retardance coefficient of the channel without vegetation.

Powell (Ref 16) gave flow data for the River Bain for twenty days of July 1973 including daily maximum and minimum discharges. The range on several days was 200 to 500 percent with wide variations of overall Mannings coefficient indicating the strong effect of discharge on the vegetal retardance. Data on the extent of the vegetation was not given but by working backwards from Equation (2) it would be possible to estimate the vegetation cover. If the equation had validity, the maximum and minimum discharges should give approximately the same vegetation cover and the mean cover should have a smooth progression from day to day. The channel retardance coefficient for the River Bain without vegetation was similar to that in Equation (2).

The result of the exercise is shown in Figure 6. The majority of the pairs of points are in reasonably close agreement, except for days 6 and 16, and show a vegetation cover of approximately 20 percent falling gradually through the month. There was a fourfold change in discharge on Day 6 but the recorded water surface slope was unusually high for the minimum discharge compared with that of similar discharges on adjacent days. Discharge was very high on Day 16 but recorded water surface slope rose by 60 percent for a drop in discharge of less than 4 percent.

Pepper (Ref 19) gave flow data for the River Ousel and corresponding values of vegetation volume ratio. Figure 5 was therefore revised using volume ratio as shown in Figure 7 and Peppers data added. There is a fair degree of scatter when using vegetation volume ratio but the two sets of data show an overlap and a smooth progression. However, if this curve was applied to Powells data to estimate weed volume, the results would not have the coherence of Figure 6 due to the low slope at the upper end.

Calculation of the effect on the hydraulics of a channel of a 'lining' that is non-uniform, constantly varying with time and that reacts to the flow over it will always be an intractable problem. The main difficulty is to define the hydraulic resistance of the vegetation in terms of measurable physical characteristics. Of the range of vegetation, grass has the most uniform characteristics and has been widely studied leading to a fairly general consensus as to the factors influencing hydraulic resistance. Aquatic plants have not received as much concentrated attention and present different problems in that mat-forming plants create a divided flow regime with clear channels and vegetation-filled channels in parallel. This is akin to a vertical section of a grass cover with clear flow above it viewed in plan except that the flow paths are more tortuous. Flume tests on submerged grass covers and simulated grass covers have shown that the internal resistance of the vegetation path is so high by comparison that the flow is heavily biased towards the clear path, the exact distribution being directly related to the cross sectional area ratio of the paths. This pattern is paralleled by the flow through aquatic plant beds.

The aquatic plant equivalent to a mean cross sectional area ratio for a submerged uniform grass cover would be the weed volume ratio. However, the results of the present tests suggest that surface area cover is a better measure of aquatic mat-forming weed. As aquatic plant beds develop, the evidence indicates that the bed thickness to water depth ratio rises faster that the bed surface area to water surface area ratio. The depth of flow over the bed therefore rapidly decreases as the bed develops and velocities over the beds become much less than in the full depth channels alongside. This premise is supported by visual observation and leads to the conclusion that surface area may well be the more important criterion.

7. CONCLUSIONS

The investigation confirms the significant effect that aquatic plants have on the flow resistance of streams. The type of vegetation investigated was dense bed-forming weed that flourishes in running water and will usually have clear channels between the beds since the increases in local velocities as the beds expand will ultimately tend to inhibit further expansion. Despite the difference in form, the resistance characteristics showed strong similarities to those established for uniform covers of grass with particular reference to the investigations carried out at the Stillwater Laboratory. Thus the experiments showed a clear inverse relationship between the resistance as measured by Mannings coefficient n and V*R, the product of the mean velocity and the hydraulic mean radius, both calculated for the channel section with the vegetation omitted. The effect also of the quantity of weed on the value of Mannings n was significant at low flow velocities but decreased quite rapidly as velocity rose. The direct effect of the vegetation is on the effective cross sectional area and wetted perimeter of the channel. It is also conjectured that this type of vegetation creates a form loss. These effects could not be separated and it was concluded that the most useful measures for this type of aquatic plant were vegetation volume to water volume ratio and vegetation surface area to water surface area. The latter ratio gave the most coherent results and would also be the more convenient to estimate in practise.

