THE GEOMORPHOLOGICAL IMPACTS OF IMPOUNDMENTS, WITH PARTICULAR REFERENCE TO TRIBUTARY BAR DEVELOPMENT ON THE KEISKAMMA RIVER, EASTERN CAPE.

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Abstract

The primary aim of this research was to develop and test a conceptual model of the geomorphological impacts of river regulation, based on a review of relevant international literature. It was motivated by the fact that there is very little local information on the topic, and it was intended that the model might provide a starting point for assessing the impact of impoundments on South African river systems. At present most research in South Africa on the impact of impoundments is undertaken from an ecological perspective.

In order to manage our water resources sustainably it is necessary to have a better understanding of our river systems. South Africa is characterised by a variable climatic regime and, in order to supply water to the various user sectors of the nation, dams have to be larger than elsewhere in the world, to trap most of the mean annual runoff and provide a reliable water store (Alexander,1985). South African dams have been designed to reduce the variability of a naturally variable regime. The impact of flow regulation in dryland rivers has been described as 'ecologically catastrophic at every level.' It is therefore hardly surprising that the impact of these dams on the natural functioning of rivers is substantial.

The conceptual model showed that there are many responses to river impoundment, which are varied and complex, both in time and space. Responses or secondary impacts depended on the nature and degree of the primary impact or process alteration, on the sediment and flow regime of the river. High flows were affected in all cases and low flows were affected in most cases. The simplest form of change was Petts' (1979) concept of 'accommodation' of the regulated flow within the existing channel form. More complex responses occurred where the channel perimeter was unstable, or where tributaries introduced fresh sediment loads. The river could adjust its long profile, cross sectional area and substrate composition by aggradation or degradation.

The conceptual model was used in the Building Block Methodology to predict impoundment impacts at Instream Flow Requirement workshops on the Berg, Komati and Bivane rivers. It was also used in assessing the impact of the Sandile Dam on the Keiskamma river. Tributary junctions were identified as likely sites of change, and the morphology of bars at these junctions was investigated. Due to the number of variables affecting the sediment and flow regime in the system, and due to the fact that the primary impacts were not substantial, it was not possible to come to any decisive conclusions. It would seem that the dam is well located in the catchment, and, because the water is not heavily utilised, the secondary impacts are not great.

The conceptual model was found to be a useful basic tool which might contribute to a better understanding of our river systems, and ultimately to improved sustainable resource management.

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CHAPTER ONE

MAN AND WATER

1.1 Mans association with water

The environment responds in a complex manner to human activities. It is not possible to optimize resource use and development without a thorough understanding of all the complex relationships between the components of environmental systems, as they occur in space and over time.

Man has always sought to control the natural world. His development through the ages has depended on his ability to use natural resources to his advantage. Water has been inextricably linked to his development in some form or another, being used for religious purposes, agriculture, transport, trade, war and recreation. The remains of the oldest hominids were found at Lake Turkana, North Africa, in association with an ancient water body. Man has manipulated this single element in many simple and complex ways, from the simple furrow-fed terrace agriculture of the Chinese and Indian cultures, which remains unchanged over centuries, to the sophisticated hydro-electric power schemes of the modern Western world. In the ancient world great civilisations flourished on the fertile flood plains of major rivers. The Egyptian dynasties were sustained by the fertile floodplain of the Nile for centuries. The empire of Mesopotamia developed on the banks of the Tigris and the Euphrates where major irrigation works were undertaken in the 4th millennium BC (Hellier, 1990) and even today, despite the heavy utilisation of the river for many purposes by several nations, plans are afoot to further harness its potential. According to Hellier (1990), current water development plans on the Euphrates will reduce it's 30 billion m^3 average annual flow by between 40 and 70% due to evaporation and abstraction.

In order to supply quantities of potable water to an increasing populus and give some assurance of supply through the wet and dry season, it became necessary to store water. The worlds oldest known dam was a masonry structure, 49 ft (16m) high, built in 2900BC on the Nile at Kosheish in Egypt. The Assyrians, Babylonians and Persians built many dams in the period 700-250BC for water supply and irrigation. One of their dams, built in present day Syria around 1300BC, is the oldest dam still in use. South Africa's water development history may be traced back to the 17th century, when the 2000m^3 Waegenaars dam built by the Dutch East India Company supplied fresh water to ships calling in at the Cape. It is ironic that the original settlement of this country can be said to have been for water supplies, but today a shortage of this resource is one of the most pressing problems facing the country and a major limiting factor to economic development.

'Big' dam building is a feature of the 20th century. According to Beaumont (1978) from a study of the World Register of dams (1973), the greatest number of dams were built in the 19th century in Western Europe. In North America, South East Asia and Japan, and southern Africa, there was intense big dam building activity before, and then after the 2nd World War. In these areas it was dominated by particular countries - the USA, India, Japan and South Africa respectively. Western Europe also saw much development, but the projects were spread amongst many countries. In a world wide survey, Beaumont (1978) found that in Africa and North America reservoirs trapped 20% of those areas available runoff, while in Europe and Asia, they capture 14 and 15% respectively. An assessment of regulated central European rivers by de Coursey (1975), cited in Petts (1979), showed a 20% reduction in the magnitude of the 50 year flood and a reduction of 25% for the mean annual flood due to reservoir construction. In South Africa, reservoirs control 50% of the available runoff. These figures serve to highlight the degree of control world wide which man exerts over our water resources. They point to the fact that dam building must have had a significant impact on the natural functioning of river systems, particularly in terms of runoff, and the control of discharge in the last century.

It is evident that the habits of men and the forms of their social organisations have been influenced by their close association with water. Yet, vital as water is to our existence it is possibly the single most abused natural resource on this earth. Modern civilization makes heavy demands on water resources: manufacturing, mining, power generation, domestic users and agriculture all consume and pollute vast quantities of water because it is a seemingly abundant, cheap and renewable resource in many parts of the world. Development and growth have occurred despite water shortages or imbalances in the distribution of resources. Engineering feats - the building of vast reservoirs, and the construction of water transfer schemes across watersheds has enabled the transfer of water from where it is abundant to regions where it is not. In South Africa, the industrial heartland of Gauteng province has flourished despite the lack of naturally occurring water resources - complex interbasin transfer schemes have ameliorated the problem for the present.

The geomorphological functioning of a river system is the basis on which all the other components of a river depend: it is the relationship between the flow of water and the movement of sediment that creates the physical channel morphology and the environment in which all the river organisms live. A change in the geomorphological variables, such as sediment and water flow will impact on all the organisms in the system. A dam by definition is the complete antithesis of a river, therefore it can be expected that a river will respond to impoundment in a complex manner. It is the aim of this thesis to investigate this response from a geomorphological perspective

1.2 South African water resources

Water resource management in South Africa is complex due to the nature of its hydrological regime: South Africa has a semi-arid climate, characterized by a hydrological regime that is highly variable both in time and space. Detailed assessment of the daily rainfall over the last century by Tyson (1986) to determine occurrence patterns for wet and dry cycles has led him to the conclusion that rainfall is extremely variable, particularly over the dry western parts of the country. Consequently runoff, and therefore river flow, is also unpredictable. Variability is least in the season of greatest rainfall and in areas of highest rainfall. A wide variety of weather systems operate across the country causing this variability. Convectional thunderstorms bring rain to the interior, but they are unpredictable; temperatures are high with low cloud cover and high evaporation. Frontal mechanisms along the coast make for more reliable rainfall and lower evaporation.

The concept of average rainfall at any one locality should be treated with caution and should be used in conjunction with probability estimates (Tyson, 1986). The average annual rainfall of South Africa as a whole is only 500mm compared to a world average of 860mm and of this amount, only 9% reaches the rivers as runoff. This amounts to a total of 53 500 x10^6 m^3, but because of variability and evaporation losses, only 62% (33 000 x10^6 m^3) can be exploited economically with present methods. Annual potential evaporation exceeds the average rainfall in most parts of the country, ranging from 1100mm to in excess of 3000mm (Figure 1.1). Compounding this problem is the uneven distribution of the water resources: the narrow eastern margin of the country making up 13% of the total area captures 43% of the runoff, while the vast Orange River basin covering 48% of the land surface, only captures 22% of the runoff (Figure 1.2). This pattern is reflected again in the perreniality of the rivers: only the streams of the southern and south-western Cape and the eastern seaboard flow continuously, while another 25% of the rivers flow periodically. The remaining 50% in the western interior are episodic and flow only after infrequent storms (DWA, 1986). It can be seen in Figure 1.3 that most of the runoff in many of the country's catchments is generated in the upper reaches. This points to the significance of careful management of these upper reaches, because the ecological functioning and therefore the sustainability of the downstream areas is dependent on the health of these upper catchments. Drought and floods are also part of our climatic regime (Alexander, 1985) which further complicates water resource management. It has been found for example that under drought conditions the presence of numerous small farm dams, which cumulatively trap large amounts of runoff and have comparatively high evaporation rates, are reducing runoff to the main streams significantly (Maaren and Moolman, 1985).

A further complicating factor is the sharing of our major river basins with other countries: the source of the Orange and the origin of 65% of its runoff lies within the 307 20km^2 area of Lesotho. It then flows for much of its length along the Namibian border with South Africa. The grand Lesotho Highlands water scheme, intended to solve South Africa's water supply problems for the next fifty years, is entirely dependent on the goodwill of a small mountain kingdom, currently in a state of political turmoil. In the north east, the middle reaches of the Komati lie in the kingdom of Swaziland. In the north west the Molopo and the Limpopo form the border between South Africa and Botswana, and further north with Zimbabwe. The rivers of the north eastern region, which rise and are heavily utilized in South Africa, flow through Mocambique for the most part of their course. These are all rivers which must be managed in accordance with the laws pertaining to international resources.

All these physical factors make for a hydrological regime that is complex to understand and difficult to manage - but the issue is further compounded by the country's social and political history: a previously disadvantaged majority population are demanding access to clean water, while at the same time adopting western living standards which require large quantities of water per capita. The need for water is driven by population and economics: more elaborate schemes are devised to provide water for a burgeoning population and economy, but South Africa's complex hydrological regime does not naturally compliment the demand. With almost all exploitable sites used and all major rivers dammed with cascades of reservoirs (Figure 1.4), there has been a realisation that alternative management strategies must be formulated, aimed at the management of water as a sustainable resource. The trend towards basin-scale management, and the importance of water in the country's development, necessitates the existence of a centralised, well managed water control body (Walmsley, 1989).

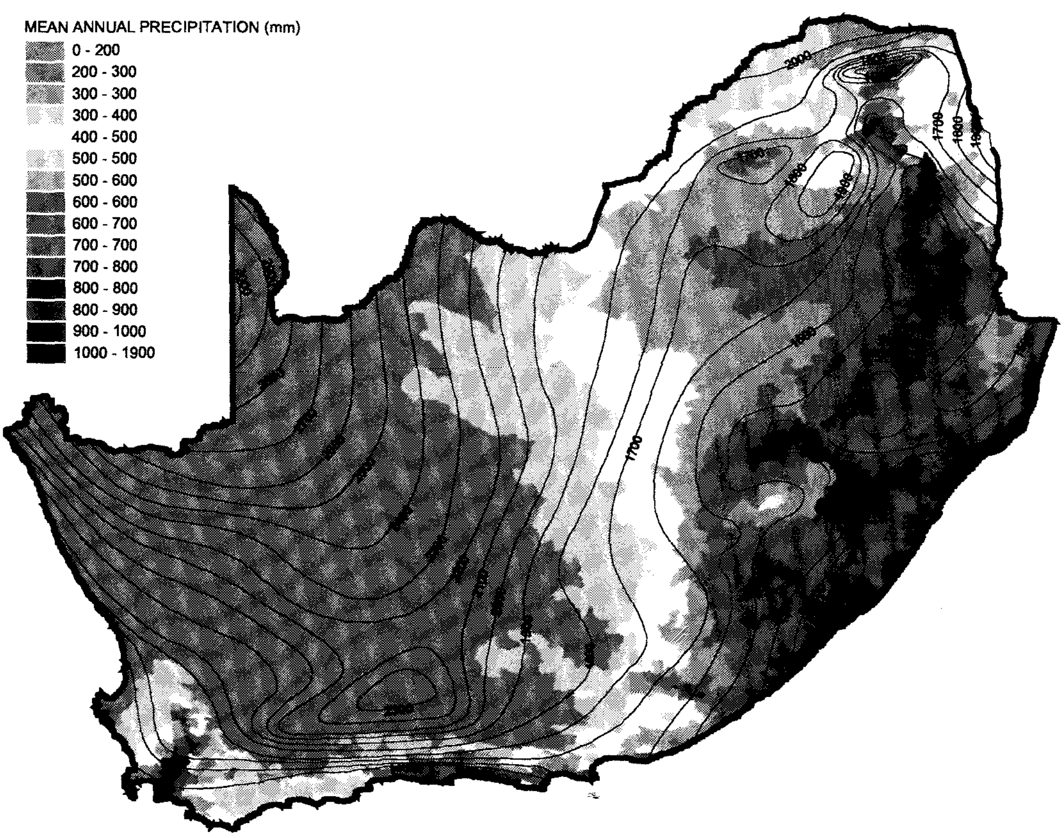

Figure 1.1: Mean annual precipitation and evaporation for South Africa

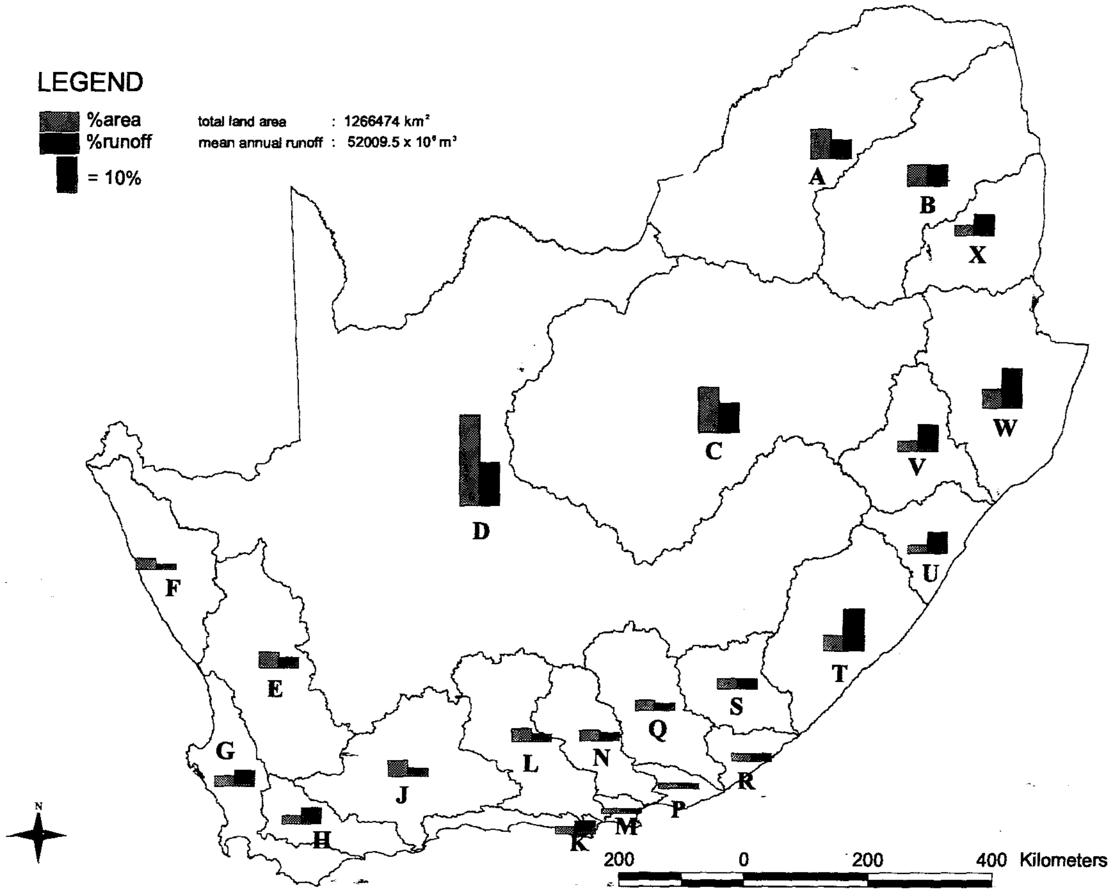

Figure 1.2: Proportional representation of primary catchment area and runoff

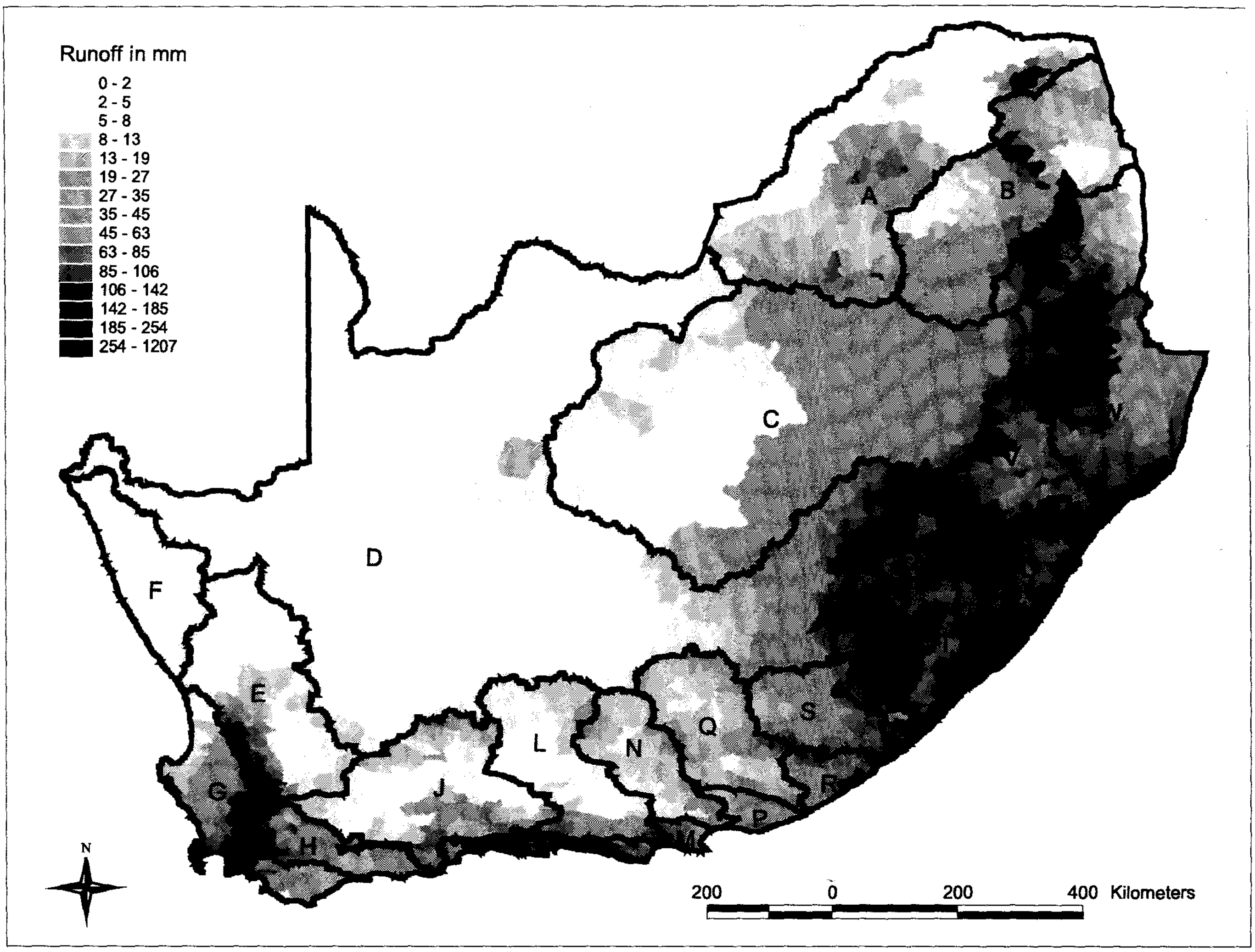

Figure 1.3: Mean annual runoff for South Africa

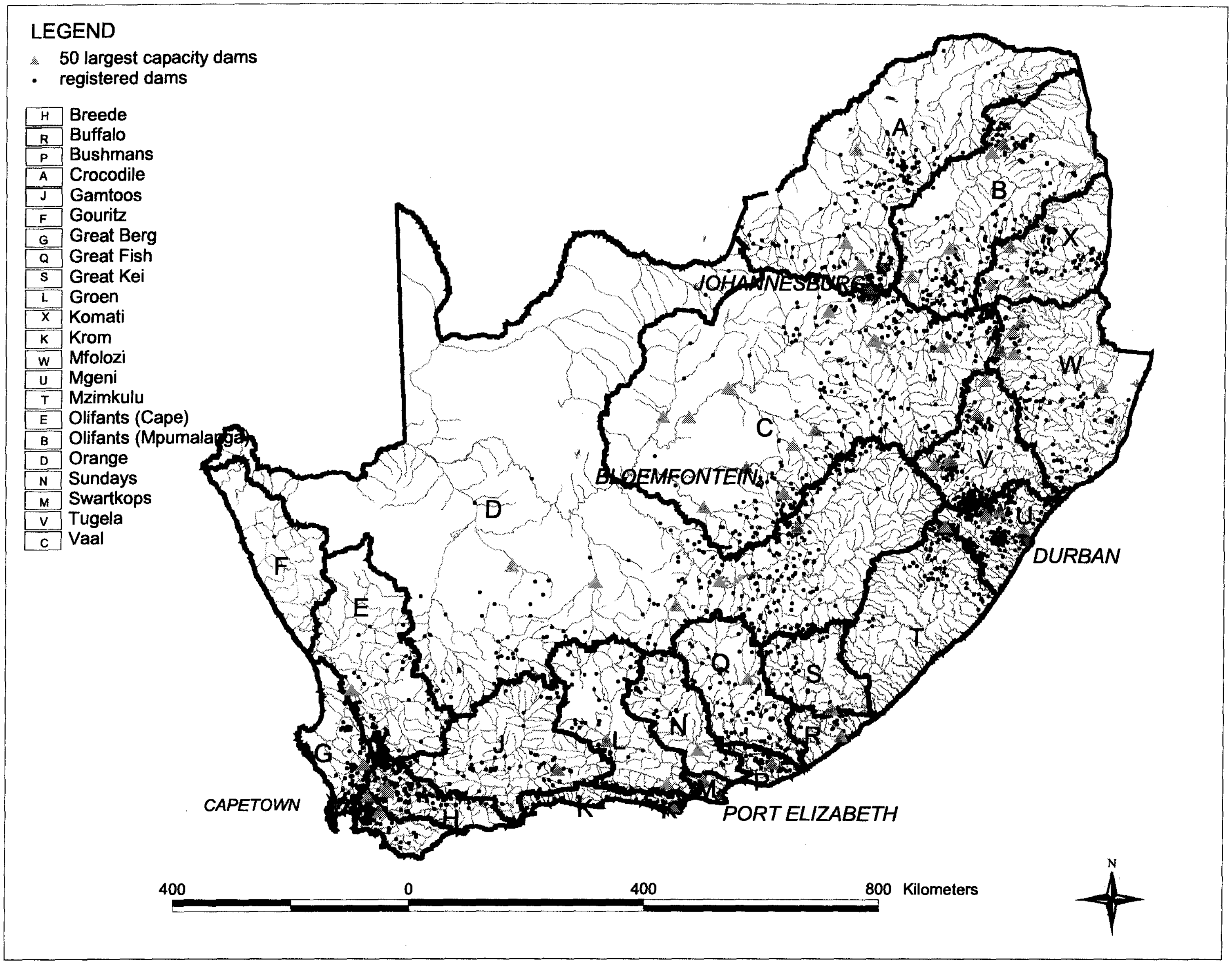

Figure 1.4: South Africa's water resources : primary drainage regions; river network, largest capacity dams, registered dams and urban areas

1.2.2. Water Management History

The status of the Department of Water Affairs was derived from the Water Act of 1956, which was promulgated in response to the need for a centralized controlling body which would be responsible for allocating water to all the sectors of a developing economy and population. At the beginning of South Africa's history under Dutch rule, the state controlled all water resources, according to Roman Dutch Law. However, under the British in the 19th century, water rights were given to riparian owners, which basically gave most water rights to farmers. In 1912, proclamation of the Irrigation and Conservation of Water Act, in further support of a developing agricultural economy, promoted the development of water storage schemes primarily for irrigation. Indeed, irrigation has played a major role in the infra-structural, economic and social development of South Africa (DWA, 1986). The effect of the 1929 depression was compounded by the 1930s drought in South Africa, and led to increased government involvement in water development. Labour intensive schemes provided employment for poor whites and allowed for the establishment of small plot farmers on projects such as the Vioolsdrift, Vaalhartz and Pongola irrigation schemes (DWA, 1986). By the middle of the twentieth century, as South Africa progressed towards an industrialized economy, the demands of industry and economic and urban development needed to be catered for, leading to the Commission of Enquiry into Water Law of 1950, resulting in the Water Act of 1956. By this stage it was obvious that water was a limited resource in the country.

The Commission of Enquiry into Water Matters of 1970 recognized that in keeping with the international trend, South Africa had progressed from an economy where the primary producers (mining and agriculture) contributed most to the GNP, to a stage where manufacturing and industry are most productive. This change had been accompanied by urbanization, and an increased demand for water from the urban and industrial sectors of the country. The commission recognized the need to allocate more water to these users, and recommended that current agricultural methods be improved rather than develop more irrigation schemes. The need for more efficient water storage, by the optimal siting of future dams, and the need for tighter control over the building of small dams (which had high evaporative losses and reduced runoff to the bigger river systems) were also identified. It was clear that future water resource development would need to be in accordance with clearly set out priorities and an optimal scale of achievement. This was a move away from the *ad hoc* immediate need type projects of the past (DWA, 1986).

The various user sectors in the country as recognized by DWAF, prior to 1994, are listed in Table 1.1. The largest users of water in South Africa are farmers who account for 67% of directly used water, the bulk of which is for irrigation. The users differ in their requirements in terms of quantity and quality of water. Some users such as 'the environment' are non-consumptive, but require water of a reasonable quality. Irrigation runoff may re-enter the river systems fairly rapidly, but return flow is usually loaded with solutes. Industrial water may also be returned quite quickly to the natural system, albeit in a polluted state.

Table 1.1: Projected water use according to DWAF (1986) and Davies and Day (1997).

Demand sector	***DWAF 1986 1990***	***DWAF 1986 2000***	***Davies and Day, 2010***
population	40 million	46 million	58 million
direct use	***volume (million m^3/annum)***		
municipal and domestic	2281 (12%)	3220 (14.4%)	7500 (27%))
industrial	1448 (7.6%)	2043 (9.1%)	2500 (9.2%)
mining	511 (2.7%)	582 (2.6%)	
power generation	444 (2.3%)	779 (3.5%)	
irrigation	9695 (50.9%)	10974 (48.9%)	16000 (59%)
stock watering	288 (1.5%)	316 (1.4%)	
nature conservation	182 (1.1%)	187 (0.8%)	1000 (3.7%)
indirect use			
forestry runoff reduction	1427 (7.5%)	11570 (7.0%)	
ecological use, estuaries and lakes	2767 (14.5%)	2767 (12.3%)	

Demand patterns are also variable: irrigation, which constitutes 75% of the agricultural demand, makes heavy demands in the dry season whereas domestic and industrial users demands are fairly constant. These disparities between supply and demand necessitate large storage schemes. Large volumes of water are required to serve a relatively small irrigated portion of the country, which employs a small sector of the population. Many irrigation schemes were developed at a time when water was not scarce, and government subsidy for development was a priority. The result is that areas which were not necessarily suitable for agricultural development both in terms of poor soils and scarce water resources were made viable. Agriculture only contributes 5% to the GNP but it must be remembered that the country must strive to be self sufficient in terms of food production.

1.2.3 The Environment as a user

With the advent of the 'New South Africa' in 1994, and the formulation of policies to bring resources to previously disadvantaged people, there has been much development in the field of water resource management. The emphasis has shifted to meeting the basic needs of rural and domestic users, and catering for the environment: agriculture and industry will in future bear the cost of the use of this resource. As written in the White paper on National Water Policy in 1997, "the achievement of South Africa's development policy will only be possible if the water resources are managed in a way sensitive to, and supportive of, the many demands placed upon them" (DWAF 1997).

The Water Act of 1998, which has replaced the Water Act of 1956, is based on the constitution, which being the supreme law in the land stipulates a number of basic rights. Section 27 (1) (b), states that : "Everyone has the right to have access to sufficient water," and section 29 states that , "Everyone has the basic right to an environment which is not detrimental to any human health or well being." Both indicate that water has to be available to all, and that the environment enjoys a high status. "The environment" is no longer seen as a user in competition with other users, but as an essential reserve. Use of this resource should be in a manner that does not affect its ability to recover.

These principles are entrenched in the new water policy in the concept of an 'ecological reserve.' Chapter 3 of the National Water Bill defines the ecological reserve as, "the water required to protect the aquatic ecosystems of the water resource." The Reserve refers to both the quantity and quality of the water in the resource, and will vary depending on the class (management category) of the resource. No other users - other than 'the basic human needs,' may tap this resource. With regard to availability - only the 'basic human needs,' and 'the environment,' demands will be guaranteed (DWAF,1997). In terms of ownership of water, the state will be the new custodian, thus abolishing riparian rights. Anyone will be able to lay a claim to use water regardless of their physical location, and the amount of use that is permitted will depend on the classification of that resource, and the setting of its Reserve. Determination of the resource base of a particular system will be based on an assessment of aspects such as water quality, quantity, risk and hazard factors and any natural flow patterns needed to maintain that river in its specific management class.

Management classes are allocated to water resources through consultation with all the stakeholders by taking into account the present state of the river and its 'desired future state.'

The idea of Catchment Management Agencies has been introduced to oversee water use at a catchment level: they will be developmental in nature and will serve the interests of equity, corrective action and optimum use of water. This will be carried out through the development of a catchment management plan, which will contain details of: water allocations; the requirements of the Reserve and international obligations; the main issues affecting water quality and quantity which require intervention; management goals for addressing the critical issues; potential management strategies and responsibilities for action to achieve these objectives and financial arrangements (DWAF 1997).

1.2.4 Towards integrated catchment management

The formulation of the new water law has in part been the result of a new understanding of the catchment as a living ecosystem. The recognition that it is a large, interconnected web of living and non-living components, linked by processes and finely tuned feedback mechanisms, has fostered the 'Integrated Catchment Management,' approach which is an integral part of sustainable water resource management. A river cannot be separated from the catchment which feeds it with water and sediment, and the processes that happen there. The principles of Integrated Environmental Management adopted by the Department of the Environmental affairs and Tourism and DWAF in 1997 are aimed at ensuring a holistic and sustainable approach to resource use. Of particular relevance to this study is the Instream Flow Requirement procedure, which uses the Building Block Methodology to determine the volume of water required in a river system to keep it functioning naturally.

Most water resource development schemes alter the natural flow of a river in some way: by diversion, impoundment or abstraction. Whatever the method, the impact will be felt downstream to a certain degree. While recognising the need for development, it is possible to minimise the negative impacts, keep the river system functioning naturally and make development sustainable. Much research has gone into devising a standardised procedure which can be used to achieve this end. It is necessary to determine the natural regime of a river, in terms of the magnitude and frequency of flows which maintain the integrity of river and the riverine environment. This has been termed the Instream Flow Requirement (IFR). A process of determining this has been developed which is known as the 'Building Block Methodology.' The method depends on the identification of the various flow components ('blocks') of a river system which can be described in terms of their magnitude, duration and timing . These components can be combined to describe a modified flow regime which would still meet the ecological and geomorphological requirements of a river.

The method is based on the notion that the biota of a river system are adapted to a particular flow regime, no matter how variable or extreme it may be (King and Louw, 1998) and it is possible to identify the range of flows which will keep the river functioning naturally. The geomorphology of the river provides basic clues as to the range of flows which the river experiences. Maintenance of channel morphology creates a diversity of physical biotopes which provide suitable conditions for ecological diversity. Essentially it is a process of determining how little water the river needs to function naturally, and therefore how much is available to other users. In order to determine the IFR of a particular river water managers, river scientists, engineers and social consultants participate in a workshop at which they all contribute to defining an acceptable modified flow regime. Each participant is required to identify characteristic features of the system from their specialist viewpoint, which must be maintained if the system is to maintain its integrity. Representative field sites are selected at which each of the specialists must conduct a detailed survey, collecting data that is relevant to their field of expertise. The assumption is that if certain conditions are met at these sites, they will also be met elsewhere in the system. Based on this assessment, specialists are able to motivate for river flows which will maintain the diversity of features and organisms that they have identified as typical of that system. The maintenance baseflows, freshes and floods then form the building blocks of an acceptable modified flow regime, which mimics the natural pattern as closely as possible. The IFR recommendations then form the basis against which any water resource development must be measured. It is one of the aims of this project to provide information on the geomorphological impacts of impoundments which will assist in making assessments of the geomorphological requirements of a river system in an IFR type of scenario. This idea is explored in chapter 3.

1.3 An Overview of South African Dams

1.3.1 Method

A register of dams with a wall height greater than 5m or a capacity of more than 50 000m^3 in South Africa is kept by the Department of Water Affairs and Forestry. This data was available in the WR90 data set (Midgley, Pitman and Middleton, 1994), along with other hydrological information, and has been used to produce the following series of graphs and maps. Only registered impoundments are considered, but it must be noted that all the catchments are also affected by numerous small farm dams and direct abstractions. In the former homeland areas, many dams were not registered as they were not controlled by DWAF.

A major problem was encountered with the dam data set. Dam locations are stored as point data, with a set of associated attributes. In the analysis stage it was discovered that the majority of the points had the wrong attribute information associated with them. For example, a selection of dams in the Western Cape bore the names and attribute information of dams known to be located in Natal. The *.pat* file of this coverage was manipulated in QUATTRO-PRO, and a new set of co-ordinates (converted to decimal degrees) taken from the co-ordinate listings in the attribute file was created. This was used to 'GENERATE,' a new set of dam location points in ARCINFO. (see Table 1.2). These corrected points were then attached to the correct attribute information according to a unique value which corresponded to the dam registration number (see Table 1.3). The product was a point coverage of dam locations, with the correct attribute information attached to them. Using the capabilities of ARCVIEW, the 'CATCH' coverage from WR90consisting of polygons delineating the quaternary catchment areas, and the 'DSM,' coverage with all the dam information, were manipulated to produce a series of

DAM_REG	ddlong	ddlat
1	25.817	-25.2003
2	27.592	-25.4042
3	27.85	-25.725
4	27.489	-25.7806
5	27.55	-25.7003

Table 1.2: New co-ordinates for dam locations.

Dam_reg_	Ddlat	Ddlong	Catnum	Dam_no	Dam_name	Capacity
1	25.200278	-25.82	A10B	A100-02	NGOTOANE	18800.0000
2	25.404167	-27.59	A21J	A210-01	ROODEKOPJE	102600.000
3	25.725	-27.85	A21H	A210-02	HARTBEESPO	195050.000
4	25.780556	-27.49	A21K	A210-03	BUFFELSPOO	10328.5000
5	25.700278	-27.55	A21K	A210-04	MIDDELKRAAL	757.000000

Table 1.3: Attribute data from original dam coverage which was joined to table 1.2.

statistics relating dam capacities to the runoff of catchments in which they are located. By using the 'MERGE' and 'SUMMARIZE' functions, data could be collated at a primary, secondary and tertiary level. For example, the two sets of data - dams (point) and catchments (polygons) could be combined to produce new information about the status of impoundments within a catchment, at primary, secondary or tertiary level. New fields were added to the new coverages expressing dam capacities as proportions of the total runoff in the catchment (Table 1.4). The legend capabilities of ARCVIEW allowed these values to be expressed graphically on a backdrop map of the catchments. Examples of the methods used are outlined in the ARCVIEW 3.1 manual.

Primary	Count	Sum_mar4q	Sum_area_i	Impounded	Imp/q	% area
A	139	2386.34	109559.00	2092.344	87.680	8.651
B	145	2904.22	73505.00	950.189	32.718	5.804
C	193	4567.41	196294.00	11716.231	256.518	15.499
D	288	7148.18	409410.00	9507.730	133.009	32.327
E	75	1008.34	49065.00	242.772	24.076	3.874

Table 1.4: CATCH.*pat* 'summarised' with new fields added

1.3.2 A brief history of South African dam building

The rate of dam building in this country has slowed considerably in the last 15 years (Figure 1.5). This is not an indication of stabilised demand - but rather an indication that all suitable sites have been utilised. There are few rivers that are not dammed by cascades of reservoirs both large and small (Figure 1.4). Certainly the most ambitious project to date must be the Lesotho Highlands Water scheme, which aims to divert 2200 x10^6m^3/annum to the Vaal River basin.

Dam building really became a feature of the country in the first quarter of the century as agriculture developed, and the need for off-channel storage schemes arose. Five of the oldest 'large dams' in the country are situated in the Eastern Cape: Lake Mentz - 1922, Lake Arthur - 1924, Grassridge - 1924, Van Rynevelds Pass - 1925, Kammanassie -1926. The first three, located in the arid Karoo region, have been beset by sedimentation problems, as predicted by the director of the Cape Irrigation Board in 1919, and have had their walls raised to compensate for the loss of supply (Van Veelen and Stoffberg, 1987). Figures 1.5 and 1.7, show the relationship between the number of dams built during the past century, measured against the total capacity of the dams. The first noticeable high capacity dam building period was in 1935 when Clanwilliam, Loskop and the first Vaal dam were constructed. The 1970-1985 period is distinguishable for the high capacities of individual dams built in that period. Four large dams: Bloemhof, Gariep, Pongola, and Spioenkop were built between 1970 and 1975. The Gariep dam on the Orange River, which has a capacity of 5958 x10^6m^3 at full supply level and covers an area of 347km^2, is the largest in the country. The dam was completed in 1971 and overflowed for the first time in March 1972. Another 4 large capacity dams: Grootdraai, Woodstock, Heyshope and Gt. Brandvlei were built in the period 1980-1985. Thereafter there is a reversal of trends with a large number of smaller capacity dams being built, hopefully an indication of improved environmental awareness, but also a reflection of a declining economy and the lack of available large dam sites. Another contributing factor may have been privatisation of many water supply schemes, with the result that the kind of money necessary for large dam building would not have been available. The impact of this extent of impoundment on our river systems over the past 30 years must surely have been significant.

Figure 1.6, which maps the distribution in time periods of dam building also points to some interesting trends: the pre 1900 distribution appears to be quite scattered, with dam building occurring evenly across the country as new areas were settled. Thereafter, dam construction was more concentrated in developing regions. The distribution of dams built in the 1930s, located in the semi arid to arid interior, is probably a reflection of government job creation during the depression, in the form of public works projects. A similar pattern is seen in the 1950s with heavy government subsidy of irrigation schemes for 'poor' farmers in the arid interior, on land that was really unsuitable for intensive agriculture.

At present the major dams (the 550 DWAF controlled structures) in the country have the capacity to hold 50% of the country's runoff. To ensure a reliable supply, our dams are built at great cost because of the higher storage capacities required on our rivers, to allow for the variability of the hydrologic regime of this country (Alexander, 1985). This has led to much ingenuity on the part of engineers in dealing with our problems. To cope with assuring supply in the face of such variability, dams are often designed to trap several times the mean annual runoff. The high sediment production rates in most catchments due to the semi-arid environment and poor land management make dam sedimentation rates a concern in 'assuring supply.' Fuggle and Rabie (1992) estimate that the average loss in capacity of South African dams is just under 10% per decade. According to Rooseboom *et al.*(1984) South African reservoirs have a sediment trap efficiency of 99%, and any dam which traps more than 5% of the MAR will have sedimentation problems. Given that few of our dams trap less than this, it is not surprising that sedimentation is a major issue. The high sediment trap efficiency and the high proportion of MAR that is stored in many reservoirs upsets both the sediment and water regimes of the river and has a complex effect on the natural regime. South African dams have been designed to reduce the variability of a naturally variable system. In accordance with the law of diminishing returns, the more a river is developed, the lower the yield will be of each equal increment of storage (Conley, 1994). With most of our rivers already regulated by cascades of dams (Figure 1.4), there is a limit to how much more water can be made available through conventional, and economically viable, methods. This points to the need for careful land management in the catchment to optimise water yields and the need to manage water sustainably through a more environmentally aware approach. The 'new' water law is designed to foster this, and with an improved understanding of our hydrological regime, this should be possible.

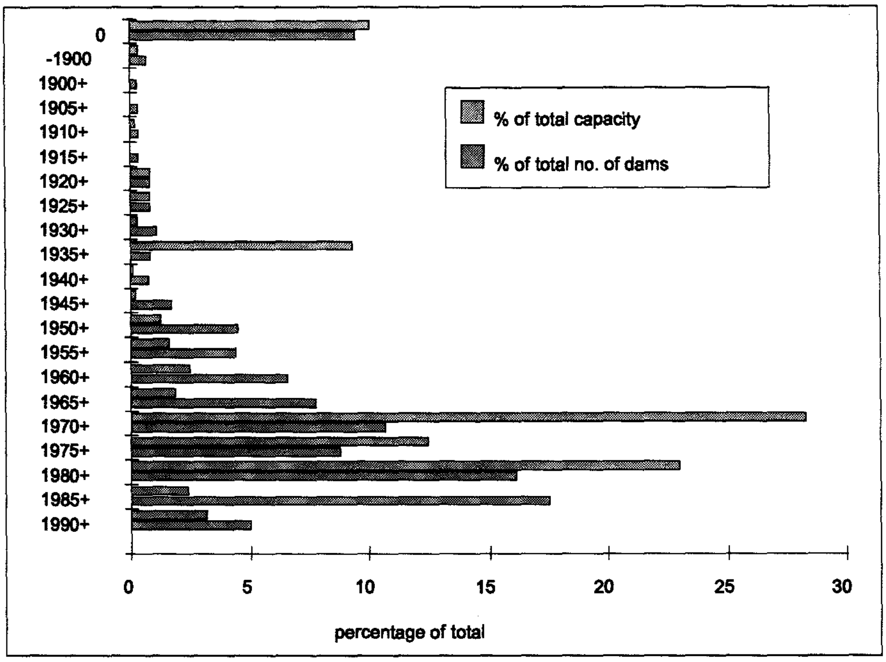

Figure 1.5: Graph showing proportion of total impoundment capacity trapped by dams in five year periods

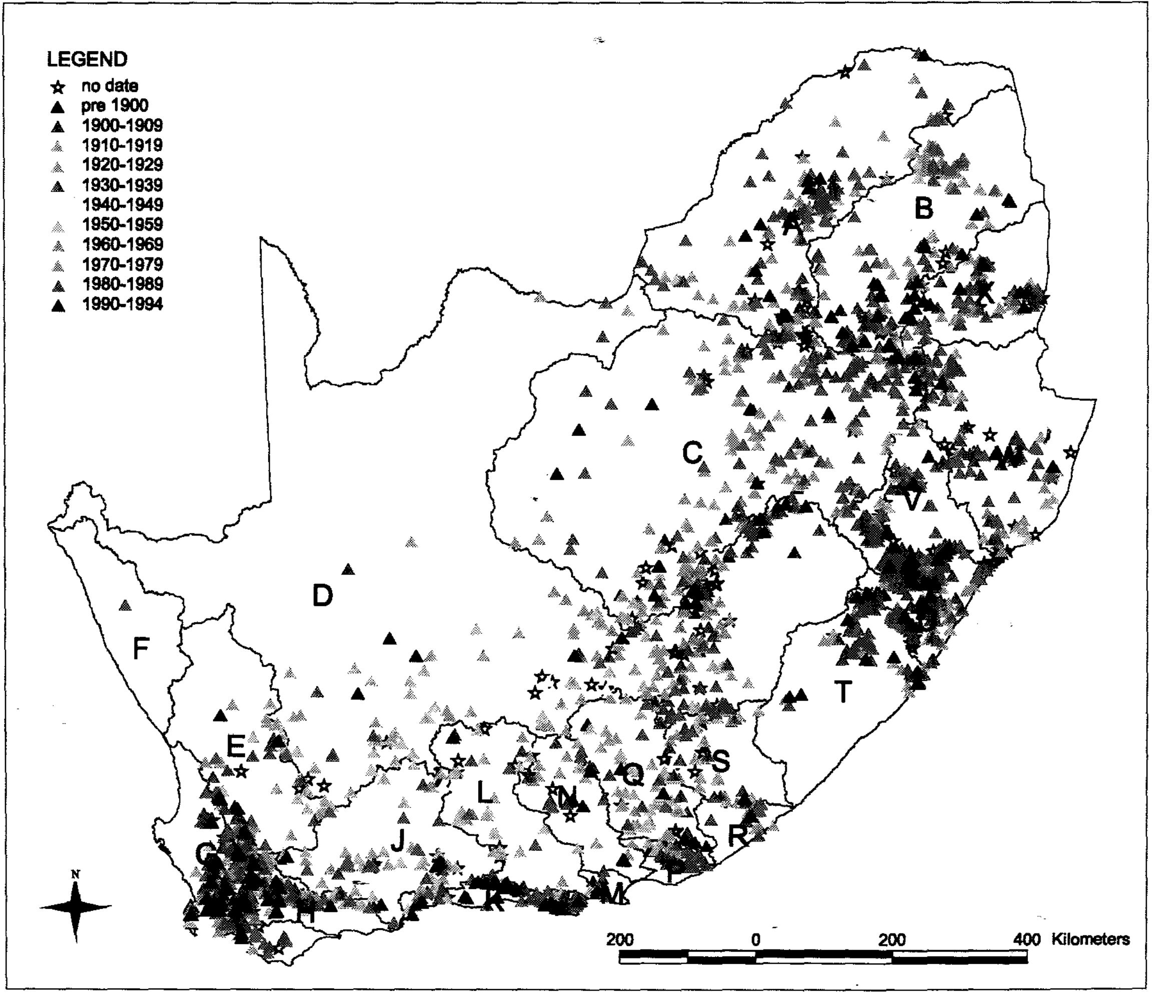

Figure 1.6: Distribution of dams built in South Africa in 10 year time periods

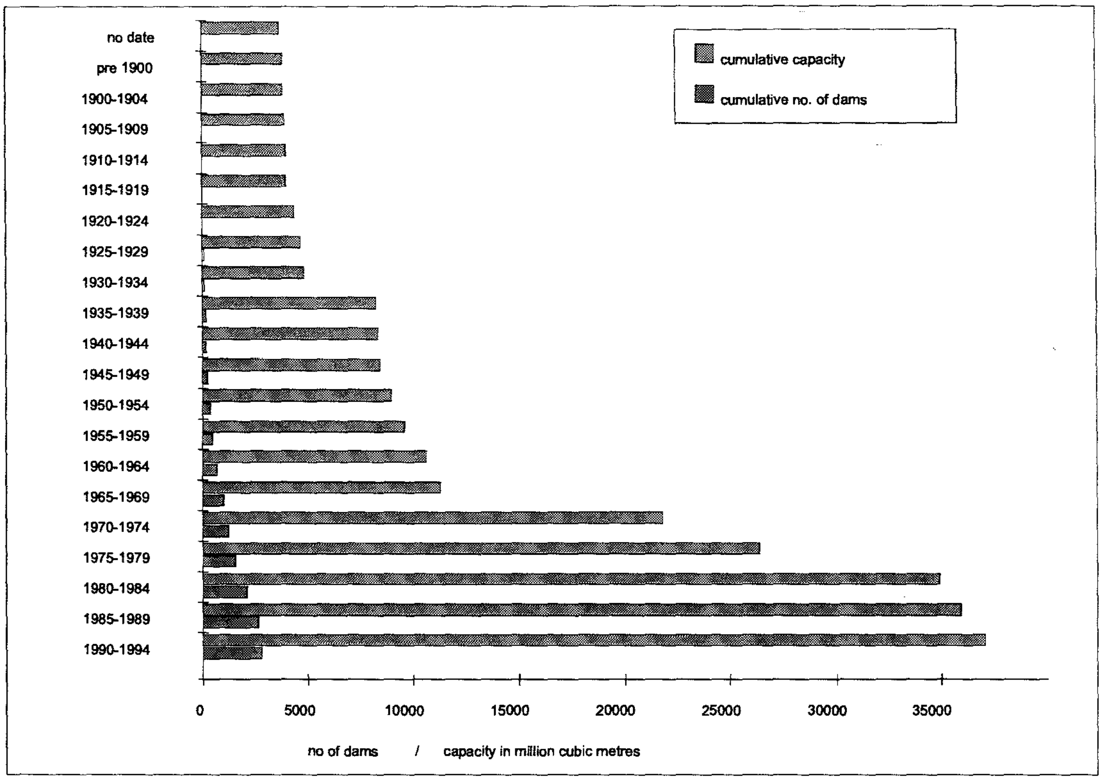

Figure 1.7: Cumulative capacities and cumulative number of dams built in five year periods from pre-1900 to 1994.

Figures 1.8, 1.9 and 1.10 show the proportions of the mean annual runoff that are controlled by impoundments, and give an idea of the extent to which impoundments control the river regimes of this country. At a primary catchment level, primary catchments D and C are developed beyond their annual capacities. The large areas of catchments C and D make this even more significant as the runoff generated in the upper reaches supplies vast arid downstream reaches: the ecological impact of this degree of control must be great. The Lesotho highlands, representing only 7,5 % of the total catchment area of the Orange River generates 65% of its MAR. At a secondary catchment level, the extent to which some regions have been over developed is also evident. The tertiary level map shows that many regions in the Eastern Cape and North Eastern Natal are developed to their capacity, while the less impounded regions are clearly the former Transkei homeland and Swaziland. The data for the arid interior show that those catchments have been developed to their capacity.

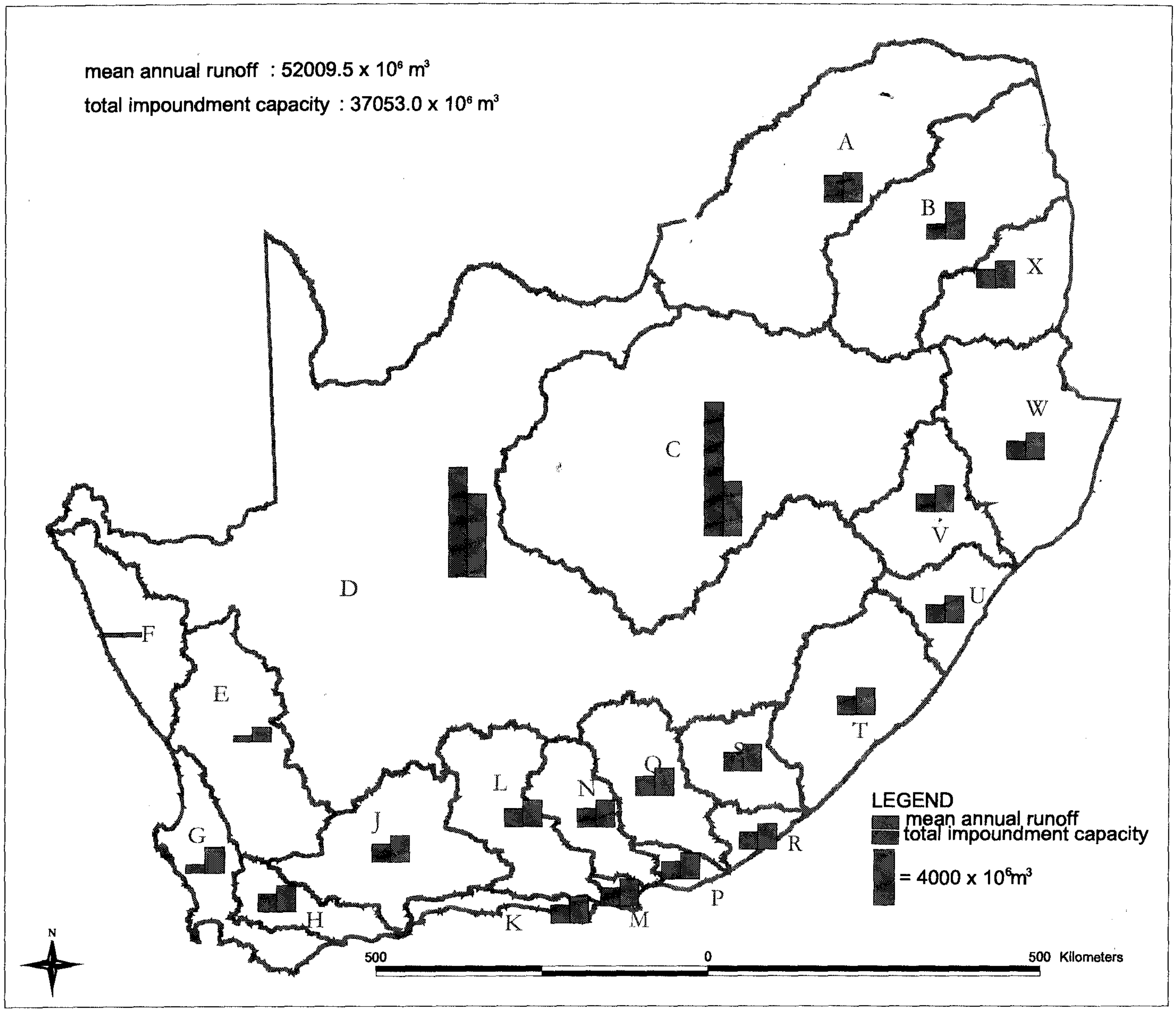

Figure 1.8: Total impoundment capacity vs primary catchment mean annual runoff

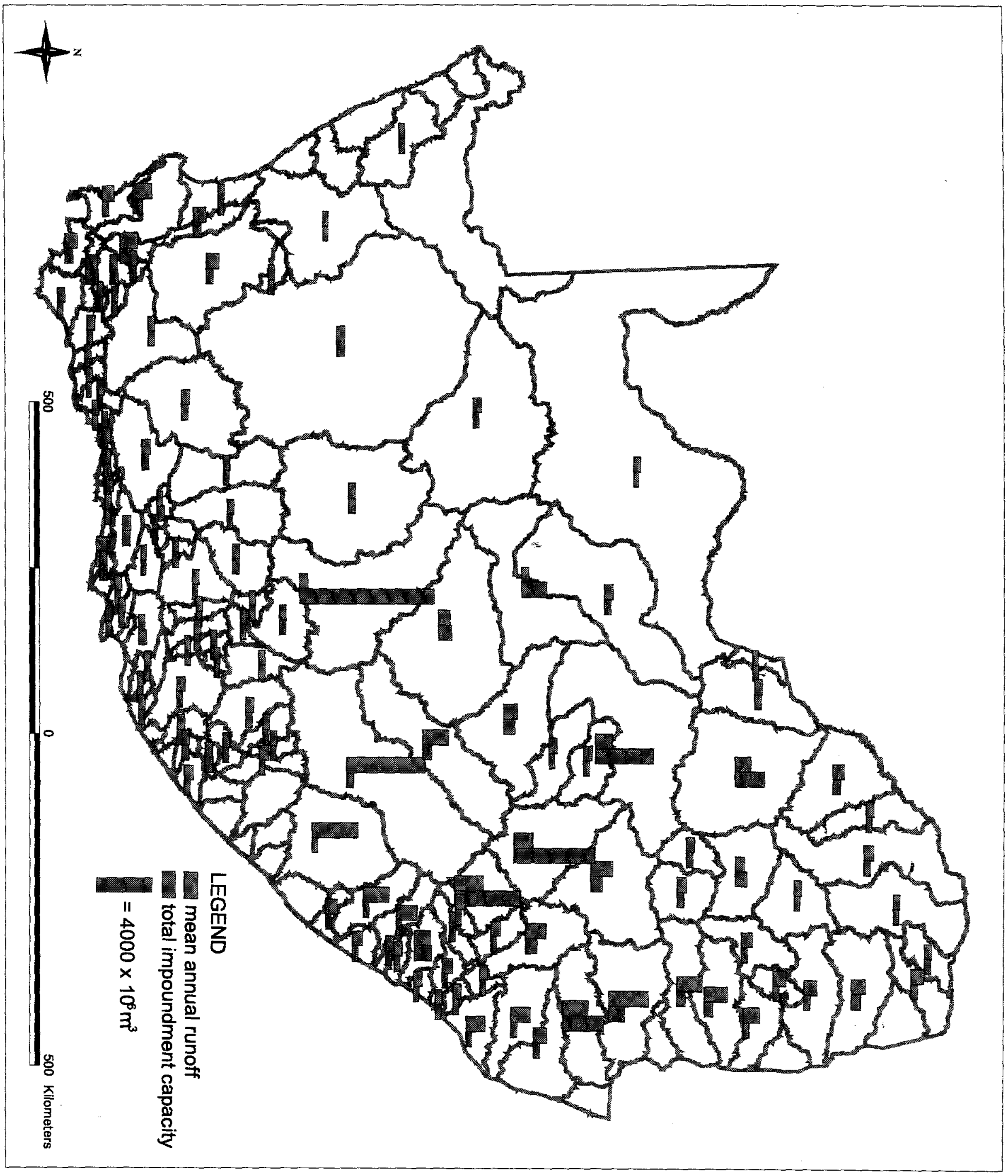

Figure 1.9: Total impoundment capacity vs secondary catchment mean annual runoff

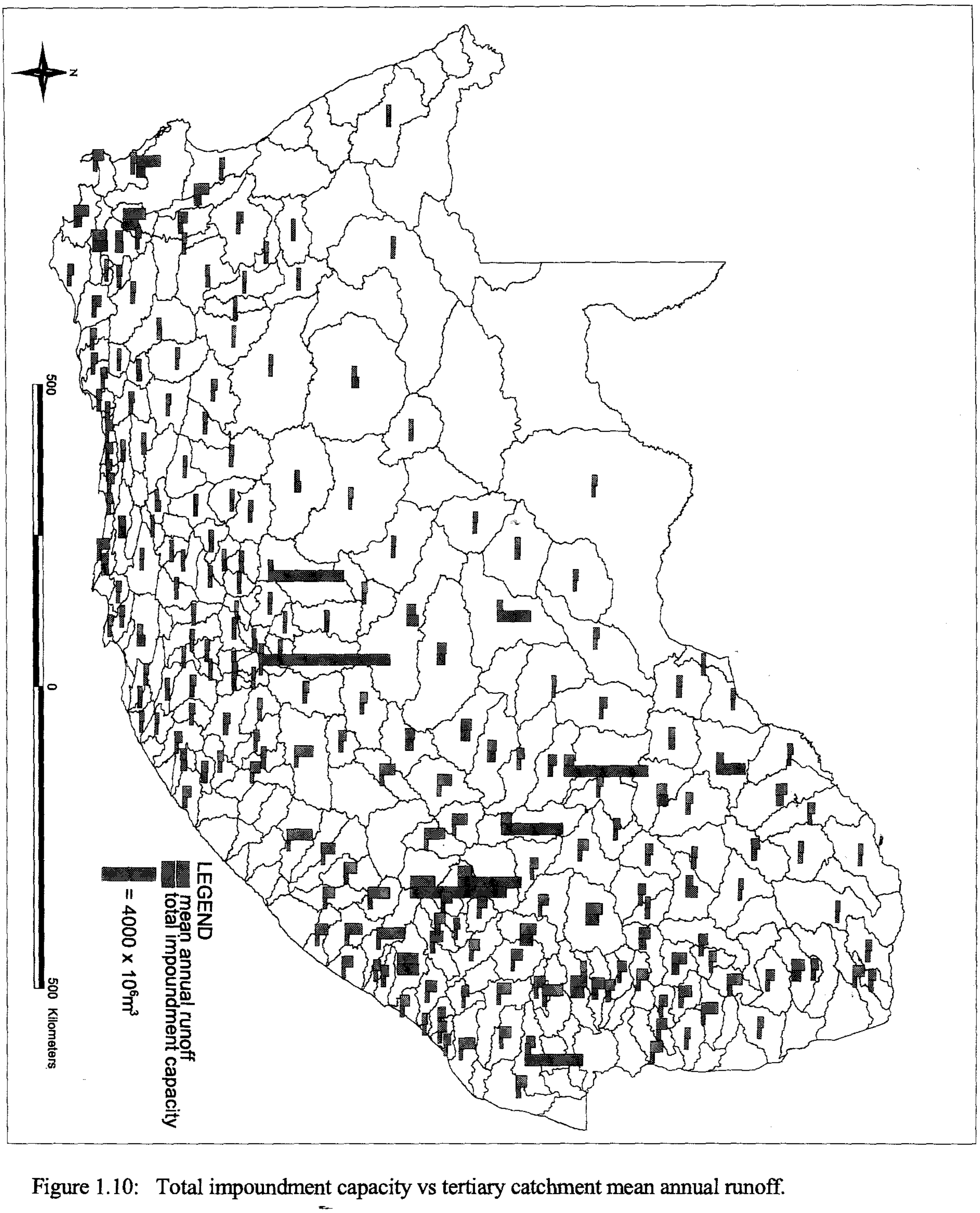

Figure 1.10: Total impoundment capacity vs tertiary catchment mean annual runoff.

1.4 The aims of this project

In order to allocate water to the environmental sector it is necessary as a first step to determine the impact of a changed flow regime on channel structure. Present assessments of geomorphological impacts are based on research from other regions of the world many of which have climatic regimes which are very different to South Africa's. Despite the extent of impoundments and inter-basin schemes in this country very little is known about the geomorphological response. There is therefore no reference against which to judge future schemes.

The aim of this project was to produce a conceptual model illustrating the range of possible geomorphological impact of impoundments, based on available literature on the subject. By looking at the impact of impoundment on the Keiskamma river, the application of some aspects of the model under typically South African hydrological conditions is explored. The applicability and usefulness of this work in South African water resource management is demonstrated through its use in compiling the geomorphological reports for the Bivane River, Paris Dam, IFR Workshop (M^{c}Gregor 1996); the Komati River, Maguga Dam , IFR workshop (M^{c}Gregor, 1997) and the Berg River, Skuifraam Dam, IFR Workshop (Rowntree and M^{c}Gregor, 1996). This work should contribute to understanding river processes to facilitate better management of our water resources.

The objectives of this study were to:

- gain insight into the status of impoundments in this country
- compile a conceptual model of the geomorphological impacts of impoundments, based on an extensive literature review of the subject
- demonstrate its usefulness as a water resource management aid, by using it to predict the possible impact of impoundments at selected IFR sites.
- apply the conceptual model to the Keiskamma River in the Eastern Cape in order to determine its relevance in a catchment which is variable in terms of runoff and sediment production and therefore typical of many South African systems.

CHAPTER TWO

THE RIVER AND GEOMORPHOLOGICAL RESPONSE TO REGULATION

2.1 Gutter of the landscape

A river channel is the product of the relationship between two variables: water and sediment, and three processes: entrainment, transport and deposition. A river forms a natural gutter in a basin, whereby the products of the natural processes of weathering and erosion in the system (sediment) will gravitate to the lowest point and be transported by the stream. There is a continuous movement of weathered material from the land surface to the stream network. The slope, depth and width of a channel are adjusted to the water and sediment load that they convey. The supply of water and sediment to this system is governed by the dominant independent variables: geology, topography, climate and time and the dependent variables: hydrology, vegetation and drainage density as illustrated in Figure 2.1. The combination of these variables will determine the frequency and magnitude of events in the basin, and their effect on the morphology of the stream channel. Man is able to affect both water and sediment supply significantly, therefore any water resource management plan must consider these two factors in their entirety.

In order to understand the impact of impoundment on river channel morphology the whole drainage basin and the many processes happening in it must be assimilated. The processes and elements responsible for maintaining the characteristic physical dimensions of the channel must be examined in detail. According to Richards (1982), understanding the relationship between water and sediment in sensitive semi-arid environments is particularly difficult.

