Natural Stream Landscaping Techniques: A Review, and an Application on Edwards Creek

By

© Gordon Thomas Smith

A Practicum Submitted in Partial Fulfillment

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ABSTRACT

Conventional techniques of channelization, while usually successful in performing the tasks for which they were designed, often have a number of detrimental effects. This study examines natural stream landscapes, natural watercourse forms and methods of bioengineering for strategies and design techniques that will maximize the beneficial aspects of channelization projects and ensure the stability of the channel, while introducing significant biological activity into the watercourse and its riparian zone. Methods of natural stream landscaping, thus determined, are applied to Edwards Creek, a watercourse in Manitoba Canada. General recommendations are given for the entire watershed and more detailed designs have been developed for two portions of the creek experiencing severe erosion.

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1 INTRODUCTION

Waterways have traditionally been viewed as resources for exploitation: as water conduits for irrigation an dland drainage, as a means of transportation, as sources of energy and as waste removal systems. Channelization projects have been used to improve the waterways function in these capacities to control flooding, improve drainage, increase the amount of tillable land in a given area and alter channel alignments. Traditionally, little concern has been expressed over the potential detrimental effects of channelization, allowing most of the physical, biological and visual characteristics that made the waterways viable and ecologically important parts of the landscape to be virtually eliminated (McLachlan, 1986). However, more recently, channelization projects have become controversial because of their environmentally disruptive characteristics (Keller, 1975). Increased erosion, sedimentation and other detrimental effects have resulted in increased maintenance costs and losses of fish and wildlife habitat, aesthetic quality and recreation potential.

The costs of conservation measures are usually very obvious and easily quantified and therefore, not often overlooked. Unfortunately, the benefits of such measures are not as easily identified and quantified, especially when they merely preserve the existing qualities of the landscape and its wildlife. However, in purely economic terms, a case may be made for developing a strategy to reduce the environmental costs of channelization.

In 1982, the PFRA estimated the direct costs of erosion on the Canadian prairies to be $368 million or $5.00 per acre ($12.31 per hectare) of land under cultivation. Channelization is responsible for a part of these costs and it also contributes indirectly to other costs. Straightening a waterway, while moving floodwaters faster and making field cultivation easier, is one of the most geomorphologically and ecologically disruptive types of channelization (Chapman, 1987b). The increased gradient of the channelized reach causes higher water velocities, which in turn leads to increased erosion and consequently increased sedimentation. Channel instability develops rapidly and

maintenance requirements are increased. Bridge support structures may be undermined by erosion and require protection or even replacement. Fields and riparian areas may be damaged as the waterway attempts to achieve a more natural alignment. The consequences of channelization may also reach far beyond the reconstructed reach. Sedimentation is an unavoidable result of erosion and reduces the downstream capacity of the channel, increasing the risk of flooding (Mackling, 1987). Suspended sediments add to the volumes of flood flows, also increasing the risk of flooding downstream. Deposited sediments may damage fields and structures such as bridges and roads. While the destruction of wildlife habitat in the waterway and surrounding riparian area is an obvious result in the modified reach, detrimental effects of channelization may also become apparent downstream. Suspended sediments may lead to diminished water quality and increased lake eutrophication. Excessive sedimentation may disrupt fish habitat by filling parts of the waterway and smothering fish spawning grounds. Increased channel erosion has been linked to the rapid siltation of Dauphin Lake in Manitoba, which has resulted in the decline of commercial fishing in the area since 1950 (Manitoba Water Commission, 1984). Thus, in purely economic terms, the direct costs and indirect results of channelization can be seen to impose a substantial loss on individuals, the public, the government and society in general.

The realization that losses of this type and magnitude are involved is making the importance of conservation increasingly apparent to all people. This study seeks to develop strategies and design techniques that will reduce the detrimental effects associated with conventional means of channelization, while maximizing the benefits of such works. Since channelization is disruptive to the natural systems at work in a waterway, natural waterways, the way in which they function and the forms that they create, are examined in order to develop a systematic approach to the design of channelization projects.

Any waterway is a system, composed of two basic components, both of which are strongly interrelated and play major roles in its functioning. One part, the 'watercourse', is composed of the water channel and its immediate riparian zone in the floodplain. The

other part, the 'watershed' is all the land surrounding the watercourse that contributes water, both overland and underground, to the channel. This study, while focusing on in-channel and riparian works, also recognizes the necessity of land based conservation techniques to ensure the success of the in-channel works. A series of design and maintenance criteria are developed and are applied on Edwards Creek, a watershed in Manitoba that is experiencing severe problems as a result of channelization.

2 CHANNELIZATION

2.1 DEFINITION

Rivers and streams provide water for irrigation, are a means of transportation and can act as a source of energy. River engineering is used to improve opportunities for these activities, as well as to protect settlements and agricultural land from flooding. Channelization is just one type of river engineering and is used primarily to control flooding, to drain wetlands and in some cases, to improve navigation.

Keller (1980) lists four common techniques that may be considered under the heading of channelization:

1) widening, deepening, straightening are the methods most often employed. Trees and other riparian vegetation are removed and streambed, bank and channel location are changed.
2) clearing and snagging involve the removal of trash, brush, logs, stumps and other obstructions to flow. Dredging of stream bed deposits such as sand, gravel and shale, that obstruct the flow of the watercourse is included in this method. Streambank vegetation such as trees and shrubs do not need to be removed but often are.
3) dyking is used primarily for flood control. It involves the increasing the height and size of one or both of the banks of the watercourse. The objective is to protect surrounding areas from flooding or to have the watercourse carry more water

before overtopping its banks. Earth fill is trucked in or dredged from the stream channel and compacted in place, to create the dykes.

4) bank stabilization usually involves sloping the banks by pulling back the top and building up the toe, implacement of stones (riprap) or the planting of vegetation on the banks to control erosion. This method is most often used in conjunction with the other techniques discussed above.

Channelization may also be known as channel or drainage improvement, channel modification or works and more recently construction known as channel restoration or rehabilitation is being undertaken on streams that have been disrupted by previous channelization works, catastrophic events or unwise landuse (Keller, 1980).

2.2 GLOBAL HISTORY

The history of river engineering is almost as old as the practice of agriculture (Binder et al, 1983). Ancient practices include canals and ditches for the transportation of water into cities and to carry sewage away from the cities, as well as diversions for agricultural irrigation (Keller, 1980). In North America, river channelization began approximately 150 years ago (Keller, 1980). As people settled the land, the first practices were to clear the land and modify drainage patterns. Land drainage was considered necessary to make valuable farmland useful. Channelization works were also undertaken in order to increase farmland area by draining wetlands and providing flood control (Keller, 1980).

These early projects were built with horse drawn slip scrapers, men with shovels and ditching plows. Unfortunately, much of this early work was poorly designed and executed (Keller, 1980). Lack of proper funding was also a problem (Keller, 1980). As a result, much of the early channel work was local in nature and while it controlled flooding in specific areas, it did not consider broader environmental issues (Keller, 1980). In the United States, the fragmented nature of drainage projects of the 19th century became more coordinated in the 20th century when unified river basin and watershed

management planning and development schemes were established through agencies such as the Soil Conservation Service and the Army Corps of Engineers (Keller, 1980).

Changes in engineering techniques have also resulted in significant changes in the design of drains and their efficiency. One innovation introduced in the mid 1950's, the bulldozer, led to the construction of wide ditches with gently sloping sides that were easy to maintain with large machinery (Warkentin, 1967).

Also, in the 1950's and 1960's, a growing environmental awareness led to the institution of various laws and policies regarding channelization projects (Keller, 1980). Major works required environmental impact studies explaining the potential impacts on fish and wildlife, vegetation and other biota and decisions regarding construction, were to be partially based on these data (Keller, 1980).

In general, the historical trend in channelization has been from small fragmented efforts by farmers to better planned and engineered projects, looking at the potential environmental impacts on the entire river basin and coordinated by government agencies (Keller, 1980). Although this is a positive trend, streams are often still being modified by city, provincial or federal agencies without coordinated environmental consideration and engineering design (Keller, 1980). Unfortunately, these agencies also often do not realize that drains had to be and still have to be constantly maintained in order to prevent flooding as the drains deteriorates (Keller, 1980).

2.3 PROBLEMS WITH CONVENTIONAL TECHNIQUES

The form of a natural alluvial watercourse evolves over time as a result of natural systems. It is a representation of dynamic equilibrium between erosion, sediment transport and deposition and is dependent on hydrology and sedimentology (Chapman, 1987a). The forms created are well known to humans and have been generalized in empirical calculations that relate channel form to hydrologic and geomorphologic processes,

describing the interrelationships between various components of the channel form (Dunne and Leopold, 1978).

Channelization projects, usually undertaken to improve drainage or to reduce flooding and based solely on economic factors, do not often take these forms into account. Unfortunately, channelization, when the design is based on inadequate data, can be terribly destructive (Brookes, 1987). Many studies have shown that conventional channelization techniques can disrupt the natural systems governing the form of water-courses (Binder et al, 1983; Chapman, 1987a; Chapman, 1987b; Emerson, 1971; Glitz, 1983; Keller, 1975; Keller, 1978; Keller, 1980; Rasid et al; 1985). While channelization is generally economically beneficial, it can disrupt the ecological systems necessary for fisheries, destroy the riparian habitat for wildlife and diminish natural, visual and other aesthetic features (Binder et al, 1983; Bolliger et al; 1984; Brooker, 1985; Chapman, 1987a; Chapman, 1987b; Keller, 1975; Newbury and Gaboury, 1988).

2.3.1 DAMAGE TO THE CHANNEL AND FLOODPLAIN

When the dynamic equilibrium of a watercourse is disturbed by channelization works such as straightening, deepening or widening, the form of the new channel is readjusted as sediment is redistributed. Dunne and Leopold (1978) cite the example of the Pequest River in New Jersey, which was channelized in the 1950's to eliminate overland flow into the flat, fertile land surrounding the river. The original channel was estimated to have a discharge of approximately 550 cubic feet per second (16 cubic metres per second), a mean width of 44 feet (13 metres), a bankfull depth of 3.3 feet (1

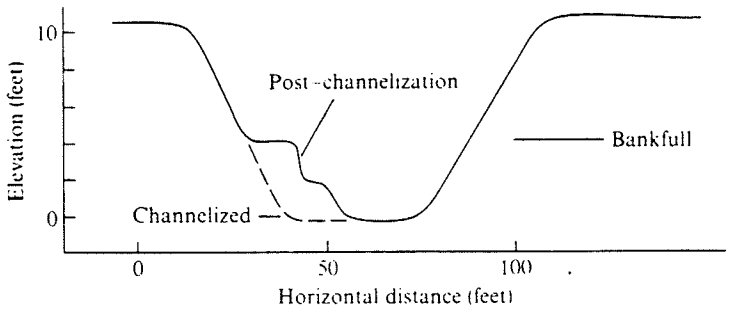


Figure 1 Cross-section of the Pequest River, New Jersey.

metre) and a cross-sectional area of 140 square feet (13 square metres). A new channel was dredged with a cross-section 10.5 feet (3.2 metres deep), a top width of 90 feet (27 metres) and a bottom width of 36 feet (11 metres) (see figure 1). In 1969, the channel was

	EXPECTED IN NATURAL CHANNEL	DREDGED CHANNEL AT 4-FT DEPTH	CHANNEL AFTER SELF-ADJUSTMENT
Bankfull discharge (cfs)	550		550
Top width (ft)	44	60	35
Mean depth (ft)	3.4	4.0	4.0
Cross-sectional area (ft^2)	140	240	140

Figure 2 Comparison of dimensions of Pequest River, before and after dredging.

re-measured. Deposition on the left side of the channel had created a berm that rose 4 feet (1.2 metres) above the bed of the channel. The new cross-section was considerably smaller than the one dredged and it dimensions were very closely related to those of the original, natural channel (see figure 2). It can be stated that, generally, a channelized reach will attempt to alter its cross-section towards a form and size in keeping with the discharge experienced in the reach. The dimensions that the channelized reach will eventually develop, unless human intervention such as dredging or channel stabilization measures takes place, are approximately equal to those of the original, natural channel or of an unaltered stream, flowing through similar conditions, with approximately the same size drainage basin. If the designer does not acknowledge this fact in the design stage and does not take appropriate action taken at that point, serious problems can occur.

Therefore, one cost or disadvantage of poorly designed channel modification is channel instability, resulting from channel readjustment to the newly imposed conditions (Dunne and Leopold, 1978). In a natural stream, channel width and depth are adjusted to the flow regime related to bankfull discharge and its recurrence interval. Any disruption of this equilibrium may lead to bed and bank erosion, increased concentration of suspended materials in the water column and sedimentation (Brookes, 1987).

An unaltered watercourse follows natural topography. It is not straight, but is often

curved, with an asymmetrical cross-section. Fast flowing water erodes the outer bank causing it to become steeper, while slow moving water deposits material on the inside curve producing a flatter bank (Brookes, 1987). This system of erosion and deposition leads to the creation of narrower and wider sections of the watercourse with a variety of different currents, as well as a regular spaced series of deep pools and shallow riffles.

In contrast to a natural watercourse, a channelization project is often straight and has a symmetrical cross-section with the same width, depth and an invariable current. It typically has a uniform gradient and no high water line. These unnatural conditions lead to environmental degradation, including such problems as a loss or disruption of aquatic life, erosion, siltation and change in channel pattern causing property damage (Keller, 1975). The deepening, widening or straightening of a channel may cause considerable erosion and has, in some cases, led to an increase in channel width of 2 to 3 times the original constructed dimension (Chapman, 1987a). Downcutting of the channel, as a result of erosion, leads to bank slumping and the undermining of structures such as bridges (Chapman, 1987a).

Straightening of the channel and the consequent change in channel gradient, is the type of channelization most likely to cause continuing problems (Dunne and Leopold, 1978). By reducing the horizontal distance that the watercourse travels, artificial straightening increases the slope of the channel leading to higher water velocities which in turn cause increased erosion of the stream bed and banks, and higher sediment concentrations. These processes continue until a new equilibrium is established between sediment concentration in the water and work done to erode transport and deposit material (Keller, 1980).

Also likely to cause ongoing channel stabilization problems, but not as often encountered, is a radical change in drainage area caused by the diversion of water from one watercourse into another (Dunne and Leopold, 1978). Actions of this sort lead to more water travelling through the lower channel, causing instability as the channel adjusts to the new flow conditions. Projects of this type can result in long term instability and it may take years

for equilibrium to become re-established (Dunne and Leopold, 1978).

In a natural watercourse, curves and the different velocities in pools and riffles cause sorting of the bed material, producing a number of habitats suitable for a variety of micro-organisms. Although incipient pools and riffles often form shortly after channelization, the amount of time necessary for them to become morphologically stable is not known (Keller, 1980). In fact, if a stream is severely disturbed or periodically re-modified, morphologically stable pools and riffles may never form (Keller, 1980).

The removal of bank side vegetation, often associated with channelization projects, is also a problem. It results in decreased soil stability, which often leads to increased sediment loads in watercourses (Keller, 1975).

2.3.2 DAMAGE TO FISH AND WILDLIFE

Although natural watercourses experience disturbances at points along their length every year due to flooding and natural bank failure, channelization does this along extensive lengths of the channel (Keller, 1980). The extension of the drainage network and channelization can significantly reduce fisheries and can damage biologically important habitats in the stream channel and downstream lakes (Newbury and Gaboury, 1988). Any activity that removes vegetation, disturbs the stream bed, increases sediment transport and deposition or changes flow characteristics will affect fish and wildlife (Chapman, 1987b; Keller, 1980). In fact, biological activity in and along some watercourses has been so severely reduced by channelization that some fish and wildlife management experts consider the practice to be completely antithetical to the production of fish and other forms of life (Keller, 1980). The important factors in the deterioration of fish and micro-organism stocks are loss of channel area, elimination of pool and riffle sequences, decreased habitat diversity and an unstable environment resulting from fluctuating water levels, shifting substrate and greater fluctuations in water temperature (Brooker, 1985; Newbury and Gaboury, 1988).

Straightening of meanders and uniform grading of the bed cause a general degradation of riverine and riparian habitat (Brooker, 1985). Qualitatively, these actions reduce the variety of channel bed forms and flow configurations, leading to a loss of habitat diversity (Newbury and Gaboury, 1988). Quantitatively, losses of habitat can also be substantial. Chapman (1987b) cites examples of portions of streams that have lost up to 87.5% of their length through straightening. This loss of length equals a direct loss in amount of habitat.

Loss of habitat can also occur due to increased flow carrying capacity, which usually leads to higher velocities.Many aquatic creatures have specific requirements for velocity and cannot survive under other conditions (Brooker, 1985).

Channelization often turns a meandering stream, with a series of long pools separated by short riffles, into a straight stream with a simple trapezoidal cross-section, few pools and many long riffles (Keller, 1980). Natural sorting of the bed does not take place, riparian vegetation is destroyed and at high flows the water velocity is greater than fish and other in-stream organisms can tolerate without cover (Keller, 1980). Because stormwater leaves the watershed quickly, the base flow, which is dependent on groundwater discharge, is reduced and the water flowing in the channel during non-flood events is reduced to only a few inches deep across the wider channelized section (Keller, 1980). Removal of bankside vegetation, for access of machinery or to reduce frictional effects and the possibility of snagging and damming, reduces in-stream cover for fish and micro-organisms as well as bankside habitat for a variety of land-based animals (Brooker, 1985).

The removal of bankside vegetation also eliminates shade protection for the watercourse which along with reduced water depth causes water temperature to rise (Brooker, 1985). Since fish and other water-based animals have only a limited tolerance of temperature fluctuations, the higher temperature may also significantly reduce habitat availability. Improved drainage efficiency increases spring runoff peaks, while reducing the duration of the flow, thus shortening the time available for fish spawning and egg incubation in

streams to below critical levels in normal and dry years (Newbury and Gaboury, 1988). Disturbance of the bed may affect bottom dwelling organisms which form the basis of the food web in the watercourse. Excessive suspended sediment loads caused by unstable channel conditions can also cause a reduction in fish populations (Brookes, 1987).

However, the most significant in -stream problem associated with channelization is the loss of the sequence of pools and riffles. This loss leads to a reduction in the variety of flow conditions suitable for fish and other organisms as well as a lack of shelter during high flows (Brookes, 1987). Alterations of the width and depth of the channel create shallow and unnatural flows that are not suitable for fish habitat and can create actual topographical barriers to fish migration (Brookes, 1987). Diverse hydraulic conditions created by meandering channels, pools and riffles and habitat conditions affected by overhanging branches, shading from near or in-stream vegetation are required, for example, by some species of fish for spawning, rearing and feeding.

In the British Isles, studies of the effects of channelization on macro-invertebrates indicate that after the initial destruction that recovery takes place, but that the recovery is not complete. Generally the sites with the greatest variety and number of habitats supported the greatest number and variety of macro-invertebrates (Brooker, 1985). For example, in Wales, a variety of habitats at ten sites along a watercourse were sampled, prior to engineering works and eighty different species were found. The next year, after channelization had taken place, the same areas were sampled. Only found only 50 species were found and several of the habitats found prior to the channelization no longer existed (Brooker, 1985). Many of the missing species were typical of the slower moving or vegetated reaches of the river (Brooker, 1985).

With regards to the effects of channelization on fish populations, reports from the British Isles are ambiguous, stating that channelization can affect fish populations through either a direct loss in numbers, a population redistribution or not at all (Brooker, 1985). However, a problem with most of these studies is that only similar habitats were sampled.

The fact that the total amount of habitat had been reduced was not considered, meaning that a drop in the overall fish population could have occurred and not been investigated (Brooker, 1985).

Most studies on the effects of channelization on fish populations have taken place in the United States. These studies generally show that channelization has a deleterious effect on fish populations. Keller (1980) states that reductions in fish populations are directly related to the intensity of channelization. He cites Graham (1975) who studied the Ruby River in Montana. The river in its natural state supported 130 lbs. (60 kg.) of trout per 1,000 feet (300 metres). After bank stabilization, the placement of riprap, it supported only 65 lbs. (30 kg.) per 1,000 feet (300 metres). Furthermore, after the river bed was reshaped with a bulldozer, the river supported only 55 lbs. (25 kg.) of trout per 1,000 feet (300 metres).

Chapman (1987b) cites a large amount of literature to illustrate the detrimental effects of channelization on fish populations. Some channelized reaches of watercourses in Missouri supported only 13 species of fish while 21 species were found in unchannelized sections. Other studies cited by Chapman (1987b) found that the numbers and biomass of fish were reduced by 80 to 100% after channelization. Some channelized reaches supported only smaller species of fish and had reduced fish density and biomass (Brooker, 1985). Recovery of fish populations can be very slow in some watercourses with no significant recovery after 30 or 40 years (Brooker, 1985).

Changes to watercourse conditions as a result of channelization affect not only the fish themselves, but also their eggs. When the natural stream bed gradient is increased, causing higher flow velocities, large numbers of fish eggs tend to be swept downstream from uniformly constructed reaches during peak spring flows (Newbury and Gaboury, 1988). Also, increased sedimentation suffocates fish eggs diminishing their survival rate (Newbury and Gaboury, 1988). In the Riding Mountain area of Manitoba, channel erosion has increased the turbidity and sedimentation rates in watersheds draining into Dauphin Lake significantly contributing directly to the collapse of the commercial

fishing industry on the lake (Newbury and Gaboury, 1988; Manitoba Water Commission, 1984; Penner and Oshoway, 1982).

While there are very few reports on the effects of channelization on bankside vegetation, it is possible to state that major destruction of vegetative cover occurs (Brooker, 1985). In Britain, the Royal Society for the Protection of Birds concluded, from a number of studies, that channelization projects have a catastrophic effect on the breeding and wintering of wetland birds, partly in relation to water status of the catchment area and partly as a result of consequent land use changes (Brooker, 1985). Channelization alters mammalian habitat conditions as well. A study of the White River in Vermont determined that the channelized reaches of the river supported only 1/3 of the total number of animals as natural river reaches.

2.3.3 UPSTREAM AND DOWNSTREAM EFFECTS

The morphology of a natural stream is a physical representation of a dynamic equilibrium between sediment entrainment, transportation and deposition and is dependent on controls of hydrology and sedimentology (Chapman, 1987a). When this balance is disturbed by human manipulation, when the channel is widened, deepened or straightened, the channel must readjust its form as sediment is redistributed in an attempt to regain equilibrium (Chapman, 1987a). Local changes in the channel may become manifest downstream of the engineering scheme, causing increased bank erosion, bed degradation and aggradation, broadening the area of ecological disturbance (Brookes, 1987; Dunne and Leopold, 1978).

Straightening a natural channel, by increasing the channel slope, causes the water flowing through the locally steeper reach to have more power per unit of channel area, increasing the water's capacity for sediment entrainment and transportation (Chapman, 1987a). The straightened channel erodes, the sediment load is transported to the downstream portion of the stream where the flatter natural reach cannot transport the sediment and aggrada-

tion occurs (Brookes, 1987). The sediment is deposited wherever water velocities are reduced: on the inside of curves, where the channel widens or where the water enters a lake. Excessive sediment and bed loads in the water, along with increased sedimentation, can have a detrimental effect not only on water quality but also on land quality. Sedimentation by reducing the capacity of downstream reaches of the watercourse may lead to increased flooding (Chapman, 1987b; Mackling, 1987), agricultural land becoming covered with gravel, shale and other materials that have a negative effect on land quality (Mackling, 1987) and the mouth of the watercourse and the nearby beaches of the lake it enters may become fouled with silt (PFRA, 1960). The water quality of downstream lakes may also be disrupted through the addition of large amounts of fine sediments and silts (Robert Newbury, personal communication, October 29,1987; Manitoba Water Commission, 1984; Water Resources Branch, 1982). This process can be especially pernicious if the upstream channelization work experiences rapid erosion (Chapman, 1987b).

The problem is exacerbated by the ability of the channelized reach to move water more efficiently in its enlarged channel. When the water is discharged into the downstream natural channel which has less capacity, flooding is more likely to occur (Chapman, 1987b). Flooding may also be increased if the effect of channel modification is to move the stormwater downstream in such a way that the flood peaks of different tributaries coincide (Keller, 1980). However, if the effect of channelization is to move the flood peak from one tributary out of the basin before the arrival of peaks from other tributaries flooding may be reduced (Keller, 1980)

Alterations of the channel may cause problems upstream as well. The lowering the stream bed elevation by dredging or occasionally, the lowering of the stream base level during the installation and maintenance of culverts may lead to channel erosion and headcutting upstream of the site of the alteration (Chapman, 1987b). Since the stream is able to transport more sediment, it obtains material from the upstream bed of the channel, creating a knickpoint in the longitudinal profile that continues to move upstream until a new equilibrium is reached (Chapman, 1987a; Brookes, 1987). A knickpoint is a sudden

drop, a scarp or small waterfall, where the stream is adjusting its gradient from the old bed elevation to a new lower one created by the lower base level downstream. However, in some cases, a culvert, rather than being a problem, may provide a stable base level elevation preventing headcutting from proceeding upstream (Chapman, 1987b).

2.3.4 AESTHETIC DEGRADATION

Landscape amenities are often concentrated in areas where water is present, along rivers or at least in valley floors created and maintained by channel systems (Dunne and Leopold, 1978). These landscapes provide aesthetic and scenic value through the provision of a diversity of sensual stimuli and physical contrasts (Keller, 1980). Visual and other sensual experiences are associated with contrasts: slow, shaded water versus fast, sunlit water, deep, slow water in pools versus fast, shallow, bubbling water in riffles and deep green reeds and rushes near the stream versus the light green or brown leaves of trees and bushes along the banks (Keller, 1980). Physical or biological characteristics such as the presence or absence of human activity, the existence of marshes, the natural curvature of the stream (meanders) and the presence of unique topography such as waterfalls, rugged rock outcrops and scenic vistas also affect the aesthetic value of the watercourse (Keller, 1980).

Unfortunately, channelization by straightening a channel, removing vegetation and obstructions to flow and using unnatural bank stabilization structures decreases the aesthetic quality of a stream (Keller, 1980). Aesthetic degradation takes place through the change in stream biota and the visual alteration of riparian vegetation, of stream banks and channel morphology (Dunne and Leopold, 1978). Because of the required stormwater capacity, the cross-section of the channel appears oversized and unnatural (Bolliger et al, 1984). Continuous bank protection on both sides of the stream form a barrier between land and water and can be detrimental to the quality of the stream (Bolliger et al, 1984). If trees are found only on the top of the embankment and have no direct contact with the water, their main function becomes that of landscape backdrop rather than being

an integral part of the ecology of the stream and the riparian landscape (Bolliger et al, 1984).

Unfortunately, too many engineering plans for development have concentrated on structural or layout aspects of the design with little attention given to the visual, ecologic or hydrologic harmony of the result (Dunne and Leopold, 1978). Many aspects of a stream or channel that may be classified as amenities are more subjective and less clearly of economic value than the engineering or construction aspects of the development works (Dunne and Leopold, 1978). But, there are values to society gained from the maintenance of beauty and from the knowledge that ecosystems continue to operate without degradation (Dunne and Leopold, 1978). People are sufficiently concerned about the non-monetary values of the environment that they are willing to forgo some opportunities for gain or are even willing to pay directly for the maintenance of the amenities of the landscape (Dunne and Leopold, 1978). Finally it is important to realize the value of these items is to society or the general public and that undue economic stress should not be placed on certain segments of the population, especially farmers, who as a group, are already financially strapped.

However, channelization, where it is not necessary or where less expensive, more ecologically sound alternatives can be used just as effectively, also costs money. Thus, projects should be carefully analyzed to ensure that they are absolutely necessary and thoughtfully designed to ensure that all alternatives are fully explored, ensuring that environmental and aesthetic costs are completely taken into account and are minimized.

3 NATURAL STREAM LANDSCAPING

3.1 APPRECIATION OF NATURAL CHARACTERISTICS OF FLUVIAL SYSTEMS REQUIRED

Up to the 1950's, economics and engineering feasibility were the deciding factors in the

alteration of watercourses (Binder et al, 1983). "In a landscape dedicated solely to production and specially prepared to meet the requirements of industrialized agriculture, rivers and streams were only seen as serving the function of drainage channels for excess rainfall and soil water, and as a medium for the dilution of liquid waste products of all kinds" (Binder et al, 1983).

More recently there has been a recognition of the significance of rivers and streams as part of the landscape, as part of an interrelated network of innumerable biotic and abiotic factors (Binder et al, 1983). Streams and rivers are important elements not only in the appearance of the landscape but are also crucial to its environmental resources (Bolliger et al, 1984). The significance of rivers and streams has been highlighted by the alarming losses of plant and animal species as well as whole ecosystems, pointing towards damage of a complex nature (Binder et al, 1983).

Today, in agricultural landscapes, watercourses often represent the last refuges for the formerly rich variety of flora and fauna of the previously stable habitat (Binder et al, 1983). The rivers and streams form a network covering wide stretches of countryside and are the ecological background of our cultural landscape (Binder et al, 1983). On this basis, the call for natural solutions to river engineering problems has become an ever-present one (Binder et al, 1983).

Channelization has become a controversial practice, because in too many instances it has caused environmental disruption that is unacceptable to many people (Keller, 1975; Keller, 1980). Until techniques are developed to minimize the negative impacts, objections will continue to be voiced (Keller, 1980). Much research is required before all detrimental effects can be minimized, but sufficient information is presently available to be able to design projects that are likely to do less environmental damage than the conventional methods now in use (Keller, 1975).

Channelization is not always bad and is not intended to damage the landscape nor to cause

environmental problems. Problems result from inadequate consideration being given to the possible adverse effects of channel modification (Keller, 1975).

Unfortunately, little attention has been given to the natural, physical processes which operate in river and stream channels. It is important to have a broader perspective of the function of time, and an understanding the regional setting, especially potential down-stream consequences and how to use fluvial processes to minimize the impact of river engineering (Brookes, 1987). Where hydraulic constructions are unavoidable, channelization methods that are floodproof yet create conditions which allow for the channelized stream to re-develop as a natural stream with a character of its own, can be found with collaboration of hydraulic engineers, geomorphologists, landscape architects and biologists (Bolliger et al, 1984).

The most important realization is that the form of the watercourse is determined by the interplay of fluvial forces and the landscape. Processes are creating forms as they are for a reason. Therefore, when humans interfere with these processes for any reason, an understanding of the consequences of their actions and how to best minimize the negative impacts must be included. On its own an alluvial river produces its form in response to geomorphological conditions and to water and sediment availability (Chapman, 1987b). Generally the form is in equilibrium and the stream channel adjusts its channel configuration only when hydrological and geomorphological conditions change (Dunne and Leopold, 1978). This information indicates that an improperly designed channel will not remain morphologically stable and also provides a basis for the design of new drainage systems (Dunne and Leopold, 1978). If a drainage system is constructed to dimensions other than those it would take naturally, material in the bed and banks will be redistributed to produce a more natural hydraulic geometry configuration (Dunne and Leopold, 1978).

3.2 DEFINITION OF NATURAL STREAM LANDSCAPING

Alterations of the landscape or parts of it can be as regarded as natural when they are

carried out with regard to the natural habitat conditions and the endemic flora and fauna (Binder et al, 1983). In the case of river engineering this involves above all an understanding of the natural hydraulic and morphological conditions (Binder at al, 1983; Brookes, 1987). "Non-natural alterations are those in which existing natural conditions are not or are insufficiently taken into account. In the case of river engineering this occurs where only technical, mathematically simple solutions are sought" (Binder et al, 1983).

As the pressure to modify streams increases, new design criteria, taking into account data on the fluvial processes of natural streams and multi-objective planning, must be developed in order to reduce environmental degradation (Keller, 1980). Designing with nature has become a fundamental principle of land-use planning and should be extended to the design of stream channels (Keller, 1980). One should use natural processes to an advantage rather than fight against them (Binder et al, 1983). The concept is to work with the watercourse rather than against it, emulating nature where possible in order to minimize aesthetic, biological and geomorphological degradation.

The importance of minimizing the negative impacts of channelization on biological systems is widely recognized. But while there is a great deal of information available on techniques to increase the biological productivity of modified channels, there is, unfortunately, little information available on techniques to reduce physical and aesthetic degradation (Keller, 1980).

Fortunately, a new and less harsh concept of channelization has been evolving recently. Brookes (1987) cites a number of studies showing that less straightening is taking place and re-sectioning based on the emulation of natural forms and the processes of meandering channels is being undertaken. The design of new channels is reflecting natural forms rather than trying to impose the artificial boundaries so often found in straight symmetrical ditches.

Several aspects of natural fluvial systems that may eventually be used to reduce

environmental degradation in channel works are (Keller, 1980):

1) recognition that the entire riverine environment, the channel and the floodplain are an open system tending to dynamic equilibrium where there is a rough balance between the load imposed and the work done, such that channel form and fluvial processes are interdependent,
2) recognition that the flow in natural watercourses, which alternates between convergence and divergence, facilitates morphological stability, the development of pools and riffles and channel maintenance,
3) recognition of geomorphological thresholds that influence erosion, deposition and channel patterns and,
4) recognition of the relationship between erosion, deposition and sediment concentration, that influences channel stability.

Holding all these environmental considerations together is the concept that the best channelization project is one that is absolutely necessary, involves the minimal modification of the natural channel (Keller, 1980) and recognizes that the watercourse is an open system interconnected with other systems, such as lakes, land and vegetation, found upstream and downstream of the reach slated for modification. In order to obtain effective and economic methods of protecting, restoring and improving our environment, the integration of scientific and technical research with the use of natural materials is required (Schiechtl, 1982).

In short, a concise definition of "natural stream rehabilitation" would be the design of channels based on the forms of natural streams, including consideration of factors such as their geometries, geomorphologies and hydraulic conditions. Natural stream rehabilitation is not an attempt to replicate a natural stream exactly, but involves an examination of natural processes, the way energy is channelled through streams in order to create situations where that energy is channeled and dissipated in a similar manner. Natural stream rehabilitation is based on the realization that a change in channel pattern is an adjustment in response to a change in energy dynamics and that a change at one point affects the entire system.

3.3 CHARACTERISTICS OF NATURAL STREAM LANDSCAPING

3.3.1 CHANNEL PLAN

The natural plan of a watercourse has developed over a long period of time in response to everpresent forces in the water working in an interdependent cycle with the geology, topography, soils, macro- and micro-climate and the vegetation of the bed, banks, floodplain and watershed. The plan of a re-developed channel should respect these forces and the channel plan that has developed naturally. Since straight channel reaches of any length are rarely found in nature, a general conclusion might be that new channel plans include or preserve meanders, and oxbows (Binder et al, 1983).

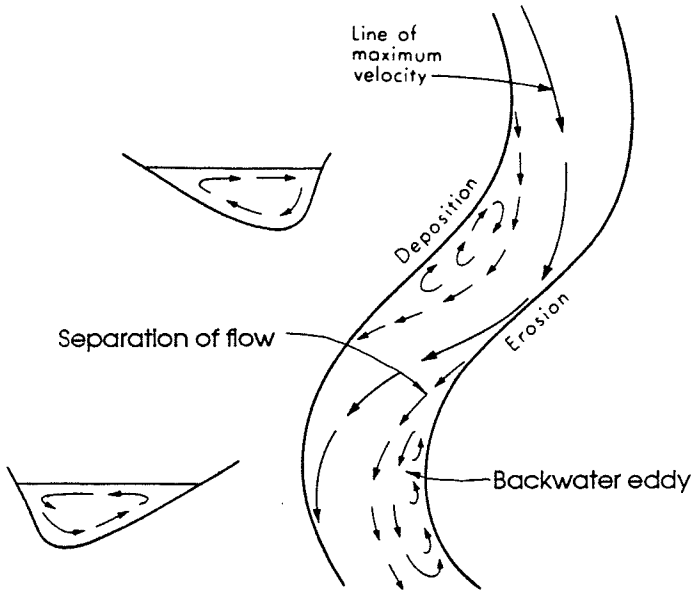


Figure 3 Meandering reach showing the line of maximum velocity and separation of flow which produce areas of deposition and erosion. Cross-sections show the lateral movement of water at the bends.

Curves lead to the development of an asymmetrical cross-section where fast flowing water tends to erode the outside of the curve forming a steep bank (Bolliger et al, 1983). As the water moves in a winding pattern it develops centrifugal force and piles up on the outside of the bend, intensifying helical flow in this area, creating a strong downward movement of water on the outside of the curve causing the erosion (Moriwasa, 1968; see figure 3). On the inside of the curve, slower moving water deposits material creating a flat bank (Bolliger et al, 1983). On the surface, a separation of flow occurs at the inner edge of the bend (Moriwasa, 1968). At this point, as a consequence of the deceleration of the

flow, a backwater eddy forms, leading to the deposition of material in this area.

For the sake of channel stability, if the channel is to be shortened, the integrity of the original slope of the channel should be maintained, through the incorporation of a series of small drop structures.

The slope, curves, meanders, and oxbows of the channel have a direct impact on riverine and riparian conditions and provide a variety of habitat necessary for a rich ecological system to develop. Therefore, alterations to the channel plan should be minimized and if undertaken, should respond to the natural forms that the original undisturbed channel developed.

3.3.2 DIFFERENTIATION OF THE WATERCOURSE INTO A VARIETY OF CONDITIONS

A watercourse should only be channelized where it is absolutely necessary and no practical alternatives exist. Diversity of conditions should be preserved, where existing or newly created, where no longer found (Binder et al, 1983). This diversity provides the necessary habitat conditions for varied flora and fauna and creates a biologically intact watercourse (Binder et al, 1983).

In a natural meandering, gravel bed watercourse, the channel cross-section alternates from asymmetric pools to symmetric riffles, in which regular changes in the slope of the channel create, at bankfull stage, a convergence of flows in pools and a divergence of flows on riffles (Keller, 1978). Convergence and divergence of flows refers to the natural three dimensional constriction or expansion of flow along along a single channel (Keller, 1980). Scour is a result of convergent flow and at bankfull flows creates pools, while deposition is a result of divergent flow and at bankfull flows, is characteristic of point bars

and riffles (see figure 4). At base flow stage, pools and riffles turn into relics and flow conditions are the opposite of those at high flows (Keller, 1980). At base flow stage, pools are associated with deep, slow moving, divergent flows, while riffles are associated with fast shallow, water or convergent flows (Keller, 1980). For physical, biological and aesthetic reasons, it is desirable to design channelization projects to converge and diverge the flows in a similar manner (Keller, 1978).

Channel form and process evolve in harmony and the manipulation of the channel cross-section morphology can influence desired channel processes. Keller (1978) planned the manipulation of a stream in an experiment to see if it could be induced to develop as desired. The experiment was a success and morphological stability, consisting of point bars, pools and riffles was maintained over a period of high magnitude floods.

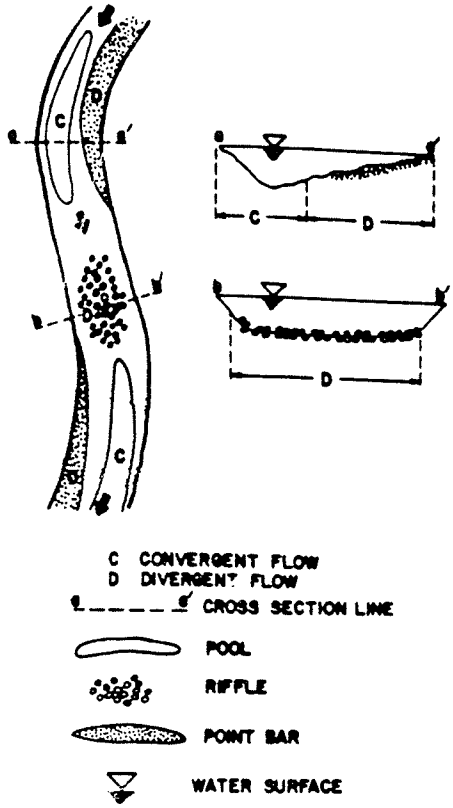


Figure 4 Idealized diagram showing the convergence and divergence of flow.