While an effort has been made to relate this investigation to others, there is a shortage of available data on aquatic plants that makes it difficult to determine whether some effects are site specific. A few comprehensive hydraulic studies and botanical studies have been made of waterways affected by strong growth of aquatic plants, commonly for practical as much as research purposes, but combinations of the two are rare.

Environmentally, it is undesirable to remove aquatic vegetation completely and there is therefore a need for more investigation of the subject. A particular point of interest that could not be clarified in this investigation is the effect of emergent plants close to the bank. Standing in the shallows at the edge of the channel, they would not normally be expected to have as much influence on the channel hydraulics as the mainstream vegetation. However, circumstances can be envisaged where their propensity for collecting silt and detritus could make them a major influence and it is not yet clear if they can be treated in the same way as mainstream plants.

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Figures

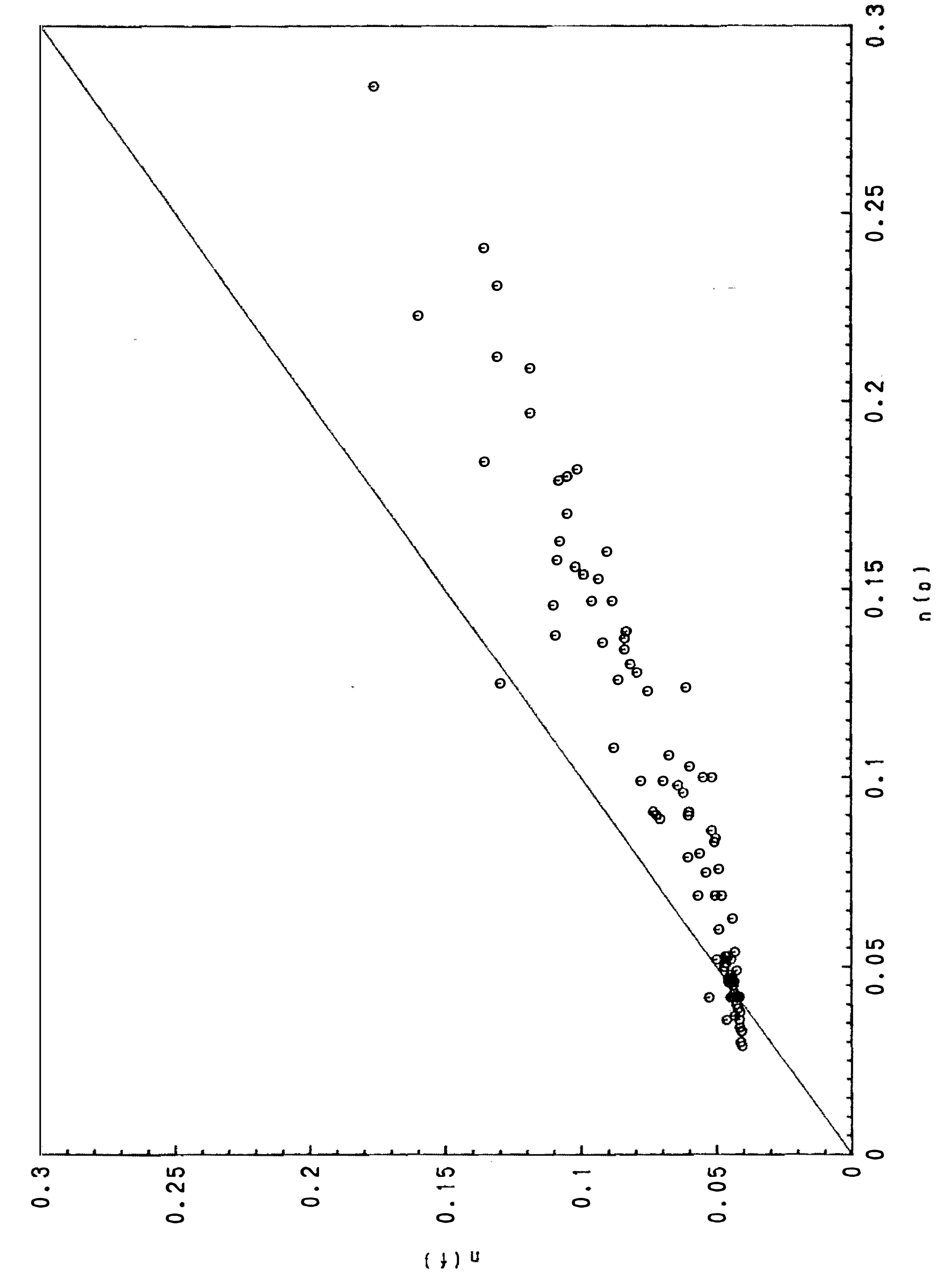

Fig 1 Proportion of overall Mannings n value attributable to channel blockage

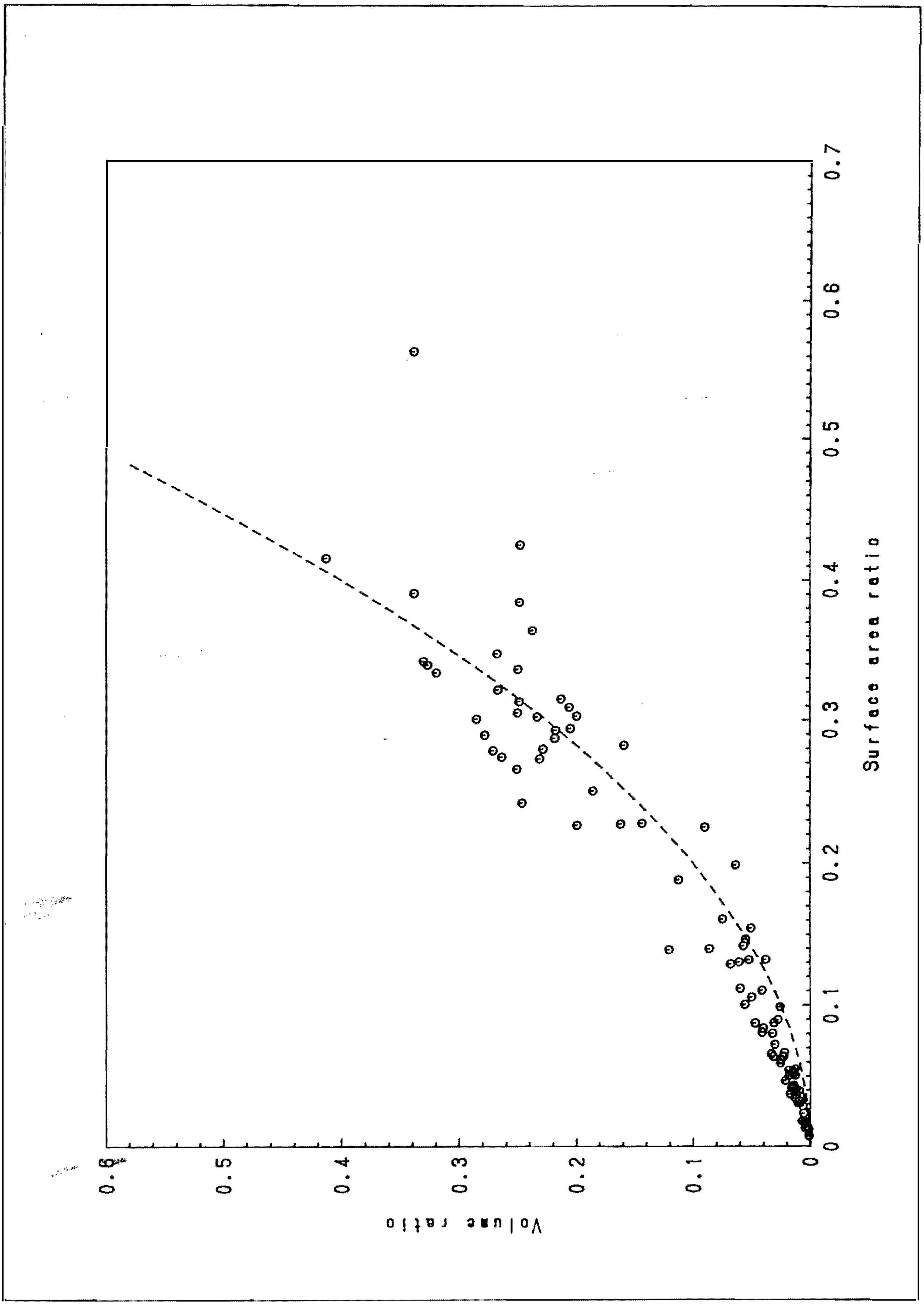

Fig 2 Vegetation volume ratio related to vegetation surface area ratio