2.1.1 Concepts of equilibrium

A natural river system will tend towards a state of equilibrium: it is not a static system, but constantly changes in response to variables operating within the system. The equilibrium state is dependent on the relationship between water and sediment and a change in one will impact on the other. There are many variables of differing magnitudes and effects operating in a river system, which means that the equilibrium state of the system must be viewed at different scales. In the short to medium time scale, the stream will fluctuate about an average state. Change and

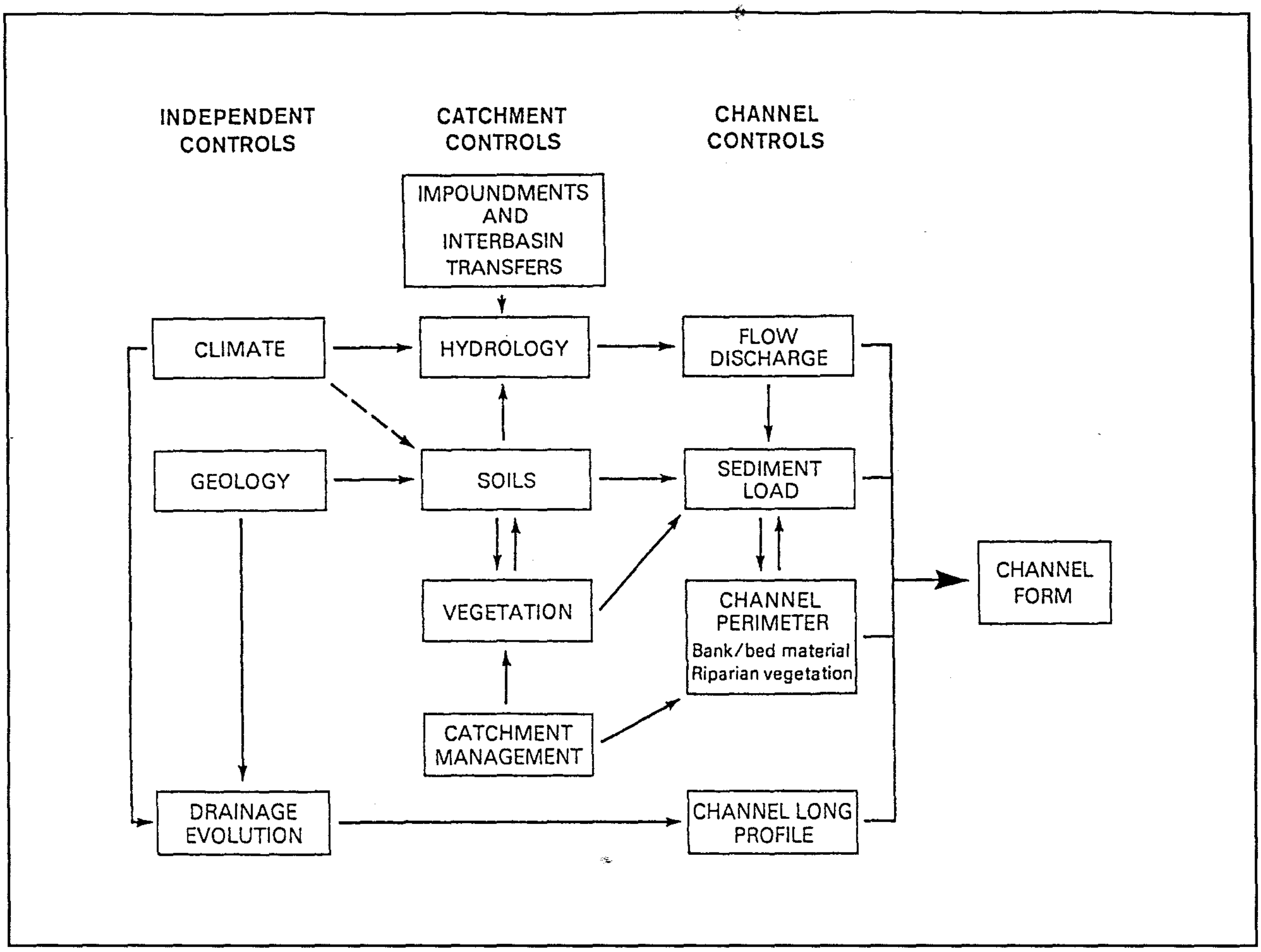

Figure 2.1: Drainage system variables affecting the dynamics and morphology of a fluvial system, from Rowntree and Dollar (1996).

recovery is effected on a daily, seasonal or cyclical basis, and controlled by internal feedback mechanisms which counterbalance each other, resulting in a steady state equilibrium. Viewed over a longer time period, the whole system would seem to be following a trend, tied to the natural evolution of the river, which may also be influenced by climatic or geological change, which is termed, 'dynamic equilibrium.' Schumm (1973) proposes that this state may be discontinuous, due to the crossing of new thresholds in the system, which is why he labels it as : 'dynamic metastable equilibrium.' Man is able to induce this state, introducing new thresholds and moving a river into a new state of equilibrium. By impounding a river, man is altering the equilibrium state, and must be prepared to deal with the consequences as the river tends towards a new equilibrium. In terms of water resource management it is important to be able to discern between features of the different states of equilibrium so that they can be catered for in the planning process. This is complex in semi-arid environments where fluctuations about a steady-state equilibrium in the short-term may be great.

2.2 Sediment

2.2.1 Sediment classification

Rivers are seldom free of a sediment load. The suspended load in perennial systems almost never falls to zero, some sediment is continually being moved through the system. There are various ways of classifying sediment, mostly according to its size and mode of transport. Considering the purpose of this project, the most useful one would seem to be the classification proposed by Hjulström (1939) and used by many authors since. He classifies sediments according to their mode of movement into suspended load and bedload. This classification is simple and convenient but in many cases there is no clear boundary between the two types of load, as is explained below. Commonly recognized sediment size classes which were used for this study are given in Table 2.1.

Suspended load

Turbulent motion causes sediment to be transported in suspension. When particles are moved from the bed they will remain in suspension until the velocity of the water drops below a critical threshold, at which stage they are deposited. The suspended load is that material which has a settling velocity which is less than that of the surrounding fluid, and so remains in suspension, rather than in contact with the bed. As a general rule, clays and medium to fine silts (<32um) will always act as suspended load (Reid and Frostick, 1994), but suspended load grain size is tremendously variable, because its composition is affected by velocity. Because suspended load increases so significantly in floods, it may dominate the bedload by several orders of magnitude (Einstein, 1961).

Very fine material may remain in suspension for long periods as long as there is some turbulence. The ability of the water to carry sediment has been termed 'competence' by Gilbert (1914). Size, shape, specific gravity and specific weight of the sediment particles, as well as temperature and viscosity of the water affect the settling velocity of sediment. Reduced temperature and a high suspended load content decreases the settling velocity of larger particles. The larger particles tend to occupy the lower layers of the stream, while the finer silts and clays may be evenly distributed throughout the profile, although turbulence causes a more even mix of particles throughout the stream profile (Hjulström, 1939).

The rate of transport is not uniform across the bed. It tends to be restricted to a belt bordering the zone of maximum turbulence which varies with discharge, and is believed to be the zone of maximum velocity (Reid and Frostick, 1994). Deposition will take place on the edge of the zone. The volume of sediment transported in a system is measured as the amount passing a cross section over a period of time (kilograms per day or per year). The amount will vary depending on water and sediment supply

Bedload

The bedload includes those grains which roll or slide along the bed, essentially in contact with the bed at all times. Their state of motion will be dependent on the velocity of the water around them, and the arrangement of adjacent particles. Pebbles and coarser gravels will generally travel as bedload (>32mm).

There is also an intermediate state of motion, as particles drop from a suspended condition to join the bedload, known as saltation. This is a hopping, motion where particles collide with obstructions on the bed, and are swept into suspension temporarily, but fall to the bed again as they lose momentum (Gilbert, 1914). Typically coarse silts, sands and granules (>32um) may switch from one mode to another depending on local flow conditions (Reid and Frostick, 1994).

Table 2.1: Sediment size classes from Rowntree (1998).

size class	*clast size in mm*
bedrock	
large boulder	1000-4000
medium boulder	500-1000
small boulder	250-500
large cobble	128-250
small cobble	64-128
coarse gravel	16-64
medium gravel	8-16
fine gravel	2-8
coarse sand	0.5-0.2
medium sand	0.125-0.5
silt	<0.125

2.2.2 Sediment sources

The nature of the river's sediment load varies depending on the geology of its source area, and the nature of the weathering processes happening there. Bed material load is usually derived from the disturbance of the river bed, whereas the bulk of the suspended load typically comes from the surrounding hillslopes, and the remainder from the bed. Processes of weathering and erosion on the land surface prepare sediment for removal by rainfall runoff, which is then able to pick up the sediment, on its pathway to the river. The channel bank is also an important sediment source area depending on its stability.

In general load estimates of rivers refer to the suspended load because this is an easily measurable component, and results suggest that 90% of the load in perennial streams is suspended material. The only reliable bedload estimates come from reservoir sediment surveys. Sediment properties interact with stream power to determine the rates of sediment transport, and the stability of the channel perimeter. The rate at which sediment is transported depends on the particles size, shape and arrangement, as this affects their resistance to the power of the water, and determines the thresholds at which erosion, transport and deposition occur. Determining thresholds of movements is a complex process under natural conditions where there are so many variables. Hjulström (1939) conducted a series of experiments to determine the thresholds of movement of sediments. Working under laboratory conditions, with a bed of similar sized gravel particles in loose formation, he was able to produce a series of graphically presented curves, representing the velocities at which different size particles would be eroded, transported or deposited (Figure 2.2). While this work has its limitations, it is still provides some essential basics to scientists today.

The most stable arrangement of particles occurs where an imbricated structure (Figure 2.3) or clustered bed form occurs. These occur typically in gravel deposits, where a collection of different sized particles are stacked against each other to form tightly imbricated or armoured formations, which have a high resistance threshold. The role of armouring in inhibiting bed material transport is significant in this study because it is a widely recognized post-impoundment impact. Sediment free water released from an impoundment has the energy to winnow out all the fines that may have settled on and around the coarser bed material. The result is a layer of coarse material, which forms an imbricated structure covering

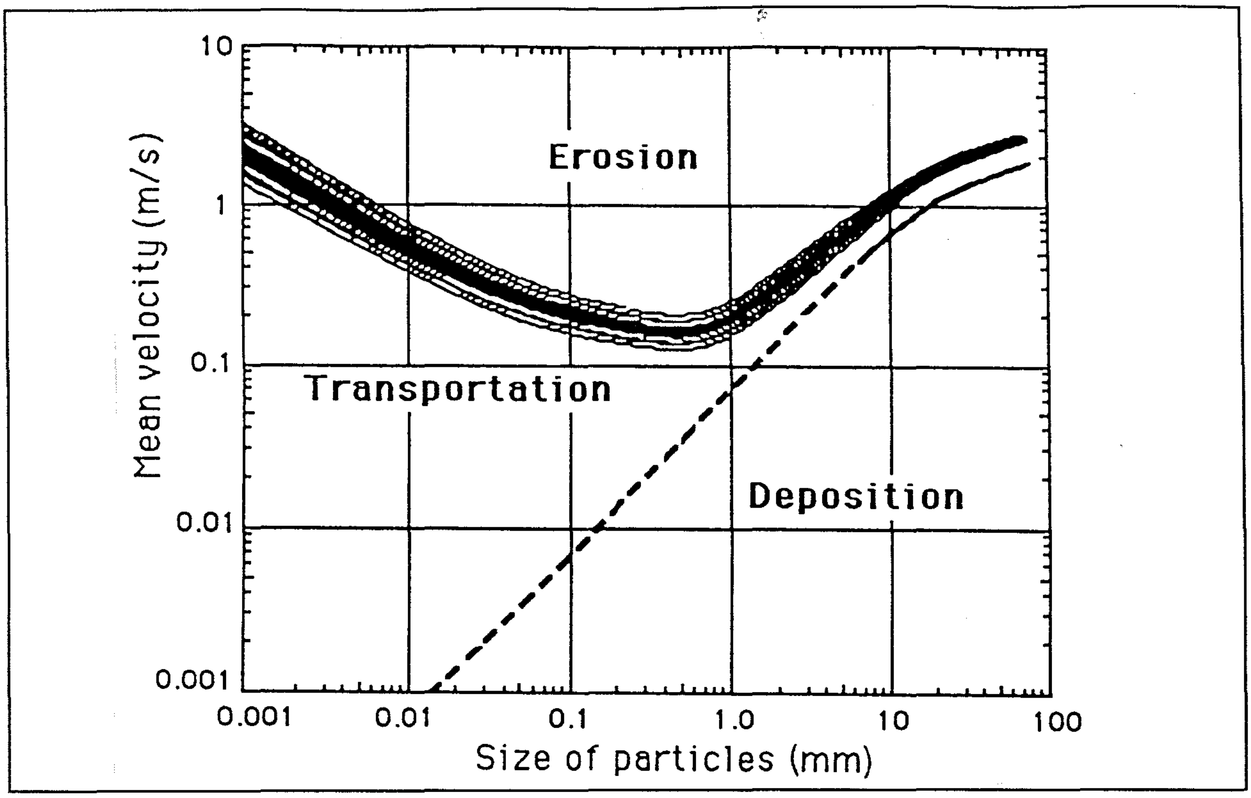

Figure 2.2: Hjulströms' (1935) curve showing the relationship between particle size and movement.

the bed, and preventing further erosion (Reid and Frostick, 1994). The thresholds for movement of the bed particles are substantially greater for a bed of this nature, due to the interlocking of the particles. The interlocking of particles is also affected by their composition and therefore their shape. This condition is particularly common in perennial gravel bed rivers which are subject to variable flows, where the substrate material is subject to periods of disturbance followed by long periods of rest. Church (1978) refers to three stages of bed consolidation: 'underloose' (fresh sediment), 'normally loose,' and 'consolidated' states. As time between floods increases, so does the stability of the bed, and the size of the force required to set the particles in motion.

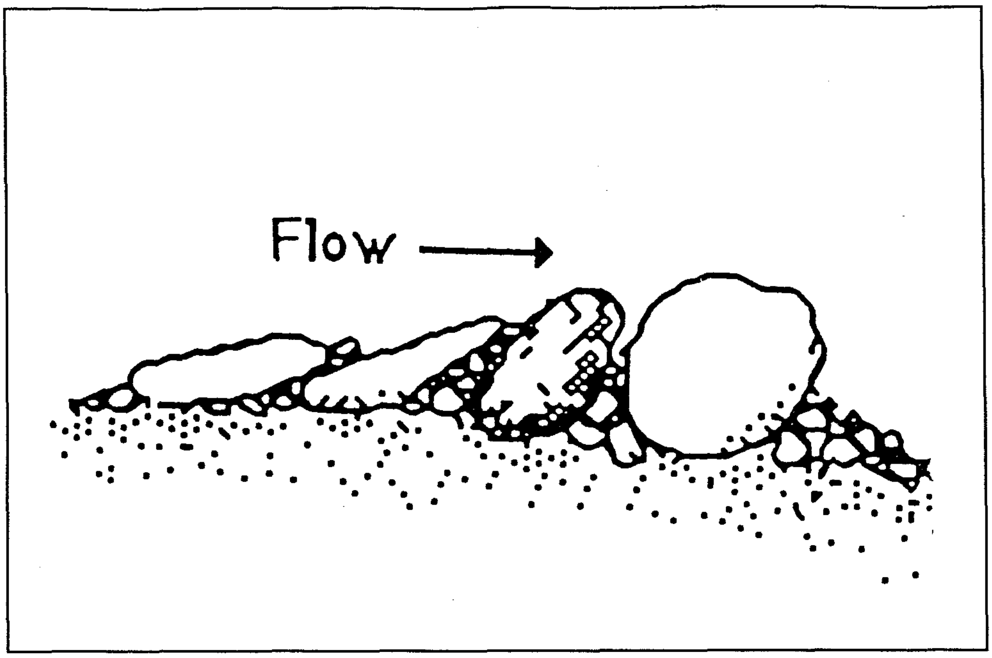

Figure 2.3: An imbricated substrate (from Gordon *et al*, 1996).

2.3 *Water*

2.3.1 *Sources of water*

Water is available to a stream as direct runoff or indirectly as baseflow, originally from some form of precipitation. The availability usually depends on seasonal patterns, or the river's 'regime.' The magnitude of flow is dependent on climate and the physical characteristics of the catchment. Typically in semi-arid environments, due to poor vegetation cover and soils which shed water easily, runoff is rapid and reaches the stream within a short time. In well vegetated areas, which typically have soils with a good moisture holding capacity, much of the rainfall will enter the system more slowly, via groundwater channels. Basin shape and drainage patterns also influence runoff: in a circular shaped basin where tributaries have a similar distance to travel and meet the mainstream in close proximity to each other, there will be a simultaneous input. In a long narrow system, where each tributary enters the main stream at some distance from the next, the accumulation of flow will be much more gradual.

2.3.2 *Water in motion*

It is the flow of water in a channel which provides the energy required to move sediment.

Stream power, which is a measure of the streams ability to do work, is a function of flow velocity. Flow velocity therefore is particularly significant in terms of a rivers ability to erode and transport sediment. There are a variety of tools in the form of equations which have been developed to assess flow conditions relative to boundary roughness, shear stresses, resistance, viscosity, turbulence *etc.* which can be applied to macro and micro scale estimations (Gordon *et al*, 1996). Flow in a natural channel is seldom predictable, so these tools all have their limitations. In terms of this study it is important to recognise that anything which influences the velocity of flow will upset the discharge/transport relationship, thereby impacting on channel morphology.

2.4 Erosion, transport and deposition

According to Hjulström (1939) the distinctive feature of the transport of detritus is its 'great variability.' The manner of transport varies from one instant to the next, and the quantity of sediment varies according to the state of the source areas with the result that the movement of sediment is seldom continuous. Stream power is a measure of a rivers ability to transport sediment and was originally described by Bagnold's equation which is a measure of the shear stress at the bed multiplied by the velocity in the cross section. This has been modified to give a measure of total stream power. An increase in slope or velocity will increase power and *vice versa*. River morphology is therefore significant in containing and controlling the power of a stream. Overbank flooding for example dissipates stream energy, prevents excessive erosion, and allows deposition. Alterations to stream power can therefore effect changes in sediment transport and channel morphology. Stream power generally increases as discharge increases, until it crosses a threshold.

The process of erosion depends on the force exerted on the river bed: when velocity and therefore pressure is sufficient to overcome resistance of a particle and set it in motion, erosion occurs. Erosion is dependent mainly on the velocity of the water and its ability to do work. The degree of turbulence in the water will also determine whether particles stay in suspension. When erosion is dominant the concentration of silt size particles near the bottom will be higher than for equilibrium conditions. When deposition is the dominant process, the concentration of particles near the bed will be less than under equilibrium conditions.

2.5 Complex Response

Complex response refers to a single trigger which initiates a series of river responses happening over time and space (Schumm and Parker, 1973). The notion of complex response discussed by Petts (1980) and elaborated on by Graf (1980) is that for every threshold overcome there will be set of reactions that will vary in time and space. Any change is propagated through the system (Gilbert 1877, in Graf, 1988) and may, according to Schumm (1973), be felt throughout the whole system. It is important to be able to predict the extent and nature of these changes throughout the system, and cater for them in the planning process. A complicating factor in dryland systems is the fact that the process/response relationship may be discontinuous because of the intermittent nature of the forces.

2.6 River channel morphology

Channel geometry at any particular location reflects the influence of upstream controls such as climate, geology, land-use and basin physiography, which together determine the hydrologic regime and the quantity and type of sediment supplied (Knighton, 1984). In terms of channel morphology, changes in width, depth, substrate, slope of the channel, its composition and its form are of significance. These are the aspects which adjust in response to changes in discharge of sediment and water and are therefore the aspects which will show change in response to a changed sediment and discharge regime due to river regulation.

Bedrock channels are a function of the resistance of their underlying geology. They typically have steep gradients such that the energy of the stream is sufficient to transport all available loose material (Rowntree and Wadeson, 1998). Alluvial rivers flow in self formed channels, which are adjusted to convey flows characteristic of their regime. Their shape is maintained by a flow which has been termed the bankfull, dominant or effective discharge (depending on the author) which can usually be equated as the same flow.

Bank material is an important control on bank strength and stability and therefore on adjustment of channel width. The cohesiveness of the bank will depend on the silt -clay content of the materials. Cohesive banks give rise to deeper channels. Well vegetated banks, particularly those that support stands of trees, tend to be stable. A channel also migrates laterally, by erosion of one bank and deposition on the opposite, thereby maintaining a constant cross section. Channels are seldom straight for any distance. Curves promote the erosion of one bank and aggradation of the other. As the concave bank recedes, the point bar builds outwards from the convex bank until it forms a floodplain. The floodplain accretes as overbank flows deposit sediment on it. In terms of channel morphometry a distinction must be made between arid and temperate climate rivers. Looking at channel width and depth, Wolman and Gerson (1978) showed that in humid areas the rate of increase in average bankfull width is constant with increase in catchment area, and that the return to normal dimensions after perturbations is relatively rapid. Width increase in arid streams with a drainage area of up to 100km^2 is higher, remaining constant thereafter.This is also an indication of the relative effectiveness of extreme flows to produce channel widening.

In terms of the channels adjustment, it is not so much the quantity of water as its capacity to do work that is significant. There is much debate amongst scientists as to which is more significant in terms of doing work: magnitude or frequency of events. According to Newson (1980) the availability of sediment and the sequence of events may be as important as the magnitude of a flood. Magnitude in geomorphological terms is a measure of the quantity of sediment transported by a river, while frequency refers to the occurrence of events of the same magnitude. From a review of the literature, it is evident that the relative importance of magnitude and frequency depends on the climatic regime. Classic work done by Wolman and Miller (1960) gave rise to the conclusion that the effectiveness of processes which control many landforms depends upon their distribution in time as well as their magnitude. Analyses of the transport of sediment by various media indicated that a major portion of a river's work was done by events of moderate magnitude and relatively frequent recurrence rather than by rare events of unusual magnitude.

Wolman and Miller (1960) identified the flow with a return interval of 1-2 years which could be equated with bankfull discharge as the most effective or 'dominant' discharge. Williams' (1978) definition of bankfull discharge as the flow which just fills the channel to the tops of the banks and marks the level of incipient flooding can be equated with this high frequency moderate discharge event which does the most work. Andrews (1980) confirmed these findings, proving that effective discharge and bankfull discharge are the same flow. In fact, the bankfull level is a product of the effective discharge, which is the discharge at which channel maintenance occurs.

Leopold *et al.* (1964) took Wolman and Miller's (1960) findings several steps further, refining their application with the following additions: in perennial streams, it is the moderate size events which do the most work, but the more variable the hydrologic regime, the greater the percentage of total load that will be carried by a few large events.

Baker (1977) explored the concept of thresholds, in the context of magnitude and frequency. He identified a threshold at which 'effective' work will begin, which is dependent on the sediment size and the magnitude of the storm event. In the context of dryland rivers, where the relaxation or recovery time between events may be great, the thresholds which must be overcome are high, and therefore only events of sufficient magnitude will do any work. Sand bed rivers with small particle size have a low threshold, while boulder bed streams have a much higher one. This concept was also investigated by Pickup and Warner (1976), who identified a range of discharges which dominate bedload transport, but found that extreme events are necessary to promote significant changes in channel morphology. It is only at competent discharges that the stream is capable of modifying its channel.

Magnitude frequency analysis has shown that the most work is done by moderate events of 1-2 year return periods in temperate regions (Wolman and Miller,1960, Pickup and Warner, 1976, Andrews 1980), while more extreme events do more work in more arid environments (Baker 1977; Wolman and Gerson, 1978). In terms of the rivers load, the type and quantity of sediment varies along the length of the river, as does the bed composition. In general bed material size decreases in a downstream direction due to weathering, abrasion, and sorting processes. The bank material usually corresponds to this pattern, with the channel banks tending to become more cohesive with an increase in silt/clay content in a downstream direction. However this is highly variable, with layers of gravels and cobbles in the bank profile. Typically valley slope also decreases in a downstream direction: a result of past sediment and flow regimes. There may be exceptions to this if there has been tectonic activity or if a tributary enters the system.

These concepts of magnitude and frequency are extremely significant in terms of understanding the impact of dams on rivers as an impoundment affects both to a greater or lesser degree depending on the flood magnitude, the dam size, its draw down level, and operational rules.

2.6.1 Flow hydrographs

The range of discharges which a river experiences can be described in the form of a flow duration curve. It takes the form of a cumulative percentage curve showing the time each discharge is equalled or exceeded (Richards, 1982). Flood frequency analysis can be used to determine the geomorphologically significant flows in a system. It is based on an analysis of instantaneous flood peaks or the daily average flow at the time of the peak. Because of the significance of being able to identify the dominant/effective discharge, this hydrological information is vital in determining the geomorphological events which are important in a system. It is these events which are responsible for channel maintenance and channel formation. While floods generally attract the most attention because of their economic impacts and cost to human life, it is equally important in river management to be able to identify the magnitude and duration of low flows in a system.

2.7 Channel pattern and morphological features

Channel patterns are a reflection of sediment and flow relationships which give rise to particular morphological features. It can be assumed that channels which exhibit common morphological features have been subjected to similar forces and can be classed together. If this can be done it is possible to begin predicting what changes will occur in particular channel types, under particular conditions.

A channel will adjust its dimensions to a state which is most conducive to the efficient transport of sediment. The pattern of a channel depends on the energy of the stream: it is a product of the relationship between stream power, resistance of bed and bank materials and sediment transport (Richards, 1982). As these three aspects change the river will reflect a different pattern: a single thread low sinuosity channel is likely to occur where the bank material is cohesive, substrate is immobile, sediment transport is insignificant and stream power is low. Meandering occurs where the bank material is less resistant and the stream power greater, allowing the channel more freedom of movement. Braiding is indicative of a high energy environment where the stream is capable of moving bedload: the channel widens to increase the width/depth ratio and deposition of the bedload creates the alluvial bars which divide the stream into more than one channel. This pattern often develops at flood discharges. An anastomosing or anabranching channel is a permanent multiple thread channel, in which the channels are divided by permanent islands.

Within each of these channel patterns there may be a variety of morphological units (Figure 2.4) depending on the composition and form of the bed, and the flow conditions therein. As discharge changes so will the variety and extent of morphological units. A straight channel has an undulating bed which forms deeps and shallows. Depending on the flow in the stream these will be continuous or discrete pools and riffles. The water gradient tends be flat over the pool, steepening over the riffle. This is also the case for meandering streams, where pools form on bends. This pattern is present in virtually all streams with bed material which is coarser than coarse sand, but is most characteristic in gravel bed streams. The pool/riffle sequence has been identified as occurring in coarser materials in South African rivers, where it often occurs on top of bedrock controls (Rowntree and Wadeson, 1998). A riffle is essentially a transverse bar which may be placed centrally in the stream, off centre, or adjoin the bank. While material on the riffle may be moved it always seems to be replaced, so that it is a fairly permanent feature (Leopold *et al.* 1964) and as such is a good 'indicator' site in a stream. There must be some heterogeneity of substrate for riffle pool sequences. Depending on the channel substrate there may also be larger features such as rapids and waterfalls.

Bars are depositional features formed about some sort of nucleus of debris. They tend to form under high flow conditions and may accrete to such an extent that they become stabilised by vegetation, eventually forming islands in a braided or anastomosing channel. They may be located in the channel, adjacent to banks or at tributary junctions. Their form and location may change, but in a system that is in a state of equilibrium their areal extent will be constant. Tributary bars form at river junctions, where a high gradient tributary injects a sediment load into the mainstream, forming a depositional feature that will only be eroded at high discharges. In arid systems, debris fans at tributary junctions indicate high capacity flows in catchments that are out of phase with the mainstream. In the absence of sufficiently high discharges in the main stream, these features may dominate a reach and become permanently established.

In-channel benches are more extensive depositional features, adjoining the river bank running parallel to the stream delineating the active channel. They are a typical feature of many South African river systems and are often a good indicator of annual flood levels, providing an overflow area for the dissipation of energy under flood conditions. Higher lying deposits form terraces demarcating the extent of less frequent flood events of a greater magnitude.

Because of the tremendous variety in natural systems, some sort of classification is needed which allows us to reduce the range of features into a number classes according to common characteristics so that we can begin to understand what is happening. By classifying channels into different types according to their pattern and composition it is possible to begin to predict how they will respond to changes. Based on the identification of certain morphological features such as bars or pool/riffle sequences that are characteristic of particular channel conditions such as size of substrate, bank stability and gradient, it is possible to estimate the magnitude and frequency of discharges which are responsible for maintaining them. A long term change in discharge magnitude and frequency, and a change in sediment regime such as is brought about by river regulation will affect the form and maintenance of many of these type of features.

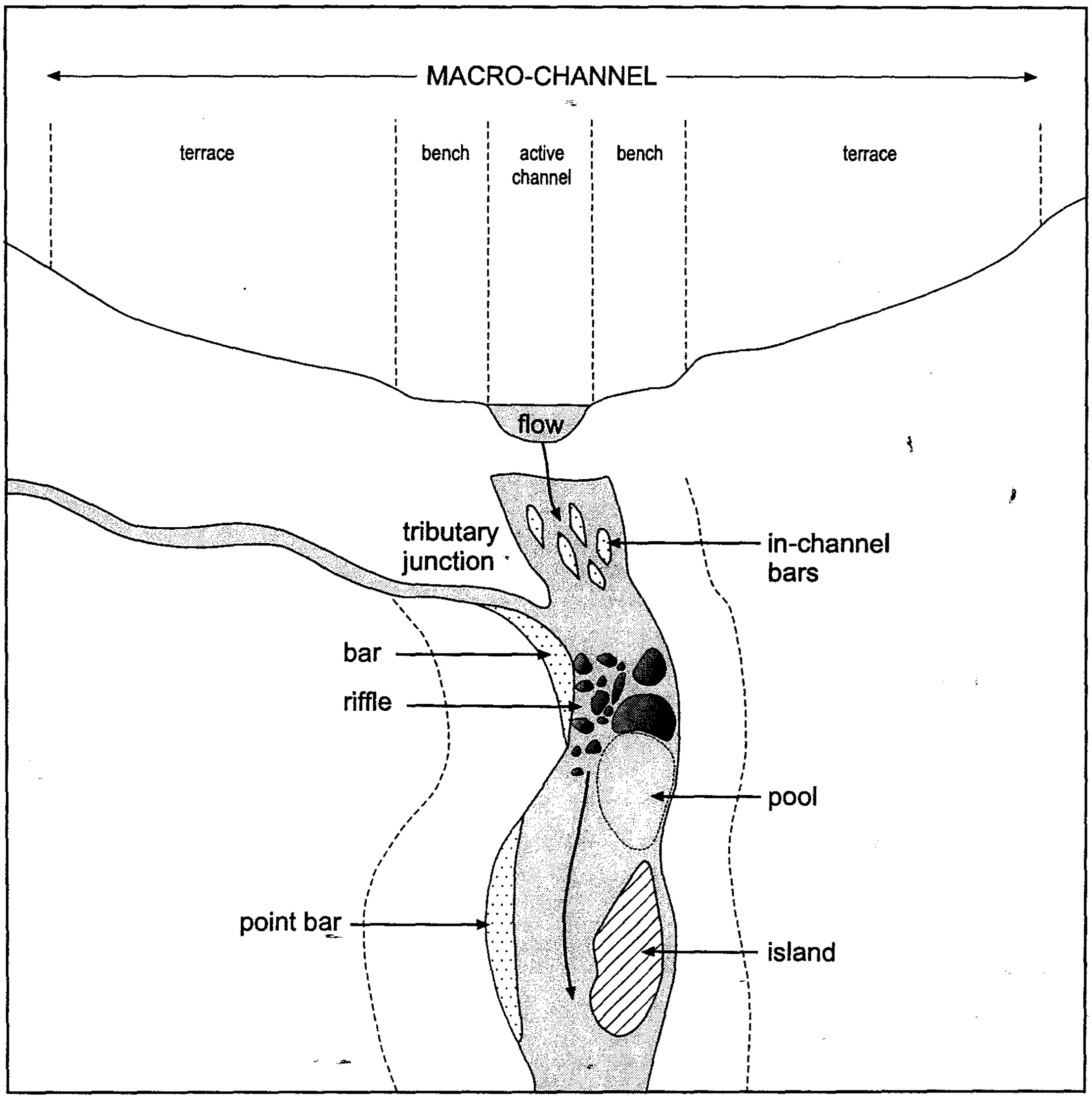

Figure 2.4: Morphological features in a river channel.

2.8 Linking the physical environment with the biota

From the ecological literature it is evident that aquatic organisms favour and inhabit certain environments created by the morphology of the channel and located within different flow regimes. The organisms are adapted to living, feeding and breeding in these particular conditions. Water brings oxygen, food and nutrients to the inhabitants of the stream. Different morphological conditions provide habitat, shelter from prey and breeding grounds for different organisms. Some creatures rely on floods as stimuli for breeding cycles. As the high water recedes, remaining pools form a haven where eggs and juveniles can mature away from the threats of the main stream. Patterns of physical habitats are created within the pools, riffles, banks and boulders of a stream. Within these micro-habitats, particular conditions of streamflow, channel shape, substrate and temperature occur which stream biota respond and adapt to. In South Africa, many aquatic creatures have adapted to the variability of South African rivers and have become opportunistic breeders, relying on occasional and often extreme events for cues. Flood waters must be able to spread into the side channels and riparian vegetation to provide habitat there, as well as wetting those plants which need periodic inundation.

From a water management perspective it is necessary to be able to identify morphologically and ecologically critical discharges, at which availability and variety of habitat change drastically.

2.9 Review of the impact of impoundments

2.9.1 The impact of impoundment on river channel morphology

By impounding a river, man is enforcing a regulated state on a natural system, upsetting the natural regime of a river, and the associated biota which are adapted to surviving under a particular set of natural conditions. The primary impact is in the control of water releases to the downstream system, and the reduction, or complete removal of the sediment load from the system. Depending on the degree of control, the impact may be large or small. River regulation is a common option for water resource management in most countries whether it is by storage for hydroelectric power generation, irrigation and domestic use or flood control. Releases must consider hydrological needs, issues of water quality from the perspective of pollution and the requirements of the lotic ecosystem.

The impact of river regulation on geomorphology has long been recognised internationally. As early as 1890, channel morphology changes below reservoirs were observed in the UK (Lane, 1890, cited in Buma, 1977). From a South African perspective this recognition has been delayed as economics drove the demand for water resource development and environmental issues tended to be sidelined by a powerful controlling Water Affairs body, answerable to a politically powerful agricultural community. From an overview of literature it is obvious that the impact of river regulation on a stream is substantial, covering a broad spectrum of disciplines and environments, although the dominant fields are ecology and engineering (Petts, 1979; Williams and Wolman, 1984; Park, 1977; Chien, 1985; Erskine, 1985; Graf, 1980; Gill, 1973; Gordon, Finlayson and McMahon, 1996; Buma and Day, 1975). In South Africa, studies have concentrated on the ecological impacts, mainly via water quality assessment (Palmer and O'Keeffe, 1990; Gale, 1992; Byren and Davies, 1989), vertebrate studies (Cambray, 1984; Coke 1970) and invertebrate population sampling (Palmer, 1991; Chutter, 1969). What is lacking in the South African literature, with the exception of a chapter in Davies *et al.* (1993), Rowntree and Dollar (19960 and some comment in Davies and Day (1997), is an assessment of the geomorphological impact of river regulation.

The most extensive work on the impact of impoundments on rivers has been carried out by Petts in Britain. His work provides a good starting point for this discussion as he provides a useful theoretical framework within which to consider other case studies on the impact of impoundment.

2.9.2 Geomorphological impacts of impoundments according to Petts (1984)

Petts' work is based on his 1979 doctoral thesis. The results of the 14 case studies carried out for that are given in Appendix A. According to Petts (1984) mans impact on the environment can be described according to three orders:

- a first order impact entails a process alteration, or a direct effect on some natural activity;
- a second order impact involves changes of form, ecological or geomorphological in response to the process alteration, striving for a new equilibrium (1-100 years);
- a third order impact involves readjustment of the system - a feedback effect from the first order impact, which may take hundreds of years.

Using a range of techniques to study 14 impounded rivers in Britain, with dam catchments ranging from 3.5 to 127 km^2, and time spans of five to 85 years, Petts came to the conclusion that second order impacts which follow a process alteration are varied and complex. A series of responses: erosion, deposition, aggradation, all interlinked, happened simultaneously, to varying degrees in different places. Stream capacity generally increased immediately below the dam, then reduced within a short distance, tending towards normal as the unregulated area increased. Based on the various case studies, Petts was able to establish that once the unregulated contributing catchment area below the dam reached 40% of the regulated catchment area, the geomorphological impact of the impoundment would be insignificant. At tributary junctions responses were complicated by injection of sediment and water. Reduction of width by deposition was found to be the main means of contraction in actively meandering sections, while simple accommodation of the reduced flow in the existing channel was the response in stable channel sections. Depending on sediment/discharge relationships, width and depth reduction was also achieved by the deposition of sediments on the bed, or in the form of channel side benches. The rate of change was linked closely to the availability of sediment and water: in the absence of competent discharges, the existing channel would simply accommodate reduced flows. Only a large event would then be sufficient to initiate change. In the case of large reservoirs, there may be a significant time lag between impoundment and channel response. The third order impacts stemming from the change in magnitude and frequency of events and reduced sediment resulting in a change in channel morphology, will have an impact on the living organisms in the system. Changes in width, depth and particle size distribution, which control velocity and flow actions, will affect organisms which are sensitive to these kinds of change. Fish and invertebrate habitats are intimately associated with the hydrological, sedimentological and morphological characters of river channels. Many are opportunistic breeders relying on stimuli from the river to trigger new life cycles.

According to Petts (1984) many of the environmental problems that have resulted from dams have been due to a failure to recognise second and third order impacts, and the time span over which they act. River systems consist of numerous inter-related hydrological, sedimentological, morphological and biological components and the response to impoundment is complex because each of these comes in to play.

2.9.3 Distribution and relevance of impoundment studies

A detailed literature review of studies on the geomorphological impact of impoundments was conducted to gather the information used in the compilation of the following sections. Summaries of all these studies are given in Appendix A.

Figure 2.5 shows the distribution of the studies discussed in this research. It is evident that most of the studies are concentrated in the UK, mostly due to the efforts of Petts. The USA has a good scattering of research too, while there is a noticeable lack of geomorphological studies in the developing world. The interesting fact about this is that large dams in these areas have notoriously negative impacts. The environmental, social and economic impacts are vast, and as such have been well documented. Most of the large dams in these regions were built at a time when dam building was slowing down in first world countries. Originally many of the dams were built by colonial powers to irrigate crops to provide the mother country with raw materials. Apart from the devastating social impacts of these schemes, there was a complete lack of understanding of the systems from a geomorphological point of view: the developers had no perception of the ramifications of their efforts. These negative impacts are particularly detrimental to people in less developed communities who still have a direct reliance on their natural resources. The following two examples from South Africa and Egypt illustrate the dependence of local populations on the geomorphological functioning of a river system.

On the Pongola River, Northern Zululand, the Tonga culture has evolved about the fertile floodplain. The alluvial terraces provided good agricultural soils for a variety of subsistence crops; the perennial pans, sustained by the annual flood provided hatcheries for a variety of fish species and a source of food for the locals who trapped them with traditional baskets; reeds from the pans and rivers edge and trees from the riparian zone provided building materials. Damming of the river at Pongolapoort in 1979 changed this complex and sensitive system considerably. Plans for irrigated commercial rice farming have been singularly unsuccessful due to unsuitable soils. In the absence of the annual flood, the diversity of the riparian zone has reduced; the once extensive reed beds are degraded and fish yields in the pans are poor.

The sediment load of the Nile has been as significant in the history of the Egyptian people as the river itself. The alluvial soils of the floodplain provided good arable lands. The annual flood with its high sediment load provided a natural fertilizer rich with azotobacter. The many small floods allowed the operation of flood fed furrow irrigation system. The alluvial deposits also provided brickmaking materials which were replenished each year by the annual flood.

The Nile was first dammed in 1902 by British colonialists by the Aswan Low Dam to allow irrigation of extensive cotton lands, providing raw material for British cotton Mills. In 1969, the High Aswan dam was built to extend irrigated agriculture. By 1993, the Egyptian government claimed that they had 'reclaimed' 690 000 hectares from the desert and put it under irrigation. In reality, the actual area of irrigated land had not changed much: degradation and problems with salinity had rendered hectares of land useless for agriculture. Some previously productive areas had been urbanised, while the brickmaking industry had begun quarrying former farmlands, in the absence of the annual flood to replenish their silt/clay sources. Traditional flood-fed furrow systems no longer operated due to a reduction in the water level (degrading bed) and reduction of small floods. The annual flood with its fertile silt load containing the 'azotobacter' was reduced by the dam and the floodplain is steadily eroding (McCully, 1996).

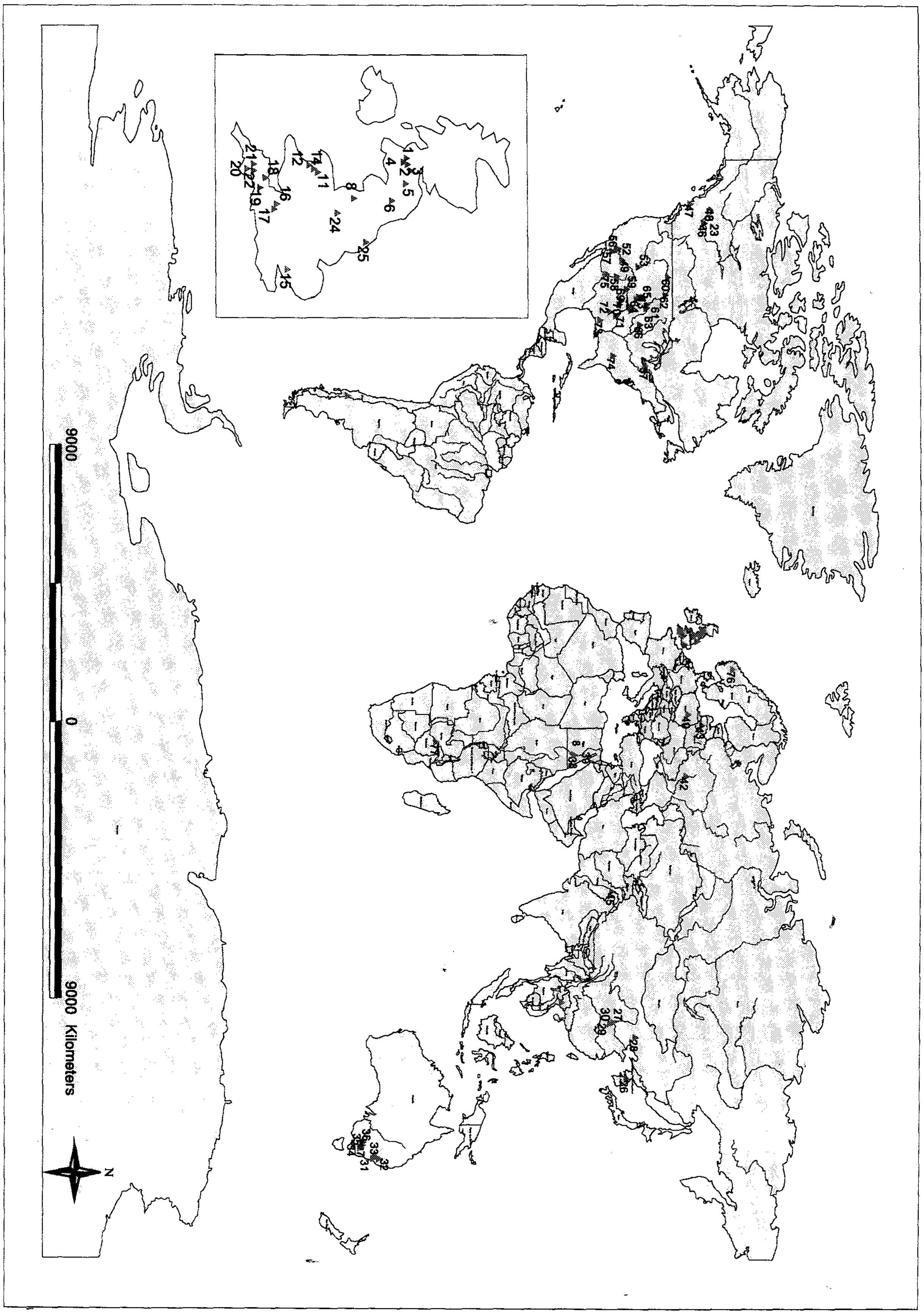

Figure 2.5: Distribution of studies reviewed on the geomorphological impacts of impoundments (refer to Tables 2.2 and 2.3 and Appendix A for study no's.).

2.10 Impoundment: an overview of the impacts.

It is evident that river response to impoundment is varied and complex - in magnitude and in time. Impoundment will affect the lotic environment and its inhabitants, as well as the riparian zone, and the floodplain. The communities influenced will be both botanical and zoological, varying in size from the minute macro-invertebrates which inhabit the spaces between substrate particles, to the large trees of the riparian zone. It is the physical channel environment which provides these creatures with a habitat, and it is the morphological response of a river to impoundment as described by all the above authors which underlies all other responses.

A dam in a river changes the normal flow pattern of the stream. Two generalisations can be made about the impact of impoundment: the flow will be altered and the sediment load will be changed. This may be exaggerated depending on the purpose of the dam, and its operational procedures. Flood storage dams drastically reduce the variability of a system. Their impact on sediment transport is as dramatic as their impact on flow. Dams operated for irrigation tend to reduce high flows in the wet season and increase dry season flows. Hydro-power dams disrupt the diurnal and seasonal flows dramatically, and introduce short-term variability to the system.

The volume of water passing to the downstream river and its timing will depend on the function of the dam. On average, the same volume of water may pass downstream, but its release pattern will be artificially controlled. If much water is abstracted, the volume and magnitude of water releases will be reduced if not stopped. While some dams allow for sluicing out of sediments, the volume released is never as great that entering the dam.

Identifying and quantifying the first order impacts of impoundment is simple if there are stream gauging records for the pre-impoundment period. Discharge data at least can give a good indication of the extent of change in the rivers flow, and its timing. Alternatively, study of a similar unimpacted catchment in close proximity can provide a valuable control and case for comparison. If sediment data is available, the normal sediment suspended load of the river can be compared with the sediment load of post-dam discharges.

It is obvious that identifying morphological change - the secondary impacts, is not simple. Until recently, it has not been standard procedure to make pre-impoundment assessments of the channel (at least not in this country). Because of the time involved (immediate to hundreds of years) and the difficulty of isolating changes due to impoundment, impacts are not simple to quantify. The downstream change is complex because of the many feedback mechanisms which operate in a natural system, and will vary in time and space. The secondary impacts which can be identified as the physical channel adaptations, will depend on the physical characteristics of the downstream channel. The response of the downstream channel will depend on the nature of the channel prior to impoundment: the composition of its substrate, the stability of its banks, the nature of long profile/gradient. Change in bedrock channels will be insignificant, while change in sandbed, or mixed substrate channels may be significant. The impact of the dam will decrease in a downstream direction, in relation to an increase in the contributing unregulated catchment area. The sediment and water balance will gradually be restored. This all takes place over time: a few years to hundreds of years.

Summarised versions of the original studies consulted are contained in Appendix A. The primary and secondary geomorphological impacts of dams have been summarised by description, tabulation, and illustration in the next section. They are essentially the results and discussion of this part of the thesis.

- Tables 2.2 and 2.3 are a summary of primary impact findings from all the studies
- Table 2.4 is a summary of all the possible secondary morphological changes described by the authors; Figure 2.7 is an illustration of these changes.
- the conceptual model illustrated in Figure 2.6, which covers first, second and third order impacts, is derived from the results of all these studies.
- Table 2.5 relates flow regime to channel type and the likely change.
- The chapter ends with Figure 2.8 which is a working flow diagram.

The changes have been organised according to the following idea: a channel will adapt itself to a new flow pattern to facilitate the optimal transport of water and sediment. A channel can change its dimensions by adjusting its width, depth, position, long profile and substrate composition in an attempt to reach a state of equilibrium with its new regime.

Table 2.2: Summary of the primary impacts of impoundments according to studies reviewed.

MAR - mean annual river flow; d/s - downstream; MAF - mean annual flood

Map no.	***Author and country***	***River and reservoir***	***Primary impact on sediment***	***Primary impact on water***
42	Assarin *et al.* 1994; **Poland**	Zimlyanskaya, Don	no figures	MAR = 22 x $10^9 m^3$ dam capacity: 23.8 x $10^9 m^3$ (108%)
43	**Lithuania**	Kaunas HPP, Neman	no figures	MAR = 9.2 x $10^9 m^3$ dam capacity: 0.46 x $10^9 m^3$ (5%)
44	**Vietnam**	Hoa Binh HPP Da	no figures	MAR = 57.2 x $10^9 m^3$ dam capacity: 9.5 x $10^9 m^3$ (16.6%)
26	Woo & Yu, 1994; **Korea**	Keum, Daechong	no figures	traps 60% (1.49 x 10^6 m^3) of the MAR
76	Fergus, 1997; **Norway**	Fortun HPP, Fortun	no figures	post regulation discharge: 35% of natural discharge; mean annual discharge reduced from 20 $m^3 s^{-1}$ to 7 $m^3 s^{-1}$; MAF reduced from 140$m^3 s^{-1}$ to 86 $m^3 s^{-1}$
27	Chien, 1985; **China**	Sanmenxia, Yellow	100km d/s: at 1000-2000 $m^3 s^{-1}$ load reduced by 64%; at 3000 $m^3 s^{-1}$ load reduced by 82%	12400 $m^3 s^{-1}$ flood reduced to 4870 $m^3 s^{-1}$ (60%); medium flow duration (1000-3000 $m^3 s^{-1}$) increased from 120-204 days
28		Gaungting, Yong-dng	Operated to flush sediment out in moderate size flows	3700 $m^3 s^{-1}$ flood reduced to 800 $m^3 s^{-1}$
29		Danjiankou, Hanjiang	6km d/s: average sediment concentration reduced from 2.92 to 0.03 kgm^3; sediment transport capacity reduced by 41%	6km d/s: average peak discharge reduced from 16600 to 78400$m^3 s^{-1}$; ave low season discharge increased from 328 to 714 $m^3 s^{-1}$
30	Qiwei *et al.* 1982; **China**	Danjiankou Hanjiang	annual sediment transport capacity reduced by 41%	annual high flow reduced from 4087 $m^3 s^{-1}$ to 3041$m^3 s^{-1}$; for 100km d/s - flow velocity is 70-80% of pre-dam velocity
49	Dolan *et al.* 1974; **USA**	Glen Canyon, Colorado	median sediment concentration reduced from 1250 to 350ppm	median discharge: 8200 $ft^3 s^{-1}$ reduced to 12800$ft^3 s^{-1}$; MAF: 86000$ft^3 s^{-1}$ reduced to 28000$ft^3 s^{-}$; 10yr flood: 122000$ft^3 s^{-}$ reduced to 40000$ft^3 s^{-1}$
5152	Turner & Karpiscak, 1980; **USA**	Glen Canyon, Colorado	26km d/s: reduced median sediment concentration from 1500 to 7ppm	average annual maximum flows reduced from 2486$m^3 s^{-1}$ to 803$m^3 s^{-1}$; median discharge increased; average diurnal fluctuation from a few centimetres to several metres
50	Kearsley, Schmidt & Warren, 1994; **USA**	Glen Canyon, Colorado	reduced from 6x10^{10}kg to 8.3 x 10^7kg	annual peak discharge: 2180$m^3 s^{-1}$ reduced to 940$m^3 s^{-1}$
53	Graf, 1984 **USA**	Flaming Gorge, Green	no figures	maximum release capabilities: 170$m^3 s^{-1}$ compared to pre-dam maximum flood of 510$m^3 s^{-1}$

10	Andrews, 1986 **USA**	Flaming Gorge, Green	105 miles d/s: mean annual sediment discharge decreased by 54% from 6.92 x 10^6 tons to 3.21 x 10^6 tons	pre and post dam flows at 3 stations in ft^3 7450 → 2750 20500 → 11500 26500 → 20500
13	Hadley & Eschner **USA**	Platte, *Several*	no figures	increased low flows, reduced floods
9 39 38	Hammad, 1977 Shalaby, 1986 Kinaway *et al.* 1973 **Egypt.**	High Aswan Dam, Nile	99.5% trap efficiency; pre-dam suspended load - 125mil.tons/yr; post-dam, 965km d/s suspended sediment load of 6mil.tons/yr	flood season flow reduced from 7-900 $10^6m^3d^{-1}$ to < 225 x $10^6m^3d^{-1}$; flow range of 720-13000 x $10^6m^3d^{-1}$ reduced to 930-2600 x $10^6m^3d^{-1}$; mean annual release to the Mediterranean of 40km^3 reduced to 2-3km^3
45	Tariq, 1994 **Pakistan**	Indus, Tarbela	97% trap efficiency	traps 15% of the MAR of 79 billion m^3
40	Hrabowski, 1994 **Poland**	Debe, Narew	no figures	no figure
7	Walker, **Australia**	Murray Darling; *several*	no figures	average monthly low flows increased from 100 m^3s^{-1} to approx 300 m^3s^{-1} ; high flows of 6-800 m^3s^{-1} , reduced by 1-200 m^3s^{-1} ; medium flows reduced by 1-150 m^3s^{-1}
34	Jacobs *et al*, 1994 **Australia**	Dartmouth, Mitta-Mitta	no figures	unseasonal high flows; reduction of floods
35		Hume, Murray	no figures	reversal of seasonal flow; total volume 9% more due to IBT.
32	Erskine, 1985; **Australia**	Glenbawn, Hunter	STE: 98-98.5% Mean daily susp.load - 659.9 to 6.6 tonnes	truncation of flows >8 x $10^6m^3d^{-1}$; reduced frequency of flows >7 x $10^5m^3d^{-1}$; increased low flows
33	Benn & Erskine, 1994, **Australia**	Windermere, Cudgegong	95% plus	truncation of high flows >3x10^9l d^{-1}; increase in low flows < 30x10^9ld^{-1} 10% duration reduced from 260 x 10^6l d^{-1} to 130 x 10^6l d^{-1}; 80% duration increased from 6 x 10^6l d^{-1} to 21 x 10^6l d^{-1}
31	Sherrard & Erskine in 1991 **Australia**	Mangrove Creek, Mangrove Creek	100%	post dam flows reduced by 70%; largest pre-dam flood - 34800 Mld-1, post dam 1710Mld-1; 1.08 return on pre dam scale; 54-66% reduction for larger floods at Mangrove Mountain; largest flood - return interval of 1.21 yrs.
37	Buma & Day, 1977, **Canada**	Deer Creek, Deer Creek	no figures	no figures
48	Kellerhals & Gill, 1973; Bray & Kellerhals 1979 **Canada**	WAC Bennett, Peace	Nearly sediment free water	annual peaks: 3500-9000 m^3s^{-1} lows:150-250 m^3s^{-1} ; regulated range:500-2000 m^3s^{-1}
46	Church, 1995; **Canada**	WAC Bennet, Peace	not an issue	peak flows reduced, mean annual flow the same; MAF reduced by 68% below dam; 42% at delta
47		Kemano IBT	no change	mean natural flow = 44m^3s^{-1}; augmented flows = 100-150m^3s^1

41	Navarro *et al*, 1994 **Argentina**	Piedra del Aguila, Limay	no figures	100year flood of 6000 m^3s^{-1} reduced to $2800m^3s^{-1}$
18	Gregory & Park, 1974, **UK**	Clatworthy, Tone	no figures	1.5yr flood and 2.33yr floods reduced to 40% of pre-dam Q.
12	Petts, 1984	Nant-y-moch Afon Rheidol	no figure	flows greatly reduced - 3 spillages since 1963
6	Petts & Thoms, 1987 **UK**	Kielder, NorthTyne	no figures	peak flows reduced by 30-50%; highest pre-dam flow $>250m^3s^{-1}$; Q = 175 m^3s^{-1} exceeded 4 times in 1966; regulated releases: irrigation flows = $1.32m^3s^{-1}$ in summer, $0.66m^3\ s^{-1}$ in winter; supplemented by hydro-electric releases of $15m^3s^{-1}$
17	Petts & Thoms, 1986. **UK**	Chew Valley, Chew	no figures	greatly reduced floods; 1968 - 100yr flood, no spillage
14	Higgs, & Petts, 1988 **UK**	Clywedog, Severn	no figure	MAF reduced at 3 stations: 192 to $142m^3s^{-1}$; 269 to $200m^3s^{-1}$; 273- to $249m^3s^{-1}$ low flows: 22% higher than the natural Q_{95}.; MAF reduced by 30%; median flow reduced by 50%
25	Richards & Greenhalgh, 1984 **UK**	Sea Cut, Derwent	no figures	bankfull reduced from $11.5\text{-}14.2m^3s^{-1}$ to $8.3m^3s^{-1}$
77	Davies, 1996; **Mocambique**	Cahora Bassa, Zambezi	no figures	floods greatly reduced

Table 2.3: Summary of the primary impacts of impoundments from Williams and Wolman (1984).

Map no.	*River and reservoir*	*Primary impact on sediment*	*dist. d/s*	Average daily Q		Annual peak Q		d_{95}	
				pre	post	pre	post	pre	post
54	Glen Canyon, Colorado	150km d/s: mean annual suspended sediment load reduced from 126mil.mgg/yr to 17mil.mgg/yr (87%)	26	480	320	2200	800	100	31
55	Hoover, Colorado	180km d/s: mean annual suspended sediment load reduced from 120-400 mil.mgg/yr to 5-30 mil.mgg/yr	180	520	400	2200	640	120	145
56	Davis, Colorado		72	400	340	640	550	145	140
57	Parker, Colorado		6.4	230	340	850	640	125	140
58	Jemez Canyon, Jemez		1.3	1.5	1.5	160	39	0.006	0.0
59	John Martin, Arkansas	water emptied annually, most sediment sluiced out with it; trap efficiency ranges from 0-99%	34	7.3	4.8	560	190	0.05	0.07
60	Fort Peck, Missouri		100	200	280	770	690	70	40
61	Fort Randall, Missouri		11	880	680	6300	1500	195	155
2	Garrison, Missouri	121km d/s: mean annual suspended sediment load reduced from 48.6mil.mgg/yr to 5.3mil.mgg/yr	120	600	660	3900	1100	140	250
63	Gavins point, Missouri	8km d/s: mean annual suspended sediment load reduced to 1% of pre-dam value (from 121 to 1.5 mil.mgg/yr); 1147 d/s mean annual suspended sediment load reduced to 30% of pre-dam value	8	930	740	5200	1200	250	220
64	Medicine Creek, Medicine Creek		15	2.7	-	530	-	0.8	-
65	Milburn, Middle Loup	operated to flush out sediment periodically	19	23	22	58	53	16.5	16.5
66	Red Rock, Des Moines		19	140	200	1200	800	7.6	13
67	Kanopolis, Smoky Hill		1.3	8.7	9.9	320	135	0.5	0.5
68	Milford, Republican		2.7	23	24	290	150	4.5	1.2

69	Fort Supply, Wolf Creek				1.7	240	35	.006	0
70	Canton, N. Canadian	99.5% trap efficiency; suspended sediment concentration takes 120-500km to recover	0.8	7.7	4.7	280	44	0.0006	0.03
71	Eufalfa, Canadian		13	175	130	3600	740	3.1	1.6
72	Denison, Red	99.22% sediment trap efficiency; 150km d/s: at a known discharge sediment concentration is 20-55% of that recorded for the same discharge before the dam was built		185	120	3000	950	7.1	3.2
73	Town Bluff, Neches		93	60	54	660	270	19.0	12.0
74	Bufford, Chattahoochee		4	60	54	660	270	19	12

Table 2.4: Summary of secondary impacts of impoundments according to studies reviewed.

CATEGORY	***IMPACT***	***AUTHORS***
cross section change	channel position change	Erskine, 1985; Williams & Wolman, 1984; Chien 1985; Buma & Day, 1977; Petts, 1979
	bank slaking	Petts & Pratts, 1983; Navarro, 1994; Walker, 1985; Jacobs, 1994; Dolan *et al.* 1974; Williams & Wolman, 1984; Sherrard & Erskine, 1991
	bank erosion	Navarro *et al.* 1994; Walker, 1985; Jacobs 1994; Chien, 1985; Buma & Day 1977; Dolan *et al.*1974; Turner & Karpiscak,1980; Petts & Pratts ,1983; Fergus, 1997; Petts & Thoms 1987; Williams & Wolman, 1984; Kearsley *et al.* 1994
	bank aggradation	Sherrard & Erskine, 1991; Richards & Greenhalgh, 1984; Buma & Day 1977; Benn & Erskine, 1994; Gregory & Park 1974; Petts & Pratts 1983; Petts, 1979; Fergus, 1997; Petts 1984
	bed aggradation	Woo & Yu, 1994; Kellerhals & Gill, 1973; Assarin, *et al.* 1994, 1994; Hammad, 1972; Hadley & Eschner, 1984; Walker, 1985; Jacobs 1994; Sherrard & Erskine, 1991; Petts, 1984; Qiwei *et al.* 1982; Chien,1985; Petts & Thoms 1986; Buma & Day 1977; Benn & Erskine, 1994; Bray & Kellerhals,1979; Petts & Pratts 1983; Petts, 1979; Kellerhals & Gill, 1973
	bed degradation	Erskine, 1985; Hrabowski, 1994; Woo & Yu, 1994; Walker, 1985; Jacobs, 1994; Sherrard & Erskine, 1991; Qiwei *et al.* 1982; Chien, 1985; Buma & Day, 1977; Turner & Karpiscak,1980; Kinaway *et al.* 1973; Shalaby, 1986; Assarin, *et al.* 1994, 1994; Petts & Pratts, 1983; Petts, 1979; Fergus, 1997; Williams & Wolman, 1984
	channel contraction	Hadley & Eschner, 1984; Navarro *et al.* 1994; Sherrard & Erskine, 1991; Petts & Thoms, 1987; Petts, 1984 ; Gregory & Park, 1974; Petts & Thoms 1986; Benn & Erskine, 1994; Petts, 1979
	bar erosion	Turner & Karpiscak,1980; Fergus, 1997; Kearsley *et al.* 1994
	bar development	Kellerhals & Gill, 1973; Hadley & Eschner, 1982; Chien, 1985; Richards & Greenhalgh 1984; Petts, 1979
	bar/bank joining	Sherrard & Erskine, 1991; Petts 1984; Hadley & Eschner, 1982; Chien, 1985
	silting/abandonment of 2° channels	Hadley & Eschner, 1982; Chien, 1985; Navarro *et al.* 1994;Fergus, 1997; Davies 1996
	accommodation	Erskine, 1985; Kellerhals & Gill, 1973; Benn & Erskine, 1994; Petts, 1979; Fergus, 1997
long profile change	gradient change	Kellerhals & Gill, 1973; Petts, 1984; Graf 1980; Petts, 1979; Hrabowski, 1994; Fergus, 1997
	channel pattern change	Hadley & Eschner, 1984; Navarro *et al*, 1994; Chien, 1985;
substrate change	coarsening/armouring	Erskine, 1985; Woo & Yu, 1994; Hammad, 1972; Assarin, *et al.* 1994, 1994; Tariq, 1994; Chien, 1985; Turner & Karpiscak,1980; Dolan *et al.* 1974; Kinaway *et al*, 1973; Petts, 1979; Williams & Wolman, 1984

	change in composition	Petts & Thoms, 1987 ; Richards & Greenhalgh 1984 ; Petts 1984; Petts & Thoms 1986; Hadley & Eschner, 1984; Chien, 1985; Qiwei *et al*. 1982; Williams & Wolman, 1984; Benn & Erskine, 1994; Graf, 1980; Kearsley *et al*. 1994
tributary zone change	downcutting	Kellerhals & Gill, 1973
	bar development and stabilisation	Sherrard & Erskine, 1991; Kellerhals & Gill, 1973; Petts & Thoms, 1987; Petts, 1984 ; Graf, 1980; Petts & Thoms 1986; Petts, 1979; Benn & Erskine, 1994
	delta growth	Kellerhals & Gill, 1973; Bray & Kellerhals, 1979; Petts, 1979
	coarsening of substrate	Benn & Erskine, 1994; Erskine 1985; Graf, 1980; Petts & Thoms 1986; Sherrard & Erskine, 1991

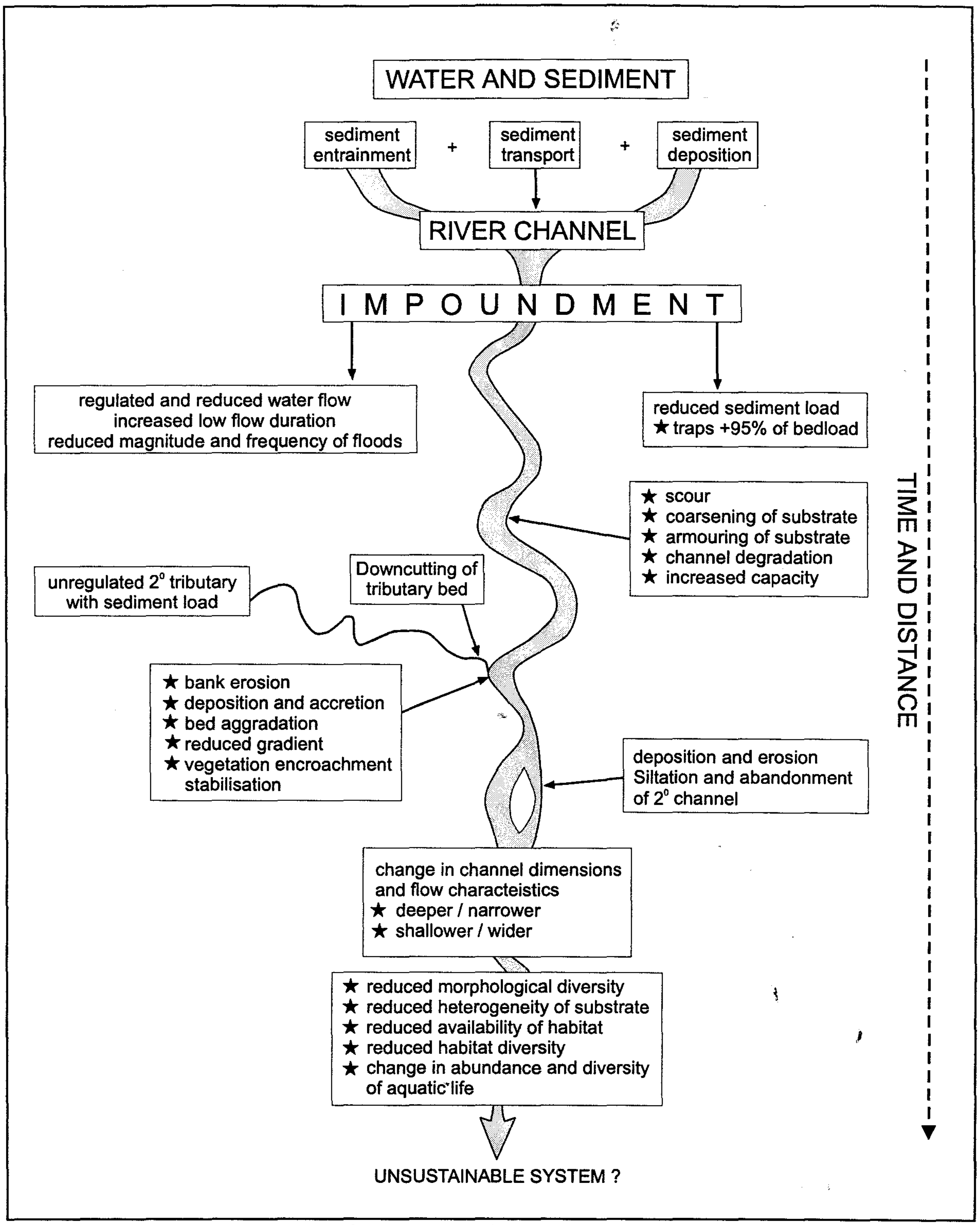

Figure 2.6: Conceptual model of the geomorphological impact of impoundments.

