WATERWAYS COMMISSION

A Preliminary Study of the Bedload Regime Response of the Avon River to Channelisation

Waterways Commission
Report 36
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A Preliminary Study of the Bedload Regime Response of the Avon River to Channelisation

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1. INTRODUCTION

In order to reduce flood levels, the channel of the Avon River was extensively cleared of vegetation during the period 1956 to 1973. This provoked major channel changes. A significant change has been the infilling of formerly deep channel pools, leading to the loss of an important ecological resource. This study represents a preliminary evaluation of the changes in the bedload regime and channel morphology which have taken place in response to channelization.

The changes that have led to the ecological problems, now so apparent in the Avon River system, have not only been dueto engineering channel modification.They are a result of both physical and chemical modifications at the catchment and channel scale. These wider changes and associated problems were recognized by Kendrick (1976), and have more recently been discussedby Hansen (1986) and Seal (1991). Our present evaluation of the likely bedload regime response to channelization hasbeen undertaken in isolation from the wider channel and catchment- scale processes, and hence constitutes only one aspect of what should be a much wider study of the geomorphological channel and catchment processes.

2. PREDICTION OF STREAM RESPONSE TO CHANNELIZATION

An indication of the major channel changes which may result from the clearing of channel vegetation can be outlined from basic hydraulic principles and anunderstanding ofchannel geomorphology. Before vegetation clearing, the Avon River possessed a channel consisting of braided channel reaches separated by a series of deep pools. The braided reaches were heavily vegetated and stored large volumes of sediments. The Manning equation demonstrates the most immediate effect of the clearing of channel vegetation (all symbols used are defined in the Appendix). The equation is:

$$U = n^{-1} R^{2/3} S^{1/2} \qquad (1)$$

During discharge events, vegetation stands form large and complex roughness elements in the flow. Binnie & Partners (1985:51), assigned a Manning `n' value of 0.05 -0.10 to the original channel which had `many roots, trees and bushes, large logs and drift on the bottom.' Parts of the present channel are also vegetated, but to a much lesser extent, being dominated by samphire and occasional casuarinas and acacias. A `n' value of 0.025 - 0.04 was estimated for the present channel. This reduction in 'n' would have led to a significant increase in stream velocity. It was noted, for instance, that at Glen Avon, (downstream of Northam), flow velocity had increased from 1.11m/s to 1.74m/s, (Hansen 1986).

Bedload transport in streams is described by a variety of models (see summaries in Graf, 1971; Raudkivi, 1990). Most bedload models utilize some measure of the shear stress (Á) acting at the bottom of the channel. For present purposes, the model originally developed by Bagnold (1966), is provided here as a convenient but highly idealized means to illustrate the bedload consequences of increased channel velocity. Bagnold used the concept of stream power (ÁU) to predict rates of sediment transport. Stream power is a hydraulic variable which has been found to be an important control of channel morphology (Chang, 1988). Ignoring all other channel changes which can result from the clearing of channel vegetation, it is clear that clearing will invoke a direct sediment response. This is further augmented by the fact that channel vegetation acts as a sediment trap, immobilizing and storing sediment in large channel bar forms (Nixon, 1966; Wyrwoll, 1992). Bathurst (1987) noted that the volume of sediment temporarily stored in bars along the channel is commonly more than ten times the average annual export of total sediment load. Consequently, the clearing of channel vegetation will result in a mobile channel bed and significant changes in the rates of bedload transport.

When channel equilibrium is disturbed, and bed sediments mobilized, an aggradation/degradation response of the stream channel will be invoked. Using the continuity equation for bedload transport in stream channels:

$$\frac{\partial z}{\partial t} + \frac{1}{\gamma s(1-\lambda)} \frac{\partial G}{\partial x} = 0 \qquad (2)$$

it is clear that the bed is lowered if the transport increases along the length of the channel reach. Where the sediment load is greater than the capacity of flow to transport this, channel aggradation will result.

As well as the channel aggradation/ degradation response, other channel variables can also be expected to change. Eskine (1990) considered that the removal of vegetation from the Allyn River, N.S.W., was a contributory factor to the subsequent increase in bank erosion. Brookes (1985) had also noted both localized and downstream bank erosion due to channelization.

The overall problems that can be expected to accompany the clearing of channel vegetation are more complex and wide ranging than those considered above (see Chang, 1988; Brookes, 1988). A good way of approaching an understanding of these wider changes is to recognize that in its new state, the river will attempt to minimize stream power expenditure. However, the outline provided does illustrate the fact that given some understanding of channel morphology, some of the less subtle consequences to channelization can be anticipated with some confidence.

In terms of our concern with the bedload transport regime of the Avon River, it should be noted that even prior to channelization there was evidence to suggest that significant amounts of sediment were moving through the channel. The Northam News (1955) printed `the river systems are gradually silting up and have already reached an alarming state of decay,' (2/3/55). The Northam Weir was dredged in 1952/53 and 47 000 cubic yards (35934m) of sediment was removed in 1954/55, (PWWS 811/62). Clearing of the river has intensified the problem of sediment movement, with most deposition occurring in pools. In the worst cases, pools have been totally filled, e.g. Mt Hardy, Muresk and Burlong Pools, whilst most other pools have been reduced in capacity by varying amounts.

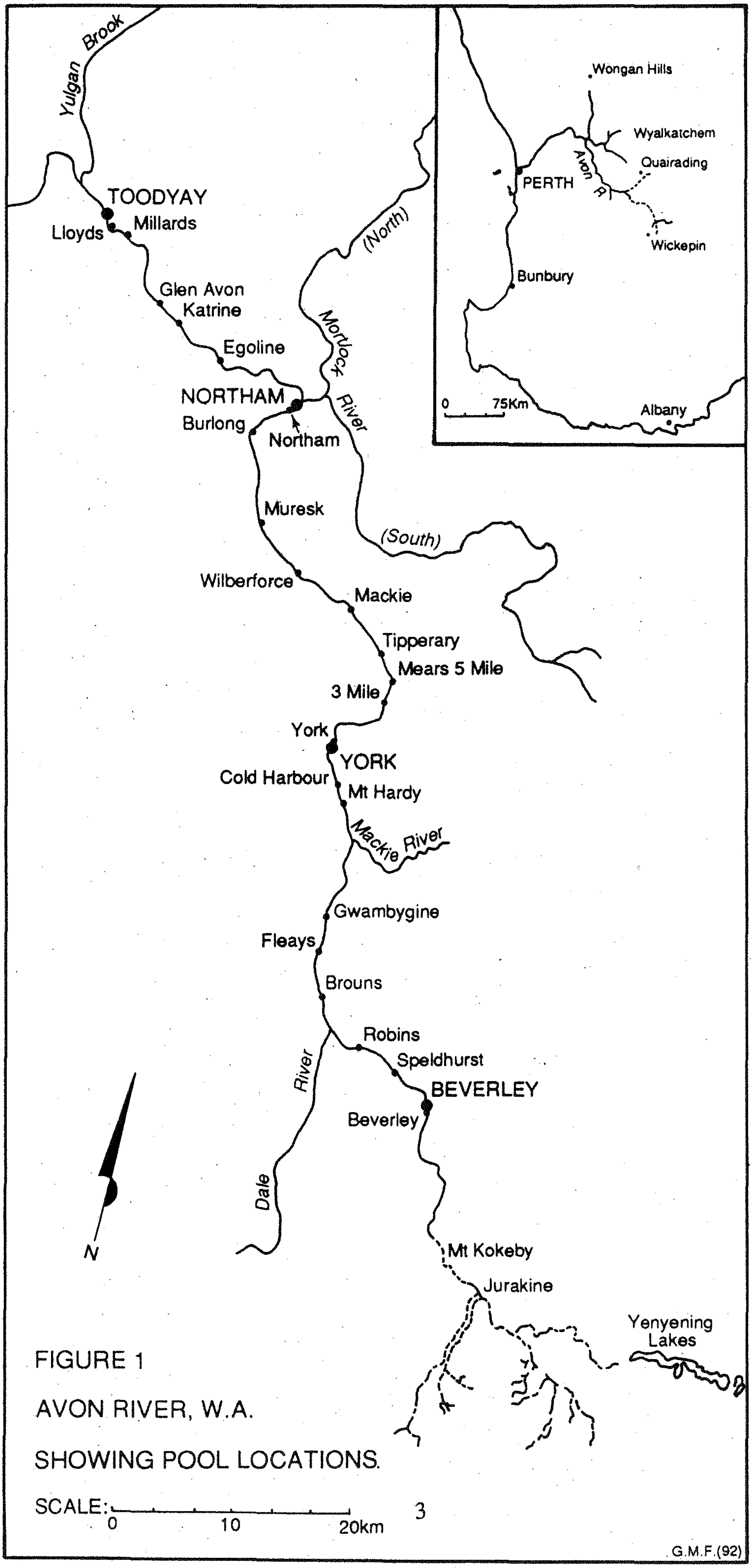
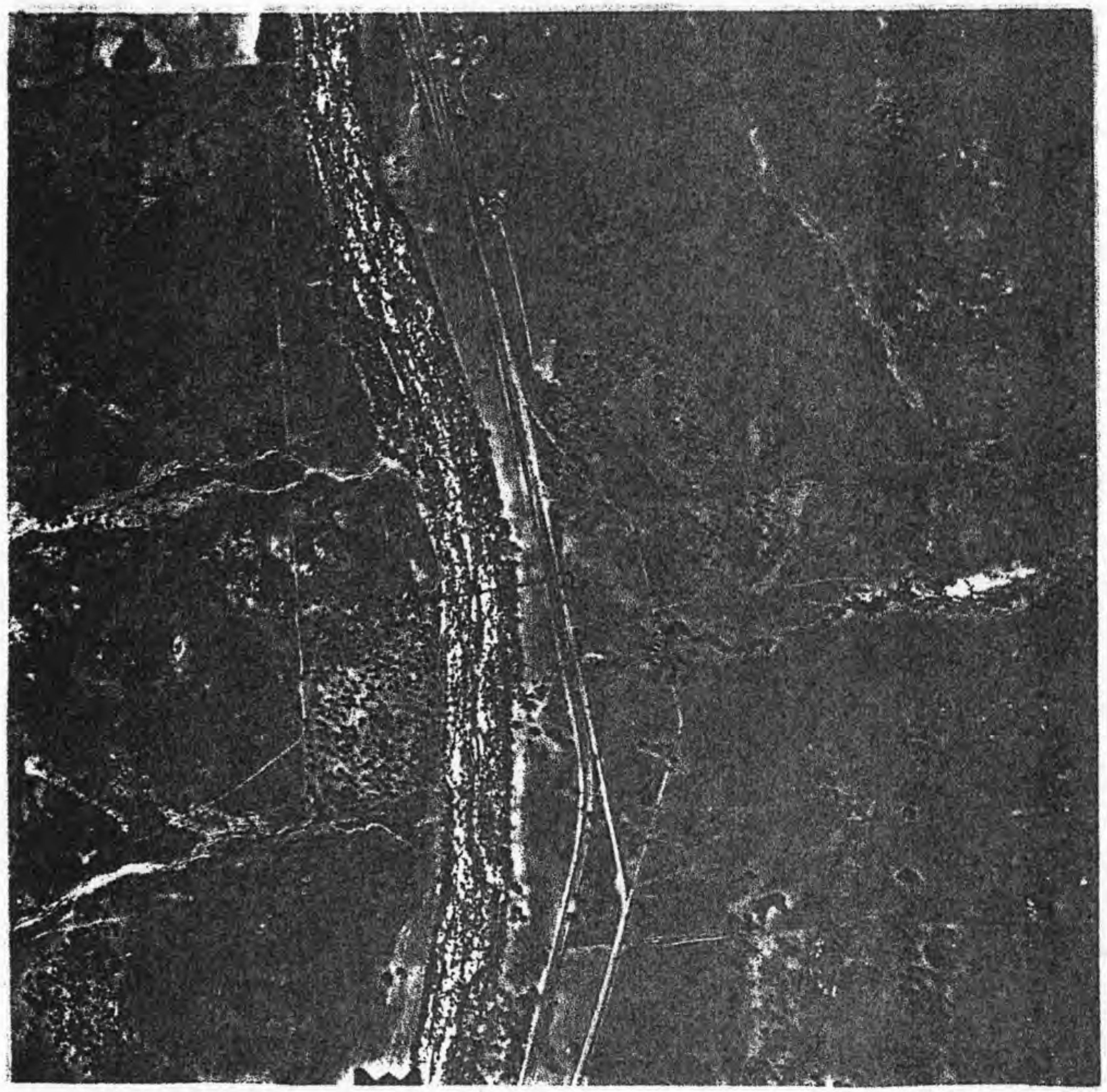