The variety of channel forms creates conditions that are required for in-stream biological activity. During base flow conditions, a range of flows from slow, deep water to fast, shallow water are necessary for breeding, feeding and cover (Keller, 1980). During periods of high flows, a variety of conditions, including shelter areas for protection from excessive velocities, are required (Keller, 1980). One result of this variety of flow conditions is the natural sorting of bed material, which leads to the development of riffles and point bars, creating a variety of habitats for bottom dwelling organisms upon which fish and other animals feed (Keller, 1980). Turbulence, through the riffles and along the edges of the point bars, allows for oxygen to be mixed into the water, ensuring that this necessary gas is present in sufficient quantities to allow the survival of a variety of organisms.

Curves, irregular cross-sections and variable gradients, create different currents and deep and shallow areas as well as wider and narrower sections in the watercourse (Bolliger et al, 1983). Consequently, flow conditions vary and rolling material is correspondingly sorted according to grain size creating areas with different bed conditions (Bolliger et al, 1983). This diversity of flow and bed conditions is a necessary pre-condition for the survival of a wide variety of fish, macro-invertebrates and micro-organisms and is the basis for the development of a rich, stable ecosystem (Bolliger et al, 1983).

3.3.3 TREE AND SHRUB GROWTH ALONG BANKS

A natural watercourse is often lined with trees, such willows, alders and ashes, that like damp conditions and grow right down to the low water line (Bolliger et al, 1984). As a natural type of woodland and simply from a species richness point of view, riparian areas are of vast importance (Binder et al, 1983). Natural stream rehabilitation seeks to preserve or re-introduce these conditions. Rather than using only hard materials such as rock or concrete, live materials such as grasses, shrubs and trees are used to stabilize the soil and to reinforce constructions.

Trees and brush provide cover, food and proper water temperatures for micro-organisms and fish. By providing food for micro-organisms, fallen leaves are the chief source of energy or fuel for the riverine ecosystem. They are the basis of the food web and are the powerhouse that drives all the other levels as one moves up through invertebrates such as insect larvae and small crabs to vertebrates such as fish and beyond. Shade, also is important for the maintenance of proper oxygen concentrations in the water. As temperatures rise, so do the oxygen requirements of the water-based animals. At higher temperatures, some animals require twice as much oxygen and if the temperature rises above 70° F. oxygen is forced out of solution causing suffocation (Quammen, 1985).

Aquatic plants are also important to the general ecology of rivers. They are a source of

energy and food, contribute to the cycling of nutrients and organic matter and provide additional habitat for micro and macro-organisms (Brooker, 1985).

The species diversity, density and health of riverine and riparian vegetation is determined by the physical and chemical properties of the channel. Alterations of depth, flow and composition of the bed, banks and floodplain are likely to cause changes in the plant communities of the watercourse (Brooker, 1985). Other than obvious effects, such as the stripping of vegetation for re-grading of the channel, the effects of river channelization on riverine and riparian vegetation are poorly documented and require further study, before complex interrelationships may be completely understood.

3.3.4 SPECIAL CONSIDERATION OF TRANSVERSE STRUCTURES, DAMS, EMBANKMENTS AND BANK STABILIZATION METHODS

In light of the above section, it is important to note that vegetation alone is often enough to stabilize some areas. However, techniques involving vegetation as the sole means of stabilization usually require more area than conventional hard techniques and require that sufficient space is available (Binder et al, 1983). Unfortunately, unused space is often scarce and compromises must be made. Thus, special bank stabilization measures to limit the dynamics of the stream are usually unavoidable (Binder et al,1983). These measures, depending on the stresses placed on them, may range from light weight timber and stone structures to the most heavy duty stone and concrete revetting (Binder et al,1983). It is desirable to use the least intrusive technique possible, but all techniques, vegetative to hard constructions, should incorporate as an essential feature, the retention of the habitats of all aquatic, amphibian and terrestrial organisms or minimally their replacement by habitats of equal value (Binder et al,1983). Therefore, as an example, dumped rock and riprap banks must be designed such that they provide habitats for micro-organisms and animals which are food for fish and also provide shelter for the fish themselves (Binder et al,1983).

The siting and structure of large features, such as dams and dykes, present particularly difficult problems. While performance and safety are the primary concerns, it is still possible to create damp meadows and dry grassland habitats by providing broad untouched areas in front of dykes and through the low key treatment of their banks (Binder et al, 1983). However, it is often not possible to keep structures far enough away from rivers or streams to allow the creation of a more natural alignment closer to the original form of the watercourse (Binder et al, 1983). Providing sufficient area is especially difficult in built up areas, so it is necessary to develop other ways to dissipate the stream's energy for example through the use of gradient control structures. However, even in extremely constricted areas, it is always possible to create small scale natural stretches (Binder et al, 1983).

3.4 BENEFITS OF NATURAL STREAM LANDSCAPING

Landscape design should be undertaken in the design stage, before natural vegetation has been destroyed or damaged by earth moving equipment. However, if development is already underway, it might still be possible to make alterations in construction, for example contouring works, that could save valuable ecosystems (Schiechtl, 1982). The application of bioengineering methods for bank stabilization, instead of conventional (hard) techniques can have considerable influence on preservation, conservation and the improved aesthetic quality of the landscape (Schiechtl, 1982).

3.4.1 STABILIZATION OF THE CHANNEL AND REDUCTION OF WATER VELOCITIES, EROSION AND SEDIMENTATION

Small gradient control dams, that create an artificial pool and riffle sequences or the reintroduction of meanders reduce the gradient of the streambed. This decreases the velocity of flow with a consequent reduction in the ability of the water to transport

material (Keller, 1978). The re-introduction of meanders reduces the gradient by increasing the horizontal length of the stream. Gradient control dams drop the channel bed elevation quickly, while dissipating energy on their face, causing a reduction of the tractive force of the water. Upstream of the dams an area of slow water allows deposition and the collection of sediment.

In Manitoba, a series of these dams were placed on Wilson Creek. In the reaches above all the dams, erosion ceased and sediment from upstream restored the pre-channelization gradient (Newbury and Gaboury, 1988). In undammed areas erosion continued at the pre-channelization rate (Newbury and Gaboury, 1988). During peak flows along the Mink River in Manitoba during 1986, no significant erosion occurred in reconstructed pool and riffle reaches where these small dams had been built (Newbury and Gaboury, 1988). However, directly upstream and downstream of the reconstructed reach, erosion of the channel bed caused slumping along 30% of the banks (Newbury and Gaboury, 1988).

The advantage of re-introducing meanders or building pools and riffles into the channel plan is improved channel stability and the reduction of the amount of energy available for erosion (Newbury and Gaboury, 1988). These improved conditions lead to a decrease in sediment inputs to the downstream portions of the channel and downstream lakes (Newbury and Gaboury, 1988).

Re-vegetation also plays a role in erosion control. Aquatic vegetation and the roots of terrestrial plants may cause a reduction in flow velocities, decreasing the erosive power of the water. Bank and shore protection plantings, consisting of grasses, reeds, shrubs and trees, can provide protection for banks, floodplains and lowlands in areas that lie above the normal water level (Schiechtl, 1982).

3.4.2 DIVERSITY OF BIOLOGICAL HABITAT

Natural stream rehabilitation techniques create favourable conditions for numerous

plants and animals through the creation of a wide range of different habitat conditions, ranging from flat banks fringed with rushes to deep scoured pools under tree and shrub roots (Bolliger et al, 1984). Even eroded areas are valuable habitats for a wide variety of pioneer plants (Bolliger et al, 1984).

Bankside vegetation shades the water, moderating temperatures and regulating the oxygen content, limiting the growth of aquatic vegetation and algae that could choke out other life in nutrient rich rivers and streams (Binder et al, 1983). Bankside vegetation also provides increased habitat for small animals such as raccoons, squirrels, skunks and birds. It can also form wildlife corridors by creating cover for the movement of larger game species such as deer and moose.

The introduction of pools and riffles into channelization projects leads to a considerable reduction in damage to biological systems, by accelerating the recovery of water-based micro-organisms, macro-invertebrates and fish populations, through the restoration of bed composition and the stabilization and creation of areas for feeding, breeding and cover (Keller, 1978; Newbury and Gaboury, 1988). Fish egg drift through rehabilitated reaches is reduced (Newbury and Gaboury, 1988). Egg survival, in riffle zones, is also increased by the aeration of the water as it flows across the riffle surface and by higher local velocities that prevent sedimentation and consequent egg suffocation (Newbury and Gaboury, 1988). Because of increased opportunities to settle behind and adjacent to larger boulders on the riffle surface and in low velocity zones created in horizontal eddies above and below the riffle crests,

3.4.3 IMPROVED WATER QUALITY

While the difference in the purity of waterways stabilized with conventional techniques and those stabilized with bioengineering methods has not been examined in detail, a large number of tests have shown that more than fifty plant species are able to destroy bacteria

such as *Escherichia coli, Enterococci and Salmonella* (Schiechtl, 1982). Reduction of the harmful bacteria appears to based on the interaction of organisms associated with the plant rhizomes and the bacteria living in the water (Schiechtl, 1982). Some plants also absorb acids, oils, heavy metals and can break down detergents (Schiechtl, 1982). Plants belonging to the lower orders, for example algae and protozoa, play an essential part in the purification of waterways (Schiechtl, 1982). Uncertainties about the water purification capabilities of higher plants exist only because of a lack of study (Schiechtl, 1982).

The physical form of the channel also plays a role in improving water quality. Oxygen, the most fundamental element necessary for life in the water, as well as other gaseous elements, are stirred into the watercourse by any turbulent movement over riffles, down cascades and where branches or roots drag in the water.

3.4.4 IMPROVED RECREATIONAL POSSIBILITIES

When channelization projects use natural stream landscaping techniques, improved fish and wildlife habitat creates increased opportunities for recreational activities such as fishing, hunting, wildlife viewing and bird watching. Since the environment created alongside the stream can act as a wildlife corridor, the benefits are accrued not only along the watercourse but to surrounding land areas as well. In conjunction with other plans, such as improved access, natural stream landscaping could be used to develop a specific type of recreational activity. For example, the Rat River, in southern Manitoba, was developed for trout fly fishing, through careful protection and manipulation of the stream corridor (Master's Studio, 1985).

In addition to increased recreational potential, there are other intangible benefits from the improved visual and aesthetic amenities provided by natural stream landscaping. The increased diversity of visual and other sensual experiences as well as greater productivity of fish and other wildlife in well designed or rehabilitated channels provides a more

positive outdoor experience (Keller, 1978). The varied landscape, the trees, tumbling water and shady patches make the stream a more pleasant place to see and to be. This may lead to a changed perception of the waterway. Rather than being perceived solely as a ditch for moving water, the watercourse becomes an important place in the landscape with a multiplicity of functions.

3.4.5 REDUCED CONSTRUCTION AND MAINTENANCE COSTS

As a result of the development of better construction methods and better knowledge of the effectiveness of different techniques, natural stream landscaping has become more economical in the last few decades (Schiechtl, 1982). The authors of many studies state that low cost is one major advantage of the use of natural stream landscaping over conventional techniques (Schiechtl, 1982). However, a direct comparison of costs is only possible if the same project is designed twice based on the two different construction techniques and each is evaluated separately (Schiechtl, 1982).

Schiechtl (1982) cites the example of bank protection construction for a power station in Austria. The original banks of the channel, below the waterline, were to be paved with concrete. The best bid at the time was $1.00 per square foot ($10.00 per square metre). Instead, critical areas of the channel were stabilized with small rocks and additional joint plantings. The larger part of the slope was stabilized with willow plantings alone. The actual cost of construction was $0.046 per square foot ($0.50 per square metre), 1/20 of the cost of hard paving, representing a savings of $56,000 on the project.

The use of gradient control structures in channelization projects can also save money. For example, the installation of 2 of these structures, on Wilson Creek in the Dauphin Lake area of Manitoba, had a cost/benefit ratio of 1.3 for a discount rate of 5% (Newbury and Gaboury, 1988). The indirect benefits were more difficult to assess, but included the prevention of further farmland erosion adjacent to the channel and a reduction of

sedimentation in downstream channels and lakes, where commercial and sport fishing take place (Newbury and Gaboury, 1988). On the Mink River, in the same region, it was estimated that over a six year period of spring floods and other peak flow events, that the costs of the riffle structures would be recovered (Newbury and Gaboury, 1988). This cost savings estimate did not include consideration of the benefits to fisheries rehabilitation, the primary motivation for the project in the first place (Newbury and Gaboury, 1988).

While natural stream landscaping is extremely useful and cost effective, it cannot replace conventional engineering in all respects, but is able to supplement traditional techniques in order to provide more effective protection, with a reduction in cost (Schiechtl, 1982). Natural stream landscaping techniques may provide cost savings by allowing (Schiechtl, 1982):

1) smaller walls to be built, shifting less soil by merely flattening slopes and then revegetating them. Instead of massive walls, rock fills with joints filled with live plantings can be used.
2) support construction, gully bottom stabilization and protection to be carried out on the stream banks using live instead of dead material or through a combination of methods.
3) immediate stabilization with vegetation of all areas where earth works have been carried out. For example, revegetation works carried out along a highway through Austria and Italy, on some slopes cost no more than the cost of repair works after a heavy rainfall or snowmelt.
4) steeper slopes because the area will be revegetated immediately, binding the soil in place. However, since it would be counter-productive to construct oversteep slopes that would be unstable in spite of revegetation, care must be taken in design.

Given these facts, it is important to realize that many natural stream landscaping techniques involving vegetation have limited effectiveness initially, but that effectiveness increases dramatically as the plants mature (Schiechtl, 1982). To accelerate

development and to reduce the time until the construction is fully functional, maintenance is usually necessary (Schiechtl, 1982). Even the smallest erosion gullies must be constantly repaired and reseeded and seedings, stabilizing constructions, plantings and reforestations have to be carefully maintained (Schiechtl, 1982). Where conditions for the plants are more harsh, maintenance standards must be correspondingly vigourous (Schiechtl, 1982).

3.5 DESIGN AND MAINTENANCE CRITERIA

3.5.1 SYSTEMS APPROACH

Rivers and streams are open systems, with distinct feedback mechanisms (Keller, 1975; Keller, 1980). A watercourse system is composed of all land and the various processes occurring on it, as well as the watercourse itself, all its tributaries and all the processes occurring in the water. Changes in the immediate riparian area can affect the watercourse directly (Keller, 1980).As well, changes far removed from the immediate channel area, in the surrounding watershed, can affect erosion and sedimentation processes occurring within the watercourse (Pokrant and Gaboury, 1983). These changes may be responsible for the improper functioning of the watercourse as a drainageway causing the demand for alterations in order to improve its performance. Therefore, an awareness of changes in land use practices and vegetative cover is essential to the redesign of any channel.

When designing channels it must be recognized that channelization, as well as having obvious direct effects in the development area, may have many indirect effects upstream and downstream of the project site (Keller, 1980). Since streams are open systems composed of interrelated parts, generally in balance or dynamic equilibrium, change in one part of the system will create change other parts of the system.

Alterations to the geomorphologic and hydrologic regime of a watercourse, such as

capacity, volume of water conveyed, sinuosity of the channel plan and gradient of the bed affect the flow of energy and will cause changes to the bed and banks of the channel (Keller, 1980). If the alterations are limited, significant changes to erosion and sedimentation rates are less likely to occur (Keller, 1975; Keller, 1980). However, if the alterations involve major changes to the channel, substantial erosion may take place and serious changes to the bed and banks of the channel may occur. (Keller, 1975; Keller, 1980).

It appears that rivers and streams as open systems respond to threshold conditions (Keller, 1975; Keller, 1980). For example, Schumm, in an experiment described by Keller (1980), found by means of a water flume experiment that small channels experienced discrete changes in channel pattern, from straight to meandering to braided, in response to changes in channel slope. The changes were not gradual or continuous, but occurred quickly after a threshold slope was reached. It is possible to conclude that threshold conditions exist in a watercourse and that alterations to the channel and watershed may be made up to these thresholds without significant change affecting in-stream processes. While it is dangerous to make analogies between laboratory experiments and natural streams, if the conclusion is valid, it has very important consequences for channelization (Keller, 1980). If changes in the stream, such as widening of the channel, take place in response to threshold changes in slope, sediment concentration and other variables, then it is theoretically possible to straighten a stream a certain amount without widening of the channel occurring (Keller, 1980). The amount of straightening would be dependent on identifying the correct threshold controlling the channel pattern (Keller, 1980). The identification of the governing threshold would be very valuable, as it would allow the design of a channel with the confidence that the finished project would not likely erode or change pattern (Keller, 1980). While, the identification of these thresholds has not yet been done (Keller, 1980), it may be possible to estimate the approximate conditions in which a channel may be stable by examining the forms that a natural watercourse, in similar watershed conditions, creates. Based on a number of studies in the United States and Canada, generalized equations, relating drainage area to depth, width and cross-

sectional area, have been developed. From these equations, it is possible to determine other factors, such as meander spacing, length and radius of curvature. These equations will be discussed in detail in the following portions of the section.

The design of a channel must not be undertaken without consideration of events occurring in the rest of the watershed. Alterations to vegetation, surface conditions and flow patterns all have a direct impact on the watercourse channel. Keller (1978) offers a graphic example of this situation. With modifications based on natural forms, a previously channelized portion of a watercourse was altered. After functioning successfully, without experiencing erosion problems for over a year, the reach was suddenly smothered by an influx of sediment. The sediment came from bank erosion in a conventionally channelized reach of the stream, as well as a construction site, both of which were located upstream of the experimental reach. Thus, without the development of an overall strategy for erosion control and rehabilitation works in a watershed, individual works are much less likely to succeed.

3.5.2 MINIMIZATION OF NON-NATURAL TECHNIQUES

The state of the art of channelization still suffers from a lack of understanding concerning the behaviour of natural streams (Keller, 1980). The desired philosophical framework in which to work would be one in which the practice of channelization itself is minimized and the least amount of non-natural control is used to satisfy the desired objective (Keller, 1980). The most important principle is that interference with natural streams should be kept to an absolute minimum, and alternatives to channelization should be fully explored (Bolliger et al, 1983). The original character of the stream should be maintained as nearly as possible, be it a gully, wood or meadow stream or even factory canal (Bolliger et al, 1983). It is most desirable to retain the natural course, particularly meanders and curves and if this is not possible, to attempt to imitate the natural course of the stream (Bolliger et al, 1983). The importance of the preservation or re-introduction of these forms is

illustrated by the necessity of meanders and the eddies that they form to walleye spawning behaviour. Without these forms, spawning is unlikely to occur (Marc Gaboury, personal communication, February 27,1989).

Means of minimizing interference with natural watercourses include the of use passive flood control measures, the development of flood retention basins, the restriction of corrections to sections, the taking of risks and the use of control measures with a clear purpose and goal in mind (Bolliger et al, 1983).

3.5.3 REMOVAL OF OBSTRUCTIONS FROM THE WATERCOURSE

The Stream Renovation Guidelines Committee (1983) has developed a system which promotes careful consideration to determine the minimum level of intervention required to develop the desired water conveyance capacity of a channel. The system, which encourages the maintenance of natural stream characteristics and offers an alternative to channelization through the development of environmentally sound techniques for the correction of stream flow problems caused by obstructions, is outlined in a report entitled Stream Obstruction Removal Guidelines (1983).

While debris and obstructions often play a vital role in the structure and health of a watercourse, excessive amounts of material can lead to flow problems. Ill considered landuse and stream use practices can reduce stream flow conditions to such an extent that corrective methods are required. Development interests and flood prone communities often successfully campaign to develop major stream modification projects in order to alleviate problems or to achieve some desired level of water conveyance.

Channelization is the traditional method used to correct stream flow problems, but first it is important to determine if channelization is actually necessary to achieve the desired result. An alternative approach involves the removal of obstructions allow to the free flow

of water within the existing channel. This removal of debris and obstructions could be sufficient to allow adequate flow through the channel without channelization.

Therefore, where blockages result in unacceptable flow problems or where a restoration of natural or former flow regime is desired, planners and designers should first determine if non-structural methods are sufficient to allow the desired rate of flow through the reach. Where non-structural methods alone are insufficient to achieve the desired result, a combination of obstruction removal and non-structural methods is preferred over more drastic channel modifications.

In the removal of stream obstructions, the level of intervention is dependent on the different flow conditions found in the watercourse (see figure 5).

Condition One

These segments have an acceptable flow and no work is required. These reaches may contain small amounts of debris and fine sediments such as silt, sand, gravel, rubble, boulders, logs and brush. In some situations, the flow may be restricted, but due to adjacent land use it is not a problem.

Condition Two

These reaches have no major flow problems, but existing conditions are such that obstructions causing unacceptable flow conditions are likely to occur in the near future. These obstructions are characterized by small accumulations of logs and other debris that span the whole width of the watercourse. Accumulations are isolated and small and do not cause blockages of the water.

In condition two areas, equipment likely to cause the least amount of damage should be utilized for the removal of obstructions. Hand tools such as axes, chain saws, winches and small boats should be selected first. If hand equipment is insufficient for the work required, heavier equipment such as small tractors, backhoes, bulldozers, log skidders

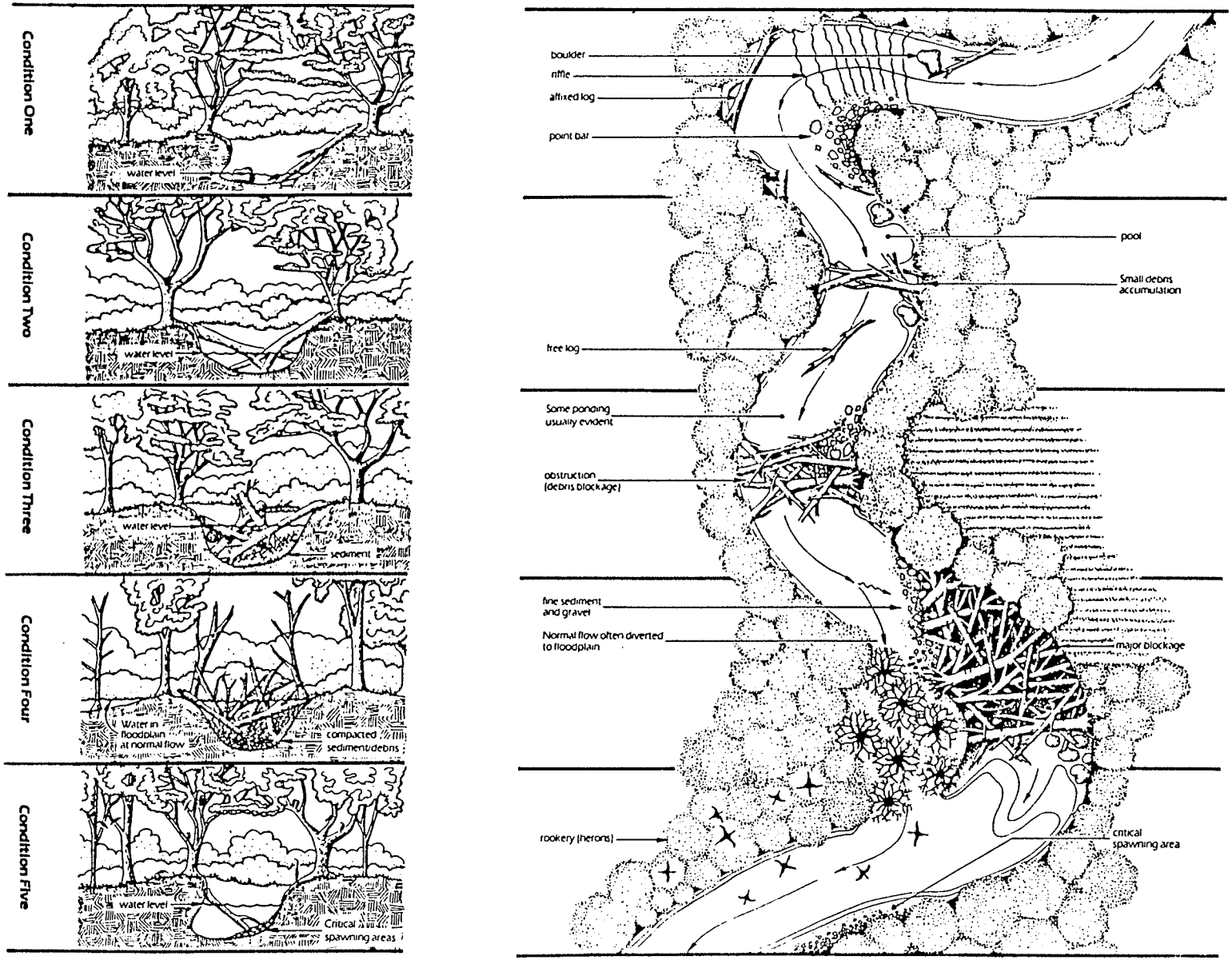


Figure 5 Stream obstruction conditions.

and low PSI equipment may be used in such a way as to do the least damage possible to vegetation and soils in the project area. Explosives may be used, in some cases, to reduce potential damage to the area caused by equipment use and access requirements. Any material removed must be secured in such a way as to ensure that it does not re-enter the channel and should be positioned so as not to cause an impediment to flood flows.

Condition Three

These Reaches have unacceptable flow problems. The obstructions usually consist of lodged trees, root wads and other debris, that often spans the whole width of the channel. While not completely free flowing, some water moves through the obstruction. Only small amounts of sediment have accumulated in the obstruction.

In condition three areas, the equipment limitations are the same as in condition two and if possible, work should only be done from one side of the channel. Tree cutting for equipment access and adequate work space should be minimized. Material should either be removed from the floodplain or burnt, buried or piled as appropriate, with the minimum disturbance to vegetation. It is especially important that fine sediments are not piled around the base of mature trees, smothering their roots.

Condition Four

These reaches have major blockages that create unacceptable flow conditions. Accumulations of material consist of compacted debris and/or sediment that severely restricts the flow causing water to flow through the floodplain at normal flows.

Blockage removal may use any equipment deemed necessary to accomplish the work in the least damaging manner. Where possible, work should be limited to one side of the channel. Material may be disposed in the same manner as in condition three.

Condition Five

These reaches contain unique, sensitive or especially valuable biotic resources and must

be dealt with on a case by case basis. Examples of reaches in this condition include areas with rare or endangered species, shellfish beds, fish spawning and rearing grounds and the nesting sites of birds. Special guidelines, for work in these areas, should be developed on a case by case basis.

The Removal of Material

Work should only be undertaken where definite, identifiable problems are occurring. Access routes to the work sites and channel excavation and debris removal methods that will minimize the destruction of vegetation should be selected. The smallest possible equipment should be used and all disturbed areas must be re-seeded or replanted with plant species that stabilize the soils and benefit fish and wildlife.

Only those fine sediment accumulations that obstruct flows to an unacceptable degree should be removed. Small accumulations do not usually cause problems and should not be disturbed. Gravel, rubble and boulders in small amounts do not usually cause problems and should be left undisturbed. But, in areas where they are restricting flows and causing problems, they may be removed. Only debris accumulations that cause serious obstructions to the flow or are likely to do so in the near future should be removed.

Affixed logs, lying crosswise in the channel, causing problems or likely to cause problems in the near future, should be moved parallel to the bank or removed. Single or isolated logs should be left undisturbed, if they are embedded, lodged or rooted in the channel and are not causing problems. Free logs that are not rooted, lodged or embedded should be re-positioned, fixed in place or removed.

Rooted trees, dead or alive, may be cut and re-positioned or removed only if they are likely to cause problems in the near future or if their removal is necessary for the access of machinery. Tree stumps with roots should be left in place to prevent bank erosion.

3.5.4 CHANNEL FORM

Natural stream landscaping recognizes that watercourse dimensions of width, depth, cross-sectional area, meander wavelength and radius of curvature have developed in response to natural forces that are fundamental to the operation of the stream. These forces, as reflected by the dimensions that they create, must be acknowledged. The dimensions must provide a fundamental basis for any design of rehabilitation works.

The morphology of alluvial river channels results from the entrainment, transportation and deposition of the unconsolidated material across which the channels flow (Chapman, 1987a). Many studies have set out generalized equations which reflected the consistent relationships of the morphology of streams (Chapman, 1987a, Leopold and Maddock, 1953; Leopold and Wolman, 1960, Leopold et al, 1964). It has been established that the width, depth, cross-sectional area, velocity, slope and roughness vary consistently with discharge (Chapman, 1987a). Since the relationships assume that discharge is the independent variable, bankfull discharge, which has a recurrence interval between one and two years and is the discharge that creates and maintains the form of the stream channel, is most often used in the calculations to determine morphological characteristics (Chapman, 1987a, see figure 6).

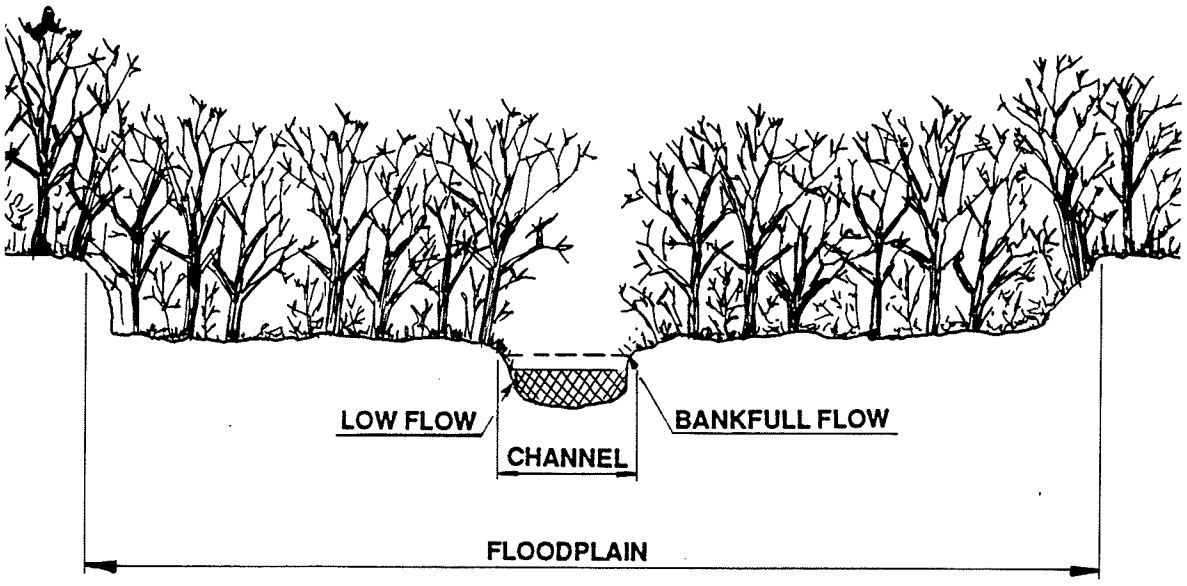


Figure 6 Cross-section illustrating various parts of a watercourse.

Fortunately, at bankfull stage, average values of discharge as well as channel width, depth and cross-sectional area are highly correlated with the size of the drainage area of the watershed, in a given region (Dunne and Leopold, 1978) Graphs and equations relating all these dimensions to drainage area have been developed (see figures 7 & 8). Drainage area functions extremely well and an independent variable in these calculations, as it is one of the easiest of all parameters to obtain (Chapman, 1987a; Dunne and Leopold, 1978). It is easily measured on a topographical map and then related to the appropriate line on the graph to determine an estimate of the channel dimensions and bankfull discharge (Dunne and Leopold, 1978). It is important to realize that variability from basin

METRIC EQUATIONS
FOR RIDING MOUNTAIN

$A_{bf} = 0.19\ D_A^{0.67}$

$W_{bf} = 1.7\ D_A^{0.36}$

$D_{bf} = 0.12\ D_A^{0.30}$

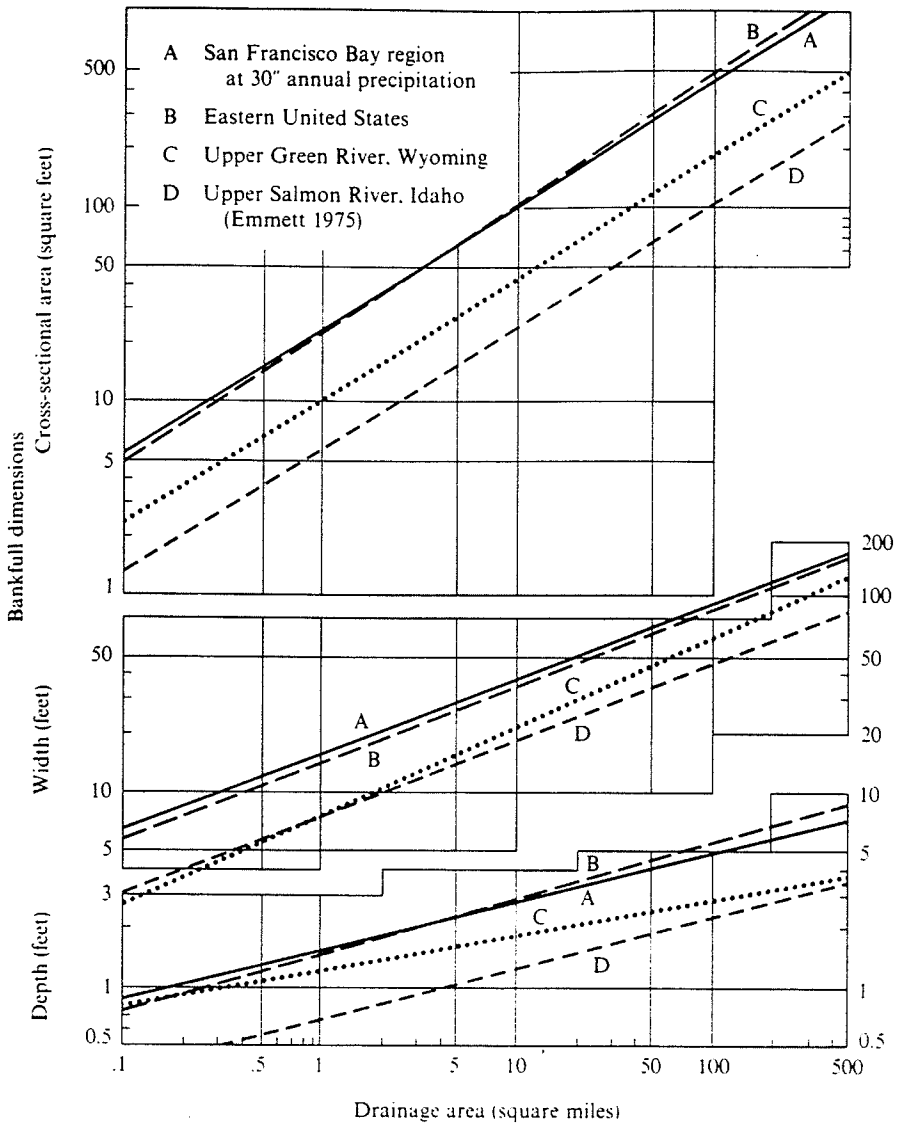


Figure 7 Bankfull channel dimensions as a function of drainage area.

METRIC EQUATION
FOR RIDING MOUNTAIN
$Q_{bf} = 0.24\ D_A^{0.83}$

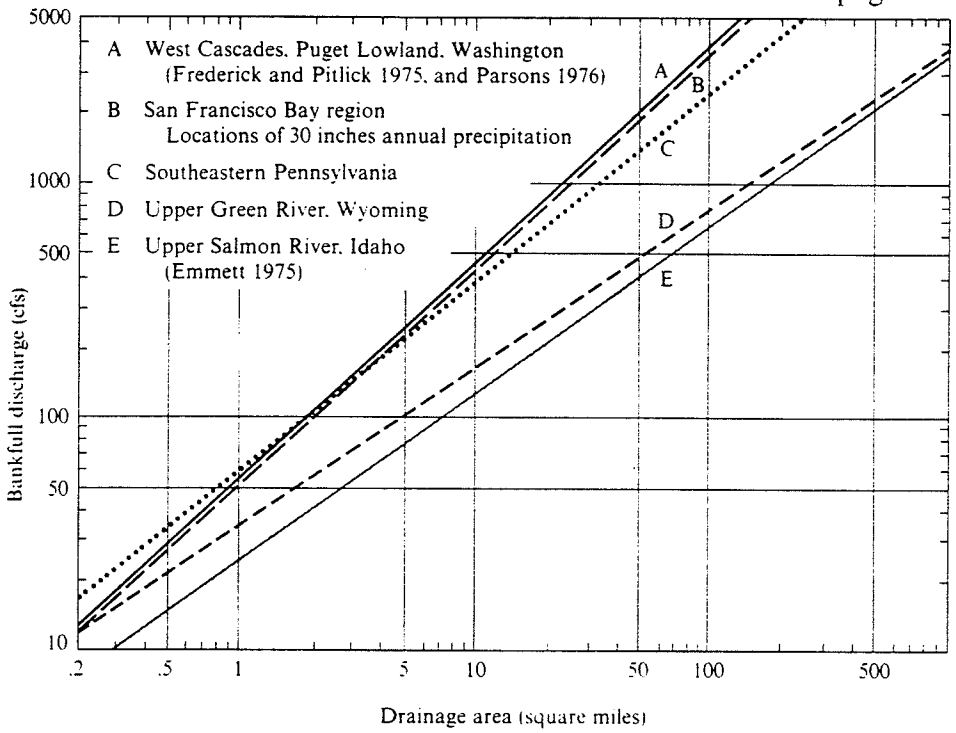


Figure 8 Bankfull discharge as a function of drainage area.

to basin is high and therefore ,that only approximate estimates of the channel dimensions are obtained with this method (Dunne and Leopold, 1978).

Even so, this method does provide a good starting point for the design of rehabilitation works. More detailed information on the stream may be obtained by examining any unchannelized portions of the stream, to determine more accurately what the original dimensions were. It is, however, important to remember that the drainage area and thus the discharge and dimensions vary as one moves up or down the stream. It must also be recognized that channelization may have indirectly affected the reaches under investigation and that the dimensions may no longer accurately reflect the original conditions of the stream. Thus, it would also be useful to examine any remnants of the stream that had been cut off by the channelization works or perhaps even to excavate trenches across the floodplain to determine the location and dimensions of the original channel (Brookes, 1987). Within the trenches, the boundaries of the original channel would be discernable because of the change in material from undisturbed earth to backfill, which will be a different colour, composition and grain size (Brookes, 1987).

Streams of similar size in neighboring catchments under identical land-use and geology may also offer clues to bankfull channel width, depth and cross-sectional area (Brookes, 1987). Mathematical investigations such as regression analysis may also prove helpful, but this for these methods to be successful, a long length of channel above the proposed project, unaffected by channelization, is required (Brookes, 1987). However, assuming the constancy of environmental controls between reaches, a relationship for the down-stream variation of the channel form parameters may be developed (Brookes, 1987). It is extremely important that all these various calculations and measurements provide the dimensions of a channel that will convey bankfull flows with little or no stability problems. However, as mentioned earlier, bankfull flows have a recurrence interval of only one to two years. Most channelization projects are developed to carry larger flows with a recurrence interval of 50 or even 100 years.

It cannot be expected that a channel, built to convey 100 year flows and containing forms such as meanders, pools/riffle sequences and other features based upon those flows, will be successfully maintained by two year flows. Once again, an examination of the way that natural watercourses function may provide a solution to the dilemma. In natural

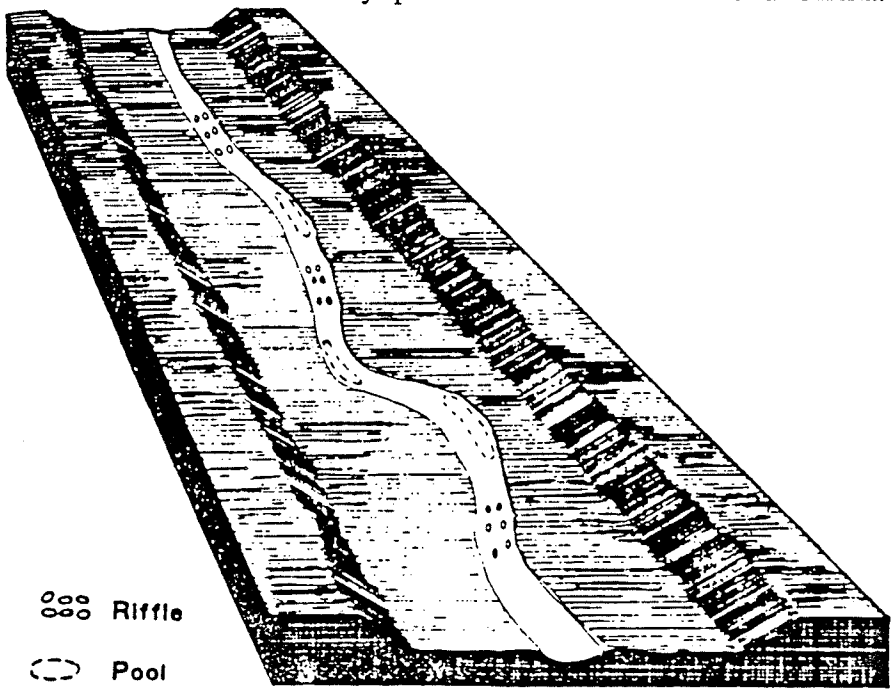


Figure 9 Pilot channel (channel within a channel) suggested for some flood control projects. Pools and riffles are constructed in meandering channel with a larger flood control channel.

watercourses, the floodplain carries flows greater than those with a recurrence interval of two years. Therefore, where possible, a smaller pilot channel should be constructed, in which a meandering channel that can be maintained by 2 year floods is superimposed on the larger flood control channel, in the same way that a natural stream has a floodplain surrounding the normal flow channel (Keller, 1975; see figure 9). Along with meanders, the pilot channel would contain pools and riffles and would provide better fish habitat and low flows conditions (Keller, 1975).