2.10.1 Change in cross sectional area

Bed degradation: this is well documented because it is the first and most easily identifiable impact occurring immediately below the dam. It is also significant because it can affect the stability of the dam structure and must therefore be catered for in the dams design. It happens initially immediately below the reservoir outfall, where the sediment free releases have a high capacity to erode and transport sediment. Its extent will depend on the availability of sediment and the nature of the substrate. The water can only erode sediment with movement thresholds within the capacity of the flow. Erosion of the bed and banks will occur until an equilibrium state is reached, by the process of armouring; by the exposure of a resistant substrate; or through reduced velocity in response to reduced gradient. The erosional front will progress gradually downstream until a state of equilibrium has been reached. This condition is most pronounced in alluvial sand bed rivers; greatly reduced in more stable gravel bed or channels; and non-existent in bedrock channels.

Bank erosion will occur where banks are not cohesive, or where reduced flows undercut the banks because of their lower position in the channel. Bank erosion is also associated with pulse type releases (typically associated with hydro-electric power generation) which wander across the channel intermittantly, causing erosion, without the follow-up of a depositional phase. High velocity discharges have the capacity to erode the river banks, particularly where the bank materials are not cohesive   A particular kind of bank erosion termed 'slaking' is associated with unseasonal high flows, and regular high releases. It occurs due to the interaction between groundwater forces and their control on bank stability, and the erosive forces of the stream flow. The presence of groundwater in the banks and floodplain adjacent to the river has an effect on the stability of the channel banks.   The groundwater table would normally be above the stream, with a steady seepage of water into the stream. This would have a destabilizing effect on the banks, which would be reversed under high flow conditions.   However, under regulated flow conditions with the continual rise and fall of stream stage, the rapid drawdown of the receding flood would destabilise the banks, during a period when the erosive forces on the bank face caused by the receding flood are higher than normal. This process would be repeated continuously with pulse type releases, thereby causing accelerated bank erosion (Taylor and Asce, 1974).

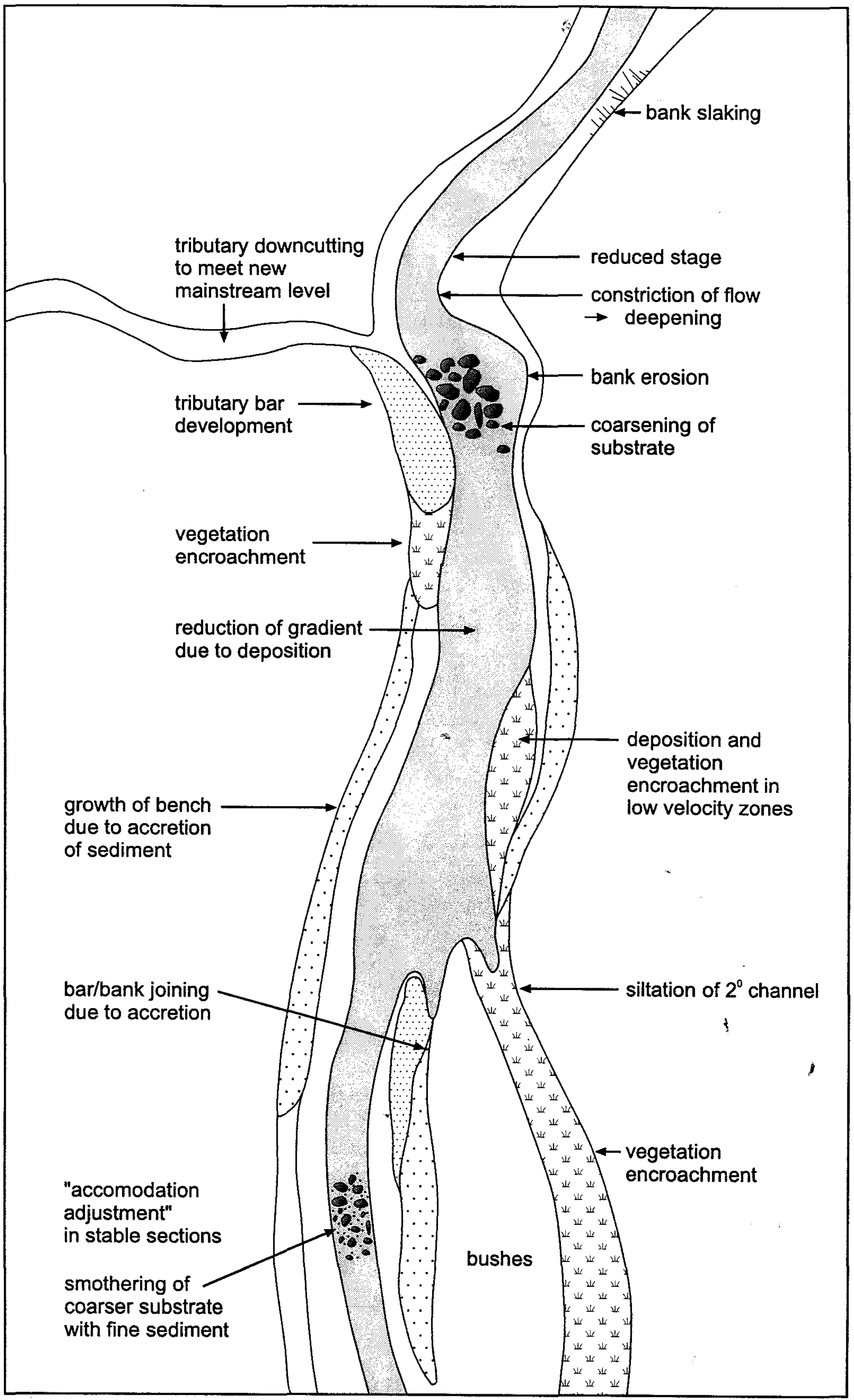

Figure 2.7: Illustration of morphological change in an impounded river.

Aggradation: the eroded material from upstream will be deposited when the transport capacity of the flow drops below a threshold. As the channel gradient reduces, flow velocities are reduced, and deposition occurs on the channel bed and banks. The velocity gradient in a channel is such that the fastest flows occupy the thalweg, with areas where there is friction or a high roughness having lower flow velocities. Anywhere where the velocity drops below the entrainment threshold of the sediment load, deposition will occur. A minor obstruction in a channel may cause a depositional zone, leading in time to the development of a bar. On the channel sides, where the water is shallow and velocities low due to friction, sediment will be deposited to form benches. Fine sediment may adhere to the banks by plastering. In this way the bank encroaches into the channel which is no longer capable of moving the sediment out, and the channel tends to deepen and narrow. The bedload will be deposited first, while finer material may stay in suspension as long as the flow has the capacity to transport it. In the absence of destabilizing high flows, vegetation is able to establish itself, and further stabilised depositional features. The channel cross sectional area is reduced in width and/or depth from its natural dimensions, to carry a much reduced flow. The stream occupies a micro-channel within the existing channel, with a bench, which marks the new bankfull level. Aggradation on the stream bed can be a problem where the stream no longer has the energy to move its load onto the floodplain - instead the load is deposited in the stream, causing the channel bed to rise.

Channel pattern change: as flow velocities change and the long profile changes, the channel may change from a braided channel to a single thread one. In the case of a multi thread channel, flow seldom divides evenly around a deposit, with the result that one channel is more active than the other (Schumm and Lichty, 1963). In the absence of high flows to activate and flush secondary channels, these channels may become silted up as the flows which pass through them are likely to be depositional rather then erosive. The main channel is likely to deepen and narrow, leading to the reinforcement of a single thread stream. The accumulation of silt and the absence of scouring flows provides suitable conditions for vegetation establishment. Linder (1952), cited in Schumm and Lichty (1963), has shown in laboratory experiments that the fork with the smaller discharge carries the highest bedload concentration, thereby making the smaller channel the most likely site of deposition. Vegetation converts once temporary bars to permanent channel features and eventually the secondary channels may accrete to such a degree that they bridge the islands/bars they once separated. In this way a multiple channel stream becomes a single thread stream, with water following the channel of least resistance. The change in channel pattern is not easy to 'certify' because it takes time, and may be an intermediate stage in adjustment (Chien, 1985).

Accommodation: possibly the simplest reaction to a changed flow regime is the 'accommodation adjustment' described by Petts (1979). Regulated flows are below the thresholds of change, so the flow simply occupies a lower position in the existing channel, for that particular reach. This would happen where the channel boundary is too stable to allow any change, as in a bed rock channel, a homogenous gravel channel, or a cohesive alluvial channel. The reduced flow is simply accommodated within the existing channel form and has sufficient power to transport available sediment through the reach.

2.10.2 Change in long profile

Gradient change: the long profile of the river will adjust depending on whether the stream is eroding or aggrading. For any significant profile change to take place a tremendous quantity of material would have to be eroded. It seems that in many cases bed coarsening/armouring causes a reduction in velocity that reduces transport capacity sufficiently to limit degradation and prevent a change in slope. Sand bed rivers are particularly susceptible to downcutting and profile change although armouring of the bed does take place thereby checking it. However, where coarse calibre sediment is introduced by tributaries, and is allowed to stabilised in the absence of high flows, the stream will at some stage respond by increasing its gradient in the form of a rapid/riffle. Under low velocity conditions, a stream with a high sediment load will gradually reduce its profile through aggradation because it is dominated by depositional processes, in the absence of erosive high flows. The process of deposition will eventually caused a localised increased gradient which will create conditions for sufficient velocity to move material through the reach.

2.10.3 Substrate change

Coarsening and armouring: the water which is released from an impoundment is free of sediment, having dropped its load in the low velocity environment of the dam. It thus has a high capacity to erode downstream of the dam. Depending on the velocity of the water, it will selectively erode particles, removing those sediments with a low entrainment threshold first. Because of the reduced discharge, the flow will be unable to move the coarser fraction of the channel substrate. The result is a protective pavement of coarse sediment with a high threshold of movement. The increased roughness reduces velocities, further reducing the capacity of the flow. Only very large flows will be able to disrupt the pavement. This forces the erosional front to move downstream to where it is able to do work, owing to the presence of finer sediments. The long term result is a coarsening of the substrate in a downstream direction, until the process is interrupted by an incoming tributary with a natural sediment load and unregulated discharge. This self protection mechanism also prevents any significant alteration of the long profile/bed slope. This process occurs across a range of substrates.

Change in substrate composition: increased flows may downcut the channel bottom until a resistant surface is encountered, in the form of bedrock or coarser sediments. Under reduced flow conditions with low velocities, deposition of finer sediments may take place over a stable bed. This is commonly associated with accommodation adjustment. Where unregulated tributaries enter the mainstream, their coarse sediment load will dominate that reach, if the main stream lacks the power to move the deposited material.

2.10.4 Tributary Junctions

Bar development and stabilisation: tributaries typically have steeper gradients than the mainstream, and therefore have the capacity to carry larger sized sediment. The status of the tributary must be considered with regard to its discharge and sediment production; the volume of water it introduces into the mainstream will be a function of its physical characteristics - geology, soils, landuse, catchment area, gradient, drainage density. The greater discharge in the main channel would normally compensate for a lesser gradient which would give it the capacity to move incoming sediment. Under regulated conditions, the mainstream lacks the energy to move the deposits, so they accumulate in the form of a delta or bars which become stable features. As they accrete, they may protrude above the water, allowing further stabilisation by plant colonisation, which further encourages deposition. Eventually they may adjoin the bank. The tributary will dominate the processes in that reach. Co-incident with this is erosion of the opposite bank by the flow directed/constricted by the tributary bar.

Petts (1984) and Petts and Thoms (1984) have studied tributary bar formation in great detail. Their findings show that the sediment is spread out in the reach in various forms: benches, bars, and channel bottom deposits, sorted according to sediment size fractions. Together these features constrict the channel flow, and raise the level of the bed. The volume of sediment in the features amounts to the volume eroded in the tributary catchment. At the bottom end of a tributary-dominated reach the channel adjusts its profile, with a rapid gradient increase. In the extremely arid environment of the Green river in Utah, Graf (1980) has identified large scale tributary deposits in the mainstream. These accumulations of landslide debris, consisting of large boulders, are immovable in the regulated stream, and they cause the formation of rapids. As the feature stabilises by the accumulation of other material, a gradient change occurs.

Downcutting: under regulated conditions, the mainstream will be out of phase with unregulated tributaries, so a high flow in a tributary will not necessarily coincide with a high mainstream stage. When this occurs, the tributary will be forced to erode its own bed to meet the reduced mainstream stage.

Table 2.5: Typical geomorphological responses to a regulated flow regime.

REACH DESCRIPTION	***REDUCED FLOW***	***INCREASED LOW FLOW***	***ABSENCE OF HIGH FLOWS***
bedrock/stable bed	accommodation, sedimentation	accommodation, armouring	sedimentation
multiple thread/ anastomosing/ anabranching	change to single thread; closure of 2° channel	deepening of main branch	closure of 2° channel; vegetation encroachment
non-cohesive banks		erosion; slaking	aggradation and deposition
stable banks	accommodation	deepening of channel; erosion of in-channel features	
single thread	accommodation; deposition on perimeter	deepening of thalweg, or widening; increased sinuosity	dominated by aggradation
non-cohesive banks	accommodation	bank erosion; widening; reduced depth	aggradation in channel
stable banks	accommodation	deepening of channel	aggradation
braided	change to single thread	erosion of bars/islands	stabilisation of bars; multiple to single thread
tributary junction	downcutting; deposition and aggradation;	armouring; coarsening of substrate	bar/delta formation opposite bank erosion; raising of bed; gradient reduction or localised steepening

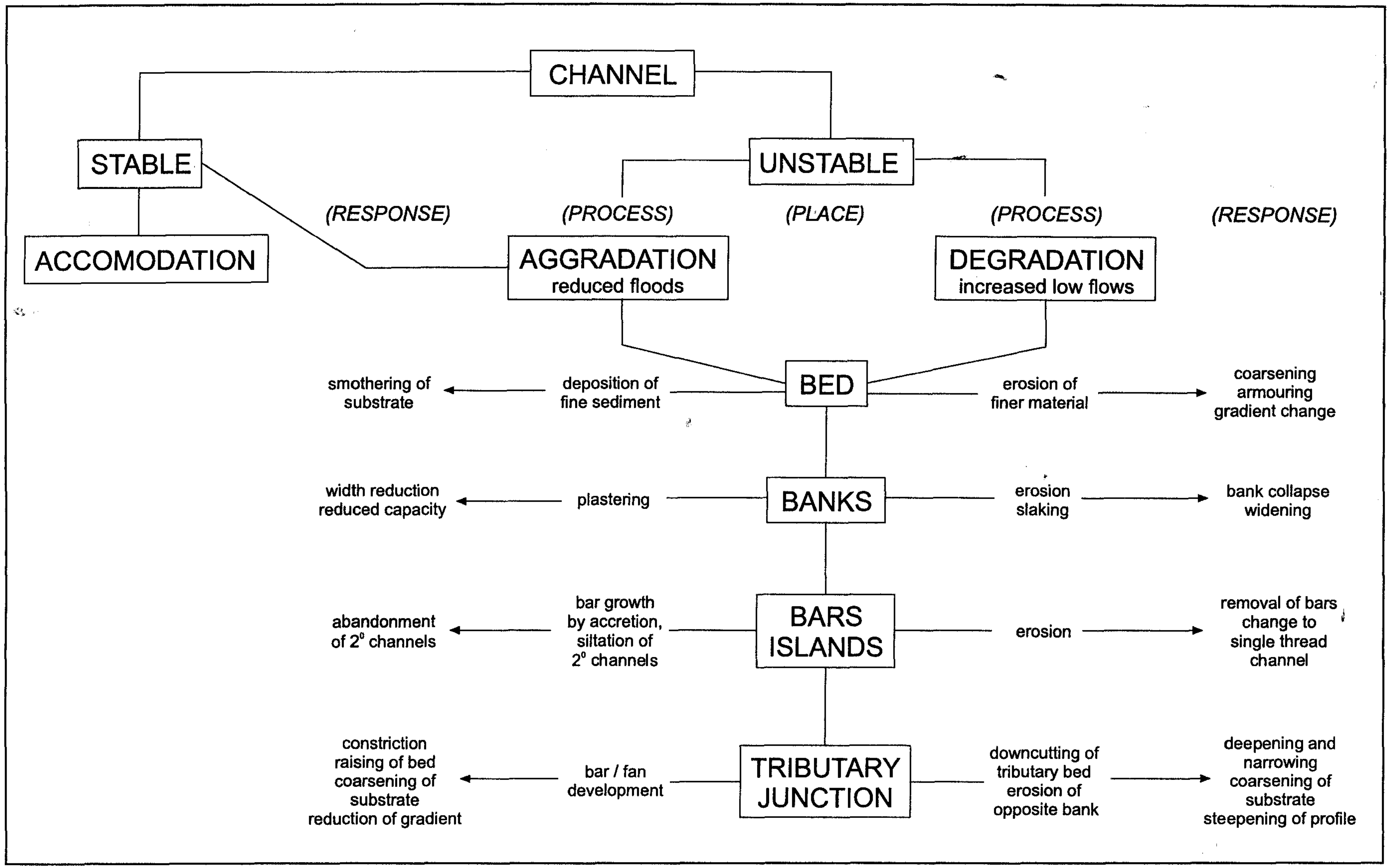

Figure 2.8: Flow diagram for predicting morphological change.

2.11 Predicting change

This chapter has presented an overview of the processes and responses in a fluvial system which give rise to particular channel morphologies. Together with a review of all the known geomorphological impacts of impoundments, a picture/pattern begins to emerge of the type of physical conditions under which particular morphological changes will occur. Using this understanding, together with a knowledge of the primary impact of an impoundment (the nature of the regulated flows), it is possible to begin to predict the nature of geomorphological change in a river downstream of an impoundment.

Figure 2.8 is a flow diagram which can be used as a preliminary guide to predicting geomorphological change. The first division is simple: channels respond depending on their stability. The processes which follow can be divided into three groups:

- accommodation which occurs in a stable channel under reduced flow conditions is the simplest, with no further responses
- aggradation which occurs under reduced flow conditions
- degradation which occurs under increased low flow conditions

The variety of responses and the places at which they can occur are then listed.

To add some substance to this flow diagram the following comments can be made about the type of channels and the responses that have been found to be typical of them.

Mixed bed channels: Change will be most complex due to the variety of impacts. Initially there will be degradation until an armoured layer is formed. Armouring may promote bank erosion while protecting the bed. Roughness will certainly increase, thereby further reducing velocities. If the channel boundary is sufficiently immobile, accommodation of the reduced flow in a 'micro channel' within the old channel will occur. Features such as rapids composed of large boulders may become permanent stable features, in the absence of large enough flows to disturb them. Where aggradation occurs in sections of an anabranching stream, the side channels will become silted up in the absence of sufficient flows to move the sediment, and will cease to function. In-channel bars would favour deposition and increase in size, forcing the channel into a more sinuous, meandering pattern. Vegetation would have the opportunity to establish itself under the low flow conditions, and there would be a progression from pioneer to secondary type species, with deeper roots which would bind and stabilised the substrate further. This would further increase roughness and encourage further deposition, promoting the process of stabilisation, and reducing the diversity of the system. All of these factors would combine to reduce the velocity further.

A bed rock channel, or a stable boulder/cobble bed will channel simply accommodate the new flow without making any morphological adjustment. Incoming sediment may be deposited on the channel bottom in the absence of competent flows to move it.

In an *alluvial channel with non-cohesive banks, and a stable bed* - there is likely to be widening of the channel, caused by bank erosion or slaking. Deposition is likely to follow with the formation of new in channel features.

A *sand bed channel* will erode until armouring develops; a resistant substrate is uncovered, or until gradient is reduced sufficiently to decrease velocity and stop the erosion process. It is likely to be followed by deposition further downstream.

In terms of these different channel types and based on information from the literature reviewed, certain areas can be identified where morphological change is likely to take place, which are listed below. These sites would be good 'indicator' sites which might be used to get an indication of the impact that an impoundment is having on a system. By monitoring these sites it might be possible to rectify the situation through different operational procedures at the dam.

- reaches which are braided or anabranching can change to single thread if conditions are altered sufficiently
- reaches of a low gradient where deposition dominates can accrete to such an extent that they outpace the growth of the floodplain

- tributary junctions where tributaries have a high sediment load are likely to be problematic with a high rate of aggradation; coarsening of substrate and opposite bank erosion
- secondary channels which only function at higher flows are susceptible to closure
- coarse substrate reaches with high sediment input from the catchment will be susceptible to sedimentation in the absence of sufficient flow
- areas of aggradation which require periodic flushing to destabilise them

In addition there are certain circumstances under which the impact of an impoundment is likely to be exacerbated, which are listed below.

- high sediment production in the catchments of the tributaries
- semi-arid environment where the main channel is often out of phase with the tributaries
- semi-arid environment where the runoff controlled by the dam is a high proportion of the whole systems flow
- semi-arid environment where tributary contribution downstream is negligible
- unstable bed and banks
- operational procedures that produce a flow regime that is very different to the natural regime
- high abstraction rates which reduce the total volume of flow.

CHAPTER THREE

APPLICATION OF IMPOUNDMENT IMPACT MODEL

The overall aim of this project was to improve our understanding of the geomorphological impacts of impoundments, that it might contribute to improved and sustainable management of this country's limited water resources. It is therefore necessary to take the conceptual model which was developed in the previous section, and apply it to South African conditions. A brief overview of South African rivers is presented, followed by application of the model to some river systems where IFR workshops were conducted.

3.1 South African river systems

South African river systems are characterized by their variability. Both flow and sediment relations are highly variable. Given that our dams are designed to counteract this variability and ensure supply it is to be expected that the impact on the functioning of these river systems will be great. Many of our river systems rise in humid mountain headwaters, and run for most of their course through arid to semi-arid environments, receiving little runoff in these regions (see Table 3.1 and Figures 1.1, 1.2 and 1.3). Thus dams situated where they control a high proportion of the total discharge in a river, will be particularly detrimental to the functioning of that system. Other factors which compound the negative effects are: naturally high sediment yields; poor land management; invasion by exotic plants and heavy utilization of water by agriculture for irrigation.

Partly as a result of the hydrology of this region, but largely as a result of geological characteristics, our river systems do not show a conventional profile from high gradient, bedrock and cobble headwaters to lower gradient sand bed streams. Instead many rivers exhibit a variety of channel types, at various stages along their profiles. Most of our rivers can be classified as mixed bed channels, with reaches of bedrock interspersed with alluvial reaches, with a variety of substrates. Bedrock channel form is dependent on the underlying geology, whereas alluvial channels are self formed by water action, and may have a substrate that ranges in size from sand to boulder. Many alluvial reaches have resistant bedrock outcrops at intervals which control their gradient. Most systems are confined by valley sides, never giving them the opportunity to develop a true floodplain. The prevalence of flood and drought coupled with high variability gives many rivers high transport capacities.

Table 3.1: Areas of the primary drainage regions generating high runoff (as proportions).

Primary Catchment	*name*	*proportion of area (%)*	*proportion of MAR generated (%)*
A	Crocodile	4.6	27
B	Olifants (Mpumalanga)	4.6	33.6
C	Vaal	9	24
D	Orange	7.5	69
E	Olifants (Cape)	4.6	45
F	Groen	22	52
G	Great Berg	22	13
H	Breede	20	50
J	Gouritz	11	38
K	Krom	26	44
L	Gamtoos	4.8	27
M	Swartkops	28	47
N	Sundays	18	33
P	Bushmans	14	26
Q	Great Fish	18	33
R	Buffalo	14	26
S	Great Kei	22	41
T	Mzimkulu	11	18
U	Mgeni	35	19
V	Tugela	10	26
W	Mfolozi	11	12
X	Komati	16	40

In terms of impoundments the impacts will be complex and varied because of the range of channel types which may occur in one system. The fact that different reaches will react differently to regulated flow conditions must be taken into account when identifying or predicting secondary impacts.

From a review of literature it is evident that there are many common responses to impoundment, which will tend to occur under particular conditions. The following list of factors which should be taken into account when predicting the secondary impacts of impoundment is derived from the various conceptual models and tables presented in chapter 2:

- hydrological regime: arid or humid
- degree of primary impact: reduced floods, and/or increased low flow
- channel type: unstable or stable
- inputs of sediment below the dam
- inputs of 'unregulated' flow below the dam
- increase in 'unregulated' catchment area
- zones of aggradation
- zones of degradation

The application of these ideas is illustrated below by reference to work carried out at three IFR workshops. As the conceptual model was still being developed at the time of the workshops, some of the information has been compiled in retrospect.

3.2 Geomorphology and the Building Block Methodology

The IFR concept has been explained in chapter 3. This section deals with the role of the geomorphologist in the IFR workshop. Rowntree and Wadeson (1998), and Rowntree (1998) give a full explanation of the reasoning and method of this in the geomorphology chapter for the Building Block Methodology manual. It is based on the notion that the geomorphology of a river system provides some basic clues as to the nature of a river's flow regime in terms of the magnitude and frequency of flows. An assessment of the morphological characteristics of a river channel such as substrate, channel pattern, long profile, channel cross section *etc.* can be used to estimate the magnitude of flows required for channel maintenance and formation. Given a knowledge of the variety of impacts described by other authors, it is possible to look at the characteristics of a river reach, predict the type of impacts that might be expected under regulated conditions, and thereby motivate for flows of particular magnitudes and frequencies that would reduce or prevent these changes. This knowledge could then be used in designing a set of dam operational rules to minimize the negative impacts.

A variety of sites investigated at three IFR workshops with different morphological characteristics are discussed below, in an attempt to show how these river reaches would be expected to respond to regulated flows, based on the conceptual model laid out in the previous section. The location of these sites and the primary catchments in which they occur is shown in Figure 3.1. Flow recommendations to mitigate these impacts are not given but the type of changes that would be expected under certain flow conditions are described.

The geomorphological reports were prepared from field surveys, GIS analysis and desk-top studies, and were included in the IFR 'starter documents' for the Berg, (Rowntree and M^c^Gregor 1996) Bivane (M^c^Gregor 1996) and Komati River workshops (M^c^Gregor, 1997). The sites which are investigated in an IFR workshop are selected as being representative of the different geomorphological reaches in a river system, and therefore would support the fauna and flora typical of that system. If the natural flow regime can be identified and catered for at those sites, then it is assumed that the requirements along the rest of the river will be also catered for. It should be noted that runoff values used in this discussion are taken from the WR90 data set, which are modeled values based on virgin conditions. Actual values may be close to these, but where catchment conditions are greatly changed, values may be a lot lower.

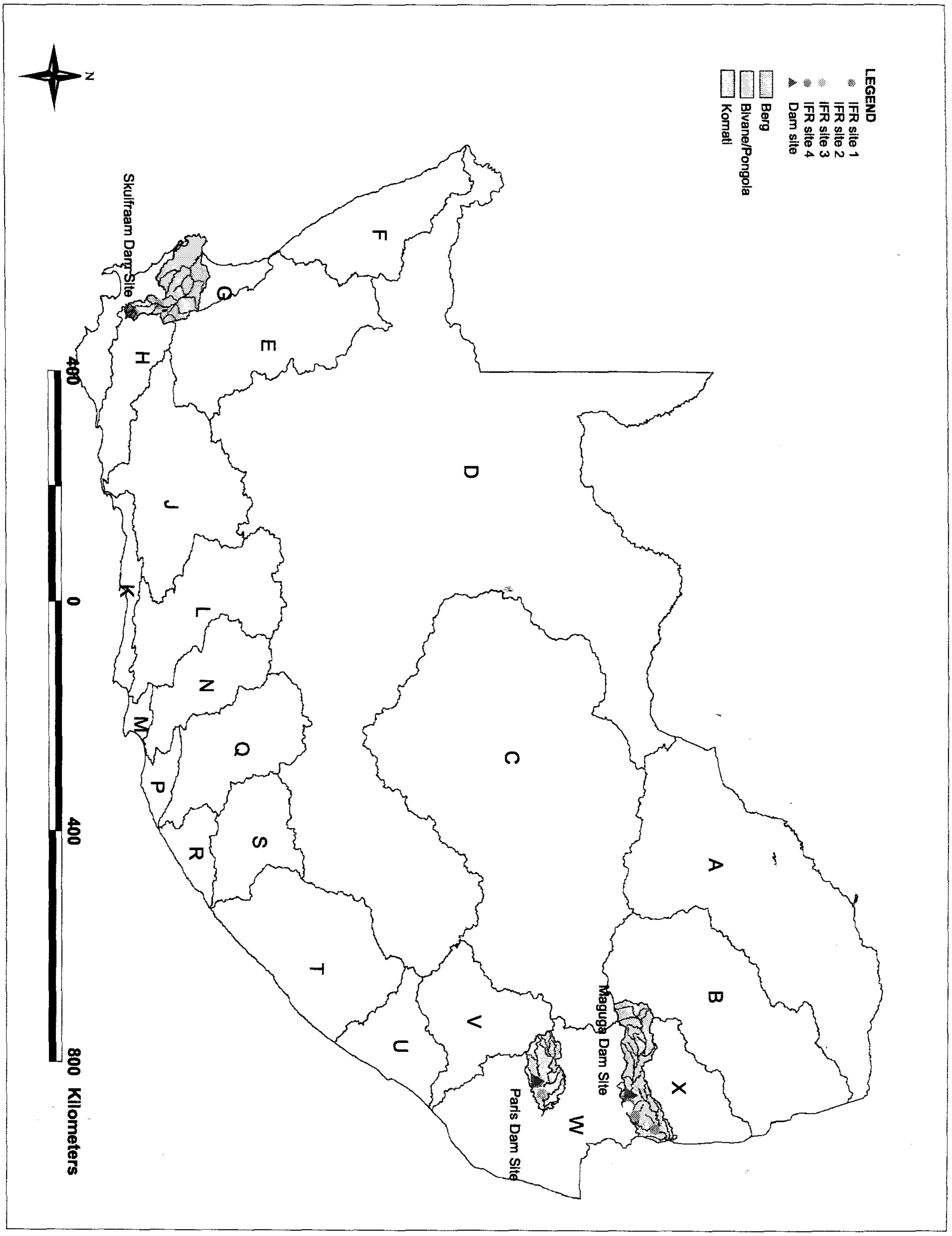

Figure 3.1: Location of IFR studies discussed in the text.

3.2.1 Berg River, Skuifraam Dam

General description of catchment

The Berg river rises in the Cape Fold mountains. The catchment above the proposed Skuifraam dam is too mountainous for agricultural use and is therefore still well protected by natural vegetation *(fynbos)*, as well as commercial plantations and some invasive species. Below the dam, the valley bottom has been extensively developed for agriculture, and industry. The channel and the surrounding catchment have been significantly disturbed. Any major tributaries below the dam have already been severely impacted by damming, pollution, direct abstraction, and diversions (Brown, 1997 pers. comm.). Sediment production in the downstream reaches is moderate. Almost all the runoff is derived from the high rainfall (2500mm/yr) headwaters. Below the dam, runoff is 500mm which has decreased to 168mm in the vicinity of IFR site 3. The mountainous catchment above the dam, representing 9,6% of the total catchment, generates 59% of the runoff. The main purpose of the dam would be for summer irrigation, in the lower reaches. Being a winter rainfall region, this would entail above average flow releases throughout the dry summer months, to such an extent that there would actually be a seasonal reversal of flows.

Table 3.2: Berg River IFR - dam, catchment and IFR site statistics.

	areas and volumes	*proportions of total*
Total Berg catchment	7715 km^2	
Total runoff	913 x 10^{6}m^3	
Area downstream of dam	7543 km^2	97.7
Runoff downstream of dam	738.8 x 10^{6}m^3	81%
Dam catchment	172 km^2	2.23%
Runoff above dam	174.5 x 10^{6}m^3	19%
Dam capacity	165 x 10^{6}m^3	1.26 x MAR at dam 18% of total MAR
Dam surface area	4 km^2	2.3% of regulated area
Recovery at IFR1: *unregulated area* *unregulated runoff*	 negligible negligible	
Recovery at IFR 3: *unregulated area* *unregulated runoff*	 1142 km^2 353.5 10^{6}m^3	 9 x regulated area 2x regulated runoff

IFR site 1 was selected as typical of the foothill zone, with a reach gradient of 0.007. It is located 3km downstream of the dam wall, where the river is broad and shallow, and has several channels, branching around islands. At high flows it would form a braided channel, which would allow some movement of the sand, gravel and cobble bed substrate. The banks were sandy but stable where vegetated with both indigenous plants and invasive species. The water was clear and sediment free at the time of the site visit.

Predicted impacts

There is likely to be an input of sediment during the dam construction phase which would be readily removed by the sediment hungry water. It is likely that any sediment deposited in the system within so short a distance of the dam, would be moved by the releases of clean water.

Depending on the volumes of water released, and therefore the competence of the flow, there would be scouring of the channel immediately below the dam, which would increase its capacity. Armouring would certainly occur, given the predominantly coarse substrate. Sustained base flows might cause the sandy banks to erode. The eroded sediment would be deposited further downstream, possibly causing aggradation in reaches with a reduced gradient further down. In the absence of high flows, there would be no flushing of secondary channels, aggradation would dominate resulting in their abandonment, leading to colonization by invasive plant species.

IFR site 3, with a reach gradient of 0.0004 is located 70km downstream of the dam, and was chosen as being representative of a single thread, incised sand bed channel, with occasional bars and rapids. Runoff and unregulated area have 'recovered' substantially (Table 3.2). The water was deep, fast flowing and muddy at the time of the site visit. There is a secondary channel at the site which would only be activated at high flows. The banks being sandy are non-cohesive and susceptible to erosion, particularly where the vegetation has been disturbed, or where the weight of invasive trees is causing them to collapse. Debris in the channel caused flow obstruction. Agricultural lands had been ploughed to within a few metres of the river, although a riparian strip of exotics and indigenous species remained intact. The remains of a flood plain could be identified on the left bank.

Predicted impacts

Sustained baseflows would be totally contrary to the natural regime often river in these middle reaches, where it is semi arid in nature. Therefore despite the distance downstream and the ‘recovery’ of flow, impacts might still be significant. Under sustained high irrigation releases, this section would most likely erode its banks, and widen its channel, destroying the remaining riparian vegetation, and cutting back into agricultural lands. The condition of bank slaking discussed in chapter three could also be a problem. Reduced floods would result in the secondary channel becoming permanently closed by siltation and the establishment of invasive species.

3.2.2 Bivane River, Paris dam

Catchment characteristics

The Bivane river is a major tributary of the Pongola. It drains a catchment area of 1691km^2, with an average annual runoff 200-300mm per annum. High rainfall and good soils make the land suitable for extensive agriculture and in recent years, more and more land has been planted to commercial forests, now covering about 35% of the catchment. Only a fraction remains as natural veld. There are also several collieries in the catchment. The proposed dam will be used for irrigation purposes in the dry winter months, to supplement flow in the Pongola system when levels are low there, and allow for irrigation offtake in the Pongola valley. The Paris dam will only affect a 40km reach of the Bivane, before its confluence with the Pongola. Runoff in the vicinity of the dam and at IFR 1 and IFR 2 is 125-135mm per annum, and reduces to around 120mm below IFR 3. Sediment input between IFR 1 and IFR 2 would be low, due to the good cover afforded by predominantly natural vegetation, but would increase downstream of IFR 3, due to agricultural activity in the catchment.

Table 3.3: Bivane River IFR - dam, catchment and IFR site statistics

	areas and volumes	*proportions of total*
Total Bivane catchment	1691 km^2	
Total runoff	327 x 10^{6}m^3	
Area downstream of dam	96 km^2	6%
Runoff downstream of dam	12.9 x 10^{6}m^3	4%
Dam catchment	1595 km^2	94%
Runoff above dam	314.1 x 10^{6}m^3	96%
Dam capacity	115 x 10^{6}m^3	37%
Dam surface area	not given	
Recovery at IFR1:		
unregulated area	15 km^2	0.9%
unregulated runoff	2,02 x 10^{6}m^3	1.5%
Recovery at IFR 2:		
unregulated area	120 km^2	7.5%
unregulated runoff	16 x 10^{6}m^3	5%
Recovery at IFR 3:		
unregulated area	4156 km^2	2.7 x regulated area
unregulated runoff	859.4 x 10^{6}m^3	2.7 x regulated runoff

IFR site 1 with a gradient of 0.01 was selected as representative of a confined mixed bed channel, with sandy banks and a cobble bed, with pools controlled by outcrops of bedrock. The site is within one kilometre of the dam wall. There is an absence of any significant riparian zone, the after effects of the 1984 cyclone Demoina. The channel banks are well grassed and seem to be in a stable state. The surrounding catchment is under grass and natural bush. The main geomorphological feature is a riffle, which at the observed flow of 8 m^3s^{-1}, created a run. An island of reed and grass, growing on a sand and cobble substrate, diverts about one third of the flow towards the right bank. There is a definite flood channel on the left bank, which is separated from the main channel by a grassy sand bar. It would be activated by high flows, approximating the five year flood. At this flow there was a minor backwater in the flood channel. A flow with a depth of approximately three metres at the deepest point on the channel cross section would inundate the flood channel. There are small cobble and gravel deposits in this channel. Above and below the site are long pools, confined by rocky faces and steep banks.

Predicted impacts

Within so short a distance of the dam, releases are likely to be sediment free, with high erosive power. In the case of sustained high baseflows there would be a danger of the island being eroded. The sand/silt banks of this reach would also be susceptible to erosion and possibly to bank slaking. In the absence of high flows, the flood channel on the left bank might be closed off by siltation and vegetation encroachment.

IFR site 2, (Plate 3.1) with a gradient of 0.005, is situated approximately 34km downstream of the dam, and a few hundred metres upstream of the Pongola confluence. The channel is less confined and represents a cobble bed reach. It is fed by an unregulated catchment area of 120km^2, with an area/runoff ratio of 1:6.

Upstream of the site, from bank to bank is a large shallow pool, with a cobble and sand substrate. extensive cobble bank. The left bank is sheer to concave, and is largely bare, and actively eroding (Plate 3.2). The right bank is an extensive cobble bank. Adjacent to the channel, the cobble bank is concave, and bare of vegetation. On the more level bank top, where sand deposition has occurred, grasses have established themselves (Plate 3.3). The cobble bank adjacent to the channel is relatively unstable due to its steep slope and large particle size. Bordering on the cobble terrace is a low, well-grassed mud bank.

Plate 3.1: Bivane IFR site 2 - upstream view.

Downstream of the riffle/rapid is a pool with a sand and bedrock substrate and some cobbles. A small cobble bar protrudes into the top of the riffle from the left bank, with some sedge like vegetation. A short line of vegetation set on a cobble bar, runs parallel to the stream and adjoins the right bank.

There are no significant size tributaries which enter below the dam, but upstream of this site are a few ephemeral tributaries which enter onto the river terrace. Their catchment areas are small (< 2km^2), but due to the steep terrain and the rocky soils, they are able to discharge small quantities of gravel size sediment onto the terrace (Plate3.4). Their entrances are a few metres above the level of the main channel. Invasive plant species are well established on this terrace.

Predicted impacts

Too many unseasonally high flows could result in further erosion of the left bank, which is already sensitive in the absence of a riparian zone. The long pool upstream is naturally an area of aggradation, and would tend to silt up in the absence of high flows. Bar and bench development would probably occur, reducing the channel width. Flows would also need to be high enough to prevent exotics from establishing themselves, on the pool edges and on the cobble bar. The angle of the cobble bank suggests that this area is naturally subjected to very high flows fairly frequently. These high flows would be necessary to keep up the bedload supply to the Pongola system.

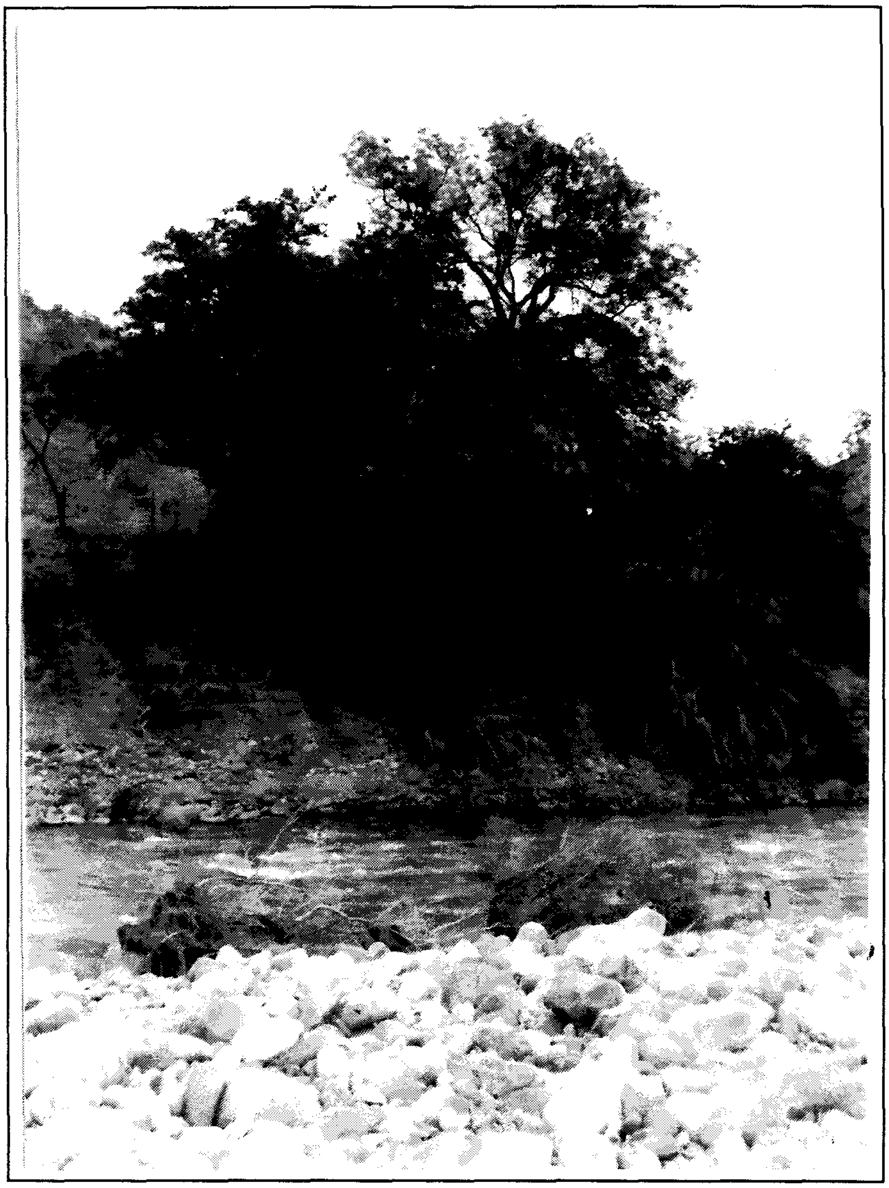

Plate 3.2: Bivane IFR site 2 - rapid feature with trapped debris in the foreground, eroding bank in the background.

Plate 3.3: Bivane IFR site 2 showing cobble terrace with vegetation growth.

Plate 3.4: Bivane IFR site 2, upstream view - gravel deposit at tributary mouth.

IFR site 3 on the Pongola, has a gradient of 0.005 , and is also representative of a cobble reach. The drainage area of the Pongola at this site is approximately 4500km^2, and the discharge has increased by 65% with the confluence of the Bivane. The river channel is less confined than in the Bivane catchment with a wider valley bottom, and some room for movement, although sheer rock faces and steep slopes descend to the water's edge in places. At the time of the site visit (November 1996), the discharge was approximately 19 m^{3}s^{-1}. The water appears to carry a moderate sediment load at this flow. Sediment input in this reach would be expected to be higher than at the other IFR sites, due to settlement and agricultural activity in the catchment. The surrounding slopes are mostly well vegetated, but there is evidence of some minor landslides.

The main geomorphological features here are a riffle with a substrate of cobble, separated from a large backwater pool by a cobble riffle leading into an extensive cobble bar on the left side. Water spills over the cobble bar into the main channel at right angles. On the right bank a secondary channel leading into a backwater pool leads off the main channel, just upstream of the riffle. It is separated by a reed bank, set in silt with some cobble sections. The backwater substrate is cobble and silt. At a slightly higher flow, water would flood backwards into the backwater, and at an even higher flow the upstream channel leading into it would be activated. The riffle ends in a bedrock rib. Immediately upstream of the riffle is a broad pool with sand, cobble and bedrock bottom. The left bank is a low mud/silt bench with some bedrock and boulders protruding from it, leading back onto a well-vegetated slope. The right bank is a terrace of sand and silt. It is a disturbed zone, which appears rather messy due to the presence of pioneer species and flood debris. *Lantana* bushes have caused a chaotic pattern of deposition, probably due to their dense bushy proportions, which would present a barrier to high waters. Two small tributaries enter onto the terrace: they have well vegetated banks and are used as game paths. There are some large trees in what would be the riparian zone, on the bank top. Trapped flood debris is evident at a height of about 2.5m in trees on the terrace.

Predicted impacts

There is evidence of aggradation and deposition at this site already: in the absence of flood flows therefore sedimentation could be problematic. The secondary channel would certainly be silted up, and in the presence of various invasive species is likely to be further stabilised. The terrace would also be susceptible to alien invasion without floods. Sustained low to medium flows would probably not be a problem as there is a lot of cobble in the channel perimeter. Given the stable nature of the bed (large cobble substrate) the channel would armour, and simply accommodate reduced flows.

3.2.3 Komati River, Maguga Dam

Catchment characteristics

The influence of the upper catchment (above 1050m) on the study reach will be buffered by the 2 large dams controlling the flow of that area: Vygeboom Dam at 1050m, capacity 79.210^6m^3 x and Nooitgedacht Dam at 1150m, capacity: 78,823 $x10^6m^3$. The new dam will control an unregulated catchment of approximately $3043km^2$, with a total runoff per annum of 433.4 $x10^6m^3$ (not including releases from the Vygeboom dam). The Maguga dam is to be built primarily for irrigation purposes, with a strong possibility of hydro power turbines being installed in a later development phase. (The area under consideration extends to the RSA/Mocambique border).

In the upper reaches of the study area, there is quite extensive afforestation. In the middle reaches, the gentler hill slopes and valley bottoms are cultivated, although much of the natural vegetation is still intact, as is evident in 'the Kings Lands.' In the lower reaches, the population is dense. Natural vegetation has been cleared around settlements, and for extensive cultivation, mostly cotton and sugar cane under irrigation. Cultivated lands lead right down to the rivers edge, and the riparian zone and terraces have been cleared for subsistence agriculture in many places. Water resources in the area are already substantially utilized, which is evident in the series of weirs on the river, with a network of off take canals. Sediment production ranges from moderate in the upper reaches to high in the lowlands. The degree of sedimentation in the lowlands is increased by the numerous weirs which severely impede the flushing of sediment through the low gradient reaches. This is an aspect of the system which must be considered in this IFR. With the Maguga dam in place, the situation could possibly be improved with a better management strategy.

Table.3.4.: Komati River IFR - dam, catchment and IFR site statistics.

	areas and volumes	*proportions of total*
Komati catchment	11091 km^2	
Total runoff	1429 x 10^{6}m^3	
Area downstream of dam	4620km^2	40%
Runoff downstream of dam	572.6 x 10^{6}m^3	40%
Dam catchment	6571 km^2	60%
Runoff above dam	857.1 x 10^{6}m^3	60%
Dam capacity	332 x 10^{6}m^3	39% of MAR at dam 23% of total MAR
Recovery at IFR1:		
unregulated area	376 km^2	5%
unregulated runoff	106 x 10^{6}m^3	12.3%
Recovery at IFR2:		
unregulated area	445 km^2	6.7%
unregulated runoff	117 x 10^{6}m^3	13.7%
Recovery at IFR3:		
unregulated area	915 km^2	13%
unregulated runoff	193 x 10^{6}m^3	22%
Recovery at IFR4:		
unregulated area	2234 km^2	34%
unregulated runoff	253 x 10^{6}m^3	29%

IFR Site 1 (Plate 3.5) is about 15km downstream of the dam wall. The reach is characterized by a confined channel with a gradient of 0,008 and pool- rapid sequences. The unregulated mean annual flow amounts to 24% of the regulated volume, and the unregulated area equals 12% of the regulated catchment. The surrounding catchment, vegetated mostly by natural vegetation is in good condition. A settlement and cultivated lands, as well as trampling on the river banks by livestock would provide localized sediment input. The site is used as a crossing point for people and livestock, with associated disturbance. The gradient of the stream in this reach is sufficient that most of the incoming fine sediment is flushed further downstream. Upstream of the site is a long pool, with a well defined right bank terrace, edged with reeds. At the lower end, where the channel gradient changes, a small side stream (Plate 3.6) divides off towards the left bank around a large, well vegetated cobble and sand island. The side channel is two to three metres wide, with shallow fast flowing water, and a clean gravel and sand substrate (Plate 3.7). The left bank of this side channel is initially vertically cut, two to three metres high. The main channel is broad (approximately 50m) and fast flowing, with a substrate of sand, cobble and boulders. At the time of the site visit the water was clear, although in the wet season suspended sediment loads can be high. At a discharge of $9m^3s^{-1}$, most of the site was a run: at lower flows it would become a riffle.

Predicted impacts

The island is a large permanent depositional feature, of sand, silt and cobble (Plate 3.8). In the absence of high flows, sediment would most likely accrete on its margins, eventually reducing flow in the side channel, and changing the channel pattern from anabranching to a single thread. Sustained high baseflow would undermine the strength of the side channel bank, causing bank collapse and increased fine sediment input, possibly smothering the gravel substrate. Most of the flow cuts across the foot of the island to join the main channel, where it forms a cobble riffle. The remaining water flows around a vegetated sand bar, in a narrow channel, before joining the main stream. This type of feature would be susceptible to sedimentation and closure in the absence of sufficient flood flows, while being susceptible to erosion by sustained baseflows.

Plate 3.5: Komati IFR site 1, showing run feature with cobble bar and island in the background.

Plate 3.6: Komati IFR site 1 - secondary channel.

Plate 3.7: Komati IFR site 1 - clean gravel substrate in secondary channel.

IFR Site 2 is a few kilometres downstream of IFR 1, the site consists of a series of riffles, rapids and runs, controlled by the predominantly bedrock substrate. At the time of the site visit, the channel was approximately 65m wide, and 1.3m deep at the deepest point. The water was clean and fast flowing. The substrate was clean, with sediments of coarse sand settled out in places. On the left side of the river against the bank, there were some muddy bottomed backwaters with deposits of detritus and silt on bedrock.

On the right bank there is a well grassed secondary channel, which leads off the main channel, across the narrow right bank terrace. It intercepts an ephemeral tributary, which crosses the terrace at right angles. The left bank has a terrace, 40-50m wide, which is well vegetated and has been burnt recently. The banks leading up from the terrace are steep.

Predicted impacts

Given the stable nature of the bedrock controlled channel, under reduced flow conditions, the flow would simply be accommodated within the existing channel form. In the absence of high flows there might be an accumulation of sediment in the back water areas. The terraces, and the

Plate 3.8: Komati IFR site 1 - bar substrate of cobble and coarse sand.

secondary channel would be colonized by plants, particularly by the alien invasive species which are present. Under sustained baseflow, this site would probably remain relatively unchanged due its stable nature. There would probably be removal of finer sediments, resulting in an overall coarsening of substrate, and erosion of mid channel reed islands and scour down to bedrock level of the small pools below the rapids.

IFR Site 3 is located in a transitional reach, mostly sand bed with occasional rocky outcrops, gradient has reduced substantially to 0,001. Geomorphologically this site is complex - probably due to the effects of the weir upstream, but also due to the use of this site as a drift in the past. Sediment input has increased due to settlement and agricultural activities. A sediment fan could be seen upstream of the site, underwater at the Mzimnene confluence on the video footage. The site is located a few hundred metres downstream of the Iysis weir, on a large riffle/rapid section, where there are outcrops of bedrock. It is about 65km downstream of the dam, and the unregulated area has increased to about 860km^2 (28% of regulated catchment) , with an increase of 253 x 10^{6}m^3 of mean annual runoff (58% increase). The river is confined by a steep right bank and bedrock outcrops. The substrate size is large, mostly cobble and boulder, with accumulations of gravel size sediment at the waters edge. On the left bank, there are heaps of cobble which are most likely man made, possibly collected for road building. The gradient of the left bank is gradual. There is evidence of a narrow, rather uneven terrace. This may have been caused by sand abstraction. Just upstream of the main site, the river divides around an island forming a large pool. On the left bank there is an accumulation of large flood debris between the main stream and a dry secondary channel. There is small scale cultivation on the left bank.

The right bank is steep, but moderately well vegetated. Due to the sandy nature of the bank, and the removal of vegetation where the track comes, the bank is eroding. A small ephemeral stream enters the site from the bank.

Predicted impacts

Impacts are likely to be small - the system is already fairly degraded, and affected by the weir upstream. Under lower flow conditions the channel would simply accommodate the reduced flow. Because much of the sediment is trapped by the weir, at this site there would not be significant sedimentation and aggradation even if high flows were reduced, but they might well be problematic further downstream.

IFR site 4 (Plate 3.9) is representative of a bedrock channel. The average gradient has increased slightly to 0.002, due to the presence of bedrock outcrops. Unregulated area has increased to 2472 km^2 (81% of regulated area). Unregulated mean annual runoff amounts to 371 $x10^6m^3$ (85% of regulated volume). Theoretically given these type of recovery values in terms of unregulated runoff and unregulated area, the impact of the dam this far downstream should be negligible. Also given that the river is in a degraded state anyway, the dam impacts are not as much of a concern as those that already exist. It must be noted that this section of the river is heavily utilized, so flow volumes are not necessarily representative of what is actually in the river. The Tonga weir immediately above the site is completely silted up.

The site is dominated by an outcrop of Tshokwane granophyre, which forms extensive bedrock cascades directly below the weir. The river flows across and down this 150m wide rock outcrop in a series of bedrock channels, chutes and cascades, forming many small plunge/pothole pools in the bedrock, before spreading out into a broad channel with numerous small islands. There is gravel substrate in the bottom of some of the pools on the left bank, but the substrate is predominantly sand and sand on bedrock. The right bank has been substantially altered to carry an irrigation furrow leading off the weir. The terrace which lies at the foot of the bank is probably natural, but a lot of the angular boulders and cobble size rocks along the waters edge are construction debris.

On the left bank there is evidence of a side channel and a terrace. The area has been disturbed in places where sand has been abstracted. Sand abstraction with mechanical diggers is obviously common in the area upstream and downstream of the site. It is therefore difficult to determine which of the features are natural.

Predicted impacts

Under reduced flow conditions, the channel at this site would simply accommodate the lower flow. In the absence of high flows given the high sediment input from the adjacent lands it is likely that sedimentation would occur in the potholes and in the pools. Reduced flow would also lead to further aggradation in the reaches upstream which are already heavily infested with reeds, and other aquatic plants. Their growth would be encouraged by higher baseflows and by reduced floods.

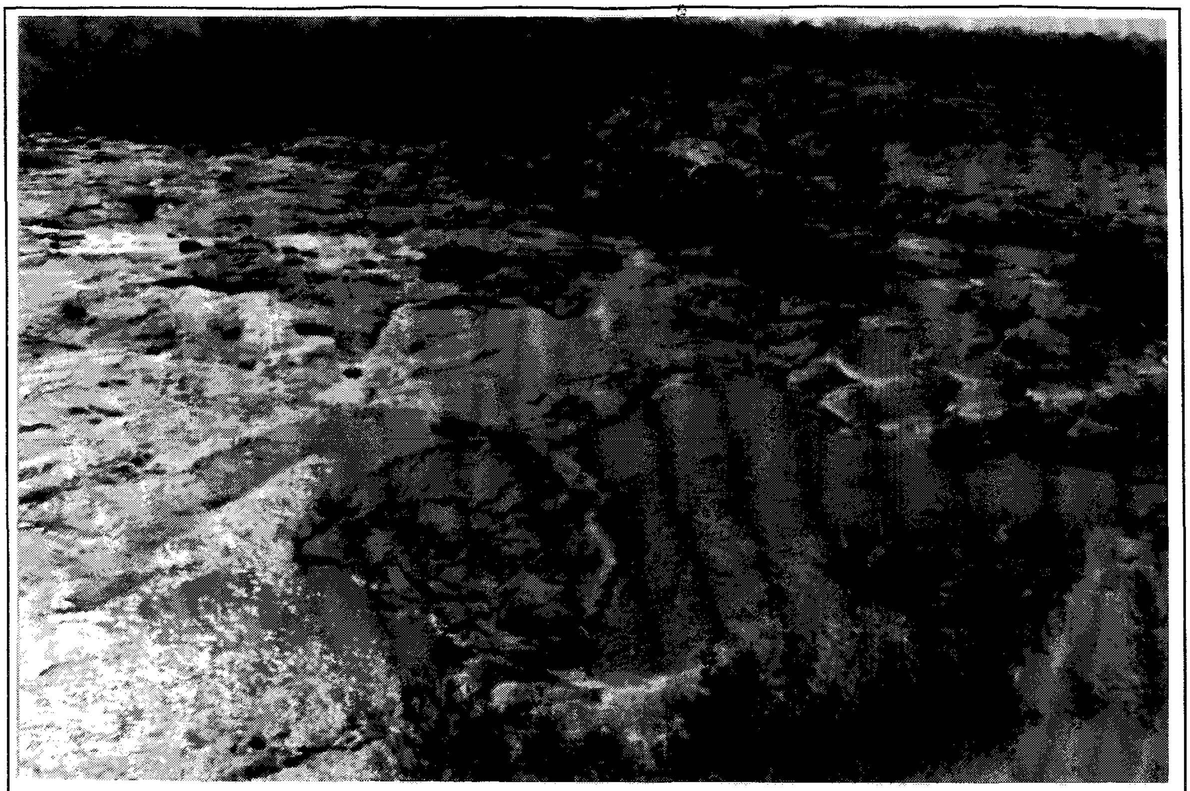

Plate 3.9: Komati IFR site 4 - bedrock channel which would 'accommodate' reduced flows.

Table 3.5: Summary of the IFR site characteristics.

	BERG SITES		*BIVANE SITES*			*KOMATI SITES*			
	1	*2*	*1*	*2*	*3*	*1*	*2*	*3*	*4*
channel type	cobble bed, braided	sand bed, rock outcrops	pool-riffle	cobble bed	cobble bed	confined pool, rapid	bedrock and boulder	boulder , bedrock, cobble	bedrock cascade
banks	sandy, vegetated	sandy, moderately stable	sand/silt, stable	sandy, undercutting	sand and cobble, stable	mostly stable	stable	moderately stable	stable, altered
gradient	0,007	0,0004	0,01	0,005	0,005	0,006	0,006	0,001	0,002
main features	pool-riffle	pool-rapid, 2° channel	run, island	cobble terrace, pool, rapid	cobble bar, riffle, terrace	run, island, bars, 2° channel	rapids, pools, islands	boulder rapid	cascade, pools
reduced floods	accommodation	accommodation closure of 2° channel	accommodation closure of 2° channel	accommodation siltation on terrace	accommodation	accommodation closure of 2° channel	accommodation aggradation	accommodation aggradation	accommodation aggradation
increased baseflow	armouring	bank slaking	armouring	armouring; bank erosion	removal of finer deposits	bank and bar erosion	bank erosion	improved sediment movement?	improved sediment movement?
sediment inputs	low	moderate	low	low	moderate/high	low	low	high	high
tributaries	none	none	none	none	none	none	none	none	none
habitat status	moderately modified	degraded	unmodified	unmodified	moderately modified	unmodified	unmodified	largely modified	largely modified

3.3. Summary of impacts

Table 3.5 gives a summary of conditions at each of the IFR sites. Together with Tables 3.2, 3.3 and 3.4, of 'statistics' on each study, and using the conceptual model (Figure 2.6) and the predictive flow diagram (Figure 2.8) developed in chapter two, some general statements can be made about the dominant processes at each of the sites discussed.

The Berg River: the initial dominant process at IFR 1 would be degradation, which would be checked by armouring. This would probably be followed by accommodation of the flow in the now stable channel perimeter. Sustained baseflows and the unstable nature of the channel perimeter would make degradation the dominant process at IFR 2. The response somewhere further downstream would be aggradation. At both sites, a reduction of floods would allow siltation in low velocity areas, vegetation encroachment and abandonment of secondary channels. The greatest impact on this system will be of unseasonally high flows through a semi arid system.

The Bivane River: the dominant process at IFR 1 would be degradation of the moderately stable bed, which is a mix of sand and cobble. Under sustained baseflows, the island feature and the sand/silt banks would also be susceptible to degradation. At IFR 2, aggradation in the pool upstream and on the cobble terrace might be problematic in the absence of floods, while bank erosion would be a problem under sustained baseflows. The impact at IFR 3 would not be great, given the recovery of sediment and flow relationships with the entrance of the Pongola. The cobble bed channel is stable enough to accommodate sustained unseasonal baseflows. The dam is well situated in that the impact is only likely to be significant in the 40km reach of the Bivane before its confluence with the Pongola, although unseasonal high flows in the Pongola could be problematic.

The Komati River: IFR sites 1 and 2 are in very good condition. IFR site 1 has a diversity of morphological units, but the best 'indicator feature' at this site is the secondary channel. In the absence of high flows, the dominant process would be aggradation, eventually leading to closure. Sustained baseflows on the other hand would favour degradation of the presently undercut banks and erosion of the island perimeter and associated bars. The predominance of bedrock and boulders makes IFR 2 a stable channel. The dominant response to regulated flows would be accommodation within the existing channel perimeter. The sand island deposits on bedrock would degrade under sustained baseflow conditions. IFR sites 3 and 4 are located in degraded reaches. The dominant process at both sites would be aggradation due to the stable nature of the bedrock and boulder channel, and due to the high input of sediment from the surrounding catchment. Sustained baseflows might actually improve the current situation, by moving sediment through these reaches. The dam will effectively control the high runoff upper reaches, with low inputs of runoff from the semi arid downstream catchments. Coupled with high sediment inputs in the downstream reaches, the effects may be significant.

CHAPTER 4

THE GEOMORPHOLOGICAL IMPACT OF IMPOUNDMENT ON THE KEISKAMMA RIVER

The aim of this project was to develop an understanding of the geomorphological impacts of impoundments, and apply this knowledge in an investigation of the impact of the Sandile dam on the Keiskamma River. The Keiskamma system was chosen because of its proximity to Grahamstown, and due to the fact that some post impoundment surveys had been conducted by Rowntree and Dollar (1994).

4.1 Physical characteristics of the basin

(Background information on the region was based on information in the Hill Kaplan Scott (1976) report, ENPAT98 digital data, and personal observations).

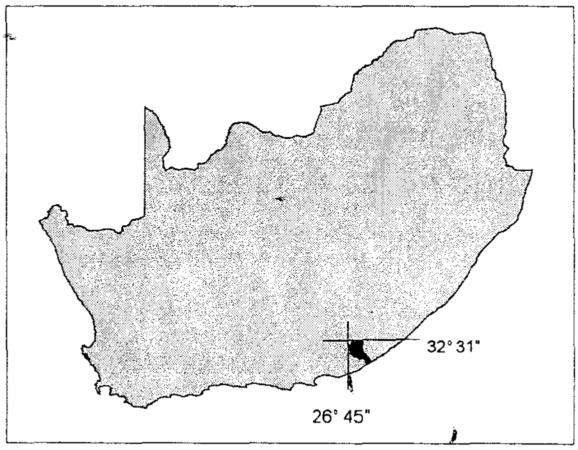

Figure 4.1: Map showing the location of the Keiskamma basin in South Africa

The Keiskamma river basin lies in the Eastern Cape Province, former Ciskei region of South Africa (Figure 4.1). It rises in the Amatola Mountains, and drains in a south easterly direction to the Indian Ocean. The Keiskamma is a steep rejuvenated river system. It has steep lateral channels, draining the mountainous areas which feed into larger tributaries, in a typical dendritic pattern. The long profile of the Keiskamma, divided into reaches is shown in Figure 4.2 and expanded on in Table 4.1. This method of classification and the procedures used are outlined in Rowntree (1998). Figure 4.3 shows the ENPAT98 depiction of the terrain into five regions. The headwaters (low mountains) are formed by the Amatola Mountains which rise steeply from the coastal plateau, to a height of 1940m. Many of the streams rise in spongy patches on the plateau of the Amatolas, ensuring their perreniality. Their steep gradients give them the power to erode the steep escarpment slopes. Above the town of Keiskammahoek, in reach 2, several perennial mountain streams meet to define what may be recognised as the main channel. A few kilometres below the town, where the Wolf River joins the Keiskamma in a more confined valley (reach 4) is the site of the Sandile Dam. 25km downstream, the valley opens out again below the Amatola tributary, in a region of 'hills and lowlands.'