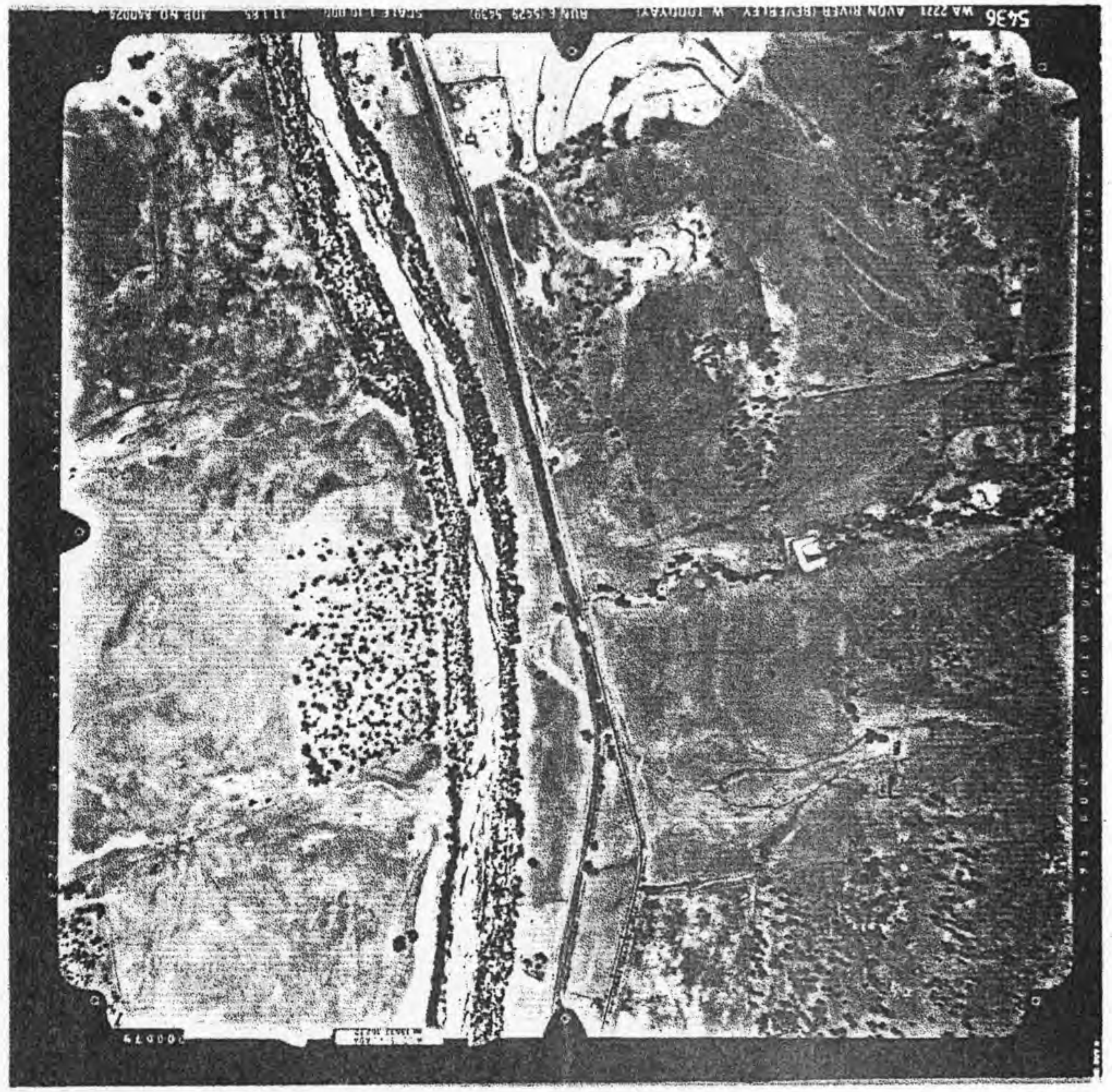
FIGURE 1

AVON RIVER, W.A.

SHOWING POOL LOCATIONS.



A



B

SCALE 1:15 840

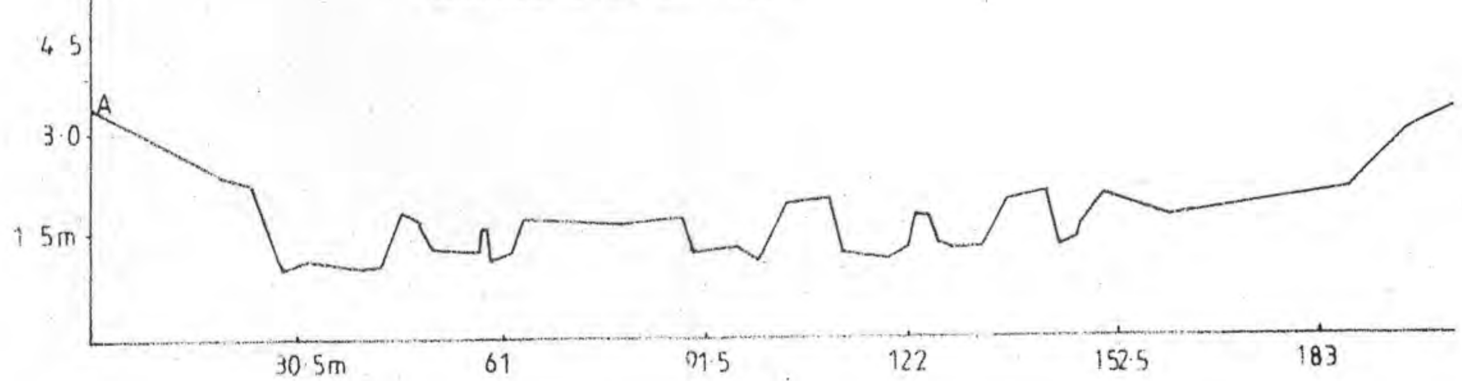
PLATE 1.

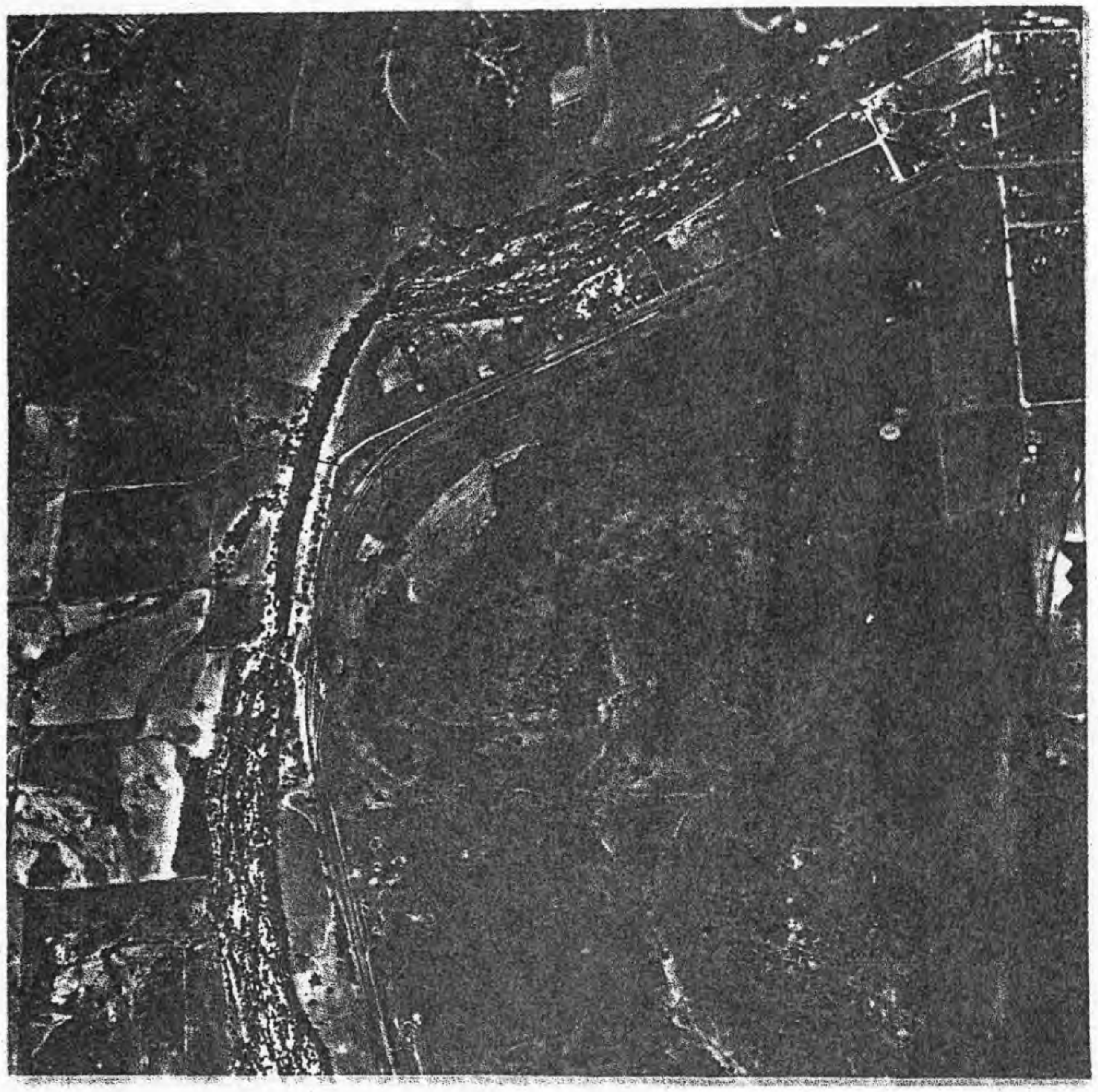
BRAIDED REGION

A) 1960

B) 1985

BRAIDED STRETCH 1960





A

B

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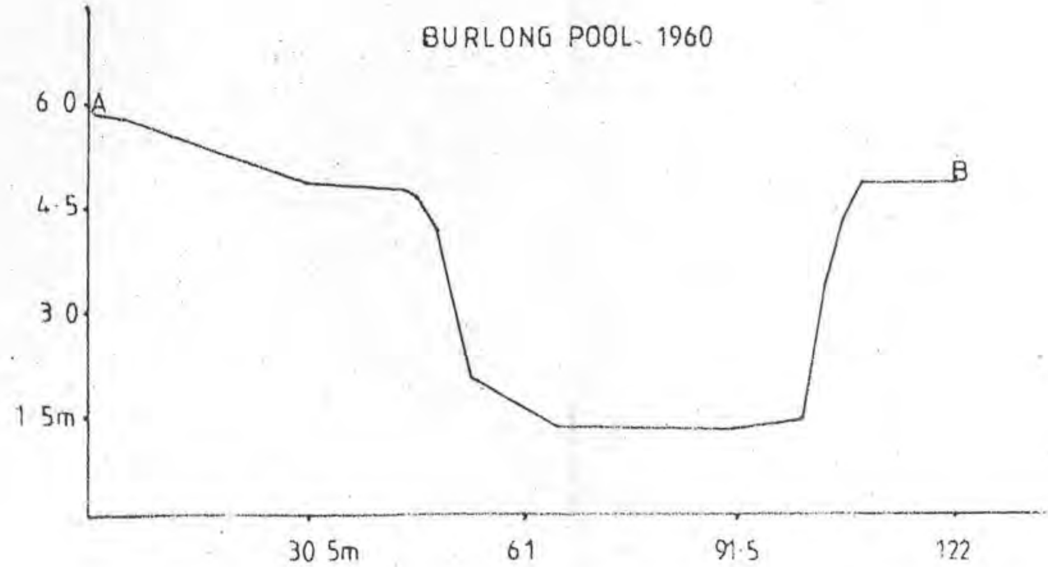
PLATE 2.

POOL REGION
BURLONG POOL

A) 1960
B) 1985



3. MORPHOLOGICAL CHARACTERISTICS OF THE AVON RIVER.

Aerial photographs allowed the identification of the channel changes which have occurred. Photographs taken in January 1960 and January 1985 at similar scales were used. At that time of the year, the channel is dry, and this facilitates the recognition of the major channel sediment bodies.