3.5.4.1 GRADIENT CONTROL

If it is deemed necessary to alter the base level of a watercourse for any reason, the overall slope of the bed should be maintained. In rehabilitation projects, the slope that the watercourse had prior to its first alteration should be re-established. The beds of natural watercourses are not flat (see figure 10). They are characterized by systematic variations as a result of pools and riffles and there must be some provision for similar forms when

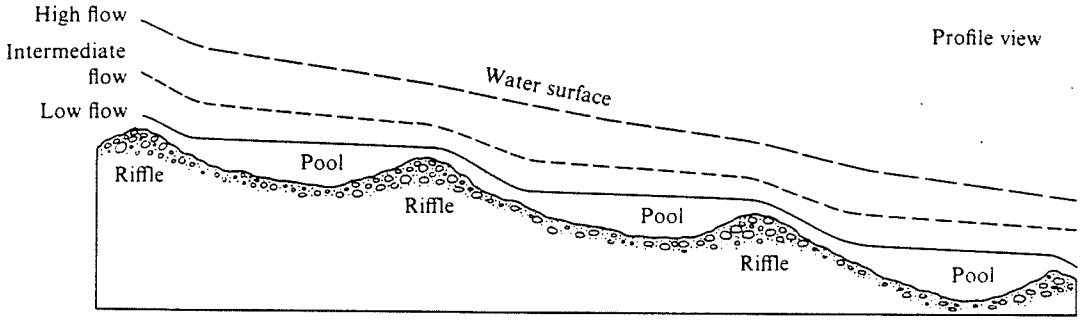


Figure 10 Profile of a watercourse showing variation in the bed and its effect on the water surface at various flow conditions.

re-constructing the slope (Brookes, 1987; Dunne and Leopold, 1978). Small gradient control dams, which allow for quick drops in bed elevation and create flatter sloped areas between themselves, emulate this natural form. Increased erosive energy of the water, caused by steeper slopes, will be dissipated on the rock faces of these dams (see figure 11).

Information on the slope, prior to alteration, can be obtained in a number of ways. The

original course can be plotted from maps, aerial photographs or other archival sources and the length of the channel determined and compared with the channelized length (Brookes, 1987). Assuming that the spot elevations, at the head and mouth of the channelized reach, remained the same as in the original watercourse, the slope may be determined easily (see figure 12). If the channelized reach has caused headcutting or a location bearing no relation to the location of the original channel, it may be necessary to dig bore holes or trenches in order to obtain spot elevations at different points along the length of the original undisturbed channel. The

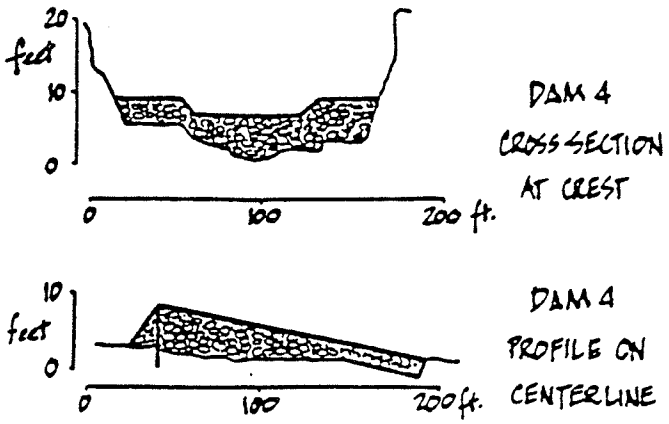


Figure 11 Typical form of a gradient control structure.

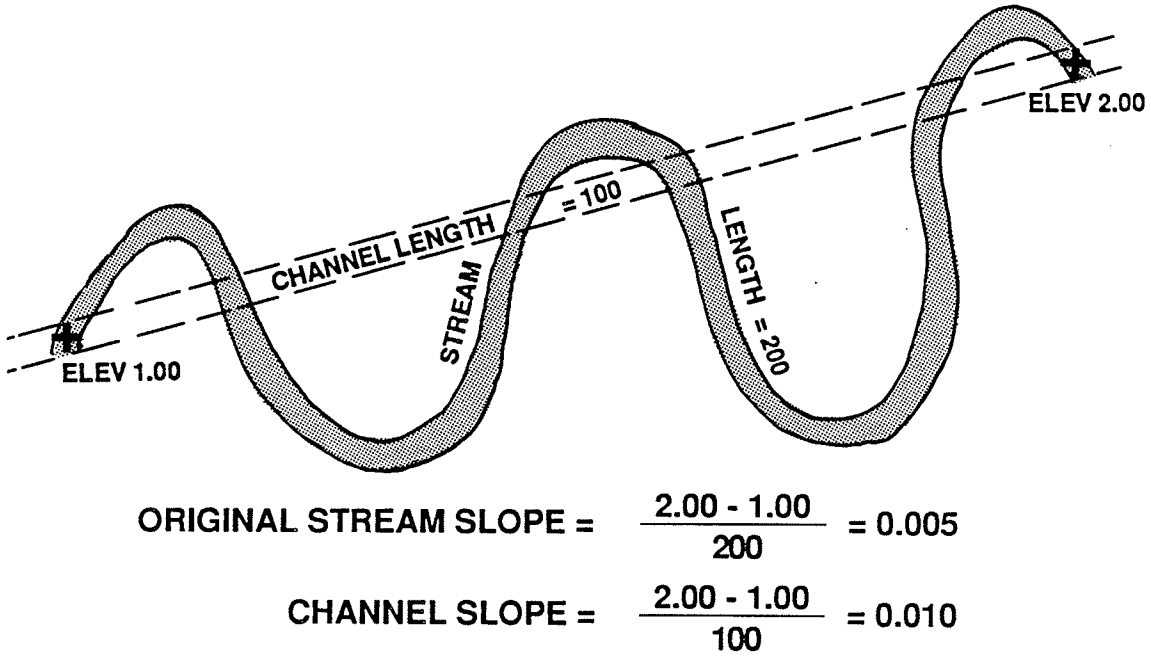


Figure 12 Diagram illustrating how the slope of the original channel may be determined from the channelized reach.

information gathered in this manner may be related to the length of the original watercourse in order to obtain slope. However, if maps are used to determine the course of the original watercourse, it is important to be aware of problems with measurement error and data misrepresentation (Brookes, 1987). With decreasing scale, map detail

becomes progressively more simple, often leading to significant differences in the representation of topographic features at different scales (Brookes, 1987). Therefore, maps should be checked against aerial photographs, if possible.

It may also be possible to gather relevant information from just upstream or downstream of the project (Brookes, 1987). However, the fact that slopes of watercourses generally decrease as one moves downstream must be accounted for when utilizing information gathered in this manner.

Generally, Keller (1975) suggests that gravel bed streams, with a channel width less than 25 metres should not have a slope greater than 0.005 (25 feet per mile, 5 metres per kilometre). In the Canadian prairies, watercourses with gravel beds are rarely encountered. Bed material is generally much finer consisting of shale particles, clay or silt. Therefore, the slopes of watercourses that are in equilibrium are shallower. For example, prior to channelization, the lower portion of Edwards Creek in the riding Mountain region of Manitoba, had a slope of approximately 0.001 (5 feet per mile, 1 metre per kilometre).

3.5.4.2 POOLS AND RIFFLES

The incorporation of pools and riffles into the the design of channels is the most significant design criteria for stream rehabilitation works (Keller, 1978). Pools and riffles are important for fish and other aquatic wildlife and the use of these forms tends to diminish environmental degradation (Keller, 1975).

Analysis of pool to pool spacing data suggests that there is no significant difference, when using channel width as an independent variable, between pools that form in natural watercourses and those that form in watercourses affected by limited human use (Keller, 1978). The tendency of pools and riffles to develop may be considered a fundamental aspect of channel morphology that is relatively insensitive to limited environmental

stress (Keller, 1978). This conclusion is crucial, if pools and riffles are to be included into design criteria for channelization projects (Keller, 1978). However, channelization, which changes the channel width and often eliminates pools and riffles cannot be considered limited human use.

Alternating pools and riffle are found in almost all perennial channels, in which the bed is composed of material larger than course sand (Leopold et al, 1964; Keller, 1978). The bars that form the riffles are generally lobate in shape and slope alternatively toward one bank and then towards the other (Leopold et al, 1964). The base flow water channel then bends around the low point or nose of each bar and thus tends to have a sinuous course, even within the banks of a reach that is generally straight (Leopold et al, 1964; Moriwasa, 1968). In a channel, that is more or less straight, successive riffle bars tend to occur on opposite sides of the channel (see figure 13). Opposite the point of maximum depth is usually a bar or accumulation of mud along the bank and these forms tend to alternate from side to side as well (Leopold et al, 1964).

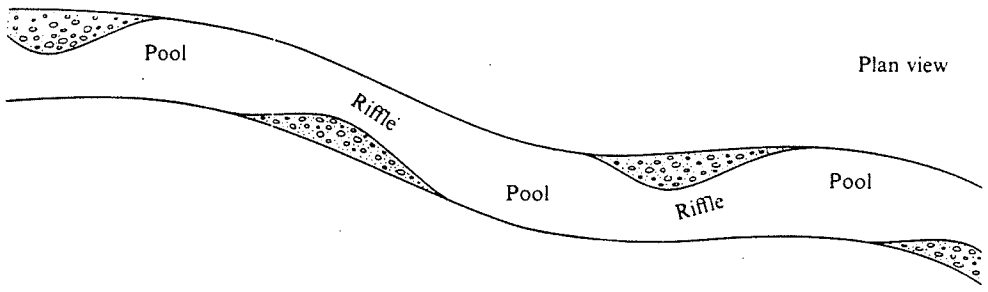


Figure 13 Plan view of a pool/riffle sequence.

One of the requirements for the existence of pools and riffles in non-meandering watercourses appears to be some heterogeneity of bed material size (Leopold et al, 1964). The material on the bed tends to be somewhat larger on the riffles than in the pools (Leopold et al, 1964). Channels that carry uniform sand or uniform silt have little tendency to develop pools and riffles (Leopold et al, 1964)

Most techniques, to improve fish productivity and other aquatic life in the modified

watercourse, consist of the construction of special structures, that provide a variety of flow conditions, similar to the flow found in pools and riffles of natural watercourses (Keller; 1980, see figure 14). However, pools formed by simply placing an artificial sill in the channel have to be constantly maintained to prevent them from filling up with sediment (Keller, 1980). In natural streams, pools are created by scour and riffles are

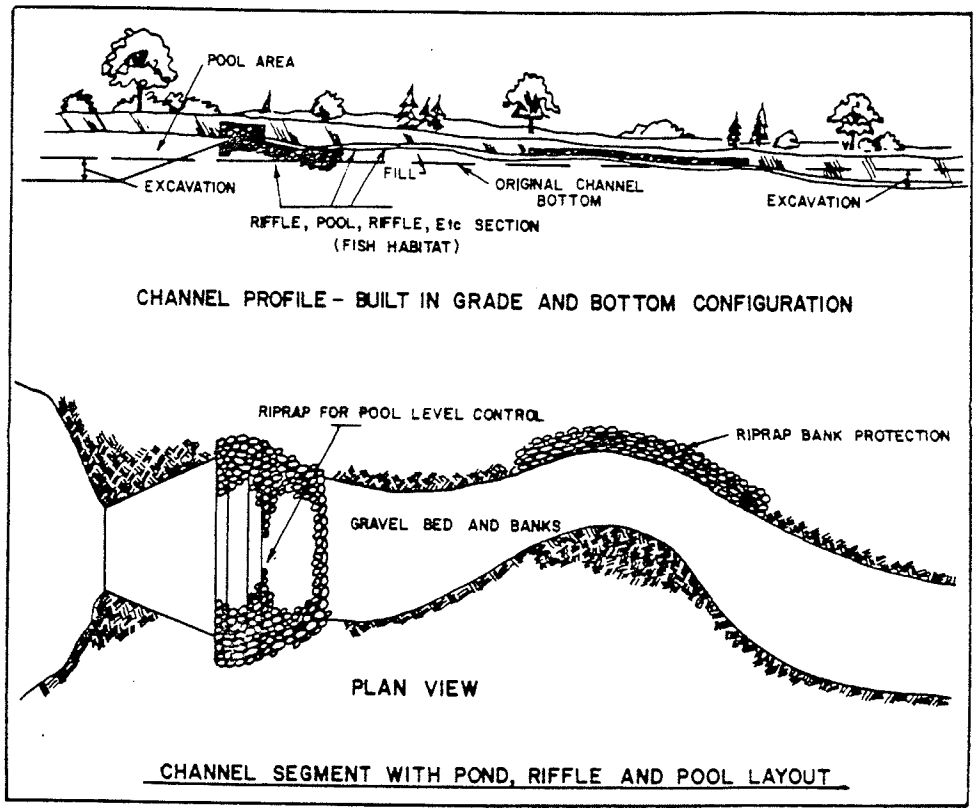


Figure 14 Idealized diagram illustrating how specially engineered structures might create a diversity of flow conditions similar to natural pools and riffles.

created by deposition at bankfull flows (Keller, 1978). This pattern is significant in maintaining the morphology of the pool and riffle sequence and producing the natural sorting of bed material that deposits coarsest material on the riffles and point bars (Keller, 1978). In channelized streams, if the pools were designed to converge the flow of water at bankfull discharge causing the bottom of the pool to be scoured, the problem of pools filling in might be eliminated (Keller, 1980). Such a self-cleaning process is an essential part of natural streams and should be designed into plans for artificial pools (Keller, 1980).

Keller (1978) used a similar concept in the design of a channel to test the hypothesis that the modification of channel form, by partially controlling the behaviour of the stream, can be used to minimize some of the adverse affects of channelization. On a previously channelized stream, a series of point bars were built by constructing an asymmetrical channel, in which one bank was sloped at 2:1, the other had a slope of 3:1 and the bottom was disturbed as little as possible. No structures of any type were used. In between the asymmetrical sections, a symmetrical section with both sides sloped at 2:1 was built (see figures 15, 16 & 17). Keller hypothesized that point bars would form on the 3:1 side of the asymmetrical section, because the 2:1 side would converge the high discharge flow, causing scour near the steeper bank and facilitating deposition on the flatter side. In fact, following the first high discharge event after construction, the point bars emerged exactly where expected and remained morphologically stable over a one year period that included a number of other flood events. Thus, as a conclusion, it may be suggested that the design of channelization projects and rehabilitated channels include pools with asymmetrical cross-sections.

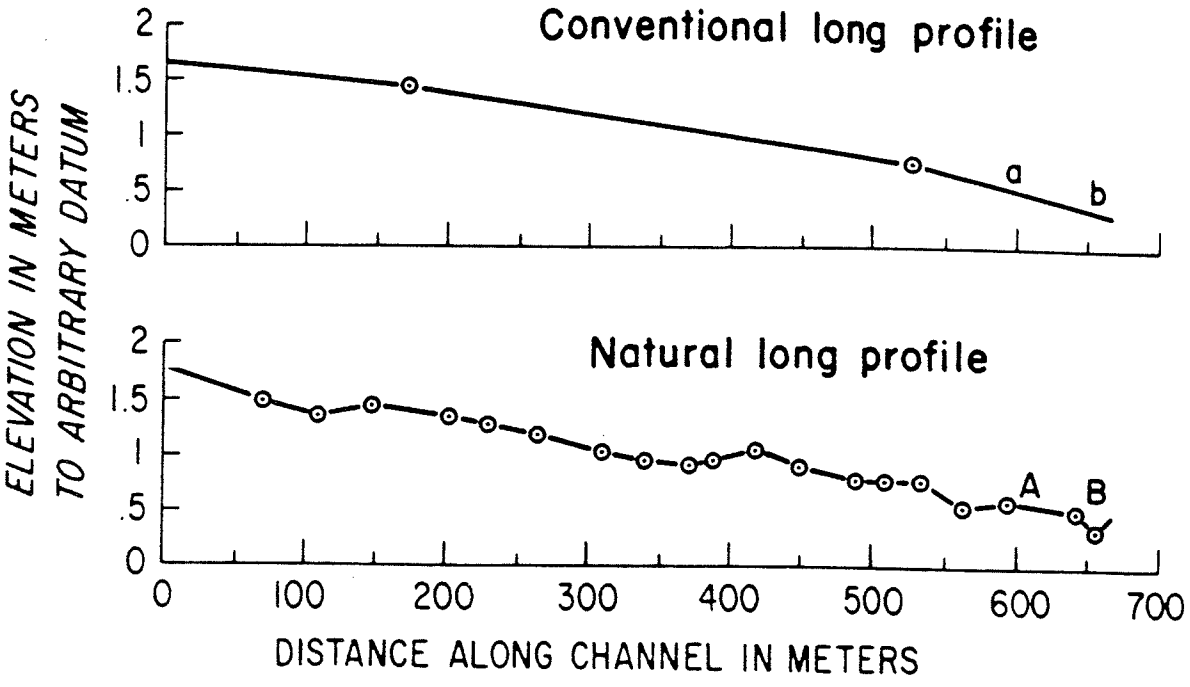


Figure 15 Comparison of a conventional long profile with the more detailed natural profile of a short reach of Gum Branch. The letters a, b, A and B are locational indicators for figures 16 and 17.

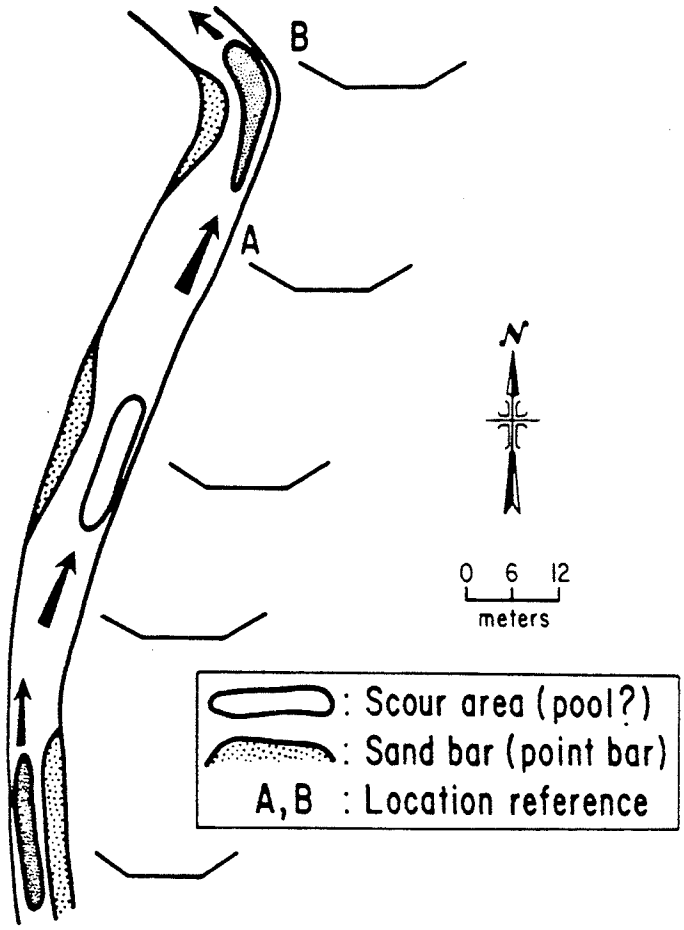


Figure 16 Idealized plan showing the desired channel morphology which will be achieved through the manipulation the cross-sections of Gum Branch. Letters A and B correspond to locations on figure 15.

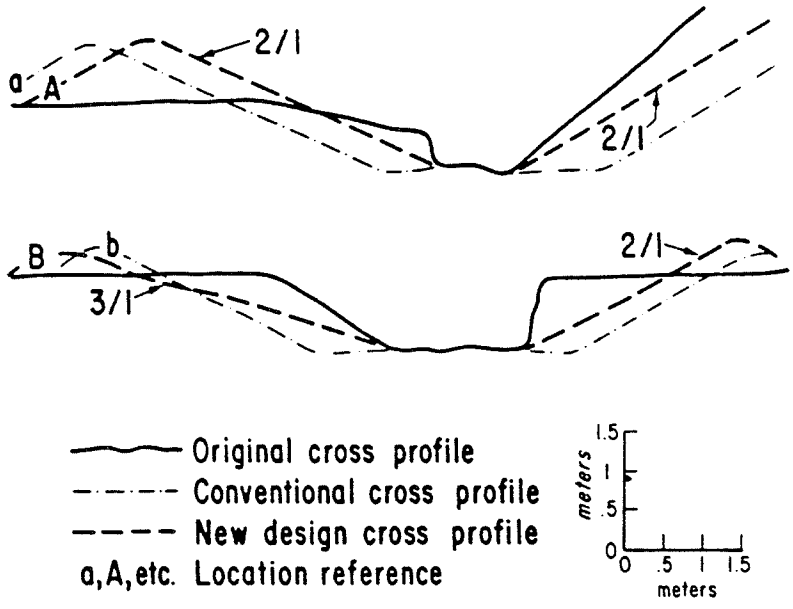


Figure 17 Comparison of cross-sections of Gum Branch. Letters a, b, A and B refer to locations given in figure 15.

Various studies indicate that the pool to pool spacing ranges from 4 to 10 times the channel width (Dunne and Leopold, 1978; Keller, 1975; Keller, 1978; Leopold et al, 1964; Robert Newbury, personal communication, Oct. 29, 1987). In straighter reaches of the channel, the deep side of the pools should alternate from bank to bank. In meandering portions of the channel, pools should be associated with the bends in the channel, where there obviously exists a tendency to erode the outer bank (Leopold et al, 1964). On very large bends, a number of pools may be located all near the outsid bank and spaced apart from their neighbors by approximately 6 channel widths (Keller, 1975).

It might be argued that the construction of these pool and riffle forms is unnecessary, because the channels will form them on their own, shortly after modification. While this is true, pools and riffles formed on their own, in re-constructed conventionally designed channels, are often poorly developed, unstable and usually spaced considerably closer than in morphologically stable channels (Keller, 1975). Unfortunately, conventionally designed channelization projects also often do not allow a morphologically stable channel to develop, even after a considerable amount of time (Dunne and Leopold, 1978). Therefore, it is advisable to provide the optimal spacing of pools and riffles in the design and construction phase of a project rather than to assume that they will develop naturally (Keller, 1975).

If the goal of the rehabilitation work is solely to develop a morphologically stable channel, no special equipment is needed to produce the pools and riffles in the channel (Keller, 1975). A dragline operator can be instructed to produce an asymmetrical cross-section at the pool sites and a symmetrical cross-section at the riffle sites (Keller, 1975).

However, if the project is intended to also develop fish and aquatic wildlife habitat, individual cobbles and boulders must be arranged on the stream bed to create specific local flow conditions, that are preferred by select organisms (Newbury and Gaboury, 1988). The creation of spawning riffles require larger scale manipulations of flow patterns, in the horizontal plane as well as the vertical plane (Newbury and Gaboury, 1988). Studies have shown that walleye prefer spawning on the edge of horizontal eddies

(Newbury and Gaboury, 1988). It has also been observed that, on re-constructed pools and riffles in the Riding Mountain area of Manitoba, walleye use 3 eddy areas: both sides of the pool immediately upstream of the riffle crest, behind large cobbles and boulders on the riffle surface and in large back eddies formed on the downstream face of the riffles at the upper end of the downstream pool (Newbury and Gaboury, 1988). Therefore, it is advisable to create a V-shaped crest of the riffle facing upstream, to concentrate the flow in the centre of the channel as it accelerates towards the crest and decelerates into the pool below (Newbury and Gaboury, 1988).

Also, riffles built in pairs 60 to 100 feet (20 to 30 metres) apart create short central pools with enlarged eddies that extend from the upper riffle to the face of the downstream riffle along each bank (Newbury and Gaboury, 1988). Based on egg density and the number of newly hatched walleye larvae caught below the riffles, paired riffles produce significantly better spawning habitat than single riffles (Newbury and Gaboury, 1988; see figure 18).

The riffles should be of sufficient height to create a pool that extends half way up the downstream face of the next riffle upstream (Newbury and Gaboury, 1988). The downstream face of the riffle should be built at a 20: 1 slope, so as not to obstruct the upstream passage of spawning walleye (Newbury and Gaboury, 1988).

The stones, cobbles and boulders used to create the riffles can be hauled from local stone piles that have been collected from the surrounding fields (Newbury and Gaboury, 1988).

3.5.4.3 SINUOSITY OF CHANNEL PLAN

In a natural stream, straight reaches are uncommon and are seldom longer than 10 channel widths (Dunne and Leopold, 1978; Leopold et al, 1964). Even though the channel banks might appear to be straight, the line of maximum depth often 'meanders' from side to side (Moriwasa, 1968).

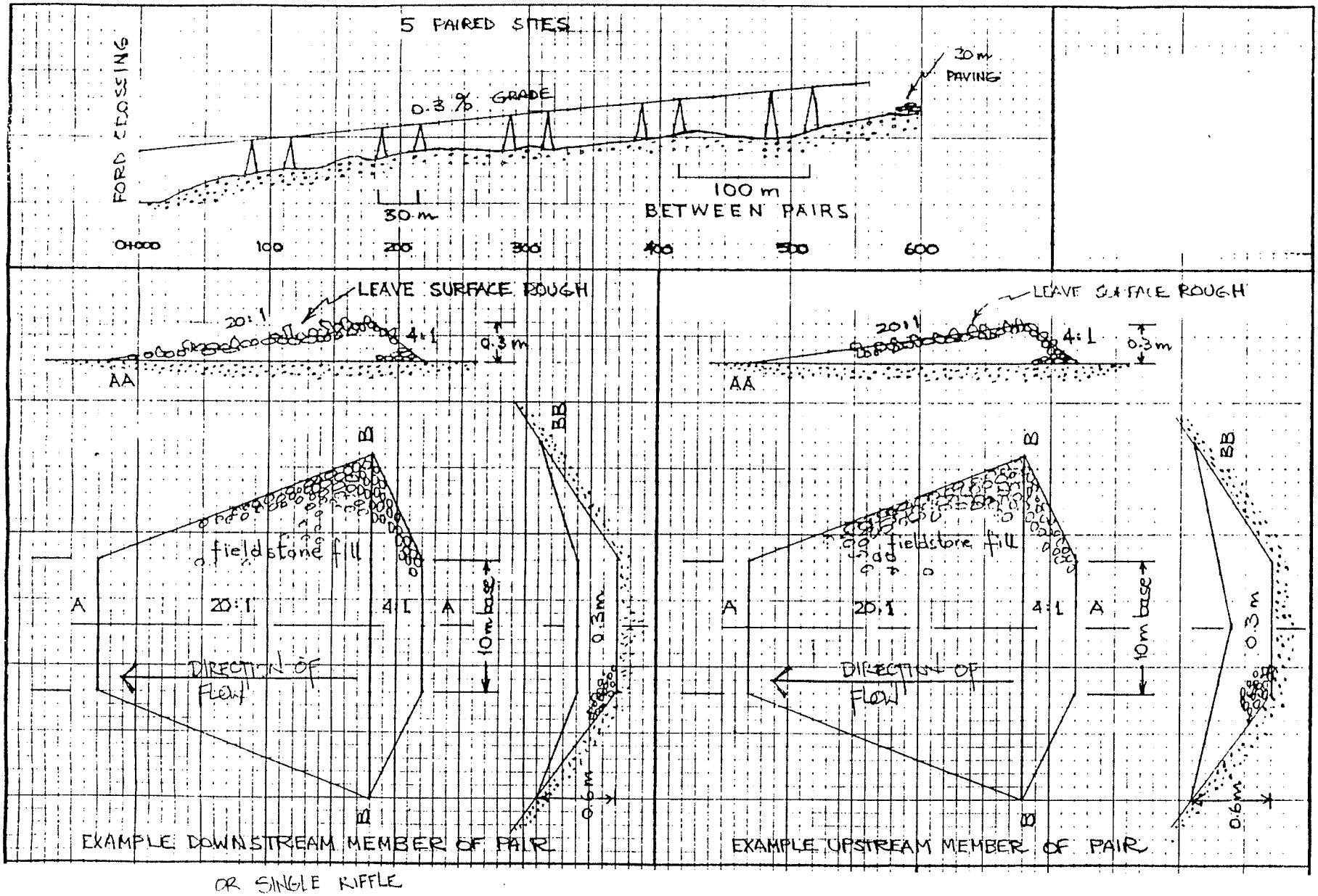


Figure 18 Diagram illustrating gradient control structures that also provide improved fish spawning grounds.

Sinuosity of the original stream may be determined directly from unchannelized portions of the stream upstream or downstream of the channelized reach, remnants of the stream outside of the channelized reach, maps and historic photographs, especially aerial shots (Robert Newbury, personal communication, September 23, 1988). The examination of streams of similar size, in neighboring catchments under identical land-use and geology, as well as the use of regression analysis, and the excavation of trenches across the floodplain, may also help to determine the location and sinuosity of the original channel (Brookes, 1987). But as mentioned previously, when using maps, it is important to be aware of problems with measurement error and data misrepresentation (Brookes, 1987).

Where these 'archival' sources of information are not available, other methods may be used to give a rough estimate of the sinuosity. There are definite empirical relationships between meander morphology and other watercourse characteristics (Moriwasa, 1968). The flows at bankfull discharge are the determinant factor in the creation of the basic form of a watercourse (Leopold et al, 1964). A particularly strong correlation exists between bankfull discharge and bankfull channel width. Thus, channel width, an easily measured dimension, may be used to determine other factors of meander morphology, such as meander wavelength and mean radius of curvature of the meander (see figure 19). While

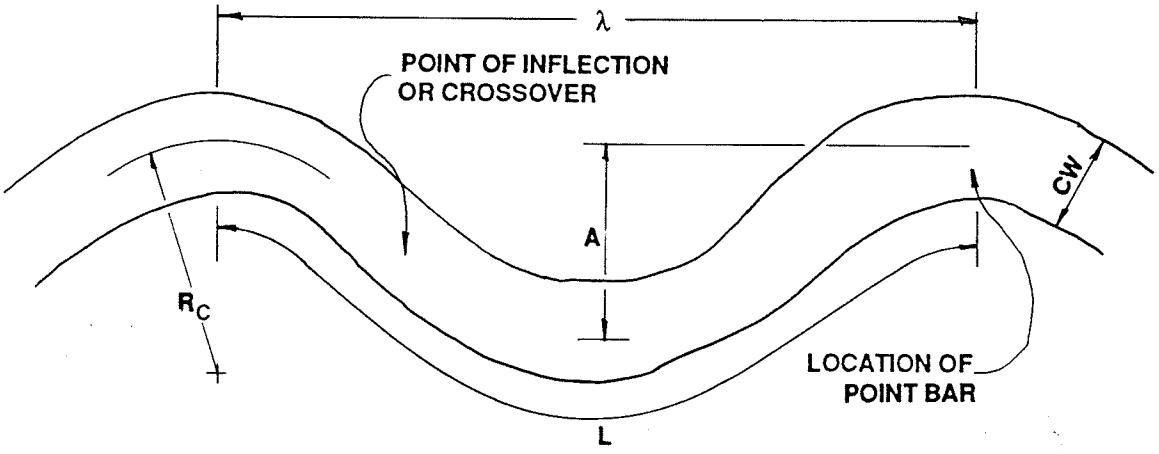


Figure 19 Definition sketch for meanders.

there are some differences due to climatic factors, these relationships hold true through a wide range of watercourse sizes, from laboratory streams, a foot wide, to the Mississippi River, a mile wide and have been generalized in equations based on regression analysis (Leopold et al, 1964; see figures 20 and 21).

METRIC EQUATIONS

$\lambda = 11.03\ w^{1.01}$

$\lambda = 4.6\ R_c^{0.98}$

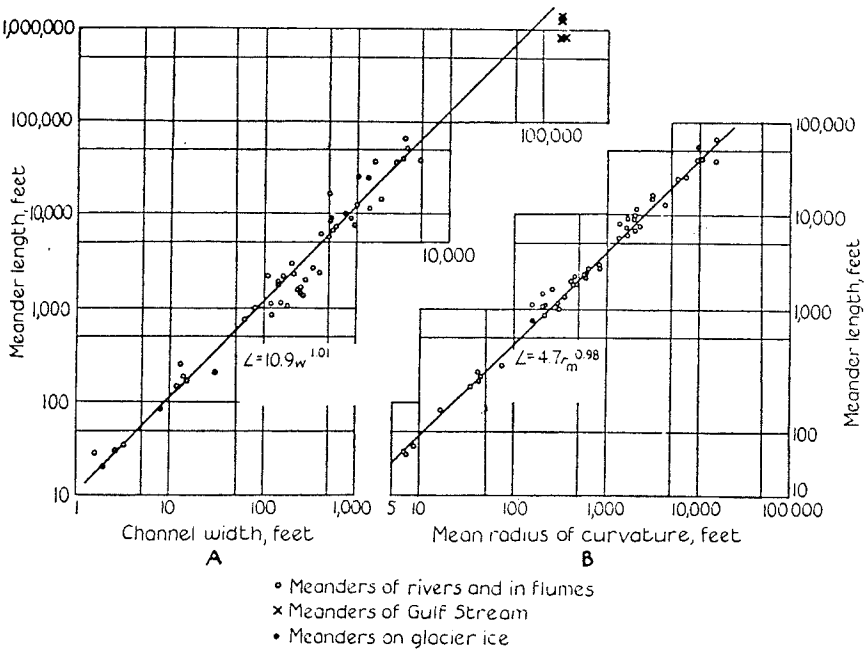


Figure 20 Relation of meander length to width (A) and to radius of curvature in channels (B).

Meander Length to Channel Width	Amplitude to Channel Width	Meander Length to Radius of Curvature	Source
$\lambda = 6.6w^{0.99}$	$A = 18.6w^{0.99}$	—	Inglis (1949, pt. 1, p. 144 Ferguson data)
	$A = 10.9w^{1.01}$	—	Inglis (1949, pt. 1, p. 149, Bates data)
$\lambda = 10.9w^{1.01}$	$A = 2.7w^{1.1}$	$\lambda = 4.7r_m^{0.98}$	Leopold and Wolman (1960)

Figure 21 Empirical relationships between size parameters for meanders in alluvial valleys. Note all equations in imperial.

Simplifying these equations it is possible to state that the usual spacing of meanders is from 6 to 10 times the channel width (Leopold et al, 1964; Moriwasa, 1968; Robert Newbury, personal communication, September 23, 1988). The ratio of meander wavelength (l) to radius of curvature (R_c) is approximately 4.7:1 (Leopold and Langbien, 1966). Sinuosity or tightness of bend is expressed as a ratio between length of the channel (L) and meander wavelength (l), with average values ranging from 1.3:1 to 4:1 (Leopold

and Langbien, 1966). Measured along the length of the channel plan analogous points of the wave are spaced approximately 11 to 16 times the channel width (Leopold et al, 1964). Successive points of inflection or crossover of a meander are spaced at about 5 to 7 times the channel width when measured along the channel (Leopold et al, 1964). These inflection points are quite comparable to riffles found in a straight stream, since they are relatively shallow and spaced at approximately the same distance apart (Leopold et al, 1964).

In contrast to meander length, radius of curvature and location of inflection points, amplitude of the meander relates poorly with channel width (Leopold et al, 1964). The size and composition of the material making up the bed and banks of the stream often has a direct influence on the erosive characteristics of the stream (Brookes, 1987). Thus, it is likely that amplitude is determined, more by the composition of the material that the watercourse flows through and other local factors than, by hydrodynamic principles (Leopold et al, 1964).

3.5.5 BANK AND BED STABILIZATION

3.5.5.1 HARD TECHNIQUES

No continuous lengthwise stone or concrete construction, which could rob the stream of its dynamism, should be used (Bolliger et al, 1984). Preference should be given to other techniques that allow silting and erosion within controlled limits (Bolliger et al, 1984).

The design of the channel should include a natural morphology appropriate to the stream size, a highwater channel of a size in accordance with the flood potential and a low water channel having natural characteristics that maintain biologic activity (Dunne and Leopold, 1978).

GABIONS

(see figures 22 &23)

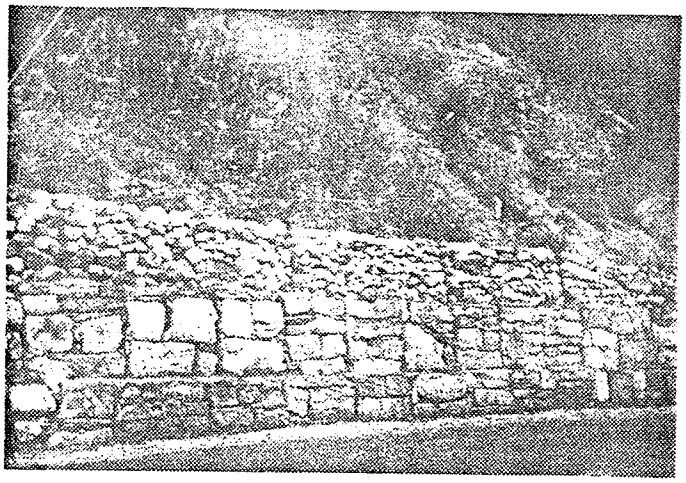


Figure 22 Gabion for the stabilization of a failure slope.

Gabions are squares of wire mesh placed and filled with rocks. The top is knit together with steel wire. Today, prefabricated forms are available in many shapes and sizes and need only filling. While gabions allow effective cheap stabilization in a minimum of area, disadvantages include an unnatural appearance, a need for an absolutely stable base and potential ineffectiveness, if the slope movement or washouts occur in the soil beneath them.

RIPRAP

(see figures 24 & 25)

Brookes (1987) has described the use of riprap in natural stream landscaping. Experience, in North America, with restoration and enhancement techniques, where hard surfacing is required, shows the advantage of riprap as opposed to more conventional techniques such as gabions or concrete revetments.

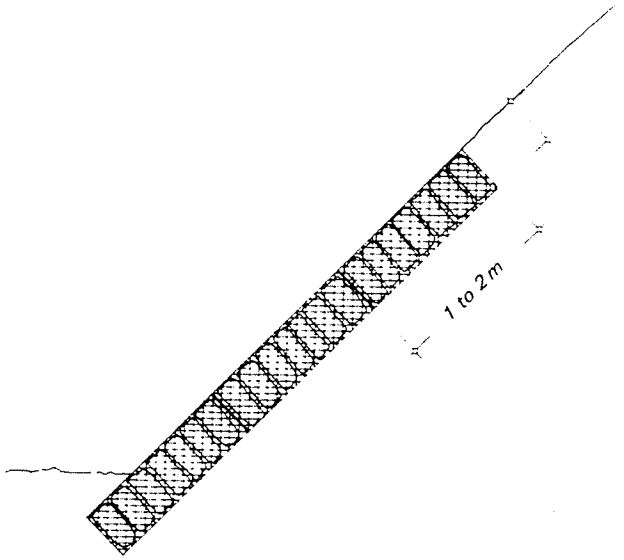


Figure 23 Cross-section of gabions for slope stabilization.