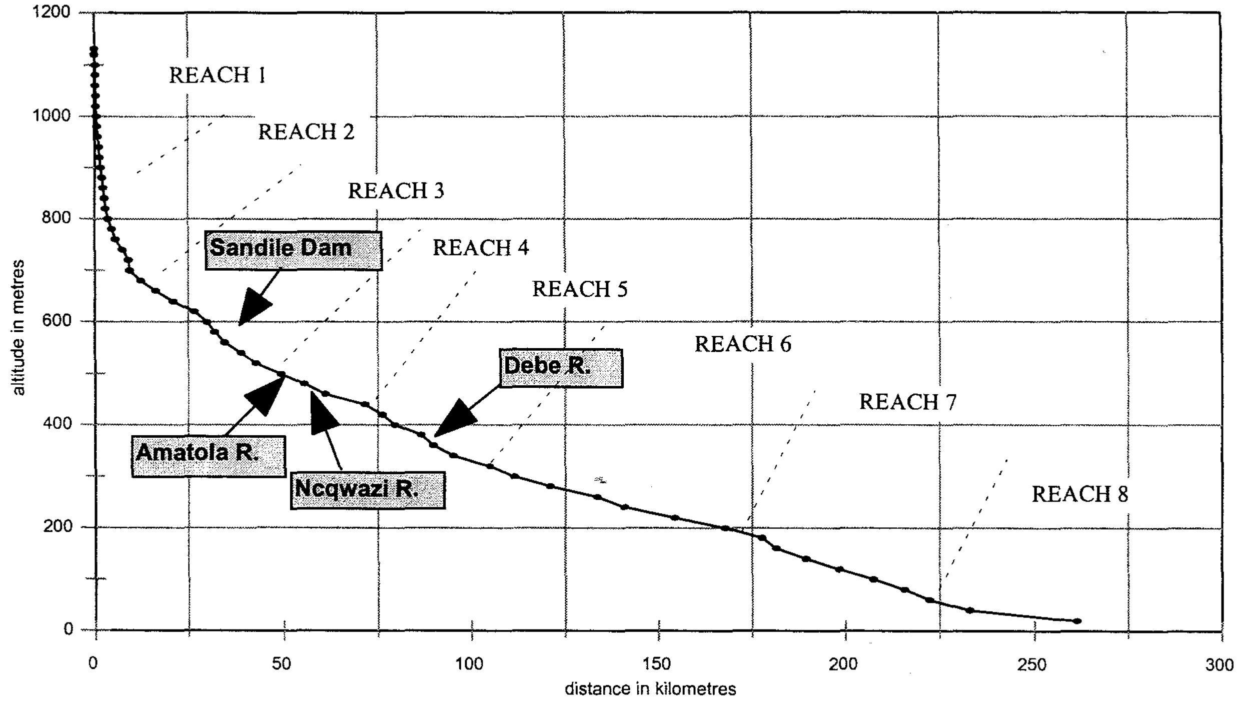

Figure 4.2: Long profile of the Keiskamma - 1130 to sea level.

Parts of the catchment are under commercial plantations, but there are large tracts of indigenous forest still intact. Alien invasive species such as black wattle (*Acacia mearnsii*) and *Sesbania punicea* are problematic and are currently being dealt with in the Working for Water Alien Invasive Clearing programme. The coastal Plateau (reaches 4, 5, 6 and 7) is deeply incised by the many seasonal tributaries which drain into the Keiskamma, to form another region of 'low mountains,' edged by 'plains' and 'hills.' The river channel meanders along a confined course in reaches 5,6 and 7. Sheet erosion and donga formations on the steeper slopes of the coastal plateau are extensive, as well as in the Tyume basin from below the forest line. Below the Tyume junction, (reach 5) the area drained by the tributaries is substantial, but insignificant in terms of runoff (Figure 4.6). The landscape is bleak, with poor grass cover, scrub, degraded valley bushveld and cultivated lands.

The Coastal Belt is a strip of low lying land (reaches 7 and 8) with a coastline of sandy beaches backed by a line of low, well vegetated dunes. The river valley opens out into a wide floodplain, (reach 8) through which the river meanders. The floodplain has been cultivated right down to the rivers edge. The main invasives in these lower reaches are *Solanum mauritianum* (bugweed) and *Ricinus communis* (castor oil plant) (Hall, 1998).

Table 4.1: Reach analysis of the Keiskamma.

Reach	*Altitude*	*Length*	*Average gradient*	*Description*
1	1120-880m	2.01	0.17	Headwaters, steep mountain stream with waterfalls
2	880-700m	10.4	0.032	Steep mountain stream, boulder and cobble bed
3	680-600m	19.6	0.005	Well defined mainstream, incised into alluvium, substrate of cobble, boulder and gravel; reduced gradient; more open valley.
4	600-420m	44.39	0.004	Confined valley at dam site; Wolf enters at about 600m; dam wall on bedrock outcrop; reduced gradient downstream; pools and cobble riffles; permanent islands. Amatola - 480m; Ncqwazi - 460m. Valley less confined below Ncqwazi
5	420-340m	13.52	0.004	Debe - 370m; valley opens out at Tyume - 360m. Long pools, backed up by bedrock ribs
6	340-160m	9.1	0.0025	Confined by steep valley sides, many ephemeral tributaries, cultivation on river terraces, and on hill tops. Pools and cobble/boulder riffles
7	160-40m	4.0	0.0024	Confined, big bends, cultivation on terraces and hilltops. Some stretches of sand bed
8	40m-0	3.9	0.001	Valley starts to open out at about 30m into a floodplain/estuary. Cultivation on floodplain.

The Acocks vegetation types (Figure 4.3) correspond with the terrain classes: low mountains are vegetated by moist upland grassland, the hills and lowlands of the drier Tyume valley are vegetated with sub-arid thorn bushveld, valley thicket is dominant in the main river valley, and eastern thorn bushveld on the low hills and slopes of the valley. The landuse categories (Figure 4.3) also correspond with the terrain: much of the high rainfall mountain area is under commercial plantations, the middle reaches are used for sheep farming and mixed farming, with subsistence farming on the hills along the main river valley. The maximum potential carrying capacity of the Keiskamma basin was estimated in the late 1970s as 45000 livestock units - it was found to have been exceeded by 173% in 1991, with a total of 78000 units (Hall, 1997). The drainage network of the Keiskamma and the quaternary catchments taken from the WR90 database are shown in Figure 4.6. The drainage network is extensive, although most of the tributaries in the lower two thirds of the catchments are ephemeral.

4.1.1 Geology

The Keiskamma basin is underlain by mudstones, sandstones and shales of the Tarkastad and Adelaide formations and subgroups of the lower Beaufort Group (SACS, 1980) as shown in Figure 4.3. The base of this series occurs in the southwestern portion of the study area, where the top horizons of the Ecca group are also exposed. In the North West portion of the drainage basin rocks of the lower Beaufort group which covers the major portion of the study area givesway to the hard sandstones of the Middle Beaufort. Karroo Dolerite, in the form of dykes and sills has penetrated these deposits in many areas, especially in the northern parts of the basin above 600m, where it forms prominent ridges such as the Hogsbacks. The river valleys in the basin are generally steep and confined. The highly dissected nature of the terrain has not allowed for the development of a floodplain. There are some patches of alluvium in the form of river terraces, where downcutting has been halted by resistant dolerite dykes.

4.1.2 Soils

The soils in the area are relatively young, so that soil formation has not reached great depths. Most soils are geogenic in character, in the drier areas they are litholic, with weathering bedrock present within 40cm of the surface. The soils in the Tyume are an example of latosols and it is not clear whether they are new soils or in fact paeleosols. Also occurring in the basin are the unique Amalinda, created by hordes of giant earthworms, found in the Debe basin (Laker, 1999).

4.1.3 Climate

The coastal belt and plateau: part of the south eastern coastal region of South Africa, described by Schulze(1965) as 'temperate to warm and humid, except that there is a definite summer rainy season which is at a maximum in autumn and at a minimum in June.' Rainfall is of a showery nature and thunderstorms are quite frequent. They are occasionally accompanied by hail, especially in the interior. Winds blow mainly parallel to the coast: north-easterly and south westerly (brings cool, cloudy weather and rain) occasionally reaching gale force. During the late winter very dry and hot berg winds may be experienced. Clear skies in winter allow for high sunshine of 70%, whereas cloud in summer reduces the sunshine duration to 50%.

The Amatola mountain region receives most of its rainfall in the summer from November to March, with 12-13 rain days per month compared to 2-3 days per month in winter, with an average annual rainfall figure of 1200mm. Due to its altitude and distance from the sea, temperatures show greater fluctuation diurnally and seasonally. Mist and drizzle are common. On average there are eight snowfalls per year, which melt in a day or two. Winds are mainly southerly, and northerly to north westerly and may be very strong in Autumn. Sunshine duration is 50-60% in summer and 70-80% in winter.

Rainfall and evaporation: Mean annual evaporation in the Keiskamma valley ranges from 1500mm in the lower reaches, to 1000mm at the dam and in the upper reaches. The Keiskamma falls within the summer rainfall region of South Africa, with nearly 70% of its rain falling in the six month period from October to March. The lowest rainfall occurs in the middle reaches of the river on the coastal plateau, where the lowest average is 420mm. Average rainfall on the plateau ranges from 450-650mm. On the coastal belt it ranges from 650-720mm. The rainfall increases rapidly with altitude, with the highest falls recorded at the Hogsback (1200mm)and Evelyn Valley (1600mm) stations. Rainfall records from 1900 to the present from the Dontsa and Hogsback stations are displayed in Figures 4.4 and 4.5. The location of these stations is shown in Figure 4.6. A view of the Keiskamma catchment from Dontsa station is shown in Plate 4.1.

Streamflow: records were available for the Keiskamma from a gauging station just below the dam (RH1005) and from RH105 situated about 25km upstream of the mouth for the period 1948 to 1996, and 1969 to 1996. Their location is shown on Figure 4.6. The data was obtained from the Computing Centre for Water Research on request, and processed to produce flow duration curves for the pre- and post dam periods, the results of which are shown later in this chapter.

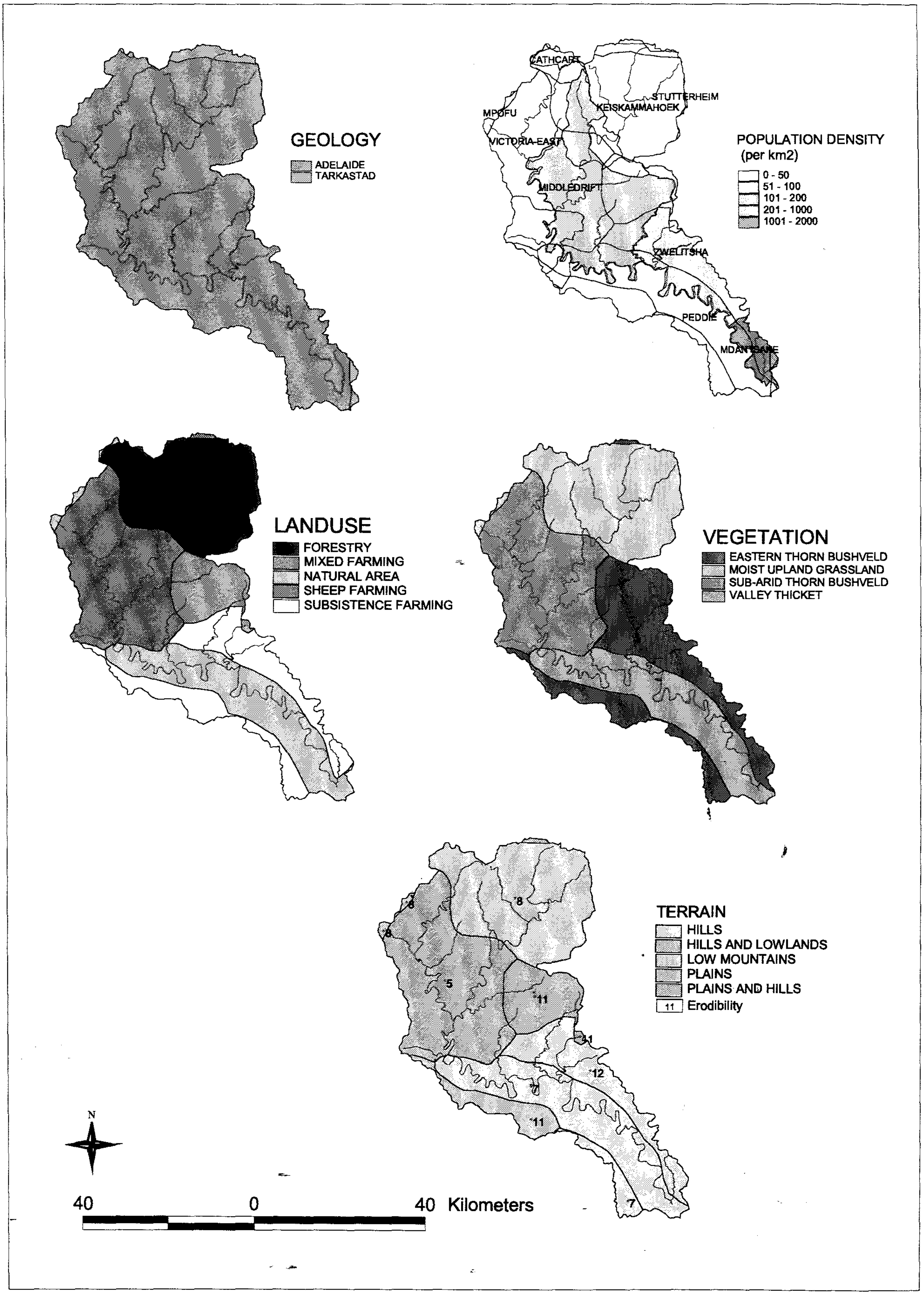

Figure 4.3: Physical characteristics of the Keiskamma basin from ENPAT98.

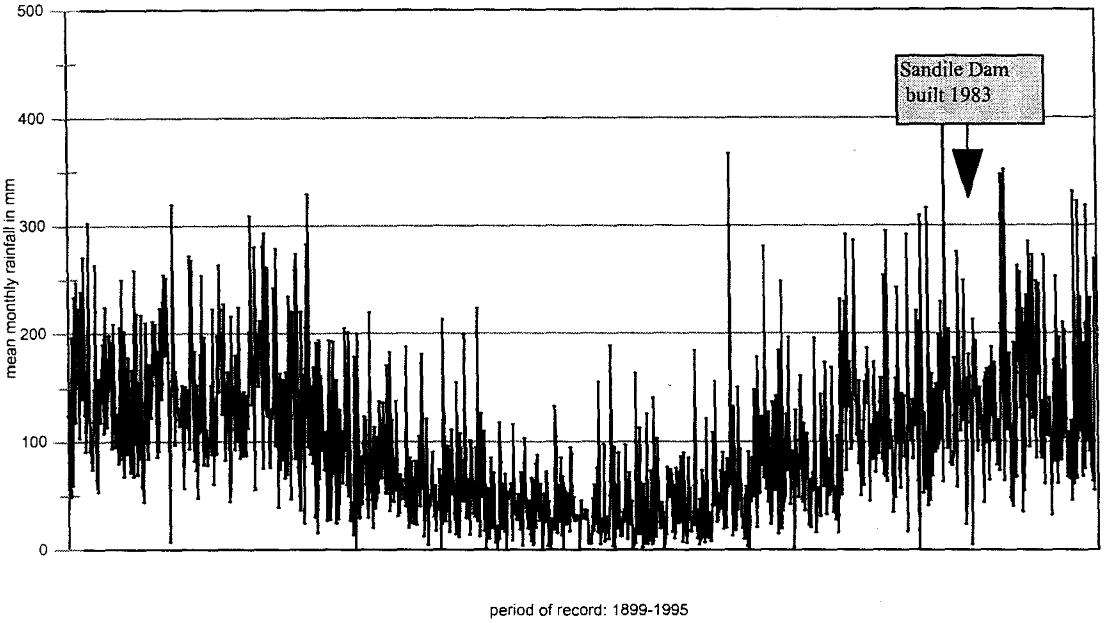

Figure 4.4: Mean monthly precipitation records for Hogsback station, 1900-1995.

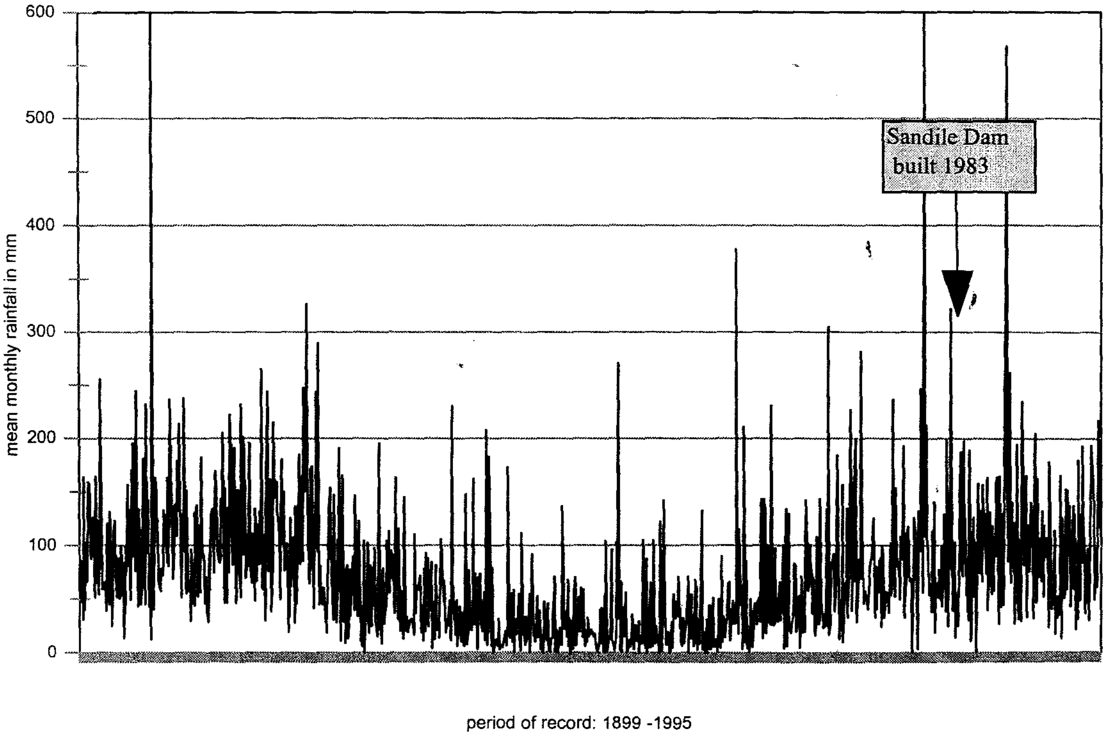

Figure 4.5: Mean monthly precipitation records for Dontsa station, 1899-1995.

Plate 4.1: Upper Keiskamma catchment from Dontsa Forest Station.

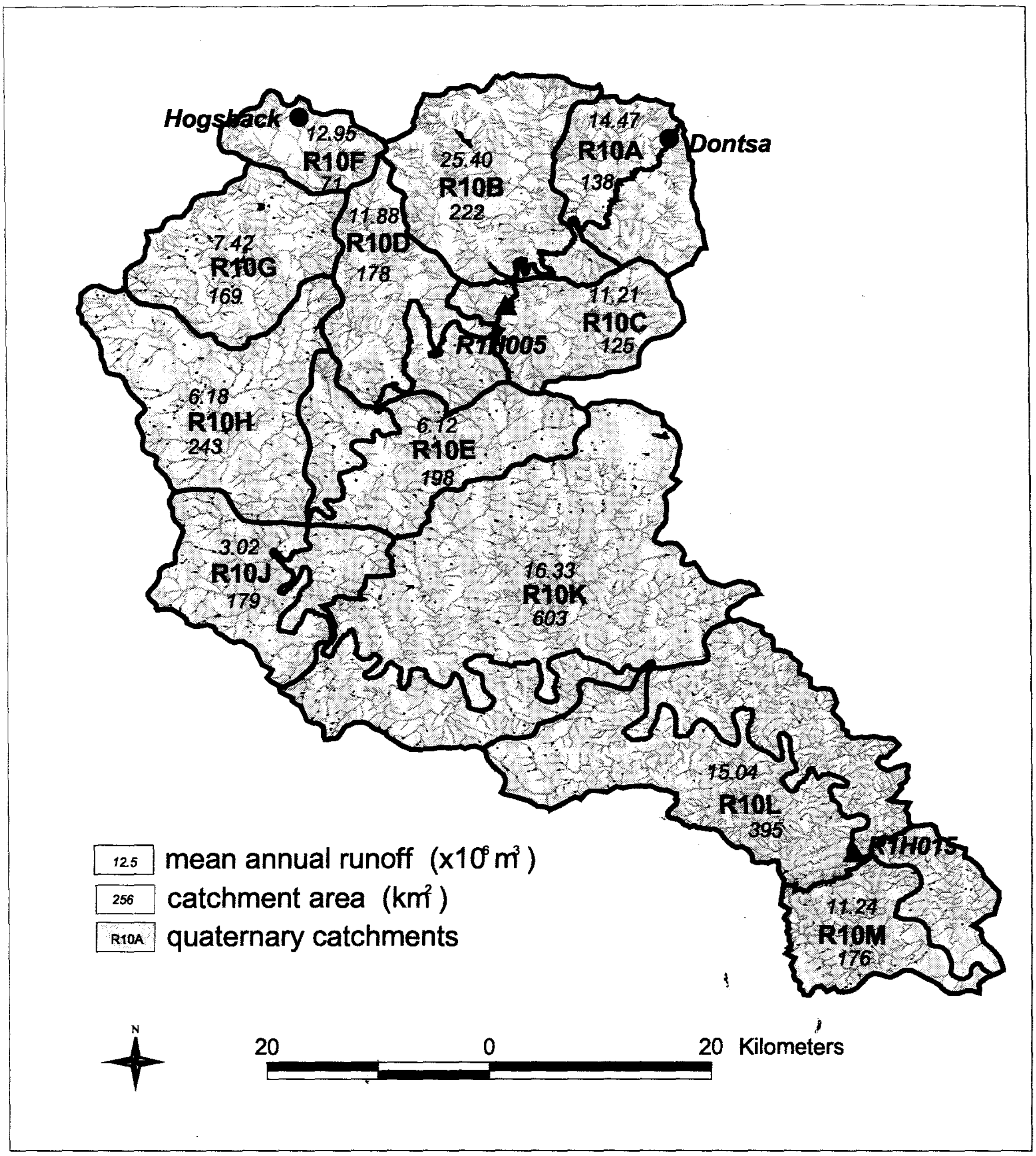

Figure 4.6:□□Water resources of the Keiskamma basin and the location of flow gauging stations and rainfall stations used in this study.

4.2 The catchment upstream of Sandile dam

Table 4.2: Dam catchment characteristics.

topography	Amatola Mountains and foothills, steep river valleys, gently sloping valley bottom	
area	360km^2	
rainfall (MAP)	835-861mm	
runoff (MAR)	R10A	R10B
In mm:	105	114
Total:	14.5 x10^6 m^3	25.4 x10^6 m^3
landuse	commercial plantations, agriculture (irrigated and dryland cultivation, livestock); rural villages; town of Keiskammahoek; light industry	
vegetation cover	extensive tall, evergreen forest; grasslands; extensive *Acacia karroo* communities; cultivated lands; commercial plantations	
other dams	Mnyameni - 12,5 x10^{6}m^3; Cata - 2 x10^{6}m^3	
state of catchment	sheet and gully erosion around populated areas; most of the steeper slopes are well vegetated with evergreen forest; problems with exotic invasives (black wattle and bugweed) along river channels	

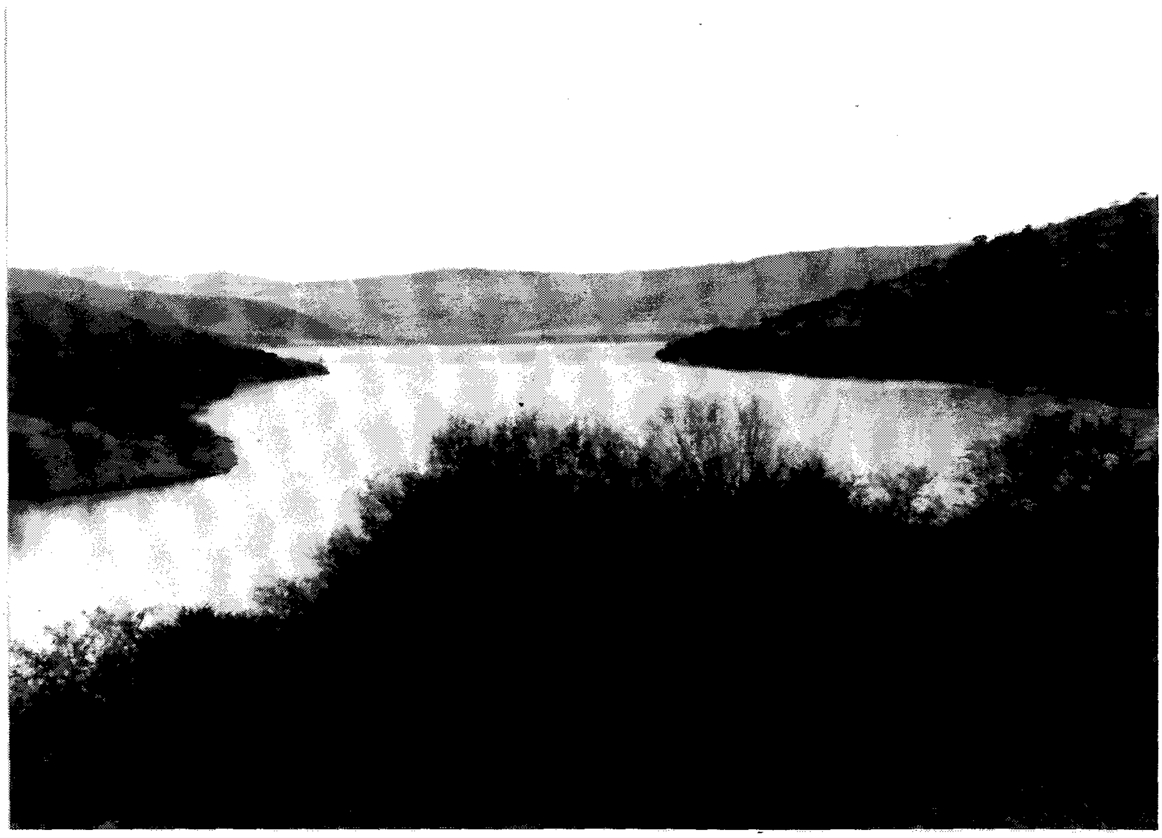

Plate 4.2: Sandile Dam looking towards the wall from the Wolf River.

4.2.1: Sandile Dam

Table 4.3: Sandile Dam statistics.

construction period	Jan 1981 - Dec 1983
surface area *as proportion of catchment*	220 ha 0.6%
Volume *as proportion of total MAR* *as a proportion of flow at the dam*	30.5 x 10^6m^3 21% of R10 R10a + R10b = 39.9 = 76%
crest ht./lt	760m by 58m
catchment area *as % of total Keiskamma area*	360km^2 13.4%
sediment trap efficiency (bed load)	100%
flow impounded	May 1983
mean annual evaporation.	1100mm
ten year flood	350m^{3}s^{-1} (HKS, 1981)
water use	domestic, irrigation

One of the noticeable features of the Sandile Dam is the turbidity of the water (Plate 4.2). The inflowing Wolf tributary input is mostly clear, except after storms, while the Keiskamma inflow is slightly more turbid. According to engineers who worked on the dam site, this has been the case since the dam was built. They suggest that it is due to the nature of the soils, which have a high sodium content, which prevents the suspended sediment from flocculating and settling out. This is also supported by the fact that the doleritic outcrops in the area would produce quantities of clay particles as they weather which would remain in suspension. At the suggestion of Prof. Brian Finlayson, water samples were examined under a microscope for the presence of diatoms which might have explained the muddy water, but none were present.

4.2.2 Water use in the Keiskamma

The water scheme was designed to satisfy the industrial and domestic needs of Middledrift Dimbaza, and the Zanyokwe irrigation scheme (Plate 4.3) and supply domestic and stock water to rural villages in the reaches below the dam. The water is not heavily utilized in the upper reaches because the irrigation schemes are only marginally functional. Water is released for uptake 150km downstream to be pumped to the village of Peddie, in the Fish River catchment.

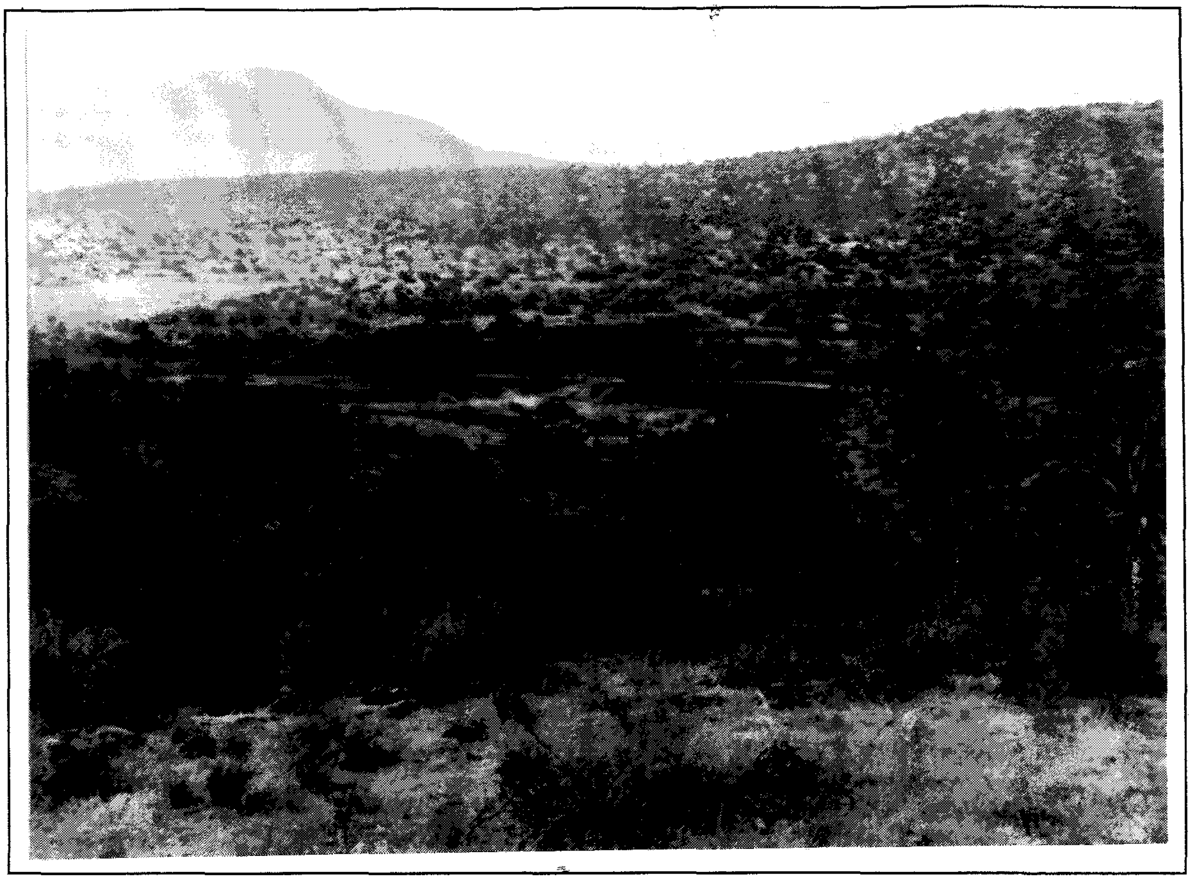

Plate 4.3: Irrigated lands below the dam in the Keiskamma valley.

4.3 Assessment of the primary impact of the dam

Streamflow data was available from a gauging station just below the dam, (R1H005) and from RH105 situated about 25km upstream of the mouth. Daily flow data was processed using the HYMAS model (Hughes, *et al*, 1994) and a flow duration curve was produced comparing the pre- and post dam periods. The results are depicted in Figures 4.7 and 4.8. It must be noted that the flat portion of the top of the curve represents the upper limit of the gauge - thus floods of a greater magnitude than 35 m^3s^{-1} at R1H005, or 125 m^3s^{-1} at R1H015 are not recorded.

Rowntree and Dollar (1994) estimated the flood with a return period of 2 years at R1H005 to be 35.2m^3s^{-1} in the pre dam period and 31 m^3s^{-1} in the post dam period, based on a post dam record of 10 years. Flood frequency analysis on such a short period of record (10 years) is not reliable. Further, the gauge limit of 35 m^3s^{-1} makes this estimate unreliable. At the recommendation of Smahktin (1997) more reliable daily records were used to produce a flow duration curve (Figure 4.7 and 4.8) instead of conducting flood frequency analysis.

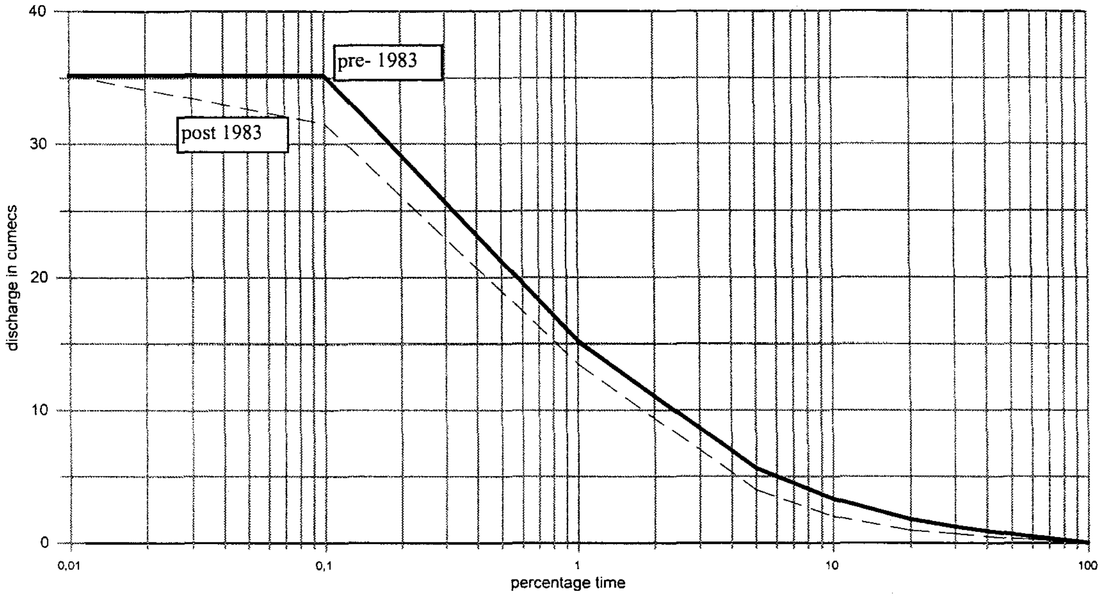

Figure 4.7: Pre- and post dam flow duration curves for gauging station R1H005.

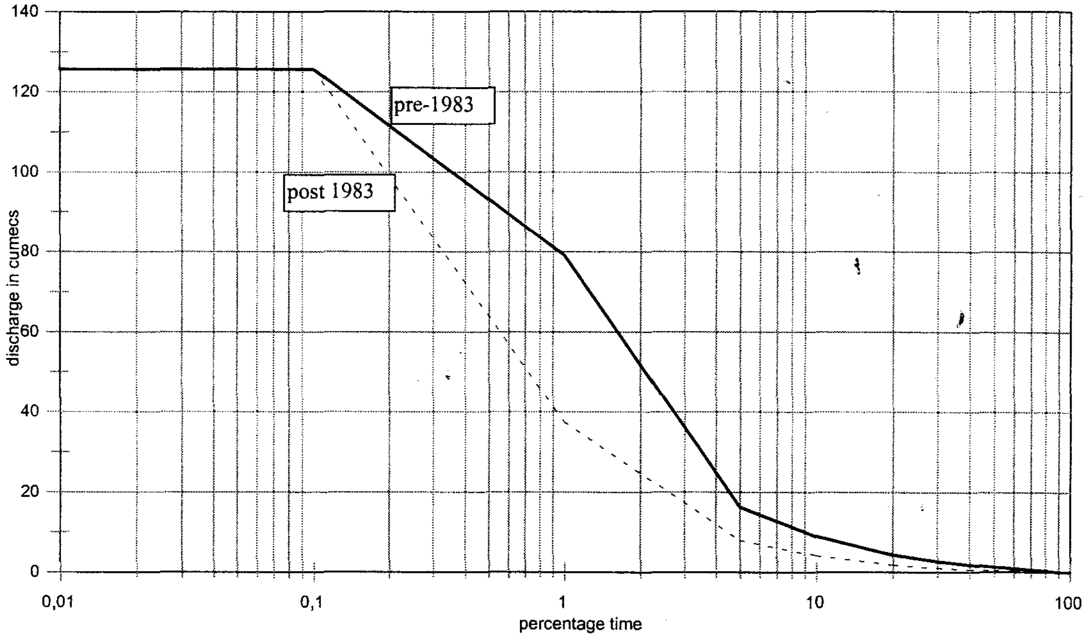

Figure 4.8: Pre- and post dam flow duration curves for gauging station R1H015.

The flow duration curves show a change in flows at both stations, although they are not dramatic. At R1H005 the unregulated catchment area is approximately 15km^2. The whole range of flows is affected at R1H005, although it is the lowest and highest recorded flows which show the greatest gap, particularly those in the 0.1 to 1% duration range. The 0.1% duration flow of about 35.5m^{3}s^{-1}, has been reduced to about 32.8m^{3}s^{-1}. All the flows with durations of 0.2 % to about 11% have been reduced by about 1m^{3}s^{-1}. The changes at R1H015 have been more dramatic: the greatest impact has been on the 1% duration flow, which has been reduced from 80 m^{3}s^{-1} to just less than 40m^{3}s^{-1}. As with the other station, all the flows which occur between 0.1 and 11% of the time have been reduced.

A visual assessment of the rainfall records depicted in Figures 4.4 and 4.5 shows no dramatic change between precipitation in the 15 years prior to dam construction and after dam construction that could account for changes in flow after the dam was built.

4.4. Assessment of the secondary impacts

4.4.1. Site selection

Based on Rowntree and Dollar's (1994) work which identified tributary bars as a feature of the Keiskamma post impoundment channel, it was decided to continue with this line of thought, and look for other bars as indicators of reaches which had been impacted. It was hoped that other post-impoundment features such as aggradation, bench development and vegetation encroachment might also be identified at these sites. Initial site selection was based on the reach classification described above and on a desk top study of the catchment using GIS which was used to identify tributaries with catchment areas of more than 10km^2. It was expected that they would generate large enough flows to produce tributary bars. In total 13 tributary junctions were visited (see Figure 4.9) and described. The Debe site was identified as having a significant size tributary bar which would yield results. The other two sites (Amatola and Ncqwazi junctions), where tributary bars were identified by Rowntree and Dollar's (1994), were also selected for further investigation. Bars were either absent at the other sites, or insignificant. The reach of channel immediately below the dam was also investigated for dam impacts: the channel substrate was sampled and the condition of armouring was noted.

The number of tributary sites visited was limited mostly by access, particularly in the lower reaches of the river where the valley is broad and road access is a problem. The only method available for looking for submerged bars was to walk about in the water and feel with a stick. It was assumed that bars would not be present beyond the junction of the Tyume, due to distance downstream of the dam. By the time the Tyume enters, the unregulated area is 501 km^2 (139% of the regulated area) , and the unregulated runoff is $29.21 \times 10^6 m^3 s^{-1}$ (75% of the regulated runoff). The Tyume is the last tributary contributing any significant quantity of flow. Its entrance increases discharge by a further 30%, while the catchment area is increased by a 55%. (It must be noted that the Tyume is dammed, by Binfield dam, but the water is not utilized.)

An assessment of sediment was expected to be an 'independent' method of pre and post dam impact assessment: it did not depend on there being pre dam data for comparison. The idea was that by measuring the sediment composition of channel bars - which are usually unstable, temporary features it would be possible to predict the discharge required to move the sediment using Hjulströms (1935) curve.

4.4.2. Methods used

Each of these 3 sites were investigated during several visits in 1996 and 1997 and the following data was collected:

- site descriptions
- detailed site surveys to show the channel morphology at one or two dates
- bar sediment samples
- suspended sediment samples
- flow readings at low, medium and high flow
- analysis of pre and post dam aerial photos

The following data was collected from the three tributaries:

- channel substrate sample
- channel cross-section
- suspended sediment sample

Using GIS techniques and working from 1:50 000 topographic sheets, a map of the sub catchments and the drainage network of the whole Keiskamma basin were captured. The following information was prepared for the three catchments of the tributaries selected for study from the Hill Kaplan Scott (1976) report:

- soils
- vegetation
- erosion data
- stream network
- long profile

Site surveys

Using standard survey techniques, sites were surveyed to determine the cross-sectional profile of the river and to create a map of the channel morphology. Surveys were constructed above (A), at (B), and below (C) the tributary junctions and the substrate on these cross-sections was described to show if the tributary influenced the morphology of the reach downstream of the junction. Cross-section B was surveyed in a series of 10 degree sections to create a detailed contour map of the tributary junction morphology. This detailed survey was carried out on two occasions, one year apart, at the Ncqwazi and Amatola junctions. The Debe was surveyed once. The information was then input into GIS to produce a digital terrain model of each site, at each date, to show how the morphology of the reach had changed.

Cross sectional surveys of the tributaries, approximately 300m upstream from the junction, were also constructed to determine their morphological characteristics, relative to the proportions of the main channel. The tributary substrate was sampled at the cross section.

Flow readings

Flow velocity readings were taken at the main cross-sections (B) at each site at every opportunity, in order to determine the discharge. Flows in the tributaries were mostly too low to measure, except at one date after heavy rain. Problems were encountered with taking readings in the main channel at a high flow, the Debe site was inaccessible at this date, and the Ncqwazi site could only be gauged by taking the surface velocity with an orange as a float. These velocity readings were converted to discharge values, using the cross-sectional area surveys. The high flow reading of about 9 m^3s^{-1} was estimated to have a 2% duration on the R1H005 station flow duration curve, while the low of 0.5 m^3s^{-1} would probably occur 100% of the time.

Sediment sampling: bar substrate and suspended sediment

According to Mangelsdorf (1980) samples should ideally be taken from a dry gravel bar on the upstream side of the bar so as not too distort the sample with fines that have settled out, or lose fines in the fluid. They also suggest removing the top 10-20cm. Wolman and Williams(1984) discuss the problems that they experienced sampling sediment in their study: it is not a straightforward task. Petts and Thoms (1986) use sophisticated methods such as freeze coring, while Sherrard and Erskine (1991) working in a mostly dry river bed were able to dig profile trenches. Due to practical constraints, none of these options were available on the Keiskamma: the methods used here were not ideal - but they were all conducted in a consistent manner.

Bedload samples of approximately 1kg were taken in each of the tributaries on the cross section surveys at 1m intervals, using a large trowel to remove a sample from the top 10cm. Sampling was done under conditions of low flow, or no flow. In the main channel bedload samples of approximately 1kg were taken at random intervals along the the 5° survey lines where they crossed the bar in and out of the water. Sampling was difficult because of the high turbidity and the depth of the water: underwater sampling proved to be problematic. At the Amatola site, sediment was collected by diving underwater and retrieving a handful of sediment - most often the 'handful' was a cobble of several kilograms. This method obviously omitted the finer sediments, but sampling with a trowel was not possible because of the size of the substrate. The finer fraction was also lost at the Ncqwazi where samples were taken underwater with a trowel and a cloth bag. Flow was low enough at the Debe that the bar was exposed and dry samples could be taken. The samples were sieved and divided into their various size fractions in the lab. The substrate composition was described at 0.5m intervals on the cross-sections above and below the tributary entrances.

Using a depth integrated sampler, suspended sediment samples were taken in the main channel on three occasions at three different flows. Under high flow conditions, samples were taken in the main stream and in the Ncqwazi and Amatola tributaries. 100ml quantities of the samples were filtered and the trapped sediment weighed.

Aerial photo analysis

Time series aerial photographs can be used to identify changes, however either the system must be large enough to show change, or the photos must be at a large enough scale to identify small changes. Aerial photos for the pre- and post dam period were available. Unfortunately their resolution was different: the post-dam ones being at a scale of 1:12 000 (August 1988), the pre-dam only at 1:20 000 (December, 1963). Any morphological features which were identified in the post-dam set could therefore be attributed to the better resolution, and not necessarily to change.

Catchment ground truthing

Various catchments were visited both above and below the dam on foot to get an impression of their state in terms of landuse, vegetation cover and erosion status. Wherever possible, tributary junctions above the dam were visited to get an idea of the characteristic channel morphology of those reaches. Junctions below the dam were checked for the absence or presence of tributary bars within 120km of the dam. The main constraint here was access to these points.

4.6 Results

4.6.1 An assessment of the sub-catchments of the Keiskamma

Table 4.4: Runoff and area for quaternary catchments in the Keiskamma, from WR90.

Quaternary catchment	*runoff x* $10^6 m^3 s^{-1}$	*area in* km^2
R10A	14.47	138
R10B	25.40	222
R10C	11.21	125
R10D	11.88	178
R10E	6.12	198
R10F	12.95	71
R10G	7.42	169
R10H	6.18	243
R10J	3.02	179
R10K	16.33	603
R10L	15.04	395
R10M	11.24	176

Figure 4.6 and Table 4.4 show the drainage network and quaternary catchments of the Keiskamma, according to WR90 with runoff and catchment areas. What is significant in terms of this study is the relative proportions of runoff generated by the different catchment areas. It is clear that the upper portion of the catchment has a high area/runoff ratio while the lower reaches are arid to semi-arid in nature. A more detailed map was compiled in ARC-INFO for working out sub-catchment areas.

The river in its upper reaches is a boulder and cobble bed stream, with bedrock outcrops and a steep gradient. The banks are of sand and silt and well vegetated with exotic and indigenous plant species. In reach 1 and 2 it is difficult to distinguish between the tributaries and the main stream. It is only below its junction with the Nqolonqolo, in reach three, that the Keiskamma becomes distinguishable as the main stream. Water quality is good: the stream flows clean except during storms, and the sand and gravels are well washed. This was confirmed by a conversation with two local inhabitants. As the stream size increases so does the degree of incision into the alluvium. In the area above Keiskammahoek, the channel is deeply incised, with large meanders, and moderately stable channel banks. The condition of the sub-catchments varies from pristine to degraded.

4.6.2. Tributaries investigated above the dam

Ngobozana: a small tributary with an area of 6.58km^2. The main stream is infested with black wattle as well as supporting a good stand of indigenous riparian trees. The channel is affected by debris jams, caused by roots and logs. The channel substrate is cobble and gravels, with a bedrock cascade where the Ngobozana enters (see Plate 4.4).

Nqolonqolo/ Mqukwane: this is a large tributary with a catchment area of 39.59km^2, and channel dimensions the same as the main stream (7m wide). There is a gradient change on both channels where they join in a long pool. The tributary has unstable undercutting banks with a substrate of mainly large cobble and boulders. The main channel above the junction is partly bedrock, with coarse sand, boulders and mixed size cobble. The banks of both are well vegetated with indigenous as well as exotic species. Black wattle has caused bank collapse and debris jams in places.

Gwiligwili: the tributary drains a catchment of 36.6 km^2. It is incised into the alluvium, as is the main channel. There are some large *Podocarpus* and *Olea* species on the banks of both, as well as black wattle. The catchment is rolling grassland, with a fair scattering of *Acacia karroo*. The tributary substrate consists of coarse sand, boulders and large cobble. There is no distinguishable bar formation at the junction.

Nxalawe: the tributary banks are nearly vertical, but appear to be stable. The water is clear, and just flowing. The is no accumulation of sediment at the confluence. The main channel is deeply incised into the alluvium, but the banks appear to be stable. The substrate is mainly coarse sand and fine gravel with cobble in the riffles. The valley is wide open and gently sloping making it suitable for cultivation. The main channel meanders in big loops across the valley bottom (Plate 4.5).

Plate 4.4: Ngobozana tributary junction.

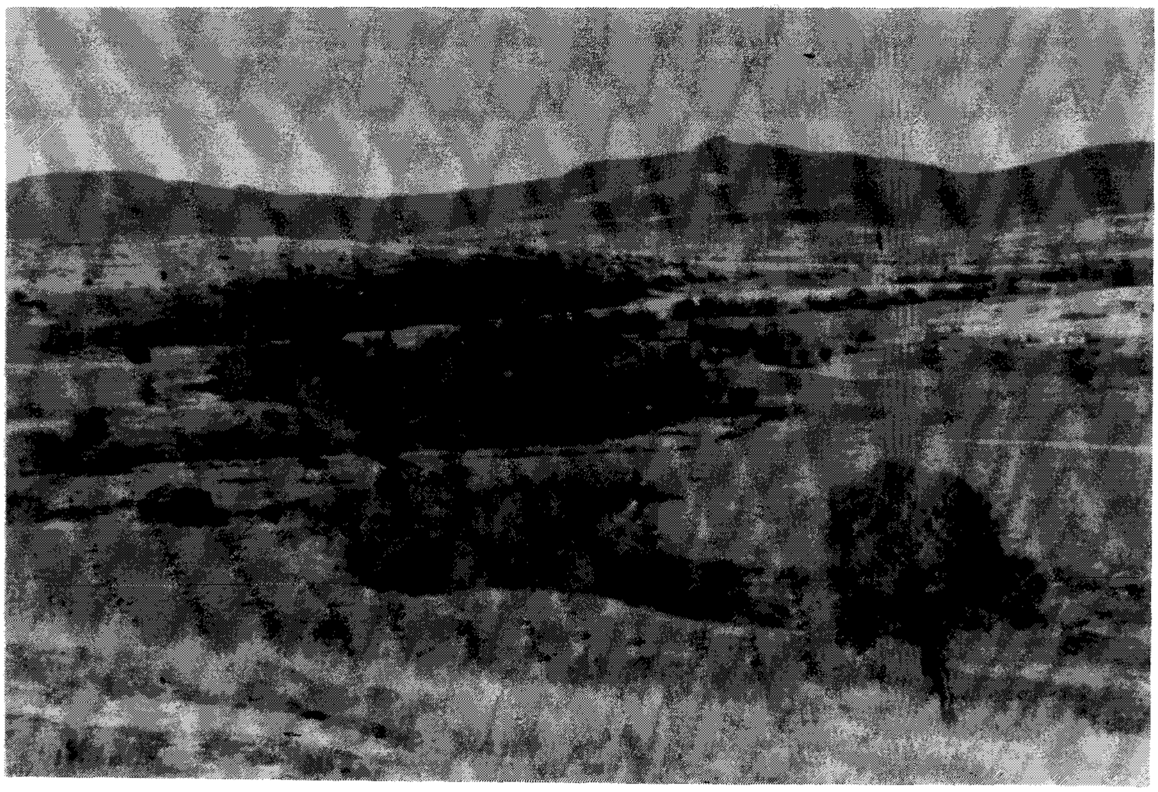

Plate 4.5: Keiskamma channel incised into the alluvium in the vicinity of the Nxalawa tributary.

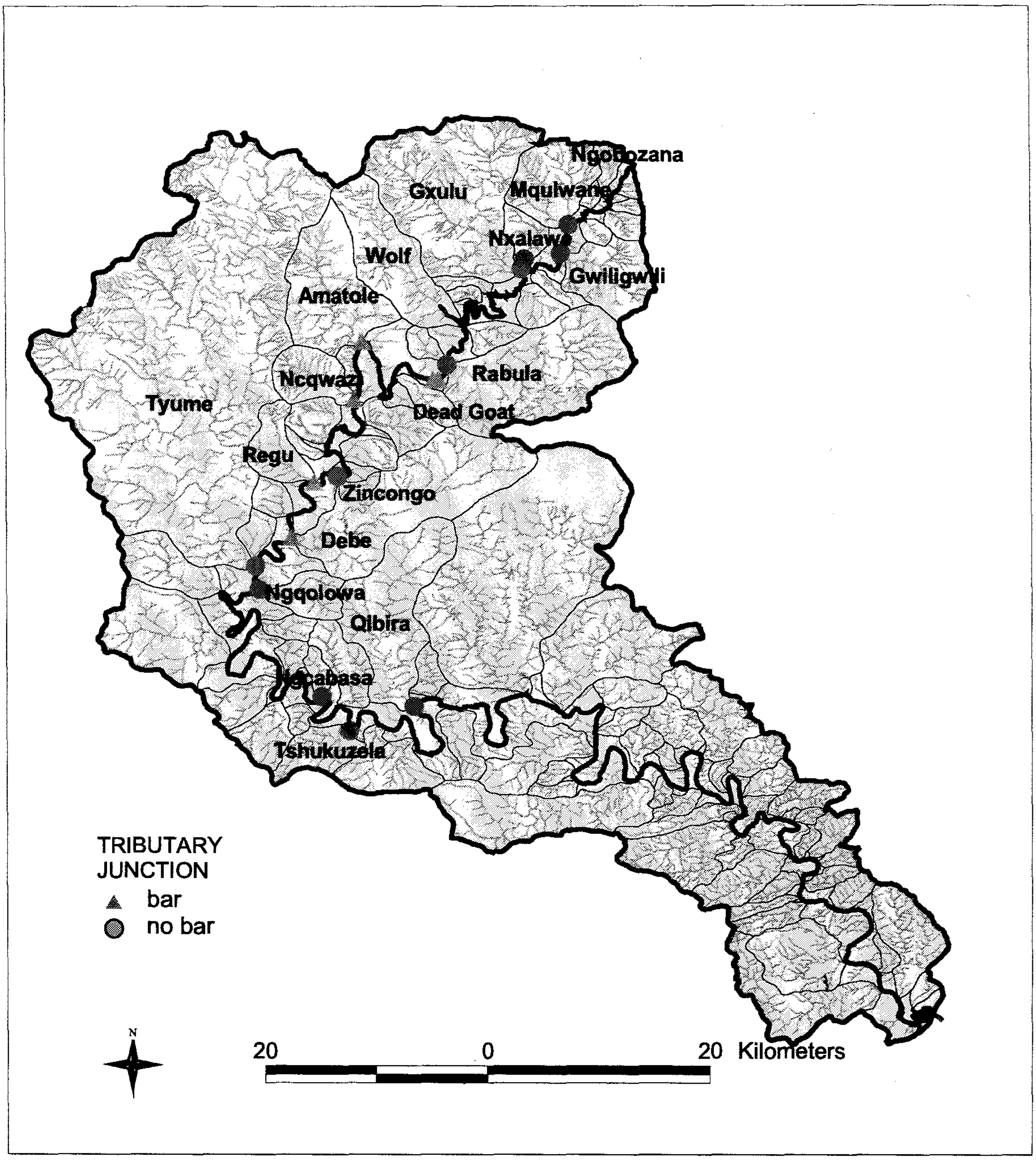

Figure 4.9: Location of tributary junctions checked for the presence/absence of bars

4.6.3. *Immediately downstream of Sandile dam*

The channel immediately downstream of the dam is dominated by cobble size substrate, with very little fine sediment evident (Figure 4.10). The cobble is also noticeably angular in shape which has allowed it to form a tightly imbricated and armoured surface. There is little variety in the channel morphology for a 2km reach below the dam. The nature of the channel and the channel substrate is illustrated in Plates 4.6, 4.7 and 4.8.

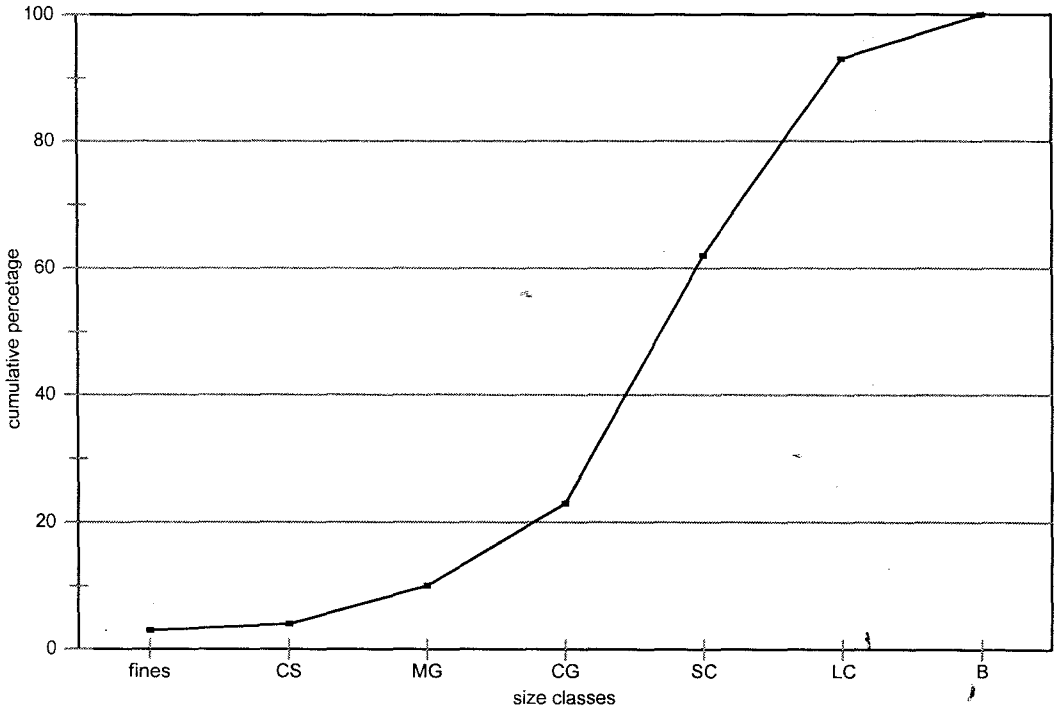

Figure 4.10: Channel substrate below Sandile Dam (for size classes see Table 2.1).

Plate 4.6: View downstream of the Sandile Dam spillway.

Plate 4.7: Channel substrate below the dam.

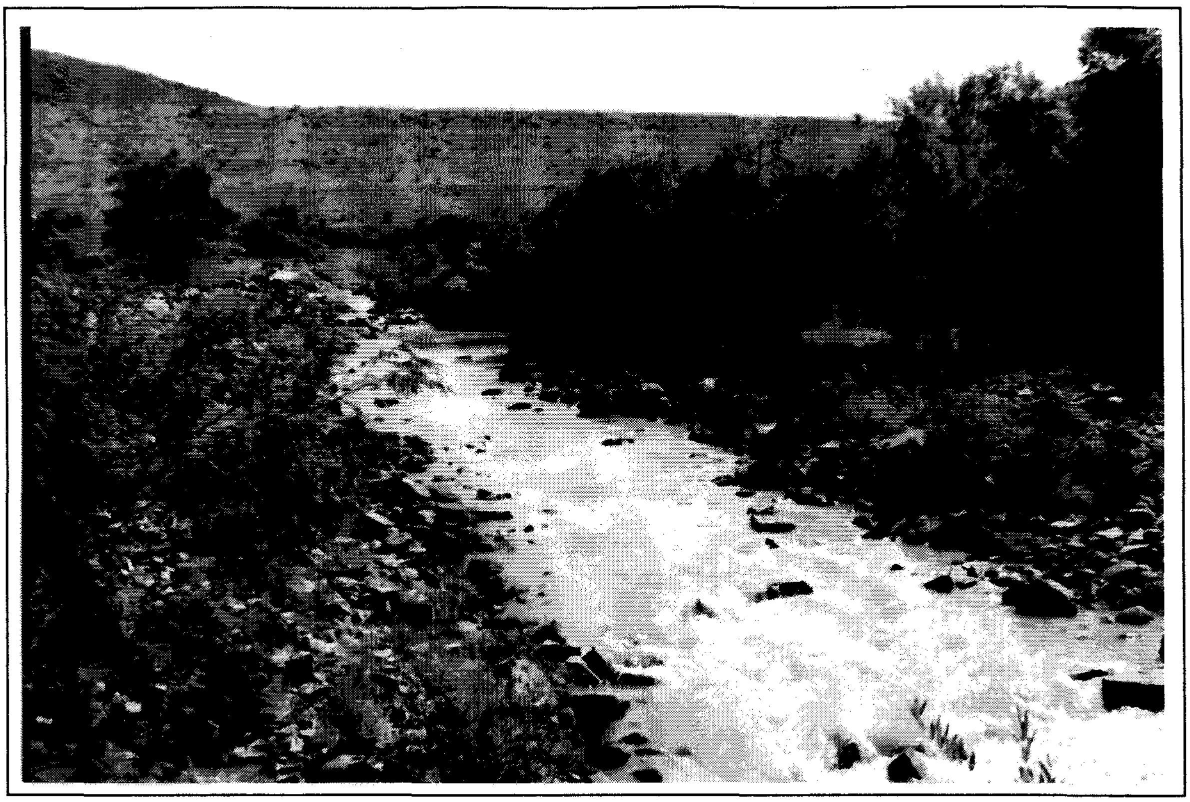

Plate 4.8: Keiskamma channel 1km below the dam.

4.6.4. Tributaries below the dam

All the sites visited are listed in Table 4.5 gives with their distance downstream of the dam and their catchment areas.

Rabula: this is a fairly large catchment, with high runoff and being only 6km downstream of the dam, one would expect to be able to identify dam impacts. However the presence of a substantial weir on the stream, 200m upstream of the confluence, explains the absence of a bar. The weir is filled with small and large cobble, which would otherwise have made its way down to the main stream. The impact of the weir gives an idea of how sediment input to the mainstream can be controlled if it is problematic.

Table 4.5: Tributary junctions checked for presence/absence of bars.

Catchment	*Tributary Bar Present?*	*Catchment Area (km^2)*	*Distance Downstream of Dam (km)*
Rabula	No	100.5	4.6
Dead Goat 1	Yes	2.5	5.9
Dead Goat 2	Yes	1.7	6.25
Amatola	Yes	67.2	20
Ncqwazi	Yes	24.5	26
Ncancawushe	Yes	10.88	37
Regu	Yes	22	41.9
Zincongo	Yes	5.09	47
Debe	Yes	220.2	49.2
Tyume	No	481.6	55.45
Ngqolowa	No	18.56	58.2
Ngcabasa	No	6.1	99.2
Tshukuzela	No	20.49	109
Qibira	No	79.6	120

Dead Goat 1 and Dead Goat 2 (Plate 4.9): two small ephemeral tributaries with catchments of 2,5 and 1,7km^2, in poor condition, underlain by friable geology (shales), sparsely vegetated with degraded valley bushveld and *Acacia karroo.* Their gradients are steep with many small waterfalls falling over rocky outcrops and are obviously capable of moving gravel size sediment when they do flow, evidenced by the gravel and sand deposits at their mouths. The deposit is of a small enough size that the material can be moved by the main stream, and deposits are therefore temporary even under impounded conditions.

Amatola: (see section 4.7 for more detailed information) the Amatola is a major tributary which flows throughout the year , draining a high runoff well vegetated catchment in reasonable condition with moderate sediment production. It substantially increases the unregulated runoff with a contribution of 16 x $10^6 m^3$ per annum (25%). It has a steep gradient and is capable of moving large material as evidenced by the bar deposit at its junction.

Ncqwazi: (see section 4.8 for more detailed information) the catchment has an area of 24.5km^2 of steep poorly vegetated slopes, with extensive erosion features. The channel is deeply incised particularly in its lower reaches, where bedrock outcrops prevent further degradation. A large bar is evident at the junction with the main stream.

Ncancawushe (10.88 km^2) *and Zincongo*: *(5.09*km^2*)*: the gradients of these tributaries is such that they do not have the power to move any large size sediment. While there were bars at their mouths, they were composed of sand and silt, with very little coarse material. They drain degraded settlement areas, with high stocking densities, and would certainly carry a high suspended load.

Regu (Plate 4.10): the main catchment area is gently sloping, sparsely covered grassland, with cultivated lands and several settlements. The channel is incised, and controlled by a series of rock outcrops in the last 3 km, where it flows through a predominantly bedrock channel of waterfalls and small pools. There is a substantial cobble and boulder bar at the junction, certainly a permanent feature.

Debe: (see section 4.9 for detailed information) the Debe drains a semi arid catchment, with stony soils and poor vegetation cover. The tributary is a seasonal stream. Mean annual runoff in this region has reduced to 6 x $10^6 m^3$ (compared to about 12 x $10^6 m^3$ in the Amatola). Runoff has recovered to 73% of the regulated flow. There is local steepening in this reach due to bedrock outcrops.

Tyume (Plate 4.11): the entrance of the Tyume increases the catchment area of the Keiskamma by about 55%, but only contributes an additional 30% flow. The Binfield dam will have affected flows in the Tyume. The junction is on a large deep pool, fringed with tall reed beds, indicative of a low velocity depositional environment. There was no evidence of a tributary bar, contrary to information from Mr Vincent Kakembo, (pers. comm.), who claimed that a bar was present in 1994 and 1995.