Twenty two well defined pools were present between Toodyay and Beverley before the river was channelized. These were found at irregular intervals along the channel, occurring on both the bends and straight reaches of the river (Figure 1).

Aerial photographs taken in January 1960 show a channel which consisted of heavily vegetated braided reaches separatedby pools. The braided reaches ranged in width from a maximum of approximately 200m with an average of 140m, (width was measured from the outer edge of the vegetation lining the channel), as shown in Plate 1a. Pool widths were characteristically less than half the braided width, approximately 40m. Channel width narrowed slightly towards a pool, with a noticeable reduction at the up stream end of the pool. This is illustrated in Plate 2a. Downstream from a pool, the channel widened, often becoming wider than average.

The braided stretches were heavily vegetated with species of Casuarina, Melaleuca and Eucalyptus. Aerial photographs also indicate areas of lighter colour intensity in the channel. These are likely to be shrub and grass species. The density of vegetation varied from very dense to relatively open, i.e. where no or very little channel bed could be seen on the aerial photographs, to reaches where the channel bed is clearly visible. The vegetation shown in Plates 1a & 2a is moderately dense, trapping a large amount of sediment. It was sometimes difficult to determine if the exposed bed was scoured and was devoid of sediment, or if it contained mobile sediment. Flow between the pools occurred in irregular deep channels with water sometimes persisting through the summer months.

Cross-sections surveyed before clearing, indicate that these areas of the channel were braided, and that braiding was confined within the outer tree line. Plate 1a illustrates the aerial view and corresponding cross section for the uncleared braided reach. For comparison, Plate1b shows thecharacteristics of the same channel reach after clearing.

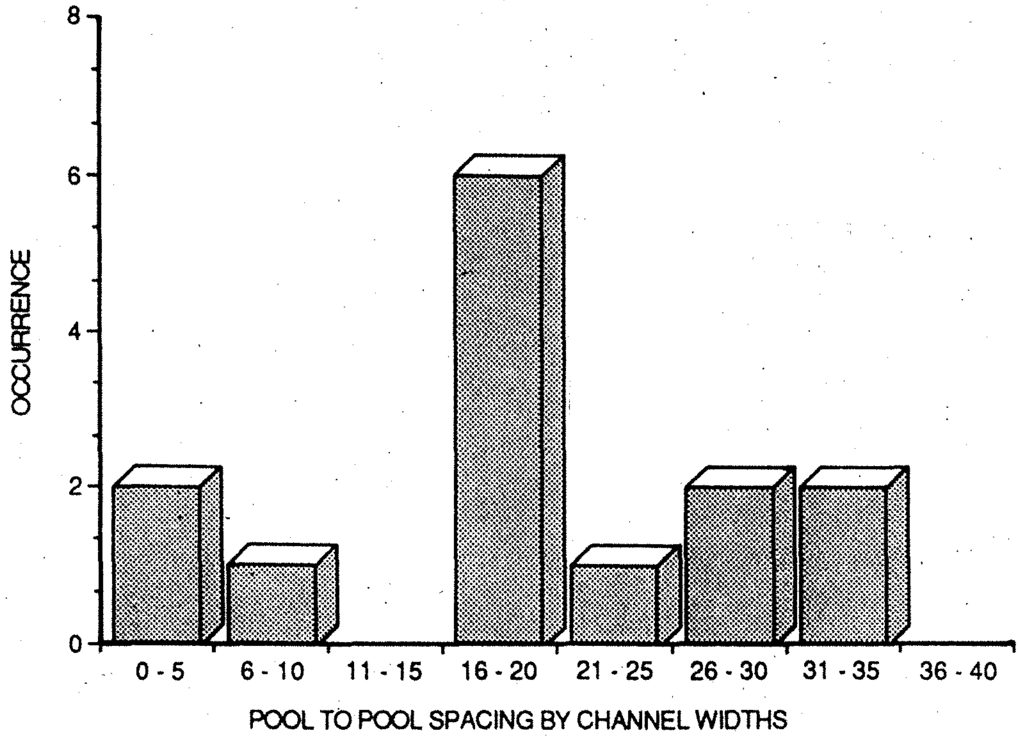
It is evident that the location of the pools coincided with a marked reduction in channel width, ranging between 20 - 40m. This is illustrated in Plate 2. The pools were deep and their banks lined with trees and shrubs. These overhung the pool edges with roots protruding from the banks into the pools. Pools varied in length from approximately 370m (Fleays Pool), to over 2km (Millards Pool). Table 1 shows pool lengths, widths and depths as ascertained from aerial photographs and channel cross-sections. (Not all pool depths are available as not all pools were surveyed prior to channel training). Pool spacing varied from a maximum of 10km between Northam Pool and Egoline Pool, to a minimum of 650m between Mt Hardy and Cold Harbour Pools.

TABLE 1. POOLS BETWEEN TOODYAY AND BEVERLEY.

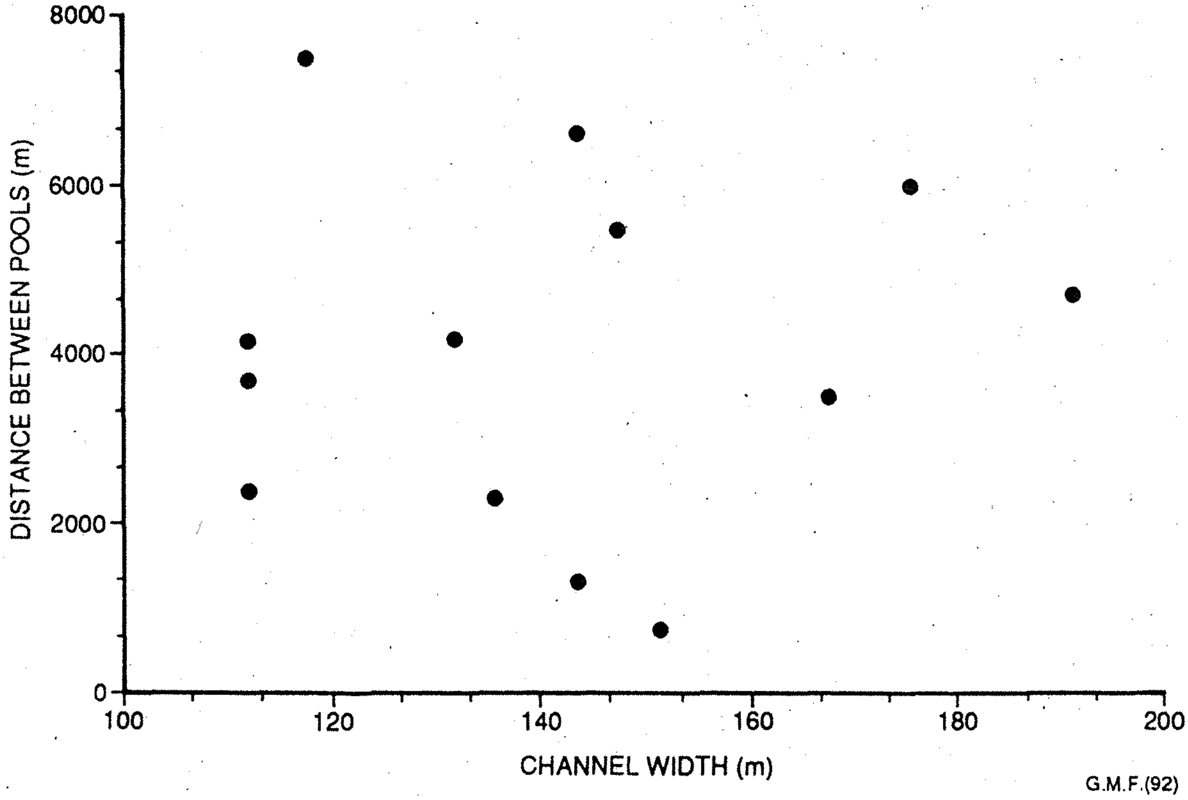
POOL	WIDTH	1960 LENGTH	DEPTH	1985 WIDTH	LENGTH
Beverley	39.6	443.52	-	30	400
Speedhurst	39.6 - 31.7	594	-	30	570
Robins	31.7	1255.3	-	30	1160
Brouns	39.6	610	-	43	610
Fleays	39.6	372	2.3 -2.5	35 - 40	370
Gwambygine	38	1109	-	40	1150
Mt Hardy	31.7	570.2	-	TOTALLY FILLED	
Cold Harbour	39.6	546.5	2.1 - 3.0	25	110 -125
York	31.7	601.9	2.7 - 2.9	30	
3 Mile	23.8	590.8	-	19 - 20	
Mears 5 Mile	31.7	380.2	-	30	
Tipperary	39.6	1180	-	40	
Mackie	31.7	1235	-	40	
Wilberforce	31.7	998	3.0 - 4.2	30 -35	
Muresk	28.5	695.4	-	20 -25	
Burlong	39.6	855.3	3.6 - 3.7	TOTALLY FILLED	
Northam	110.9	1053.4	-	No Data	
		1972		1985	
Egoline	40	1100	2.8 - 4.6	40	280
Katrine	40	640	3.1 - 4.0	60	820
Glen Avon	44	1600	4.1	40	1485
Millard	40	2200/2640	3.4 - 4.6	40 - 45	2425

All values in meters.

FIGURE 2 FREQUENCY OF POOL SPACING IN CHANNEL WIDTHS



THE RELATIONSHIP BETWEEN POOL SPACING AND CHANNEL WIDTH



G.M.F.(92)

The along channel spacing of pools does not scale with channel width (Figure 2), as has been found for pool and riffle sequences in meandering channels (e.g. Keller & Melhorn, 1978). Clearly, the hydrodynamic controls which operate to form pools in meandering channels cannot be responsible for pool formation in this part of the Avon River. In meandering channels, cross-sections are quite different between channel reaches, being asymmetric in pool reaches and symmetric in riffle sections. The cross-sections of the Avon River tend to exhibit symmetrical pool cross- sections and asymmetrical riffle sections (Plates 1 & 2).

It is clear from fluvial mechanics, that there is a cause and effect relationship between channel width and pool formation/location. The explanation for this is straightforward (e.g. Breusers and Raudkivi, 1991) . The increase in channel depth at a channel constriction can be derived from the equations of motion and continuity for sediment and water. It can be shown that the relationship between depth and width between two stream sections is given by:

$$\frac{y_2}{y_1} = \left[\frac{w_1}{w_2} \right]^{\alpha_1} \qquad (3)$$

where $w_1(w_2)$ and $y_1(y_2)$ are the stream width and depth upstream (downstream) of a channel constriction. The exponent $\alpha_1 = (m-1)/m$; with m = 3 to 5, $\alpha_1 = 0.67$ to 0.8. But while this explains why pools have developed at channel constrictions, the actual cause of channel narrowing remains unclear. The channel constriction could well be due to some substrate control but this would have to be determined. However, whatever the cause, the relationships outlined above make it clear that it is imperative that bank stability is preserved over pool reaches.

Clearing of channel vegetation has significantly altered the river. Aerial photographs of the original channel upstream of Burlong Pool, (Plate 1a), and to a lesser extent Mt Hardy Pool, show vegetation `choked' with sediment. These pools have totally filled since clearing. Braided channel reaches now exhibit a channel with a central 30 - 40 meters clear of vegetation, (Plate 1b). Maximum channel width has been reduced to approximately 190m, but the average width is about the same (144 m). In some parts of the channel small shrubs/trees have regrown. A ground survey conducted in 1983 (WAWA) shows young casuarinas growing on more established bars, and extensive samphire and grass development in the channel. It was evident during field work, that the casuarina and acacia stands were stabilizing small bars and were well enough established to withstand the flood and winter flows of 1990 (Plate 3).

No reliable estimates of channel sediment volumes in cleared channel reaches, could be obtained from the aerial photographs. A ground survey (WAWA) demonstrated that loose sediment did not occur along the entire channel, but was found over small distances, i.e. as sediment plugs. For example, in March 1983, there was a plug between Fleays and Gwambygine Pools and upstream of Mt Hardy, Tipperary and Burlong Pools. Major sediment accumulations were present in the infilled pools of Mt Hardy, Muresk and Burlong. There was little visible sediment between Northam and Toodyay due to water in the channel. Both the 1960 and 1985 aerial photographs show extensive channel water in this section. This suggests that water bodies frequently persisted throughout the summer in this region. There is evidence of infilling at the upper ends of the pools between Northam and Toodyay, implying that there is also sediment movement through this section.