Riprap is natural rock or quarry stone, dumped or hand placed

against the banks of the stream in locations that are scouring (see figure 25). If the bank is too irregular or too steep, the sides of the watercourse are re-graded before placement of the stones, . Riprap, in addition to providing a less erosion prone surface as a result of increased surface roughness, reduces water velocities and the tractive force of the water. Riprap can also be used on the bed of the stream to control bed erosion at selected locations.

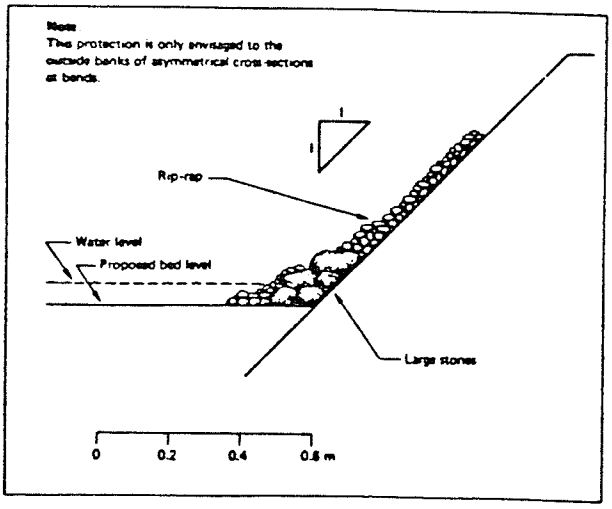


Figure 24 Placement of riprap for bank protection at bends.

Riprap is an effective, flexible method, that is not weakened by movements of the bank, as a result of minor adjustments. It is a simple means of stabilization, requiring no special equipment and is easily maintained by placement of further rock. Riprap does not have as large an effect on the flora and fauna of the watercourse, as smooth constructions, although as with any construction activity which disrupts the channel, species diversity is greatly decreased in the short term. The advantages of this technique are the relatively natural appearance of the stone and the fact that vegetation can become established between individual stones, especially if a soil cover is applied. The vegetative growth thereby provides a stable environment for benthic micro- and macro-invertebrates and fish, as well as cover for animals on land. The weathering of the stones in the channel may also result in the formation of gravel beds suitable for fish spawning. Because of its potential to appear slightly more natural and its ability to shift with ground movements, riprap is vastly superior to gabions, from a natural stream landscaping viewpoint.

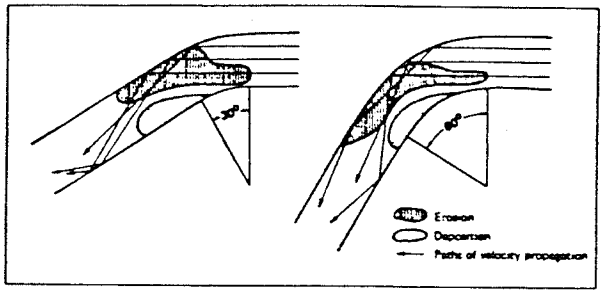


Figure 25 Diagram showing where riprap protection is required on bends.

Schiechtl (1982) has done extensive studies on bio-engineering methods and describes three hard techniques that may be used.

ROCK PLACING

(see figures 26 & 27)

Large rocks of some weight are placed around the banks of the stream in a specific pattern. Placement can be done manually or, if the rock is very large, with machinery. Construction begins at the bottom of the water channel and has to be protected against movement. One method is 'elastic rock construction' in which rocks weighing 650 to 1100 lbs. (300 to 500 kg.) are connected by a cable and tied to pegs anchored in the soil. The cable is hooked onto the rocks by pegs or with V-shaped steel anchors set in holes that have been drilled into the rocks. This set of rocks is protected against washouts by ground sills or spurs consisting of a row of

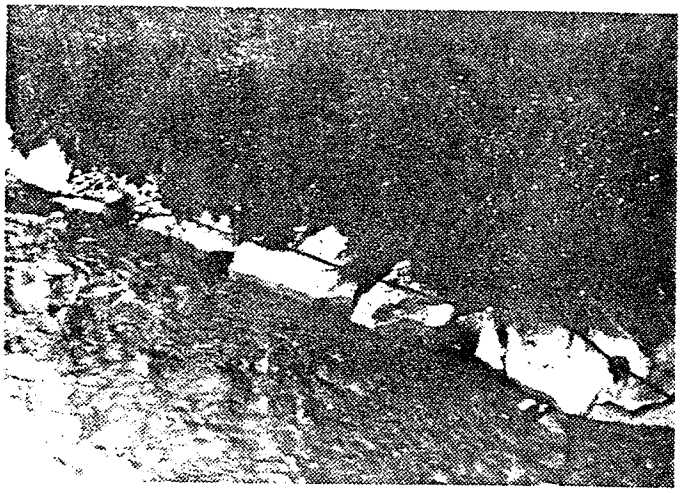


Figure 26 Flexible rock construction for bank stabilization. Rocks weighing 650 lbs. to 1100 lbs. (300 kg. to 500 kg.) are connected by cables which are tied to poles.

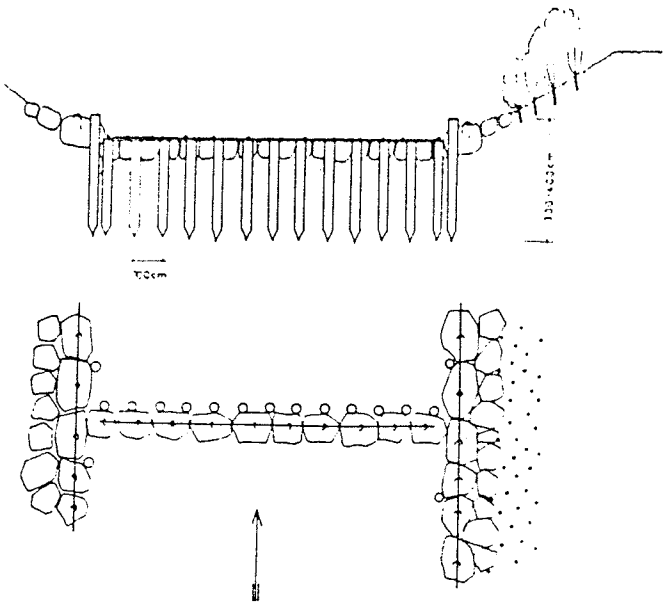


Figure 27 Flexible rock construction for bank stabilization and ground sills.

pillars with a set of stones laid behind them (see figure 27). The top of the riverbank is protected above this set of stones with live plant material. Due to its flexibility, this system can survive the worst conditions. It changes according to water and bedload movement in the watercourse. The system, if properly designed and placed, blends unobtrusively into the landscape.

LOOSE ROCK AND BLOCK FILLS

(see figure 28)

This method, similar to riprap, consists of the dumping of rocks along the stream bank or bed. The faster the water the larger the rocks must be. Since the size of the stones is limited by transportation difficulties and since stones weighing over 2 tons have been moved during floods, it is best to connect individual stones with cables along the river-bank and to drop the entire rock chain into the water. Rock fills are generally used for the protection of channel banks from fast flowing water and are established below the water surface. Until a balance is reached, spare rocks may be required after the initial dumping as some filling up with additional material may be required at various points.

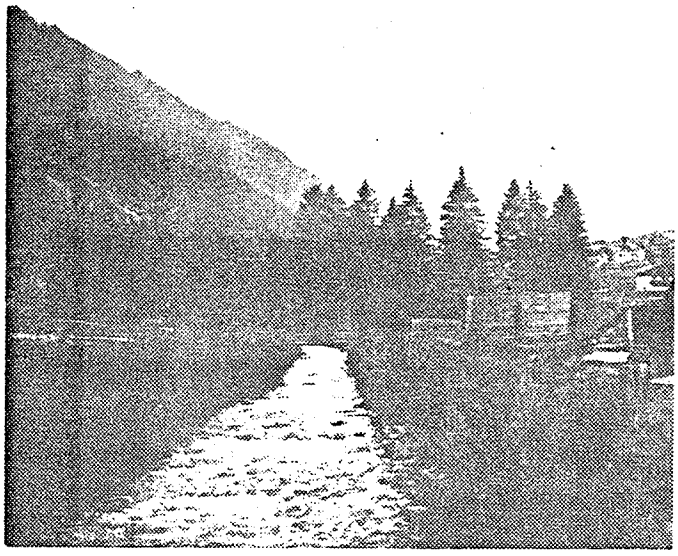


Figure 28 Mountain stream in Italy protected by flexible rock construction and ground sills.

ROCK PAVINGS

(see figure 29 & 30)

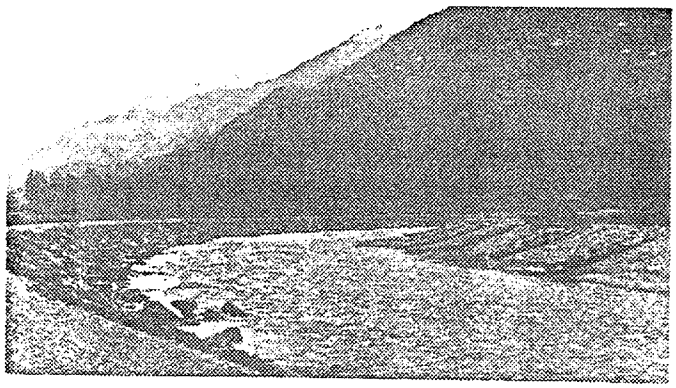


Figure 29 Bank stabilization using uneven rough rock paving in a stream experiencing dynamic changes in discharge and heavy boulder movement.

Rock pavings are built to protect slopes and the bed of water channels, that experience heavy ice and boulder movement. While, standard construction consists of uneven or rough rock paving laid in concrete or asphalt, it is also possible to use dry rock pavings without mortar or bitumen, in which the stones are placed on top of a gravel layer and the joints filled with gravel. It is built with rocks, 8 to 24 inches (20 to 60 cm.) thick and heavy enough to resist the tractive force of the water. Longitudinal joints in the direction of the water flow must be avoided and all joints can be joint planted (see below). The faster the current, the rougher the surface should be. If the gradient of the bed is steep, stone paved water channel beds should be subdivided by ground sills or rows of poles into different sections, similar to the construction shown in figure 27.

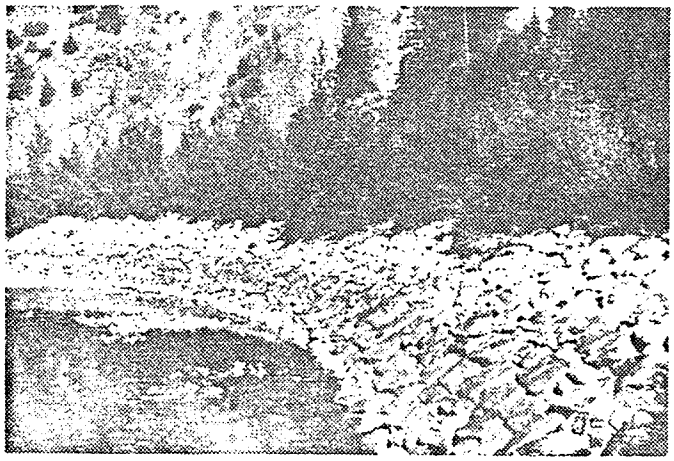


Figure 30 Stabilization of a riverbank with highly fluctuating water levels using rough rock paving. The top of the bank has been protected with willow cuttings.

Rock pavings can also be built with concrete parts. However, the fairly smooth surface that this creates often has hydraulic disadvantages. The use of concrete slabs and rocks with rough edges would correct the problem.

3.5.5.2 BIO-ENGINEERING TECHNIQUES

To be effective, constructions for erosion control and the stabilization of channel beds and banks do not have to be made out of hard, dead materials alone (Schiechtl, 1982). Very effective stabilization can often be obtained through a combination of hard constructions and vegetation or through the use of vegetation alone. Stabilization and protection constructions, combining live and dead materials, are effective immediately on completion of construction (Schiechtl, 1982). With the rooting development and growth of the plants, the technical effectiveness increases accordingly and gets even stronger as the plants grow older (Schiechtl, 1982). When compared to conventional engineering techniques, live systems have many advantages including longer durability, better aesthetics, higher effectiveness, less maintenance and reduced cost of the entire project (Schiechtl, 1982). In his book, Bioengineering for Land Reclamation and Conservation (1982), Schiechtl describes a large number of possible techniques in detail. Listed below are some of the methods.

PROTECTION SEEDING FOR ROCKY BANK AND SHORE SURFACES
(see figure 31)

Seeding with grass will improve the effectiveness and increase the durability of conventional engineering techniques, such as riprap, rock fills or concrete blocks. Clayey, humic sand or dry, loamy gravel and seed is washed in with water or brushed in with a broom into the spaces between the rocks.

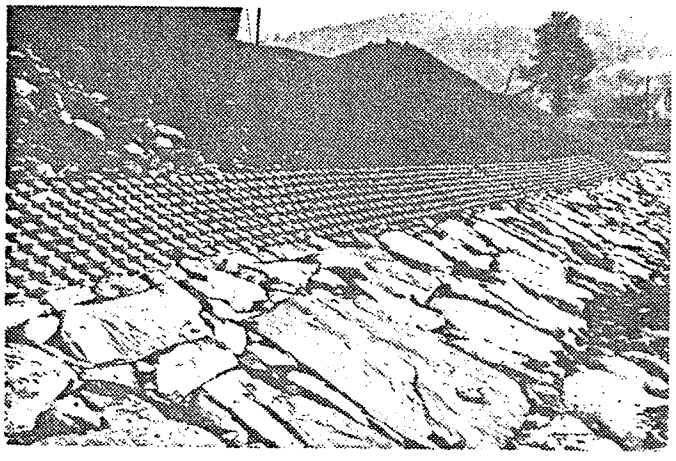


Figure 31 Riverbank stabilized with rock paving (natural stone) and concrete gratings before revegetation with grass seeds (sodding). The joints are filled with clayey humic sand, the seed material is broadcast and brushed in.

SODDING

(see figures 32 & 33)

It is best to use commercially produced sod for the protection of water channel slopes. In order to further stabilize the construction, it may be necessary to place a wire mesh underneath the sod or even better, to use sod that has been grown on a wire mesh or nylon nets and has taken root. If the slopes are steep or water velocities high, the sod may require pegging. Pegs keep the sod from drifting and washing away during floods.

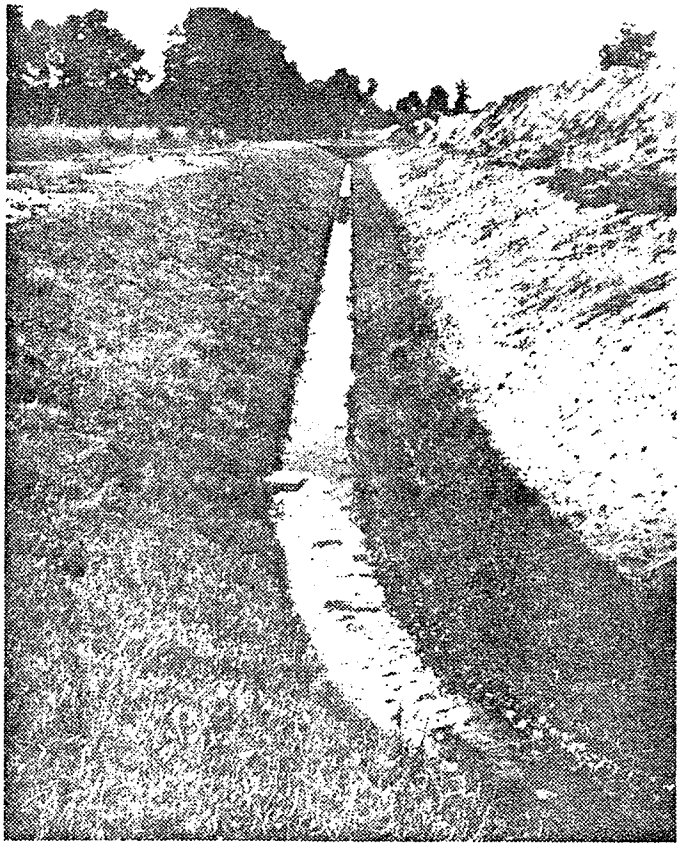


Figure 32 Sod slabs obtained while excavating ditch are placed in strips on the most critical sections of the slope.

WATTLE FENCES

(see figure 34)

Wattle fences are massive constructions of interwoven branches, that are approximately a half metre tall and used as protection against washouts. The inland side of the fence is often secured with

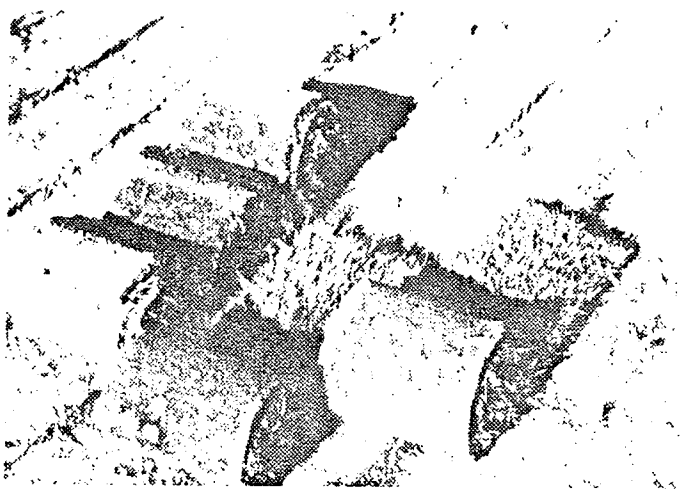


Figure 33 Placement of commercial sod strips.

rocks. The live branches, on the water side of the construction must stick out of the fence 20 to 30 inches (50 to 80 cm.) Wattle fences are often used to secure branch packings and brushmattresses and in combination with rough bedded channels in drainage ditches. Along a water channel where a shrub belt did not exist, wattle fences have been used by E. A. Keller to protect the lowlying areas. Wattle fences can also act as a concentrating agent, protecting the floodplain from the deposition of material such as floating logs, pieces of lumber and branches without preventing the overflow of floodwaters which can then deposit their fine grained material.

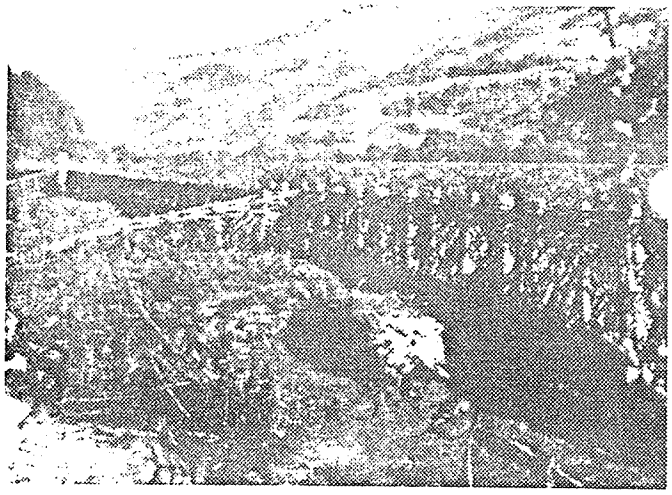


Figure 34 Wattle fence with washout protection.

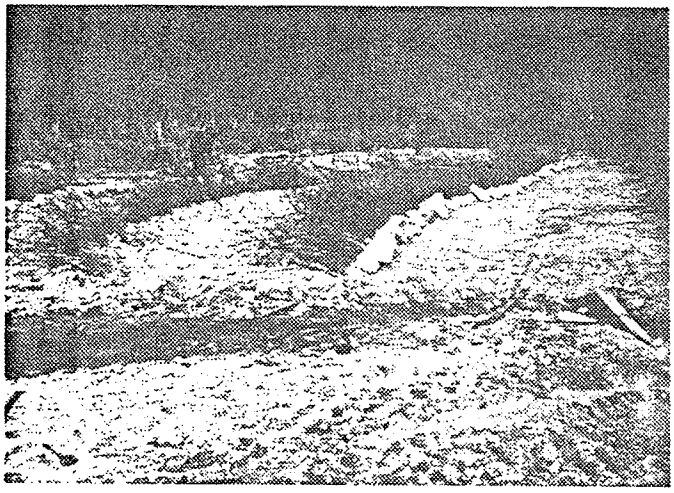


Figure 35 Live brush and comb construction immediately after placement.

LIVE BRUSH AND COMB CONSTRUCTION

(see figures 35, 36, 37, 38 & 39)

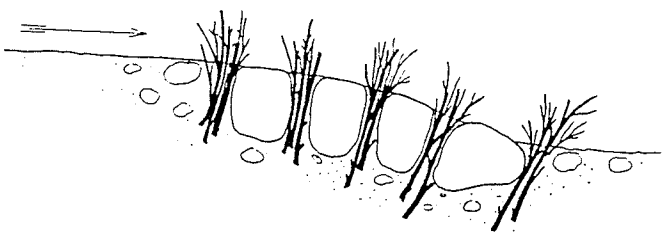


Figure 36 Diagram of a live brush and comb construction built as a ground ramp.

To build live brush and comb

constructions, triangular ditches, facing about 10° to 30° from the current, are excavated in the water channel. Live cuttings and branches are placed into these ditches, pointing upstream at a 60° angle. The vegetation should be placed so that approximately 1/3 to 1/2 the length of the branches is underground. Finally, the branches are further protected with rocks, gabions, fascines, round timbers or wattle fences. After the ditches are filled, with the material previously excavated, about 4 to 8 inches (10 to 20 cm.) of the branches or cuttings should protrude.

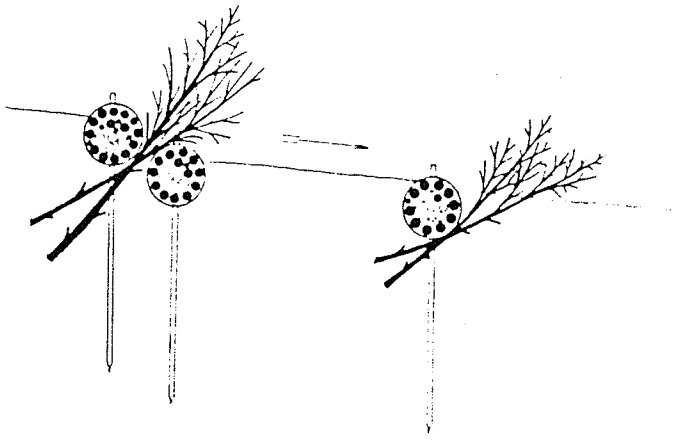


Figure 37 Diagram of a live brush and comb construction incorporating live fascines.

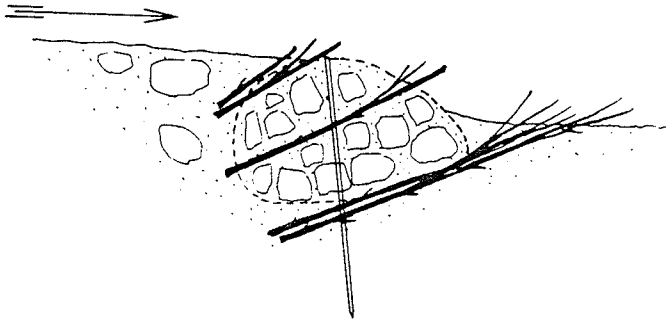


Figure 38 Diagram of a live brush and comb construction incorporating gabions.

Fascines, usually 4 to 6 inches (10 to 15 cm.) in diameter and 6 to 12 feet (200 to 400 cm.) long, consist of live branches tied together with wire at least 1/10 inch (2 mm.) thick, every 12 inches (30 cm.) (see figure 40) While they are usually made of live material, it is

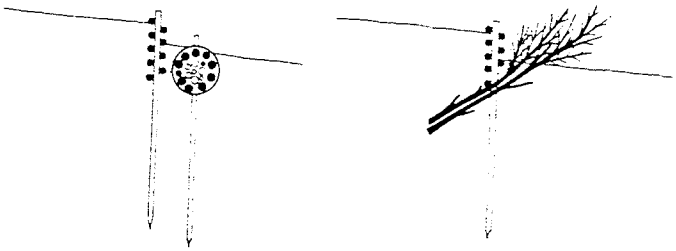


Figure 39 Diagram of a live brush and comb construction incorporating submerged wattle fences.

possible to fill the centres with some dead material. If the whole fascine is to go underground, then the entire construction can consist of dead material.

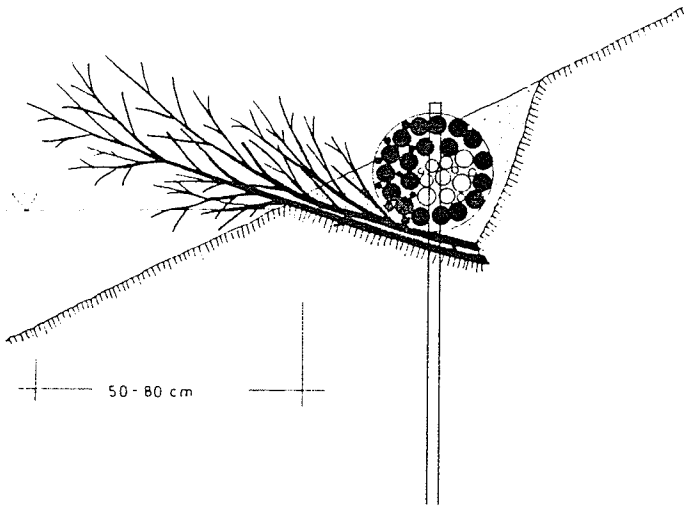


Figure 40 Diagram of a live fascine.

Live brush and comb constructions reduce the tractive force of the watercourse and therefore promote siltation. The roots of the vegetation prevent erosion of the stream margins after the plants have become established. It is a simple, cheap, fast building method, good for use on berms or stream margins, but can only be used in wide deep, shallow floodplains. When the vegetation is immature, repairs are necessary after a flood.

The live brushes and combs develop rapidly into a dense thicket. As siltation increases and flooding decreases, other species will invade and the area will progress towards a more stable plant community.

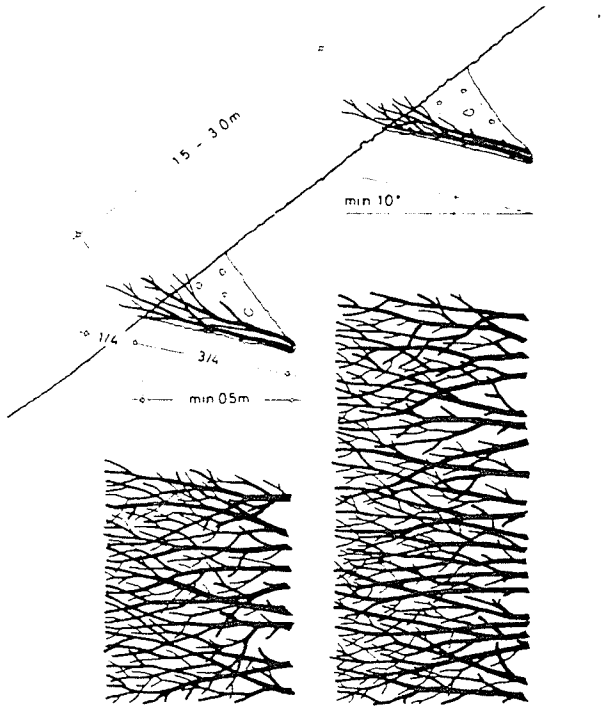


Figure 41 Diagram of brushlayer construction on a cut slope. Work should be done from bottom to top.

BRUSHLAYER BARRIERS
(see figure 41)

Brushlayers barriers are most effective in controlling erosion occurring down the slope.

A terrace, 6 to 40 inches (15 to 100 cm.) wide, is cut out of the slope at an angle sloping up at an angle of at least 10°. Branches, placed in the trench, should be at least 1 metre long and only 1/5 to 1/4 should stick out. The branches should be placed crosswise, not parallel to each other, so as to allow the uses of longer branches and should be covered by as much soil as possible. It is very important to mix branches of different species, different ages and different thicknesses to promote a deeper penetration of roots and more variety of surface growth. To ensure that the ground will not dry out before the placement of the live material, the complete set of ditches should not all be excavated at once. The use of shorter ditches, that are extended as work proceeds, is recommended.

BRUSHMATTRESS CONSTRUCTION

(see figures 42, 43 & 44)

Brushmattress construction consists of live branches laid flat such that a complete cover is established. The butt ends of the branches are placed in the soil and well covered so that they can root and do not dry out or wash away. If the branches are not long enough to cover the entire slope, the lower ones must cover those further up the slope by at least 30 cm. The brushmattress is then secured to the ground with wire, cross laid branches, fascines or wattle fences in rows 30 inches (80 cm.) apart. Finally, the whole construction is lightly covered with earth or fill. Root penetration is improved if the soil is dry and permeable. Therefore, topsoil is not necessary and compost should not be added to the soil.

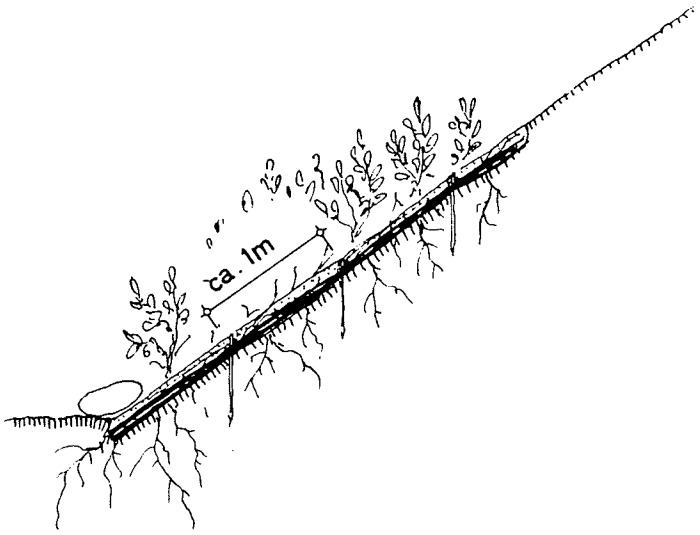


Figure 42 Diagram of brushmattress construction.

It is easiest to anchor brushmattress constructions with strong wire. Live or dead wood pegs are driven in to the ground 20 to 30 inches (60 to 80 cm.) apart. Wires are tied to the pegs and the pegs are then driven deeper into the ground, stretching the wire tight, pressing the brushmattress firmly into the ground. In particularly endangered areas, such as wavelap zones, it may be necessary to anchor the brushmattress more securely with wire mesh that covers the entire construction.

Figure 43 Brushmattress immediately after placement.

The brushmattress gives immediate cover after installation, protecting against erosion by waves and flowing water, even before the branches take root. Using live materials gives a permanent effect and under the protection of the growing branches, it is possible for climax vegetation to establish itself quickly. The dense root net-

Figure 44 Detail of a newly constructed brushmattress.

work and brush thicket that develop from the construction are very effective in repairing damaged areas. Since construction time ranges from 2 to 5 hours to place each square metre, cost is moderate. But, this method does include a number of disadvantages. Large amounts of material and labour are required. Regular pruning, every 2 to 4 years, is required to maintain a flexible, elastic growth. Where growth does not hinder water flow, the vegetation may be allowed to develop into a tall shrub thicket, requiring cutting only every 7 to 10 years. In order to promote growth with flexible branches, it is also important to regularly remove any invading plants.

JOINT PLANTINGS

(see figures 45, 46, 47, 48 & 49)

By reducing the water speed and absorbing waves, drifting ice and boulders joint plantings offer excellent protection for riverbanks and are frequently used to replace constructions of stone, cement, mortar and concrete.

Joint plantings consist of cuttings that are placed into the mortarless joints of stone walls and stone piles. A hole is made in the joint, with a large crowbar or pick and a cutting is put in, as the crowbar or pick is being removed. Any soil around the cutting is firmly tamped down to ensure that the cutting is securely in place. After the joints have been planted, it is advisable to fill them with dry sand or better still, to wash in fine material, such as clay. The use of topsoil is optional.

Figure 45 Seventeen year old joint planting for bank stabilization.

A hammer may be used to drive the cuttings in, as long as the bottom of the cutting has been sharpened to ensure easy

entry. The cuttings must be long enough to penetrate into the soil behind the stone walls. No more than 1/3 of the cutting should be left above the ground to avoid it drying out. Preferably, the cuttings should be placed irregularly. Under no circumstances should they be placed in rows, because the appearance then would be too artificial. The number of cuttings to be implanted is dependent on the size of the paving stones. However, on rivers and creeks with strong bedload movement, a minimum of 5 cuttings per metre square should be used when smaller stones are used, the plantings must be more dense. Since most woody plants cannot survive more than 6 weeks of flooding, joint plantings should not be placed lower than the normal summer waterline.

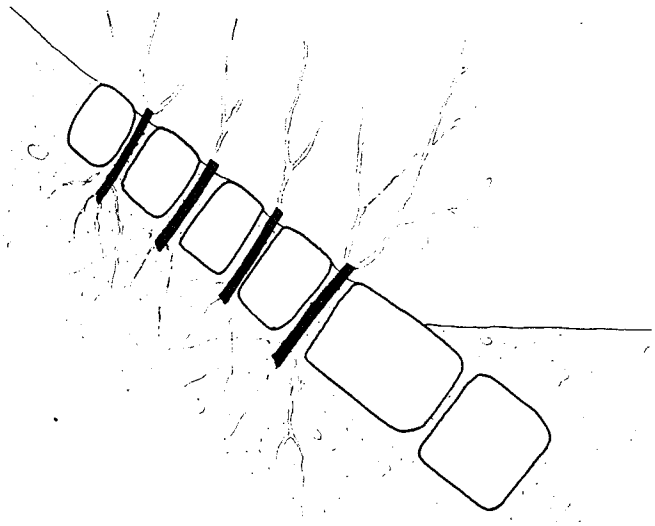


Figure 46 Diagram of a joint planting.

Healthy 1 to 2 year old cuttings, without branches, 1 to 2 inches (2 to 4 cm.) in diameter and 8 to 16 inches (20 to 40 cm.) long, should be used. Unfortunately, plant losses ranging from 30 to 50% is common with this technique. However, cuttings of 16 to 24 inches (40 to 60 cm.) long will have a better survival rate, if the water supply is poor. When placing the cuttings, approximately 50 to 75 square feet (5 to 7 square metres) of area may be covered in an hour. This time includes all auxiliary work such as cutting, transporting and backfilling.

Soil stabilization commences with root formation and the rock paving is fortified so well by the roots of the vegetation, that smaller rocks of lesser quality, than those that would normally be required in the circumstances, can be used (see figures 46 & 47).

Joint plantings improve the local micro-climate. Pruning will further improve this micro-climate and will result in a fast developing vegetative cover. Falling leaves and rotting ground vegetation forms a humus layer which protects the wall effectively. On dry sites the cuttings grow better in the joints of rocks than those that are planted in the open because more moisture is retained than in the bare soil.

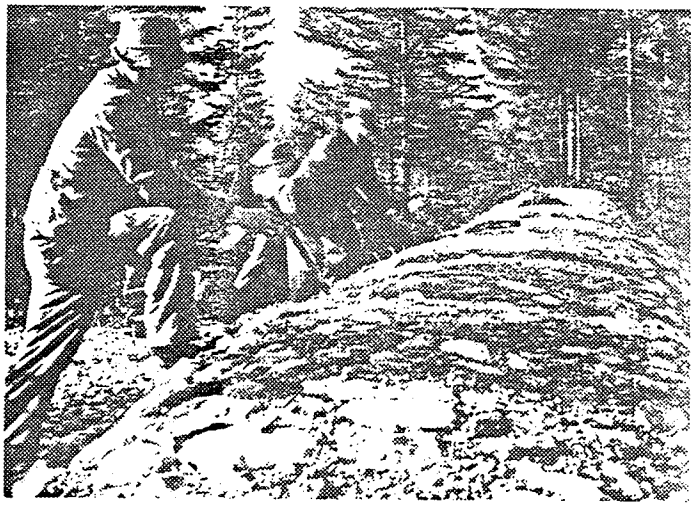


Figure 47 Joint planting on a dam with rock pavings.

One problem often incorrectly associated with joint plantings is that the cutting as they mature and grow, lift the paving stones. Only trees, because of their heavy roots, lift the paving. The roots of shrubs are small and shallow, growing parallel to the soil surface and the deep, widely penetrating roots of hardwood cuttings planted close together increase in diameter very little (see figure 48). The close planting prevents individual shrubs from becoming very large and thus possibly destructive.

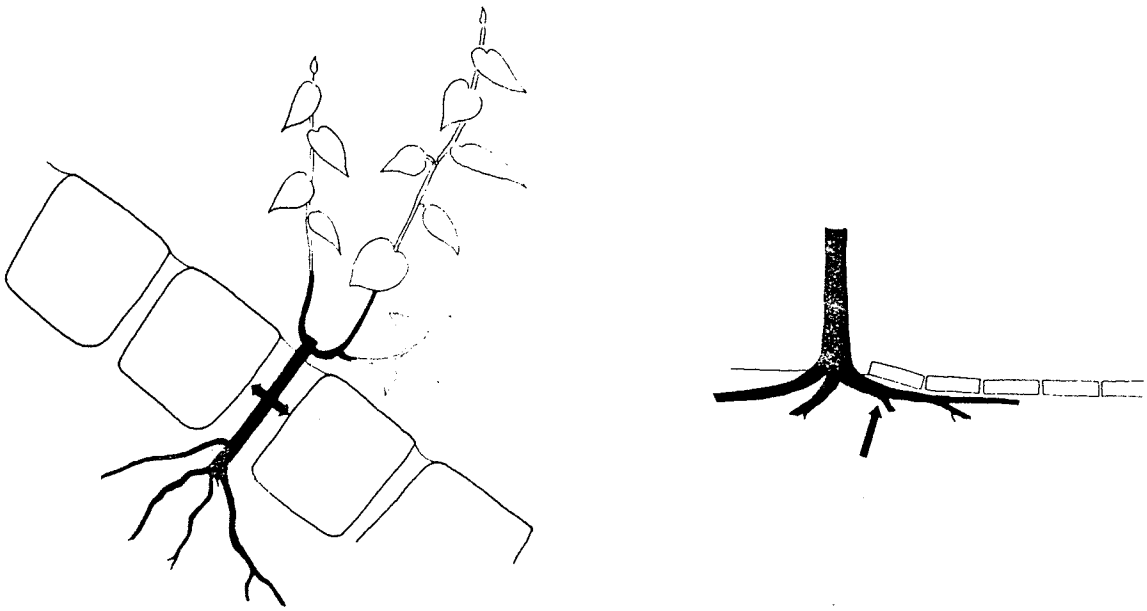


Figure 48 Diagram of deformation of rock pavings through plant growth.

While joint plantings are inexpensive, the placing of the rock paving may be costly. However, the construction is flexible, permeable cheap and durable. Should a joint planting construction become overloaded or break, the stones may be re-used and the wall easily rebuilt, whereas a concrete or mortared stone wall would be completely destroyed and the ensuing repairs exceedingly costly.

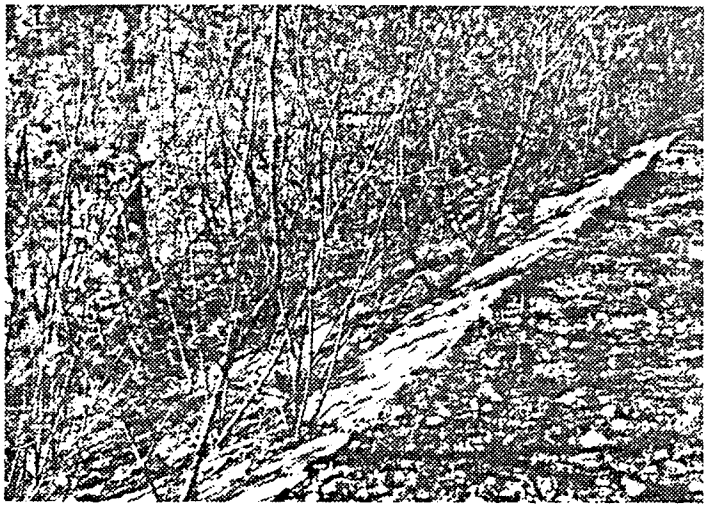


Figure 49 Four year old joint planting in a bank stabilization construction. Note that no deformation of the rock paving has occurred.