Ngqolowa (18,56 km^2*), Ngcabasa (21.06* km^2*), Tshukuzela (20.49* km^2*), Qibira (79.58* km^2*)*: the gradient of the river is very low at this stage (0.002) and runoff from the surrounding catchments is low. The river is pooled up behind weirs in some places, further reducing flow velocities. No bars were distinguishable at these tributary junctions, although the pools at each junction might have concealed deposits. Either this is an indication that the dam effect has been nullified this far down the system, or it is a natural occurrence. There is certainly plenty of sediment available from the degraded, sparsely vegetated catchment surfaces, but due to low runoff and reduced gradient resulting in low stream power in the tributaries, they do not have the capacity to move large sediment.

Plate 4.9: Bar deposit at Dead Goat tributary.

Plate 4.10: Keiskamma/Regu junction.

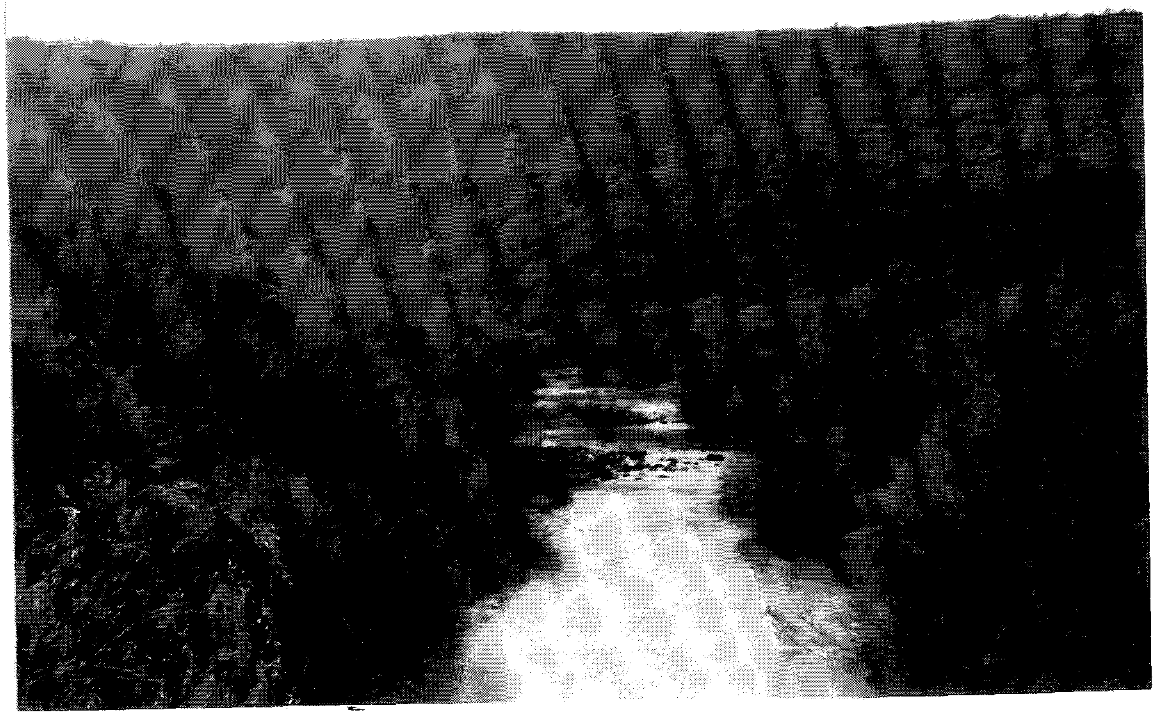

Plate 4.11: Keiskamma valley in the vicinity of the Tyume junction.

4.7 The Amatola tributary bar

4.7.1. Description of the Amatola

The Amatola drains a steep mountain catchment of 60km^2. The south facing slopes are still vegetated with indigenous *Podocarpus* forest, as well as commercial plantations (see Figure 4.11, and Plate 4.12). There are extensive grasslands, and cultivated lands in the valley bottom. The high rainfall makes the valley suitable for cultivation on the right soils. Most of the soils are shallow with a tendency to droughtiness, making them susceptible to erosion if mismanaged (Figure 4.12). There are well established settlements in the catchment, and associated erosion due to footpaths and stock grazing. The map of erosion (Figure 4.11) compiled from Hill Kaplan Scott (1976) does not show the sheet erosion features which are now evident on the slopes in Plate 4.12. The Amatola rises in the marshy plateau region of the mountains, and flows down a steep boulder and bedrock channel, with many waterfalls, before it reaches the foothills, where the stream forms a series of pools in the grasslands. The long profile of the river is depicted in Figure 4.13. In its lowest reaches it forms a series of pools and wide boulder cascades/riffles, entering the Keiskamma at right angles, from the right bank. The stream banks are stable, and the riparian zone is still intact, except where stock have trampled pathways down to the water edge. The size of the bedload suggests that the stream may be prone to significant flooding (Plate 4.13). A cross section of the tributary channel and substrate sample results are shown in Figures 4.14 and 4.20, to gave an idea of the dimensions of the stream in comparison to the main channel. Where it enters the Keiskamma, there is a bar of mostly cobble and boulder size rocks, which periodically builds up with the deposition of finer fragments. At low flows the water is clear, pushing a distinct tongue into the turbid water of the Keiskamma (Plate 4.14).

4.7.2 Morphology of the Amatola Junction

A plan of the site is shown in Figure 4.15. Plates 4.15 and 4.16 show the upstream and downstream views at the site. Cross sections and substrate descriptions taken at, above and below the tributary are shown in Figures 4.16 to 4.19. The Amatola enters on a slight bend in the river - in the middle of a long pool, bounded by moderately stable, well vegetated sheer banks. The upstream cross section is dominated by a bedrock and boulder substrate, with silt deposits on top of it. There is a substantial bar deposit at the tributary mouth, extending into the main channel. The substrate at this cross section is dominated by the bar material of cobble and gravel. On the left bank just down from the tributary entrance is a deposit, presumably derived from the flow dynamics at the junction, of silt and sand which has been stabilised by reed growth. Below the junction the left bank reduces its slope, while a bedrock face along the right bank forms a sheer wall extending into a steep well vegetated bank. The pool opens out at its lower end, where the flow divides around a large island. The substrate is a mixture of cobble and gravel size material, with silt deposits in the low flow velocity areas against the banks. The main channel falls over a wide bedrock cascade, while the left channel forms a slow flowing, sinuous mud bottomed channel, enclosed by dense riparian vegetation, ending in deep weir, built on bedrock. The left bank in the vicinity of the island has been heavily trampled by cattle.

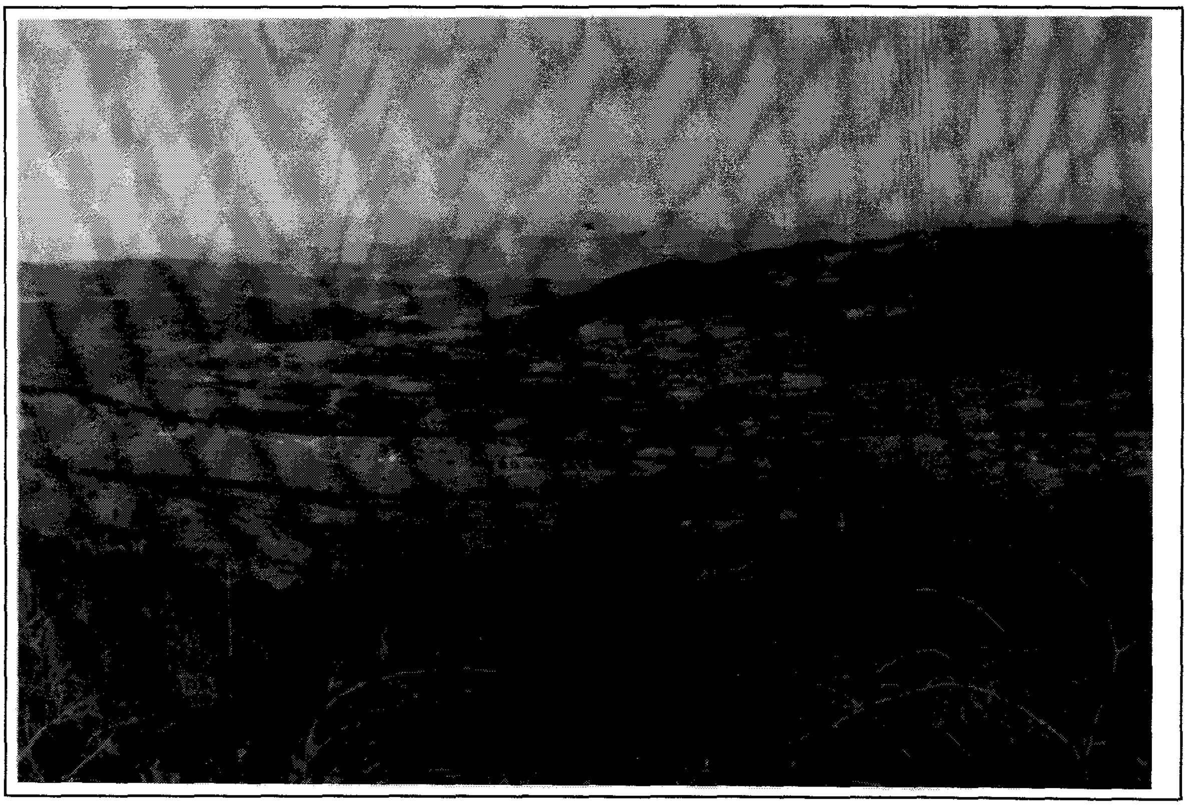

Plate 4.12: Aerial view of the Amatola catchment.

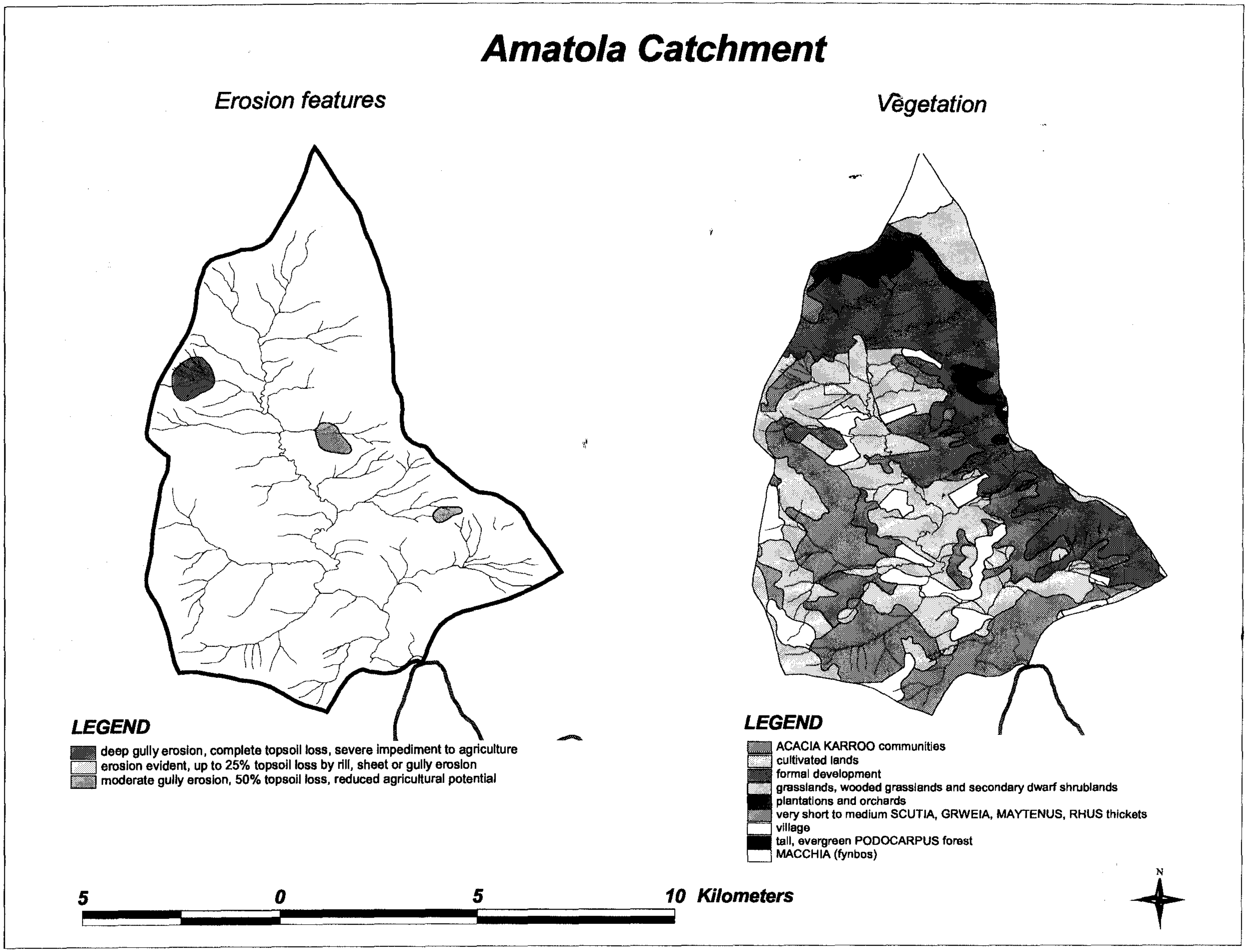

Figure 4.11: Amatola catchment: - erosion features and vegetation.

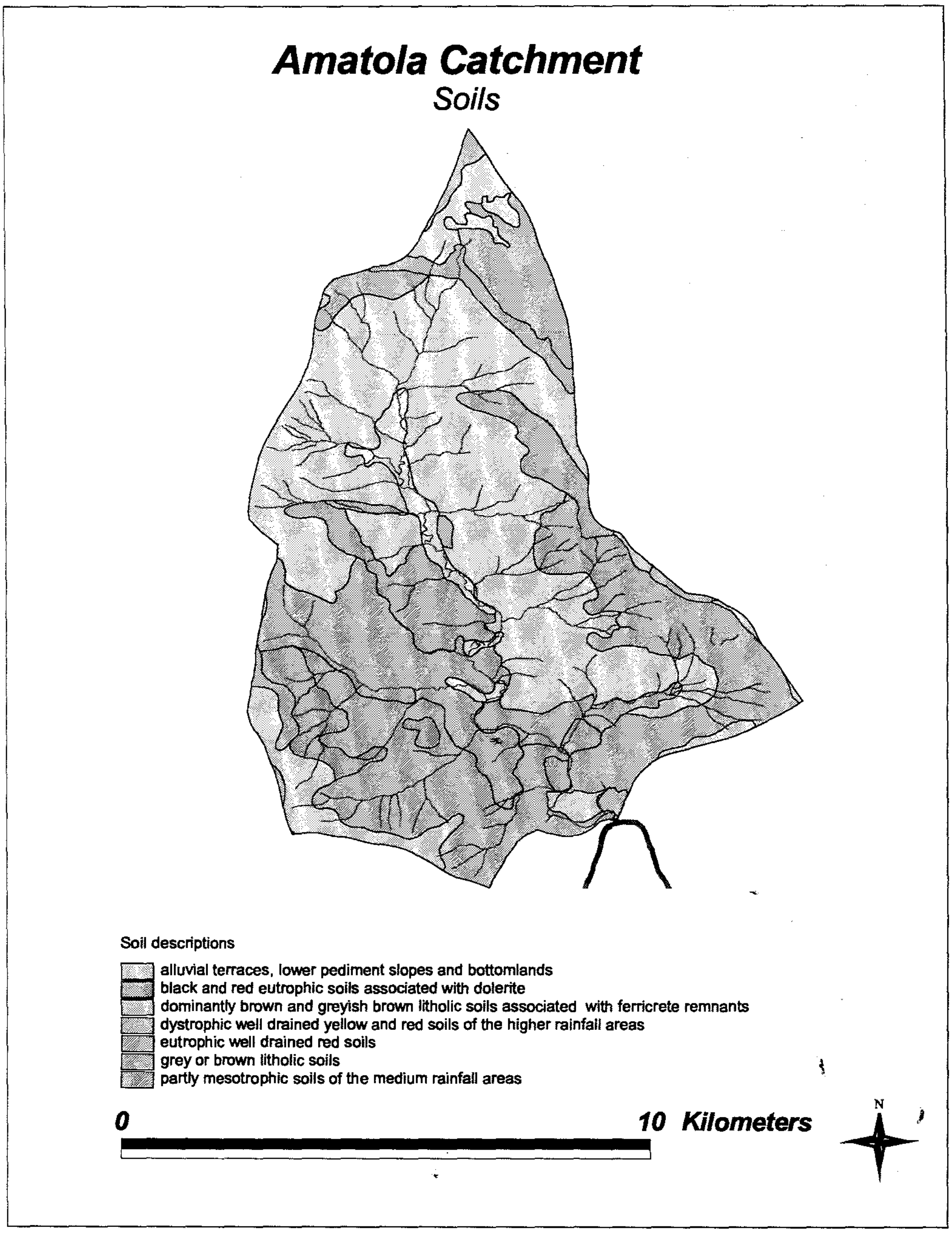

Figure 4.12: Amatola catchment - soils

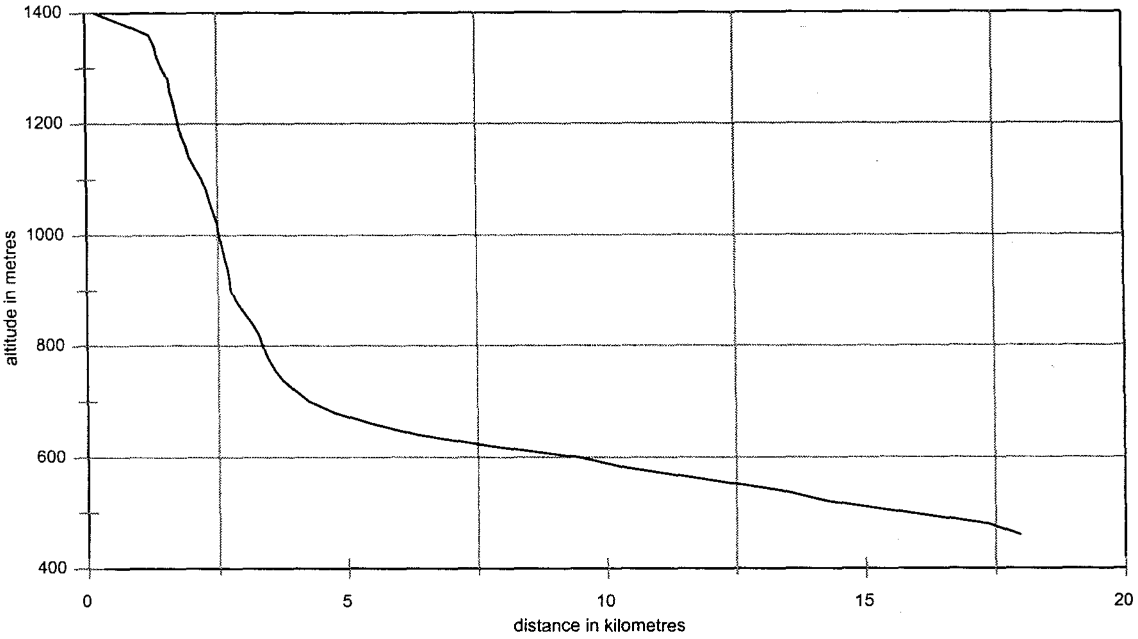

Figure 4.13: Long profile of the Amatola.

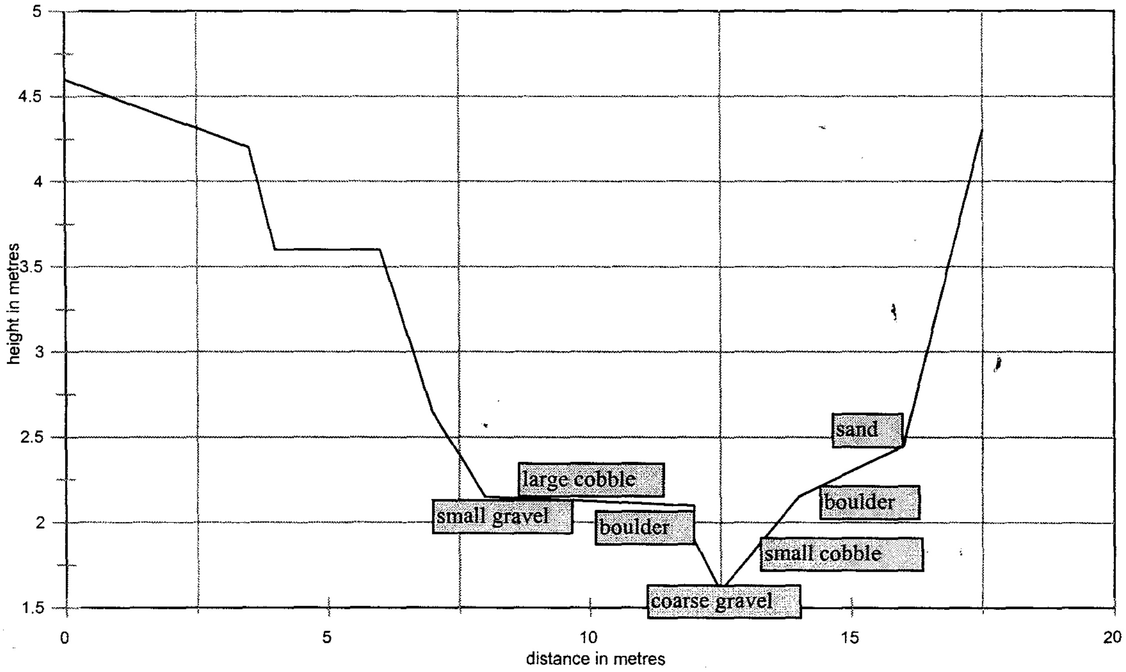

Figure 4.14: Cross-section of the Amatola.

Plate 4.13: The Amatola River in its lower reaches.

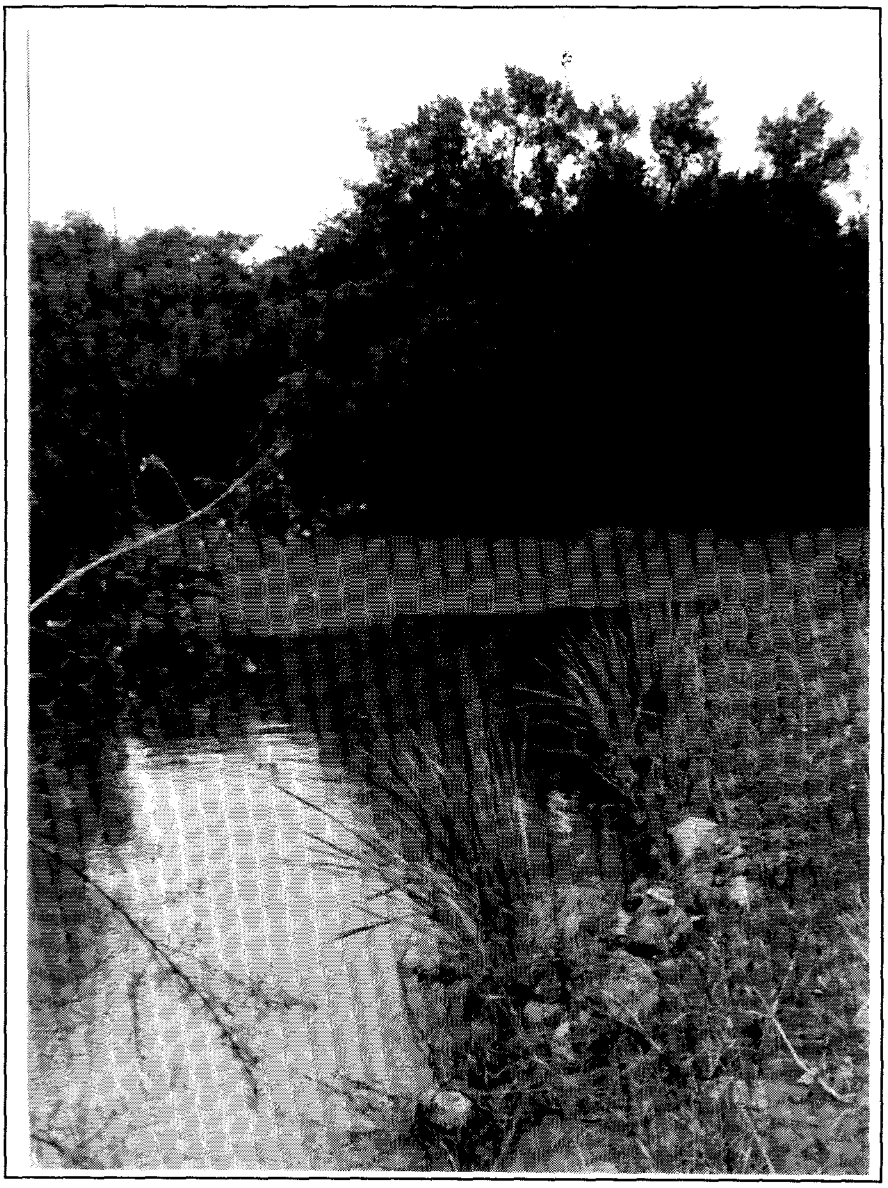

Plate 4.14: Clear Amatola flow pushing into the Keiskamma at the junction.

Plate 4.15: Keiskamma/Amatola junction - downstream view.

Plate 4.16: Keiskamma/Amatola junction - upstream view.

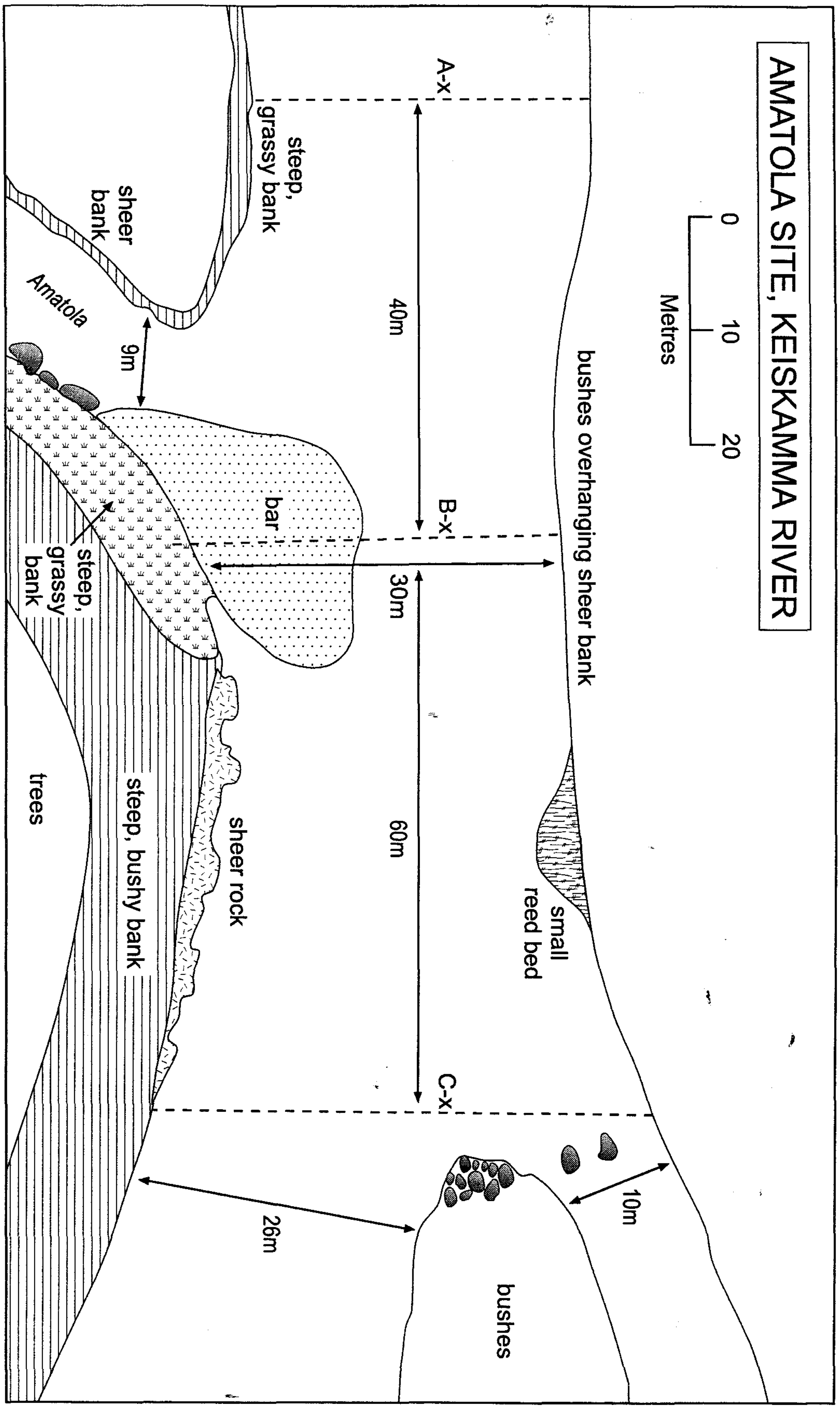

Figure 4.15: Plan view of the Amatola site

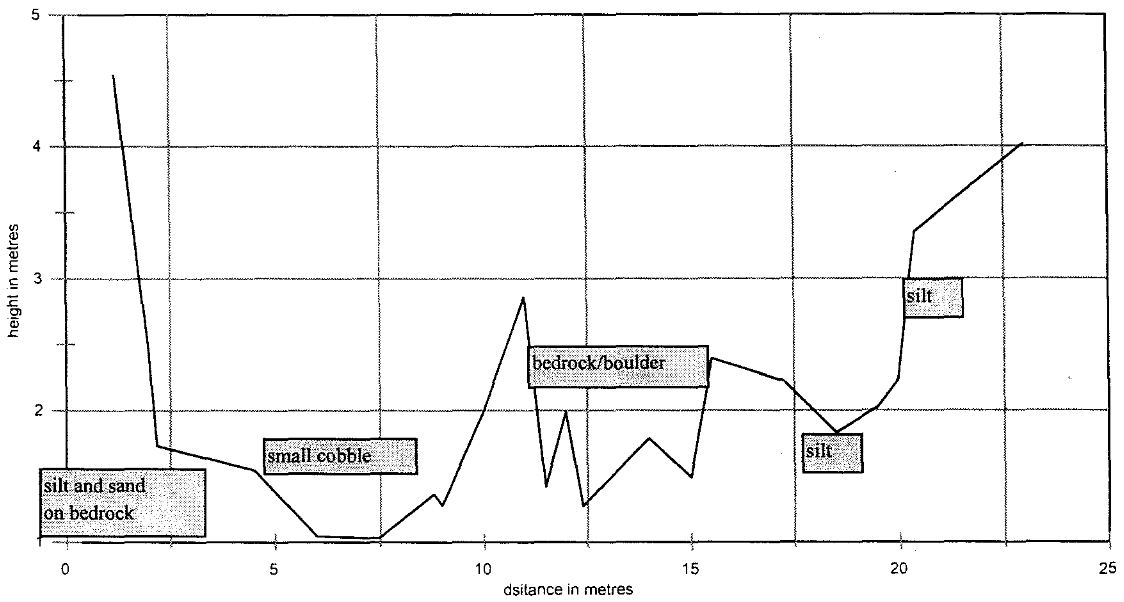

Figure 4.16: Keiskamma/Amatola cross-section A, upstream view.

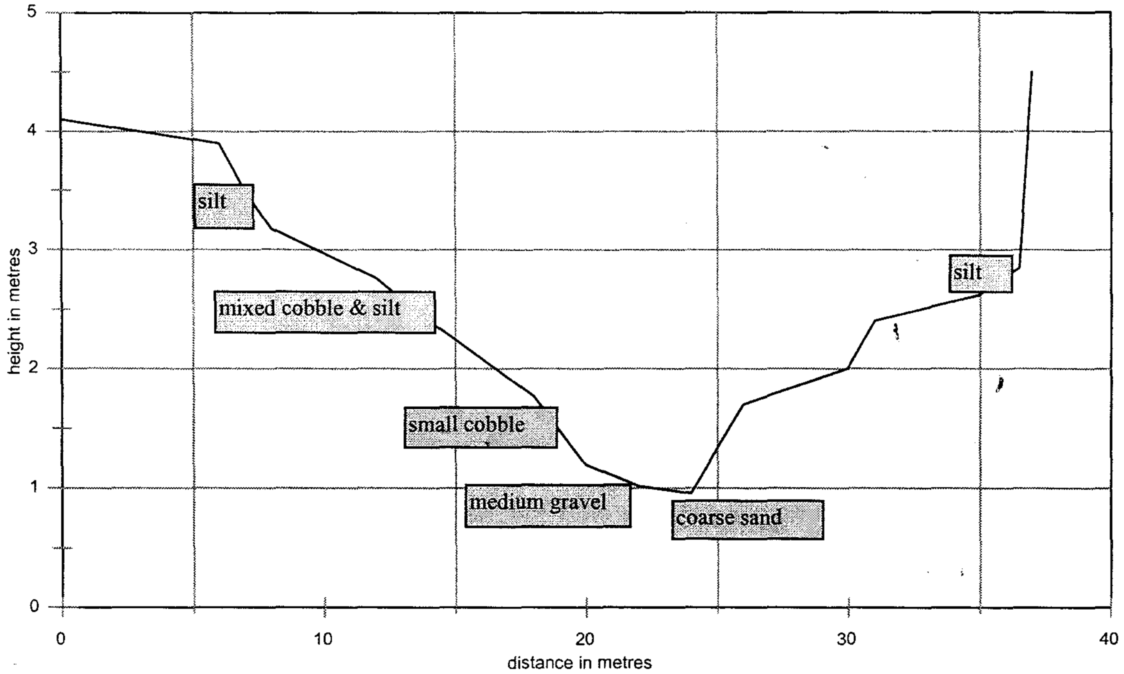

Figure 4.17: Keiskamma/Amatola cross-section B, 1996, downstream view.

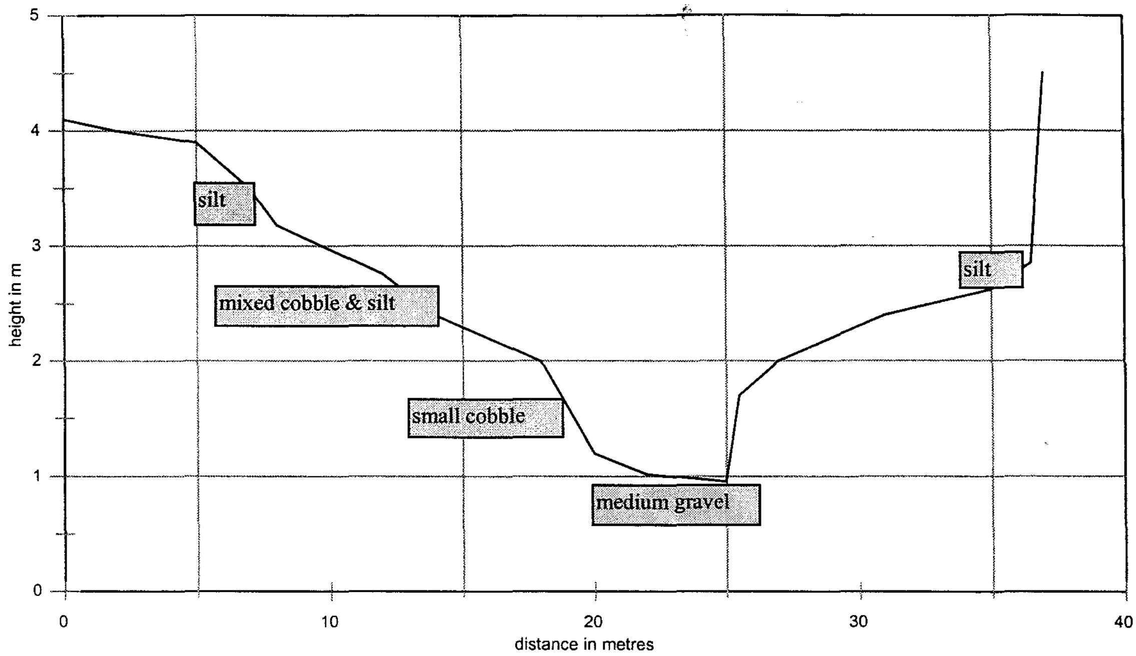

Figure 4.18: Keiskamma/Amatola cross-section B, 1997, downstream view.

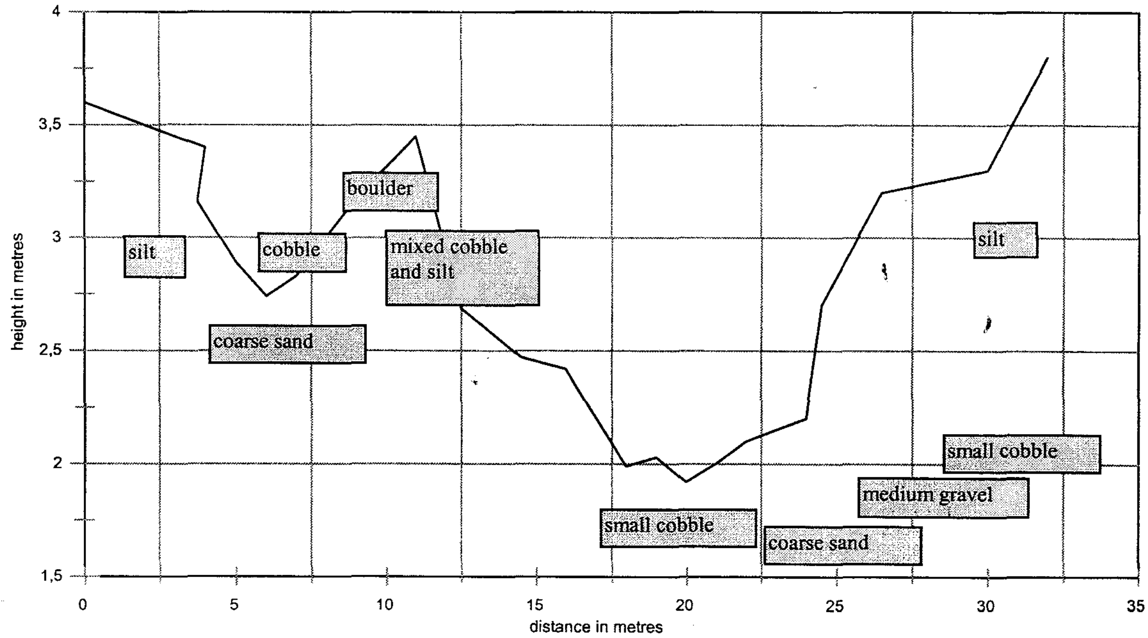

Figure 4.19: Keiskamma/Amatola cross-section C, downstream view.

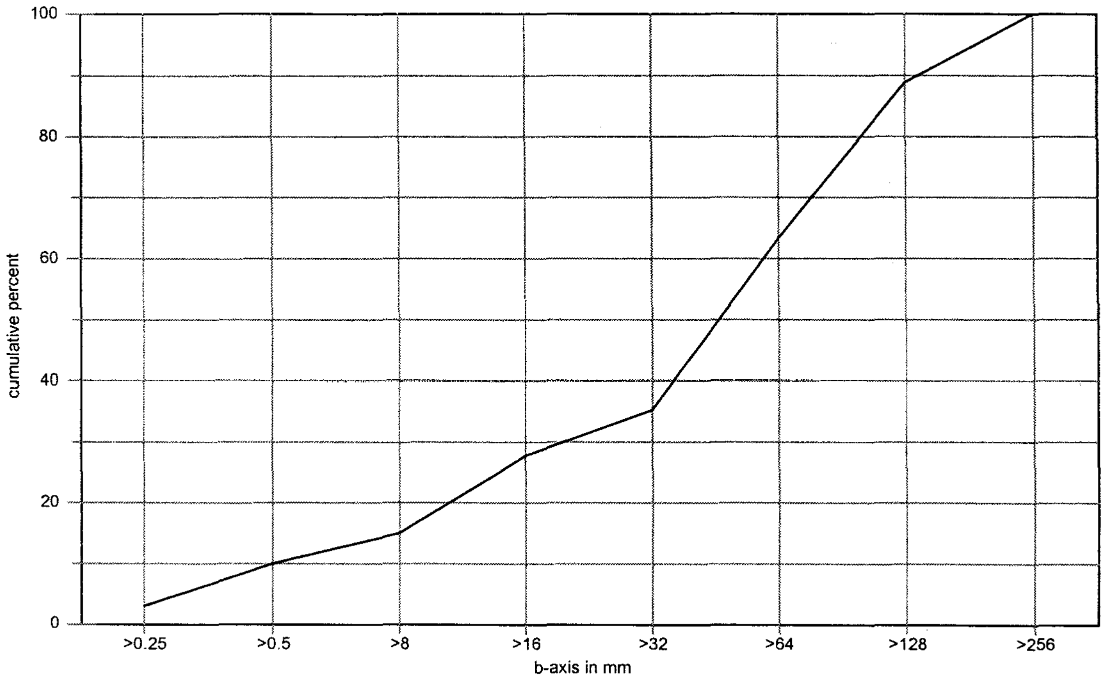

Figure 4.20: Amatola tributary substrate sample.

4.7.3. Bar sediment samples

A comparison of Rowntree and Dollars (1994) sediment sample (Figure 4.21 and 4.22) and the 1996 sample (Figure 4.23) show a great change in composition of bar. The d_{50} in 1980 was 1.12mm and 2.54mm in 1993. The 1996 sample showed a d_{50} value of 50.75mm. Photos from the earlier date suggest that the bar was higher, such that it even supported some grass growth, whereas even at the lowest recorded flow in 1996 the bar was at least 40cm under water. With a d_{50} size of > 50mm measured on the Hjulström (1935) curve, it would take velocities of about 1.1 m/s^{-1} to initiate erosion of the median size particles The highest velocity measured in the vicinity of the bar was $0.204m^3s^{-1}$, at a depth of 1.04m, at a discharge of approximately $9m^3s^1$.

4.7.4 Bar morphology

The bar at this site is probably a permanent feature, given the size of the sediment of which it is composed. While it was impossible to sample the bar accurately - the sediment sample taken shows the predominance of cobble to large cobble size rocks, which have probably been moved under high flow conditions in the tributary. It is about 5m wide and 10m long extending into the main channel from the tributary mouth, at an angle, pushing the channel thalweg towards the opposite bank. High velocities would be created by the steep gradient of the tributary, as well as significant turbulence created by the boulder and cobble bed which would give it the velocities required to move such large bedload.

Change can be seen in the bar as indicated on Figure 4.24 from one date to the next, although it is not substantial. This change can also be seen on cross-section B, Figure 4.17 and 4.18. The difference in the cross section is more likely a result of surveying inaccuracy than actual change. It is not possible to tie these exactly to Rowntree and Dollar's (1994) map, but the approximate position is sketched in on Figure 4.24. There is a noticeable change from the earlier morphology. It would seem that the Amatola is a high energy stream with a steep gradient and high runoff giving it the capacity to deliver a large load to the main stream. Given that velocities of up to $1m^3s^{-1}$ would be required to move the d_{50} size sediment, it certainly would need the added power of the main stream in flood to destabilise the bulk of the bar.

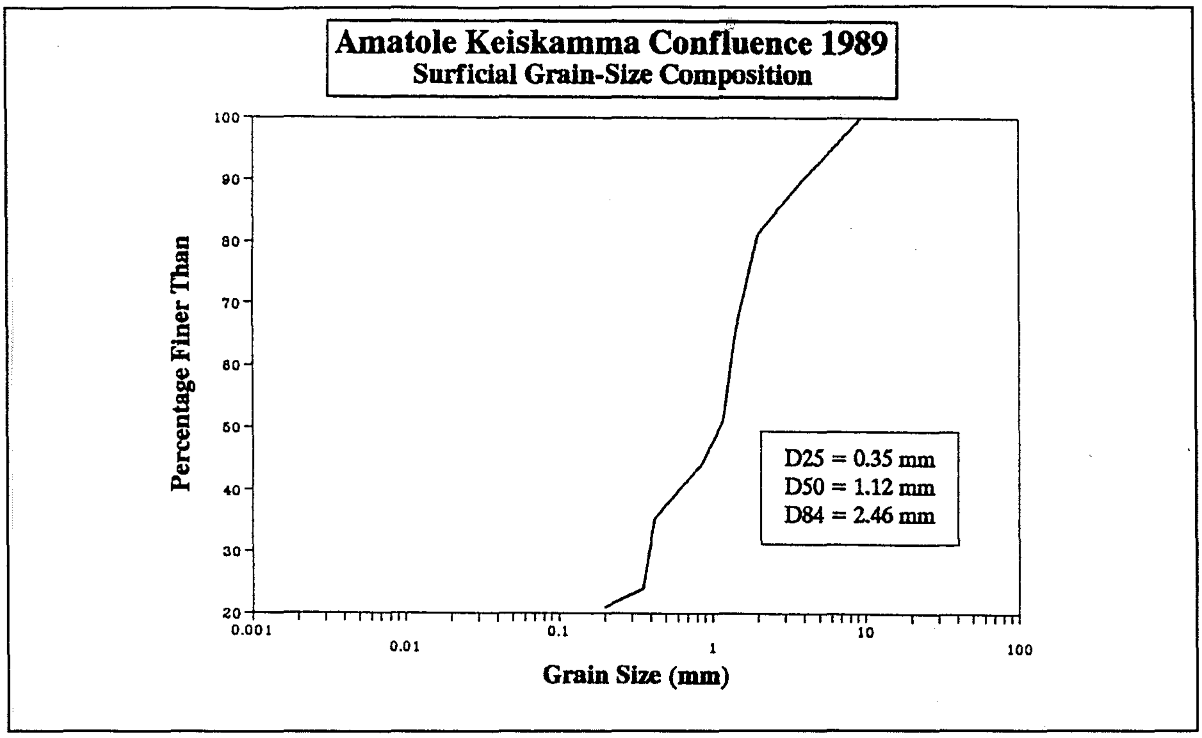

Figure 4.21: Keiskamma/Amatola bar sediment - 1989, from Rowntree and Dollar (1994).

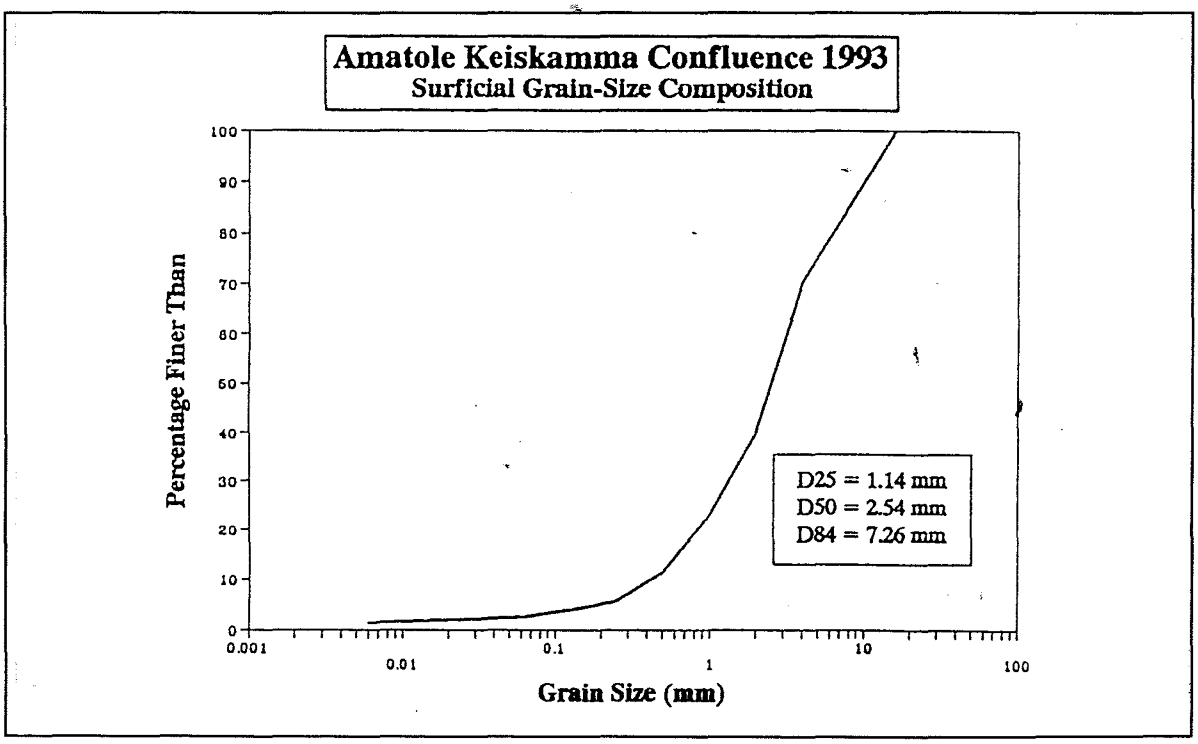

Figure 4.22: Keiskamma/Amatola bar sediment - 1993, from Rowntree and Dollar (1994).

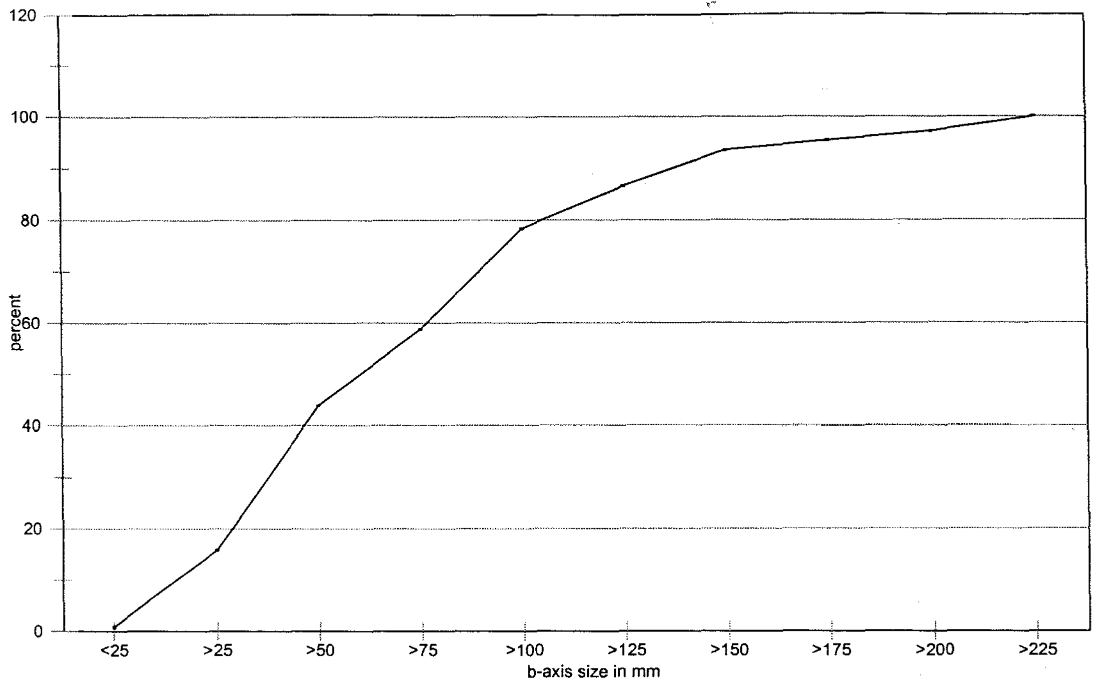

Figure 4.23: Keiskamma/Amatola bar sediment, 1996.

The suspended sediment readings in Table 4.6 correspond with the discharge readings: at the highest flow the sediment concentration in the tributary and the main stream is highest, with the main stream carrying the higher load of 0.156g/l. The highest flow 9 m^3s^{-1} has a flow duration of 2% of the time on the post dam flow duration curve (Figure 4.7). It would have occurred slightly more often on the pre dam (2-3%).

Table 4.6: Amatola site - suspended sediment and discharge.

date	*site*	*discharge* m^3s^{-1}	*sediment g/l*
5/96	Amatola/Keiskamma	0.4345	0.03
	Amatola tributary	too low	too low
11/96	Amatola/Keiskamma	9.169	0.1546
	Amatola tributary	1.114	0.071
3/97	Amatola/Keiskamma	1.533	0.05
	Amatola tributary	0.19	0.009

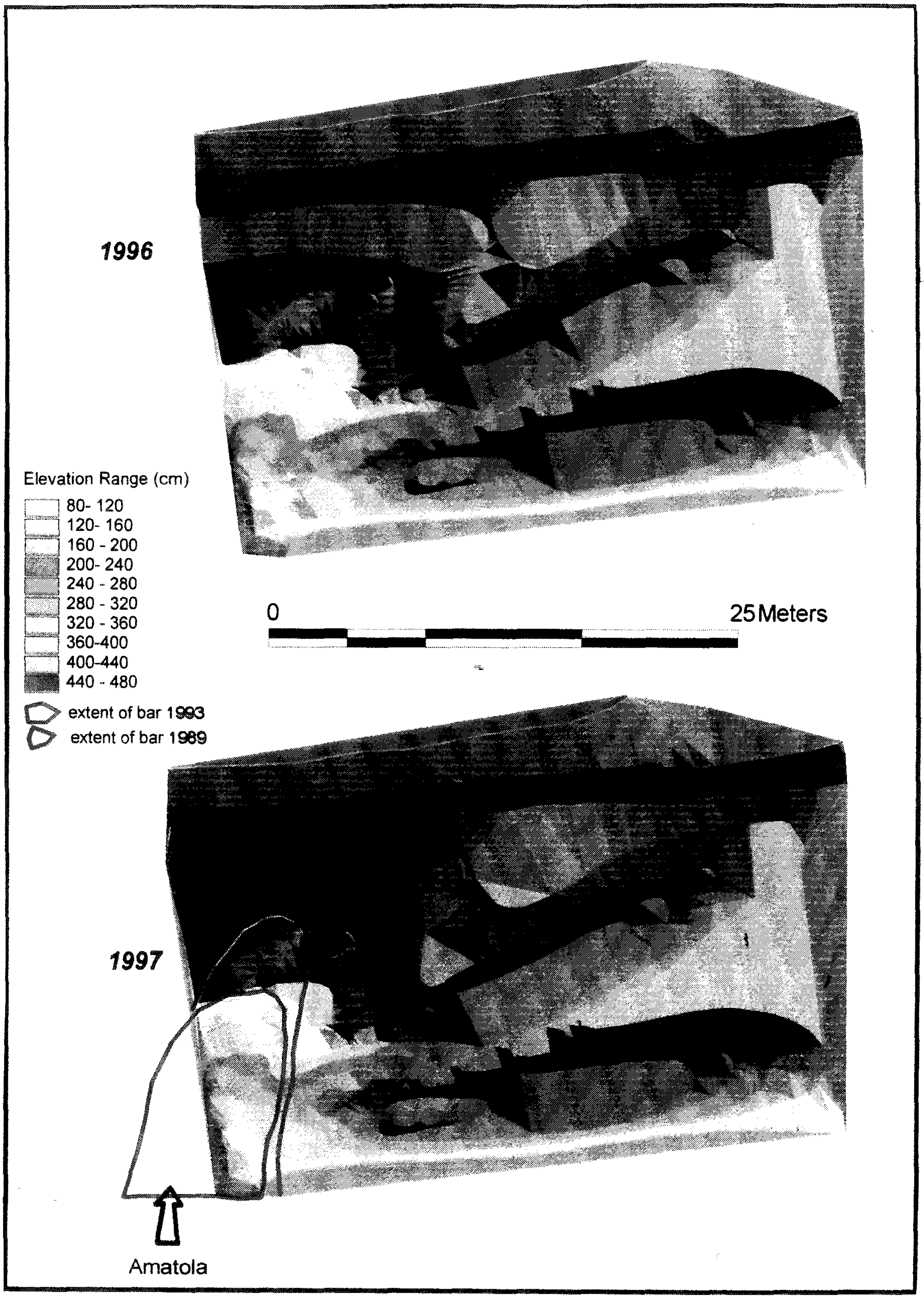

Figure 4.24: Keiskamma/Amatola bar morphology in 1996 and 1997.

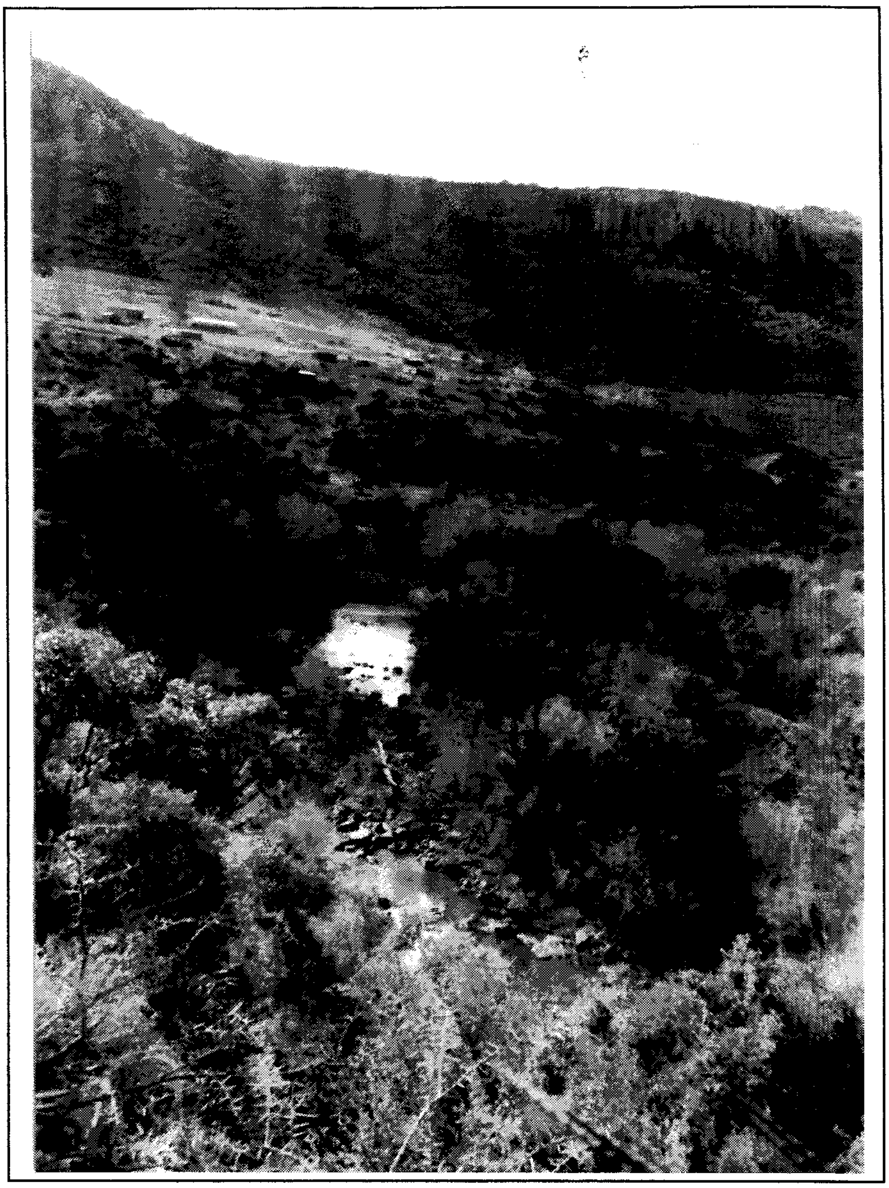

Plate 4.17: Aerial view of the Keiskamma/Amatola site showing the island.

4.7.5 Assessment of Aerial photos

The pre-dam photo taken in December 1963, at a scale of 1:20 000, shows no evidence of a bar at the tributary mouth. An assessment of the catchment/sediment producing area, shows it to be in a reasonable condition, with scattered settlements, some extensive cultivated lands, but predominantly natural vegetation in the form of forest and grasslands. The island at the lower end of the pool shows two distinct channels - a short one cutting off a small section of island, about 2m wide and a much longer one which skirts the edge of the rocky outcrop and is dammed by a weir. Both channels are clearly flowing. Three boulders in the pool above the tributary junction give an indication of water level.

In the 1988 photo taken in August, at a scale of 1:12 000, the river is obviously at a lower level, but the three boulders are still visible. There has been significant removal of vegetation particularly in the riparian zone. At the road crossing, on a slight bend where a secondary channel and scour line can be identified, a patch that was once thickly wooded is now bare. The smaller channel on the island appears to have silted up, and probably only flows at high flows. There are sandy deposits at the head of the island, around the mouths of the side channels. There is a bar sticking out of the water at the tributary junction. Areas of dense thicket have been thinned considerably probably due to stock grazing. The riparian zone along the left bank on the Amatola pool has been depleted.

What is also evident from the photos in terms of the general state of the catchment, is that the population density has increased, as has the extent of cultivation and the livestock numbers, indicated by the pathways criss-crossing the landscape. A random hut count on the same 1km square in 1963 and 1988, showed an increase from 14 huts to 20 huts which suggests a population increase. This was supported by ENPAT98 data which shows an increase in population from 64512 in 1991 to 75564 in 1995 for the Middledrift census district (which the Amatola catchment falls within).

4.8. The Ncqwazi tributary bar

4.8.1. Description of the Ncqwazi

The catchment can be described as a very responsive surface in terms of sediment production. Vegetation cover is poor on the steepest slopes and soils are described as erodible (Hill-Kaplan Scott, 1976). Stock grazing and crop cultivation (see Plate 4.18) on quite a large scale, increase the erosion potential. The erosion features from the Hill-Kaplan Scott (1976) map series are shown in Figure 4.25 while present erosion gullies can be identified in a view of the catchment, (Plate 4.18) on the far slopes. The stream has a gentler gradient than the Amatola with an average gradient of 0.02 as shown in the long profile, Figure 4.27. A cross section of the stream shown in Figure 4.28 and illustrated in Plate 4.19 shows the depth of incision of the stream channel. With sheer banks of five to six metres in the last 500m, this is also evidence of the volume of runoff which is generated by the catchment. The rate at which runoff is generated is evident in the state of the road crossing which is frequently washed away and repaired.

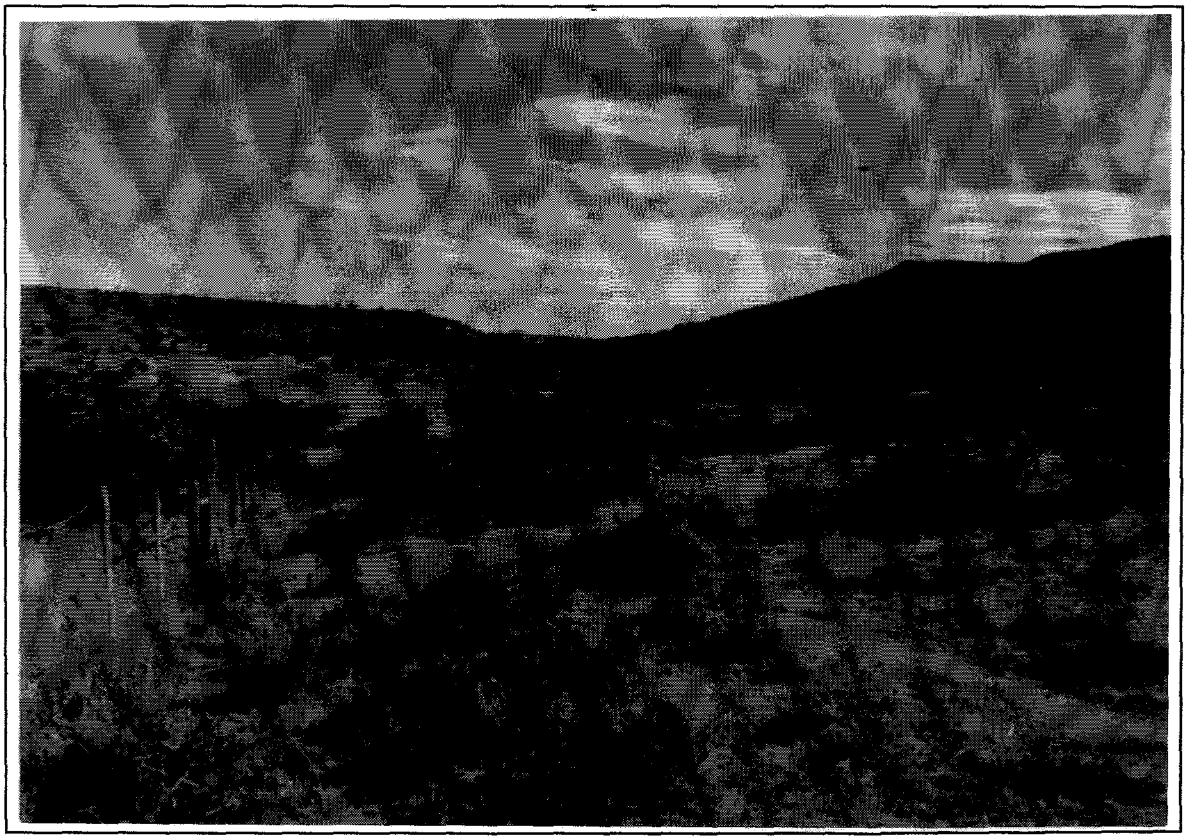

*Plate 4.*18: View of the Ncqwazi catchment.

Table 4.7: Ncqwazi catchment characteristics.