Plate 3: Casuarina stands at Muresk, looking downstream.

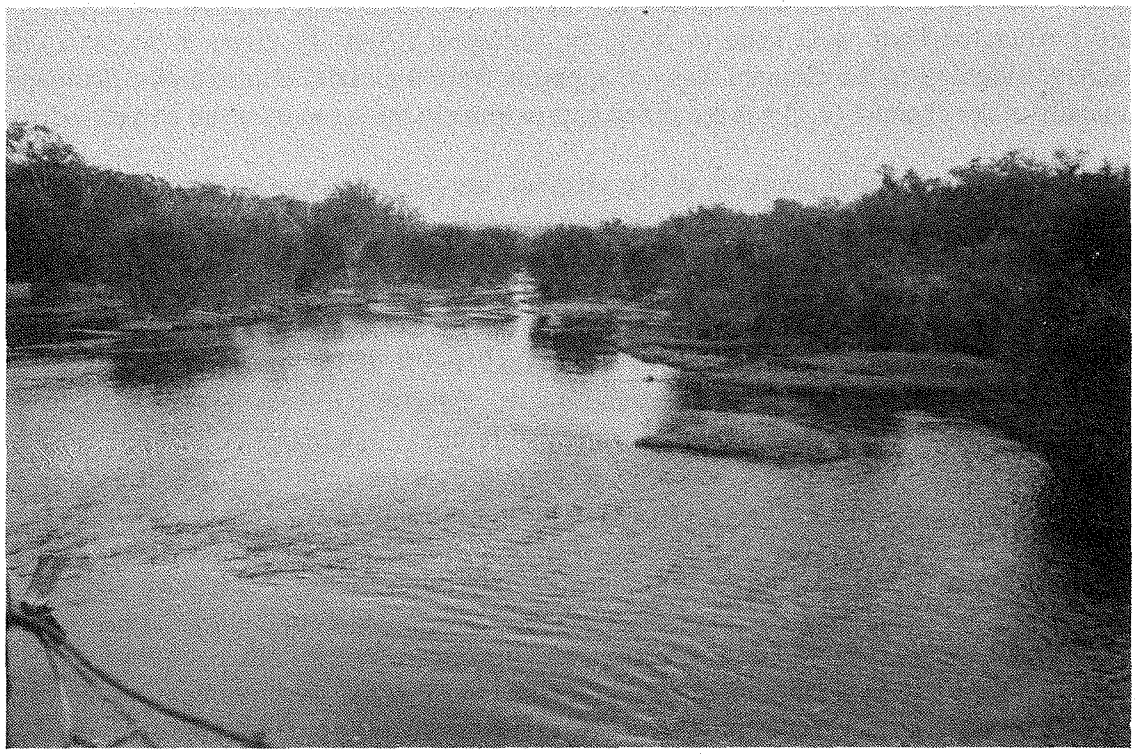
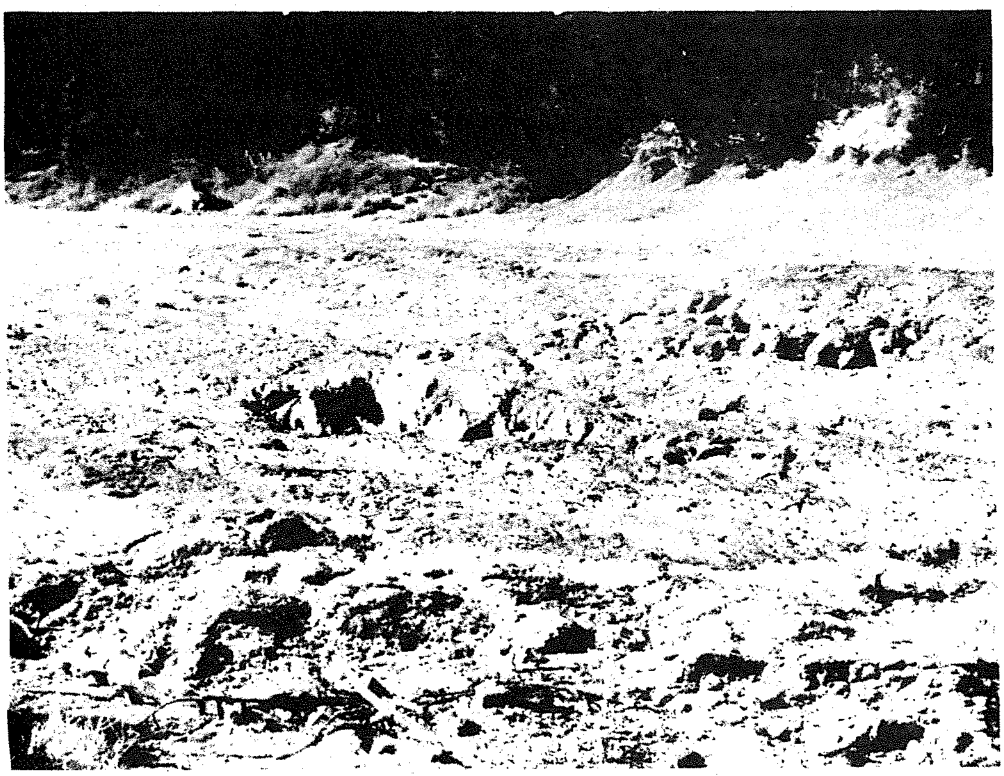


Plate 4: The scoured channel bed exposed during summer.



Scoured channel reaches are evident along much of the river and become especially prominent where the channel bed has been ripped to induce scouring. But as the substrate generally consisted of indurated and partly cemented sediments, which are resistant to erosion, "ripping" could not be successful in inducing channel incision. Instead, these channel reaches now form hard corrugated beds with little or no loose sediment (Plate 4). Even in scoured channel reaches, widening of the channel was not apparent from the aerial photographs. Similarly, the sinuosity of the channel (1.1) has remained approximately the same over the 25 year period.

Scattered debris is found along all of the channel, trapped by samphire mounds or buried by sediment. Most debris consists of roots and occasionally large sections of tree or stump. Debris is also notable within pools, protruding from below the water surface.

The pools in the river did not change noticeably in width over the 25 year period. But the pools have been infilled to varying degrees. Mt Hardy Pool and Burlong Pool have completely filled, and Burlong has since been used as a sand quarry. (Burlong Pool is shown in Plate 2b). In 1985, Cold Harbour and Egoline pools were also reduced in length by 80% due to sediment infilling. Similarly, Muresk Pool was reduced by approximately 40% and by January 1990 was no longer sufficiently deep to remain as a pool during summer.

It is clear from the aerial photographs, that Brouns Pool, Fleays Pool, Gwambygine Pool, York Pool, Three Mile Pool, Mears Five Mile Pool, Tipperary Pool and Millards Pool did not alter significantly in length. The remainder were reduced in length by 5-13%, excepting Egoline. Burlong and Mt Hardy were the first pools to fill, and it is significant that the channel distance between each pool and the next respective upstream pool, was the second and third longest pool to pool distance. The longest distance is between Northam and Egoline Pools. Egoline appears approximately 80% filled in 1985 (Northam Pool is maintained by a weir which prevents sediment from upstream moving into the Egoline stretch. Sediment deposited in Egoline is entirely from the region between Northam and Egoline, whereas sediment deposited in Burlong and Mt Hardy Pools can, in theory, originate from any point upstream).

A frequently observed effect of channelization has been the rapid widening of the channel. At present, channel widening does not appear to have been a major response of the Avon River. Localized bank erosion of the Avon River was evident from field work, surveyed cross-sections, and a ground photograph survey (WAWA 1983). Erosion occurred in areas where the banks were largely clear of vegetation. Plate 5 shows Gwambygine Pool with little bank vegetation remaining. Erosion of the bank is quite evident. Once the few remaining trees are removed, or undermined, there will be no protection for the bank.

The most severe bank erosion occurred at Lloyd Pool, (up stream from Toodyay). Despite a 5 - 10 m thick tree line, flow has eroded the channel to a depth of over 1.5m (Plate 6a). Bank erosion at Lloyd Pool appears to result from some form of cantilever failure, (as defined by Thorne & Tovey 1981), where the base of the bank has eroded, leaving an overhanging upper edge. The upper layer is strengthened by the presence of root systems, but eventually collapses. This process has undermined the surrounding trees, as seen in Plate 6b. Neither Plate 5 nor Plate 6 show any significant build up of bank material at the base of the banks, suggesting that flow is of sufficient strength to continually remove the sediment.

Plate 5: Erosion of the east bank at Gwambygine Pool

Plate 6a: Bank erosion of the west bank at Lloyd Pool.

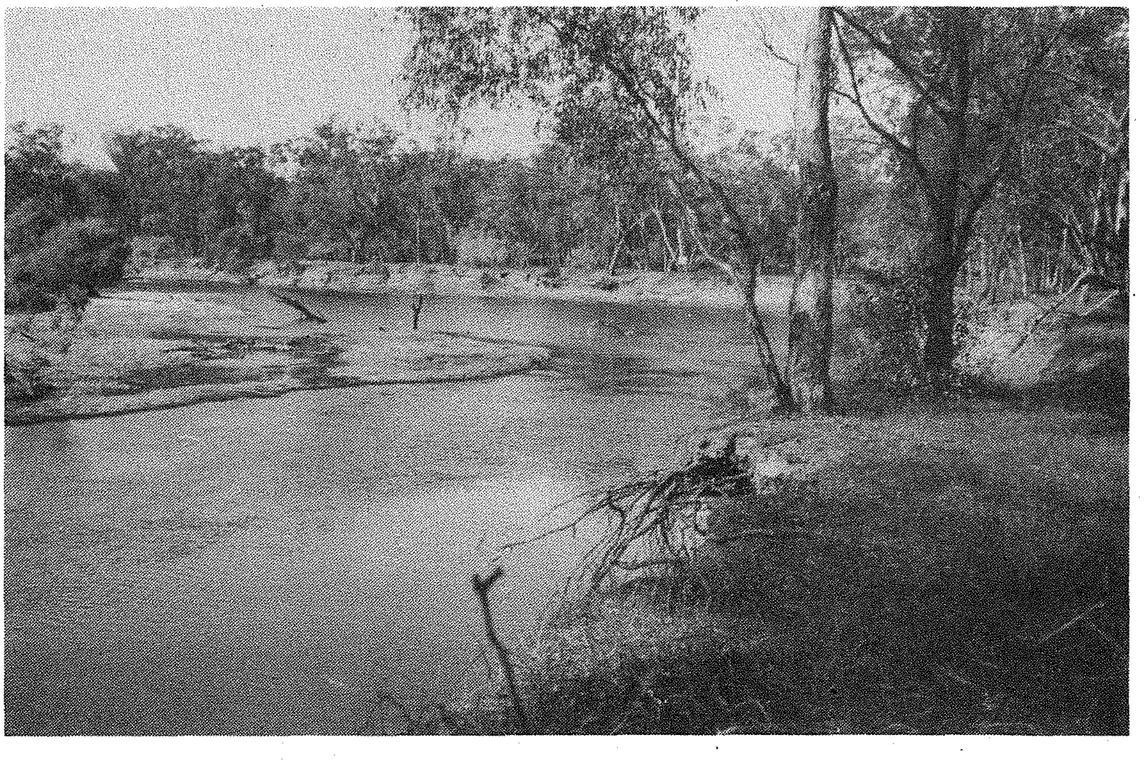


Plate 6b: Bank erosion undermining trees at Lloyd Pool.