The advantages of joint planting are that it is a cheap, quick building method that will produce an excellent effect over an entire area. It is a fast and inexpensive way to plant slopes in order to control water quickly and permanently and provides instant shading over an entire area. Maintenance, only necessary where the initial vegetation is the desired climax community, involves cutting out all invading vegetation every 3 to 5 years. The main disadvantage is that there is no stabilization, other than what the paving provides, until the roots of the plants have taken hold.

ROCK FILL WITH LIVE BRANCH LAYERING

(see figure 50)

After only a few years, construction sites, where rock fill with live branch layering has been used, look like naturally grown shorelines. To build it, large rocks are deposited in a layer onto the damaged streambank, long live branches are placed on top and then another rock layer is placed over top of the whole construction. The rock fill must follow the original shoreline and the slope angle should be as shallow as possible, so that the

rocks will not roll down when floods occur.

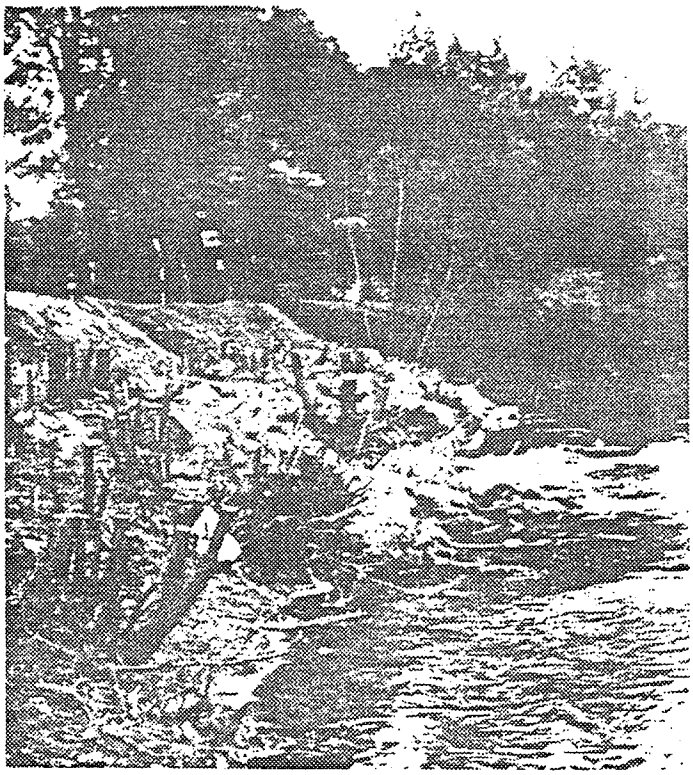


Figure 50 Rock fill with live branch layering, 10 years after placement with foreground pruned to show growth of brush.

The branches are placed butt end into the ground, at an upward angle toward the outside, so that they can take root. When the construction is completed, the branches should protrude 20 to 40 inches (50 to 100 cm.) out of the rocks. The branches should be placed such that the rocks hold them in place and not even floods can pull them out. To improve plant growth, the branches should be pruned and fertilized, during the second year.

Rock fill with live branch layering is a fast, simple method that produces a natural looking result. It is used, primarily, to repair small breaks in banks and along shorelines. The rough surface of the rocks and the protruding flexible branches reduce the water velocity. Rapid siltation occurs between the cracks in the rocks, improving growth conditions for the branches and within a few years a growth of dense brush is achieved.

BRANCH PACKINGS

(see figures 51, 52 & 53)

The method of branch packing was developed in order to shift large gravel banks, by the confinement of the current to a single channel and making use of the energy of the flowing water. To present, no more economical method has been found to obtain the same results.

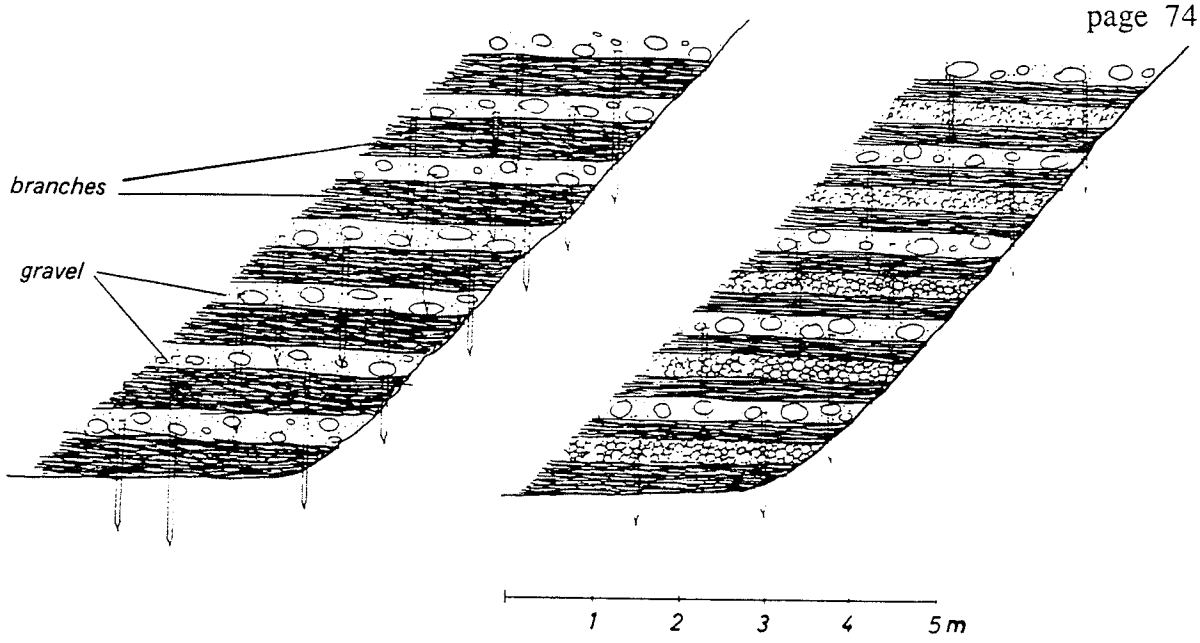


Figure 51 Diagram of branch packing for gully stabilization.

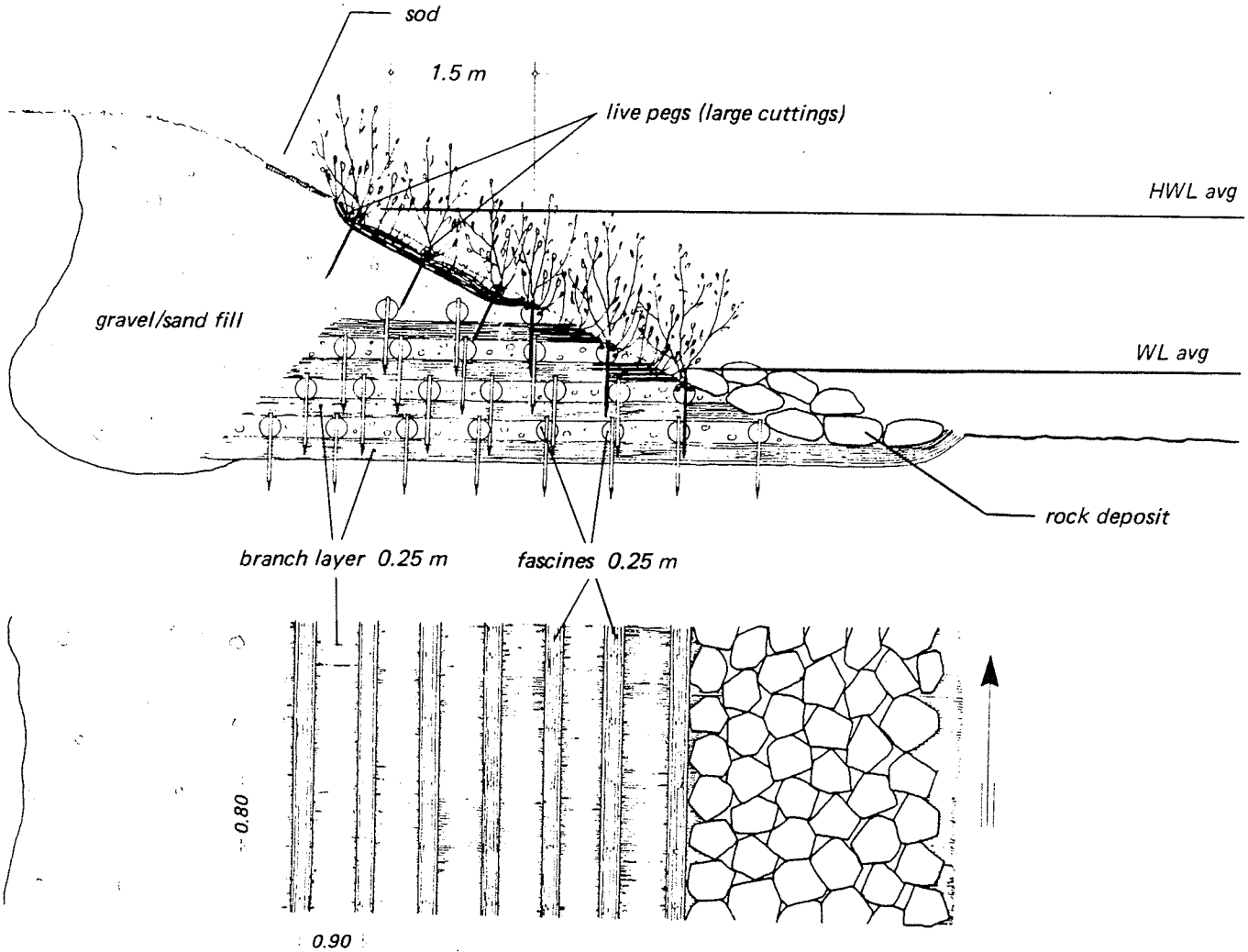


Figure 52 Diagram of branch packing for shore protection.

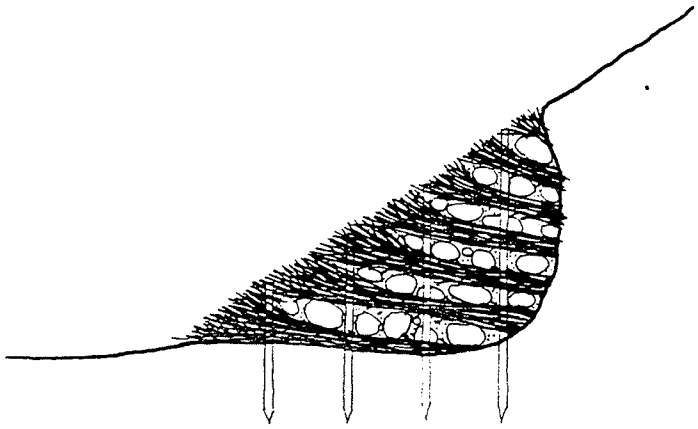


Figure 53 Branch packings between poles previously driven in.

To implement this technique, branches are placed in layers 8 to 12 inches (20 to 30 cm.) thick, covered with gravel, rocks or fascines and tied down to pegs, before the next layer is put in place (see figures 51 & 52). Branch layers may also be placed between previously secured poles (see figure 53). For shallow breaks, live branches should be used. Individual layers of branches may be placed in the same direction, but are usually placed at right angles to each other. It is important that the tips of the branches be placed in line with the planned future shoreline. The toe of the slope is a critical portion and should be further protected with rock fill. Branch packings placed well below the water level, where rooting and new shoots are not expected, should be of dead material.

This is a sturdy, stable construction that can be placed in deep water and can withstand the heaviest flooding. Branch packings are especially effective for the repair of large breaks in the banks of very deep waterways. The densely packed branch tips protrude into the water, effectively directing the water flow, so that radical changes in flow direction are possible. Along the entire length of the construction, water speed and tractive force are reduced by the exposed branch tips, allowing a large amount of siltation to take place rapidly.

LIVE SILTATION BARRIERS

(see figures 54, 56, 56 & 57)

Live siltation barriers involve the construction of massive forms of live branches or live brushlayers. When the ground is dry, a ditch approximately 12 inches (30 cm.) deep and

20 inches (50 cm.) wide is dug with machinery and the excavated material is placed on the downstream side of the ditch. Live branches, 3 to 5 feet (100 to 150 cm.) long, are driven into the ditch, so that they point out at a 45° to 60° angle. Enough live branches must be used to form a solid wall. No gaps can be left, because they will allow damage to occur, destroying the whole construction. The branches are then covered with rocks, rubble or cylindrical gabions to keep them from drifting. In an infertile creek or riverbed, the branches should be first covered with topsoil. The top of the rock fill, rubble or gabions should be at the same level as the average water level. If the construction is underwater, where a ditch cannot be dug, logs or square timbers, which can be removed and reused after construction, are used to form a trench and the construction is placed inside.

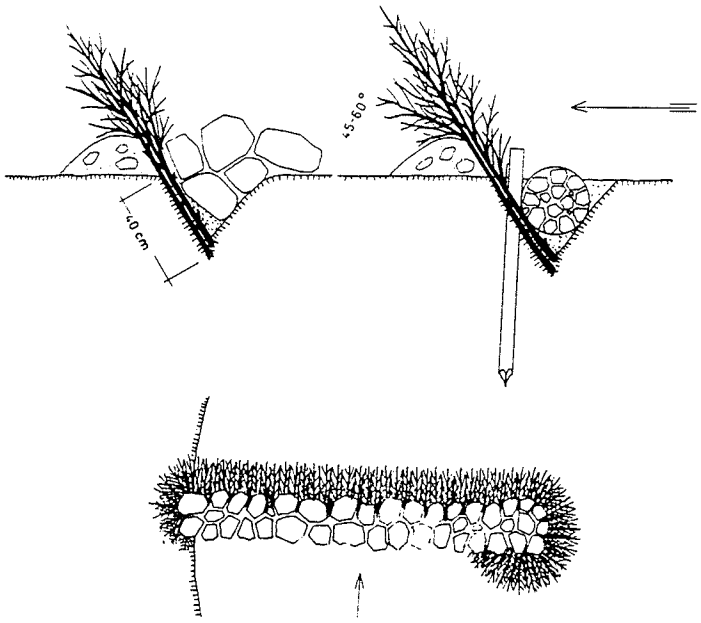


Figure 54 Live siltation construction. Top left: live siltation construction with riprap. Top right: with fascines for stabilization. Bottom; diagram of plan view.

Because of the great water pressure at the ends of the live siltation construction, these points must be carefully built. The 'head' end, that faces the river, has to be built such that the branches create a fan form.

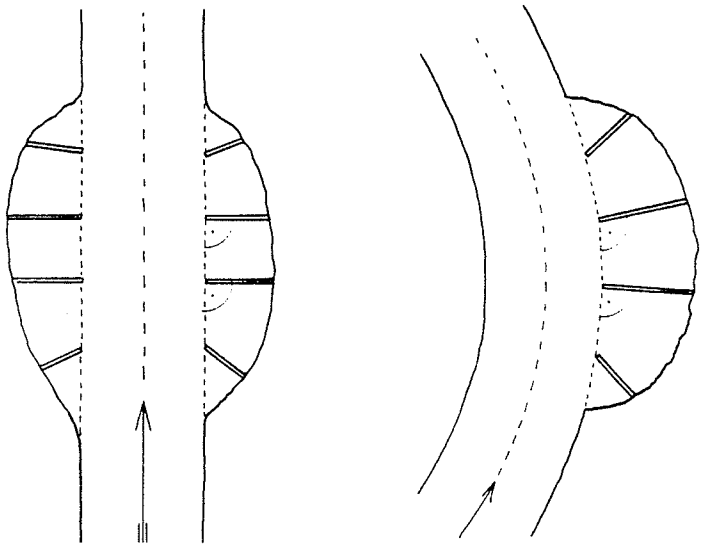


Figure 55 Diagram of a live siltation construction for the restoration of a shore break.

It is extremely important that there are no gaps and that the rocks are carefully placed (see figure 54). The other end of the construction, the 'root', is less endangered and may be secured by digging a deeper ditch, using larger rocks and raising the top of the rock fill towards the bank.

In order to stabilize the bank, a system incorporating a series of live siltation constructions may be necessary to obtain complete siltation. The first barrier must be placed at an acute angle to the water flow, so that only slight resistance is created. All the following barriers should be placed at right angles to the water flow, except for the last one, which is placed at an obtuse angle, facing slightly downstream. If the channel is straight, then individual barriers on both sides must be placed exactly opposite each other (see figure 55). Individual barriers should be placed apart at a distance 1 to 1.5 times their length. Fortunately, if an error has been made in the design and the distance chosen between barriers is too wide, it is a simple matter to add in barriers at a later date.

Figure 56 Live siltation construction.

Where the barrier is longer than 30 feet (10 m.) or in fast flowing waterways, with heavy bedload movement, the addition of a baffle along the planned future shoreline is recommended to reduce the water speed and protect the live siltation construction. The baffle consists of stout poles driven vertically into the ground. The distance between the

poles should be approximately 6 feet (2 metres) and they should stick up above the average flood level. Boards, a minimum of 2 inches (4 cm.) thick are then nailed to the posts on the side facing the water.

The hydraulic effect of live siltation barriers is based purely on the live part or brush. The large number of flexible branches in the branch wall slow the water, causing it to lose its tractive force. A series of live siltation barriers behind one another encourages a more complete deposition of the suspended sediment and bedload material. Coarser material will be deposited first, with finer material deposited later. With only a single flood, siltation up to the average water level can occur and the rooted branches ensure the effectiveness of the barrier until complete siltation takes place. After complete siltation, the brush develops into a plant community that is natural to the site. The pruning of branches is essential to keep them flexible until complete siltation is accomplished. Generally, pruning every 5 to 10 years is sufficient.

For waterways with a very strong current, this technique should be combined with brushlayer barriers and log brush barriers (see section below). The log brush barrier is placed at the beginning of the section that is to be stabilized (see figure 57).

Costing 1/50 to 1/100 of the cost of conventional engineering techniques, live siltation barriers are the most simple, least expensive, reliable method for the repair of breaks in

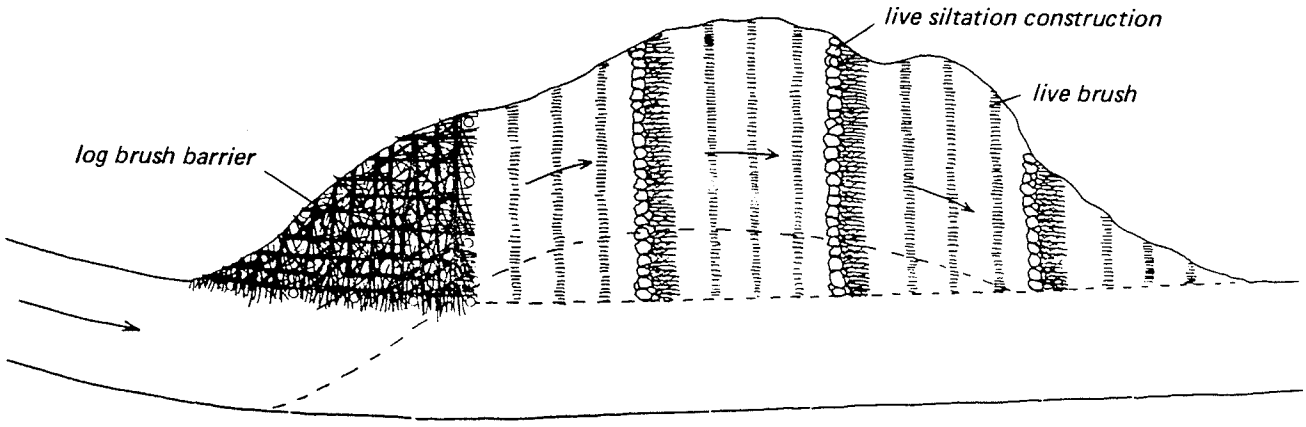


Figure 57 Diagram of log brush barriers at the beginning of a shore break.

water channels. The system is simple to construct, immediately effective and very resistant to high water pressure. By grading siltation, building up the banks and limiting the current to a single channel, live siltation barriers are an excellent means of restoring overflowing watercourses. For waterways with an average bedload movement, live siltation barriers should be applied in the zone between the low water line and the average flood level. Control of their function during floods is essential. If they are not working properly, repairs must be made at once and if necessary, additional rehabilitation measures undertaken.

LOG BRUSH BARRIERS
(see figures 57, 58 & 59)

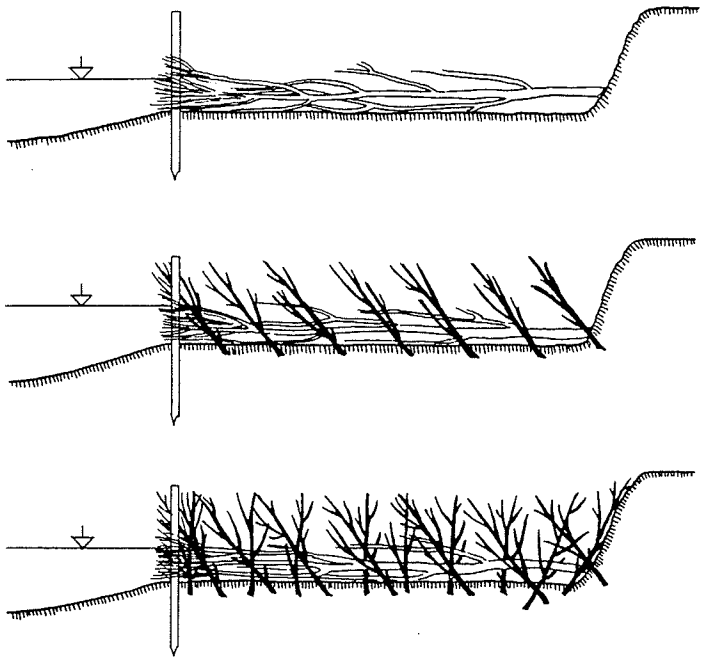


Figure 58 Diagram of log brush barriers.

To construct log brush barriers, a row of pegs is driven into the ground, 6 to 10 feet (200 to 300 cm.) apart, along the planned shoreline. These pegs are temporary support and should be removed as soon as construction is finished. Large branches or tree trunks, up to 8 inches (20 cm.) in diameter, are placed at right angles to the shoreline so that the butt ends reach the damaged shore and the tops protrude 20 to 30 inches (50 to 80 cm.) past the pegs. The branches and trunks, by covering the whole eroded area plus a little extra, provides protection against washouts. This layer of branches need not be alive. The bottom layer of plant material should be thick enough to reach the water surface and need not be alive (see figure 58).

The next layer consists of live branches stuck, through the bottom, horizontal layer of

branches, into the ground at an angle. The area between the pegs should have very dense cover. The branches should be covered with rocks to prevent them from drifting away. A final layer of live branches is placed at right angles to the first set of live branches that were stuck in the ground. This last layer of branches should be placed as densely and deeply as possible (see figure 58). Finally, the entire structure is covered with rocks or pieces of concrete, especially the 'head' or front end where water velocities are the highest and the danger of destruction is the greatest (see figure 59).

Where large breaks of the bank have occurred, only the most endangered sections need coverage with this technique. Further downstream, lighter elements like live siltation constructions and live brushes can be used (see figure 57). Log brush barriers are very sturdy and stable and can withstand even the heaviest flooding. The packed branch tips which protrude into the water effectively direct the water flow, so that even radical changes in the direction of flow may be achieved. Along the entire length of the area secured by this method, the water speed and tractive force of the water are also reduced considerably by the great number of flexible branches.

Figure 59 Log brush barrier.

Growth of vegetation is encouraged by the deposition of fine soil particles, leaves and humus, so that the branches grow into bushes within one year. A bush thicket then develops.

By the formation of a distinct channel allowing for the radical re-direction of the current, the promotion of siltation, log brush barriers are useful for the repair of watercourse bank

or bed damage from overflowing water and washouts. Thus, log brush barriers are especially useful in watercourses experiencing fast flowing water with depths of up to 10 feet (3 m.), high fluctuation in water level and average bedload movement. Usually, the cost of this method is 1/5 to 1/100 of the cost of hard conventional engineering techniques. Log brush barriers are a natural building system that is immediately effective and completely resistant to the strongest water pressure. Unfortunately, labour costs associated with construction are high.

CRIB WALL CONSTRUCTION WITH LIVE BRANCH PACKINGS

(see figures 60, 61, 62, 63 & 64)

This type of construction is particularly useful for bank and margin protection of watercourses experiencing a highly fluctuating current and a heavy bedload movement consisting of small grained material. Crib walls are built from round poles, roughly 4 to 10 inches (10 to 25 cm.) in diameter or square timbers, such as old rail road ties, held together by nails or bolts. Crib walls are usually built as single walls or boxes backilled with rocks or gravel. However, since the wood quickly rots, this method lacks durability. Therefore, instead of rocks, live willow branches with some should be used, because the growing plants gradually take over the function of the rotting lumber (see figure 60). If durability remains a concern, pre-fabricated concrete parts may be used instead of logs (see figure 61).

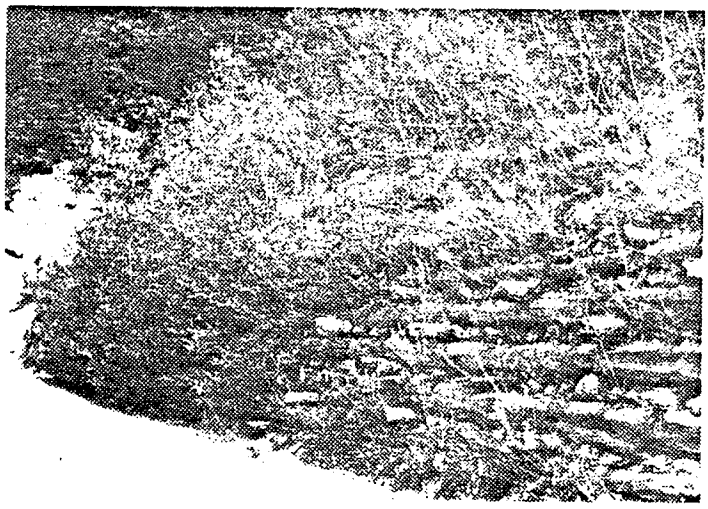


Figure 60 Live wooden crib walls, 10 years old. Willow cuttings placed in the walls remain functional after the timber has rotted.

Crib walls should never be placed vertically, but should slope back into the bank at an angle of at least 10:1 (see figures 62 & 63). Crib walls, built of timber, should not be higher than 12 feet (4 m.). The spaces between the timber parts should be approximately the same width of the thickness of the timber. Strong live branches, at least 1 metre long with a lot of side branches and from a species that roots easily, have to be placed in the spaces, at a minimum 30° angle towards the outside. They must be surrounded by rich soil, which must be protected against washouts with rocks and branch packings. At least 10 branches per running metre are required. However, for the best plant growth, it is important not to pack the branches too thickly. Also, if possible during construction, the branches should be arranged so that no more than one quarter of their length

Figure 61 Concrete crib walls with live willow branches and rooted alders.

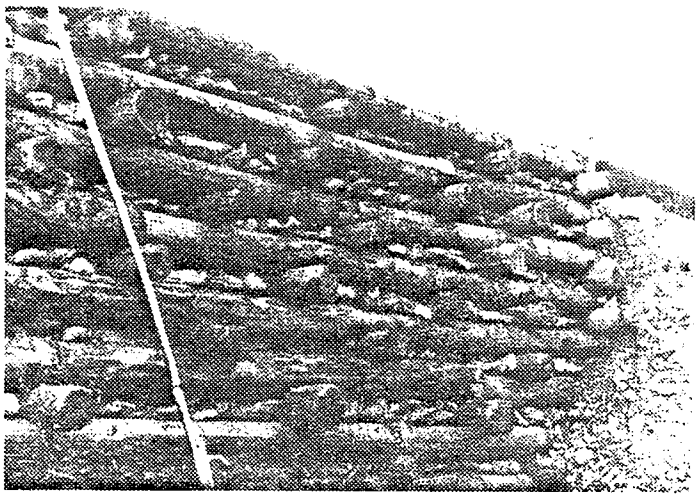


Figure 62 Crib wall as temporary stabilization construction. The gaps are filled with rocks. If long durability is required the gaps must be filled with live branches of woody species or rooted plants.

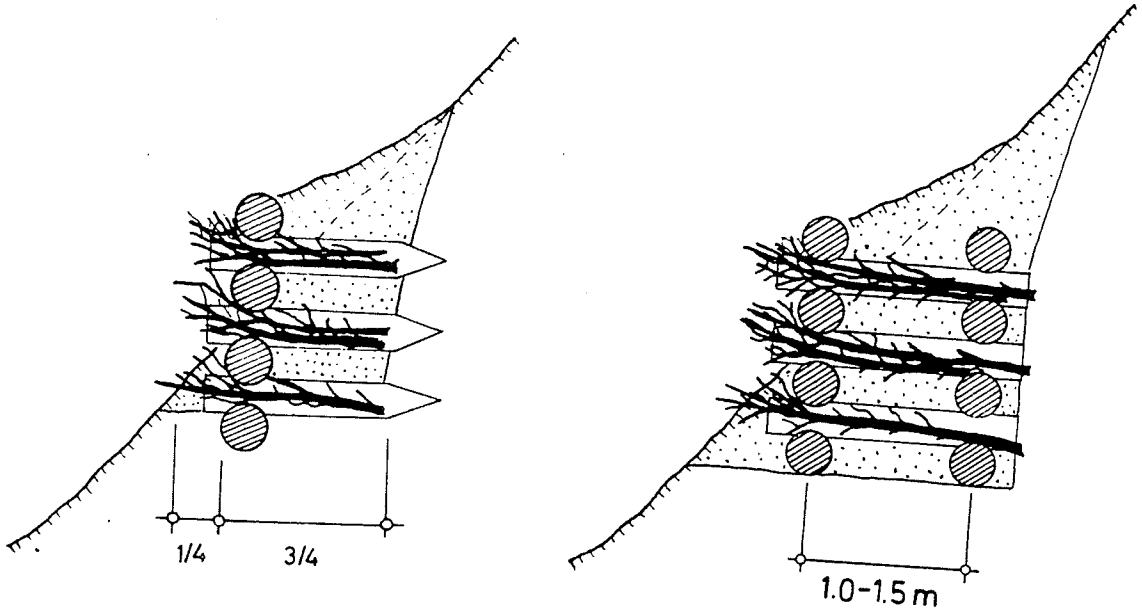


Figure 63 Diagram of a live wooden crib wall. Left: single walled. Right: double walled.

sticks out. When the fill material is dropped into the openings between the timber, large hollow spaces should be avoided, so that the branches can root properly. Topsoil or humus is not necessary for filling the walls, but the fill material should contain enough fine grained material to ensure growth. If possible, the basal cut of the branches should reach into the soil behind the wall (see figure 63). The addition of strong rooted, pioneer, woody plants is advantageous and is advisable on sites where the local native

Figure 64 Three year old live wooden crib wall made of square timbers.

vegetation includes no species that will root from cuttings or where appropriate material for cuttings is not available.

During the first year following construction, regular inspection of all types of crib wall constructions is necessary to prevent washouts. In areas with good growth conditions, pruning is only advisable in order to promote root formation.

All-in-all, crib wall construction is an easily and quickly built stabilization system. It is effective for securing critically endangered portions of the landscape. Since it is instantaneously effective, it is one of the best suited building methods for the immediate repair of areas where a catastrophe has occurred. In such cases, because of the lack of time, the planting may be done at a later date. However, as a disadvantage crib walls could be unattractive because the hard parts of the construction will show even if live filling is used.

VEGETATED GABIONS

(see figures 65, 66 & 67)

Often, gabions, on their own, are not flexible enough to withstand the pressures put on them. The introduction of live material can offer some further stability.

To construct vegetated gabions, fine wire mesh is laid flat on the ground where the gabions are to be built, covered with coarse gravel or crushed rock, and interspersed with live branches and rooted plants. The branches and cuttings should be poked through the mesh. Rooted plants may

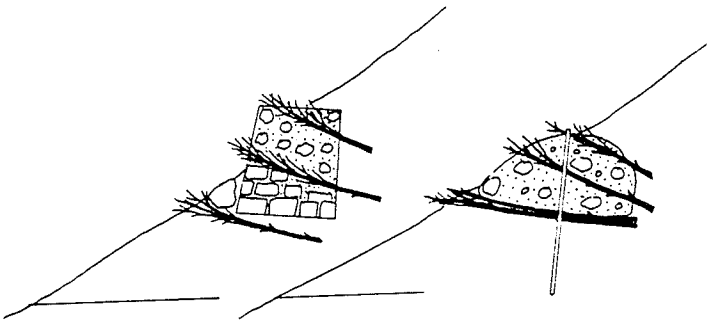


Figure 65 Vegetated gabion. Left: steel mesh. Right: wire mesh.

be placed so that they poke through at the joint. The cuttings and rooted plants have to be placed deep enough into the soil behind the gabions to ensure good root formation and growth (see figures 65 and 66). Finally, the wire mesh is pulled together and sewn with wire into a form, appropriate to the site. Where the gabion may be displaced by mechanical forces, it may be secured with steel pegs driven into the ground. To protect the gabions from washouts, it is advisable to lace them on top of brush layers (see figure 65). With gabions that are made of very heavy netting and filled with larger rocks, live branches or cuttings cannot be placed among the rocks, but can only be placed at the joints between the gabions.

Gabions that are leaning against the slope, when used in combination with healthy live cuttings or plants, provide excellent protection for un-

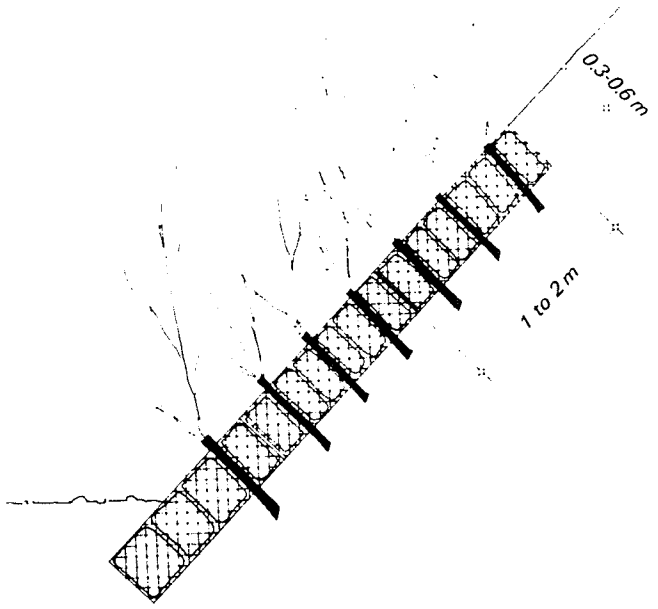


Figure 66 Diagram of a rock packing wrapped in wire (gabion) vegetated with live branches for slope stabilization.

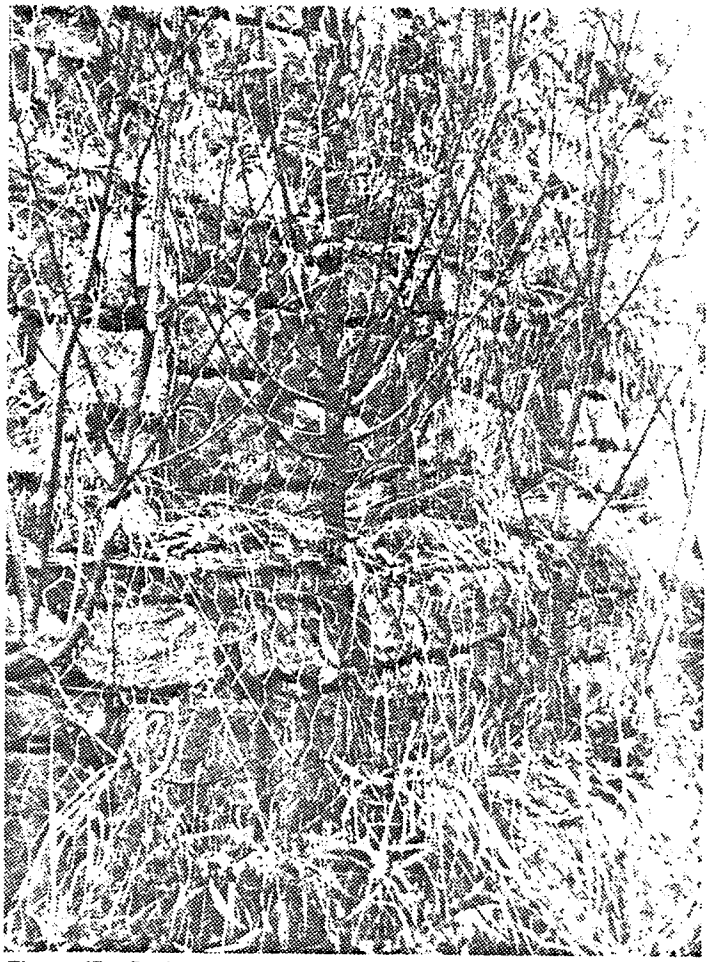


Figure 67 Gabions consisting of a rock pile wrapped in wire mesh, vegetated with live branch layering. If large rocks are used, the branches can be placed only in the joints between the individual gabions.

stable moist areas at the toe of a slope. Vegetated gabions form solid protection points, remaining completely elastic and permeable and cost only slightly more than plain gabions to install. They are a fast, simple construction method and can be erected as a longitudinal construction along watercourse channels. They are, however, only applicable where gravel and small rocks are available. Because of their flexibility, they are suited for point-to-point and linear constructions, especially in wet areas with fine grained soil. They can also be used for the rapid repair of water channels and dam breaks and for the constraint of broad rivers that experience significant bedload movement. Disadvantages include their unnatural appearance and a need for an extremely stable base.

3.5.6 SELECTION OF PLANT MATERIAL

Species of plants that may be planted in conjunction with stream rehabilitation works, include grasses, small plants, shrubs and woody varieties (Brookes, 1987). Tall plants, large shrubs and trees, have extensive root systems that extend through the bank and provide excellent reinforcement (Brookes, 1987). Grasses are quicker to establish themselves, but offer less protection in extreme events (Brookes, 1987).

Channels that have been re-vegetated often appear, to the untrained eye, no different from a natural channel (Keller, 1978). However, in channelized reaches, where sedimentation rates are high, vegetation is often buried and killed. But, if sediment production is reduced through the application of conservation practices, the area will benefit from a more aesthetically pleasing and useful watercourse (Keller, 1978).

When designing watercourse rehabilitation works, the character of the natural stream should be maintained and natural bank vegetation should be allowed to grow (Brookes, 1987). Depending on the character of the stream, a more or less comprehensive planting of the banks with native bushes and trees should be undertaken with at least some of the vegetation reaching the base flow line (Brookes, 1987).

It is imperative, that as soon as a new watercourse channel is completed, that some suitable vegetation be put in place (Brookes, 1987). It has been demonstrated that even grass can reduce velocities at the boundary layer by as much as 90%, significantly reducing the tractive force of the water (Brookes, 1987). Vegetation is both a highly desirable and an economical stabilization method, but it must become established before a major flood event (Brookes, 1987).

Thus, temporary erosion control treatment is often required to ensure that the vegetation has a chance to become established (Brookes, 1987). A variety of methods including mulches consisting of materials such as straw, wood chips and sawdust, as well as the installation of straw bale barriers, prevent erosion and encourage the generation of seedlings (Brookes, 1987).

Schiechtl (1982) has described how to chose the appropriate plants for utilization in watercourse bio-engineering. The use of unsuitable plant material has been the major reason for the failure of many bio-engineering projects in the past. But, in some cases, the method of planting may be as critical as the choice of plant species. Even for short lived pioneer plant communities, those plant species that promise the fastest and most success are the best to use to establish initial cover. It is , however, very important to make a careful selection of the plant species for the planned climax vegetation on such sites, as well .