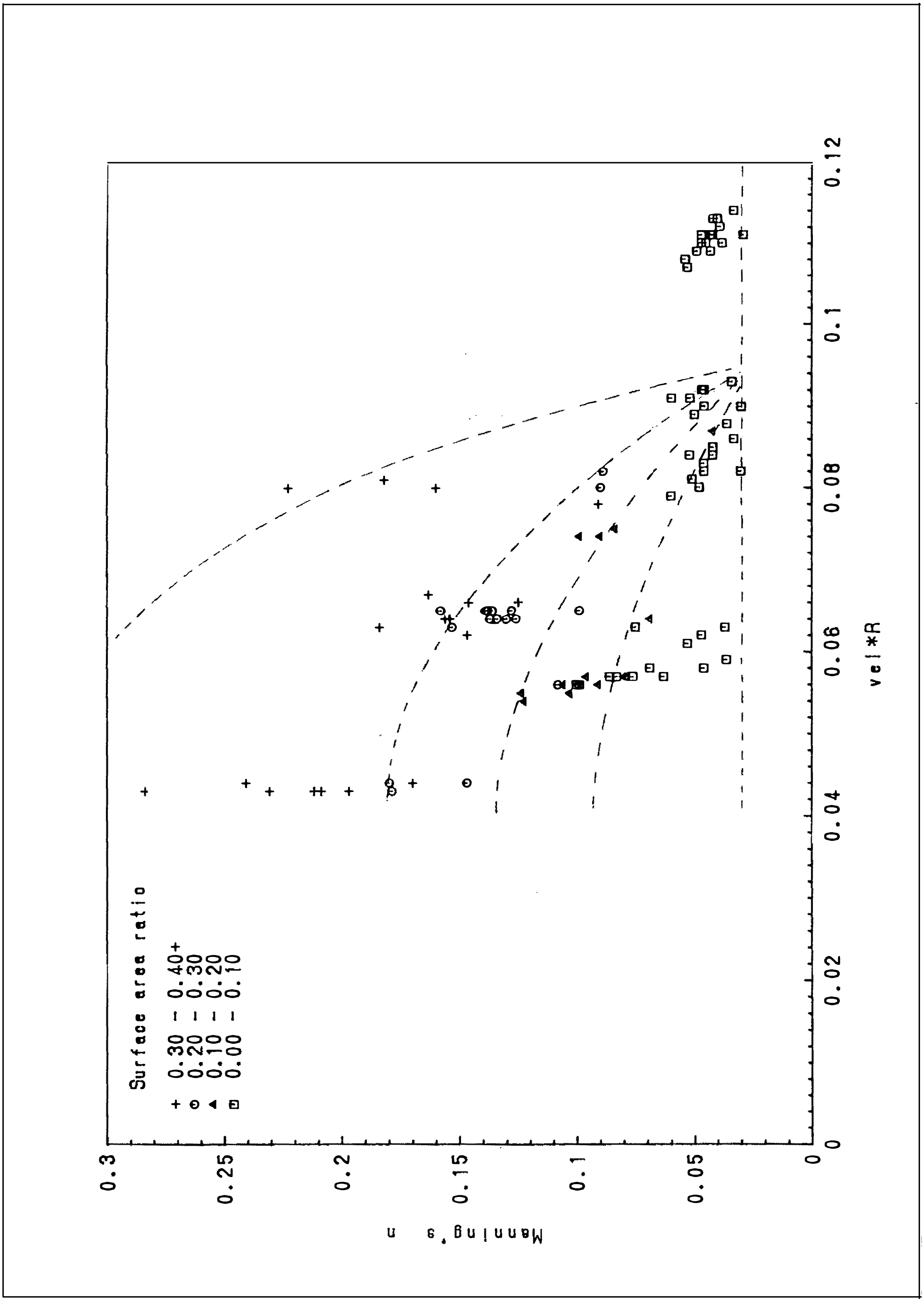

Fig 3 Overall Mannings n related to V*R and vegetation surface area ratio

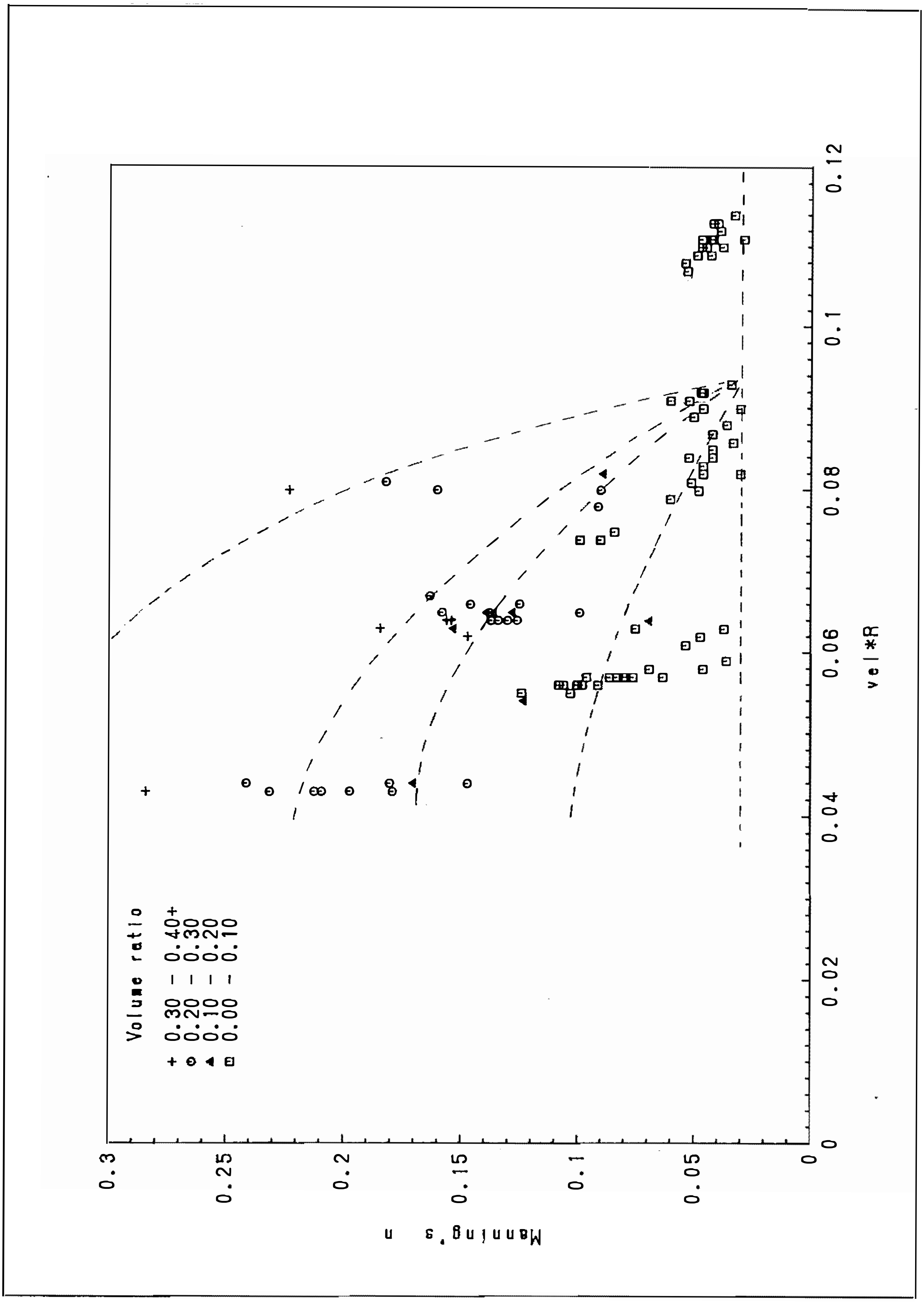

Fig 4   Overall Mannings n related to V*R and vegetation volume ratio

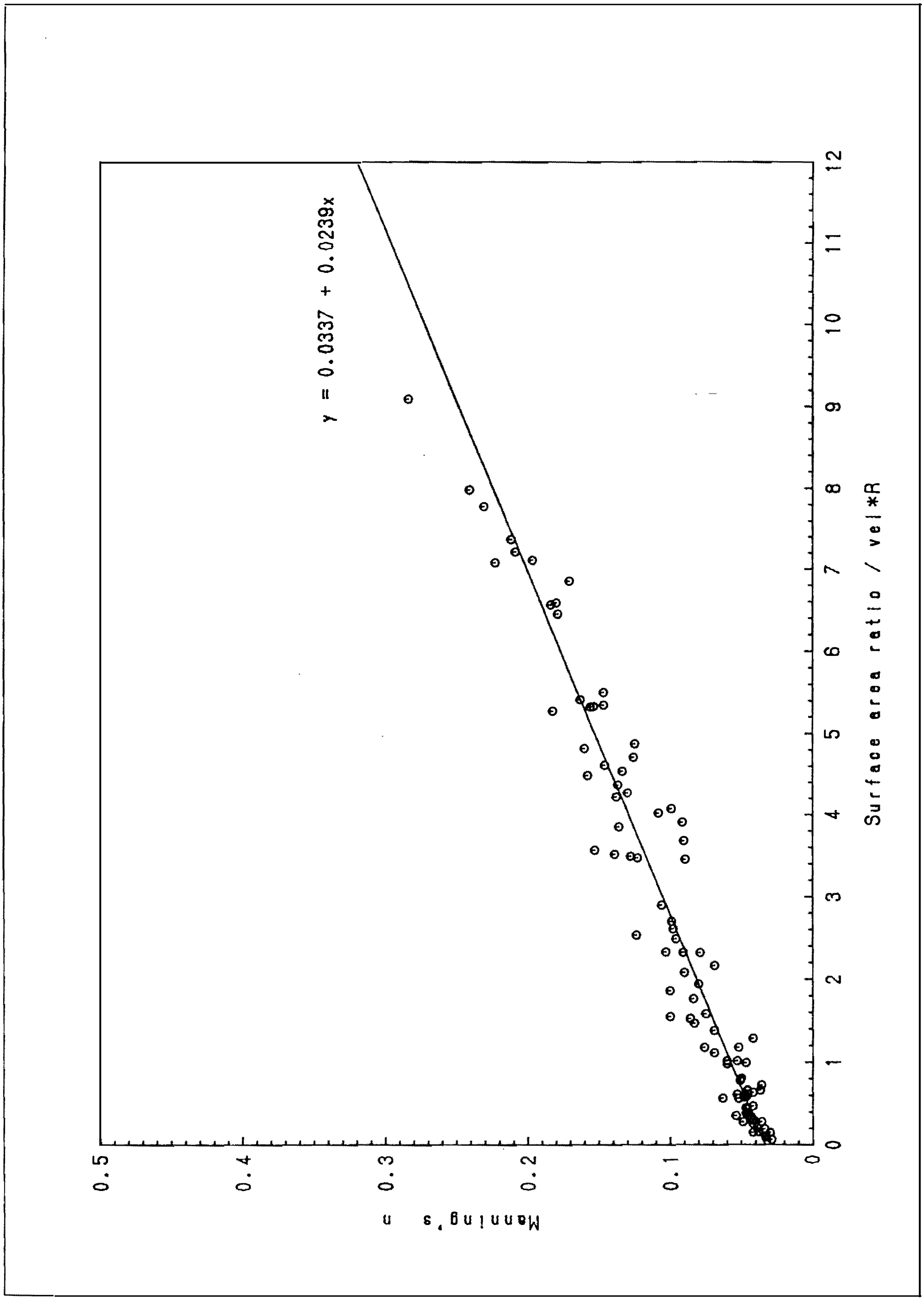