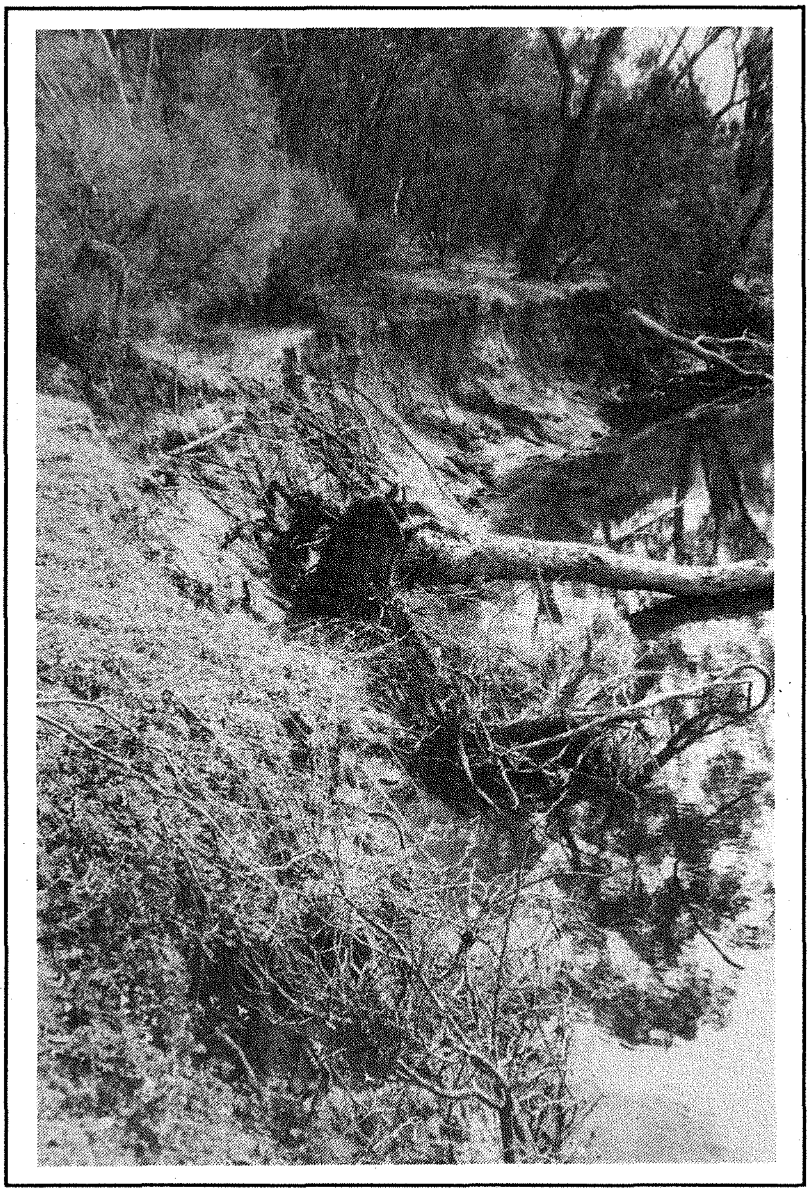


FIGURE 3 Calculation of Net Scour for Cross Section 4.

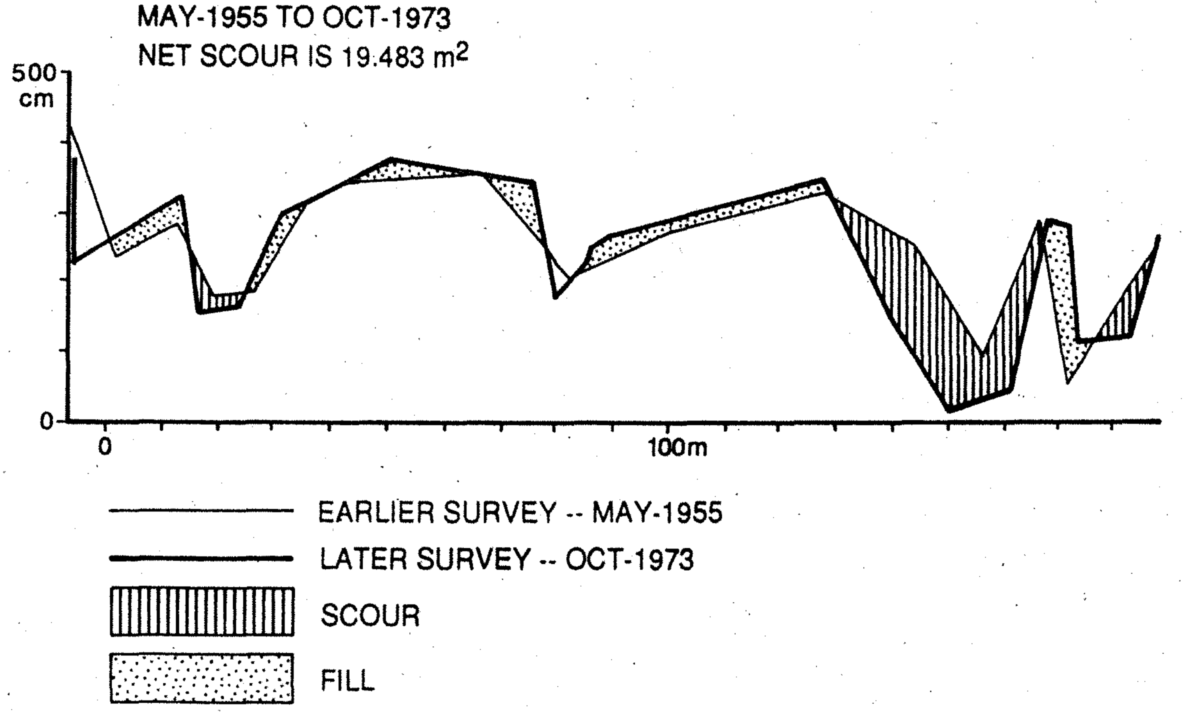
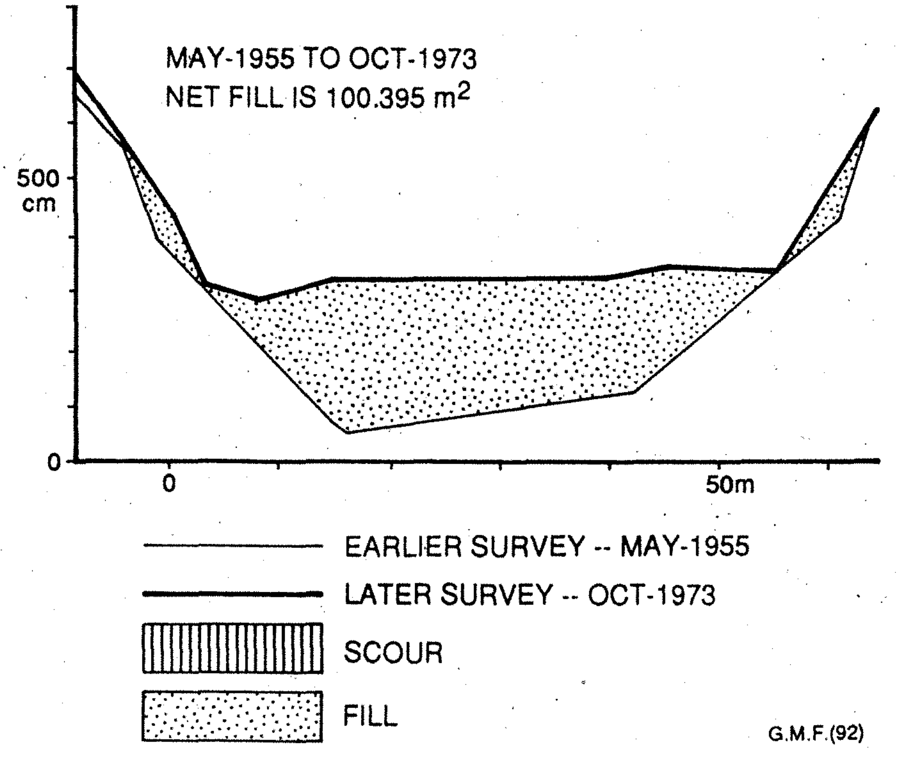


FIGURE 3 Calculation of Net Fill for Cross section 13.



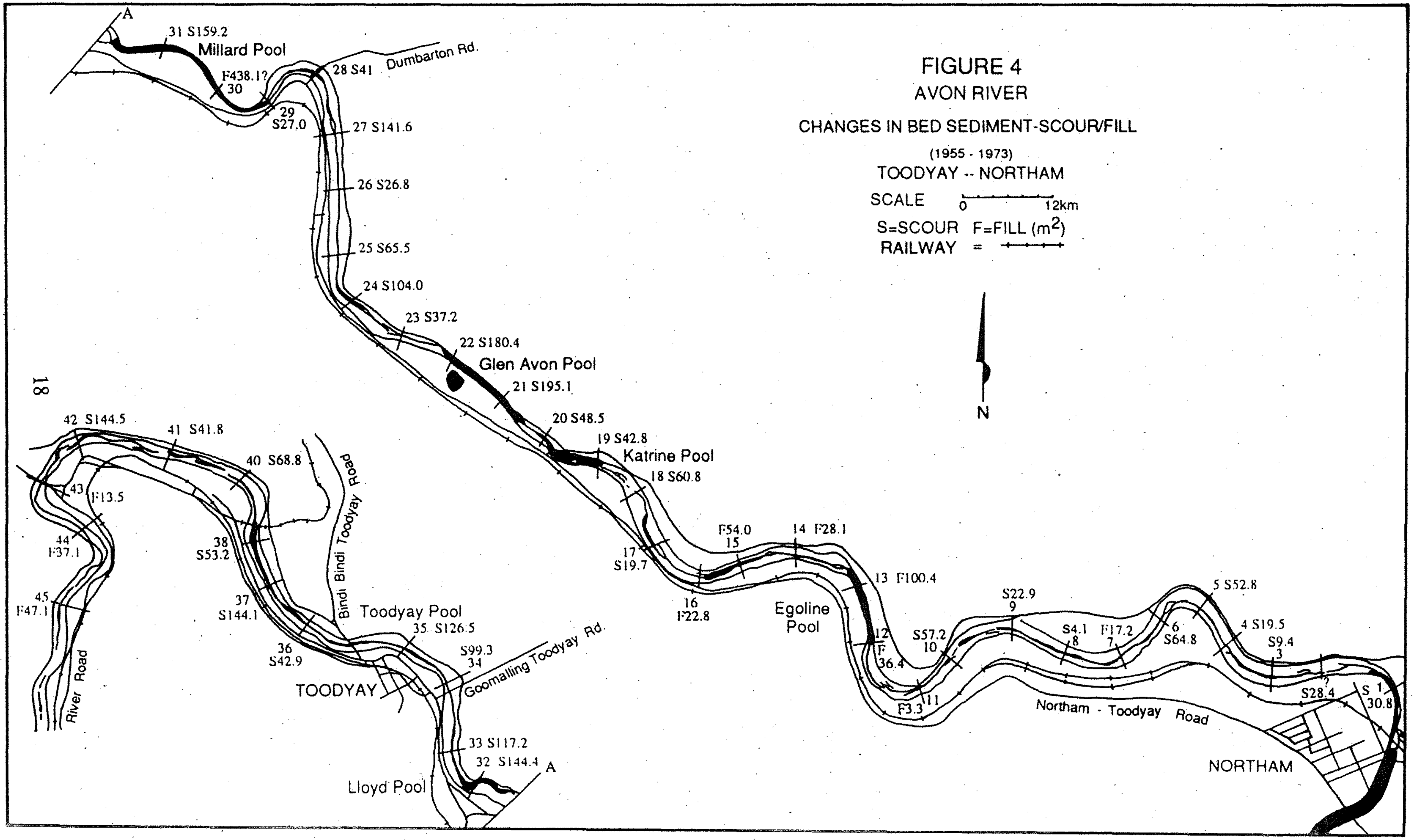


FIGURE 4
AVON RIVER
CHANGES IN BED SEDIMENT-SCOUR/FILL
(1955 - 1973)
TOODYAY -- NORTHAM

G.M.F.(92)

Pickup & Warner (1976) have suggested that while moderate flows do most of the work of redistributing sediment along the channel, they are not primarily responsible for bank erosion. Only the larger flows, which are able to saturate a greater proportion of the bank, cause bank collapse. Much of the erosion observed along the Avon was above the winter flow level, indicating that erosion may have occurred during the floods of 1983 and 1990. Bank erosion of the Avon River urgently requires further investigation, and this must focus on the mechanics of bank failure.

The cross-sectional volume changes resultant from channelization were calculated using a computer routine. Figure 3 shows the extent of scour and fill in some representative cross-sections. The compiled results for the cross-sections surveyed are shown in Figure 4. Generally, the cross-sections show that since training, a significant amount of channel scour has occurred throughout the formerly braided channel reaches. Deposition is clearly indicated in Egoline Pool and field observations make it clear that many other pools have also been affected. Deposition was also recorded within central Toodyay and over a distance of approximately 2.4km downstream of the Chittering Bridge (downstream of Toodyay).