A general rule in bio-engineering is that only plants from sites with identical or at least very similar ecological conditions should be used. Therefore, an analysis of local plant communities is the first step in obtaining an overall view of potential plant material to be used in a project. Since sufficient information about a site's plant material cannot always be obtained from the site itself, nearby areas with similar characteristics should be studied as well. This analysis suggests possible plant species that may be used as primary vegetation for the site as well as suggesting what the climax vegetation will be. The analysis of natural factors also helps to determine which climax vegetation or permanent

artificial community will be maintained. It is only when the natural sequence of succession of plant species and communities is known, that the best procedure for the bio-engineering construction can be decided upon and the selection of plant species and construction method be made.

Only when it is impossible to obtain sufficient species from this list of natural plants should other species be used. In that case, care must be taken to time the planting and propagation of the vegetation so that the initial plant community develops into the desired climax community.

Since species rich ecosystems are always healthier, more stable and more resistant to damage and disturbances than those which are species poor, a primary goal of bio-engineering should be the promotion of species diversity in the shortest time possible. Exceptions should only be made if certain requirements of a technical, economic or aesthetic nature do not allow for ecosystems consisting of a large number of species.

Large scale bio-engineering works require the consideration of other factors as well. They include (Schiechtl, 1982):

1) the ecological conditions of the work site,
2) the propagation techniques for each species and the best time for gathering and treating propagation material,
3) bio-technical suitability, plant vigour and growth rate, and
4) the final goal of the bio-engineering works, the practical effects and the desired aesthetic effect.

3.5.6.1 ECOLOGICAL CRITERIA

It is extremely important to know the requirements such as soil moisture, soil fertility, temperature and light of the various proposed plant species. Fortunately, it is not

necessary to measure all the site factors since the limiting factor is usually extremely obvious and may in most cases, be quickly determined.

Since the rich topsoil has been scraped off, usually,soils that have to be re-vegetated are only raw mineral substrates. Analysis of these soils is important to determine what, if any nutrient content they have. For rapid classification, it is helpful to know that well-aerated soils are usually more favourable to plant growth than compacted ones. Permeable soils usually experience a smaller range of moisture and temperature extremes than compacted soils. Raw mineral soils, with a high pH, have a more positive physiological effect on plants than soils with a low pH. Silicate soils and very compacted, heavy, clay soils have a less positive effect.

While macro-climatic factors determine the plant species that can survive in an area, an examination of the micro-climate, and its correlation with existing plants, will provide a finer grain of information. For example, after completion of contouring work, involving a reduction of the slope angle and re- grading, relief and its effect on micro-climate has to be considered when choosing plant species. Especially on larger slopes, variations in factors, such as solar access, aspect, elevation, moisture regime and slope angle, may be very large. Therefore, on a single slope, it may be necessary to introduce several areas of different plant species that respond to the special conditions of specific sites.

Usually, competition from other naturally occurring plant species is not recognized until a substantial density and wide diversity is reached. Unfortunately, if invading species are not controlled early enough, success of the re-vegetation project may be compromised. If the destructive biotic factors cannot be controlled or eliminated, they must be integrated into the succession sequence of the re-vegetation project.

Species which can tolerate a wide range of site conditions, and thus reduce the risk of mis-matching vegetation and site, are generally to be preferred in re-vegetation work. Such

species may also be used over large areas, even though the site conditions may vary significantly from location to location.

3.5.6.2 EASE OF PROPAGATION

The suitability of a plant for use in bio-engineering works is determined by ease of propagation. Factors such as selection of the mother plant, temperature, humidity, soil, naturally occurring growth promoting hormones nutrient content of the cuttings, the use of synthetic growth inducing chemicals and the influence of light all affect the success of the cuttings. Unfortunately, in bio-engineering works, control of all these factors is impossible. For example, because of the quantity of cuttings required, the selection of cuttings only from exceptionally healthy mother plants can rarely be achieved. It is also impossible to control the temperature of the outdoors and very rarely can the chemical properties of the soil, or the humidity and soil moisture conditions of the planting site be influenced.

For practical application:

1) root production and shoot growth depend on the condition of the vegetation at the time of cutting,
2) rooting capability varies with the species according to its particular physiological rhythm and is often not correlated with the beginning of the growing season,
3) cuttings from deciduous woody species usually root best if planted during the dormant season. Rooting ability is either greatly reduced or entirely absent between the period of flowering and seed ripening and the time when the leaves turn colour and fall, and
4) for at least three years after planting, the time of year that the cutting was gathered influences not only root formation but also subsequent plant development.

A variety of plant species may be used. The propagation of plants through tip and hardwood cuttings is the oldest method of re-vegetation for mineral soils. Willow

cuttings have also become increasingly popular. With willow cuttings, rooting capability increases with age and diameter of the cutting. Since older material is not always available in sufficient quantities, the use of two to three year old material is possible. When cuttings are planted horizontally, it has been shown that, over a period longer than two months, the longer and thicker cuttings displayed the best growth and the length of the roots increased in relation to the length and volume of the cuttings.(see figures 68 & 69). Vertically planted cuttings showed less difference in the development of their roots because all the root-promoting hormone found naturally in the cutting, moves down to the basal area. From there, even the roots of short cuttings soon reach a favourable depth where there is no danger of drying out and they stop growing. However, horizontal planting is preferred, since numerous strong roots form, not only at the basal area, but also along the entire length of the stem, increasing the total root length dramatically (see figure 69).

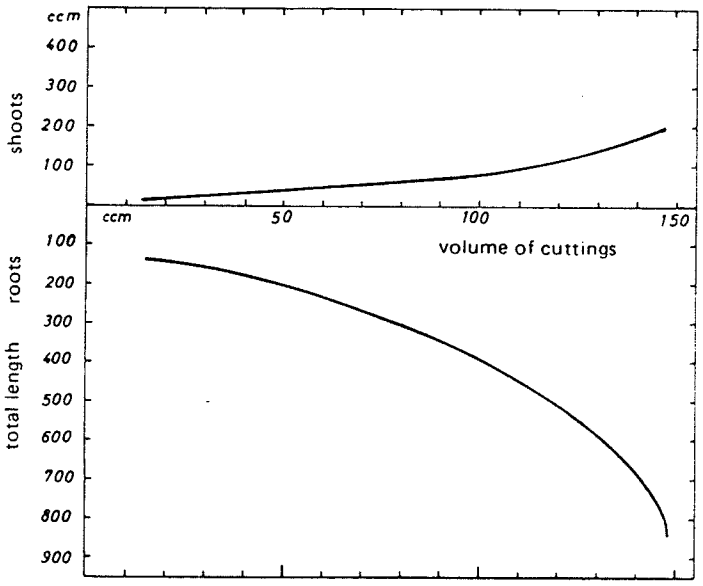


Figure 68 Interdependence of growth and cutting volume of purple willow (*Salix purpurea*).

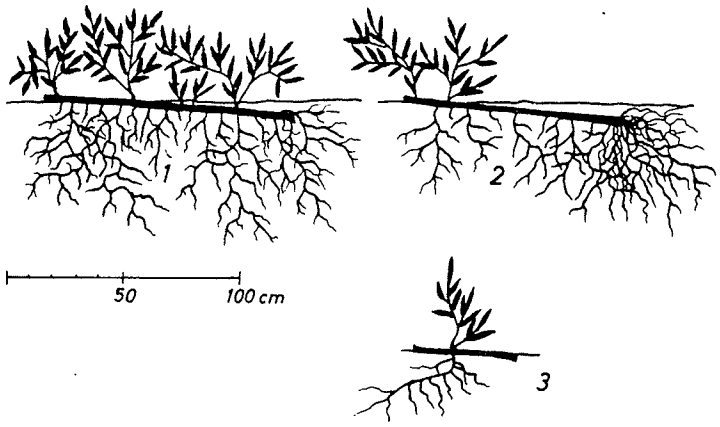


Figure 69 Typical growth forms of horizontally placed cutting of *Salix purpurea*.

In practice, the thickness of the cutting is only limited by practicality, profitability based on transportation and other costs, and the supply available from natural areas and nurseries. If possible, large branches should be used but very often this material is in short supply. Therefore, small branches and branch tips may be mixed with the stronger, older branches. If the cuttings are to be placed vertically, as in joint planting, they should reach a minimum depth of 12 inches (30 cm.). However, this depth is not sufficient on slopes where erosion, burying, drying out and shearing may affect the plant. There the cuttings should be at least 2 1/2 to 4 feet (0.75 to 1.2 m.) long and they should not be cut and placed as individual cuttings, but as branches with all their side growth still affixed.

Shrubs and young trees should be cut directly above the ground. If the trees are more than 4 inches (10 cm.) in diameter they should be topped. The cut should be smooth and the cut surface should be kept small. The use of large pruning shears or with larger branches power saws is recommended. Due to the high material loss and reduced rooting capability as a result of the oblique cut, the use of axes or similar tools is not advised. Larger wounds also encourage greater disease problems.

When using live material, the entire length of the branches should be transported to the construction site and then cut to the desired length. If this is not possible, the branches must be protected from drying out, before and during transport. Live branches and cuttings should be planted immediately. If they must be stored, they must be protected against overheating and drying out, with methods such as storage in the shade, under the cover of evergreen branches or plastic, placement in moist pits, or treatment with anti-transpirant chemical spray. These methods can allow the successful storage of live material for up to one week. Where water is available, the cuttings should be sprayed, or bundled and immersed. However, water warmer than 60 ° F. (15° C.) stimulates growth and should only be used where no other is available. Immersion under water has preserved willow cuttings that had an establishment rate of 100% after planting, for over three months.

Plants tend to sprout and dry out more easily at the end of the dormant season than at the beginning (Schiechtl, 1982). Therefore, spring or the beginning of the growth season is generally considered to be the best time for the propagation of cuttings. Often in bio-engineering failures, it has been incorrect time of planting rather than incorrect selection of species that has caused the failures.

3.5.6.3 BIO-TECHNICAL SUITABILITY

Plants must be able to meet particular requirements if they are to be used in bio-engineering. These requirements are (Schiechtl, 1982):

1) the ability to stabilize the soil,
2) the ability to survive in stressful conditions,
3) the ability to promote the growth of other desirable plants, and
4) fast juvenile growth.

The Ability to Stabilize the Soil

As long as the soil surface is exposed to weather, soil movement will occur, even if slope angles have been reduced and the slopes properly reshaped through earthworks. The efficacy of the various forces in the soil depends on properties of the soil and slope angle as well as external influences such as rainfall, wind, frost, drought, fire,floods and damage by animals and humans. It is these external forces that can be absorbed or even eliminated by vegetation.

The ability of a plant to stabilize the soil is dependent upon the mass, depth, density, penetration and composition of its root system. Pioneer species may be classified into groups of extensive, intensive or mixed rooters. Extensive rooters are those plants that develop a deep, far reaching, root system. The soil body penetrated by these roots is often

up to 100 cubic feet (several cubic metres) in size. Intensive rooters include most grass species, especially bunch grasses or tussock grasses. Although the roots of these species mostly remain flat and shallow, they bind the soil to a high degree. In the rootball of extremely intensive rooters, the root mass often weighs more than the soil mass. The use of deep rooters in conjunction with intensive rooters is very effective for fast soil binding and stabilization. Very good soil stabilization is also obtained with single plants that have both extensive, deep reaching roots and intensive very tightly arranged roots on the surface.

Layered root systems, those with a number of 'horizons' of roots stabilize the soil more effectively than unlayered ones. Therefore, monocultures should be avoided whenever possible. Species with great

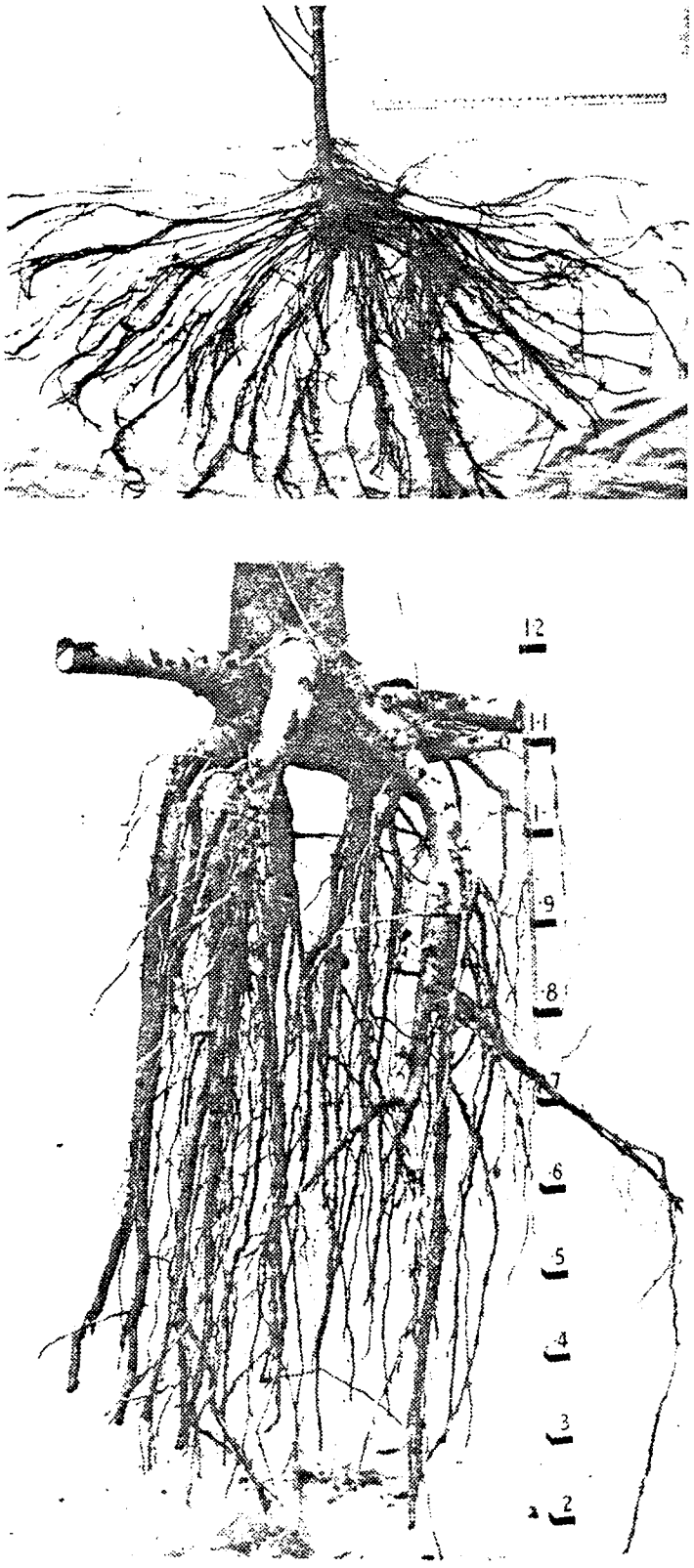


Figure 70 Root formation of plants that have been propagated from cuttings. Top: *Salix matsudana*, after one growing season. Bottom: *Populus maximowiczii*, after four growing seasons; mainly sinker roots.

resistance to coverage by loose gravel, soil movement and erosion are almost always good soil stabilizers. Plants used to stabilize the soil must have either very deep reaching, elastic, root systems with great tensile strength or a very dense root system, that can recover quickly after being damaged (see figure 70).

One way that woody plants may act to stabilize the soil is in reaction to one sided pressure or tension. Root material grows both in length and diameter and the plant develops specific stabilization tissue. The roots may divide as to function, with separate anchoring roots and feeding roots forming.

Plant species	*Min*	*Max*	*Mean*	*No. of repeats*
Gramineae				
Agropyron repens (Stiny)	72	253	—	—
Chloris gayana (Cheng)	49	133	84.5	8
Cynodon dactylon (Cheng)	35	120	61.1	8
Digitaria decumbens (Cheng)	23	127	66.4	11
Panicum maximum (Cheng)	25	211	108.4	14
Paspalum notatum (Cheng)	31	216	81.1	10
Pennisetum purpureum (Cheng)	39	161	97.3	6
Setaria sphacelata (Cheng)	38	60	51.8	7
Forbs				
Amaranthus retroflexus (Stiny)	19	48	—	—
Artemisia campestris (Schiechtl)	91	264	107.8	5
Atriplex patulum (Stiny)	93	306	—	—
Campanula trachelium (Stiny)	0	37	—	—
Capsella bursa-pastoris (Stiny)	37	101	—	—
Convolvulus arvensis (Stiny)	48	210	—	—
Medicago sativa (Schiechtl)	254	665	417.1	5
Plantago lanceolata (Stiny)	40	74	—	—
Plantago major (Stiny)	26	60	—	—
Rumex conglomeratus (Stiny)	14	62	—	—
Solanum nigrum (Stiny)	162	389	—	—
Taraxacum officinalis (Stiny)	0	44	—	—
Trifolium pratense (Stiny)	109	185	—	—
Woody plants (shrubs and trees)				
Alnus firma var. *multinervis* (Kumagai)	150	967	522	31
Alnus firma var. *yasha* (Kumagai)	44	753	—	4
Alnus incana (Kumagai)	70	573	322	33
Alnus japonica (Kumagai)	127	923	418	49
Betula pendula (Turmanina)	—	—	382	?
Cytisus scoparius (Kumagai)	62	655	327	29
Lespedeza bicolor (Kumagai)	108	1580	703	65
Picea abies (Turmanina)	—	—	278	?
Pinus densiflora (Kumagai)	91	726	331	20
Populus nigra (Schiechtl)	49	120	—	3
Populus deltoides (Turmanina)	—	—	391	?
Populus deltoides (H & P)	—	—	370	20
+Populus '1-78' (H & P)	—	—	465	20
++Populus '1-488' (H & P)	—	—	329	20
Populus yunnanensis (H & P)	—	—	391	20
Quercus robur (Turmanina)	—	—	324	?
Robinia pseudoacacia (Kumagai)	56	1425	697	21
+++Salix "Booth" (H & P)	—	—	366	20
Salix matsudana (H & P)	—	—	371	20
Salix fragilis (Hiller)	97	255	179	15
Salix dasyclados (Hiller)	94	256	177	15
Salix elaeagnos (Hiller)	115	163	150	15
Salix helvetica (Hiller)	76	240	139	15
Salix hastata (Hiller)	86	178	131	15
Salix starkeana (Hiller)	88	203	127	15
Salix cinerea (Hiller)	89	122	109	15
Salix hegetschweileri (Hiller)	68	145	94	15

Figure 71 Tensile strength of plant roots (kg/cm^2).

While there appears to be some regularities in the ability of roots to withstand tensile and shearing stress, generalizations are not easily made. Whereas tensile strength increases with root diameter (see figure 71), shear strength drops (see figure 72). The roots of woody plants have higher shear strength than tensile strength, but the opposite is true of herbaceous plants. However,one generalization that

may be made is that 'anchor' roots usually have a higher tensile strength than other roots.

Technical engineers may be skeptical about the ability of plant roots to withstand the stresses produced by earth movements, such as slippages, since even steel cables used in attempts to control such situations often fail. While it is true that not all failures can be stabilized through the use of vegetation alone, problems usually occur because the major stresses of the earth movements occur beyond the reach of the roots of the large plants. All their pull and shear resistance are thus rendered irrelevant. Therefore, it is important to ensure that the proper plants are placed in the proper areas,. guaranteeing maximum performance.

	Minimum	*Maximum*
Artemisia campestris	65	477
Medicago sativa	103	262
Populus nigra	101	105

Figure 72 Breaking point of plant roots under shear stress (kg/cm²).

The Ability to Survive in Stressful Conditions

Plant resistance to mechanical forces is essential, with even the most solid and stable constructions, which in the first years, experience some movement or settling of the soil even. Thus, the ability of plant species to adjust to extreme conditions and to adapt to 'abnormal' growth patterns is important. Plants best suited for bio-engineering are able to call upon a variety of response mechanisms in reaction to stresses imposed by the loss of terminal shoots, slanting position, snow pressure and movement, soil erosion, burial by silt or gravel and fluctuating ground levels.

All plants that grow naturally in loose gravel are especially resistant to erosion. Therefore, to find these plants as pioneer species on soils that are still unstable is not surprising. Since shallow roots are destroyed when erosion occurs, deep rooting plants are usually more resistant to exposure. A lowering of the soil through erosion can force the plants to develop stilt like root formations or hanging roots (see figures 73 & 74). The existing roots become a holding mechanism and adventitious roots develop along the bare taproot.

When an existing root system is covered by more material, the roots must be able to survive increased mechanical stresses such as compression as well as possible shear stress, resulting from soil movements brought on by differential loading. Coverage can be survived by species whose lowest root horizons remain functional after being buried and which develop a new adventitious root system. Coniferous species, especially well known for demonstrating this ability, include *Pinus sylvestris, Pinus banksiana* and *Thuja plicata.* Deciduous species include most *Salix* species, *Populus balsamifera, Populus tremuloides, Betula Papyrifera, Betula pubescens, Rosa woodsii, Shepherdia canadensis, Vibernum* species, Cornus species, and *Acer* species.

Willows are especially good for surviving coverage and subsequent erosion. Since they are better able to survive

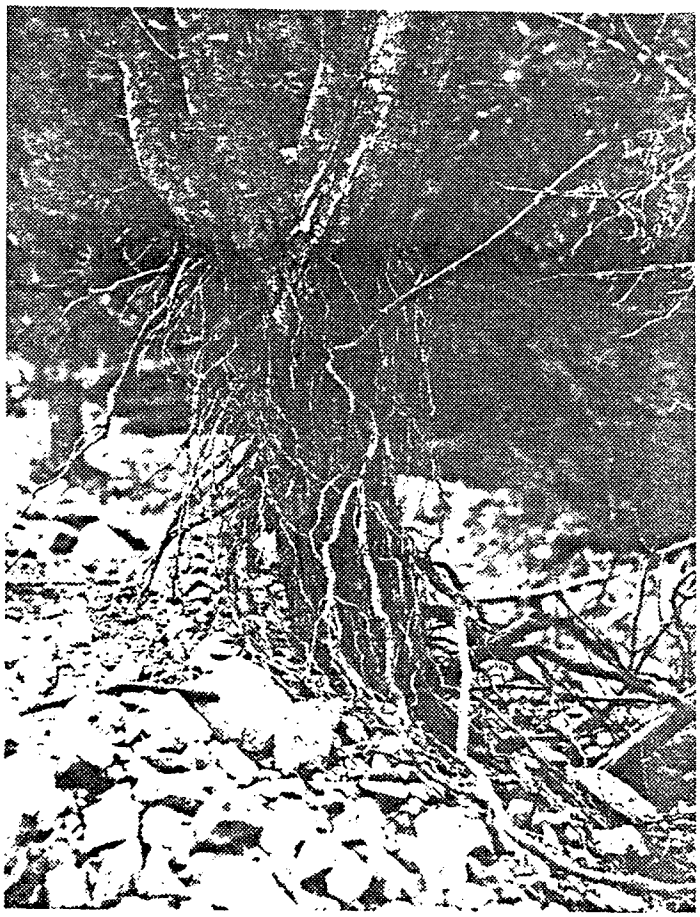


Figure 73 Adventious roots on the trunk of a grey willow (*Salix elaeagnous*) which was buried and later freed from the covering material.

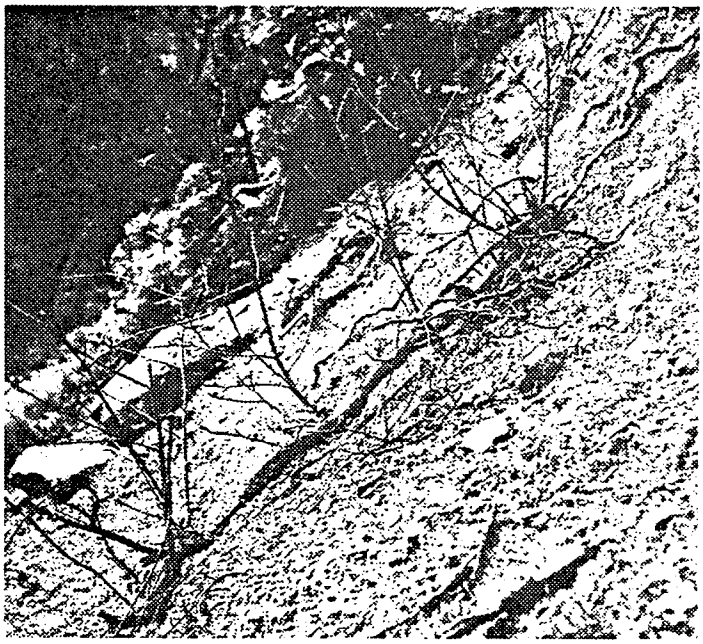


Figure 74 Hanging root formation on a young tree (*Sorbus*) caused by erosion. Notice the development of adventious shoots along the downhanging root.

changes than shallow rooting species, willows often develop to the climax community on river and creek banks. Other species of plants such as *Quercus, Fraxinus, Acer* and *Pinus* are able to surviving root exposure due to their ability to adjust quickly to the altered conditions.

Toughness of the wood, during the frost period, may help the plant defend itself from having its roots shorn off by soil movement or drift ice. The roots are stiff and resistant and do not bend. In tree like species the adjustment to stress may result in the growth of a large number of sturdy shoots from the base of the trunk. These shoots then develop into large shrubs. Other species, such as *Salix,* are flexible and bend under pressure, thus avoiding damage. These plants in protecting themselves from shearing damage also cover the soil, protecting it against erosion.

Growth Promoting Properties

The growth promoting qualities of a plant is based upon its ability to initiate a natural plant succession. General pioneering qualities, such as the ability to spontaneously invade raw mineral soil, to reach their climax and then disappear after providing the necessary conditions for the development of more complex plant communities are essential. Plant species, which grow rapidly, spread readily and propagate easily, can encourage the desired plant community development are highly desirable.

Soil rehabilitation characteristics such as the penetration of strong roots, the creation of humus and the improvement of nutrient content through the return of organic material to the soil are also essential. Plant species with deep, far reaching roots loosen the soil, promoting the access of oxygen and moisture, thus facilitating the development of micro-flora and micro-fauna. Plants that shade the soil surface with large leaves change the micro-climate drastically and enable soil fauna and humus to develop rapidly.Legume species, due to their ability to increase the nitrogen content of the soil, are of great

importance to any system designed to improve vegetative ecosystems. Thus, the growth promoting properties of legumes are often used for rapid ecological reclamation and biologic activation of the soil.

Fast Juvenile Growth

The selection of fast growing plants, which also have growth promoting properties, is important for the success of bio-engineering projects. By obtaining a complete ground cover and an extensive root system as soon as possible, the dangerous erosion period is shortened and the desired technical and ecological effectiveness is achieved more quickly.

The more storeys a plant cover has and the sooner that multi-storey stage is reached, the more quickly soil stability will be achieved. It is most important to establish the initial cover as soon as possible, but one must also ensure the means for the further development, of this newly established plant cover.

3.5.6.4 GOALS OF BIO-ENGINEERING

Bio-engineering has to fulfill special functions. The final climax vegetation has to meet technical, ecological and aesthetic requirements. These requirements have already been discussed in detail. However, before construction, one has to decide how these requirements can be met in the quickest, most economical way and thus, what plants and plant communities are to be used.

3.5.7 MAINTENANCE

Maintenance is an essential part of any restoration project and includes operations such as pruning of the vegetation and the removal of debris such as sediment and tree branches

(Brookes, 1987). However, sediment deposited as point bars must not be removed and pools and riffles should be allowed to develop and to be maintained naturally by the redistribution of the bed material (Brookes, 1987). However, if a knickpoint starts to develop, remedial actions must be taken immediately to resist further degradation (Brookes, 1987). Thus, it is necessary for the maintenance supervisor of the watercourse to be aware of the processes of natural watercourse, the intentions of the rehabilitation project and to realize that even stable channels undergo selective erosion and deposition (Brookes, 1987). The restored channel should be inspected regularly, especially after high flow events to ensure that eroding banks are properly protected (Brookes, 1987).

While it is possible to manipulate the channel form to initiate processes that induce the watercourse to erode and deposit in desired locations, experience also shows the need of a sediment control and storm water management program, in conjunction with such work (Keller, 1978). Without sediment and storm water control, a channel morphology program is most likely doomed to failure (Keller, 1978). High sediment loads tend to fill pools and to bury pool and riffle sequences, whereas frequent high magnitude flows wash them out (Keller, 1978) and may cause damage to any bank protection works that have been put in place.

3.5.8 ACCESS TO AND OWNERSHIP OF LAND AROUND THE CHANNEL

Rehabilitation works can only be undertaken where watercourse access is possible. Easy access for heavy machinery is vital. The disruption and destruction of the land and ecosystems surrounding the stream should be kept to an absolute minimum. For example, it would be better not to cut a swath through the riverbank forest, if access might be gained in some other way. Also, if possible, rehabilitation works should be done when damage to the adjacent land is minimized. When working around agricultural fields, fall or winter, when the crops are in, would be best or if marshy land must be crossed, winter, when the ground in frozen would be a good time to undertake work.

Often, the re-creation of the form of a natural stream in straightened and channelized reaches is only partially possible without using adjacent farmlands to reform meander loops (Newbury and Gaboury, 1988). It would be best if the land upon which the work is to be done is publicly owned or at least, be controlled through a long term lease. It would be most desirable not to take any agricultural land out of production, but if it is absolutely necessary, the farmer should receive some form of negotiated compensation. Perhaps a land swap such as the one illustrated in figure 75 would reduce the amount of land lost to production and allow the farmer to keep roughly the same amount of land in production. Unfortunately, this type of land swap would only be possible in areas where both sides of the stream are farmland. In order to maintain the goodwill of the local landowners and residents, a factor often necessary for the success of these projects, it is very important that the design and development of rehabilitation works include public input and that the project does not cause undue hardship to anyone in the area.

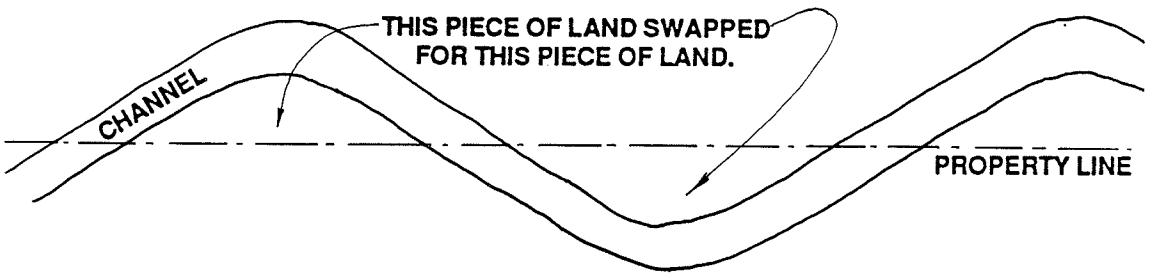


Figure 75 Diagram illustrating possible land swap that may be arranged.

3.5.9 SYNOPSIS OF DESIGN AND MAINTENANCE CRITERIA

SYSTEMS APPROACH

Changes to watershed characteristics such as vegetation, surface conditions and flow patterns as well as changes to morphological conditions such as capacity, volume of water carried, sinuosity of channel plan and gradient of bed will cause changes to the bed and banks of the channel. It is important to recognize that these changes will occur and to try to address them in the design of the project.

MINIMIZATION OF NON-NATURAL TECHNIQUES

Channelization should be undertaken only where absolutely necessary and only when no alternative means exist. The least amount of non-natural controls should be used to satisfy the objectives of the project.

REMOVAL OF OBSTRUCTIONS

Where blockages result in unacceptable flow conditions, it should first be determined if non-structural methods are sufficient to achieve the desired result. As a second choice, a combination of obstruction removal and non-structural methods is preferred over more drastic channel modifications.

CHANNEL FORM

Where channel modifications are deemed necessary there are a number of concepts that should be recognized. Watercourse dimensions of width, depth, cross-sectional area, meander wavelength and radius of curvature have developed in response to natural forces fundamental to the operation of the watercourse. It is bankfull flow that creates a relatively stable channel form. Therefore, a pilot channel, based on bankfull dimensions, should be created in large capacity channels. While equations for generalized dimensions have been developed, similar size watersheds under similar conditions should also be examined for prototypical forms. Pools and riffles should be included in the bankfull channel. They may be created through the development of an asymmetrical cross-section with one side slope of 2:1 and the other at 3:1 to cause convergence and divergence of the flow. Pool to pool spacing should be 4 to 10 times bankfull channel width. On bends, a number of pools, all near the outside bank, can be spaced every 6 channel widths. Riffles should be developed as small gradient control structures which dissipate the excess energy of the stream on their faces, reducing erosion. The riffles should be of sufficient height to create pools that extend halfway up the downstream face of the next riffle upstream. To provide suitable fish spawning grounds, every fourth gradient control structure should consist of two riffles built 60 to 100 feet (20 to 30 metres) apart. In natural streams, straight reaches are seldom longer than 10 times the channel width. Therefore, when designing channel modifications, meanders should be included. To determine the sinuosity of original channel, remnants of the original channel, maps, historic aerial

photographs and similar watersheds should be examined. Generally, the spacing of meanders is 6 to 10 times the bankfull channel width. The ratio of meander wavelength to radius of curvature is about 4.7:1 and the ratio of channel length to meander wavelength is from 1.3:1 to 4:1. Since the amplitude of meanders is usually dependent on soil conditions, it does not relate well with channel width and an accurate generalized equation cannot be given.

BANK AND BED STABILIZATION

The rehabilitated channel should appear as natural as possible. No continuous lengthwise stone or concrete construction which would rob the stream of its dynamism should be used. Bank protection techniques using vegetation as the primary means of stabilization are preferred. A range of stabilization techniques should be examined and the least intrusive should be used. Immediately following construction, suitable vegetation should be put in place. Temporary erosion control may be required to allow the vegetation to become established. If possible, vegetation should be allowed to grow right up to the low waterline.

SELECTION OF PLANT MATERIAL

The choice of vegetation and the types of stabilization techniques to be used should be based upon:

1) the ecological conditions of the site,
2) the ease of propagation of the plant material,
3) the bio-techniacl suitability of the plant, i.e. its ability to stabilize the soil, to survive stressful conditions, to promote the growth of other desired plants and to grow quickly in its juvenile stage and
4) the final goals of the project.

MAINTENANCE

Maintenance is an essential component of any restoration project. A maintenance supervisor has to be aware of the processes of natural watercourses and the intentions of the rehabilitation project and must realize that channels undergo selective erosion and deposition. Sediment control and storm water management programs play a very impor-

tant part in the success of a rehabilitation project.

ACCESS TO AND OWNERSHIP OF LAND

Rehabilitation can only be undertaken where access to the watercourse, by the required equipment, is possible. Access routes should be carefully chosen and work timed to minimize the disruption and destruction of the land and ecosystems surrounding the stream. Land swaps may be arranged to ensure ease of cultivation and to minimize land loss for farmers and landowners after the project has been completed.

4 EDWARDS CREEK AND DRAIN

4.1 LOCATION AND PHYSIOGRAPHIC REGIONS

The Edwards Creek watershed is located approximately 150 miles (250 km.) northwest of Winnipeg, near the town of Dauphin (see figure 76). The watershed is situated on the northern edge of Riding Mountain National Park, a part of the upland region known as the Manitoba Escarpment. The creek has its source, Edwards Lake, in the park and flows off of the escarpment and through a floodway to drain into Dauphin Lake, at a point approximately 10 miles (16 km.) east of Dauphin (see figure 77). The watershed has an area of approximately 130 square miles (360 square km.), of which roughly 45% is located within Riding Mountain National Park (Inland Waters, 1971). The remainder of the area, between the park and the lake, is under cultivation (Inland Waters, 1971).

Edwards Creek flows through four physiographic regions (Mackling, 1987):

1) THE LOWLANDS include all lands located below the 1000 foot (300 m.) contour level and is the largest area in the watershed. The surface texture varies from gravel to clay.Soils are characterized by flat lake, alluvial and glacial till deposits. The soil drainage varies from poor to good. Mixed farming is the primary agricultural activity in the area and land not used as pasture is used for the production of wheat, oats, barley and flax (Inland Waters, 1971). The

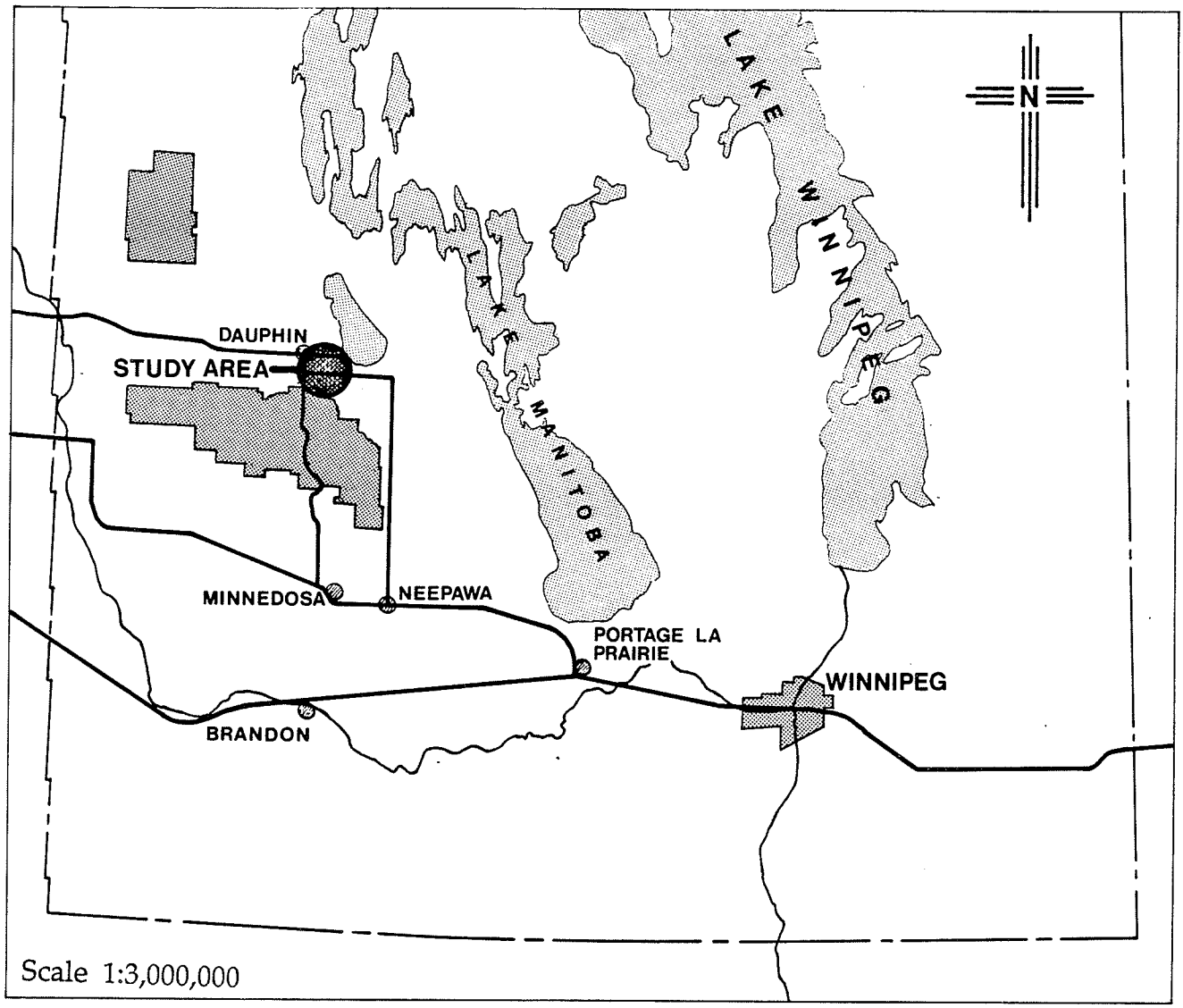


Figure 76 Location of study area.

sediment production from the agricultural land is dependent on a number of factors such as crops, cultivation practices and rainfall-energy conditions (Inland Waters, 1971). Generally, in this area, agricultural practices are the major contributor to surface erosion, while the floodway has experienced a great deal of channel erosion since it was built.

2) THE SUB-ESCARPMENT is a narrow band of land located between the 1000 foot (300 m.) and 1200 foot (360 m.) elevations. The soils vary from sandy loam to silty clay and drainage is from good to imperfect. The area contains many former beaches ridges and the alluvial fans of many streams that drain off the escarpment. Agriculture plays only a minor role in the general erosion of the area.