Area	24.47km^2
Channel length	9.2km
Average Gradient	0.05%
Rainfall (MAP)	710mm
Runoff (MAR)	67mm
Topography	Pear shaped basin with steep sides and a gently sloping valley floor
Geology	Sandstone and dolerite of the Karoo Super-group
Soils	Black and red eutrophic soils: fertile, with a high erosion hazard due to sloping pediments. Grey or brown litholic soils of limited depth, very high erosion hazard due to steepness of pediments.
Sediment production	High - due to erodible soils, poor vegetation cover, cultivation and overgrazing
Landuse	Dryland cultivation and grazing, rural villages
Vegetation cover	Cultivated lands, short open shrub land and grassland, and *Acacia karroo* communities
Erosion status	Extensive erosion - gully and sheet

4.8.2. Morphology of the Ncqwazi Junction

The Ncqwazi tributary enters from the west/right bank where it deposits sediments in the form of an extensive tributary bar. The Keiskamma channel is incised into the alluvium, forming a long deep pool. Its left bank is sheer and unstable, with woody vegetation and grass. The right bank is less steep and well vegetated with trees and grass. There is minor erosion on the right bank caused by livestock. The bar is about 50m long and 8m wide at present and lies parallel to the channel. The pool ends in an extensive cobble bar which constricts the river towards the right bank in a riffle of bedrock and cobble. Upstream and downstream views of the site are shown in Plates 4.20 and 4.21 and cross-sectional profiles are depicted in Figures 4.30 to 4.33. Substrate material is mostly sand and coarse gravel, with cobble size material closer to the riffle. The substrate of the pool upstream of the junction is mostly silt.

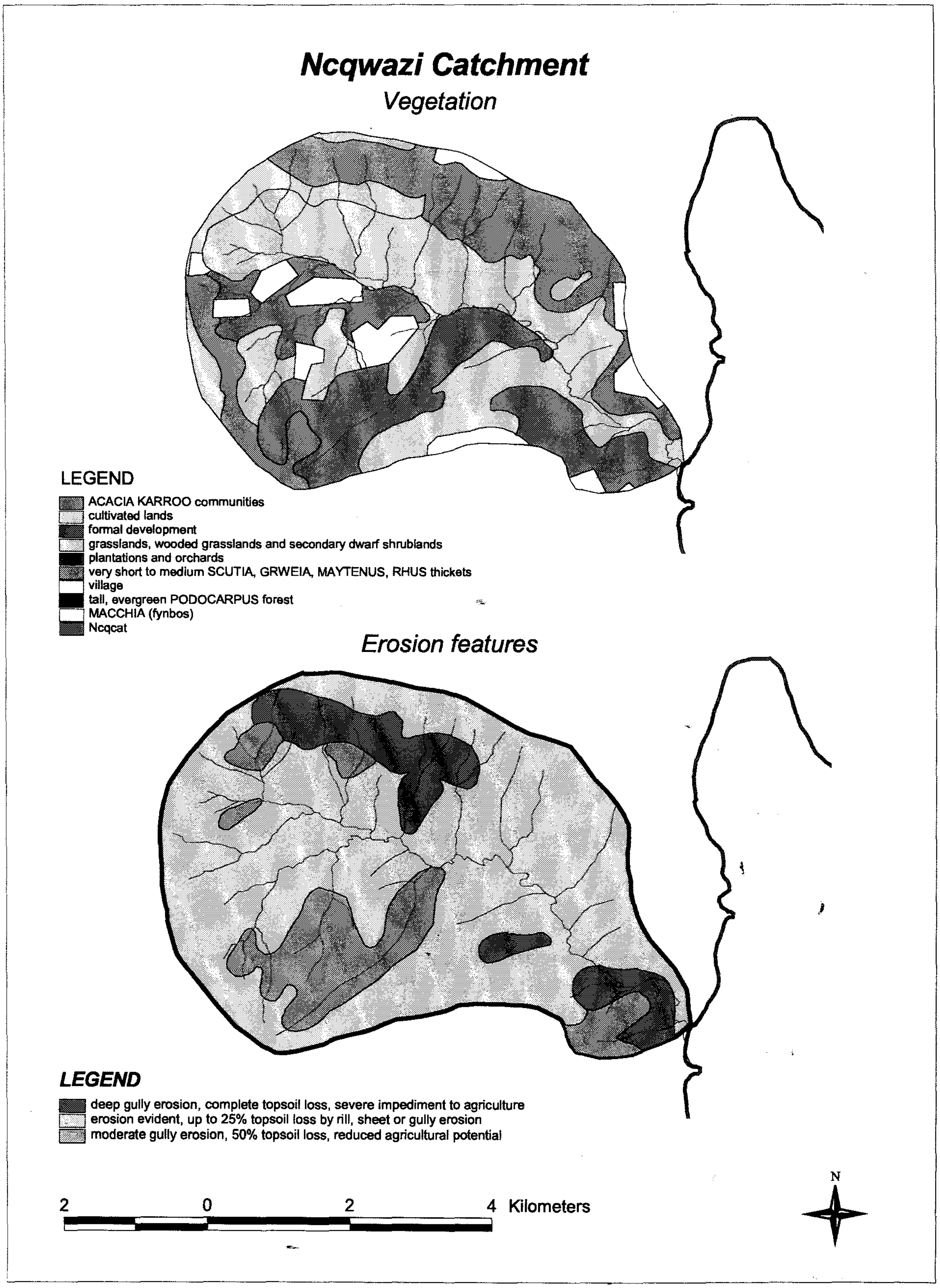

Figure 4.25: Ncqwazi catchment - erosion features and vegetation.

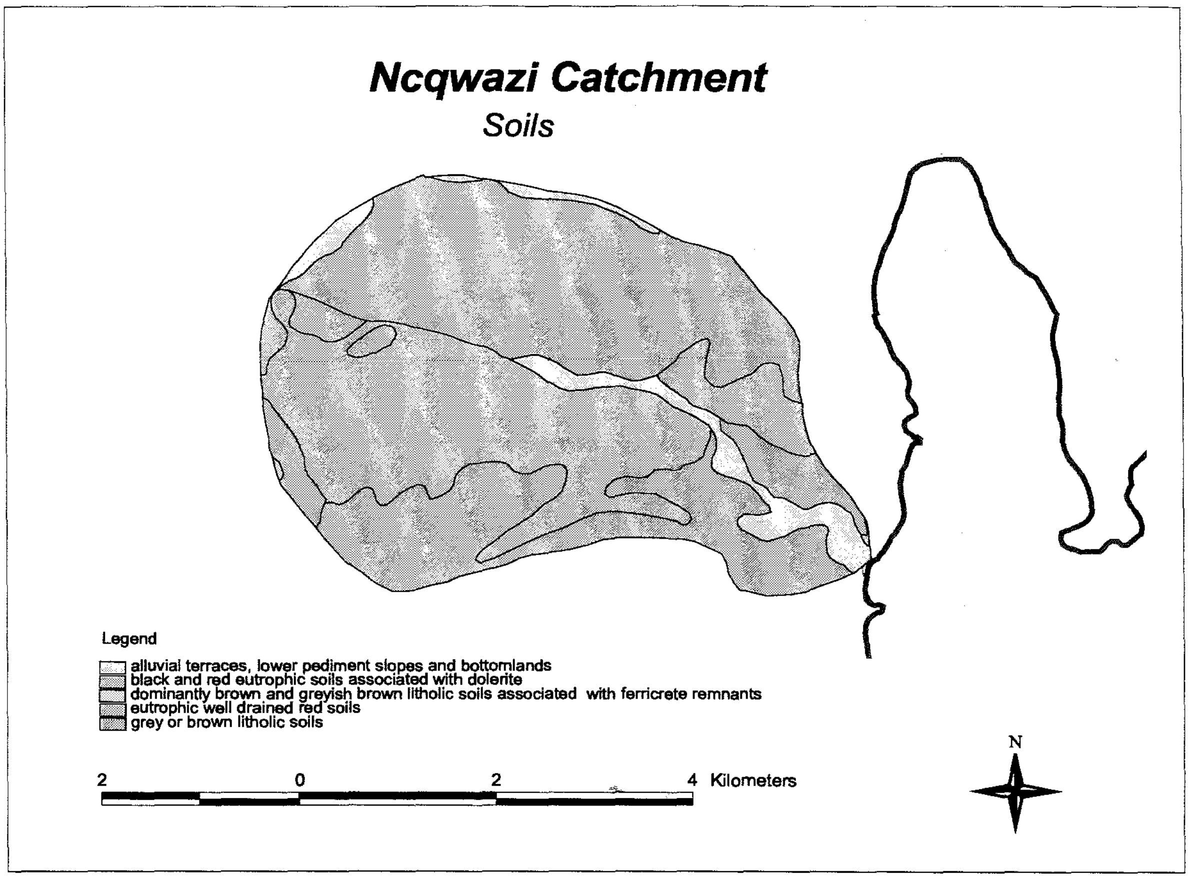

Figure 4.26: Ncqwazi catchment - soils

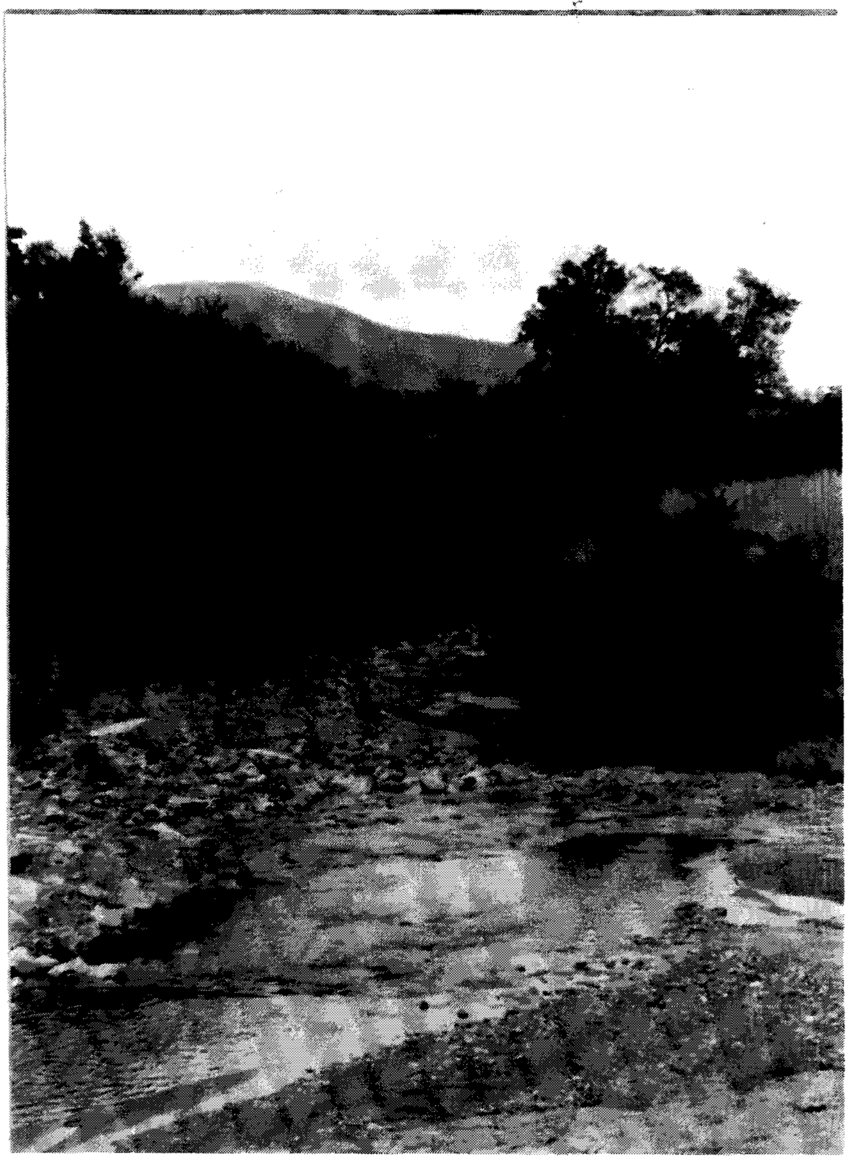

Plate 4.19: Deeply incised Ncqwazi tributary.

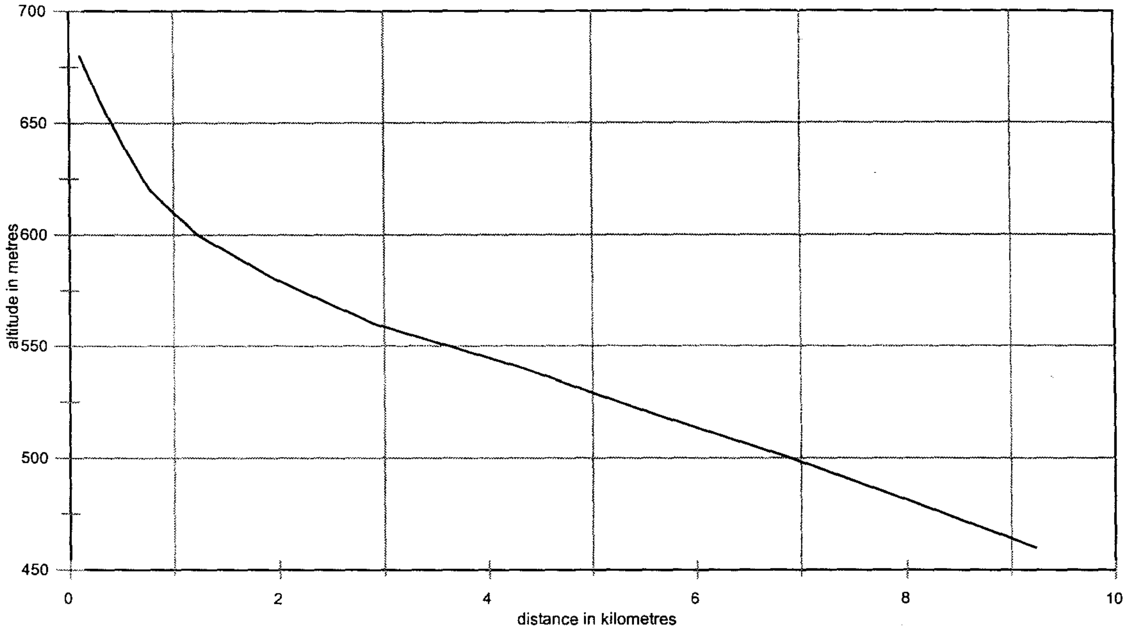

Figure 4.27: Long profile of the Ncqwazi.

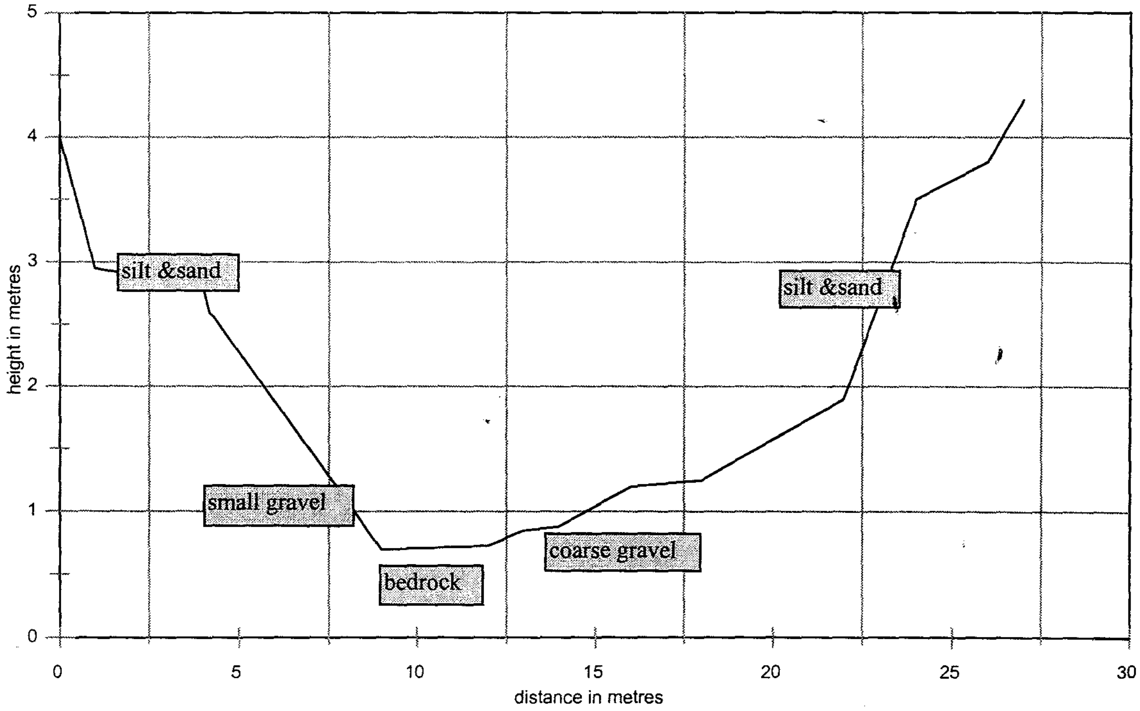

Figure 4.28: Cross-section of the Ncqwazi.

Plate 4.20: Keiskamma/Ncqwazi junction, downstream view.

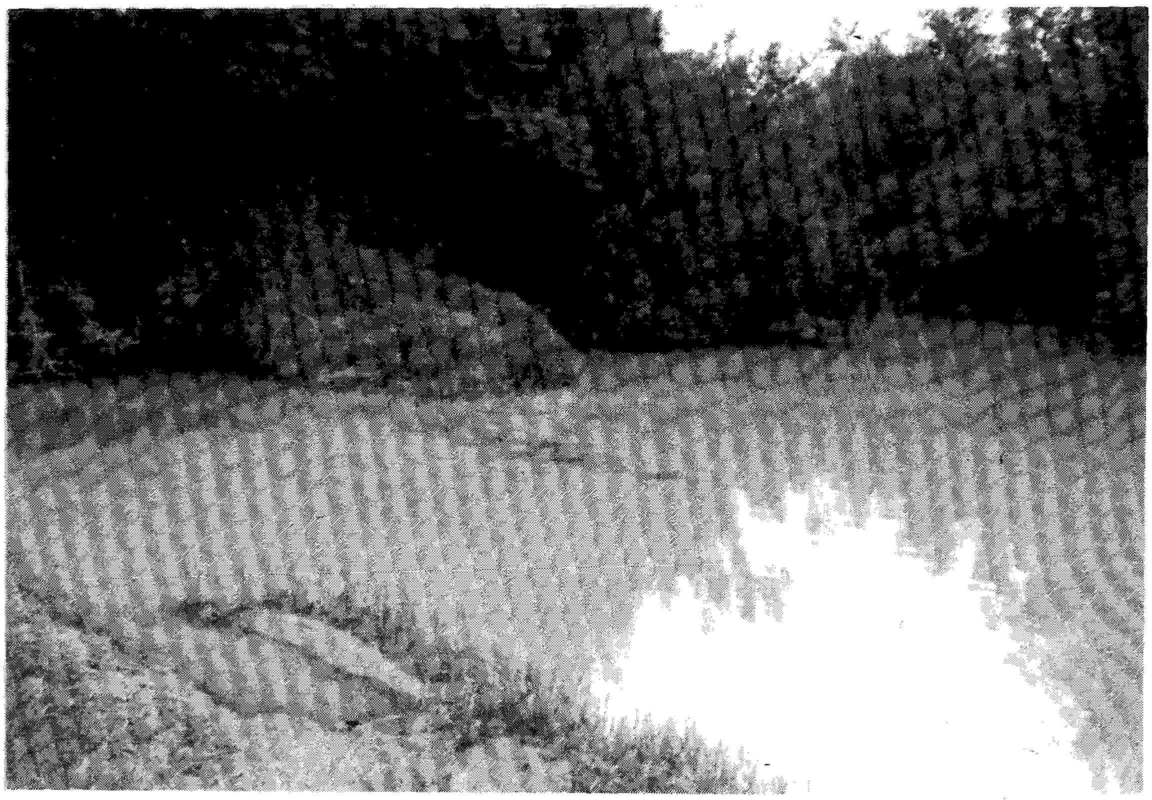

Plate 4.21: Keiskamma/Ncqwazi junction, upstream view.

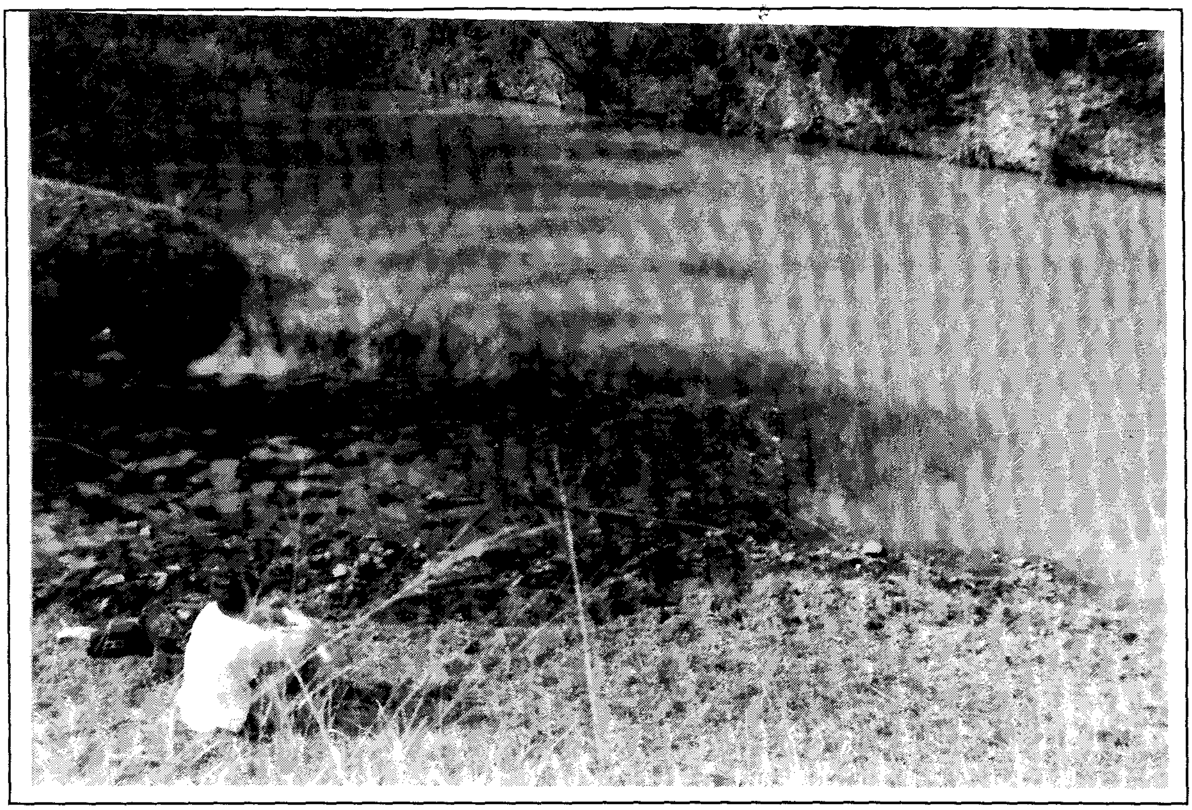

Plate 4.22: Keiskamma/Ncqwazi junction, tributary bar, 1996.

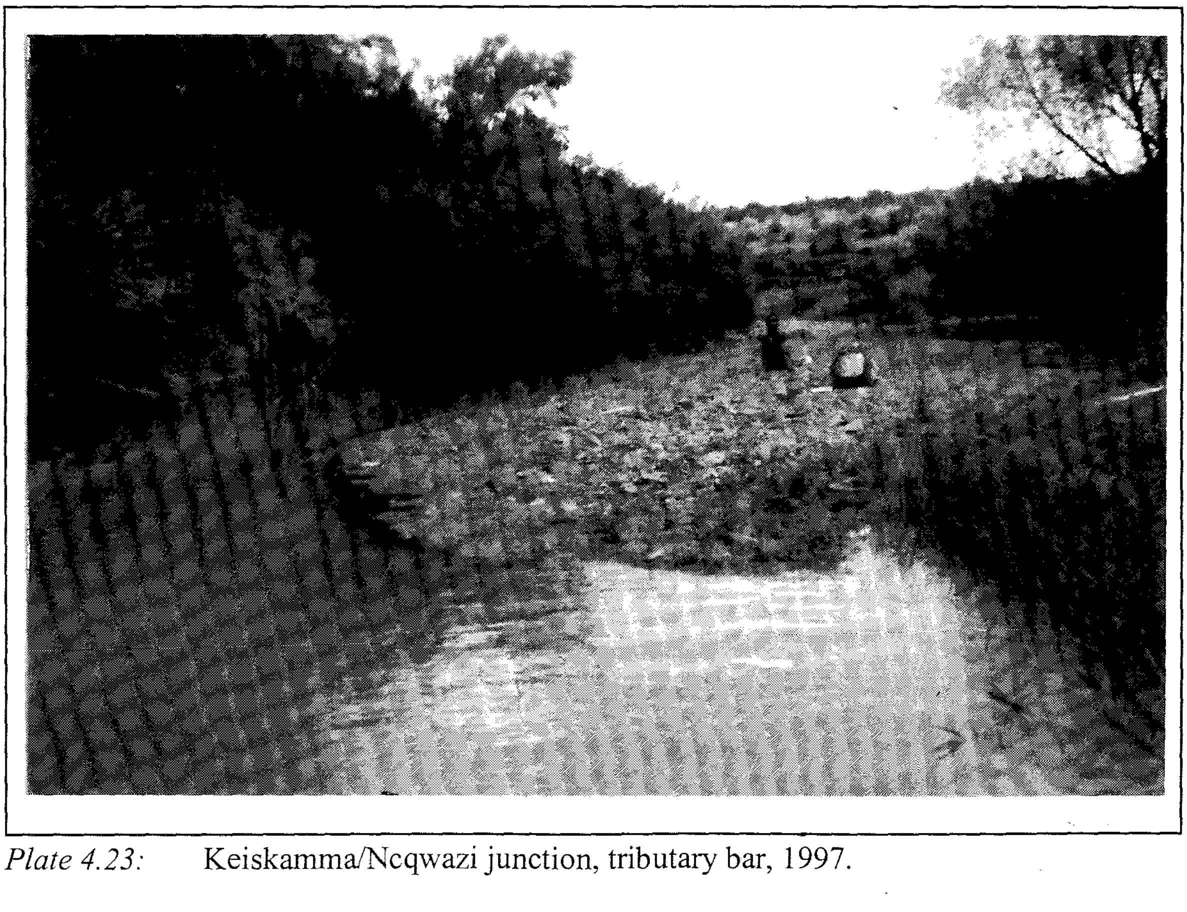

Plate 4.23: Keiskamma/Ncqwazi junction, tributary bar, 1997.

Plate 4.24: Keiskamma/Ncqwazi junction, lower end of bar, 1997.

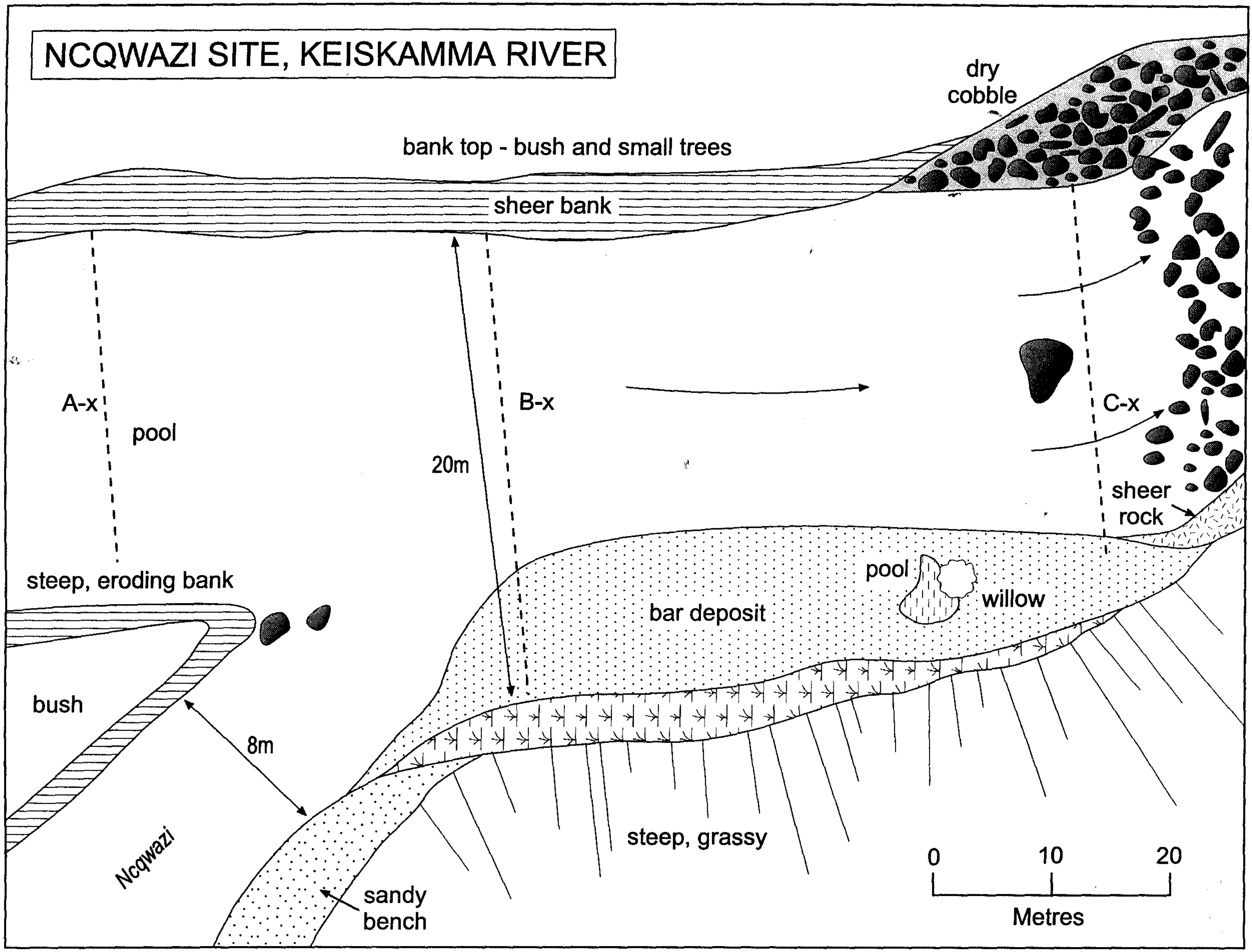

Figure 4.29: Plan view of the Ncqwazi site

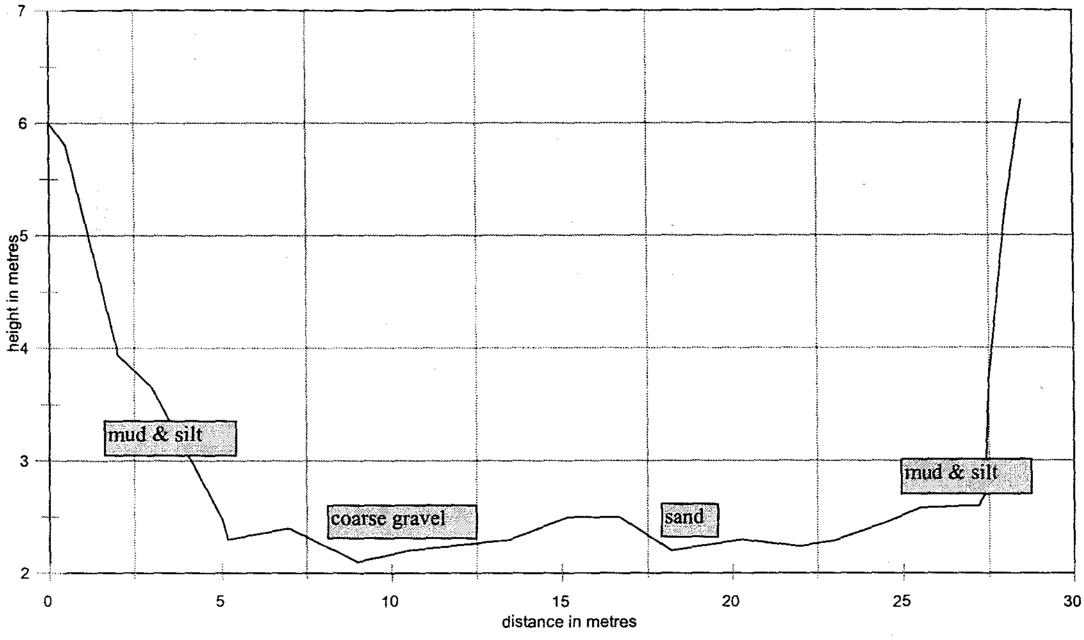

Figure 4.30: Keiskamma/Ncqwazi cross-section A, 1996, upstream view.

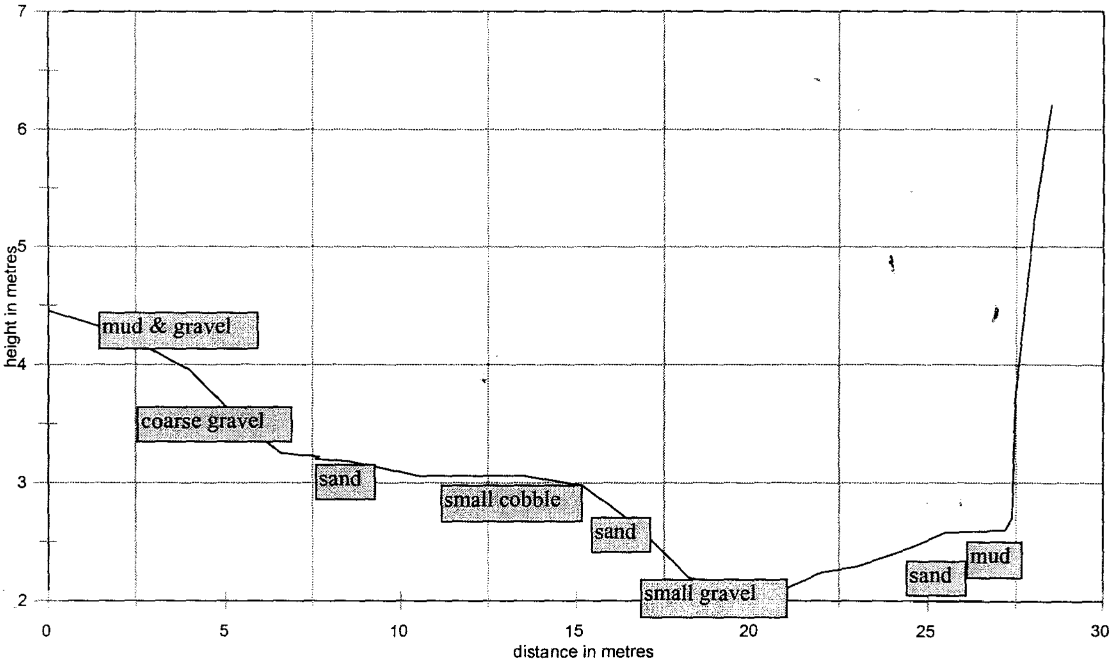

Figure 4.31: Keiskamma/Ncqwazi cross-section B, 1996, downstream view.

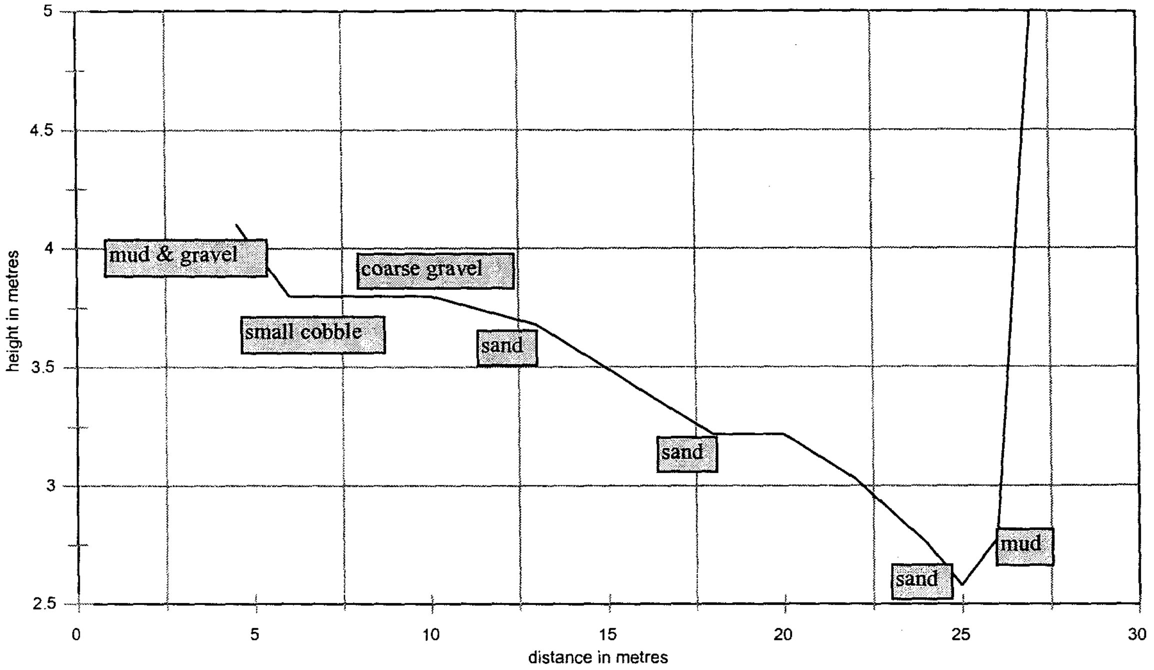

Figure 4.32: Kesikamma/Ncqwazi coss-section B, 1997, downstream view.

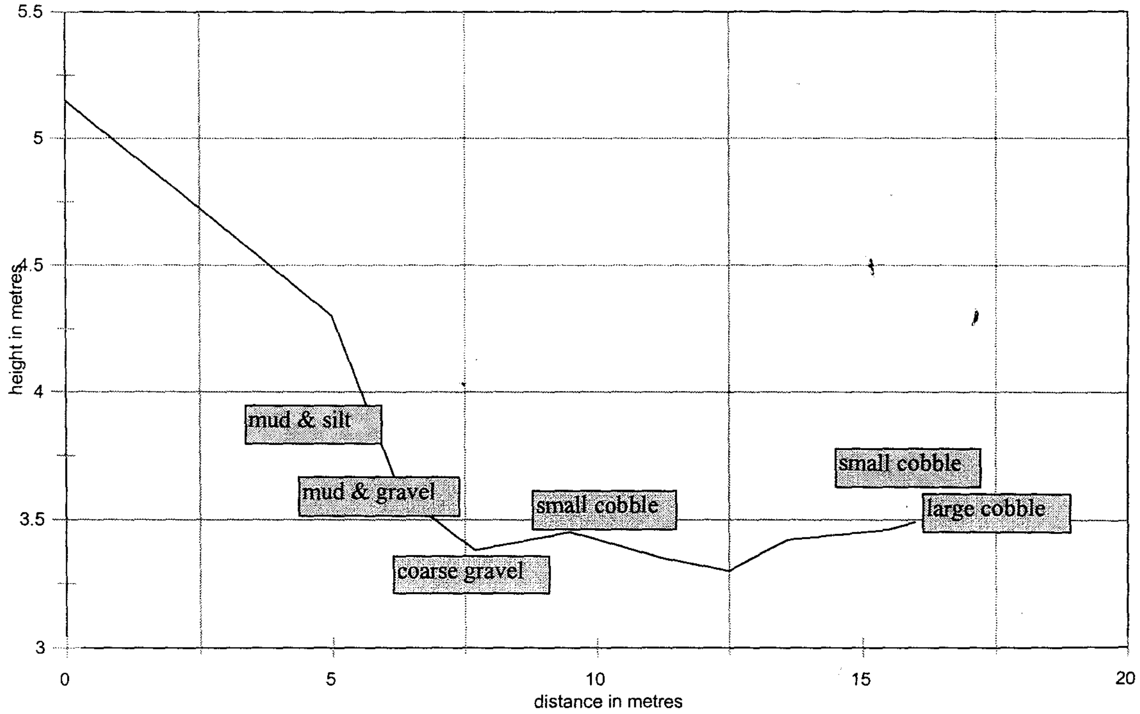

Figure 4.33: Keiskamma/Ncqwazi cross-section C, 1996, downstream view.

4.8.3. Ncqwazi tributary bar morphology

The extensive tributary bar at the intersection with the Keiskamma is the product of the erosion of sediments from the Ncqwazi catchment. Composed mostly of unconsolidated gravel size and smaller sediments (Figure 4.36) the bar is substantial in extent, stretching downstream for some 50m. Field visits at two different dates show how changeable it is as is illustrated in the bar morphology maps done at two dates (Figure 4.34). Plates 4.22 and 4.23 show the change in the bar from 1996 to 1997, while Plate 4.24 shows the form of the lower end of the bar. The bar maps in Figure 4.34 show that the form of the bar has changed from one year to the next. These are also be related to Rowntree and Dollars (1994) sketches made in 1989 and 1993, which are indicated in the figure. A sizeable section of the left bank had collapsed between 1996 and 1997 which can be seen in Plate 4.23.

The sediment sample size composition (Figure 4.36) suggests that the bar sediment is derived mainly from the tributary, mainstream sediment upstream being of a smaller caliber.
The d_{50} sediment size in the bar sample is of material with a b-axis of 2-4mm in the 1996 and 1997 samples. According to Hjulströms curve it would require velocities of about $0.8ms^{-1}$, to begin eroding this size fraction. Unfortunately it was not possible to get flow readings over the bar on an occasion of high flow. The highest flow recorded in the channel against the left bank was $0.16\ ms^{-1}$. The d_{50} size class in the tributary sample (Figure 4.35) was also 2-4mm, which suggests that the bar material is derived from the tributary.

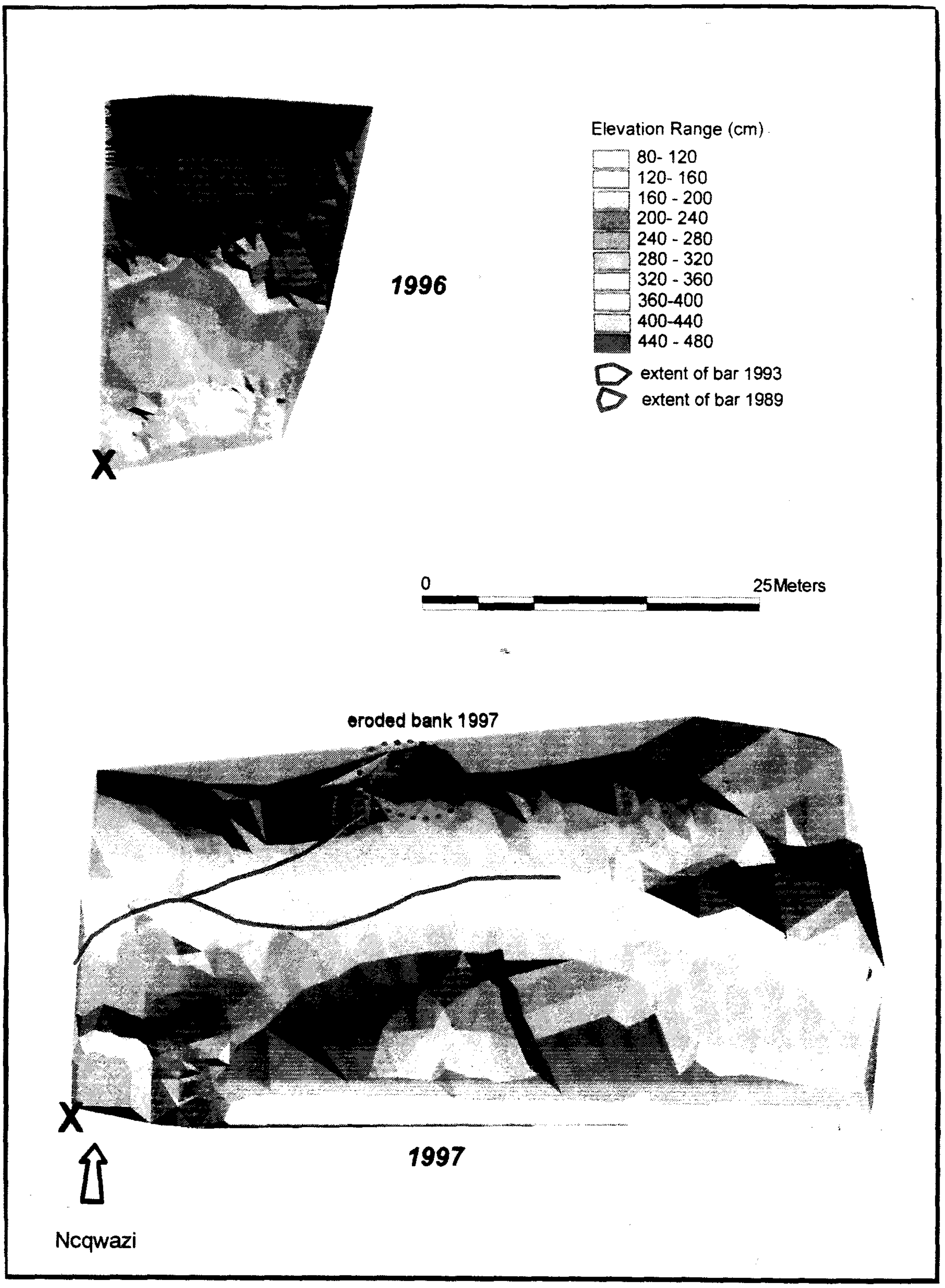

Figure 4.34: Keiskamma/Ncqwazi bar morphology in 1996 and 1997.

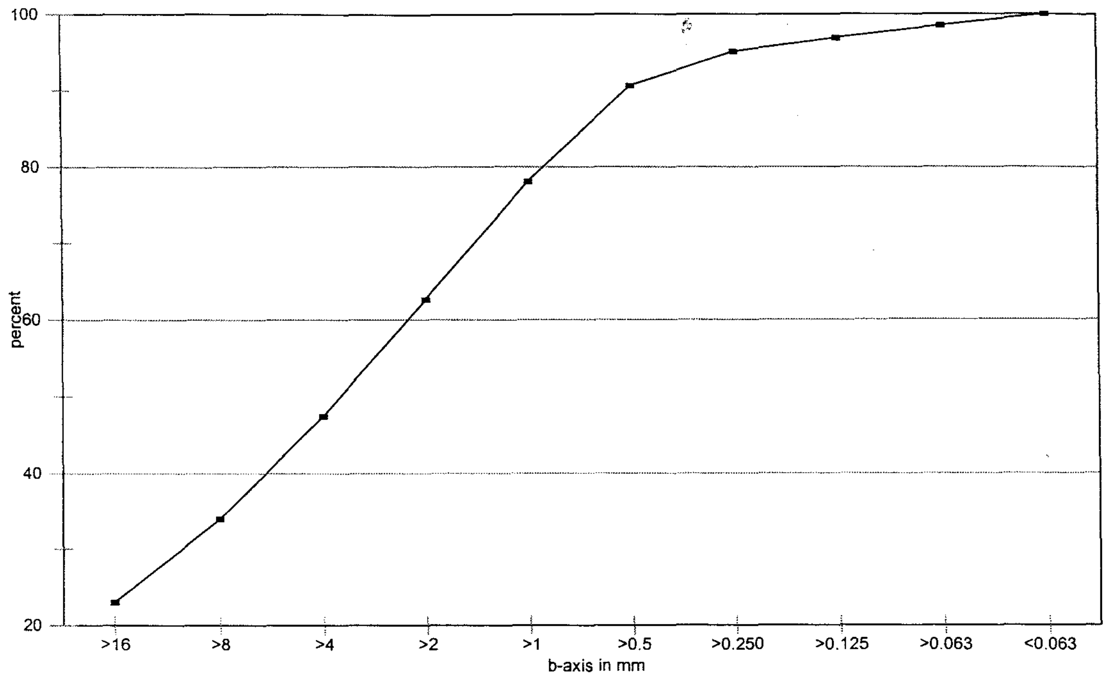

Figure 4.35: Ncqwazi substrate sample.

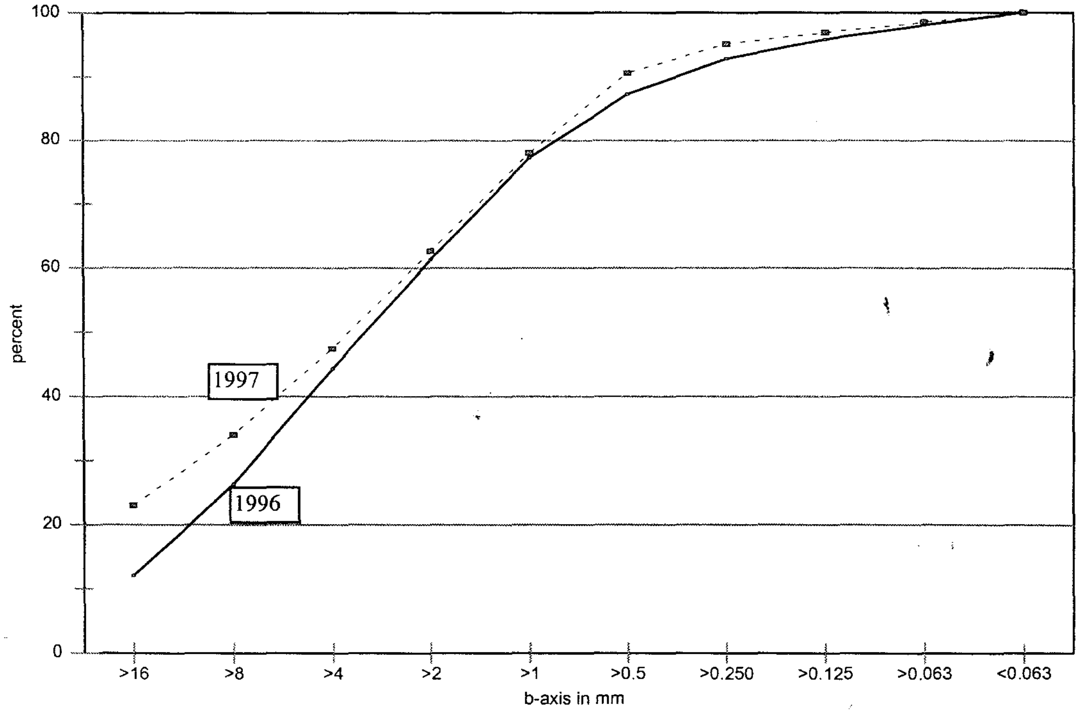

Figure 4.36: Keiskamma\Ncqwazi bar sediment for 1996 and 1997.

The readings in Table 4.8 of discharge and suspended sediment load show that the river carries a high suspended load at high flows. The suspended load in the tributary is higher than that of the mainstream at a high flow. The suspended sediment sample in the Amatola tributary was lower than this at the same date, and so was the mainstream value, which suggests that sediment input to the system increases in a downstream direction..

Table 4.8: Ncqwazi site - suspended sediment and discharge

date	site	discharge m^3s^{-1}	sediment g/l
5/96	Ncqwazi/KK	0.4124	0.036
	Ncqwazi trib.	no flow	no flow
11/96	Ncqwazi/KK	11.5	0.1686
	Ncqwazi trib.	0.887	0.19
3/97	Ncqwazi/KK	1.426	0.047
	Ncqwazi trib.	too low	too low

4.8.4. Aerial photo maps

Due to the steep banks at this site, which cast a shadow, it is difficult to pick up any detail at the river confluence on the 1963 photo. However in the larger scale 1988 photo, the bar stretching along the right bank is clearly visible. What is also evident is the increased settlement and associated erosion in the catchment. There is evidence of extensive erosion even in 1963, which has worsened by 1988: gullies have developed into extensive networks and the extent of rill and sheet erosion has increased.

4.9 The Debe tributary bar

4.9.1. Description of the Debe

The Debe River enters the Keiskamma 49km downstream of Sandile dam. It drains a gently sloping area of 220km^2, with steep slopes in its headwaters. The long profile of the stream is shown in Figure 4.39, and its cross sectional profile in the lower reaches is shown in Figure 4.40. At the confluence of the Debe, the unimpounded catchment area of the river has recovered to 501km^2. The ground is stony, with poor cover. There is extensive gullying leading directly into the stream (Plate 4.25). The channel is deeply incised down to bedrock in the lower reaches. The rainfall here is less than in the Amatola and Ncqwazi, most of the catchment falling within the 500-600mm isoheyt. In terms of rainfall, this catchment would respond to localised showers, rather than the widespread weather systems dominating the catchment further up the system. This is confirmed by a study of a map of the rainfall erosivity storm intensity over the Keiskamma basin (CCWR GIS MAPS, 1997). This implies that the tributary would be out of phase with the mainstream and would be likely to deposit sediments in the main channel when it was at a lower stage. Because of the poor ground cover and the thin soils, rainfall/runoff ratios would be high, and flows are likely to be flashy, with the ability to carry a significant sediment load. There is plenty of evidence of goats and cattle trampling the banks of the tributary and using it as pathway. The soils map of the catchment (Figure 4.38) shows that the area is dominated by grey or brown litholic soils, which are shallow and have a high erodibility rating. Given the extent of overgrazing and rural settlement there is likely to be high sediment production in this catchment.

4.9.2. Morphology of the Debe Junction

A plan of the site is shown in Figure 4.41. Plates 4.27 and 4.28 give a view of the site. The main channel is well defined, with an identifiable bench marking the edge of the low flow channel/wetted perimeter. The long pools are broken by ribs of bedrock, and associated sediment deposits which break the gradient of the river. An assessment of time series aerial photos shows that the catchment has been degraded over the past twenty years. The riparian zone has been degraded by stock grazing, which means that runoff delivers sediment directly to the stream channel.

Plate 4.25: Gullies leading into the Debe.

The Debe enters the mainstream from the left bank at 90°. It is incised into unconsolidated material, forming steep, sheer banks (Plate 4.26). The bed is a mixture of cobble and gravel set in mud. Immediately below the tributary entrance a bedrock rib crosses the main channel, forming a rapid, which causes a gradient change, and creates a bedrock pool against the right bank. Cobble and gravel deposits form a low lying , unconsolidated bar deposit on the left bank. About 120m hundred metres downstream is an extensive, flat gravel and finer sediment bar 100 by 40m in extent, which constricts the water to the left side of the macro channel, before the river bends to the right. The site cross sections (Figures 4.42, 4.43 and 4.44) show the presence of a bench on the right bank, which is well defined in this reach.

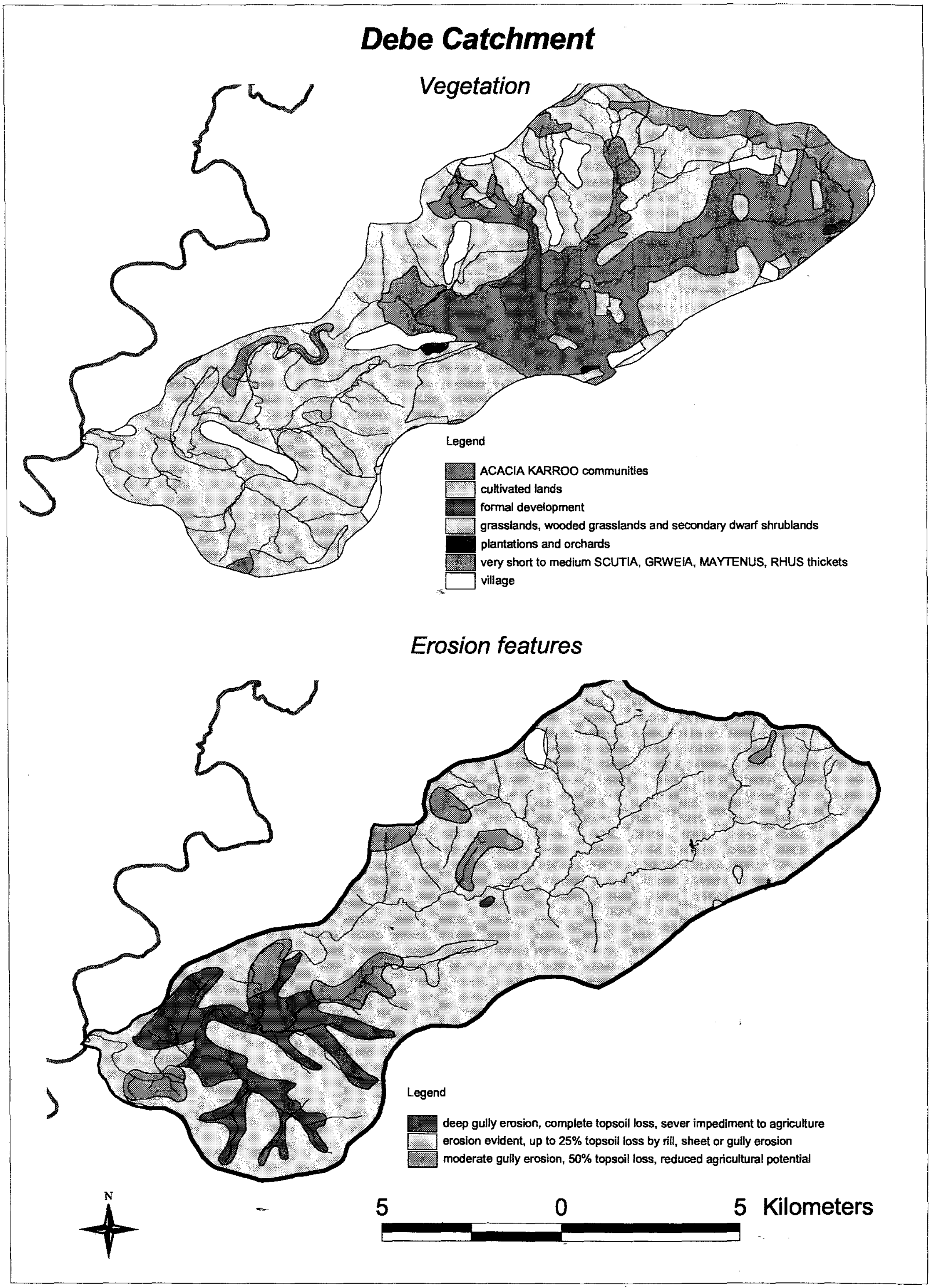

Figure 4.37: Debe catchment - vegetation and erosion features.

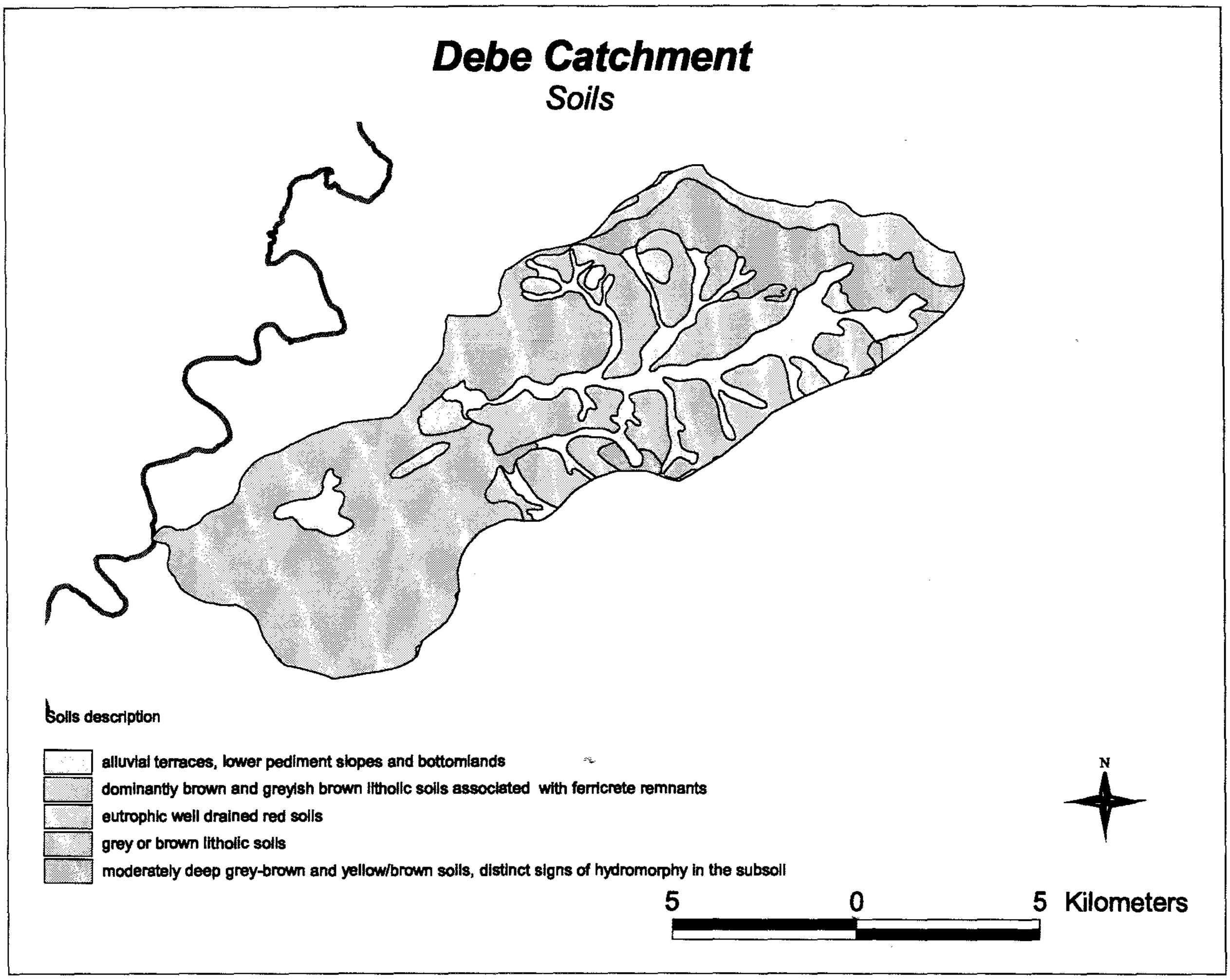

Figure 4.38: Debe catchment - soils.

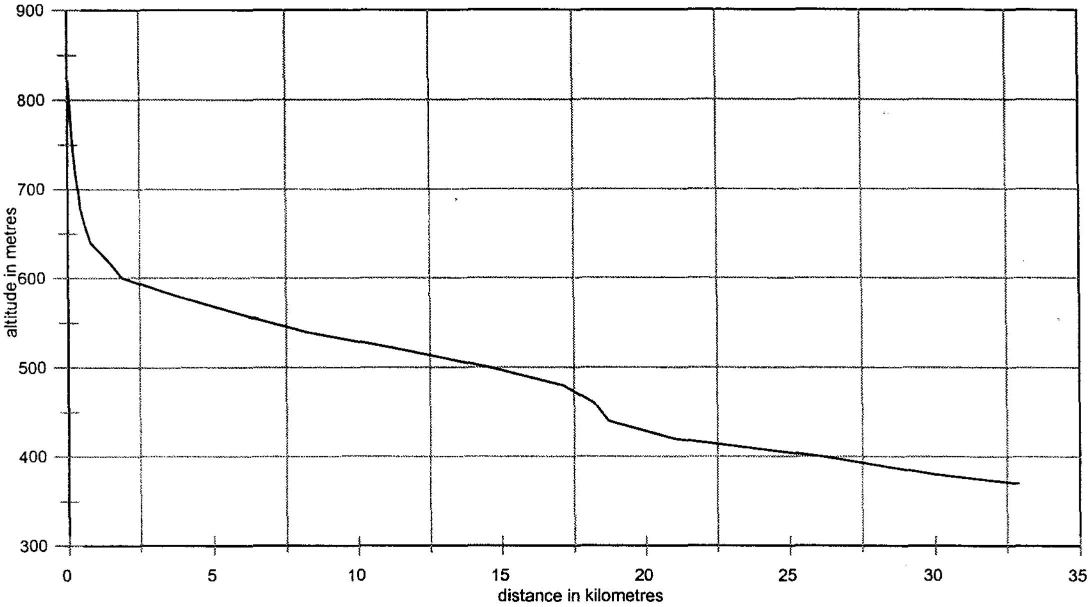

Figure 4.39: Long profile of the Debe.

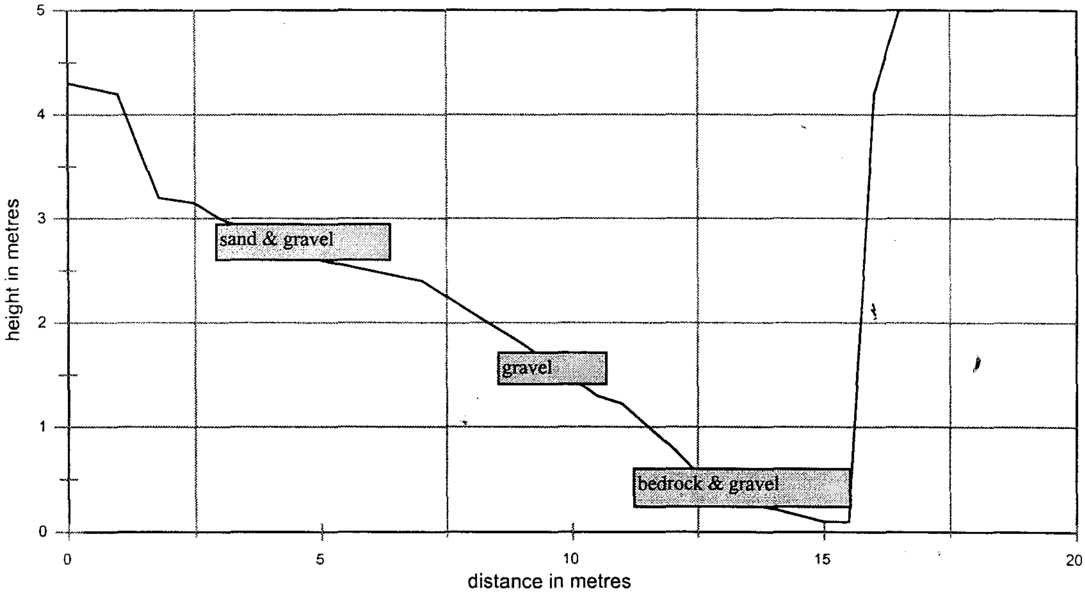

Figure 4.40: Cross-section of the Debe.