The results of the channel cross-section analysis were compared with the WAWA ground survey (1983) and aerial photographs (1985). The most significant association was found between sediment volumes and vegetation. Larger bars and some localized bed elevations were vegetated, mainly with samphire, but occasionally with shrubs and small trees. The vegetation both trapped and stabilized sediment.

It is clear from the sediment characteristics of the infilled pools, that the pools have been filled by bedload sediments. But questions as to the ultimate source of the sediments remain. The obvious sources are channel sediment bodies that have been mobilized through channelization. However, suggestions have been made that higher catchment sediment yields are partly responsible. At present the actual rates of bedload transport are not known and no work has been undertaken on the sediment yield characteristics of potential catchment sources.

It is to be expected that if sediment infill of the pools originated in the channel immediately upstream of the pool, an indication of the amount of fill would bear some resemblance to the volumes of sediment eroded from the upstream channel reach. To ascertain this, the reach between Northam Pool and Egoline Pool was used because (i) Egoline Pool was the only pool to be surveyed for depth in 1955, allowing amounts of fill to be determined, and (ii) the Northam Pool is maintained by Northam weir, and it seems likely that this structure effectively stops most of the sediment from passing through Northam and into the Egoline pool. Any sediment deposited within the Egoline stretch may largely originate from within the channel or from adjacent land.

Along this channel reach, cross-sections 1 to 10 (excluding section 7) show a net scour, while cross sections 7 and 11 to 16 show a net fill. While these data are clearly insufficient to undertake an accurate mass balance determination, they suggest that the volume of sediment deposited in Egoline Pool, relates to the volume of sediment eroded from the upstream channel reach. Again, more work needs to be undertaken to confirm or refute this conclusion.

In summary, it is clear that channelization has changed the river from a well vegetated, partially braided channel, to an open singular mobile channel. Much of the sediment released has been deposited in pool regions, or is moving as `sand plugs' along the channel. Scour of the bed has been a dominant response, while channel widening does not appear as important. There was no apparent change in the sinuosity of the channel.

4.0 SIMULATION OF CHANNEL CHANGES.

The HEC-6 model (US Army Corp of Engineers, 1977) was used to simulate the long-term channel changes of the Avon River and address the question of whether, with time, the pools could re-establish themselves. A good overall discussion of the uses and limitations of this model are given by Thomas (1982) and Pickup (1988).

The model requires specified channel cross-sections and uses Manning `n' values for measures of hydraulic roughness. These data are combined to calculate water surface profiles. Sediment data incorporates the amount of inflowing sediment in relation to water discharge, and the size distributions are identified by percentage of sediment in each size category (A summary of the sediment size characteristics are given in Figure 5 and Table 2). Transport capacity is then calculated for each cross section, dependent on specified water discharge and flow duration.
The basic flow equations used by the model are the equation of motion for water:

$$\frac{\partial h}{\partial x} + \frac{\partial (\alpha u^2 / 2g)}{\partial x} = S_f \qquad (4)$$

the continuity equation for water:

$$Q = uA + Q_l \qquad (5)$$

and the Manning resistance equation (Equation 1). The model uses the sediment continuity equation (Equation 2) to model channel aggradation/degradation . Sediment transport (G) is defined in the model as a function of:

$$G = fn(u, h, s_f, W_b, D_{eff}, T, D_{si}, P_i) \qquad (6)$$

The model uses two sediment transport equations, or allows the user to define their own. The equations used by the model are Toffaleti's application of Einstein's bedload function, and Laursen's relationship as modified by Madden. The total sediment transport is calculated by summing the separate transport rates of each size class, according to the proportion of that size in the total sample. Einstein's equation was considered most applicable for the study and consequently Toffaleti's (1966) modification of Einstein's (1950) procedure was used.

A major limitation associated with the use of the model was that the channel width must be defined for each cross - section, and after definition, remain constant throughout the simulation. The model moves the bed vertically over the entire defined width. Where the channel is actively widening, or where the channel cross-section has been modified, this will result in errors.

The Avon River width can be defined by (i) the entire channel width including the vegetated borders, the latter only affected during large flows, and (ii) the central cleared region, exposed annually to flow. Differential hydraulic conditions across the channel will cause differences in sediment transport.

FIGURE 5 STANDARD DEVIATION AGAINST MEAN SEDIMENT SIZE

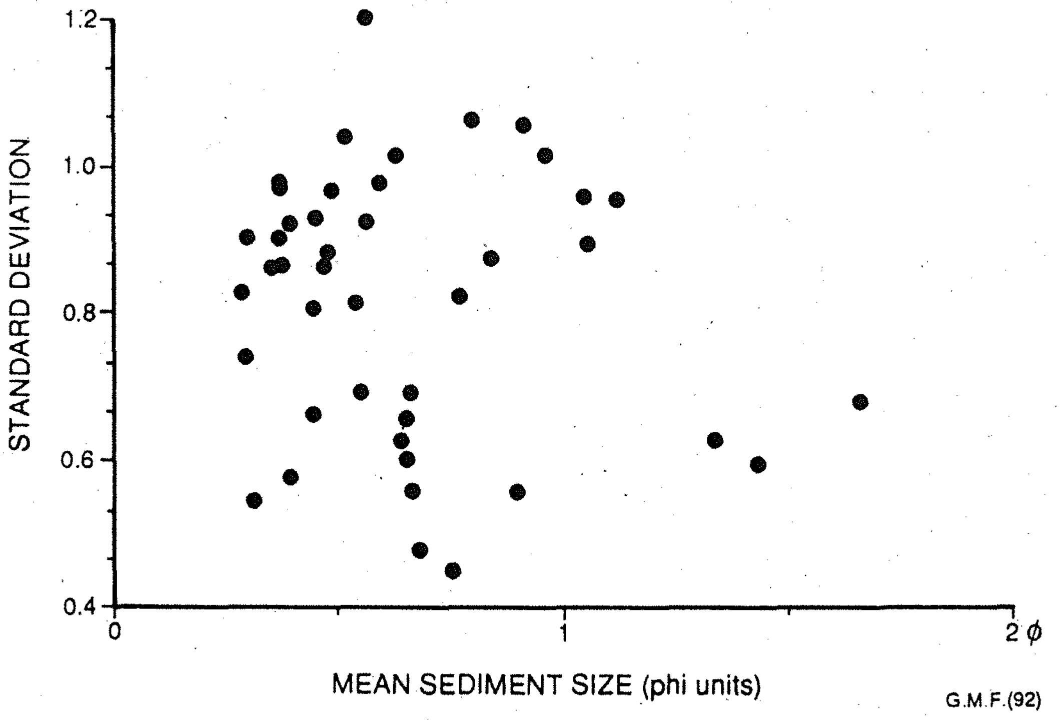


TABLE 2. AVERAGE SEDIMENT SIZES FOR THE AVON RIVER (PHI UNITS).

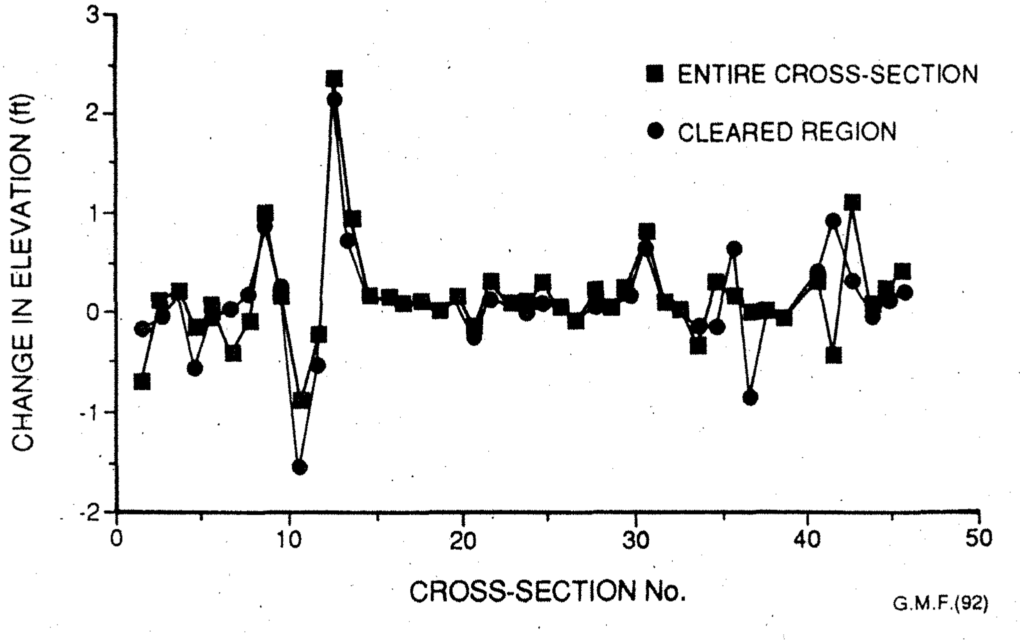
d^{25}	d^{50}	d^{75}	d^{84}
0.045 ± 0.410	0.586 ± 0.343	1.131 ± 0.306	1.400 ± 0.326

TABLE 3. FLOOD HEIGHTS AND DISCHARGES.

YEAR	B&P	PWD	DISCHARGE (m^3/s)	
1917	148.22	148.25	1010.7 - 1033.8	
1926	148.25	148.26	1033.8 - 1041.5	
1930		147.44	492.6	
1932		146.6	124.4	
1945	147.84	147.85	738.4 - 745.1	
1955	148.31_F	147.56_S	1080.6_F	560.9_S
1963	147.77		692.34	
1974	147.4		470.45	
1983	147.18		356.4	372_{obs}

All values in Meters
$_{obs}$ = Observed Value
$_F$ = February, $_S$ = September

FIGURE 6 SIMULATED CHANGE IN CHANNEL ELEVATION FOR THE PERIOD 1955-1973.



The model is unable to reproduce detailed local variations, but is capable of reproducing general trends. This may be useful for the prediction of long term adjustments (Pickup, 1988). The large data requirements of the model are frequently difficult to meet and the accuracy of predictions will reflect the amount of input data available. Where data is lacking, default values can be used in order to run the simulation.

The major deficiency of routing models, as stressed by Pickup, is the inability of the model to accommodate large increases in sediment load. In the case of the Avon River, this is very important, as the removal of vegetation produced a very large sediment input into the channel system. This limitation reduces the reliability which can be placed on model output. Model results should therefore be considered as indicative of possible trends - no more!.

The previous sections of this report have discussed most of the input data used by the HEC-6 model. Geometric data was comprised of the channel cross-sections of 1955 (as these show the original distribution of sediment), estimates of the Manning roughness coefficient, and definition of the width of movable bed. Sediment data was extracted from a comprehensive analysis of channel sediment. Categories applicable for sand sized sediment were used. Sediment depth was unknown so an arbitrary value (the default value of the model) of 10ft (3m) was assigned (HEC-6 uses Imperial units).

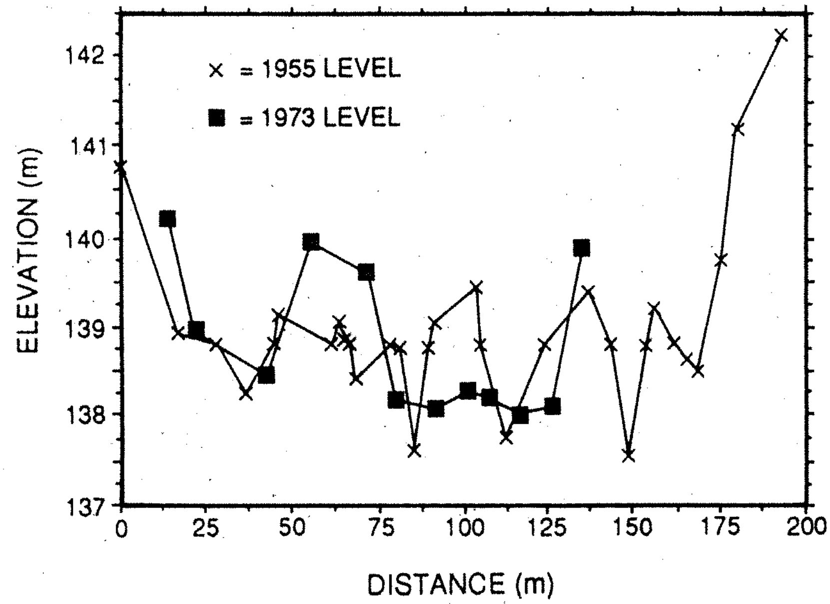
The model requires a discharge rating curve at the downstream boundary of the profile to calculated water elevations, upstream. There is no gauging station at Toodyay, so that no rating curve was available. Binnie & Partners (1985), have simulated flows for Toodyay. Their results show that discharge is approximately 1.3 times greater at Toodyay, than at Northam.Data from Northam was converted by this factor to provide estimates of discharge at Toodyay.