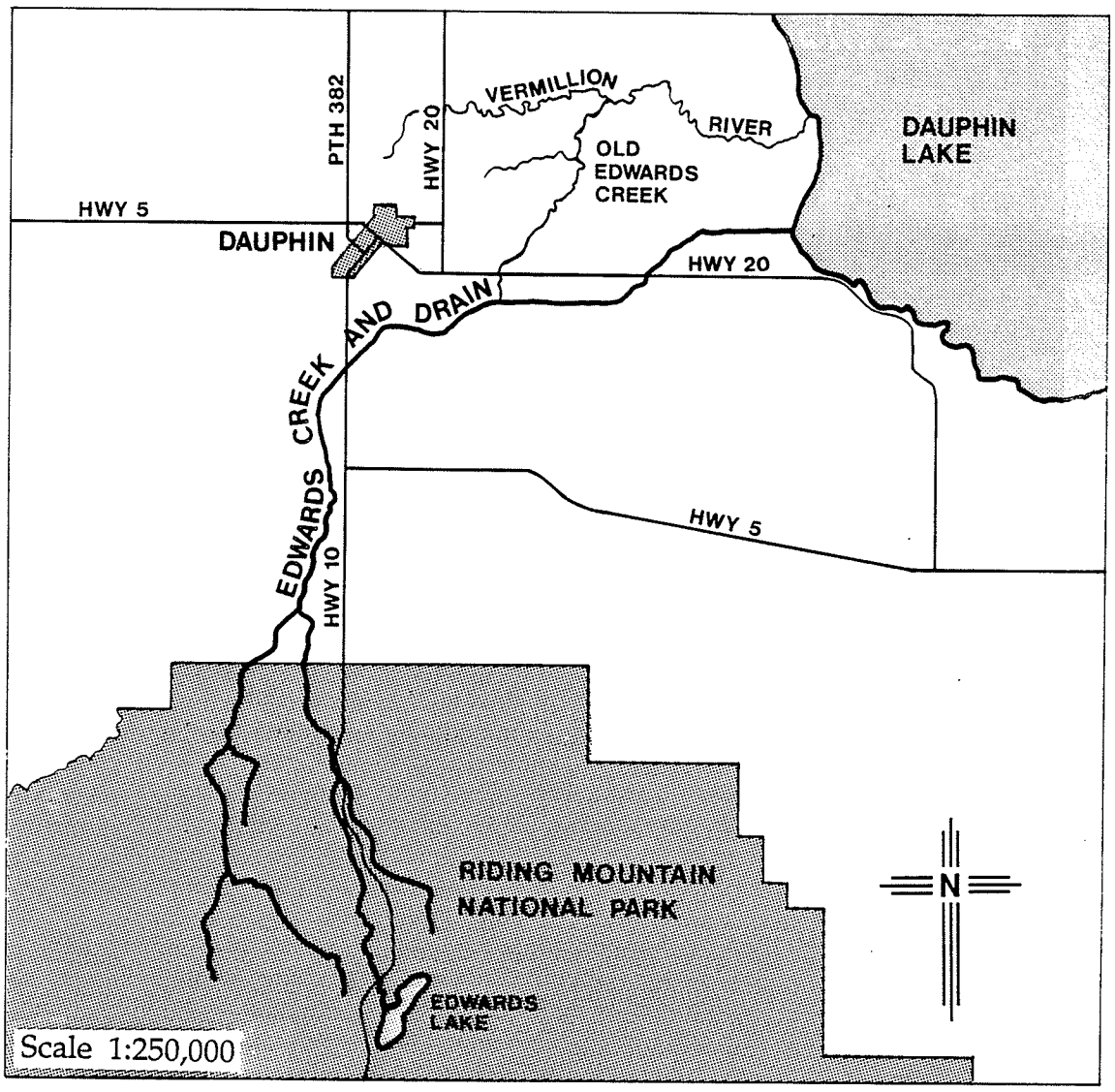


Figure 77 Key map location of showing Edwards Creek.

Through this area, the Edwards Creek channel is well-defined with moderate slopes.

3) THE ESCARPMENT is a steeply sloping band of land between 1200 feet (360m.) and 2000 feet (600 m.). It is the source of the shale that is deposited in the sub-escarpment. Erosion in this area is generally the result of natural processes.

4) THE UPLANDS is the rolling, forested, till plain located in Riding Mountain National Park, above the 2000 foot (600 m.) mark. This area contains the head-waters of Edwards Creek and many other watercourses that drain off the escarpment. The area of the watershed within Riding Mountain National Park, is heavily vegetated. The park was withdrawn from settlement entry in 1895 for use

as a timber reserve and became a national park in 1930 (Inland Waters, 1971). Therefore, only mature timber has been harvested from 1930 on (Inland Waters, 1971). This type of timber harvest has not significantly altered the conditions of vegetative cover (Inland Waters, 1971). Thus, the production of sediment within the park boundaries could be expected to be homogeneous as of 1930 (Inland Waters, 1971). Generally, all erosion in the area is the result of natural processes. The Riding Mountain escarpment and uplands are composed of two different shale layers, a hard top layer and another softer one, lower down (Inland Waters, 1971). Glacial action wore away much of the hard shale and laid down a thick layer of drift (Inland Waters, 1971). However, portions of the soft shale have been exposed due to stream erosion in Edwards Creek (Inland Waters, 1971). These beds break down rapidly to a colloidal sticky clay. They are easily eroded by water and contribute to the fine sediments found in the Edwards Creek basin (Inland Waters, 1971).

Erosion, in the Riding Mountain area, is due not only to steep slopes and highly erodable soils, but also to the micro-climate that the escarpment creates (Carlyle. 1980). "Heavy, intense rainstorms are more frequent on the higher parts of the escarpment than elsewhere in Manitoba.... Its higher eastern portions annually receive 20 to 40% more precipitation than the surrounding plains" (Carlyle, 1980). These high intensity summer rainstorms rapidly produce peak flows, that usually arrive in the lower watershed within 24 hours after the rainfall has occurred (Stanton and McCarlie, 1962). It is this combination of heavy rainfall, steep slopes and erodable soils that leads to increased erosion in the escarpment and sub-escarpment areas, which in turn causes reduced agriculture yields and higher drain maintenance costs (Newbury and Gaboury, 1988).

4.2 HISTORY OF THE WATERSHED

Dauphin Lake and the rivers draining into it from Duck and Riding Mountains have

experienced morphological and ecological problems since the area was developed for agriculture (Chapman, 1987a). Increased river channel erosion has led to the rapid siltation of Dauphin Lake, which has resulted in the decline of commercial fishing in the area since 1950 (Manitoba Water Commission, 1984).

While Riding Mountain National Park has protected most of the upland forest, agricultural development has taken place right up to the base of the escarpment, including most of the alluvial fan areas of watercourses draining off the escarpment (Chapman, 1987a). The perceived need by the agricultural community for land drainage below the escarpment has resulted in many of the river channel erosion and sedimentation problems in the area (Chapman, 1987a). All the major rivers entering Dauphin Lake, with the exception of the Valley River have been extensively straightened, with an overall loss of length ranging from 13 to 50% (Chapman, 1987b). Edwards Creek and Mink River have been almost completely straightened with few vestiges of the original natural fluvial ecosystems remaining. Along the Vermilion and Wilson Rivers, severe channel erosion began after channelization and substantial amounts of bed material have been transported downstream, likely into Dauphin Lake (Chapman, 1987b).

Due to human manipulation of natural drainage systems, the upper reaches of many streams have eroded deep canyons through their alluvial fan deposits along the foot of the escarpment (Mackling, 1987). The eroded material has been transported out of the fans and deposited in the downstream channels (Mackling, 1987). The coarser material has usually been deposited 1/2 to 1 mile (1 to 2 km.) downstream from the erosion sites, while the finer material has been transported further and has led to increased turbidity and silting downstream (Mackling, 1987). Flood peaks have been increased by the excavation of local drains following the one mile grid of roads, which reduced the length of the flood peak and decreased time of concentration of the floodwaters (Newbury and Gaboury, 1988). The connection of headwaters directly to drains also led to increased flood peaks as well as sediment loads downstream (Newbury and Gaboury, 1988). These problems have led to the straightening and enlargement of the downstream channels to improve

their flood carrying capacity (Newbury and Gaboury, 1988). The straightening and enlarging of these channels has resulted in an increase in downcutting and bank instability (Newbury and Gaboury, 1988).

Historical observation of cut banks suggests that, in the past, Edwards Creek wandered a great deal and had a history of violent flow followed by periods of moderate to low flows (PFRA, 1957). As a result of this regime and the meanders of the creek course, the banks of the creek north of the Riding Mountain National Park boundary are composed of a mix of fine sediments and coarse re-worked shales with pockets of shales found throughout most of the first 3 miles (5 km.) north of the park (PFRA, 1957). It also appears that even minor floods carried very heavy loads of trees and shales (PFRA, 1957).

Before 1948, the lower portion of Edwards Creek flowed due north of from the base of the escarpment to within approximately 2 1/2 miles (4 km.) south of the Town of Dauphin (Inland Waters, 1971). The creek turned here and flowed northeast to join the Vermillion River approximately 4 miles (7 km.) above the mouth of the Vermillion at Dauphin Lake (Inland Waters, 1971). At the upper end of this portion, near the escarpment, the channel was bounded for the first kilometre and a half by relatively high banks on either side (Inland Waters, 1971). As the creek reached the less steep gradient of the lower watershed, the channel widened and assumed a braided pattern over the channel bed during low flow periods (Inland Waters, 1971). This condition was typical of the major portion of the remaining channel, with increased meandering as Edwards Creek approached its junction with the Vermillion River (Inland Waters, 1971). Because of the form and flow conditions of the creek, flooding was a problem in the area east of the town of Dauphin. In an attempt to control flooding in order to permit better agricultural use of the land, the lower portions of the creek were channelized (Manitoba Water Commission, 1982)

Edwards Creek has traditionally been viewed as a single resource, simply as a water drainage system for the surrounding agricultural land, and it was with this attitude that

the design of the floodway channel was undertaken, leading to the virtual elimination of most of the physical, biological and visual characteristics that made this a viable and ecologically important creek (McLachlan, 1986). An 11 .4 mile (18.3 km.) long floodway, to divert flows from Jackfish and Edwards Creek, was built between 1948 and 1951, (Manitoba Water Commission, 1984) at a cost of $555,000.00 (PFRA, 1960). The drain was designed to be fully uniform in size with a 40 foot (12 m.) base, a top width of 60 feet (18 m.) , a mean depth of 6 feet (2 m.) and 2 1/2 to 1 side slopes (Clayton, 1954). Average longitudinal slope was approximately 12 feet per mile (2.25 m./km.) with a maximum of 26 feet per mile (5 m./km.) occurring in some reaches (Clayton, 1954; PFRA, 1960).

A siltation basin, approximately a quarter section (45 hectares) in area, was built immediately upstream of Highway 10 to capture sediments entering the channel from the upstream portions of the creek. During low flow periods, the creek flowed through the basin in the original channel until it reached the weir at the outlet (Inland Waters, 1971). The water then backed up and ponded in a relatively small, low, marshy area to the northwest (Inland Waters, 1971). Under these conditions, the flow over the weir still carried particles in the silt/clay range, which had a low silting rate and required a longer detention period for settling out than the basin provided (Inland Waters, 1971). Under high flow conditions, the water overtopped the original channel banks and spread over the entire basin area (Inland Waters, 1971). As the water spread out, flow velocities were reduced, allowing deposition to occur (Inland Waters, 1971). The sediment trapping ability of the basin increased as the flow increased, until an optimum level was reached, after which the efficiency began to drop (Inland Waters, 1971). Unfortunately, the removal of the sediment from the water column meant that the water leaving the siltation basin had a high sediment entrainment capacity, leading to degradation of the down-stream channel (Inland Waters, 1971). Also, during high flow events, great quantities of large size shale particles were transported as bedload along the original channel (Inland Waters, 1971). These particles were swept over the weir by the turbulence of the water immediately above the weir and deposited in a bar immediately downstream (Inland Waters, 1971).

In 1947, disastrous flooding occurred along all the streams draining the north and east slopes of Riding Mountain National Park. Edwards Creek was particularly troublesome (Stanton and McCarlie, 1962). Floodwaters carried great quantities of silt scoured from stream banks, as well as debris of all descriptions (Stanton and McCarlie, 1962). The initial reaches of Edwards Creek fall gently for a short distance before it begins a rapid 385 metre descent of the cretaceous shale escarpment, which ends when the creek reaches the agricultural plains (Stanton and McCarlie, 1962). During the course of this sudden fall, Edwards Creek flows through a rugged ravine that contributed large amounts of shale and tree debris to the stream flow during the flood (Stanton and McCarlie, 1962). Much of this material was carried a great distance, perhaps all the way to Dauphin Lake, but as the waters subsided, their ability to transport material decreased (Stanton and McCarlie, 1962). Deposition occurred and the entire channel became blocked with shale and other debris (Stanton and McCarlie, 1962). The deposition of material in the lower reaches caused channel deflection and it was this channel deflection that led to erosion along the banks of the creek (Stanton and McCarlie, 1962). This pattern, of floods carrying material and depositing it, causing the realignment of the channel, was typical of the problems that the creek experienced at the time. Consequently, physical land loss was a serious problem (Stanton and McCarlie, 1962). Since most of the land being lost was productive farmland, it was felt that some action was required. It was decided that the creek should be confined to a single channel and that low maintenance methods for controlling its alignment should be developed.

Thus, in 1949, shortly after the construction of the floodway was begun, an experimental program of stream bank stabilization measures was started along the middle reaches of the creek, just upstream of Highway 10 (Stanton and McCarlie, 1962). This program tried a number of different approaches to solving bank stabilization problems. Given the inexperience in stream rehabilitation at the time, the PFRA showed a great deal sensitivity in the design of these works. Vegetation was to be the primary or secondary stabilizing factor in an effort to achieve stabilization with a minimum of mechanical protective work (PFRA, 1957).

The different methods that were explored have been described by Stanton and McCarlie (1962):

Sloping, Seeding and Planting

Initially, the overall aim of the program was to find the cheapest, effective means for vegetative stabilization of the banks. Therefore, trees behind the top edge of vertical banks were felled and bulldozed over the edge. The banks were sloped and the butts of the trees were covered with soil. Branches were left projecting into the stream to serve as minor deflectors.The banks were then seeded to grass and willow cuttings were planted.

Overall, this method was successful about 50% of the time. However, the success was due in a large measure to changes in channel alignment which resulted in less direct action by the stream on the seeded banks. The success of this method appeared to be dependent on:

1) very moderate curves, almost to the point of being a straight channel,
2) freedom from grazing animals or fire,
3) freedom from excessive flooding for at least 2 growing seasons.

This study also revealed that 1 year old rooted willow stock was better than hardwood cuttings for the establishment of an effective cover in the area.

However, this technique resulted in the destruction of the existing riparian vegetation, an essential component in the overall watercourse ecosystem and an existing natural system of bed and bank erosion protection.

Pile Lines

On sharper curves, pile lines were established, in which piles were driven 12 feet (3.7 m.) deep at 15 foot (4.6 m.) intervals (see figure 78). Brush was wired and cabled to the line to act as a sediment filter. In some cases, brush tie backs, to help re-direct scouring streamflow back into the main channel, were run back to deadmen in the bank. When brush supplies were depleted, 15 centimetre wire mesh was used. After spring runoff

deposited a large amount of sediment behind the lines, willows were planted to consolidate the dump.

This experiment demonstrated that:

1) the lack of adequate tie backs could cause 'blowouts' of the bank at the downstream end of the protected area,
2) the brush, in most cases, was a more effective silt filter than the wire netting,
3) willow plantings needed to be heavily concentrated behind the line so that well rooted trees could take over bank protection as the original work deteriorated,
4) willow plantings on raw dumps often failed due to lack of adequate moisture, and
5) the best willow species were Russian laurel-leaf, Russian sharp-leaf, golden and silver in that order.

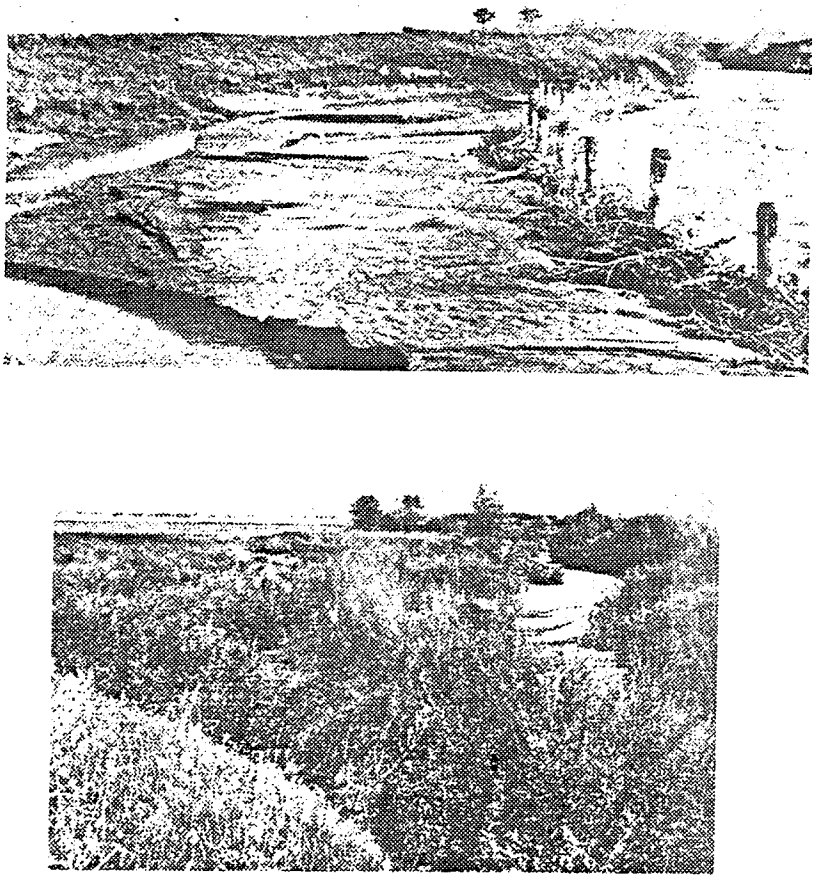


Figure 78 Pile lines. Top, shortly after construction. Bottom, 8 years later. Some of the pile lines have been lost but a good growth of golden willows has kept the creek within the desired channel.

Netted Riprap

On 2 very sharp curves, where it was impossible to make the slopes less than 2:1, a gravel

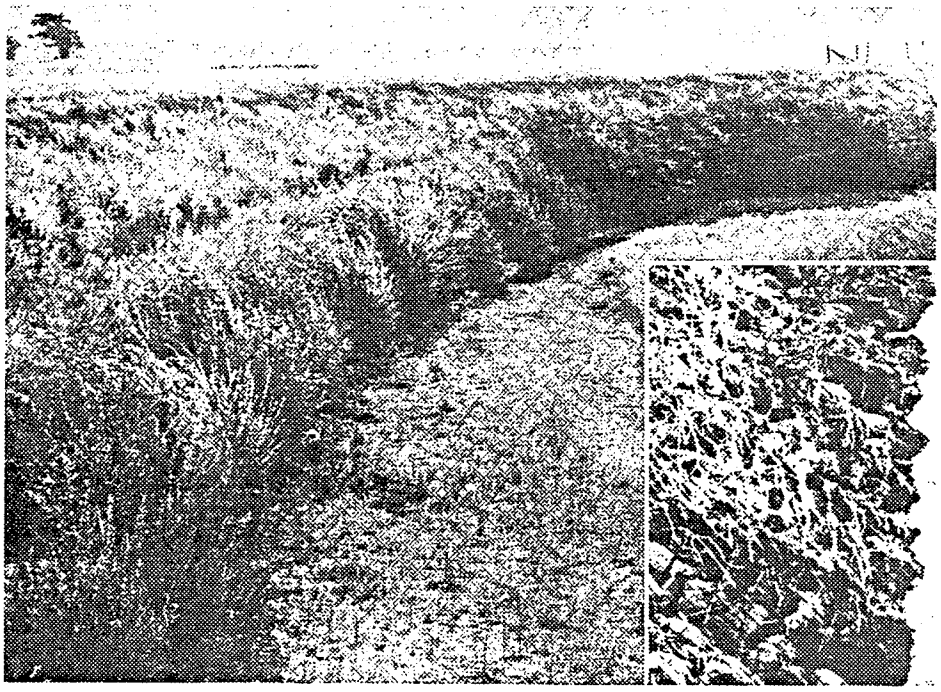


Figure 79 Netted rock riprap 9 years after construction. Inset shows a section of the bank as constructed with the netted rock in place.

blanket was laid on the ground and wire netting was laid over top. Rock was then placed over the netting. The netting was then drawn back down over top of the rock forming an envelope that was then tied shut. The whole construction was anchored to deadmen at 25 foot (7.5 m.) intervals, covered with topsoil and seeded to grass. Willows were planted between the rocks and the wire at the toe of the slope in order to provide additional stability (see figure 79).

This experiment demonstrated that:

1) it was difficult to establish a gravel blanket on steeper slopes,
2) the rock fill should contain at least 30% cobble to fill in the smaller spaces. Failure to do so resulted in local pockets of erosion that could only be repaired by opening the net, and
3) the lowest attachment for the deadman, at the toe of the slope, should be angle iron placed to cause the last amount of turbulence.

Low Rock Toe

On streams similar to Edwards Creek, solid dumps of rock had been shown to stop erosion along the bank. Unfortunately, work of this type was very expensive. To lower costs, it was decided to dump rock only at the toe of the slope and to plant grass on the upper portion of the bank. To start, a fill of shale was bulldozed from the floodplain into the base of the slope to create a 2:1 slope, roughly 6 feet (1.8 m.) high against the bank. Rock was dumped over top of the shale base to a depth of 1 foot (0.3 m.) and the bank above was seeded (see figure 80). Unfortunately, the effectiveness of this method was never reported. While the construction costs were 50% lower than solid riprap, this technique, if successful, would only have been practical where the floodplain was wide and where plenty of shale or gravel available for the initial fill.

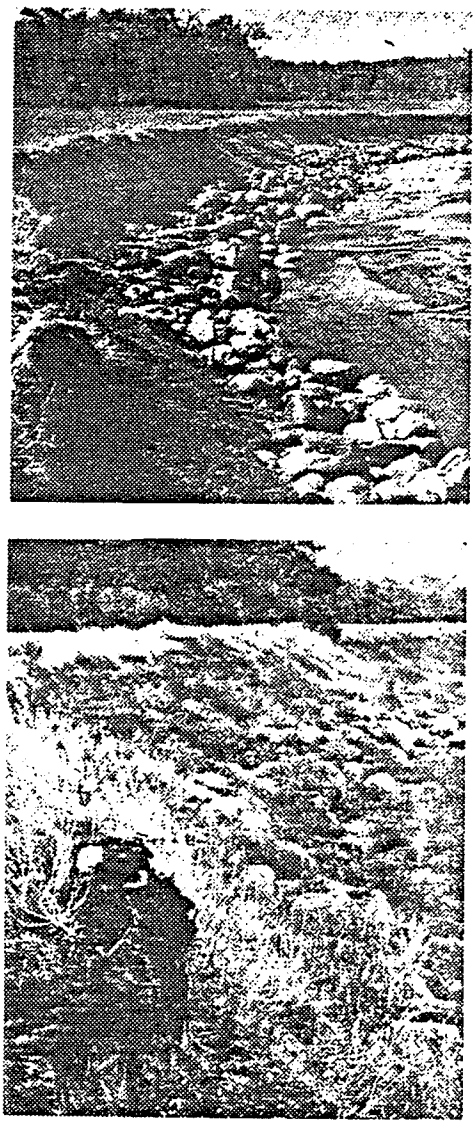


Figure 80 Top, minimum rock dump on a shale pile. Bottom, the same bank 4 years later.

Rolled Willow Toe

At the time, if small local failures occurred on a bank where vegetation was well established, the area was generally re-graded and re-seeded, sacrificing all existing vegetation. Rolled willow toes were developed in reaction to such drastic measures. The technique required that young trees or cuttings had to be anchored to the toe of the slope, in such a way as to give them the resilience to withstand ice action in the spring and scouring from floods in the summer. Thus, willow wands, pushed into the ground at the toe of the slope with tips pointing downstream, were formed into tight rolls by wrapping them with wire. These rolls were then secured to posts every 3 to 4 feet (0.9 to 1.2 m.). While these constructions survived the spring ice breakup, their ability to withstand large summer floods was not recorded. However, Stanton and McCarlie believed that they

would have an excellent chance of withstanding flooding, while successfully protecting the bank. On the other hand, it was felt that a serious flood during the first two years might adversely affect this construction. While plant survival rates were generally good, planting in the fall led to a more successful 'catch' of the vegetation than spring planting. Overall, this method, which was inexpensive to build, was only useful where the upper banks already had an established protection.

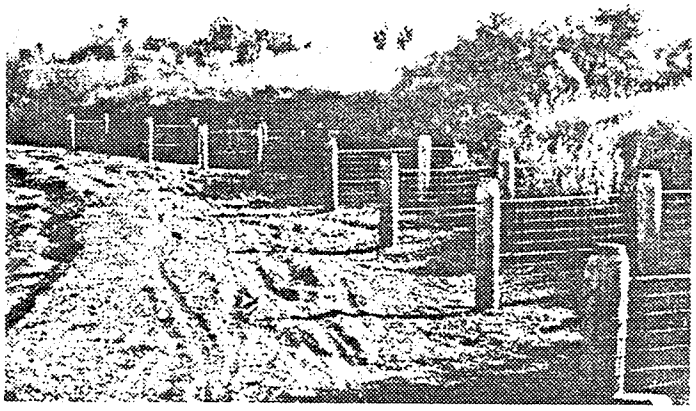


Figure 81 Pile jetties shortly after construction.

Pile Jetties

This experiment consisted of three piles placed in a line forming a 60° angle with the stream flow (see figure 81). The piles, 18 feet (5.5 m.) long, were driven 12 feet (3.7 m.) deep, 10 feet (3 m.) apart. Galvanized, 15 centimetre wire mesh was attached to each jetty and strengthened by 3 lines of 3/8 inch (9 mm.) galvanized telephone cable. The spacing between the jetties was determined by the point where the re-directed streamflow would hit the bank. It was at this point that the base of the next downstream structure began.

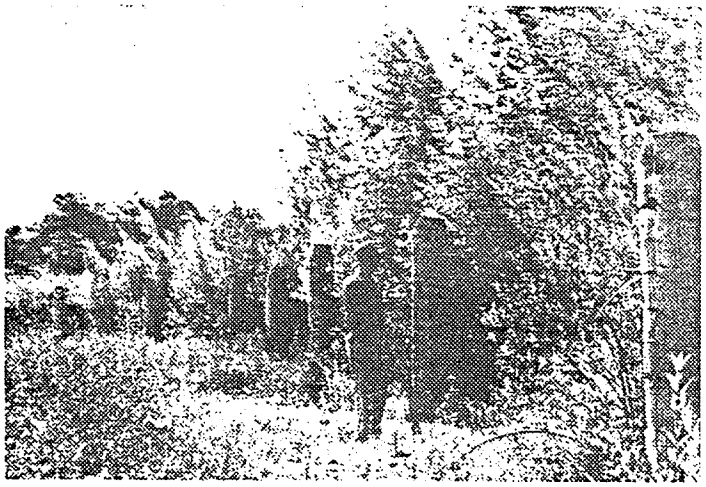


Figure 82 Russian laurel-leaf as it has grown after it was planted on the silt dumps between the pile jetties.

The wire netting rapidly caught fine debris such as grass and twigs and a large amount of silt was deposited between the jetties. With the goal of establishing trees to take over the protection of the bank when the piles and wires had deteriorated, concentrated plantings of willows, using 1 year old rooted stock were made on the silt deposits and along

the upstream side of the jetties (see figure 82).

Points illustrated by this experiment were that:

1) jetties cost slightly more than an equivalent length of straight line piling, especially in terms of labour,
2) due to the impact of heavy debris on the outside pile, a jetty may fail, and
3) since telephone cable stretches, woven wire was better for reinforcing the jetties.

Another experimental bank stabilization technique, Cabled Trees, was tried in the reach (PFRA 1950). This experiment involved the felling of trees which were then moved into lines. Each tree was overlapped a third of their length by the next one in line and the whole line was cabled together. Willow poles were planted behind the line but the survival rate was very low. It was hoped that the poles and cuttings would form a permanent solution in 2 years. Unfortunately, this method, like the first technique described, Sloping, Seeding and Planting, involved the destruction of the existing vegetation which was already providing some natural stabilization of the bank. Perhaps methods that augmented the function of the existing vegetation would have proved more effective in securing the creekbanks against erosion.

While periodic maintenance of the works was necessary, by 1952, most appeared to be doing a fairly good job of stabilizing the improved experimental reach (PFRA, 1952). The PFRA kept Edwards Creek clear of debris and obstructions ad maintained one clear channel open from 1949 to 1956 (PFRA, 1957). In 1956, a flood equal in magnitude to the 1947 event, filled the experimental reach to the same condition as in 1949, when the experiments began (PFRA, 1957). It was felt that even a small flood in 1957, would make conditions worse (PFRA, 1957). It appears that the PFRA discontinued maintenance after the 1956 flood. While at least one further inspection was undertaken in 1963 (Stanton, 1963), no further reports on the condition of the rehabilitation works was made.

While the experimental techniques were relatively successful in stabilizing the banks of the creek, the hypothesis upon which their necessity was founded was not based on an

understanding of the natural processes of watercourses and the local conditions. The area chosen for the experimental reach was a prime deposition zone for material that Edwards Creek transported out of the escarpment. An examination of other watercourses in the area shows the sub-escarpment zone, where the experimental reach was set up, to be the area where alluvial fans and other deposition forms have developed. (Chapman, 1987a) The gradient of the watercourses flatten in this area, causing a decrease in water velocities and ability to transport material (see figure 83). Consequently, deposition occurs. Due to this deposition, over time, the watercourses substantially alter their channel locations (Robert Newbury, personal communication, Oct. 29, 1987).

Thus, the attempt to rigidly control the creek channel location through this reach may have exacerbated downstream problems. Confining the creek to a single permanent channel disrupted the functioning of the natural sedimentation processes in the sub-escarpment area and may have caused shale and other debris to be carried further, leading to increased deposition in the lower reaches of Edwards Creek. Unfortunately, while the experimental techniques were enlightened in their use of vegetative means of stabilization, a lack of understanding of natural watercourse processes had not allowed a recognition of the possible effects of the works on the overall functioning of the creek. The sediment basin, just upstream of Highway 10, functioned in the same capacity as the natural area upstream was functioning, prior to its alteration. Since the shale and debris that would have been deposited naturally in the upstream reaches was being transported further downstream, it is possible that the siltation basin filled faster than it might have otherwise.

An examination of the sediment deposition mass curves for the siltation basin, appears to support this conclusion (see figure 84). Sedimentation occurred rapidly from 1951 to 1960, the period during which the bank stabilization experiments were taking place. From 1960 to 1969, another 9 year period, during which it appears no maintenance of the the experimental reach was undertaken allowing the creek to recover its natural state in the reach, sedimentation was considerably reduced. From 1953 to 1957, the area experienced above average precipitation (see figure 85) and that the creek likely carried more material

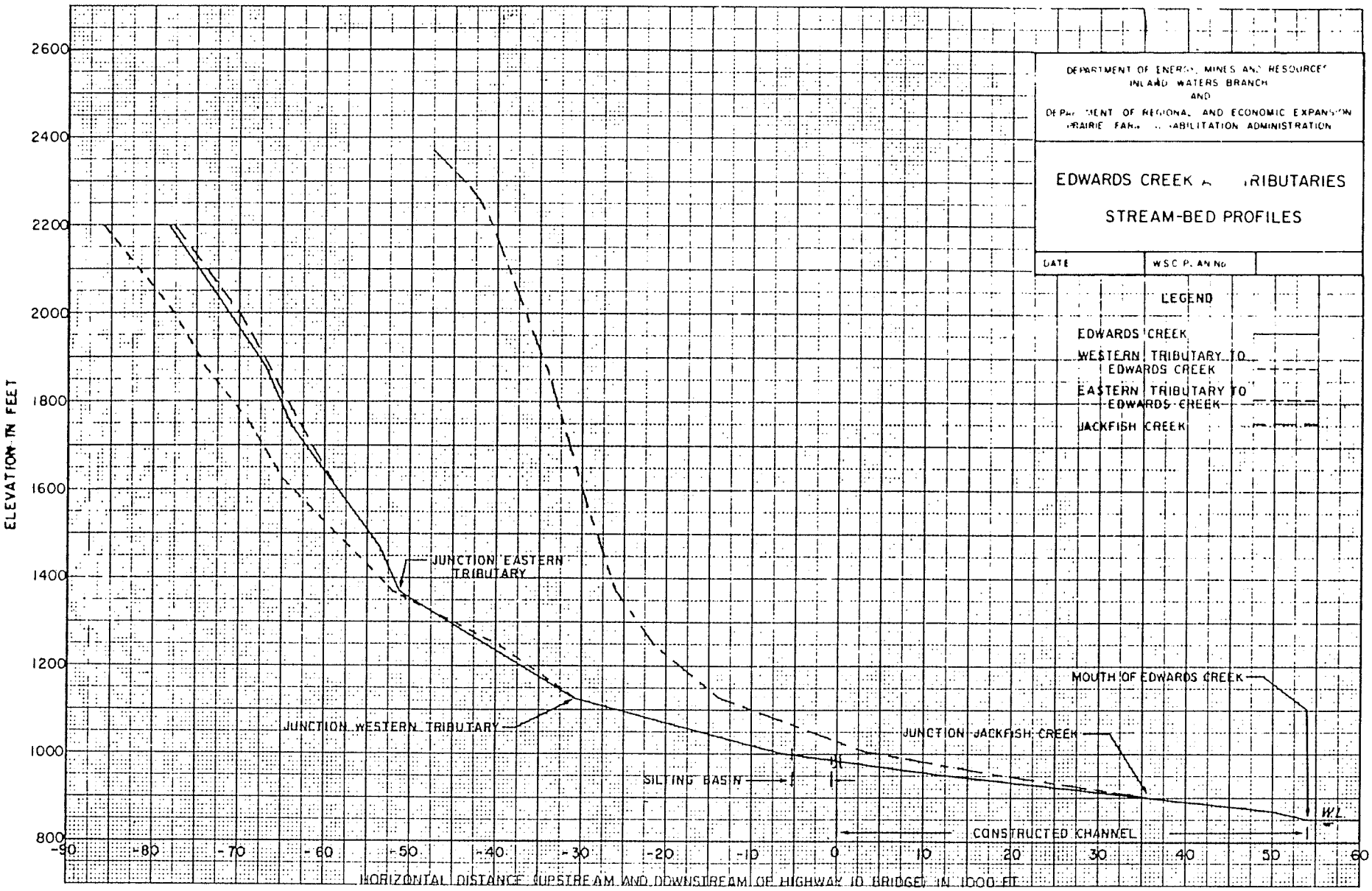


Figure 83 Edwards Creek and tributaries streambed profiles.

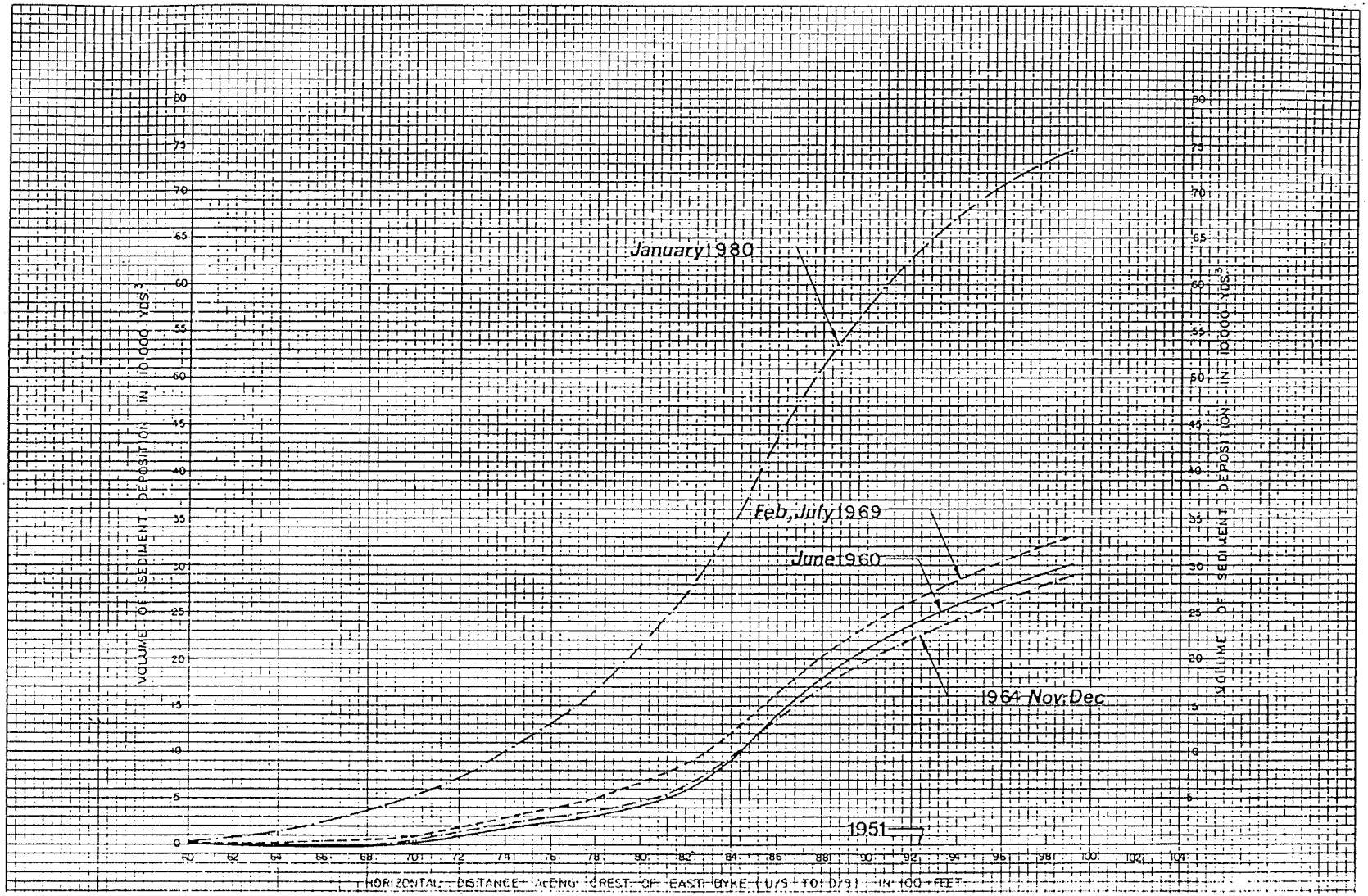


Figure 84 Edwards Creek siltation basin sediment mass deposition curves.