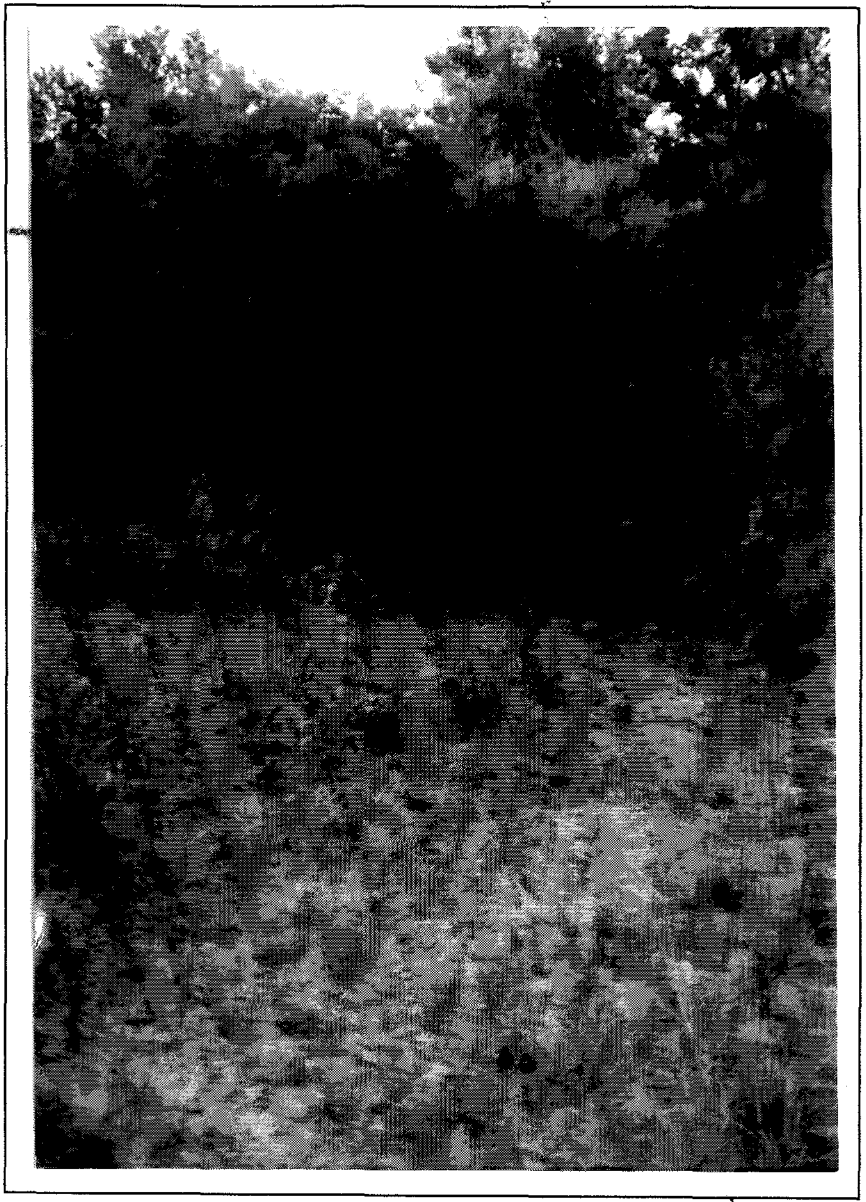

Plate 4.26: Debe tributary.

Plate 4.27: Keiskamma/Debe junction.

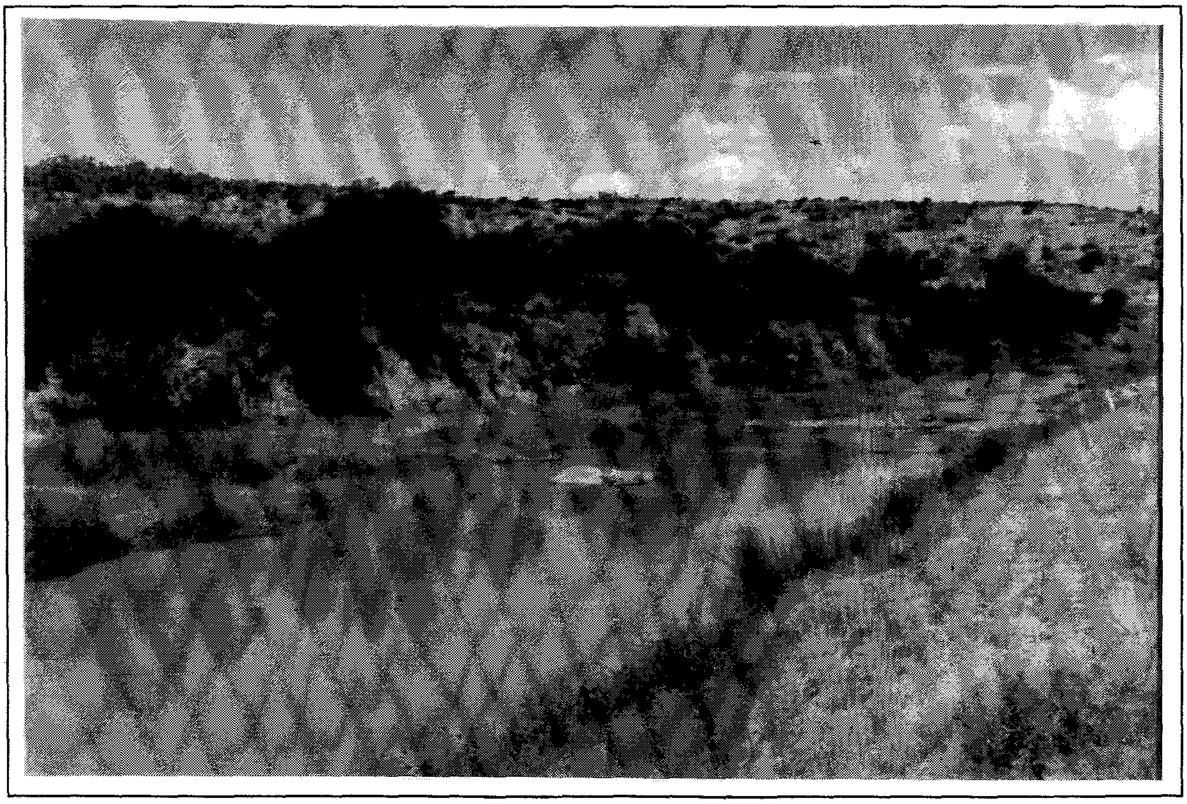

Plate 4.28: Keiskamma/Debe junction, downstream view.

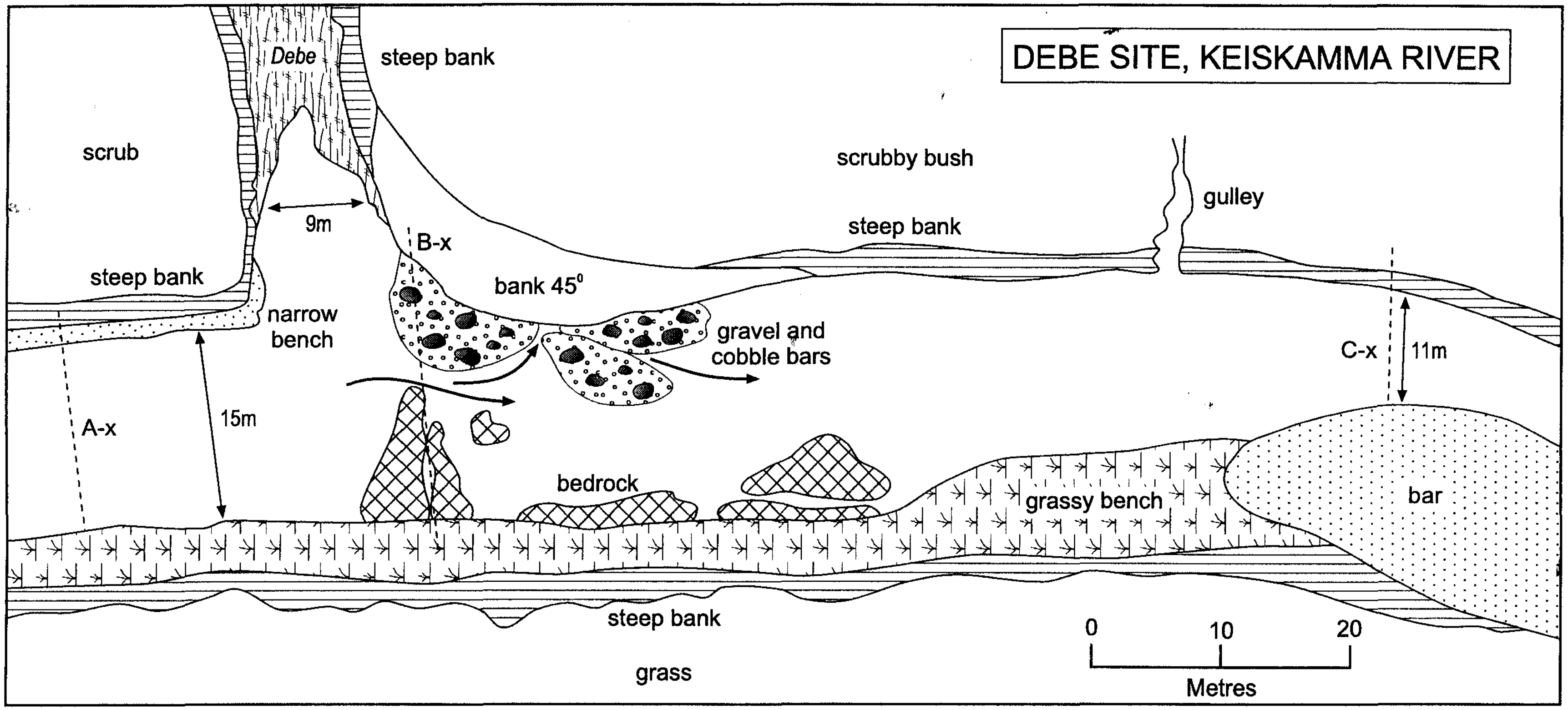

Figure 4.42: Plan view of the Debe site.

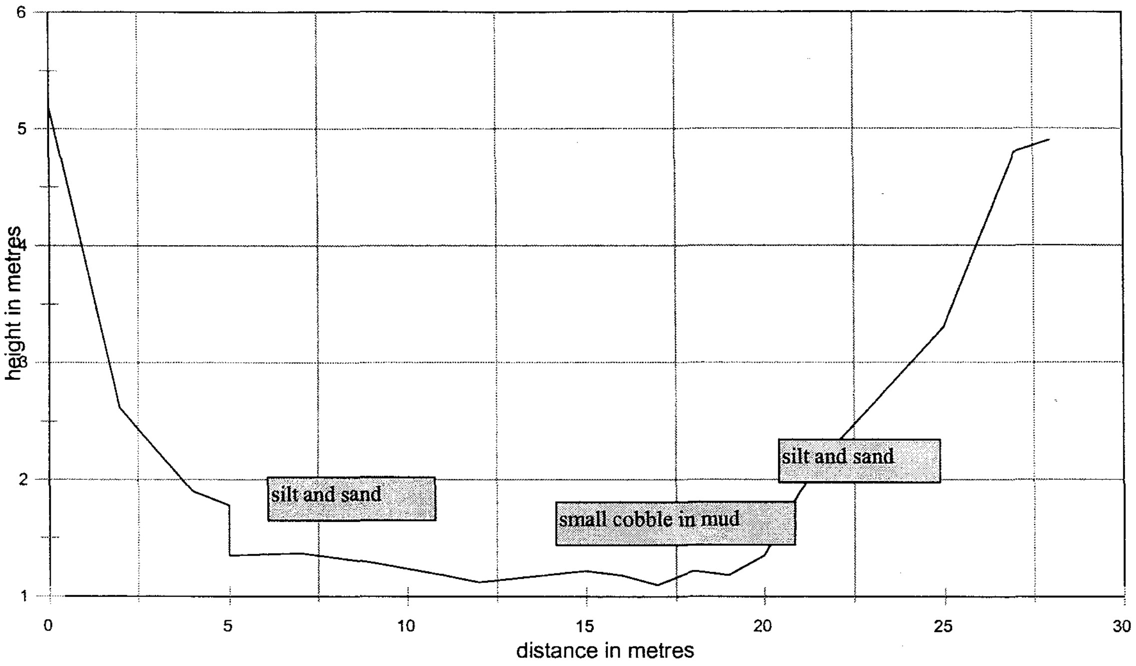

Figure 4.42: Keiskamma/Debe cross-section A, upstream view.

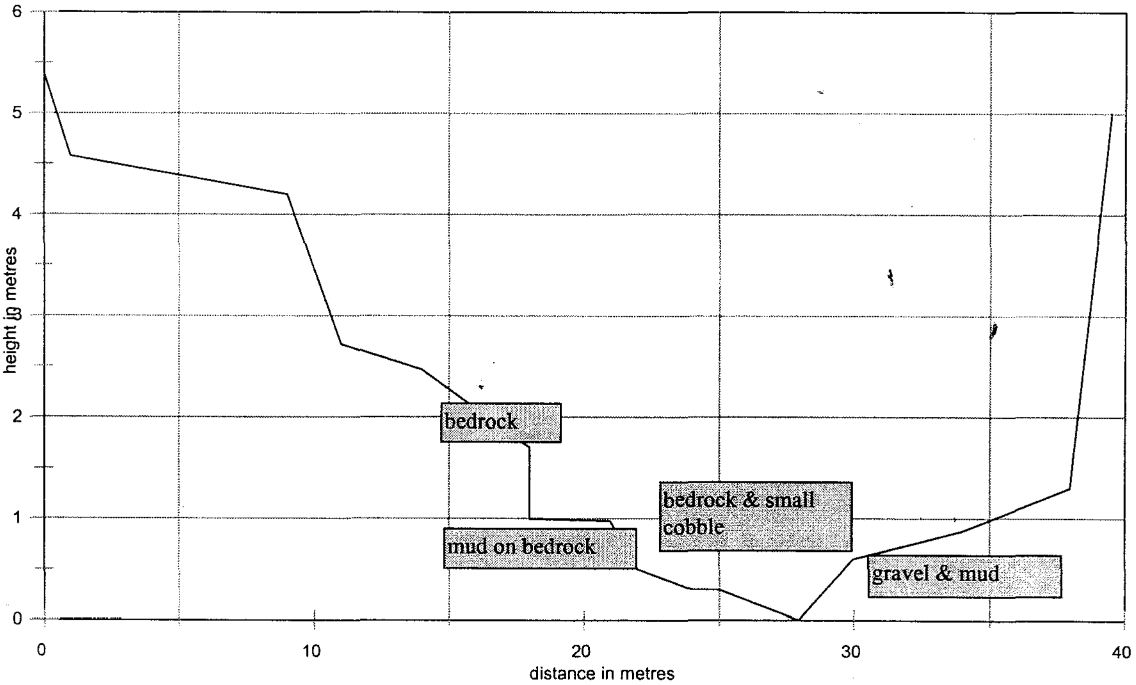

Figure 4.43: Keiskamma/Debe cross-section B, downstream view.

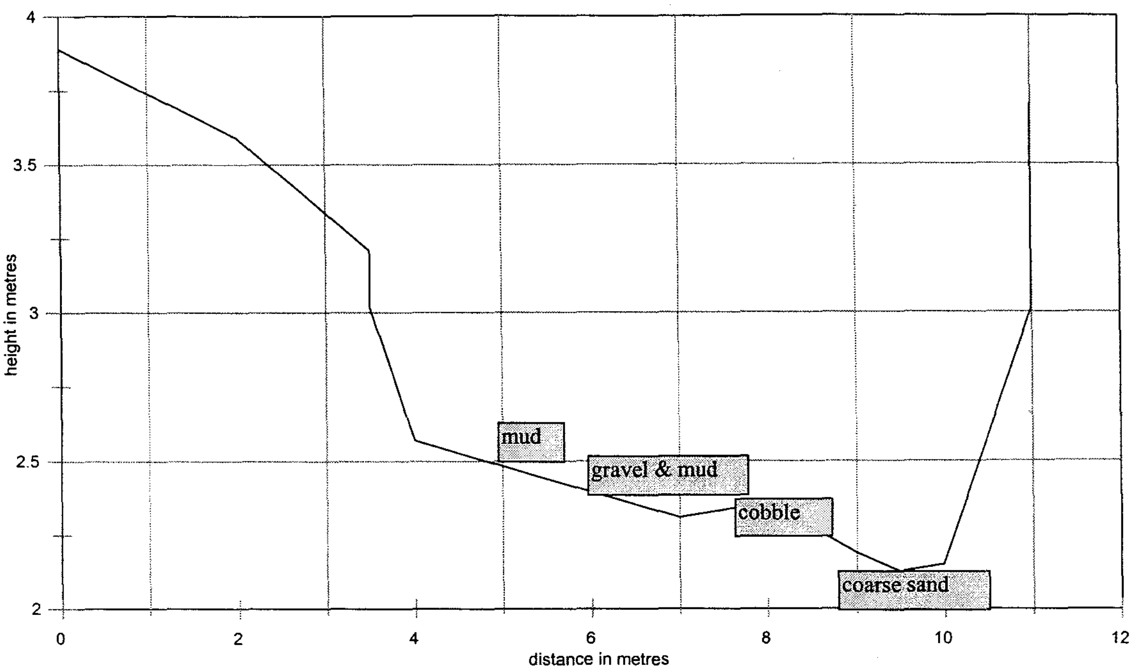

Figure 4.44: Keiskamma/Debe cross-section C, downstream view.

4.9.3. Morphology of the Debe bar

The bar consists of an accumulation of coarse sand and gravels, deposited on the left bank of the main channel. Its location is shown in Figure 4.41. It is not as extensive or as high as the bars at the other two sites, but it consists of fairly coarse material, making it distinguishable from the bank material.

The sediment samples from the bar (Figure 4.47) show a d_{50} size of greater than 4mm which is fine gravel. It would would require a velocity of at least 1.3 ms^{-1}. to transport this size sediment according to the Hjulström (1935) curve. The tributary substrate consisted of much larger material, but the d_{50} size was 0.125-0.5mm, which would move at a velocity of less than 1 ms^{-1}. The nature of the channel at this point with bedrock rapid probably creates high enough velocities to move coarse sediment through the reach.

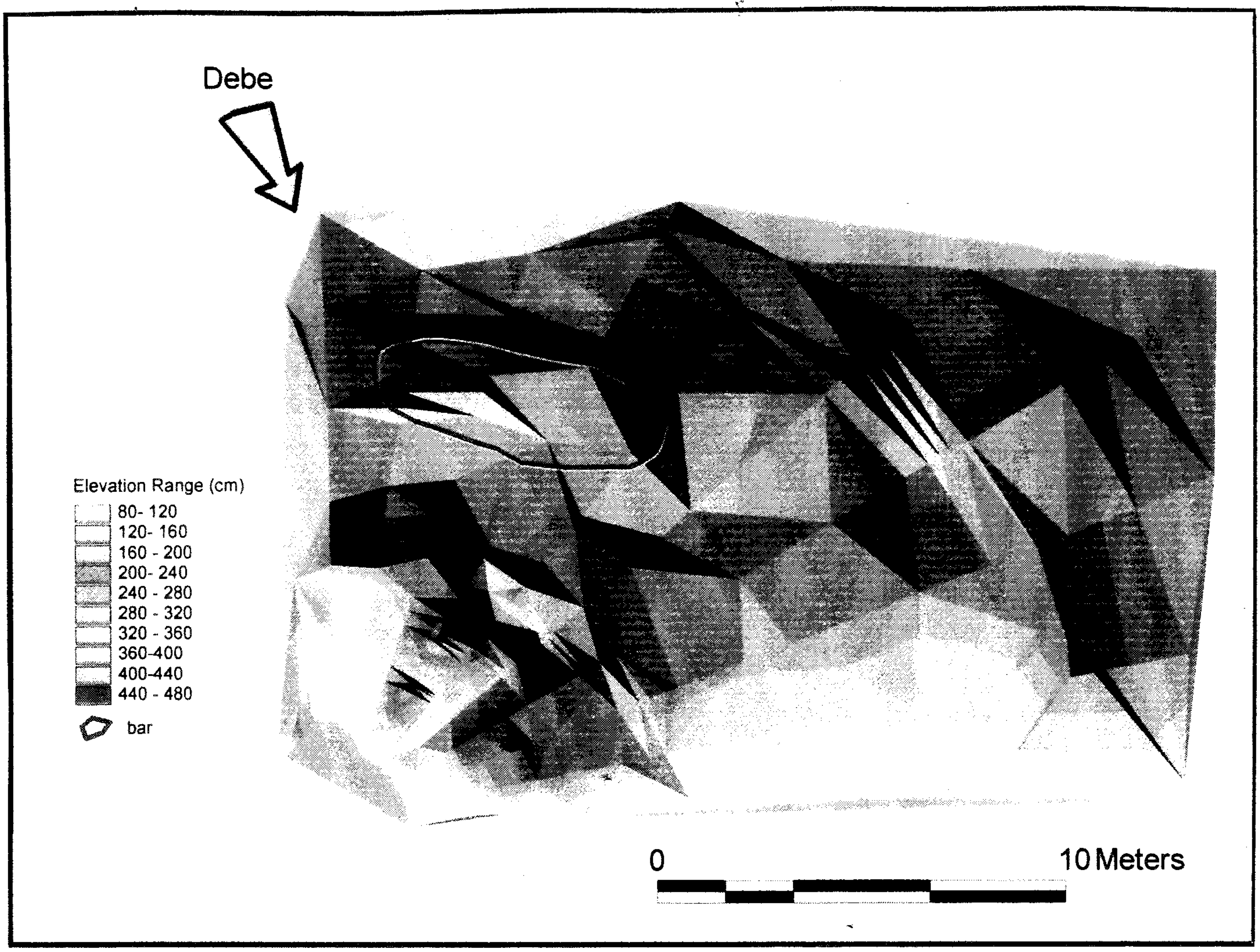

Figure 4.45: Keiskamma/Debe bar morphology in 1997.

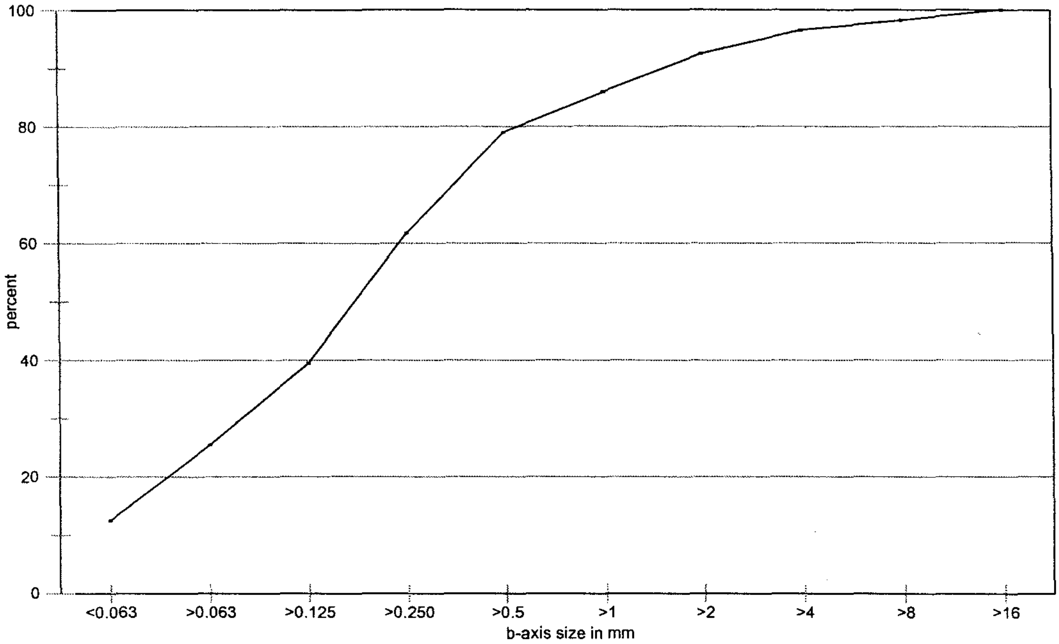

Figure 4.46 : Debe substrate

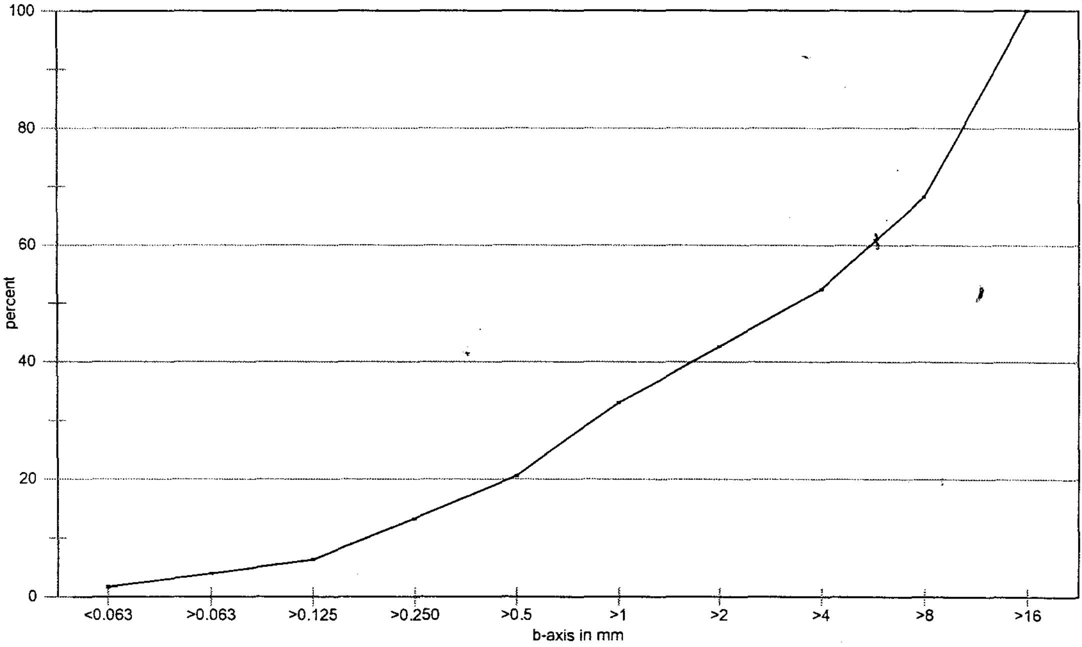

Figure 4.47: Keiskamma/Debe bar sediment.

Table 4.9: Debe site - suspended sediment and discharge.

date	*site*	*discharge m^3s^{-1}*	*sediment g/l*
3/97	Debe/KK	1.855	0.044
	Debe trib.	no flow/sub-surface flow	no flow

The sediment concentration reading is slightly lower than that taken at the Amatola site on the same date. At such a low discharge, load would not be expected to be high. No high flow reading was available as road access to the site at that date was problematic.

4.9.4. Assessment of aerial photos

The river channel is wider and much more open in these reaches, with very little riparian vegetation and is therefore more suited to analysis. Agin the problems of scale difference between the pre and post dam photo sets make it difficult to make any judgments about change.

The extensive bar which is evident below the junction is easily distinguishable at both dates. The catchments has certainly become more degraded over the years with evidence of sheet erosion that has worsened into severe gullying in the later photos. The number of settlements has increased.

4.10: Summary and discussion of results

4.10.1. Summary

Table. 4.10: Summary of results from the Amatola, Ncqwazi and Debe sites.

	AMATOLA	*NCQWAZI*	*DEBE*
catchment area	67.2km^2	24.5km^2	220.2km^2
distance downstream	20km	26km	49,2km
runoff recovery	16.52 x10^{6}m^3 (41%)	19 x10^{6}m^3 (48%)	29.21 x10^{6}m^3 (73%)
area recovery	223km^2 (62%)	272km^2 (74%)	501km^2 (137%)
nature of site	stable	unstable	moderately stable
ave. gradient	0.057	0.023	0.015
mainstream gradient	0.0035	0.0019	0.0029
MAR	11.88 x10^{6}m^3	11.88 x10^{6}m^3	6.12 x10^{6}m^3
MAP	709.89mm	709.89mm	545.9mm
sediment production/ erosion status	moderate	high	high
bar sediment - d_{50}	75-100mm	2-4mm	0.25-0.5mm
tributary sediment d_{50}	16mm	2-4mm	0.125-0.5mm
features	large permanent tributary bar; island with silted 2° channel; sand deposit with reed growth	extensive tributary bar; eroding left bank	small tributary bar; in channel bench

The results summary table brings together all the available information from this study which is relevant in assessing the geomorphological impacts of an impoundment using the conceptual model developed in chapter two. The main consideration in this system is the high sediment production rate in the catchment, which makes tributary junctions likely areas of change. The Ncqwazi in particular has a high sediment production rate which is evidenced in the extent of the bar at is junction with the Keiskamma. The commonly occurring pool/riffle sequence controlled by bedrock outcrops makes many of the reaches susceptible to aggradation. One would expect the secondary channel and island feature downstream of the Amatola junction to be affected by aggradation. It is a limitation of this study that impacts other than tributary bar development were not investigated. The steep gradients and high runoff of tributaries in the upper reaches such as the Ncqwazi and the Amatola, give them the ability to deliver coarse material to the main stream. Lower down in the vicinity of the Debe, the valley has opened out and the tributaries do not have a high transport capacity. Their sediment supply is not limited, but runoff and therefore stream power is low. Local steepening of the main channel such as occurs in the vicinity of the Debe, would facilitate movement of sediment through the reach.

4.10.2. Discussion of results

This discussion looks at the impact of Sandile Dam on the Keiskamma River in the context of the conceptual model developed in chapter three. Where relevant it also refers to individual authors studies (summaries of which are to be found in Appendix A) which were used to compile the conceptual model.

From the results of this study it would appear that the impact of the Sandile dam on the Keiskamma River has not been great. The primary impacts as determined from flow duration records from the system show small changes in the pre and post dam flow periods. At R1H005 the unregulated catchment area is only about 10km^2 (3.6%) of the regulated catchment. With such a small unregulated contributing area the primary impact of the dam will be at maximum because sediment and flow recovery are at a minimum. The pre and post dam curves run parallel to each other which shows consistent change at all flow durations. The greatest impact has been on the 1% duration flow at R1H015 which has been reduced by 50%. The greater impact at R1H015 could be explained by abstractions for irrigation in the lower reaches, as well as the impact of Binfield dam on the Tyume river. That this degree of change is not reflected at R1H005 suggests that there must be some other influence lower down in the catchment. It must also be noted that while the flow duration curve for R1H005 does not show a large impact on the annual flood, measurements are limited by the gauge to 35 m^{3}s^{-1} - so if floods were larger than that in the pre dam period, they would not be reflected.

The sediment trap efficiency of the dam is high, but in this system sediment recovery is rapid due to high inputs from the downstream reaches. If the primary impacts are not great, it is unlikely that the secondary impacts will be significant. In fact, it would seem that the dam has been well designed: it is located in the middle of the high runoff upper reaches, so the impact on flow is soon recovered; the size of the dam is such that it does not store too high a proportion of the river flow, and always spills over and it is located on a perennial system. Another important factor in minimizing the impact is the fact that the water is not heavily utilized and there are no demand driven unseasonal releases which would affect low flow duration. Although higher flows may be cushioned by the dam, the total volume of flow going down the system is close to normal.

To put the primary impact of this dam into perspective, it is necessary to review the degree of impact measured in other systems by authors reviewed in chapter two. As stated previously, sediment trap efficiency is always in the order of 95% and above. The impact on flow and on different types of flows is much more varied. Examples of the variation from a number of authors a variety of environments are given in Table 4.11. Because the mean annual flood has been identified as a significant event responsible for maintaining channel morphology in many systems, most of the studies give figures for the change in this particular flow. In the semi- arid and arid systems of the USA, reductions in the magnitude of the flood were mostly in the range of 60-85%, while in the humid British systems reductions ranged from 9% to 73%. Increased low flows in the USA ranged from 20-80%. Benn and Erskine (1994) refer to severe primary impacts below Windermere dam on the Cudgegong River, Australia: at the time of writing, the dam had only spilled once since it was built in 1990. They recorded a 350% increase in the 80% duration flow and a 50% reduction in the 10% duration flow. They remark that these kind of changes are so extreme as to be the equivalent of changing from a flood dominated climatic regime, to a drought dominated one. Petts (1979) describes the impact below Meldon reservoir where the reduction in the mean annual flood is only 9%, but the entrance of a tributary draining a quarried catchment delivers so much sediment to the channel, that there is a 60% reduction of channel capacity. The stream recovers with distance from the sediment source.

The first impact which was confirmed as expected, since it is probably the most commonly cited impact (see Table 2.4), was that of channel armouring immediately below the dam. The substrate of the 2km reach immediately downstream was noticeably lacking in fine sediment. The angular shaped cobble and gravel size material formed a tightly packed imbricated structure. This type of channel was only identified below the dam, all other cobble stretches in this system showed evidence of the high sand and silt content proportion, derived from the surrounding catchment. The case with the lowest degree of impact was Petts (1979) Meldon reservoir survey, where the reduction in the mean annual flood was only 9%, but armouring was still evident. It is a noticeable feature immediately below dams, even in the case of small farm dams in this country.

Table 4.11: High degrees of primary impact from selected studies.

AUTHOR	*PRIMARY IMPACT*	*DEGREE OF CHANGE*
Kearsley, Schmidt and Warren, 1994	MAF: 2180 m^{3}s^{-1} reduced to 940 m^{3}s^{-1}	57% reduction
Walker,	Average monthly low flows: 100 m^{3}s^{-1} to approx 300 m^{3}s^{-1} , high flows : 6-800 m^{3}s^{-1} , reduced by 1-200 m^{3}s^{-1}	77% increase 75% reduction
Benn and Erskine, 1994	10% duration reduced from 260 x 10^6l d^{-1} to 130 x 10^6l d^{-1}; 80% duration increased from 6 x 10^6l d^{-1} to 21 x 10^6l d^{-1}	50% reduction 72% increase
Petts & Thoms, 1987.	highest pre-dam flow >250m^{3}s^{-1}, Q = 175 m^{3}s^{-1} exceeded 4 times in 1966.	Peak flows reduced by 30-50%
Gregory and Park, 1974	MAF: 6.5 m^{3}s^{-1} reduced to 2.6 m^{3}s^{-1}	60% reduction
Petts, 1979	MAF reduced	50-75% reduction 7 out of 14 cases
Kellerhals & Gill, 1973	Annual peaks: 3500-9000 m^{3}s^{-1} lows:150-250 m^{3}s^{-1} Regulated range:500-2000 m^{3}s^{-}	peaks reduced by 78% lows increased by 50%

Gregory and Park (1974) caution against comparison of the above and below dam channel. While this is a means of identifying change due to impoundment, a dam is usually sited at a point along the channel where some significant change occurs naturally *e.g.*: bedrock intrusion, gradient change *etc.* so the downstream channel is likely to be different). In the case of the Sandile dam the wall is situated at a point where there is a change in the nature of the river, it is built on a rock outcrop where there is a natural gradient change. The entry of the Wolf tributary also substantially increase the discharge of the Keiskamma by 63% at the dam site, so the channel dimensions are naturally quite different below the dam. Nevertheless an important observation could be made about the upstream channel which is that tributary bars are not a feature in the upstream reaches. This is probably because the main stream and tributaries are in phase with each other, and respond to the same rainfall events. The velocity of flows is probably similar, due to similar gradients, and similar runoff. There is a balance between sediment delivery and removal. In the downstream reaches, tributary bars were identified, with three of significant size at the Amatola, Ncqwazi and Debe junction being investigated in detail.

The unregulated catchment area increases to 223km^2, which is 62% of the regulated area with the entrance of the Amatola. Discharge recovers to 41% of that above the dam (16.52 x 10^{6}m^3). According to Petts (1979) the impact of an impoundment will be negligible once the unregulated catchment area recovers to 40% of that controlled by the dam. The Amatola site is in a stable state in terms of bank and bed condition, with bedrock outcrops in the banks and on the bed. Aggradation is likely to be problematic here in the low velocity pool environment and with increased sediment input from the Amatola. In the absence of sufficient mainstream flows, the bar which was identified at Amatola junction will have become a much more stable feature than prior to the dam - something similar to Graf's (1980) idea of rapid stabilization in the Green River. While seasonal changes will occur, the effect of the dam is probably that less and less coarse sediment is being destabilised. Fine material will be removed periodically, but coarser material will remain at the junction, instead of being moved downstream, resulting in a coarsening of substrate on and in the vicinity of the bar. This is supported by a comparison with Rowntree and Dollar's (1994) results which show a much finer sediment sample at the earlier dates.

A study of aerial photos of the area showed substantial changes in the Amatola catchment, that are likely to have increased suspended sediment load in the Amatola system. While the river would derive most of its coarse load from its bed and banks, trampling of banks, landslides on the steep slopes and collapse of gullies induced by poor land management would introduce coarse sediment. So whether the dam impact on flow has been great or not, anthropogenic influences in the catchment have affected the sediment regime. This type of coarsening at tributary junctions has been described by Petts and Thoms (1986), Benn and Erskine (1994) and Erskine (1985). In terms the impact of Sandile dam this is not a new feature, but its nature has possibly been altered by flow regulation. The deep-silt substrate in the pool suggests that it is already a low velocity environment, which may have been reinforced by reduced flows. The other evidence of the tributary dominating this reach is on the left bank diagonally opposite the junction, where a small sand bar has been colonised by reeds. This is presumably a tributary deposit which has accreted sufficiently to allow colonisation by plants.

The other area which is susceptible to siltation is the secondary channel to the left of the island. At the lowest recorded flow, there was no flow in the channel, and the water depth was only 10cm. The deep silty substrate suggested that the channel had not been flushed out for some time. This siltation had also been increased by bank collapse caused by cattle trampling. It also appeared as though the point bar (tip of the island) was growing due to accretion and stabilisation by grass and *Acacia karroo* saplings. Both of these are typical post impoundment impacts that have been described by several authors listed in Table 2.4, which one would expect to find at a site with these morphological features. On the Han river, Chien (1985) notes that under regulated conditions secondary channels flow less frequently and when they do it is at velocities that are conducive to deposition and channel contraction. Hadley and Eschner (1982) also describe how many secondary channels on the North Platte river have been abandoned, silted up and vegetated. The gravel substrate had also been smothered by silt.

The suspended sediment samples at each site at different flows simply show that the concentration increases with increased discharge. At the highest recorded flow, the concentration of sediment in the Ncqwazi tributary of 0,19g/l was greater than that in the Keiskamma at 0,16g/l. This is the type of response that would be expected given the nature of the Ncqwazi catchment. Several authors (Qiwei, 1982, Hammad, 1977, Dolan *et al.* 1974) have studied the change in sediment concentration with increased distance downstream of a dam. Normally low values would be found closest to the dam as the water that is released is sediment free, gradually recovering its load with distance. In this case - the overflow is already loaded with suspended sediment. The river is fed with small streams with catchments that have a high erosion potential due to poor landuse, thin soils and poor vegetation cover, so the sediment load is likely to recover rapidly. Therefore, no conclusive statements can be made about the change in the suspended sediment concentration.

A comment from Benn and Erskine (1994) which is partly relevant to the Ncqwazi junction is that change depends on the input of sediment if the flow is incompetent to erode fresh sediments and the rest of the load is trapped in the dam. Deposition of coarse sediment at tributary junctions results in the formation of tributary bars which cause channel contraction, which in turn causes local degradation and armouring. Some of the fine material is deposited in the downstream pool resulting in bed aggradation and bench formation. Vegetation rapidly colonizes these areas. Due to the finite amount of sediment contributed by tributaries, sediment exhaustion occurs at a distance downstream, resulting in accommodation adjustment. Nevertheless some biogenic sediment will collect in most pool sites. These findings are confirmed by Petts and Greenwood (1985).

The results at the Ncqwazi site show nothing conclusive in terms of the impact of the dam, but it is likely that changes have occurred since dam construction. Change certainly occurred during the study period, but it is not possible to determine whether this was due to the impoundment or due to other factors. The site has the potential to be a problem, it is fairly unstable with erodible banks in the tributary and the main stream . The catchment is of a sufficient size to generate significant runoff and sediment. Steep slopes, poor soils, poor vegetation cover, dense settlement, cultivation and overgrazing all lead to high sediment production in the catchment, creating the potential to create a reach which is dominated by aggradation in the vicinity of the tributary under regulated conditions.

The results from the Debe site do not show any evidence which can be conclusively linked to the impact of impoundment, although the channel is moderately stable, with some localized degradation, and a degraded catchment. The type of bench formation which is evident here creates the sort of reduced capacity channel that one would expect to find in an impounded river based on the literature reviewed (Petts, 1979, Benn and Erskine; 1994, Petts and Thoms, 1986; Richards and Greenhalgh, 1984). In this case it is probably a feature which marks the annual flood level which is typical of an arid environment channel. The tributary junction bar material is of a size that would be moved by flows in the channel. The large downstream bar is not a new feature and could be identified in the pre and post dam photos. Considering that the unregulated area has recovered to 501km (1.37 times the regulated catchment) and the unregulated runoff has recovered to 29.21 x $10^6 m^3$ (73% of the regulated runoff) geomorphological impacts would not be expected to be found at this site.

Of the many possible impacts that have been described in chapter two, the only observed changes in this system have been channel armouring below the dam, and tributary bar development. The other secondary impacts that would be expected in this system are as follows.

The Keiskamma is a mixed bed channel, with stretches of cobble and gravel bed, some bedrock reaches and more sandy stretches which would make for complex response. In the stable areas, such as in the vicinity of the Debe junction, accommodation adjustment to low flows would be expected. Bench formation marking the new flow level in much the same form as occurs there now would be expected. Given the high rates of sediment production in the catchments, tributary bar development would be expected, and was found to be significant at the three tributary junctions discussed above. The siltation of secondary channels which are certainly a feature of this system, which has many islands, would also be an impact. This is possibly a feature at the island downstream of the Amatola site. With the prevalence of exotic invasives and local pioneer plants like *Acacia karroo*, vegetation encroachment would also be expected. Siltation is already evident in the system. Given the occurrence of bedrock ribs which act as controls and tend to back up pools behind them, the system is already sensitive to aggradation, which would be intensified without natural flushing flows.

CHAPTER FIVE

CONCLUSION

5.1. Overview of the study

As dependent as man is on water it is possibly one of the most abused resources because it is seemingly abundant. During the last century it has become evident in many parts of the world that this is not the case, and has prompted research into understanding the various systems of which water is a part. One of the major ways in which man impact on water is through the impoundment of river systems. It was the aim of this thesis was to investigate these impacts from a geomorphological perspective and further to take this understanding into a South African context that the concepts might ultimately be used to assist in improving sustainable water resource management.

The role of fluvial geomorphology as a key to sustainable water resource management has been emphasized by many scientists, such as Rowntree and Wadeson (1998). It is the geomorphology of a river system which creates the environment in which all other organisms exist, and is therefore the 'ultimate variable,' in a river system. Recognition of this fact has led to the consultation of geomorphologists in dealing with water resource management issues in this country. The maps and discussion in chapter 1 outline the complexity of water resource management in South Africa. They highlight the scarcity of this vital resource and the extent to which our river systems have already been regulated.

There are many recognised geomorphological impacts which occur across a wide range of conditions. According to Petts (1984) they can be divided into three orders: primary (a process alteration); secondary (changes of form, ecological or geomorphological in response to the process alteration) and tertiary (readjustment of the system - a feedback effect) . This study was primarily concerned with the primary and secondary impacts. The primary impact on the flow and sediment was in all cases dramatic, with predictably significant secondary impacts.
In terms of primary impacts, a dam always alters the flow regime of a river. The extent of the change depends on the operational procedures followed at the dam (controlled by dam purpose)

as well as dam size. In all cases there was an impact on floods, and in most cases, low flow magnitude and duration was increased. The impact on sediment was always high, although the sediment load was able to recover more rapidly that the flow. The review dealt mostly with studies conducted on large river systems with large dams across the world. Work done in Britain was on relatively smaller systems with smaller dams, but the results showed many common impacts. The studies were predominantly first world examples, with very little data from the developing world, yet, it is in the arid and semi-arid parts of the world which tend to also be developing regions, that the natural balance is more precarious, and less understood. Many large dams in the developing world have been funded and promoted by well meaning First World agencies, lacking in the necessary awareness of the long term environmental implications.

Table 5.1: Summary of secondary impacts of impoundments.

place	*process*	*response*
substrate	selective erosion	coarsening armouring
channel bed	aggradation degradation	deepening narrowing
banks	erosion slaking	aggradation by plastering bench development
channel pattern	siltation deposition	closure of secondary channels bar/bank joining
tributary junction	deposition erosion	bar development opposite bank erosion downcutting coarsening of substrate

Certainly the most dramatic impacts have been recorded on arid and semi arid river systems: the Colorado (USA) , Murray Darling (Australia) the Nile (Egypt) , the yellow River (China), where the nature of an impoundment is the complete antithesis of the variability of the hydrological regime. Some of the most extreme primary impacts are shown in Table 5.2. In these systems where work is done by the less frequents events, which the dam always impacts on, the result is most significant. It is in semi-arid environments that big dams are essential for development in order to ensure reliability of supply. Also a complicating factor in the semi-arid environment is that while the flow is dramatically altered by the dam, the sediment input below the dam can still be substantial, so the imbalance is great, and recovery is slow if it happens at all. The catchment areas, river dimensions and length also tend to be large in the semi-arid systems. Dams located in high runoff highland areas may control the entire river flow of a system which still has thousands of kilometres to travel to the sea. The upper reaches of the Orange, which generate 65% of the flow of the Orange river flow, will be impounded by a series of large dams of the LHWP, and will dramatically affect the remaining 2000km of river, as it flows through a vast, arid catchment. The primary impacts will be dramatic and the secondary and tertiary impacts can be expected to be equally so. Many of the exacerbating factors listed in Table 5.3 will also be of relevance in this case, so the impacts will be further intensified. The Pongolapoort dam controls the flow of the Pongola river at the point where it opens out onto a floodplain. The downstream morphology of the system, as the term denotes, is created and maintained by floods which the dam now controls. It is hardly surprising that the primary, secondary and tertiary impacts have been far reaching.

Table 5.2: Severe primary impact cases.

RIVER	*CHANGE IN SEDIMENT*	*CHANGE IN FLOW*
Yellow, China	at a discharge of 3000m^3s^{-1} sediment load reduced by 80%	12400m^3s^{-1} flood reduced by 60%; medium flow duration increased by 70%
Colorado, USA	median sediment concentration reduced by 72%	MAF and 10yr flood reduced by 70%
Murray Darling, Australia		average monthly low flows increased by 3 orders of magnitude; high flows reduced by 75%
Nile, Egypt	suspended sediment load reduced by 95%	mean annual release to Mediterranean reduced by 75%
Peace, Canada		low/high range reduced by 99%
Chew, UK		peak flow reduction 73%

In South Africa, impoundments have a major impact on water resources in almost all the primary drainage regions across the country. Resources are extensively developed and heavily utilised, to the extent that many catchments are impounded beyond their annual flow capacities. This cannot be healthy for river ecosystem functioning. Big dam building has slowed, (Figure 1.7) but there are still many smaller dams being built, the impacts of which are not well understood or documented, with the exception of Maaren and Moolman (1985) and Adams, (1997), cited in Davies and Day (1997). With so many of our river systems dammed by cascades of reservoirs, it would help greatly if, through an improved understanding of the impacts and the conditions under which they occur, we could at least improve operational rules and move away from 'ad hoc' user demand driven operation. Compounding the situation is the fact that many of our catchment areas are degraded due to poor management which greatly complicates the issue of sustainable resource management. Minimising the impact of dams through improved operation will only be effective if the whole system is healthy.

A conceptual model of all the known the geomorphological impacts of impoundments was constructed by extracting the impacts identified by 75 authors in their studies and summarizing them in the form of a conceptual model. Tables of primary and secondary impact details were created as well as illustrations of morphological change. In accordance with the aims of this project - one of which was to develop tools for use by water resource managers - a flow diagram for predicting change was constructed which could be used to identify sites of change in a river system. A summarized version of each case study was included in the appendix as a reference source for other researchers.

The conceptual model was used in three studies undertaken in preparation for Instream Flow Requirement workshops, which the author of this thesis was involved in. Information about factors affecting the geomorphology of the reach such as sediment inputs, flow, catchment condition and river gradient was collected. Geomorphological features at the selected IFR sites were assessed in terms of how their morphology would change under regulated flow conditions of either increased low flows or reduced floods. Using this information along with the conceptual model and the flow diagram for predicting morphological change, it was possible to describe the likely change at these sites in the event of impoundment and describe the types of flow which might have negative impacts on the geomorphology of the channel.

A case study was conducted on the Keiskamma River impounded by the Sandile Dam in 1983. It was found that the primary impacts in/to the system have not been great enough to induce significant secondary impacts. While there has been a small reduction in flows it seems that because not much water is utilized the effects are not marked. The total volume of water going through the system in the post dam period is much the same as in the pre dam period. Tributary bars were identified which might have been the result of a changed flow regime. It was not possible to separate the dam impacts from other anthropogenic influences in such a short study period. Location of the dam would appear to be good: it is situated in the middle of a high runoff area and the tributaries entering downstream still deliver sufficient flow to the stream for it to recover a lot of its flow before entering the low runoff semi-arid middle reaches. In this system, high sediment production due to degraded catchments is probably the most significant exacerbating factor. It is difficult to identify impacts if there are not adequate pre dam records, such as large scale aerial photographs or channel surveys. Alternatively, the study must be conducted over a long enough time period that changes can be linked conclusively to a changed flow regime.

The choice of the Keiskamma as a study site was based on the fact that Rowntree and Dollar (1994) had done some work on impoundment impacts, and this made it an attractive option. In retrospect , it seems that it would have been better to choose a bigger river system, where more use could have been made of aerial photography and other methods for detecting changes. With a view to establishing baseline data for the South African situation, it would have been useful to work on a system where impacts were known to be severe. As always, logistical problems of access to sites, data collection at high flows *etc,* were a limitation.

5.2. Future research

There is a need to assess the impact of the numerous unregistered and registered small and large farm dams on the sustainability of water resources. There has been little control on these types of dam building activities and water diversions, due to the nature of the pre-1998 water laws, resulting in a lack of data in this area. The results displayed in chapter 1 of this thesis clearly indicate that although the volumes impounded by new dams in the last decade have decreased, the actual number of dams has increased and this should be cause for concern.

The geomorphological impacts on some of the larger systems, which have become obvious, need to be assessed and documented. Flow data is available for many of the systems, and a survey of the primary impacts, to determine the most significantly impacted systems would give an indication of where the most dramatic impacts might be found. This would contribute to classifying and identifying rivers according to the impacts they would be likely to exhibit.

The large body of IFR work will provide some useful baseline data: sites have been thoroughly surveyed by the various specialists prior to dam construction and the follow-up monitoring programme which is a requirement of the IFR process, should yield some valuable information which will provide baseline data for future reference. Hopefully these monitoring programmes will also show that impacts can be reduced by improved operational rules that are closer to the natural flow regime.

In terms of sediment movement in South African river systems there is still a large gap in our understanding. While there is plenty of theoretical data available, working with sediment in the field is an educated guess. Because of the intimate relationship between sediment and water, particularly in the context of the geomorphological impact of impoundments, some understanding needs to be gained about recovery rates, scour, armouring, substrate coarsening *etc.* Despite the fact that armouring is probably the earliest and most easily identified impact, no local literature was found on the topic. Research in this area would also shed light on the processes happening at tributary junctions.

5.3. Conclusion

A summary of what this research has achieved in terms of understanding the geomorphological impacts of impoundments is given in the form of tabular overview of all the most useful information that was extracted/developed/processed in this study, (Table 5.3).

Table 5.3: Conclusion table on the geomorphological impact of dams.

Arid/semi arid catchment	the system operates on variability: fauna, flora *etc.* are adapted to cope with it; work is done by less frequent events; regulation is totally contrary to the natural variability, even more so than in a temperate system
operational response to demands far from natural regime	dry season user demands are greatest, leading to unnaturally high flows at a time when the river should be 'dormant.' A low reservoir level after a dry season means that the first floods of the season are absorbed

homogenous catchment - less impact	If runoff and sediment production along a catchment are homogenous, then both the downstream water and sediment regimes should recover together
big dam	big dams have large impacts: long construction periods, big changes at the dam site. Big storage volumes can even impact on big floods, degree of control over the natural system in terms of sediment and water is very high. Impact on other aspects like water temperature, turbidity, oxygen content *etc.* is also complex
controls a high proportion of MAR	the higher the proportion of MAR controlled the greater the degree of regulation, the greater the downstream impact will be
location in catchment relative to runoff generation	a dam located where it controls a high proportion of the entire catchments runoff will have a dramatic impact (*eg*: Gariep, Aswan). A dam located such that runoff/riverflow 'recovers' below the dam is a better option
nature of downstream catchments	tributaries which due to hydrological and physical characteristics such as basin shape, geology, soils, landuse, vegetation cover *etc.* are out of phase with the main stream, and have high sediment production, can show significant impacts at their junctions
utilization of water is high	where the total volume of flow passing through the system is greatly reduced due to utilization, the impacts are likely to be felt. May also be problematic if quantities of water are abstracted below the dam, so that well constructed operational rules are not effective

The conceptual model which was developed has proved to be useful in its applications in the IFR context and less so in assessing the impact of Sandile Dam on the Keiskamma river. Whether it is of future use or not as a basic tool for predicting change, depends on it being applied to other systems. South African river systems are notoriously variable and unpredictable, and the model needs to applied in a variety of contexts.

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APPENDIX A

Review of literature dealing with the geomorphological impacts of river regulation

(Note: map no's correspond to figure 2.5 in the text)

UNITED KINGDOM

Petts, 1979, conducted an extremely derailed survey of 14 reservoirs in Britain. Summarised details of the reservoirs catchment, as well as the findings in each case are summarised below.

Table A: Summary of primary impacts on rivers studied by Petts, 1979.

Map No.	River and Reservoir	Primary impact
20	Fernworthy, S. Teign R.	Peak flow reduction: 28%
22	Avon, Avon R.	Peak flow reduction 16%
21	Meldon, West Okement R.	Peak flow reduction 9%
2	Camps, Camps Water	Peak flow reduction 41%
4	Daer, Daer Water	Peak flow reduction 56%
3	Cowgill, Cow Gill	Peak flow reduction 58%
1	Leadhills, Elvan Water	Peak flow reduction 47%
16	Blagdon, Yeo R.	Peak flow reduction 51%
19	Sutton Bingham, Yeo r.	Peak flow reduction 35%
17	Chew Valley Lake, Chew R.	Peak flow reduction 73%
5	Catcleugh, Rede R.	Peak flow reduction 71%
24	Lady Bower, Derwent R.	Peak flow reduction 42%
8	Stocks, Hodder R.	5yr flood reduction: summer - 50%; winter - 8%; Peak flow reduction 70%
11	Vyrnwy, Vyrnwy R.	Peak flow reduction 69%

General description of the Upper Clyde Reservoirs: *catchments are well vegetated with grass, heather and moss, and large tracts of peat. Despite a high MAR of 1500mm, the sands, gravels and peat in the catchment reduce runoff, which gives a low degree of flow variability, and slows the likely increase in channel capacity with distance. These channels, set mostly in mobile materials have adjusted their capacity by a reduction in channel width, which occurs where the channel has an actively meandering planform. Vegetation encroachment in catchments of less than 5km^2 seems to control the direction, rate and magnitude of change. Large reservoirs on small systems, result in straightforward accommodation adjustment, where only flood events are competent enough to do any work, whereas moderate size impoundments evoke a more complex response.*

Leadhills: located on Elvan Water, impounds a catchment of 3.4km^2. Channel capacity immediately below the dam was reduced to 46% of the predicted value, but recovered to 15% below the entrance of the first tributary, which increased the unregulated area to 60% of the regulated catchment area. Above the tributary channel width was reduced, downstream, width and depth were reduced probably due to sediment input from the tributary.

Cowgill Upper: located on Upper Cow Gill River, impounds a catchment of 3.33km^2. Channel capacity immediately below the dam was reduced to <20% of the predicted value. There was a complete change in channel form, with width reduction enhanced by vegetation growth. It appeared that in a small catchment such as this (<5km^2.) vegetation played a dominant role in channel adjustment. By the time the catchment area is 29.25km^2 (2.3x the regulated area) the channel is within 20% of its predicted capacity.

Camps: located on Camps Water impounds a catchment of 24.59 km^2. This is an actively migrating meander system, which becomes less sinuous four kilometres below the dam where the stream is constricted by bedrock controls. Channel capacity immediately below the dam was increased by 80% due to degradation, but reduced to 50% of predicted value within 250m. The reduced capacity was maintained until the unregulated catchment area reached 25% of that feeding the reservoir. Once the unregulated area equalled 50% of the regulated area, channel capacity reached the predicted natural values. A number of processes were operating in this system: bank erosion due to bed armouring, deposition of the load in the form of channel side berms and point bars, all in the process of downstream meander migration.

Daer: located on Daerwater, impounds a catchment of 47.33 km^2. Immediately below the dam, boulders and concrete blocks prevented degradation. A compound channel shows evidence of the pre- and post dam morphology, with the bankfull stage of both regimes evident. An in channel bench formed, delineating the new bankfull capacity, thereby reducing capacity by 50%. Below the first major tributary junction, (about 8km) 13 km downstream, the channel is 68% of its former size. This has been achieved by a reduction in channel width within the actively migrating meander system. Distribution and sorting of sediment introduced by the tributary has occurred. Above this reach, flows are accommodated within the old channel form. 26km downstream capacity returns to normal after the entrance of another tributary.

***General description of the Dartmoor reservoirs**: high rainfall area, a flashy flood regime and steep slopes have led to the occurrence of coarse lag deposits in the streams. The rate of channel adjustment in this region is linked to sediment supply from tributaries, particularly where the channel has a stable form controlled by bedrock outcrops and vegetation.*

Fernworthy: closed in 1942, with a catchment area 9.95 km^2. Immediately below the dam the channel is well protected by a cobble and boulder bed. Development of a bench has reduced the channel capacity to 33%. Along the 3 reaches which were investigated on 35km stretch of river, there was some significant reduction, but in many places capacities were as predicted. Stable sites with wooded banks were found to show little change, whereas areas where there was some active channel migration had reduced their capacity. Channel slope was found to play a part too. Sedimentological analysis showed a decrease in sediment size in a downstream direction.

Avon: closed in 1958, with a catchment area of 12.03km^2. Reduction of channel capacity to less than 60% of predicted values and a change in channel slope were identified, until the unregulated catchment reached 18 km^2 and the channel entered a bed rock reach. Although Bala Brook joins the main stream 3km below the dam, increasing the unregulated area by 50%, it is not until the unregulated catchment reaches 2.5 times the regulated catchment, 7.75km downstream that the channel form reaches predicted dimensions. Along bedrock channel sections, changed flow levels are linked to lichen growth. In other reaches, channel berms and side benches are indicative of the changed regime. Change is related to the availability of sediment and the frequency of competent discharges to sort it.

Meldon: closed in 1970, with a catchment area of 16.83 km^2. There is a major sediment input 750m downstream of the dam wall in the form of an alluvial fan draining from a quarry. The stream then flows through a short gorge before emerging onto a floodplain. Accommodation adjustment has been identified immediately below the dam, with reduction in capacity of up to 60%. Downstream of the gorge, capacity has been reduced by 50% due to deposition, but as the distance from the sediment source increases, so the degree of reduction decreases.

***The Lowland Reservoirs:** Mean annual rainfall and runoof for these reservoirs is similar - about 100mm and 510mm respectively. However, Sutton Bingham has a much larger mean annual flood of 350m^{3}s^{-1}/1000km than Chew Blagdon which is only 200m^{3}s^{-1}/1000km. The rate of adjustment in this region seems to be dependent on the capability of flows. Cohesiveness of banks prevents erosion, but slumping and tributary input may provide a source of sediment which results in channel contraction. In the absence of competent flows, and no additional sediment input, simple accommodation would be the expected response.*

Sutton Bingham: located on a tributary of the Yeo river, impounds a catchment of 30 km^2. The channel bed is paved with gravel which protects it from degradation. Change has been primarily a reduction in width, except in the vicinity of Gallica Brook Junction, which increases the unregulated catchment to 70% of the impounded area, where there has been aggradation. The channel is incised into the valley bottom sediments and most channel narrowing has been achieved by bank slumping and erosion and redistribution of the material. By the time the unregulated area reaches 67 km^2, reduced channel capacity is 68% of predicted values.

Blagdon and Chew Reservoirs: Together they drain an area of 85km^2, each comprising about 8% of the surface area of their catchments, so their impact is substantial. The impact of Chew Valley Lake is such that the 100yr flood did not even overtop the wall. Below Blagdon there has been channel contraction of 70% by bench formation of silt/clay (45%) over gravel, for a distance of 250m, beyond which dimensions approach those that would be expected. 5km below the dam aggradation in the vicinity of a tributary has probably caused reduced capacities too. Chew Valley controls a catchment of 58 km^2. For 1.5km below the dam the channel bed is composed of fine sediment and organic material. It is only the first 150m stretch in which there has been channel contraction of 50%. Tree dating on the bench in this reach suggests that bench formation coincides with the date of dam closure (1955). Beyond the compensation outflow point, dimensions are regular. There is some coarse material deposition at Chew Stoke Brooke entrance and channel contraction of 50% below that, but dimensions gradually approach normal. For the 3-12km reach, where the channel is incised into the alluvium, bank slumping and subsequent deposition has occurred, resulting in channel contraction of 60%. The lack of a riffle-pool sequence suggests that the pools have been filled with sediment under the low flow regime. Because of the size of the impoundments, these two streams are probably still adjusting. In the absence of any significant sediment inputs competent discharges will be the controlling force in maintaining the channel.

'Other' reservoirs

Lake Vyrnwy: located on the river Vyrnwy impounds an area of 73.87 km^2 with a high mean annual rainfall of 1908mm, and a high conversion to runoff of 75% (1437mm), which causes high magnitude floods. The reservoir occupies 6.1% of the catchment, and thus has a large impact on floods. The channel bed is of cobbles and pebbles, leading into a bedrock and boulder channel 8km downstream of the dam. Riparian vegetation stabilises the system further. The two large tributaries which enter the system are also dammed. Reduced channel capacities were identified downstream of small tributaries (where sediment was deposited in a delta form, or more widely spread depending on the volume) and in active meanders where deposition had occurred on the channel perimeter. In the stable channel section, reduced flows were simply accommodated within the channel.

Stocks Reservoir: located on the river Hodder controls a catchment of 37.45 km^2, with a mean annual rainfall of 1656mm, and a mean annual runoff of 1195mm (72%). The area is prone to high magnitude flooding. The dam with an area equal to 3.7% of its catchment has a significant effect on floods. Channel slope is controlled by bedrock outcrops and the channel is stable except in one meandering reach. Degradation below the dam doubled the channel capacity, but channel capacity was reduced to 50% of the predicted value within 300m. Eroded sediment deposited in the form of a bench and subsequently vegetated was the main means of capacity reduction. The channel proportions returned to normal once the unregulated catchment area reached five times that of the dam catchment.

Catcleugh: on the river Rede, controls a catchment of 39.9 km^2, with a mean annual rainfall of 1255mm, and a mean annual runoff of 1026mm (82%). Although the runoff conversion is high, and the catchment surface is impermeable, the low slope of the catchment prevents high magnitude floods. The dam with an area equal to 2.72% of its catchment has a significant effect on floods. It also traps the fairly high coarse sediment load from its catchment. Immediately downstream of the dam the channel is poorly defined, but within 100m, a greatly reduced channel (40% of predicted value), confined by bench development and vegetation encroachment is identifiable. 200m downstream the channel pattern is of unconstrained meanders incised into clay, which straighten out further down and are stabilised by woody vegetation. Channel capacity reaches as little as 20%, but recovers progressively with an increase in unregulated catchment area. Where tributaries join the mainstream there is evidence of aggradation, and a reduction in capacity due to reduced depth at these points. About 27km downstream of the dam, with the entrance of Sills burn, the unregulated catchment reaches three times that controlled by the reservoir and the impact of the dam on channel form is no longer identifiable. Channel change appears to have occurred where the channel is unstable, whereas stable reaches only respond to sediment inputs and very high flood flows.