Two water elevations and discharges were recorded at Toodyay during the 1983 flood (Binnie & Partners 1985), and were used to construct a regression curve from which water elevations for the estimated discharge could be determined. Average monthly flows from the Water Authority record at Northam were used and flood discharges were extracted from Table 3.

5.0 USING THE HEC-6 MODEL TO EVALUATE HISTORICAL CHANNEL CHANGES

The model was initially run to determine if it could simulate the changes documented between 1955 and 1973. In order to achieve this, the 1955 cross-sections were used. The movable bed width was defined firstly, over the entire channel width (to the limits of the vegetation) and secondly, forthe cleared channel width only. During this period, floods occurred in 1956 and 1963. These were simulated, and average winter flows were used for the remaining years. The final changes in elevation produced by the model are shown in Figure 6. The first curve is for the entire movable channel width, and the second for the limited bed width. Negative values indicate channel scour and positive values, channel fill. The second simulation exaggerated the extremes, and smoothed the smaller variations. (The differences at the end of the graph are due to error in data input).

FIGURE 7 CHANGE IN BED ELEVATION FOR THE PERIOD 1955-1973 AT CROSS SECTION 11.



SIMULATED CHANGE IN BED ELEVATION FOR CROSS SECTION 11.

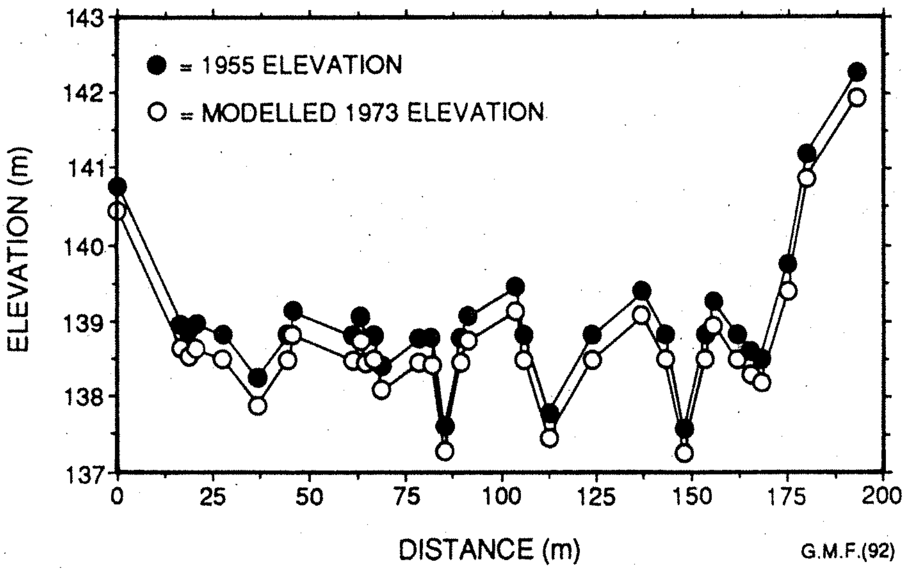


FIGURE 8 CHANGE IN BED ELEVATION DURING A LOW MAGNITUDE FLOOD

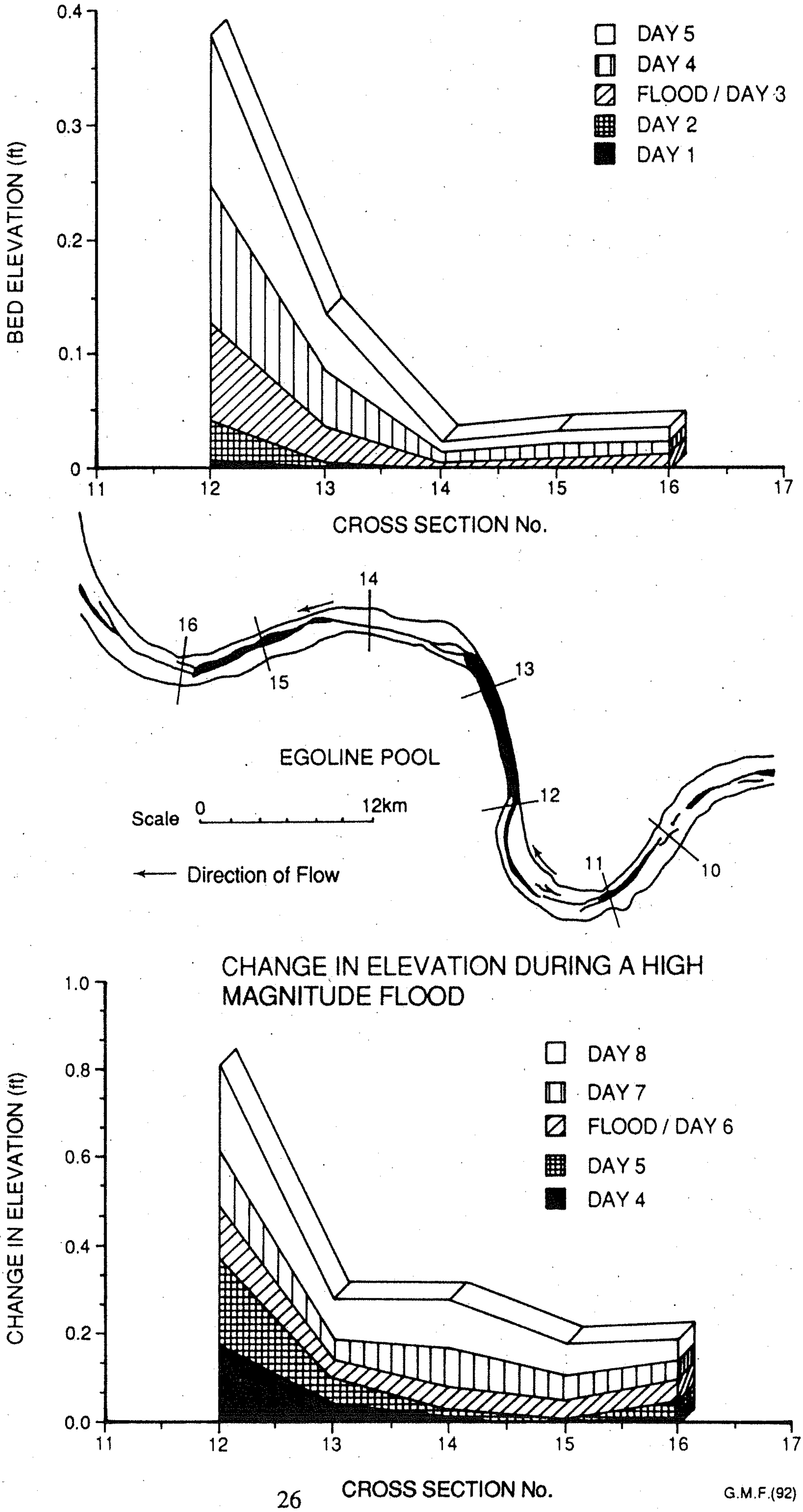
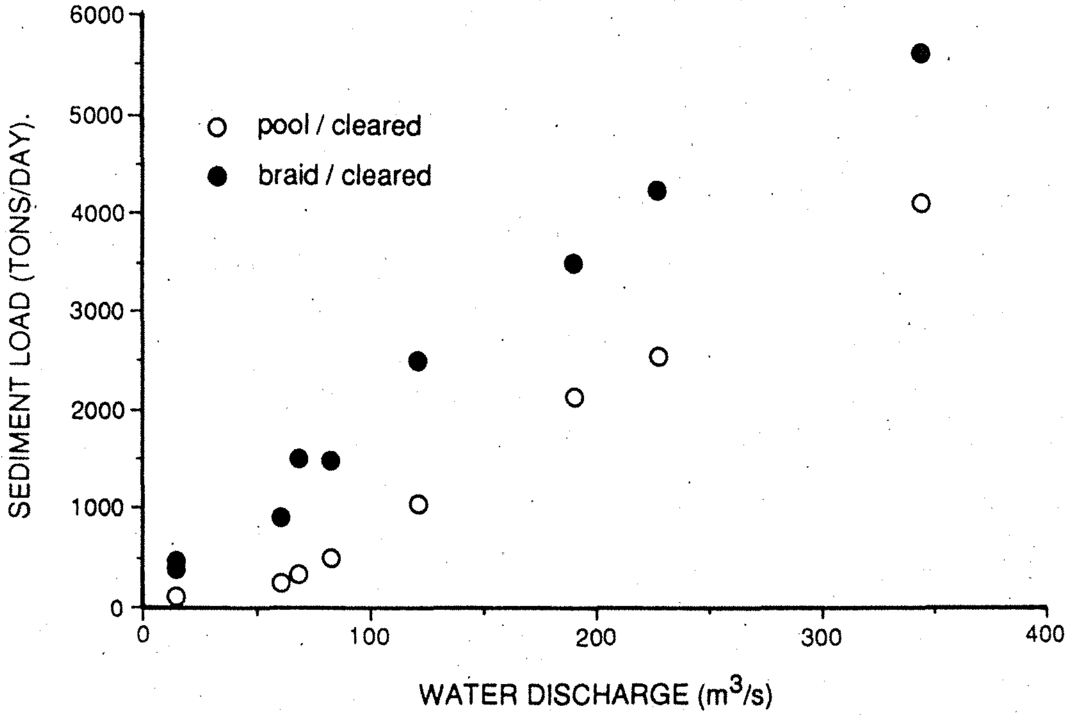
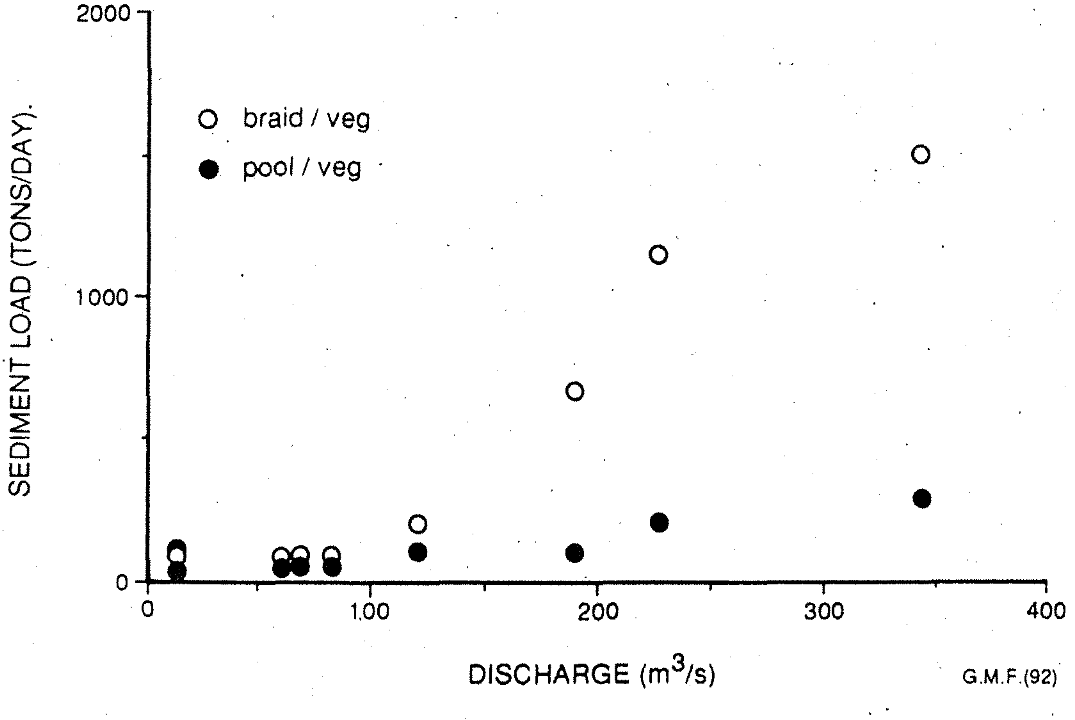


FIGURE 9 CHANGES IN SEDIMENT LOAD WITH DISCHARGE SIMULATED FOR A CLEARED CHANNEL.