Fig 5 Overall Mannings n related to vegetation surface area ratio divided by V*R

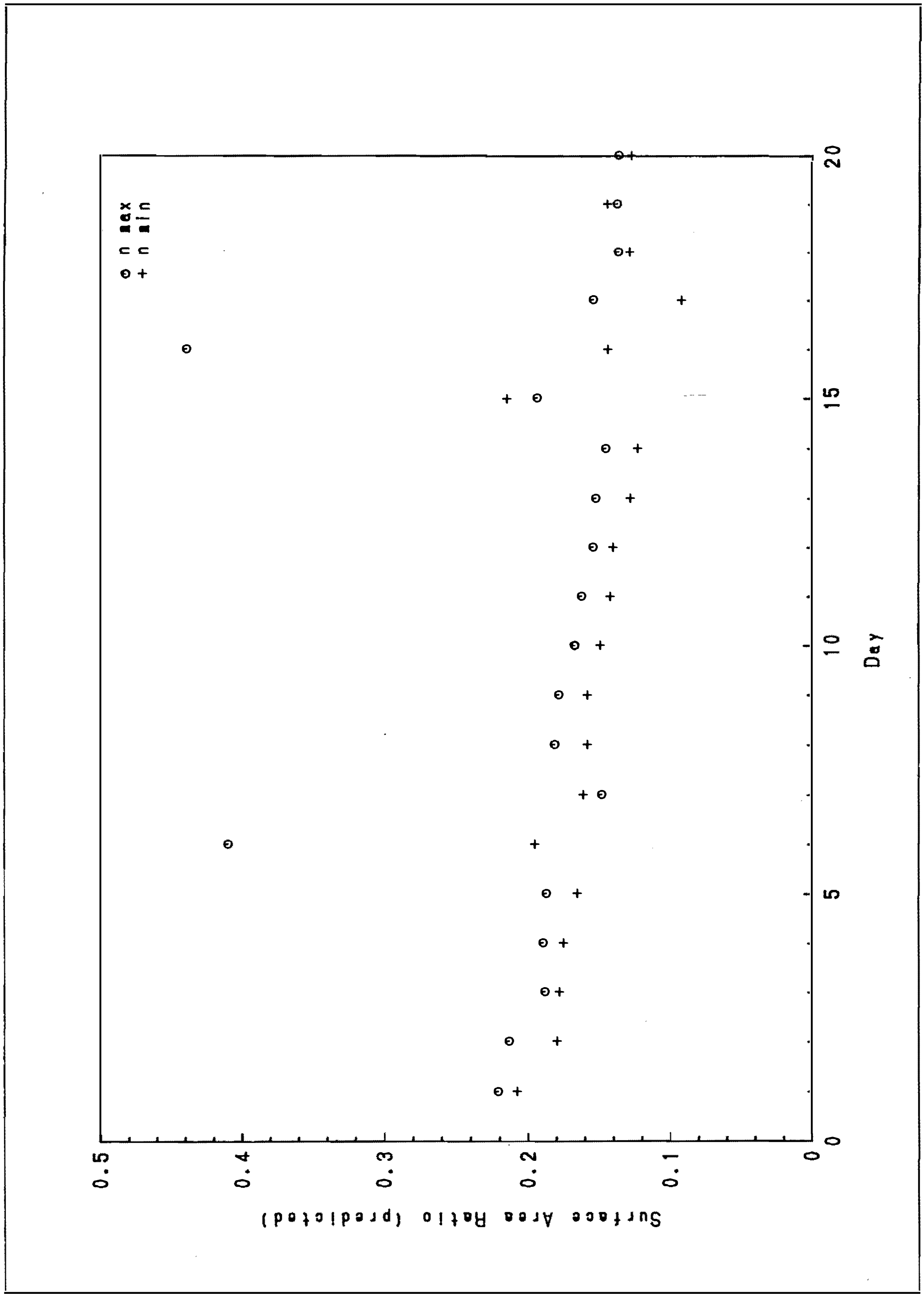

Fig 6   Application of results to Powells data

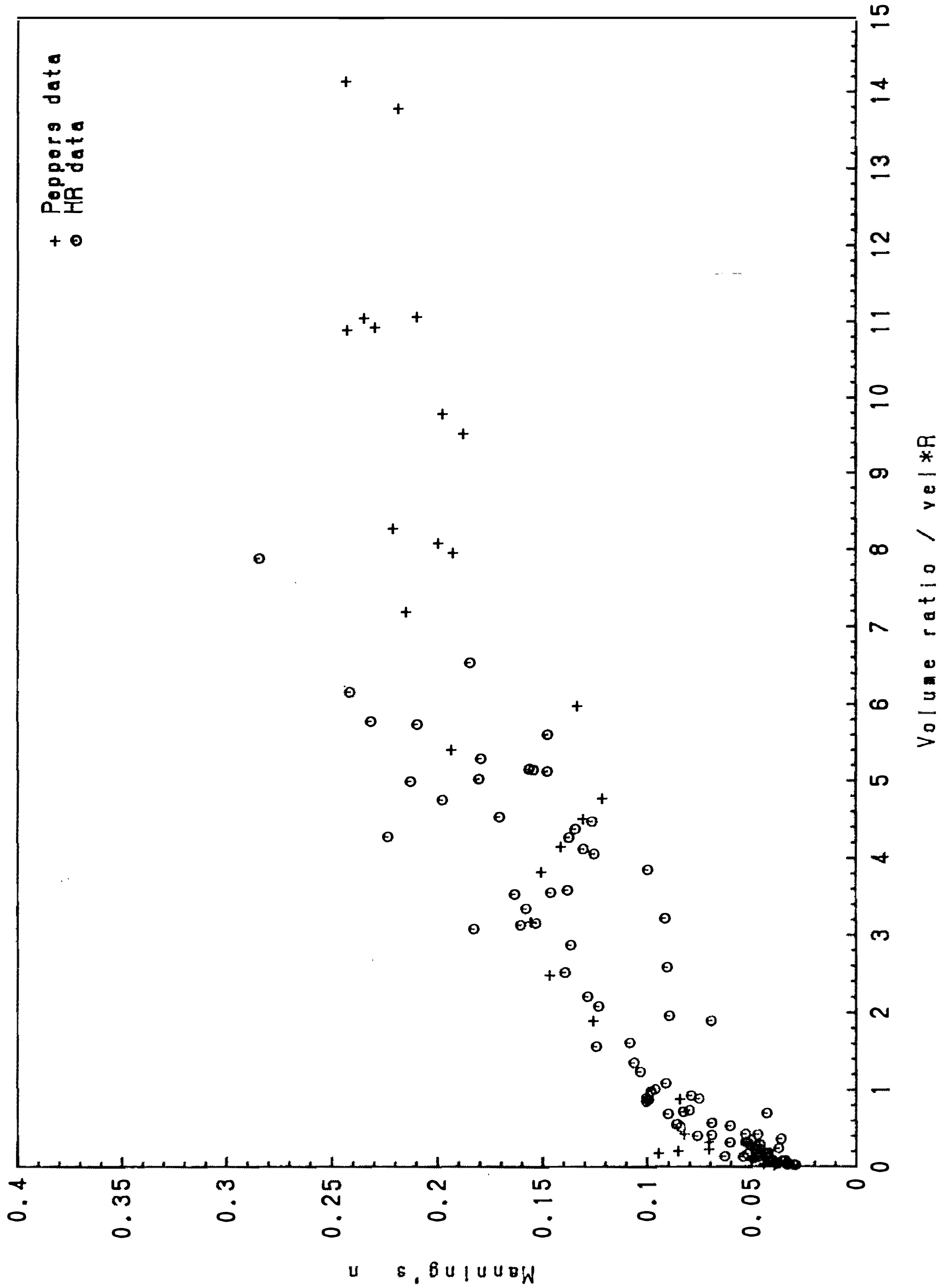

Fig 7 Comparison of results with Peppers data