Leighs: on the river Ter, controls a catchment of 29.9 km^2, with a mean annual rainfall of 587mm and a mean annual runoff of 100mm (17%). It is a pumped storage reservoir, operated to augment summer baseflows. Despite a low slope and high evapo-transpiration, flood peaks may be high. Immediately below the dam the channel capacity has doubled, but soon reduces to between 107% and 20% of predicted values. Substantial bank erosion of up to 1m and increased depth has created capacities of up to 30% more than the predicted values. Investigations of the bank stability gave no clear relationship between erosion and silt/clay proportions, but it is likely that the magnitude of change is related to the resistance of the bank sediments to erosion. Change appeared to be greatest where channel dimensions were small and banks were erodible. The reservoir is operated to increase baseflows in the summer and this appears to increase the susceptibility of the banks to erosion. The problem is likely to be intensified at high discharges.

Lady Bower: on the River Derwent, built in 1945. Rates of runoff in the catchment are variable due to differing geology. Immediately below the dam, a stable gravel and boulder bed resulted in accommodation adjustment. Most change has occurred in a reach 4-9km downstream. Using aerial photographs change was identified just below the Noe confluence, where benches had developed since dam closure, reducing channel capacity by as much as 50%. Sedimentological analysis revealed that the benches were formed of coarse sand and gravel, with a coating of finer sand and silt, whereas the terrace materials were composed of 16-45% silt and clay, more like the bank materials. Tree ring evidence suggested that the benches were less than 51yrs old, whereas the terrace top was dated at 100yrs. Bankfull estimates put the five year flood at $38.7m^3s^{-1}$ immediately below the dam, and 50 m^3s^{-1} at the Noe confluence. Overall there has been a reduction of channel capacity in response to reduced flows with sediment for the benches derived from the unregulated Noe river.

Significant findings from Petts' study can be summarised as follows:

The rate of river response will depend on the frequency of competent releases and sediment input from regulated sources. The quantity and calibre of sediment introduced from non-regulated sources impacts significantly on channel form in a regulated system. Rate and direction of change is related to the area of the reservoir as a proportion of its catchment and the level of the reservoir at the time of flood. Examples from Britain show that the main impact is on moderate size, more frequent events, rather than rare large events. Impact will also depend on the catchment condition at the time of the flood as that will influence runoff. As the flood frequency decreases, so does the reservoir impact. Change below large reservoirs whose purpose is flood regulation may be slower than below smaller reservoirs where competent discharges occur more frequently. The stability of the pre-dam channel planform, the composition of its banks and dimensions of the channel at individual locations before dam closure all affect the degree of change which can occur. River channels having a meandering planform appear to be more sensitive to change, straighter, more stable ones are less affected. Baseflow augmentation can have a significant effect where banks are non-cohesive.

Downstream of British reservoirs, the main response has been channel contraction, and in free meander systems an increase in sinuosity. The result is a reduction of channel slope and an increase in deposition. The downstream impact decreases as the unregulated catchment area increases. Once the unregulated contributing area reaches 40% of the regulated catchment, the river channel returns to normal dimensions.

No. 18, Gregory and Park (1974) suggest that there are two forms of adjustment: where floodwaters are released as surges, the channel can adjust by increasing its capacity, or, where floodwaters are impounded a decrease in capacity would be expected. This change was investigated on the river Tone, below Clatworthy Reservoir (1959) in Somerset.

Channel cross sections showed a multiple channel with only an active inner element, which is the present bankfull channel, delineated by vegetation. 14 sites were surveyed, eight showed these characteristics, the others showed reduction by the accumulation of sediment as shoals, which were vegetated and thus stabilised. Multiple cross section reaches occurred where the channel slope was greatest. Scour has only occurred on reaches with the greatest slopes.

To compare pre/post dam capacity, 15 sections above the dam were surveyed. Results show that the channel has reduced to 54% of its expected capacity immediately below the dam, and increases to normal capacity where the catchment area reaches 78.5km^2, 11km downstream. This amounts to four times the area controlled by the reservoir. They were able to come up with a formula for the relationship between channel x-section and catchment area above the dam. An assessment of high flows of channel forming/maintenance proportions, by comparison with similar neighbouring streams, and predicted flows. As the drainage area increases the flows approach 'normal.' Based on the regional pattern, post dam flows could be expressed as proportions of the expected values:

Q2.33 - 33.8% (about 3m^3 vs 9m^3)
Q1.5 - 39.5%.(about 2.6m^3 vs 6.5m^3)

With the drainage increased to 57.8km^2:

Q2.33 - 39.5% (about 24m^3 vs 9m^3)
Q1.5% - 35.7% (about 9m^3 vs 17m^3)

Overall they showed that discharges have been reduced by a third to half of their expected proportions.

No. 17. A paper by **Petts and Thoms (1987)** describes the morphology and sedimentology of a tributary confluence bar formed at the junction of Tarset Burn, which drains a catchment of 108km^2 and the North Tyne river, regulated by Kielder reservoir (188Mm^3) which controls a 241.5km^2 catchment. Mean annual runoff in the catchment is 1026mm which is 82% of the mean annual precipitation. The primary impact of the reservoir has been to reduce peak flows by 30 - 50 % which has created flow conditions that have allowed the development of a bar at the junction only 3 years after reservoir construction. It has formed by lateral accretion on the inside of the tributary dominated flow thalweg, and extends for nearly 100m (three times bankfull width) and has an exposed surface area of about 900m^2 . A riffle separates the main thalweg into two components. Opposite the mid bar lobe the thalweg is forced to the west side of the channel, upstream it flows on the east. Further erosion is prevented by anti-erosion works on the west bank.

The bar consists mainly of pebbles and cobbles with mean grain size ranging from 8mm to 64mm. Sample data display a pattern of lateral coarsening towards the main channel with the exception of the bar tail, which is in a slack zone. Bar pit samples showed a sequence of upward coarsening, with one exception.

'In gravel bed rivers bedload transport is characterized by a distinct threshold below which little gravel moves, ' (Petts, 1987). A small reduction in flows can have a dramatic effect on sediment movement. The highest pre-impoundment high flow in the North Tyne exceeded 250m^3, while a discharge of 175m^3 was exceeded four times in 1966. The regulated release pattern is dramatically different: irrigation flows are 1.32m^{3}s^{-1} in summer and 0.66m^3 s^{-1} in winter. They are supplemented by hydro-electric releases of 15m^{3}s^{-1}. Calculations suggest that the volume of bedload moved by the stream amounts to 800m^3. The volume of sediment stored in the bar amounts to about 650m^3 which suggests that most of the load brought down by Tarset Burn is located in the 100m stretch below the confluence. Peak flows in Tarset Burn exceed 50m^{3}s^{-1}, 2 to 3 times per year, with a maximum discharge of 81m^{3}s^{-1} since dam closure.

Processes at the bar were observed at a special dam release of 50m^{3}s^{-1}, which created flows of 58m^{3}s^{-1} below the Burn. The bar provided major flow resistance, maintaining a steep energy gradient over and around it. Tracer pebbles placed on the bar were recovered after the event and results showed that all those with a b-axis of <35mm were removed. Fine rippled sand draped the bar tail, and a layer of sand up to 10cm deep had been deposited on the upstream portion of the bar head where eddies occurred. Opposite the bar, channel width is constricted by stable, erosion resistant banks, so a narrower (20m vs 35m) high velocity section is created. Under present conditions, the burn flow controls the geomorphology of this reach by increasing the competence of the channel and facilitating the movement of progressively coarser sediment through this reach.

No.14. Higgs and Petts (1988) study concentrates on the primary impacts of the Clywedog reservoir on the river Severn. It is a purely analytical approach looking at the change in flood distributions, variability of flows, low flows *etc.* and is suited to a system with a flow monitoring network. Two sets of factors were considered: the morphometry of the reservoir basin and its spillweir characteristics and a second set which refer to reservoir operational characteristics.

They found that relatively frequent events were greatly affected, the more extreme ones less so. The 10 year flood was reduced by 5%, while the 1.5year flood was reduced by 17%. Seasonally there was an effect too: the magnitude of the 5yr winter flood was reduced by 8%, but the 5 year summer flood was reduced by 50%. Looking at the low flows they found that extremely low flows had been eliminated, while there had been an increase in the duration of low flows, linked to downstream demands in industry. Pulse releases had increased to meet requirements from canoeists, flushes, irrigation and hydropower demands. The results of the study were complicated by land-use changes and by climatic changes, which serves to illustrate the difficulty of isolating impacts. Overall they found a decline in flood frequencies and in the size of the mean annual flood. Median flows have been reduced by about 50%, mean annual floods by 30%, and low flows maintained at 225% higher than the natural flow with a duration period of 95%.

No. 25. Richards and Greenhalgh' (1984) study assesses the impacts of diverting water from the River Derwent via the Sea Cut, to the sea to prevent flooding in winter. This feature has been in operation since the early 1800's, and has caused the channel to change from a gravel bed upland stream to a sluggish stream with heavy summer weed growth, where it transports sand over a paved bed in the Forge Valley sites.

Reach analysis was carried out above and below the Cut, with transects done on riffles. Based on estimations of bankfull capacity, it was found that the channel is 31% of the expected size based on upstream trends. There has been a 61% reduction ratio for width and 47% for depth. The stream no longer has the capacity to transport sand sized sediment through the Forge Valley sites. Substrate size declines for d_{84} values from 30cm in the headwaters to 3cm above the Sea Cut, to sand over an inherited paved surface in the Forge valley. The sand and silt have accumulated in lateral berms within the original channel, with their tops just below the level of the original floodplain. Sedimentation on the river banks has been encouraged by weed growth, which survives well with the low water levels and stagnant conditions.

No.15, Petts and Pratts (1983) study on the river Ter makes an important contribution to understanding the impact of baseflow augmentation on cohesive channels. Erosiveness of discharges depends on 'pre-conditions' especially wetting. The study was carried out on the river Ter where since 1967 the Leighs irrigation storage reservoirs filled from groundwater supplies, have augmented summer flows. The area has a relatively low MAR of about 700mm, with a high evapotranspiration rate of 80% of the MAR. Most major flooding is produced by low intensity winter rainfall coinciding with small floods. Baseflow increases rapidly in a downstream direction - the 50% duration discharge increases from 0.023 m^3s^{-1}, to 0.085 m^3s^{-1}. Baseflow is increased by 0.25 m^3s^{-1} in the summer months for irrigation.

Based on surveys carried out at14 sites before the reservoir was built, with re-surveys in 1975 and 1981 it was possible to measure the change in channel dimensions. Overall there has been an increase in channel capacity by 45%, although the change was complex in time and space. During the first 8 years, 3 sites immediately below the dam were eroded and increased their capacity significantly from 1.96m^2 to 4.23m^2, (81%) while other sites only increased by 25%. The range of change was from a 43% increase to a decrease of 21%, with an average increase of 18%. From 1975 to 1981, the 3 near dam sites continued to expand but only by 18%. Many of the downstream sites started to aggrade, compensating for the previous period of erosion. There was erosion of the bank and channel bottom, as well as deposition on the channel bottom, and aggradation of fines on the banks, by 'plastering'. Feedback mechanisms were in operation - when the bed degraded, the banks aggraded and vice versa. Overall though the dominant impact has been an increase in channel width. It is likely that this is the result of increased baseflow duration which makes the banks susceptible to erosion. The fact that there has been no climatic change and therefore no change in high flows (the mean annual flood in particular) make it unlikely that the change is a response to a new dominant discharge. The increase of baseflow and augmented low flows have probably affected channel bank stability and increased the susceptibility of the bank materials to erosion. The study emphasizes the need to monitor change over longer time periods: changes occurring in the first ten years may be counteracted in the next ten.

No. 17, Petts and Thoms (1986) study of the impact of Chew Valley Dam on the river Chew is an extremely detailed study of channel substrate response to impoundment. The lake impounds a 58km^2 catchment and has a surface area of 8% of the catchment. MAR is 1050mm, of which 530mm is converted to runoff. Summer drawdown results in most of the winter floods being stored to such an extent that the 100yr flood in 1968 did not spill over the dam wall. The maximum recorded discharge below the dam in a five year period was 4.21 m^3 s^{-1}, and for Strode brook, 0.8 m^3 s^{-1}. The number of competent flows with a D_{60} of 0.72 m^3 s^{-1} was much greater in the brook (281 to 109). For 1km below the dam, channel capacity has been reduced by more than 40%. Changes are related mainly to the influence of sediment loads introduced by Strode Brook. The former gravel bed has aggraded since 1953 to form a sand bed as a result of the deposition of tributary injected sediments.

The study area was a 100m reach below the dam incorporating the Strode Brook entrance, and two control reaches below that. Sediment samples from the control sites were predominantly gravels, with less than 10% by weight of fine sediment, arranged in a self supporting open framework. In the study reach, bulk samples have a 28% fine sediment composition (finer than 4mm, mode of 1.5mm) with the remainder of the substrate 8-32mm in size. The Stoke tributary substrate sample showed poorly sorted sands and gravels with a mean size of 3.6mm, and 35% of the samples are finer than 2mm. Samples from Strode brook were also poorly sorted with 55% of the sample finer than 2mm. Freeze core results were different but comparable. They represented the grain size characteristics of the gross deposit and gave an idea of the general pattern of aggradation, while the bulk samples were representative of the surface sediments and related to recent hydrological history.

Sediment was found to have accumulated in a deposit of up to 1.5m in height on the pool bottom. Grain size distribution is predominantly sand with 50-10% of the sample finer than 2mm, and is comparable to that of the Strode brook samples, and offers a contrast to the control site samples. Just above the confluence, a backwater forms a settling area for silts (finer than 4 phi) which makes up 21-48% of the deposit. Aggradation below the confluence has produced a substrate dominated by poorly sorted sands in a gravel-sand mixture. There are some fine slackwater deposits at points along the channel margin associated with the thalweg meandering. As would be expected, grain size relates to the pool riffle sequence with fine r material in the pool and coarser material on the riffle. Pool and slack water deposits show erratic variation in grain size, whereas riffle deposits show a definite increase in mean grain size: 0.3mm, 5m below the confluence, to 1.2mm, 42 metres downstream. The freeze cores show a different pattern: coarse sediments of 0.88mm are found near the confluence, with finer sediments of 0.25mm in the sample taken 20m downstream.

Channel sedimentation at and downstream of tributary confluences is being recognised increasingly as a feature of impounded gravel bed rivers. **No.12. Petts (1984)** study investigates the situation on the River Rheidol where the Peithnant tributary with a catchment area of 4.1km^2 joins the main stream 2km below the Nant-y-Moch Reservoir. Alluvial rivers commonly show an inverse relationship between bed material size and distance downstream, but where a tributary enters with a steep average gradient, and an unregulated flow from a sediment productive catchment, coarse sediment is injected into the main stream. Due to the regulated releases in the mainstream the reach will be dominated by the tributary processes.

The main channel is relatively wide (17.5m average) and shallow, with a bankfull depth of 0.5m; channel slope averages 0.002)units) ; the bed is lined with boulders. The general appearance of the aggrading reach under low flow conditions of 0.16 m^{3}s^{-1} is of a braided channel. Pre-dam bankfull width was estimated at 17-24m, while the present bankfull is only 6-8m. At this stage the drainage area of the stream has been reduced from 65 km^2 to 7.5 km^2, so a reduction of channel dimensions is to be expected.

The Peithnant bed consists of mostly poorly sorted gravels with an average size of 18mm, the largest being 90mm. Landuse practices in the catchment (ditching) have made coarse sediment available from disturbed colluvium.

Gravel deposits on the boulder bed of up to 130cm deep have accumulated. The distribution of particle size is competence related: sand only forms 15% of the bulk sediment sample but increases in relation to competence in a downstream direction. Mean particle size ranges from >65mm at the top of the reach to less than 2mm, 250m downstream. In the lower third, a low velocity zone of aggradation at the 'old bar' causes average grain size to decrease rapidly. A sand matrix amongst some of the gravels is assumed to have been deposited during receding flood stages. Even amongst the sands there is size sorting in a downstream direction. Characteristically, coarse sediments line the active channel, finer sediments are found on the bars except on the upper lobate bar where the tributary comes in.

The dominant feature is a lobate bar, 60m long, up to 1m in height and 12m in width. It is 20cm higher than the former bankfull level. Sediment deposits are coarser than in the adjacent channel. This type of bar is a typical feature at a junction, but under the regulated conditions it has become permanent. The bar tails off in a downstream direction, backing up a long deep pool above the tributary entrance, which traps sediment moving in the main stream. Lying parallel to the flow direction, just below the old bankfull level, are elongate bars composed of sediments finer than the adjacent channel. In some cases they form channel side berms. At the lower end of the reach submerged even at low flow, is a transverse bar. Up to 65cm in height it is composed mainly of fine gravel and sands. The deepest and fastest flow occurs at its upstream end where the bar begins to slope upward and forms the new channel bed where it maintains a critical channel depth necessary for sediment transport. The channel has adapted to a narrower and deeper form to facilitate sediment transport under the new conditions

No. 67, Hey's (1975) study is based on geomorphological theories relating to magnitude and frequency of channel forming events and sediment transport. He looks at these theories in the context of river regulation, in an attempt to come up with some predictive ideas about what will happen to a river reach under regulated conditions. He outlines a program to test the thresholds of bedload transport in a section on the Severn, which would be receiving Inter Basin Transfer water from the Wye basin. He predicted that under regulated conditions, riffles would be scoured and pools would fill with sediment, leading to the formation of a braided channel. Cobbles of different sizes would be marked and tagged before reservoir releases were made upstream from Llyn Clywedog Reservoir. The thresholds of movement for various sizes of sediment under different flow conditions could then be determined, and releases could be determined which would not erode the stream bed. The stability of the system could then be maintained.

THE REST OF EUROPE

No. 40, Hrabowski (1994) concentrates on the impact of reservoirs on the surrounding environment, particularly with reference to groundwater movement and its effect on the stability of surrounding land. He also includes a comment on the changes to the river bed, downstream of an impoundment, which are particularly severe in river beds composed of easily erodible material such as sand and silt. He discusses the significant potholing which has occurred below Debe Dam on the Narew River, Poland, as a result of a poorly designed outlet. It occurred mainly as a result of a flash flood which eroded the river bed and the surrounding slopes, despite the protective measures which were in place. The weir was eroded seriously on the upstream side, but more significant was the formation of a pothole 50m downstream with an area of 1500m^2, and a depth of 11m, below the weir. A quantity of 56000m^3 was estimated to have been eroded. It has seriously compromised the stability of the whole structure. The water level of the downstream reach has been significantly reduced

No. 76, Fergus (1997). The study is carried out on the river Fortun in Norway. It has a total catchment area of 508km^2, of which 367km^2 or 73% is regulated by three hydro-electric power stations, built between 1959 and 1963. Mean annual precipitation is 800mm, most of which falls as snow. High flows occur in mid July as a result of snow melt and glacial runoff. Heavy precipitation coincident with glacial runoff causes autumn floods. Sediment production rates are high due to the natural processes such as avalanches, debris flows, tributary flooding and glacial erosion. None of the minor tributaries are regulated.

Detailed cross sections surveyed in 1973, 1989 and 1995 were available for a 1600m reach of river just above the third power station. The surveys are extremely detailed, with only a channel width between cross sections which provides some impressive results. From 1973 to 1989 the volume of aggradation amounted to 27000m^3, with degradation of about 15000m^3. The summarized results are as follows: aggradation has occurred in the upper half of the reach, degradation has occurred in the lower half, resulting in a longitudinal change to a steeper channel bed. The slope of the water has increased from 0.0016 to 0.0023 at a flow of 80 m^{3}s^{-1}. In response to the aggradation the channel has widened, eroding the unarmoured right bank and in the confined bedrock section, it has broken through the armoured left bank eroding laterally up to 30m before being stopped by plastering with large stones. Complete erosion of a vegetated bar has also occurred. Sediment moving into the reach has accumulated around islands in the middle of the reach, which has reduced velocities and allowed stabilization by vegetation. Benches and bank bars have been vegetated and so have in channel bars. It appears from diagrams in the paper that side channels have been closed by vegetation encroachment. Vegetation debris adds to the process of aggradation by creating dams and backwaters ideal for sedimentation. Below profile 41 the channel substrate of bedrock has prevented any change, a case of simple accommodation adjustment.

Degradation for the 1989-1995 period was estimated at 5400m^3 and aggradation at 3900m^3, with a net degradation of 1500m^3. The pattern and location of these processes was the same as before. The annual degradation rate for this period was 900m^3 as opposed to 940m^3 for 1973-1989, while aggradation averages were 650m^3 and 1700m^3. This reduction is probably an indication that the channel has adjusted to the new flood regime. Adding to this effect is the fact that three major (>100 m^{3}s^{-1}) floods occurred in that period. Because of reduced flows, a lowering of the water table was expected. Instead, the raised channel bed has raised the water table and caused problems of water logging in adjacent fields.

Discharge has been considerably reduced with post regulation values 35% of the natural discharges. The mean annual flow has been reduced from 20 m^{3}s^{-1} to 7 m^{3}s^{-1}, and the mean annual flood from 140m^{3}s^{-1} to 86 m^{3}s^{-1}. The magnitudes of post-regulation floods are to a great extent dependent on reservoir conditions at the time of the event. Sediment supply to the channel has not changed - but the frequency of competent flows has with the result that aggradation has been the dominant process.

The result of steepening of the reach is that the channel bed is raised and overbank flooding occurs at lower more frequently occurring flows: a 25 m^{3}s^{-1} flow now reaches the level of a pre-regulation 50 m^{3}s^{-1} flow. The implications of this are significant for the farmers who have riparian lands.

ASIA

No. 45, Tariq (1994) discusses the main impacts of Tarbela dam, Pakistan, which regulates a 10360 km^2 area of the Indus River (6% of the total upper Indus drainage area of 169635 km^2). With a surface area of 260km^2, the reservoir was built in 1974, for irrigation purposes as well as for hydroelectric power. It only stores 15% of the annual 79 billion m^3 river flow, but when operated in tandem with Mangla reservoir plays a major role in flood mitigation. It supplies 12km^3 of water to the Indus basin irrigation system. Like all dams, it has a high sediment trap efficiency with only 2-3% of the suspended load passing through it By 2057, the reservoir will have lost 80% of its original capacity. The drainage area is geologically unstable and it therefore has a high sediment production rate. According to Tariq, the reservoir has not had any impact on the downstream channel because the cobble size channel substrate has armoured it against the effects of scour.

Chien (1985) has documented the impact of impoundments on some major Chinese river systems.

Sanmenxia Reservoir (no. 27) on the Yellow river was built in 1960 as a storage reservoir. Due to excessive sedimentation, design alterations were carried out from 1965 in several stages to allow for the sluicing of trapped sediments. Due to its increased capacity, it now serves as a flood detention reservoir from July to October and stores water for irrigation and power generation for the rest of the year. Flood peaks have been reduced by up to 60%, while the duration of medium flows have increased, from 130 to 204 days per year. Pre and post dam sediment concentrations in the river are on a par, (average annual sediment concentration of 37.4kg/m^3.) Below the dam, the river showed has shown an alarming rate of aggradation, making the water level higher than the adjacent lands, with the result that the river has actually become a dividing ridge across the flood plain. Prior to impoundment along one reach, 3.6 % of the sediment load accumulated from 1953-1960. After impoundment from 1973-1980, this reach 'gathered' 29.3% of the total load.

Chien has identified some impoundment impacts with reference to the sediment load, which are characteristic of the flood detention reservoir. The incoming flood peak is collected and released gradually to minimize downstream impacts. The natural sediment/discharge relationship is reversed: the flood flow carrying a large load, is attenuated by the dam, causing it to drop its load. The subsequent low and medium flows already loaded with sediment, are loaded with an additional supply from the reservoir, which they carry to the downstream reaches. This obviously has a far reaching effect on the fluvial processes downstream. A braided stream under these conditions, will tend to aggrade; under flood conditions it will down cut, but overall, the bed will rise. This change is commented on by Li *et al* (1980) cited in Galay (1983) who describes a rapid change from a braided channel to a single thread channel with occasional side channel bars. Secondary channels are silted up and no longer flow. While the high flows free of sediment may degrade the reach below the dam, their impact is not sufficient to balance the rate of aggradation. The floodplain receives little sediment as high overbank flows are infrequent, of short duration, and carrying only a small load they do not supply the floodplain anymore. These factors together raise the bed, and reduce the difference in elevation between the river and the floodplain.

The impoundment of the Han River by the Danjiankou Reservoir (no29) cut off the rivers sediment supply, attenuated flood peaks, increased 'low water' discharges and extended the duration of medium flows. In the absence of any tributary entries downstream the sediment load cannot recover. Leveling off of flood peaks has reduced the rivers transport capacity by 41 %. The more frequently occurring low flows have the energy to move fines, but not bigger material, resulting in coarsening of the bed material. Coarsening in turn increases roughness and further reduces velocity . In terms of bed degradation, most of the reaches have stabilised, but this effect is identifiable as far as 480km downstream and seems to be moving further downstream. Four years after dam closure it was found that due to bed degradation, the water level at a discharge of 3,000m^3s^{-1} was lowered between 0.6 and 1.3m, for a 490km stretch Chien has found that the first 26km of the channel are stable, the next 40km stretch only erodes under flood conditions, in the next 43km reach sediment moves as bedload, and the last 138km is the most extensively downcut reach. Based on these observations Chien predicts that the 800km stretch to the junction with the Yangste will eventually be degraded. It may take some time for channel pattern to change, but Chien has made some preliminary observations: because of the reduction in floods, in-channel bars have stabilised and accreted, side channels flow less frequently and at low velocities conducive to aggradation and channel contraction. The increase in medium size flows leads to channel deepening, width reduction, and leveling of bed undulations (ie: reduced heterogeneity of substrate). There is also a reduction in the radius of curvature of river bends. In the braided reach from the dam to Huangzhang, 15 out of the 26 'large' branches were found to be silted up, resulting in the amalgamation of the small islands/mid channel sand bars into point bars. Change from a braided to a meandering river is gradually taking place, and seems to be similar to the changes described on the Yellow River, by Li *et al*, (1980) cited in Galay (1983).

The Liu River has an annual average sediment load of 52kg/m^3, which was greatly increased after the construction of the Naodehai Reservoir, due to increased activity in the catchment. In the absence of competent flows, aggradation has dominated the downstream reaches. Bedrock sections have become smothered in sand and the bed has risen 1.5m in 10 years. The channel banks have receded to form a wider and shallower channel.

Qiwei, *et al* (1982) have also done an detailed study of the sediment load in the Hanjiang river since the construction of the Danjiankou (no. 30), reservoir. Their work on the changes in sediment transport capacity, is based on the theory of non-equilibrium transportation of nonuniform sediment. (Han, 1979) With regard to the state of post-impoundment sediment characteristics, they have made the following observations:

- recovery occurs over a long distance
- the rate of increase in sediment concentration is uniform
- corresponding to the change in concentration, the size distribution of the suspended load becomes more uniform and finer along the channel.
- the degradation and aggradation characteristics of each particle size group are different. Generally the fine fractions are scoured more than the coarse. The coarse sediments may even

be deposited during the scouring process. Hence the average particle size of the load becomes finer with distance and the settling velocity also becomes smaller.

- the development of the degradation and the increase in sediment transport along the river are not due to an increase in flow intensity.

In the same reach after dam construction the sediment carrying capacity will be much less because the particles of the suspended load are much coarser with larger settling velocities. With the flood peaks reduced the annual sediment transport capacity of the river is also reduced. As a result of erosion of the channel immediately after closure, the flow velocity is smaller and the depth greater for the same discharge. The bed material becomes finer along the river course, due to the exchange which occurs between the bed and the load, with the coarser fraction being deposited while the fines get picked up. The average particle size of the load becomes finer, while settling velocity becomes smaller, and the transport capacity increases. Therefore the amount of erosion exceeds deposition. This occurs at a very low rate in a downstream direction and extends for some distance.

No. 42. Assarin (1994) discusses the impact of three reservoirs in Poland, Lithuania and Vietnam. The Zimlayanskaya dam is part of a hydro-electric power scheme on the Don River, with a storage capacity of 23.8 x $10^9 m^3$, which is greater than the mean annual river discharge of 22 x $10^9 m^3$. The bed is of fine sand with 0.25-0.05mm the prevalent size. The alluvium is up to10m thick in place, underlain by coarser alluvial material with some gravel\pebble intrusions. Degradation has been observed for 50km below the dam, in an irregular pattern. Progressive scour and fill, has led to changes in width and depth. An estimated 8 x $10^6 m^3$ of sediment was removed from the first 20km reach. Coupled with dredging on the channel banks, and straightening of the rivers course there has been a 0.92m lowering of the water level.

No. 43. Kaunas HPP on the Neman River, Lithuania, regulates 0.46 x $10^9 m^3$, of the rivers total runoff of 9.2 x $10^9 m^3$. The channel is trough shaped, 180-300m wide, and 1.5-2.5m in depth in the low season. It has a substrate of gravel and sand bed, of up to 8m in thickness. Coarseness decreases in a downstream direction. Under natural conditions the river bed was hardly movable, change was due to sediment drift. During and after impoundment, the river bottom in a 4km stretch was noticeably degraded. The most affected section, a 0.9km stretch below the dam was lowered by 0.6m on average, with scour of up to 2m in places. The zone of degradation moved downstream with time extending 8km after 5years, it had move down 8km. An increase in bed material size within the ninth kilometre downstream of the dam, effectively halted the process of degradation. Of particular concern in this case was the accompanying reduction in water level - 0.65m in total.

No. 44, Hoa-Binh HPP on the Da river, Vietnam, impounds 9.5 x $10^9 m^3$, of the mean annual normal flow of 57.2 x $10^9 m^3$. The channel substrate of thick sand strata was particularly susceptible to degradation. Immediately downstream of the dam, (0.3-0.6km) degradation was severe, with scour of 5-6m, and even 8-10m. Degradation of 4-4.5m and 2-3m at downstream sites was predicted and confirmed for up to 57km downstream.

No. 26. Woo & Yu (1994) are mainly concerned with predicting channel degradation using computer modeling. They investigated the impact of the Daecheong multipurpose dam on the Keum River, Korea. The reservoir has a storage capacity of 1.49 x $10^9 m^3$, representing 60% of the annual inflow of 2.5 x $10^9 m^3$. There is regular spillage from the dam. It is an alluvial stream, with a bed of fine and medium sands. Degradation was measured by assessing 2 channel surveys, 10 years apart, from pre and post dam periods. Actual change was found to have occurred below the regulatory dam, 10km downstream of the main reservoir. The study reach extended for 78km and incorporated 2 major tributary junctions.

Below the regulatory dam for a 15km stretch, degradation of 2-3m was evident. However due to the exposure of gravel and cobble substrate degradation has ceased. Downstream of that, degradation was less severe. Some of the degradation must be attributed to gravel mining which is allowed for in the modeling. In the last 20km of the study reach, aggradation of 0-1m was measured. Using the HEC-6 modeling program, the field results were matched with modeled predictions, and a good correlation was found. The model was found to be useful on a general scale, rather than on localised sites.

AMERICA

No.'s 54-74. Williams and Wolman (1984) is a major undertaking looking mostly at the primary impact of big dams in the USA. The study focused on was measuring changes in bed elevation and width of channel after river regulation. Channel changes below 21 dams in the USA were investigated, through an assessment of 287 cross sections, which have been periodically re-surveyed since dam closure. Pre- and post dam flow records were available for all the studies. Gauge height-water discharge information was available for 14 gauging stations. Pre- and post dam sediment concentration data were available for a limited number of dams. The sort of changes found here are great enough to be attributed to the impact of a dam as they greatly exceed natural fluctuations about a mean. However, due to the number of variables operating in the system and the range within each variable, as well as the variability between samples, it was not possible to characterize the post-dam conditions, but thorough assessments were made for each case.

Their study records the changes that have taken place in terms of the channel dimensions. They do not describe the actual morphological change in any detail. They consider the following aspects of change: water discharges, sediment loads, mean bed elevation, bed material and degradation, channel width change and vegetation change. Their results showed a number of trends which are summarized be;ow.

Average annual peak discharges have been reduced by 3-91% of pre-dam values, while mean daily flows and average annual low flows have increased and decreased. Degradation of the channel bed was the most common adjustment, occurring in all 21 cases. The rate of degradation ranged from 0.1-1m/yr to as much as 7.7m/yr, with a depth range of 1-7.5m at certain points. In a reach with a gradient of 1 to 3m/km, 1m of degradation has a significant effect on the longitudinal profile. Maximum degradation was usually near the dam, and decreased in a downstream direction. Based on observations made, average rates of degradation and changes in channel width could be described by the equation:

$$(1/Y) = C_1 = C_2 (1/t)$$

y is either bed degradation in metres or relative change in channel width
C_1 and C_2 are empirical coefficients
t is the time in years after onset of change

The accuracy of the equation would be dependent on the presence of controlling variables such as a bedrock outcrops, coarse substrate, erodible banks *etc.* which would determine the 'conformity' of change.

Variations in the length of the degraded reach ranged from 4km on the Neches river, to 120km on the Colorado below Hoover dam. Time wise, this front could continue migrating, or might have stopped already, depending on flow releases, bed material and topography. If degradation is occurring in one reach, aggradation must be happening somewhere else.

Closely linked to degradation is the nature of the substrate. Few channels are underlain by uniform sediments and in the absence of varied flows, transport becomes highly selective, moving particles of a particular size, which leaves coarser fragments behind in an armoured layer. Livesey (1965) has shown that as little as 10% coarse material while provide bed armour. Armour is only a veneer, beneath it is unsorted, unwinnowed material. There is no documented work on it , but the veneer is only likely to be disrupted by large discharges, with high competence.

The variations in bed material size after dam closure was also examined by d_{50} median grain size assessment at various times by the US Army Corps. of Engineers. Initially size increased, particularly at sites close to the dam. Over a ten year period the change stabilised and there was sometimes a reversal, possibly due to sediment input from a tributary, breakup of the armour, channel migration, or sampling inaccuracies. This effect lessens in a downstream direction because a river with a bed of mixed particle sizes will be sorted by size in a downstream direction. Kira (1972) has shown a gradual decrease in the mean diameter of bed surface materials with distance over a 5 year period on the Aya river, Japan, after impoundment. This was also the case on the Red river, below Denison Dam. On the Colorado below Hoover dam, bed material sizes were measured before closure, and the changes which occurred after the building of the dam could definitely be attributed to impoundment. In the first year, a 10km reach downstream of the dam was affected, after years the affected reach extended 20km. After 13 years, it was estimated to have an extent of 135km.

According to Williams and Wolman, erosion will continue until a combination of the following factors leads to a new, stable channel:

- local controls of bed elevation such as bedrock or armoured alluvium. Degradation should decrease with time as the bed tends towards a stable state via the armouring process, or until the channel slope becomes too flat for the bed material to be moved (reduced velocity and competence). Results showed that 50% of the degradation takes place in the first 5% of the time, and 75% of the degradation will be reached in 13% of the time.
- on encountering base level controls such as a lake, larger river, man made structures or an ocean
- a decrease in flow competence (flattening of slope due to degradation) due to an increase in channel width and reduced velocity
- an infusion of sediment from a tributary to restore the balance between arriving and departing sediment
- the growth of vegetation which binds materials

They also found tremendous changes in channel width: it narrowed, widened or stayed constant . On four rivers where the post dam channel was greatly reduced, reduced mean bed elevation occurred because only the lowest part of the channel was occupied. In the various studies, bank erosion was found to be a major source of sediment, particularly in reaches with non-cohesive banks. The location of controls and fluctuations in discharge accounted for the varying rates of erosion. Sediment change is significant – lateral erosion and degradation cease when flow no longer transports the sediments. This results from reduction in flow competence, bank resistance, tributary inflow and sediment injection, and armouring. In terms of vegetation growth , 90% of bars and benches below dams were found to have been colonised after dam closure. While this was also related to other changes, it was certainly encouraged by changes in the flow regime due to impoundment. They found that recovery distance is tremendously variable. It may be so great that the river never achieves it.

No. 49. The Colorado River has been significantly impacted in many ways since the construction of Glen Canyon dam (Lake Powell) in 1963. **Dolan, Howard and Gallenson (1974)** have investigated the impact on a 280 km study reach down to the Grand Canyon. The dam is a major sediment trap and eliminator of the flash flooding that is associated with the rivers of the southwest. High flows derived from snowmelt, peaking in May to June, with a second peak in the late summer due to flash floods are a feature of the system. Large quantities of sediment were moved in high flows and as the water receded in the summer much of the sediment was be deposited in the form of bars and terraces: a process of periodic erosion and replenishment of sediment. Under the present regulated conditions the higher terraces are no longer flooded and the lower ones are eroding. Vegetation encroachment has occurred and wind erosion is removing sediment above the lowered water line.

Changes in the flow regime have been dramatic. The pre-dam mean annual flood height was10 times the present median discharge. Floods of more than 100000 ft^3s^{-1} occurred every few years. Sediment surveys of deposits downstream in Hoover dam (Lake Mead) show that the river carries a very high suspended load. Under natural conditions, the river averaged 0.38 million tons of sediment per day. Most deposits along the channel are fine grained terraces, although pebble and cobble bars do occur locally and may underlie the finer material. Floods with low sediment concentrations resulted in erosion of these features, whereas, occasional summer peaks resulted in deposition, resulting in the fluvial terrace morphology of the system. The position of the terraces corresponds to the pre-dam mean annual flood of 80,000 ft^3s^{-1}, and the frequent 12000 ft^3s^{-1} peaks. They occur in low velocity zones and are often associated with tributary entrances where the river is constricted by fan development, causing the formation of rapids and low velocity reverse eddies above and below the falls that create a depositional environment. A line of hardwoods is associated with the higher terraces whereas the lower terraces were unsuitable for any permanent growth.

Under regulated flow conditions there has been a slight increase in median discharge and a great decrease in the number of flood peaks. Diurnal fluctuations are dramatic from 4600 ft^3s^{-1} to 20000 ft^3s^{-1}, (amounting to a fifteen foot stage difference) to meet the hydro-electric power demands. Close to the dam the median suspended sediment load has been reduced by a factor of 200, although this recovers with tributary entrances and erosion of terraces, so that within 100km downstream it is only reduced by a factor of 3,5. Erosion is due to direct water action and the process of 'bank slaking' which occurs when the water is low and the groundwater seeps from the terraces. Bed coarsening prevents further erosion in many places. Lower down in the canyon, tributary flows help to restore equilibrium in terms of flow and sediment proportions. Wind erosion of the high terraces is also significant. The Tamarisk shrub has invaded many areas and algal growth has increased in the clear sediment free waters. Associated with this is a change in fauna.

No's 51 and 52. Turner and Karpiscak (1980) have made the link between geomorphological changes on the Colorado river and riparian vegetation change, since the closure of Glen Canyon dam. A summary of the primary impacts is as follows: average annual maximum flows reduced from 2486 m^3s^{-1} to $803m^3s^{-1}$; median discharge increased from 210 m^3s^{-1}, average diurnal fluctuation changed from a few centimetres to several metres, median sediment concentration was reduced from 1500 to 7 parts per million. Over a period of 17 years since the dams completion in 1963, various significant geomorphological and associated ecological changes have occurred and will continue to happen. The study concentrates on the stretch that traverses the Grand Canyon.

Prior to dam construction, the confined nature of the channel prevented the development of a floodplain and associated riparian community. The river banks were periodically stripped of plant colonizers. The rivers gradient is under the dominant control of the tributary fans. Since 1963 floods have been dramatically reduced and the flow regime has become much more stable. The co-efficient of variation at Lees Ferry, 26km below the dam has changed from 0.19 (for the 42 year pre-dam period) to 0.06 (for the 13 year post-dam period). The entry of the unregulated Little Colorado River 140km downstream reduces this difference and the pre-and post dam CV's there are 0.2 and 0.17 respectively. Reduced flooding has provided stability in a previously highly unstable habitat.

In the post dam period, typical daily stage fluctuations are of more than 1.5m and seldom less than 0.3m. A weekly Sunday drop is common as power demands are low then as they are on public holidays. The range of annual flows has reduced greatly: from a low of 5200 hm^3/yr in 1934 and a high of 24500 hm^3/yr in 1929, the post dam range was 2000 hm^3/yr in 1962 to a high of 14500 hm^3/yr in 1965. The general range is 9900-12300 hm^3/yr per calender year. Maximum monthly discharges generally occurred in June as a result of spring snow melt while in the post dam period, the greatest discharges are released in May in response to irrigation and power demands. In the pre-dam period, the maximum mean monthly discharge of 4300 hm^3 was more than 10 times greater then the lowest monthly mean discharge. The post dam maximum/minimum ratio is only 1.8 to 1. The seasonal variability has been removed.

Alluvial deposits are a major feature of this arid river system. The sediment regime has been dramatically altered by the impoundment. A major proportion of the sediment is trapped in Lake Powell and clear water releases have a large transport capacity. However reduced flood peaks do not have the capacity to rework coarse sediment tributary deposits. Essentially there have been four impacts: accelerated erosion downstream of the dam site, followed by armouring of the substrate by coarse material, stabilization of sand bars by vegetation, erosion of talus slopes, benches and bars. This degradation front is likely to move downstream.

No. 50, Kearsley, Schmidt and Warren's (1994) study is very much an applied paper, looking at the effect of Glen Canyon Dam on Colorado River deposits used as campsites in Grand Canyon National Park. The sand bars are characteristic of the pre-dam river morphology and are being eroded under regulated flow conditions. Campsite capacity has been reduced by 44%. While this was not a direct geomorphological approach as it was done via the assessment of available sandy areas for campsites and the change in that availability at different flow levels, it serves as a useful example of the practical implications of geomorphological change due ti river regulation. Campsites changed in terms of erosion of sand, substrate change or invasion by vegetation.

The closure of Glen Canyon dam reduced the annual sediment load of the river below the dam from $6x10^{10}$kg to 8.3×10^{7}kg. The magnitude and frequency of flooding has changed dramatically: the post dam annual peak discharge is controlled by the maximum capacity of the hydroelectric power plant at 940 m^3s^{-1} compared to the natural annual flood of 2180 m^3s^{-1}. Only occasionally is this flow exceeded. While high flows in 1983 served to increase bar size in some areas, they eroded them in other critical reaches. Sediment may accumulate in low flow years, but so does vegetation rendering many sites unusable. A comparison of sites for 1973, 1983 and 1991 was possible, using aerial photograph records. Results showed a 34% increase in sites from 1973 to 1983, but a 48% decrease from 1983 to 1991, giving a net decrease of 32%. 44% of the large campsites were lost to erosion and/or vegetation growth. In the 'critical' reaches (ie: high demand zones), there was a loss of campsites during both periods.

No. 53. One of the problems associated with regulation in this arid system is related to the rapids: they have become permanent in the absence of destabilizing flows and are causing navigational problems. This particular problem has been investigated by **Graf (1980)** on the Green River, a tributary of the Colorado above Lake Powell. Since the closure of Flaming Gorge Dam in 1962, the maximum release of 170 m^3s^{-1}, has not come close to the 100 year flood of 510 m^3s^{-1}. While the benefits to development have been many, the impact on the river channel has not easily been quantified. One of the obvious effects has been the increase in the occurrence of rapids in the system, due to the reduced water levels/flows which is felt particularly by the many recreational users of the river. Along a 69km stretch of river, there are 55 rapids formed by tributary flash floods, landslides or prehistoric floods on the main stream. A rapid is defined as an accumulation of boulders in the channel where the particles are numerous enough or large enough to break the water surface at mean annual discharges. Conventional sediment movement equations were developed for much smaller sediment sizes, so the author used a hydraulic empirical technique. By calculating the particle resistance based on friction and buoyancy, the downstream force of flowing water against the particle and the ratio of force to resistance as a measure of stability, it was possible to estimate broadly the stability of the largest boulder in each rapid. By establishing the stability of the rapid as a whole by looking at the largest particle it could be assumed that if the force of the water was below the threshold for movement of the largest particle, the feature would be stable. This method can be used to determine what effect a reduction in flood flows will have on the stability of the system.

The overall results can be summarized as follows: 290 miles downstream of the reservoir, the effect of the dam is still significant although the contributing area is 2.7 times that of the regulated catchment.

No's 38 and 39. Hadley, & Eschner (1982) describe the changes which have occurred in the the Platte river system, as a result of extensive regulation. The system has a large catchment area of 223000km^2. Water developments and extensive landuse change have been a feature of the basin since European settlement in the 1860's. The North Platte River has been extensively dammed and has therefore been significantly affected, while the South Platte river is less developed. Most of the rivers flow is derived from snow melt, and a small proportion from rainfall, which ranges from 330 -635mm/annum. Written historic observations on the nature of the river in the early nineteenth century provide a valuable impression of its pre-settlement condition: it was a wide (2km), shallow (0.3-1.8m) river, characterized by annual bankfull spring floods and low summer flows. It was shallow enough to cross in most reaches except during spring floods. It was common for the river to stop flowing in the dry season. The bed material is described as being mostly gravel and sand, (although there are also descriptions of more silty conditions.) whereas today much siltier conditions persist. A current hydrograph of the system shows a reduction in the occurrence of short duration flows and an increase in the magnitude of long duration flows. The flow has become less variable and the baseflow contribution has increased. The impact of the changed flow regime on channel morphology is confirmed by survey comparisons at different dates. By 1951, at Cozad for example, the width had been reduced from 1161m to 204m. This had halved again by 1979. Using maps and aerial photos, it has been possible to measure the considerable reduction in width, which has taken place as a result of in channel bar growth and stabilization.. The 'old channel' was broad and open, with few large islands, whereas by 1938, bank/bar formations stabilised by vegetation, had constricted the channel. In time the number of islands diminished, but their size increased as the secondary channels were abandoned, filled in and vegetated. Low flows and a reduction in floods created favorable conditions for vegetation establishment on previously temporary features. The river has been transformed from a multiple thalweg to a single thalweg stream.

CANADA

In Canada in the late fifties, power producers began to look northwards, beyond the developed regions, to the sparsely populated northern areas, in search of new dam sites for hydro electric power supply . **No. 48, Kellerhals and Gill (1973)** working on the impact of impoundment on some of these northern rivers in Canada, have identified significant impacts at tributary junctions. The Peace River had a highly variable natural flow regime: flows ranged from annual peaks of 3500-9000m^{3}s^{-1} to lows of 150-250m^{3}s^{-1}. Regulated releases from Bennett dam have reduced this range to between 2000 and 500m^{3}s^{-1}. This river channel was maintained by the 1.5 yr flood, but with this removed the new flow is simply being accommodated in the old channel, which is entrenched in stable, resistant bedrock and gravels. In some reaches, deep scour holes on channel bends are filling in, while gravel bars which are exposed above the new high water mark, are aggrading and becoming stabilised by vegetation (balsam, poplar and willows). The sediment load of the river is generally low with little sediment storage, but under flood conditions it carries a small but significant suspended load. After four years, the most significant changes have occurred at tributary junctions, where the unregulated tributaries have built deltas into the main channel, causing distinct breaks in its longitudinal profile. The regime of the main river would normally be in phase with its tributaries but river regulation upsets this condition, so that tributaries may flood when the stage at the junction is considerably lower than under natural conditions. This causes the tributaries to erode their beds to meet the new level of the main stream. A tributary entering the Peace River has eroded its own bed to such an extent that it has exposed foundations of two bridges crossing the tributary.

No. 23, Bray, and Kellerhals (1979) give some more information about the impact of WAC Bennett dam, a few years after Kelerhals and Gill's (1973) study. 1800km downstream of the dam, spring peak flow (about 9000 m^{3}s^{-1}) reduction by 3000 - 6000 m^{3}s^{-1} has resulted in a stage reduction of 2-4m. Flow regulation reduces summer peak water levels by 0.6m for a stretch of 80 km at the delta, 1200km downstream, which is highly significant on this flat land. Winter flows immediately downstream of the dam increased by a factor of 10, (dam releases are 1500-2500m^{3}s^{-1}) and by a factor of 5 to 8 at Athabasca lake. At the lake there have been problems with ice-jams associated with the high winter flows, causing uncharacteristic flooding and associated silt deposition. They also note the growth of deltaic tributary deposits in the main channel. Where the tributaries have a steep gradient with coarse gravel bedload and a high transport capacity and are relatively close to the dam, this phenomenon is apparent. For example, 35km downstream, at Farrell Creek, a bridge 300m upstream from the confluence on the tributary has become unstable due to exposed foundations. Further down, the eroded material forms a large delta in the main channel.

No. 37, Buma and Day's (1977) work on of the impact of Deer Creek Reservoir (30ha), Deer Creek, southwestern Ontario is a very detailed study, only possible in such a small system (catchment area approximately 10km^2). The climate is mild with an average temperature of 8° C; rainfall is high with an average 940mm per annum and evapo-transpiration rates of 530mm. The river flows through an alluvial floodplain of sand and silt. Channel downcutting due to sustained clear water releases was the major impact below the dam. Detailed examination of nine sites over a period of five years, within 3km of the dam wall, failed to produce any general trends. A summary of the site results are presented in the table below.

	D/S	DESC.	BANK	BED	THALWEG	X_SECTION
1	63m	straight, stable bed, meandering thalweg	r/b eroded by 0.458-0.610m		moved from L to R and partially back	increase in x-sectional area
2	127m	at a tributary junction	r/b eroded 0.214m, l/b aggraded 0.153m	bottom level reduced by 0.153	minor movement	no change in x-sectional area
3	254m	straight	r/b eroded by 0.61m; l/b aggraded slightly.	channel bottom degraded	deepened by 0.122m	small increase in x-section.
4	256m		minor change	bar adjacent to left bank bottom, in 1971 and 1975		little change
5	317m	in a meander	r/b eroded 0.458m; equal aggradation on l/b	rapid downcutting 0.305-0.458m of material removed	shifted laterally by 0.915m	x-sectional area increased
6	1.334 km	straight reach	r/b eroded; l/b aggraded	downcutting up to 0.458m	migrated from left to right bank - 1.312m	Increased x-sectional area.
7	1.651 km	in a meander	minor r/b aggradation 1971-1974; substantial erosion,1975; l/b showed a tendency to erode - up to 0.61m	large bottom shape variations	fluctuation over 0.122m vertically, and 0.610m horizontally from left to right	overall increase in x-sectional area
8	2.032 km	straight reach cut into floodplain	degradation of up to 0.61m in some places on r/b; with the l/b aggrading by 0.214m	steady rise of up to 0.244m	thalweg shifted from left to right about 0.305m	Cross sectional area maintained. Overall channel shifting in a westerly direction.
9	2.222 km	close to confluence with Big Creek,	l/b eroded 0.6m; r/b 0.458m.	Bed rose 0.763m in 71-72;rose in 75 by 0.305m	shifted back and forth laterally 1.83m	slight increase in cross sectional area

Table B : Summary of Buma and Day's 1987 study.

In Canadian papers there seems to be a strong concern for lowering of the groundwater table on floodplains in impacted systems, because of it's impact on vegetation succession, related to the presence of permafrost/climatic concerns which as outlined by Gill, 1973 is complex.

AFRICA

No. 38, Kinaway, *et al* (1973) give a comprehensive overview of the impact of the High Aswan dam on the sediment balance in the Nile. River flow in the Nile is completely regulated by the High Aswan dam. The dam has a total capacity of 164 km^3 (30 km^3 for silt, 90 km^3 for live storage and 44 km^3 for flood control). Only when the reservoir is at full capacity does excess flow overflow naturally. The Nile used to transport 80% of the total sediment load of some 125 million tons in the flood season, from July to October. The suspended load becomes negligible when the discharge drops below 200 million m^3/day. Estimates were made that the silt deposited on the floodplain so vital to agriculture, equaled only 12% of the total load of which, the essential nutritive azote factor amounted to only 0.13%. This was to be compensated for with calcium nitrate fertilizer. Immediately below the HAD (7km), degradation has been checked to a certain extent by the old Aswan Dam. The river channel is mainly a single thread, 500-600m wide on average, but sometimes divides into two or three branches where it is up to 1.5km wide. Depth at high water is up to 20m in pools, and 5-6m over bars, or 1-1.5m at low levels. Since 1964, there has been a reduction in water levels due to bed degradation. Initially the rate of degradation was rapid, but gradually reduced as the channel became armoured.

No. 39, Shalaby (1986) gives a more up to date summary of the impacts of the HAD, with an assessment of the change in flows and sediment regime. Before the construction of the HAD, discharges passing Aswan were highly variable. The flows which ranged from 720 -13000 m^{3}s^{-1}, now have a range of 930-2600m^{3}s^{-1}. Total annual flow to the Mediterranean which used to average 40km^{3}yr^{-1}, are reduced to 2-3km^{3}yr^{-1}. Degradation has been a major impact ranging from 1-10m at various points, with average bed level drops of 0.25 to 0.7m, over a distance of 540km. The subsequent water level drop ranges from 0-1m depending on the discharge.

No. 9, Hammad's (1972) study is an investigation of the sediment relationships after the closure of the dam. The dam traps the rivers whole sediment load. Recovery below the dam is no where near the original value amounting to only 5% of pre-dam values. Degradation begins with the movement of fine particles, leaving a plane bed of coarser material or a rippled bed of coarser materials, which tends to happen at the end of a degrading sequence. Coarsening of bed material increases roughness and reduces flow velocities further. Suspended flood material consists of fine sand (30), silt (40%), clay (30%). Bed material is largely coarse sand. . This is due to coarsening of the bed downstream

No.76. According to **Davies (1996)** in the Zambezi valley, downstream of Cahora Bassa the natural flow regime of the river has been substantially altered. The greatest impact has been on the floods which are vital to the maintenance of the floodplain. The channel is changing from a braided stream where islands are temporary, to an anastomosing, or single thread channel, with large islands which are aggrading and stabilising and being inhabited and utilised by the local population.

AUSTRALIA

Walker (1979) and **Jacobs (1994)** have assessed the impact of water resource developments on the Murray-Darling system in Australia. Being the biggest system in the country its correct management is of importance to the whole country. The Murray (the principal stream), flows through well watered mountainous terrain for 350km, the remaining 2200km flows through semi-arid desert. It is difficult to generalize about the hydrological behaviour of this river because the flows are so variable. (Walker, 1985) The system is regulated by a variety of structures: in total there are 4 major reservoirs, 16 weirs, and 5 barrages. This intensive regulation has been a response to the tremendous variability of the system (Walker, 1979). With the exception of Menindee Lake on the Lower Darling, 2 weirs on the lower Murrumbidgee river, and the largest and newest Reservoir - Dartmouth Dam on the Mitta Mitta River, all the other structures are on the Murray River. Although much of the system is unregulated due to a lack of suitable reservoir sites and shortage of finance, flow is estimated to have been reduced to a third of its natural volume by the time it reaches the rivers mouth. This is attributed mainly to increased irrigation demands in the last 30 years (Jacobs, 1994).

According to both authors, the main influences of impoundments have been: a change in the seasonal distribution of flows due to irrigation requirements where winter flow is reduced by storage, and summer flow increased as water is released for irrigation. Flow regulation has been used to ameliorate the impact of floods, and there has been a trend towards the reduction of average flows in the middle of the river. Severe bank erosion has been experienced in some areas (for example, below lake Hume) because of the sediment free releases.

Jacobs (1994), describes the processes which operate below two of the reservoirs . Dartmouth Dam (no. 34), the largest in the system on the Mitta Mitta river has capacity of 3906 x $10^6 m^3$ and stores water for irrigation. Releases of $115 m^3 s^{-1}$ are designed to correspond with the channel capacity below the dam, while a minimum release of $2.3 m^3 s^{-1}$ ensures that the river is never dry. During the construction phase, the downstream river bed became silted up and algaefied, with an associated bio-diversity reduction, for up to 50km below the dam. It has been flushed out subsequently by irrigation releases and at one site only 10% of the bed is now composed of sand/silt. Algal growth is still a problem due to the intensive agricultural production in the valley. As is particularly common with irrigation type releases bank erosion downstream has occurred, which has been counteracted by anti-erosion measures. The nature of irrigation demands has resulted in a reversal of flows: the winter flow is stored and released in the dry summer period when irrigation demands are greatest. The first major tributary enters the system 25km below the dam.

Downstream of Hume Reservoir (no. 35) for a distance of 80km to Yarrawonga weir the channel is still adjusting to the changed flow regime, 52 years after the reservoir was built, and 32 years after it was enlarged. Lake Hume is situated where the Murray emerges from the mountains onto the plains and is not ideally suited to the delivery of irrigation flows, because the alluvial channel is easily eroded. Bank erosion is high due to maintained irrigation releases. The mainstream river and its anabranches are widening, with the bed deepening in the upstream section, and becoming shallower downstream. More anabranches are developing as fallen trees (due to undermining of banks) divert the flow and capture part of the remaining stream flow. Expensive erosion controls and 'desnagging' measures have been instituted too rectify some of the problems caused by bank collapse, with associated debris jams. The systems wetlands have also been degraded. *The process of anabranching is typical of a river which has reduced its flow velocity and is therefore depositing its load to form a braided, anabranching channel.*

A detailed investigation carried out by **Sherrard and Erskine (1991)** investigates the impact of Mangrove Creek Dam on Mangrove Creek (no 31). The stream has a catchment area of 420km^2, while the the dam has a catchment area of 100km^2. Most of the catchment is still under natural vegetation. Average annual rainfall at the dam is 1200mm and annual evaporation 2400mm. The study reach which extended for 16km below the dam, consisted of a sand bed stream, laterally confined by bedrock valley sides. This was further divided into three reaches, according to morphological characteristics: the upper reach (dam to Warre Warren Creek), characterized by a low bankfull sinuosity with a meandering thalweg and a narrow, constant width, sand bed channel; the middle reach (Warre Warren to Dubbo Creek), a wider more active sand bed, with a higher sinuosity and channel expansion at bends; the lower reach (Dubbo Creek to Mangrove Mountain station), a constant width sand bed channel, narrower, deeper and straighter than upstream.

Readings taken at the gauge below the dam are a reflection of the size of the unimpounded catchment which at this point is only 4km^2. Discharge had been reduced by 70%. At the end of the study reach, (Mangrove Mountain gauging station) the effect is not as drastic as the proportion of unregulated catchment has increased. Flows of more than 10% duration have been reduced by 50%, while more frequent flows have been reduced by 29 - 36%. Overall the change in flood frequency curves has been significant. At both stations the upper limb of the bi-linear flood frequency curve has been eliminated, thereby restricting floods to the lower limb with a recurrence interval of less than a year. The resultant reduction of channel capacity is supported by a study by Pickup and Warner (1976) conducted in a neighboring creek, which found that the larger events are responsible for determining channel capacity, but the smaller more frequent events carry most of the bedload and therefore control the channel form. The largest flood (peak instantaneous discharge of 34 800 Mld^{-1}) recorded at the dam station has been reduced by an order of magnitude to1710Mld^{-1}, with a recurrence interval of only 1.08 years. Overall there has been a reduction in larger floods of 80% and further down at Mangrove Mountain, larger floods have been reduced by 54-66%. There the largest flood recorded after impoundment, had a recurrence interval of only 1.2 years on the pre-dam flood frequency curve.

With such substantial changes in the hydrologic regime of the river, significant second order impacts were clearly recognizable. The most severely impacted section was a 1km stretch below the spillway, where a new complex morphology with alternating reaches of aggradation and degradation developed. Aggradation was caused by a concrete causeway and by sediment wedges deposited by incoming tributaries. Cross sections show that a very narrow channel with a capacity of 205 Mld^{-1} had developed. Aggradation on the unincised portion of the pre dam channel caused the development of a 0.4m high bench, which became well vegetated For one kilometre downstream of the dam, channel width contracted by 50% and mean depth increased by 53%, while mean velocity decreased by 8%. At Mangrove Mountain, bankfull width had been reduced by 7-15% due to oblique accretion. Mean depth and bed elevation were unchanged, which could be attributed to the different channel type and the smaller reduction in flows and sediment loads. In the middle and upper reaches the reduction in channel width was significant, particularly where the channel was not confined by bedrock. Second order impacts included stabilization by vegetation of bars and bank attachment of mid channel bars. Trenches were dug to determine the composition of the bars and a distinct break was identified between the coarse basal sand and overlying finer bench sediment which corresponded to the dam closure time. According to Erskine(1986a) bench construction of this sort marks a phase of channel recovery by contraction. This discovery was confirmed by a comparison of pre and post impoundment aerial photos of the channel, which verified extensive bar development since impoundment. The entrance of Warre Warren Creek , halfway along the study reach, with a catchment area of 50km^2 provides a significant sediment input where it enters Mangrove Creek which at this point only has an effective catchment of 39km^2.

Erskine (1985) studied the the Hunter River, New South Wales, Australia, which was dammed for water conservation and flood mitigation by Glenbawn reservoir (no. 32) with a capacity of 228 x 10^{6}m^3, and a 1214ha surface area. It has a sediment trap efficiency of 99%. There has been no overflow since completion in 1958 and all releases have been artificially controlled. Reduced runoff since 1959 amounts to the volume lost to evaporation. Flow records below the dam show a truncation of high flows (>8 x 10^{6}m^{3}d^{-1}); reduced frequency of intermediate flows (>7 x 10^{5}m^{3}d^{-1}) and an increased frequency of low flows. Seasonally, there has been a decrease in the frequency of all discharges, the other eight months reflect the pattern described above. The biggest flood (7.83 x 10^{6}m^{3}d^{-1}) recorded since 1959 has only been marginally bigger than the maximum capacity of the dam valves. This equates with the pre dam flood with a probability of accedence of 87%. Concrete bars and bedrock immediately below the dam have limited scour, while the stable nature of the channel banks, vegetated by willows whose roots form a dense mat on the bank foot have only allowed minor changes in bankfull width, cross sectional area, and mean depth of less than 10%. This can be described as 'accommodation adjustment,' (Petts, 1984). Site four just below the entrance of Rouchel Brook is an exception, where there has been 45% contraction, and 69% deepening, as well as lateral migration onto the floodplain with reworking of sediment.

Bed material size change has been most marked at site four where there has been a progressive coarsening of bed material. This would be the influence of an unregulated tributary introducing coarse sediment which the mainstream is incapable of moving. The armouring on the bed was investigated by sampling the surface and sub-surface layers and by determining the mobility of the bed material at various flows. There was little sediment finer than 8mm in the surface sample, but 22-38% of the sub-surface sample was finer than 8mm. The presence of algal growth on the coarse fraction suggested that the sediment had not been moved in a while. The regulated water releases were not competent to move coarse sediment, but were able to winnow out fines. This is a typical impact of a flood retention reservoir where high flows are eliminated. Associated with the absence of 'flushing flows,' has been the encroachment of willows onto bars and bank feet, which have had to be cleared manually to maintain the conveyance capacity of the channel.

No. 33, Benn and Erskine (1994) have investigated the complex response of the Cudgegong River, to the construction of Windamere dam in 1984. It is a large capacity storage dam, with a full supply level storage capacity of 368 x 10^9l, regulating a catchment area of 1070km^2. It meets irrigation demands for a 120km stretch downstream and provides water for the townships of Mudgee and Gulgong. The dam has spilled only once since construction for a three month period in 1990. It has a sediment trap efficiency of 95% plus. The channel is confined by bedrock which prevents meandering and forms a pool -riffle gravel-bed stream with occasional bedrock outcrops in the bed and banks.

The first Order impacts to the system are significant. Flow duration curves indicate a truncation of high flows greater than 3 x 10^9l d $^{-1}$ and an increase in duration of lowest flows with discharges less than 30 x 10^9l d $^{-1}$. The 10% duration flow has been reduced from 260 x 10^6l d $^{-1}$ to 130 x 10^6l d $^{-1}$. The 80% duration flow before the dam was built was 6 x 10^6l d $^{-1}$, after 1984 that flow is estimated at 21 x 10^6l d $^{-1}$. As would be expected with an irrigation dam the large and moderate flows are reduced and baseflow increased.

Despite the significant change in flow regime, channel pattern change has not occurred due to lateral confinement by bedrock valley sides. Channel cross sectional change has been monitored at 6 sites, 1.6km apart, as well at the 2 gauging stations, with the following results:

- 6 sites exhibited < 5% width contraction,
- 2 sites exhibited > 15% width contraction
- cross sectional area of the channel decreased by more than 10% at 6 out of 8 sites, mostly by width contraction (5 sites)
- width contracted at 2 sites
- 5 sites degraded by 13 - 31%.
- 2 sites showed aggradation of 5 -18%

This range of responses has been termed 'complex' by Petts (1984) and overall the morphological change can be described as 'accommodation adjustment,' because there has been no major morphological alteration.

Bed material samples at nine sites show the dominant response in this system to be aggradation and a decrease in bed material size due to incompetence of flows. Two sites show substrate coarsening: this is associated with unregulated tributary sediment input, tributary bar development and channel constriction, which would cause higher velocities capable of moving the finer fraction of sediment through those reaches. This was confirmed with bed material mobility estimations. Using Neill's (1968) criterion the competence of the maximum regulated flow was determined as 2.3 x 10^9l d $^{-1}$ and it was found that regulated flows do not exceed the threshold of motion at any of the other cross sections. Competence is so low that armouring has not even occurred.

Four new tributary bars were identified as having developed since closure of the dam. Floods in the tributaries in 1986 and 1990 generated sediment loads which were deposited in the mainstream and became permanent in the absence of sufficient mainstream flow to destabilise them. Vegetation has further stabilised these features. Bench development is shown at three of the sites since dam closure, the most extensive one occurring at site five, where an armoured gravel bar formed the nucleus for the deposition of finer sediment, which regulated flows did not have the capacity to move. The bench is 0.3m high and 12m wide and has been invaded by a dense stand of *Casuarina.* This is a means of channel contraction which allows the channel to adjust to post dam flows. According to Erksine and Benn, the response here is from a flood dominated to a drought dominated regime and is identical to that proposed by Erskine and Warner (1988) in response a rainfall regime change. The regulated system is comparable to a natural regime change.