CHANGES IN SEDIMENT LOAD WITH DISCHARGE SIMULATED FOR A VEGETATED CHANNEL



The bed elevation changes simulated for the first twenty cross-sections compare relatively well with actual changes. Fill is indicated for sections 12 - 15 (Egoline Pool), and scour is shown upstream of this. Pool depths were not surveyed for the remaining sections. There is clearly less correspondence between the figures after Section 20 and this is likely to reflect stream planform differences.
As is to be expected from the constraints placed on the model, calculations of scour or fill for individual cross-sections do not correlate well with actual volume changes. This problem is illustrated in Figure 7 which compares the actual and simulated changes for Cross-section 11. The difference in the two cross-sections shown in this figure is marked, with the model simply displacing the entire channel bed vertically. This is a general limitation of the model, but one which does not invalidate its use in determining spatial trends in the channel response over prescribed channel lengths.

5.1 Patterns of pool fill and sediment loads.

Some indications of the patterns of fill in Egoline Pool, caused by a low and high magnitude flood, were obtained with the model. Flow records of the 1983 flood at Northam were adjusted for Toodyay, and a low magnitude flood simulated for 10 days. The five days covering the flood peak are shown in Figure 8. Simulation produced small amounts of deposition prior to the flood peak, with the majority deposited during and after the flood. Deposition occurred at the up stream end of the pool (sections 12 & 13). Over a series of events, sediment could progressively fill the pool. Simulation of a high magnitude flood resulted in a similar pattern of fill (the 1926 flood was used). The amount of fill is greater (Figure 8), particularly for the downstream cross-sections 14 & 15.

The model calculates the sediment load at each cross-section, dependent on discharge. As a range of discharge was used (i.e. from monthly averages to flood peaks), a water - sediment discharge graph could be drawn (Figure 9). As the sediment load through pools was significantly less than sediment load over a braided region, the two were considered separately (here a braided region refers to the channel reach between pools).

The sediment load of average winter flow varied from 0 - ≈ 455 tons/day for a braided region, and 0 - ≈ 54 tons/day through a pool section. As the magnitude of the event increased, the difference in sediment transport between pools and braids decreased. The ten year event produced loads of ≈8 000 tons/day and ≈ 5 000 tons/day, and the twenty five year event - ≈ 12 000 tons/day and ≈8 500 tons/day for braided reaches and pools, respectively. These results were compared to a simulation of a totally vegetated channel, as was the case prior to clearing. The simulation showed much smaller sediment loads, particularly for lower discharges (Figure 9). Sediment load increased with discharge, but not to the same extent as for the cleared channel. The rate of sediment loads over braids was again clearly greater than that through pools.

The model results indicate that since clearing, the sediment loads for both pools and riffles have increased, with the proportion of sediment entering a pool, being far greater than the proportion leaving the pool. Consequently, although rates of sediment movement are greater, much of the sediment moving into the pool does not move out, and pool fill has resulted.

					simulations			
		Original	LM Flood	HM Flood	LM / Orig Veg	LM / Total Veg	HM / Total Veg	50 year
1		+	-1.84	-3.04	?-0.30	?-0.27	-0.85	-4.17
2		+	-0.85	-1.06	0.02	0.03	0.16	-1.59
3		+	0.57	0.51	0.08	0.07	0.16	-0.24
4		+	-2.69	-1.45	-0.02	-0.01	-0.09	-2.98
5		+	-1.19	-1.46	-0.12	-0.12	0.02	-1.79
6		+	-1.14	-1.81	-0.30	-0.30	?-0.35	-1.91
7		+	0.64	-0.08	0.43	0.44	0.44	0.51
8		+	2.76	3.05	-0.01	-0.01	0.01	2.71
9		+	1.56	1.51	0.00	0.01	-0.14	1.60
10		+	?-4.41	?-4.73	?-3.71	?-3.03	-2.14	?-4.86
11		+	0.77	0.48	2.44	3.19	2.40	0.17
12	Egoline	-	-3.56	-2.90	-3.61	-0.76	-0.96	-3.69
13		-	-1.77	-2.14	-5.06	-4.80	-4.89	-5.03
14		-	6.49	6.56	6.19	4.27	4.31	9.90
15		-	-0.02	0.22	-0.02	0.08	0.03	0.89
16		+	0.19	0.37	0.42	0.07	0.40	0.62
17		+	0.09	0.24	0.01	0.01	0.01	0.50
18		+	-0.35	-0.42	-0.03	-0.02	-0.28	-0.76
19	Katrine	-	0.04	-0.05	-0.22	-0.02	-0.13	-0.34
20		+	?-1.63	-2.19	0.10	-0.14	-0.15	-2.31
21	Glen Avon	-	0.78	-0.09	-0.42	-0.25	-0.36	-0.44
22		-	-0.81	-0.89	-0.05	-0.17	-0.21	-2.78
23		+	-1.80	0.02	0.77	0.65	0.92	-2.68
24		+	-1.28	-0.43	-0.19	-0.18	-0.04	-1.81
25		+	-0.15	-0.93	-0.15	-0.06	-0.14	-1.67
26		+	-0.04	-1.17	0.41	0.36	0.58	-0.07
27		+	0.54	0.09	-0.19	-0.08	?-0.22	1.64
28		+	0.72	0.88	-0.05	0.01	0.04	2.07
29	Millard	-	0.77	0.61	-0.52	-0.17	-0.58	1.78
30		-	2.48	2.12	0.41	-0.01	-0.37	4.15
31		-	-0.20	-0.42	-0.09	0.01	0.14	-0.67
32		+	-0.99	-1.32	-0.11	?-0.88	?-1.85	-0.73
33	Lloyd	–	-0.91	-0.94	0.68	0.55	1.07	-0.82
34		+	-0.32	0.39	?-0.56	?-0.58	?-0.45	3.31
35		+	2.79	3.26	0.71	0.67	0.88	5.22
36		+	-3.57	-4.76	-0.28	-0.28	-0.28	-5.15
37		+	-0.85	-0.16	-0.22	-0.22	-0.21	-1.87
38		+	-0.79	-1.33	0.08	0.08	0.18	-1.52
39		+	0.82	-0.53	0.11	0.11	0.09	0.25
40		+	2.34	2.09	0.01	0.01	?-0.23	2.74
41		+	2.97	11.63	0.52	0.52	1.08	?-2.31
42		+	?-1.16	?-2.31	?-0.20	?-0.20	-0.20	0.14
43		+	0.31	0.39	0.00	0.00	-0.02	1.63
44		+	0.57	0.92	0.03	0.03	0.06	

TABLE 4. RESULTS OF HEC - 6 SIMULATIONS.

ACTUAL POOLS

SIMULATED 'POOLS'

? POSSIBLE POOL

The model results suggest that only events with return periods in excess of 30 years can scour pools. Since clearing, the largest flood has been in the range of a ten year event (as that of 1983), or if the 1963 flood is considered (for the Northam - Toodyay reach), approximately a 20 year return event. According to these calculations much of the sediment transported will have been deposited in pools. Without the occurrence of high magnitude discharge events or channel revegetation and continuing sediment supply, fill can be expected to continue for all pools.

5.2 Simulation of future changes in the channel.

The use of the model was extended to establish if filled pools would rescour and/or new pools form. Pool depths were reduced in these simulations to approximate "filled" pools. The pool sections from Egoline Pool were adjusted to mean section height, but the other pool sections were not adjusted as they had not been originally surveyed for depth.

The first simulation was run for a twenty year period. According to historical record, two floods are likely to occur during this period. Two low magnitude (LM) floods were used, as flood trends did not suggest increasing flood magnitudes. Monthly average discharges were used for the winter months of the remaining years. The results of this simulation can be seen in Table 4 (LM simulation). A string of negative numbers was considered to indicate a possible region of pool development. Scour (negative numbers) overlapped with the current pool positions - the upstream end of Egoline Pool, and the downstream ends of Glen Avon and Millards Pool. Pool formation was suggested both up stream of Egoline and down stream of Lloyds Pool (sections 4 - 6 and 36 - 38). Question marks were used to indicate possible smaller pools.

A second series of simulations were undertaken using the high magnitude (HM) flood level estimates of the 1926 flood. The results (Table 4) indicate a very similar pattern of pool distribution, but also produced a pool covering the Katrine - Glen Avon reach. The current channel contains a great deal of water in this area. Pools upstream of Egoline and downstream of Lloyd Pools are again produced and `question marks' correspond to a series of relatively closely spaced pools.

A 50 year simulation was performed using four low magnitude events and one high magnitude event. The simulation results (Table 4) echo the results of the high magnitude flood simulation. Two very large pools were located over the first six sections and between sections 18 - 26. In reality, the development of the first pool would be constrained by Northam Weir. Sections 12 &13
have scoured with significant deposition immediatelydownstream. The cross-sections and aerial photographs show that the channel width is less than half the average width at this point. (This is the current position of Egoline Pool which occurs in a channel constriction). The preceding simulations have all assumed that there will be no revegetation of the channel. However, it is apparent that the survival of the remaining pools is dependent on reducing sediment mobility; this can be achieved most directly by channel revegetation.

Three further simulations were made to explore the effect of vegetation on pool formation. The first simulation attempted to artificially recreate present pools by vegetating the regions between the original pools. This simulation produced pools in almost the exact locations of the present pools, which is hardly surprising! But it is encouraging, as it indicates there may be some possibility of the long term redevelopment of pools. Pearce (1987) also reached a similar conclusion based on flume results for the Northam Pool, i.e. the pool could scour again if incoming sediment was retained upstream. The same conclusion can be obtained from Equation 3.

Two further simulations were conducted with the entire channel revegetated, for both low magnitude flood events and high magnitude flood events. The results approximate each other (Table 4), with the main difference being the greater depth of scour which occurred for the high magnitude simulation. These simulations did not alter the locations of `possible pools'.

The simulation runs have shown that, in the long-term, the river may be able to scour pools. The deepest pools are a product of the higher magnitude events. Pool depth was also dependent on the length of time for which the simulation was run, the longer simulations producing the deeper pools. Revegetation of the channel reduced bedload movement throughout the channel. All simulations indicated that a number of smaller pools may develop between the larger pools. But these "additional pools" are artifacts of the model, and result from the changes in channel geometry as a consequence of channelization. The possibility of these pools forming in reality is constrained by bank stability and channel substrate controls.

6.0 CONCLUSIONS.

It is clear that the clearing of channel vegetation has had major detrimental effects on stream channel characteristics and function. It is known from fluvial geomorphology, that given time, streams can accommodate changes in water and sediment discharge. So given the present channel characteristics, in the the long term, and without further "simple" engineering modifications, the stream can enter a new " equilibrium" state in which pools may well re-establish themselves. But this gives little solace to the environmental manager. Given the discharge regime of the Avon River, the time-scale over which this adjustment would take place is likely to be large, well exceeding management time-frames. Furthermore, the wider catchment changes in hydrology, sediment yield and water chemistry are additional factors which need to be considered when inferring future stream function and ecological status.

Given the present state of the river, it would seem desirable that some attempt be made at a partial restoration of the natural channel characteristics. But any attempt at this would be frustrated by the lack of data on fluvial mechanics, the rudimentary understanding of likely geomorphological controls of channel characteristics and the absence of sediment transport/sediment yield data. All these gaps in our knowledge need to be filled before a thorough understanding of the functioning of the Avon River can be obtained and before any future modification of channel morphology is attempted.

Finally, we stress that this report represents no more than an exploratory study of the problem and that the inferences drawn in this work must be treated with reserve.

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APPENDIX 1 : List of Symbols

n	=	Manning roughness coefficient,
z	=	elevation of the bed above datum
l	=	porosity of the sediments.
α	=	velocity distribution coefficient
A	=	channel area
g	=	acceleration of gravity
h	=	flow depth
n	=	Mannings roughness coefficient.
Q	=	discharge
Q_l	=	tributary inflow
R	=	hydraulic radius
S	=	slope
u	=	velocity
x	=	distance
W	=	bed width
q	=	lateral inflow of sediment from tributaries
G	=	sediment transport rate by weight
h	=	effective flow depth
D_{eff}	=	effective grain size of sediment in class `i'
T	=	water temperature
D_{si}	=	geometric mean of a grain size class interval i
P_i	=	percentage of a particular grain size class in the sediment surface layer.