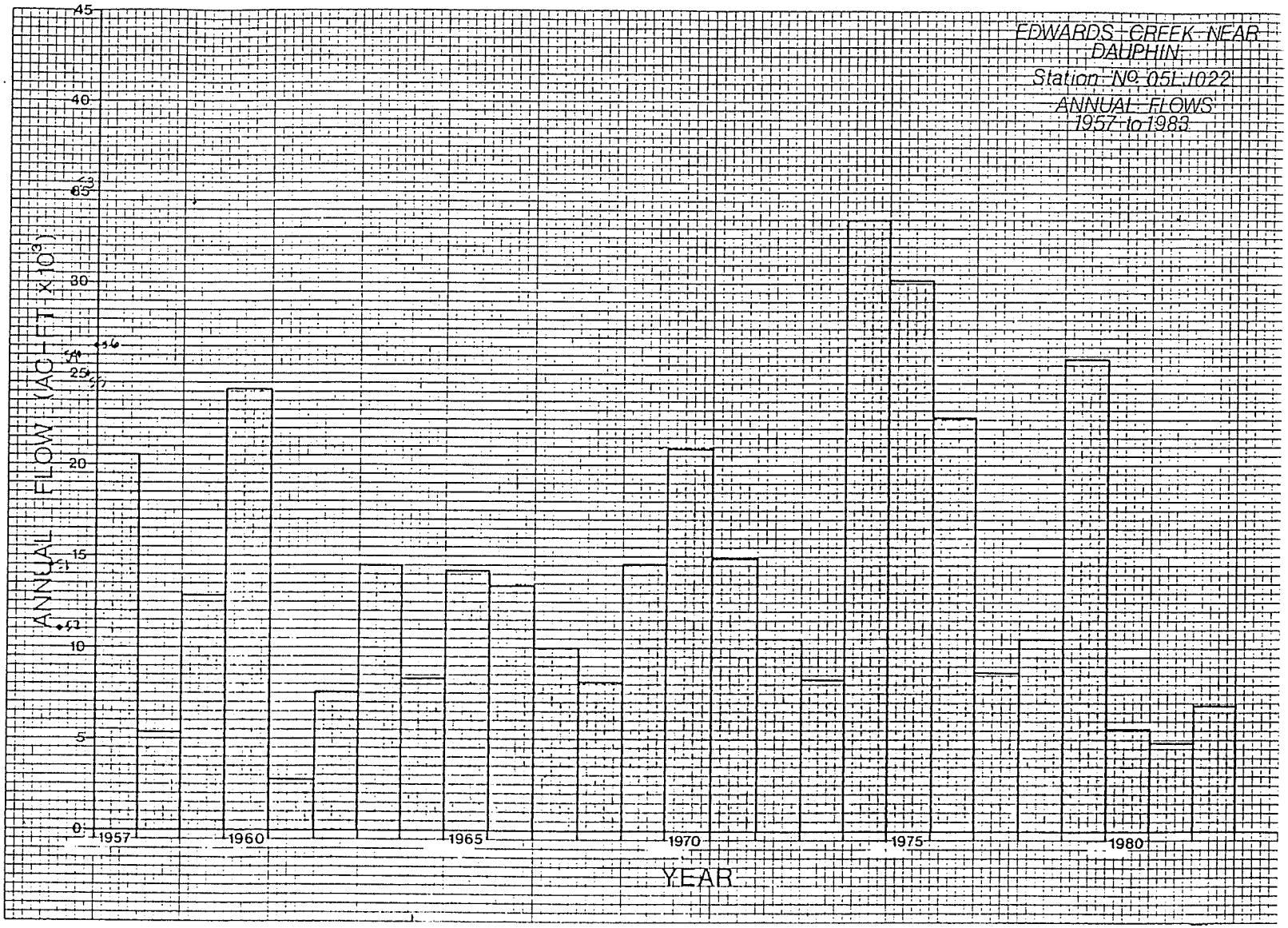


Figure 85 Annual flows of Edwards Creek, 1957 to 1982.

than normal. But, during the period of normal flows from 1960 to 1969, when the creek was functioning in its natural state, very little deposition occurred in the siltation basin. The mid-seventies also experienced above normal precipitation and in 1975, Edwards Creek experienced its highest ever recorded maximum daily discharge (see figure 86). The sediment deposition mass curves for the siltation basin shows that substantial deposition took place between 1969 and 1980. Overall, these observations would appear to indicate that under normal flow conditions, the reach just to the north of Riding Mountain National Park, when in its natural state, functions as a deposition area and that little sediment is carried into the downstream portions of the channel. It is during high flow events that the reach cannot absorb all the sediment produced in the escarpment and the siltation basin then absorbs the material.

Unfortunately, repeated attempts to place vegetative protection in other locations along the floodway outside of the experimental reach were largely unsuccessful (PFRA, 1960). By 1960, only a few sites have taken and only with difficulty (PFRA, 1960). While Inland Waters (1971) cites above normal flows in 1953 through 1957 as the cause of the erosion problems in the drain, the PFRA (1960) states that none of the plantings were ever exposed to a severe flood. The reasons given for the plant failures include the infertility of the soils on the streambanks, the lack of adequate moisture during low flow periods and the indifference of the farmers (PFRA 1960). In more than one case, willows were killed by cattle grazing or trampling before becoming established (PFRA, 1960). All protection works also required continual observation and upkeep (PFRA, 1960). When discharges remained low, maintenance costs were correspondingly small, but when discharge became high, maintenance costs would increase dramatically (PFRA, 1960).

Edwards Creek also experienced other problems, especially after the channelization and re-alignment of the channel, from just upstream of Highway 10 to Dauphin Lake. The pre-channelization length of Edwards Creek, from the siltation basin, upstream of Highway 10 to the connection with the Vermillion River and on to Dauphin Lake was approximately 21.5 miles (35 km.). The floodway reduced this to approximately 10.5 miles (17.5

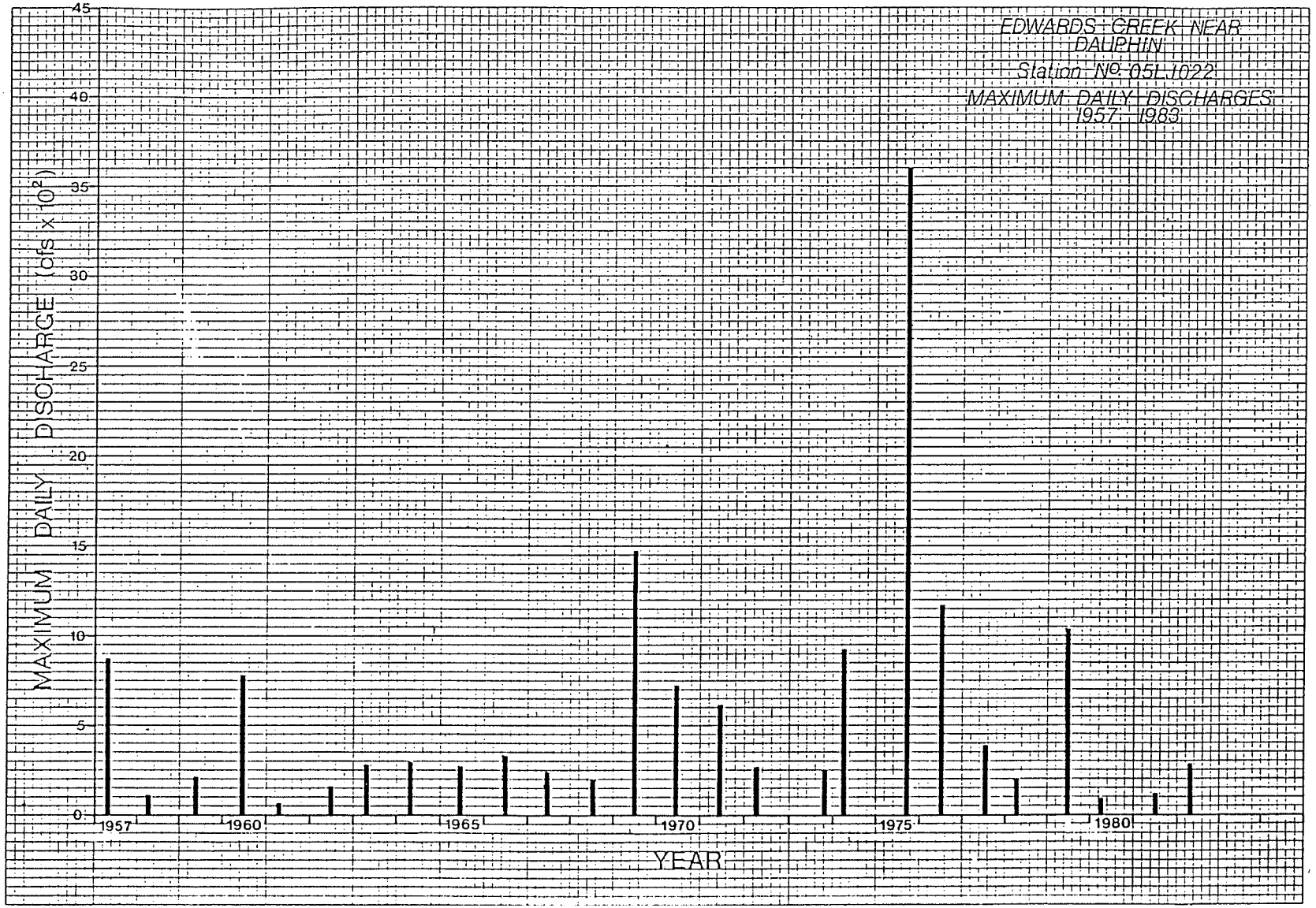


Figure 86 Maximum daily discharge along Edwards Creek 1957 to 1982.

km.), half of the original length. This essentially doubled the slope of the channel bed and the dramatically steepened channel soon began to erode severely along its entire length (Chapman, 1987a; PFRA, 1960).

Since the floodway was constructed on a slope of about 12 feet per mile (2.25 m./km.), with no provision for grade control, water velocities in excess of 10 feet per second (3 m. per second) occurred (PFRA, 1960). In order to prevent scour in the type of soil encountered along the drain, velocities should not have exceeded 5 feet per second (1.5 m. per second) (PFRA, 1960).

Thus, since it began operation in 1951, the floodway has undergone considerable change in an attempt to achieve equilibrium within the parameters of its new slope (Inland Waters, 1971). Channelization led to degradation and lateral erosion, due to not only an increase in the channel gradient as a result of the overall shortening of the length of the creek, but also as a result of a decrease of suspended sediment concentration in the flow into the floodway from the siltation basin and Jackfish Creek, and a decrease in channel roughness with a consequent increase in the flow velocity in the channelized sections (Inland Waters, 1971).

These conditions, all conducive to erosion, came in operation when the floodway opened in 1951 (Inland Waters, 1971). Above normal flows that occurred in every year from 1953 to 1957 made the problems with the channelization works immediately evident, as the floodway changed its boundaries to accommodate the increased discharge (Inland Waters, 1971). In the spring of 1953, scour, lateral erosion and overtopping of berms affected the entire length of the channel (Inland Waters, 1971). Bridges and bridge approaches were extensively damaged and the entire reach between Jackfish Creek and Dauphin Lake experienced dramatic alterations (Inland Waters, 1971; see figure 87).

By March of 1954, the berm on the left side of the drain from Jackfish Creek to Highway 10 had been entirely washed away (Forsyth, 1954). The possibility of erosion in this reach

had been recognized in 1949 and in an endeavour to control it, an unsuccessful attempt was made to vegetate the banks in 1950 (Forsyth, 1954). Unfortunately, the problem of erosion was not confined solely to this reach. Bank slopes also initially disappeared for long stretches in a 3 mil3 (5 km.) reach downstream from Highway 10 and in a 2 1/2 mile (4 km.) reach downstream from Highway 5 (Forsyth, 1954). It was felt that the dykes in these areas would be threatened within a few years (Forsyth, 1954).

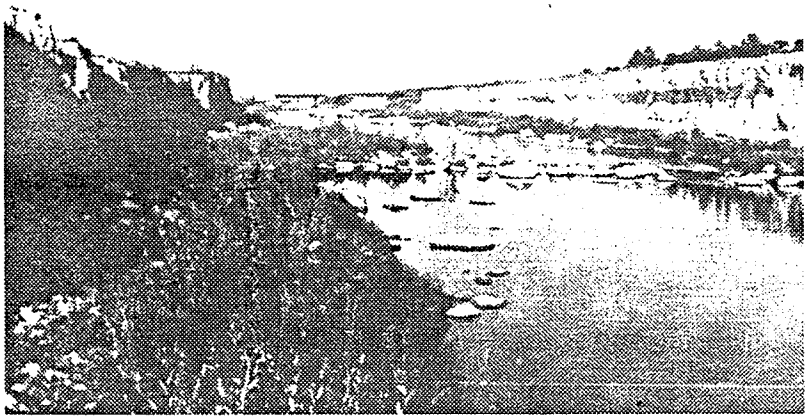


Figure 87 The Edwards Creek floodway between Dauphin Lake and the junction of Jackfish Creek, circa 1971.

In May of 1954, the floodway was re-examined and was found to be very bad condition. Most banks were vertical, the depth had increased as much as 2 feet (0.6 m.) in places and the bottom width had increased by about 10 feet (3 m.) (Clayton, 1954). Antithetical to Forsyth's assessment of the situation, Clayton (1954) stated that since floodwaters had only overtopped the berms in a few places, with very little depth, the berms and dykes were relatively unharmed. Clayton (1954) also believed that as the bottom of the channel eroded that rocks would be exposed. These rocks would act as paving for the creek bottom, causing the channel to become "self riprapped", reducing the rate of erosion (Clayton, 1954). Unfortunately, an examination of the channel cross-sections over time has shown that this has not been the case and that erosion has continued ever since the drain opened, with many sections of the creek requiring riprap protection.

The higher velocities, resulting from the increased slope of the channel, also contributed to lateral erosion, which in turn led to the progressive washout of the abutments of the timber municipal bridges and the undermining of the concrete footings of the the piers

of the 2 highway bridges over the creek (PFRA, 1960). As a result of the exposure of their end piles by erosion, all wooden municipal bridges along the creek required extensions and wing walls or rock paving of their abutments (Clayton, 1954; PFRA, 1960). At the Highway 5 and 10 bridge, a major crossing, erosion was so severe that the bottoms of the bridge footings were exposed (Clayton, 1954). Almost immediately after the channelization project opened, both the Highway 5 and 10 and the Highway 20 bridges required protection by grouted dumped rock weirs downstream of the crossings, (PFRA, 1960). Fortunately, the sediment transported by the stream rapidly backfilled the space behind these structures and covered the exposed footings (PFRA, 1960). Erosion also exposed the Town of Dauphin watermain located just downstream of the Highway 5 and 10 bridge (PFRA, 1960). Prior to the installation of the grade control structure for the bridge, the bottom of the main was at least 1 foot (0.3 m.) clear of the streambed in the middle of the channel (PFRA, 1960). Unfortunately, the grade control structure was not sufficient to protect the watermain and at present, the main is still exposed and no longer in use. The remains of the pipe can be seen resting about 2 feet (0.6 m.) above the creekbed.

Over time, a great deal of money and effort has been expended to try to reduce erosion in the drain. Between 1952 and 1960, the eight years following the construction of the drain, a total of $190,000.00, more than one-third of the original $555,000.00 cost of the drain, was spent on the construction of protective works, maintenance and upkeep of the drain (PFRA, 1960). Similar amounts of money have continued to be spent until the present day. Examination of the provincial government's correspondence file on Edwards Creek shows that the creek has continued to experience problems with erosion washing away dykes and threatening to take its channel through farmers' fields. In 1975, the siltation basin was cleaned out and in 1976 alone, $45,000.00 was spent to clean out a half mile (0.75 km.) reach just upstream of the basin. Today, an examination of the channel still reveals evidence of serious erosion (see figures 88, 89, 106, 107, 108, 109).

The design of the drain alone is not solely responsible for all the problems along its length. As the PFRA (1949) reported, the problem of bank erosion was initially bound up with

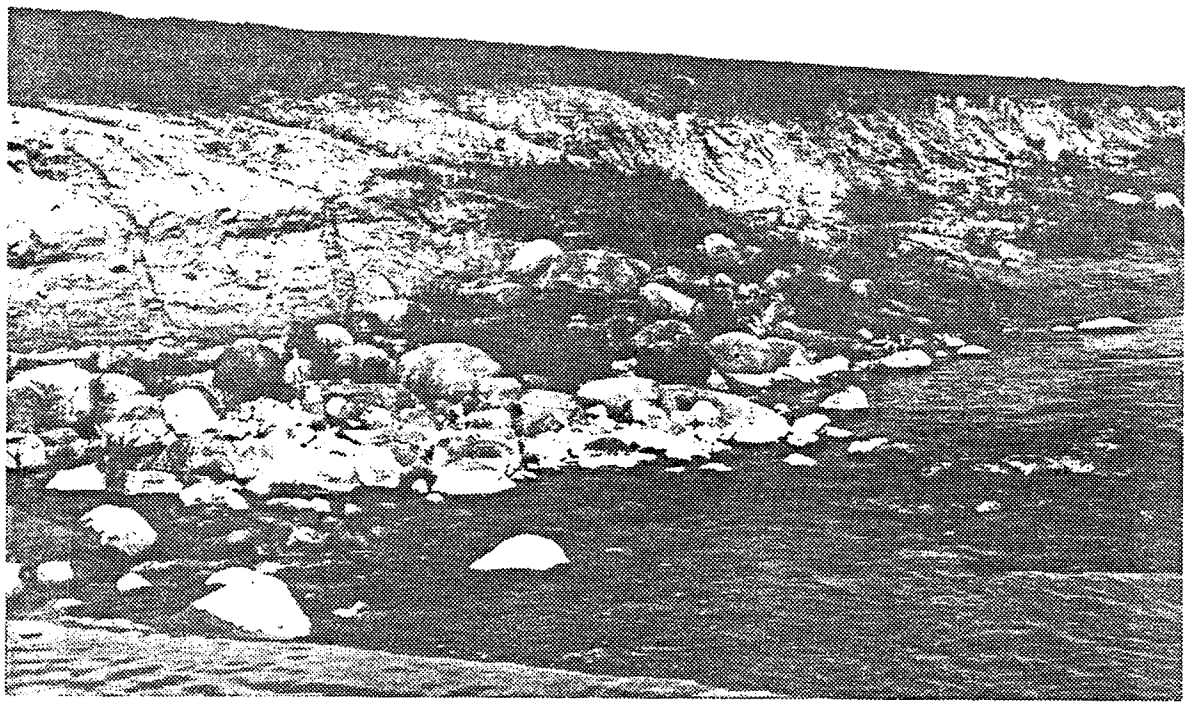


Figure 88 The Edwards Creek floodway in 1988.

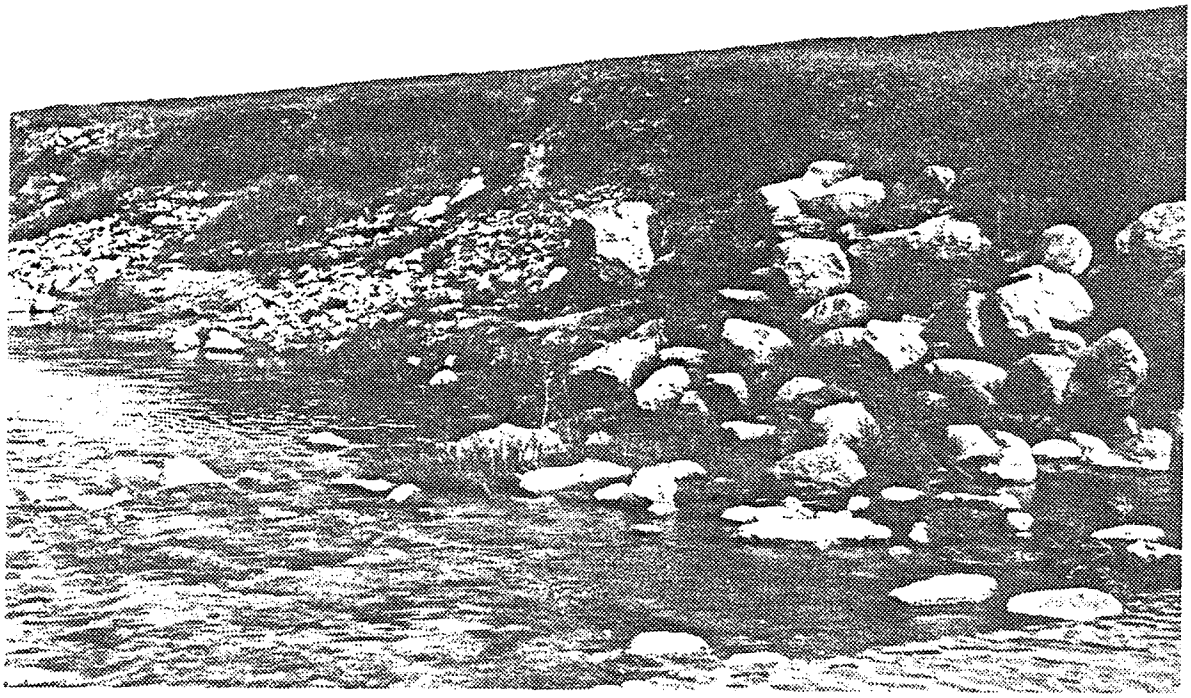


Figure 89 The Edwards Creek floodway in 1988.

that of flood control. An attempt to alleviate bank erosion, without attempting to lessen flood peaks and the debris load carried by the stream, would throw the maximum strain on all protection works (PFRA, 1949; PFRA, 1957). As a result, a novel approach to the development of headwater storage basin was instituted. Historically, there was a great deal of evidence of beaver activity in the Edwards Creek watershed (PFRA, 1949). Local residents said that before the beaver had been trapped out, the creekflow in the summer was only a trickle and they felt that the beavers and their dams were directly responsible (PFRA, 1949). With this in mind, fourteen beaver were released into the upper reaches of the watershed with the hopes of improving headwater storage (PFRA, 1949). In 1952, although there were some problems with bridge culverts being dammed, the project appeared to be successful and plans were made to release at least 50 more animals along the whole north and east faces of the Riding Mountain Escarpment (PFRA, 1952). While no further mention of the beaver release program is found in literature relating to Edwards Creek, the author while exploring the watershed in the spring of 1988, found evidence of recent beaver activity in two locations within Riding Mountain National Park and in one location just outside of the park.

Flooding, affecting farmland and threatened the Highway 10 bridge, has resulted from the almost complete blockage of the channel by snow and ice during spring breakup, (PFRA, 1950). Thus, in 1959, a snow fencing experiment was undertaken, just to the west of the Highway 10 bridge to determine if it would be possible to prevent the build up of ice and snow along the channel (PFRA, 1960). While the 1 year experiment should not be considered conclusive, the snow fencing was successful in completely preventing the critical build up of ice and snow from occurring in the area that was previously chronically troublesome (PFRA, 1960). The PFRA wished to continue the experiment to see if some permanent solution, perhaps involving the establishment of hedges, could be developed (PFRA, 1960). The Department of Public Works of the Government of Manitoba was approached, at the time, to see if they wished to become involved. An agreement was struck, in which the Department of Public Works would place snow fencing in the experimental area from 1961 to 1964 (Blackman, 1960). Unfortunately, no record

Near Stream Activity	Negative Physical Effects	Negative Effects On Fish In Streams and Lakes
Removal of Shoreline Vegetation	Increased bank erosion	Sedimentation of spawning grounds and suffocation of eggs Sedimentation of invertebrate fauna on stream bottom
	Increased water temperature	Sub-optimum temperatures for coolwater fishes
Wetland Drainage and Stream Channelization	Reduction in wetland areas/peripheral marshes Lower water table Increased peak rates of flow in spring with reduced summer flows	Loss of spawning and nursery areas Reduction of food source
	Changes stream substrates See: Removal of Shoreline Vegetation	Reduction of stream habitat during the summer
Land Clearing and Cultivation	Increased surface run-off in spring with rapid attenuation of flows after peak discharges	For spring spawners: reduction in available spawning areas and incubation success Increased transport time of passive larvae to suitable nursery areas
	Increased wind and water erosion	Increased sedimentation Increased lake eutrophication from fertilizer use Sub-lethal and toxic effects from chemicals (eg. pesticides)
	See: Removal of Shoreline Vegetation and Wetland Drainage	
Livestock Operations	Shoreline trampling causing bank slumping/erosion	Sedimentation of stream substrates
	Manure input to streams See: Removal of Shoreline Vegetation	Lake eutrophication
Instream Obstructions (ford and culvert crossings, and water supply dams)	Local increased water velocities and/or turbulence Impassable barriers	Partial or total blockage of fish movement Reduction in access to fish habitat and spawning areas
Roads	Bank de-stabilization and erosion Sediment from roadside ditches See: Removal of Shoreline Vegetation	Sedimentation of stream substrates

Figure 90 Effects of various landuse activities on fish and fish habitat in small watersheds.

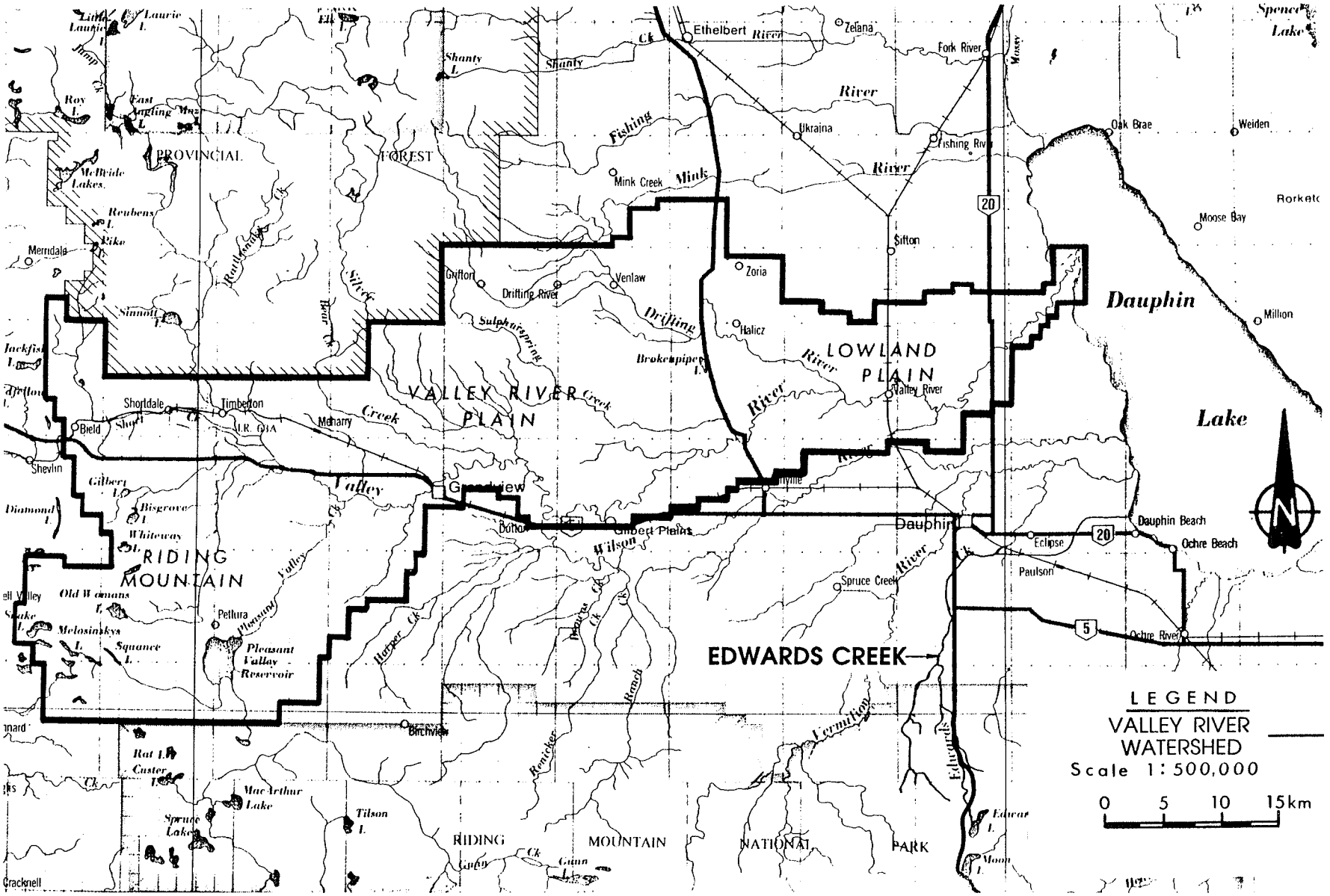


Figure 91 Location of Edwards Creek in relation to the Valley River.

describing the results of this experiment was found and it does not appear, at present, as if any permanent hedging was put in place.

Figure 90 (Pokrant and Gaboury, 1983) illustrates the variety of factors that contribute to channel erosion problems in the area. After channelization, land use changes in the watershed have had the most substantial effect. Studies along the Valley River,a watershed near to Edwards Creek indicate significant changes in landuse patterns from 1948 to 1980 (Pokrant and Gaboury, 1983; see figures 91 and 92). In 1948, cultivated land in the Valley River watershed covered 37% of the land area outside Riding Mountain National Park and Duck Mountain Provincial Park. By 1980, cultivated land had increased to 60% of the total land area at the expense of all other categories, with woodlands experiencing the largest loss.

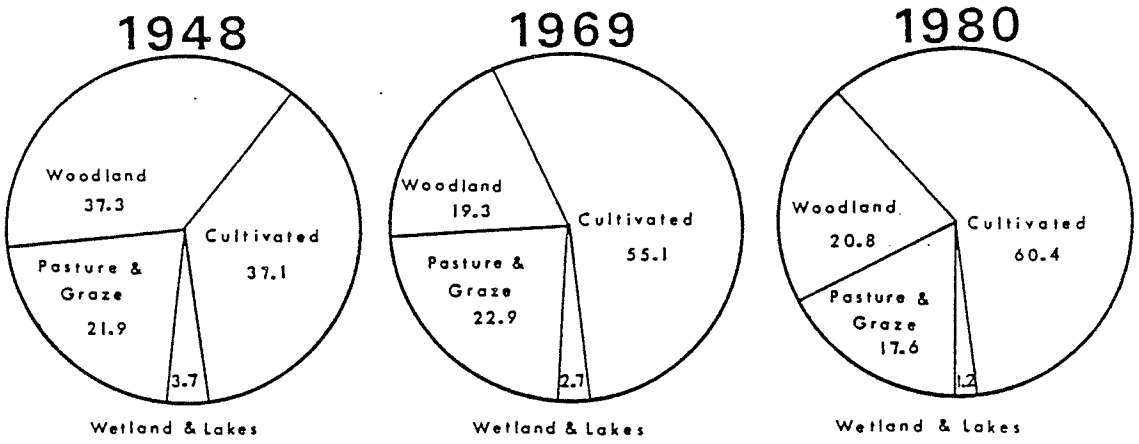


Figure 92 Percentage of the Valley River watershed, outside of Riding Mountain National Park and Duck Mountain Provincial Park, occupied by various landuses, in 1948, 1969 and 1980.

Land clearing and the associated activity of wetland drainage, both of which are required to increase the land under cultivation, have had a very significant effect on the hydrologic regime of the Valley River (Pokrant and Gaboury, 1983). Since the Valley River watershed is located in the same area, it can be assumed a similar situation has occurred with Edwards Creek. In the Valley River, present day water flows have almost doubled from those recorded in 1913 to 1928 (Pokrant and Gaboury, 1983). Also, the rapid attenuation of flows after a peak event and the flushing of the drain are probably due to

the loss of woodlands in the drainage basin (Pokrant and Gaboury, 1983). Wooded lands retain water longer causing lower peak flows and a more gradual decline in flows after the peak (Pokrant and Gaboury, 1983). The loss of wetlands is also significant, since these areas act as water storage reservoirs (Pokrant and Gaboury, 1983). All-in-all, the clearing of large tracts of land and the construction of many roads and ditches, together with large amounts of rainfall during the 1950's would have increased the speed and erosive capacity of the runoff into the lake (PFRA, 1960).

While the Valley River is likely experiencing more streambank erosion than it was previously, its sediment load per unit of watershed area is the lowest of all streams entering Dauphin Lake (Pokrant and Gaboury, 1983; Manitoba Water Commission, 1984; see figure 93). The Valley River is one of the least channelized watercourses in the Dauphin Lake watershed (Chapman, 1987a) and it is believed that other tributaries of Dauphin Lake have higher sediment loads, primarily due to stream channelization and the extensive drainage improvements made to adjacent lands (Pokrant and Gaboury, 1983).

Stream	Average Annual Susp. Sediment (Tons)	Drainage Area (mi^2)	Average Suspended Sediment Yield ($Tons/mi^2/yr$)	Expected* Yield ($Tons/mi^2yr$)
Mink River	5,959	106	56	no information
Valley River	16,069	1108	14	25 - 50
Wilson River	47,896	357	134	51 - 250
Vermilion River	95,596	260	367	51 - 250
Edwards Creek	36,502	55	663	50% @ 51-250 50% @ 251-1000
Ochre River	90,962	133	683	251 - 1000
Turtle River	60,445	376	161	51 - 250

*Range of values for expected yield are taken from "Suspended Sediment Yield for Canadian Rivers" map 1972 published with "Sediment Loads in Canadian Rivers" Technical Bulletin No. 74; Stichling, Inland Waters Directorate, Ottawa

**Water Resources Branch - "Dauphin Lake Sedimentation Study", 1982

Figure 93 Annual sediment yields from computed data for watercourses entering Dauphin Lake.

Edwards Creek is one of the most severely channelized watercourses in the Dauphin Lake watershed and a recent study indicated that Edwards Creek carried an average sediment load of 36,000 tons per year, not including bed load (Water Resources Branch, 1982).

This translates to 663 tons per square mile per year, an extremely high sediment yield (see figure 93). Only one other river in the Dauphin Lake watershed has a slightly higher yield. By comparison, the Valley River the least channelized watercourse in the Dauphin Lake watershed produces only 14 tons per square mile per year.

Higher water velocities, increased bed and bank erosion and higher sediment loads as a result of land clearing lead to the sedimentation of bottom substrates, covered suitable fish spawning grounds and suffocated incubating fish eggs (Pokrant and Gaboury, 1983). Similar processes are likely to have occurred in Edwards Creek. The rapid attenuation of flows after the spring discharge has lead to low flows during walleye spawning and/or incubating periods, an especially critical factor in low flow years when eggs become de-watered or subject to wide fluctuations in water temperature (Pokrant and Gaboury, 1983). Newly hatched walleye larvae are be stranded in the river, where preferred food is limited causing a substantial decrease in survival rate (Pokrant and Gaboury, 1983).

Increased sedimentation, while directly affecting the channel, has also affected the water quality of Dauphin Lake. Local residents around the lake stated that the entire bed of the southern portion of the lake had become covered with a thick bed of silt in the 1950's (PFRA, 1960). The formation of this bed of silt corresponded closely with the mouths of the major watercourses entering the lake, the period of wet years from 1953 to 1957 and the intense development of the surrounding land in the post war years (PFRA, 1960).

In 1959, a representative from the Rural Municipality of Ochre River suggested that, to a great extent, the present drainage system in the area was causing the silting problem in Dauphin Lake (Minutes from Meeting of Interested Parties, 1959). The meeting, at which this suggestion was tabled, resolved that a study of the Riding Mountain area should be undertaken by the Department of Mines and Natural Resources with the view that water entering the drain should be impounded rather than sped up, providing a steady flow of water throughout the year and that no further drainage ditches be built in order to prevent further silting (Minutes from Meeting of Interested Parties, 1959).

Edwards Creek's new entry into the lake, which rapidly silted up, was seen to be representative of this trend and was the impetus for many complaints and the resultant studies. Figures 94 to 100 show the enormous sediment delta deposited in only 18 years.

In the fall of 1956, complaints regarding the volume of sediment being deposited at the mouth of the floodway were received from the owners of cottages in the Dauphin and Oaka Beach areas (PFRA, 1960). It was feared was that a fine recreation area would be destroyed (PFRA, 1960). Therefore in 1957, a comprehensive study of the delta that was forming at the mouth of the floodway was begun (PFRA, 1960). Observations were continued on a regular basis until the late 1960's. Cross-sections of the delta were run along a series of baselines in an effort to determine the rate of formation of the deposit. In 1959, two years after the first cross-sections were run, it was established that an increase in the lake bottom elevation of 6 inches (0.15 m.) had occurred over a 30 month period (PFRA, 1960). Unfortunately, no plan of the lake bottom as it was prior to completion of the floodway was available. Thus, the PFRA (1960) stated that no true estimate of the total build up of the bed at the mouth of the floodway was possible.

Based on estimated original lakebed contours (which apparently were not good enough to use to determine the volume of the delta) and the fact that the delta increased in size during 1958 and 1959, two years of below normal flows, when not much evidence of erosion was observed along the channel, a PFRA report, The Edwards-Jackfish Creeks Floodway Dauphin Lake Silting Problem (1960), concluded that the build up of silt could not be not entirely attributed to the floodway. While it is probably true that the floodway was not entirely responsible for the siltation, the veracity of the data that this conclusion is based upon is questionable. A detailed investigation, entitled Morphological Study Edwards Creek Watershed (Inland Waters, 1971), determined that the delta experienced a net decrease in size from 1957 to 1960. As well, during these years lake levels were more than 0.5 metres lower than they were previously (see figure 101). Along with wave action on the lake, which may have piled up sediments, the lower lake levels could have made the delta appear visually larger than it did in the mid-1950's. Also,

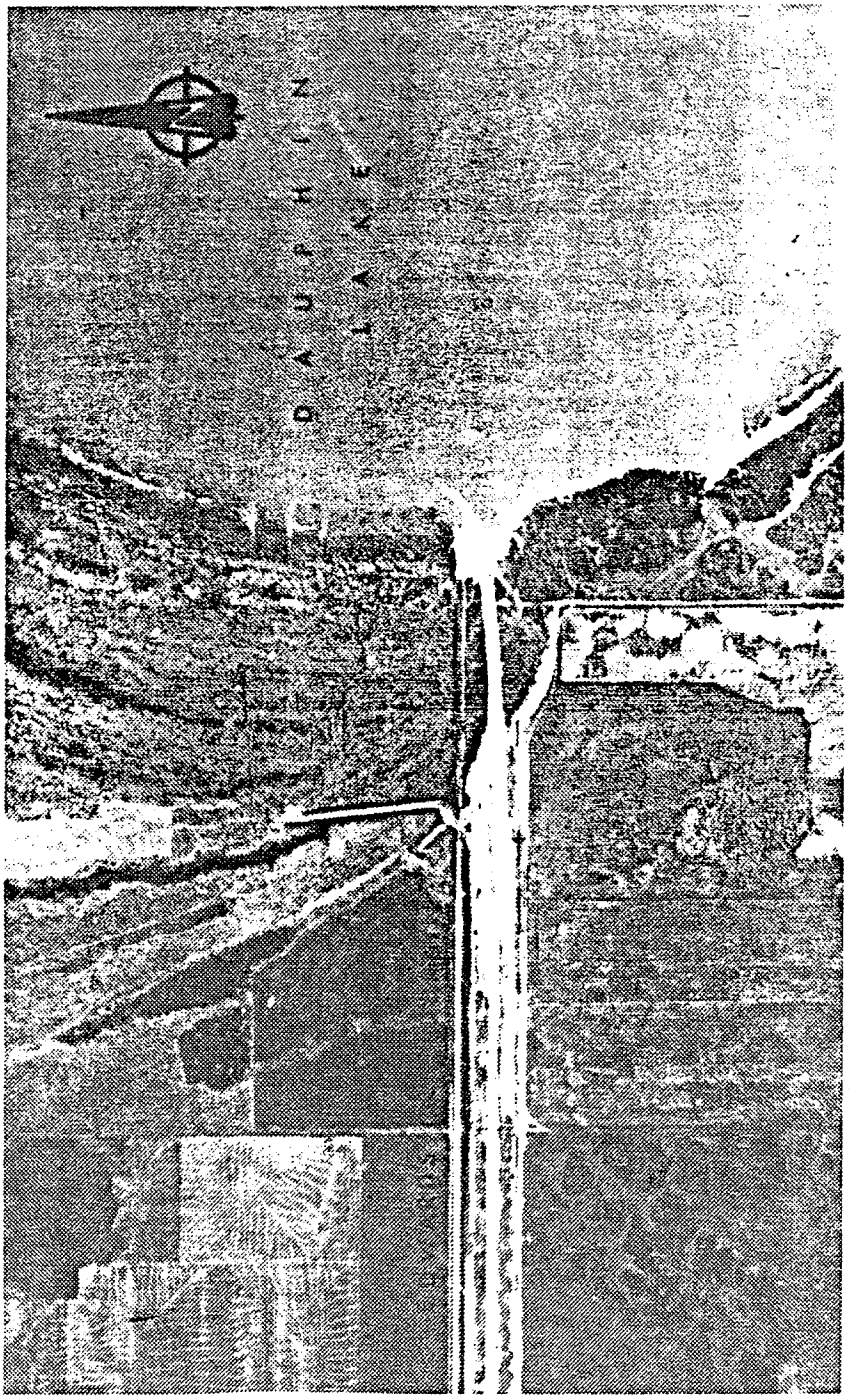


Figure 94 1950 photo of the mouth of Edwards Creek just after construction.

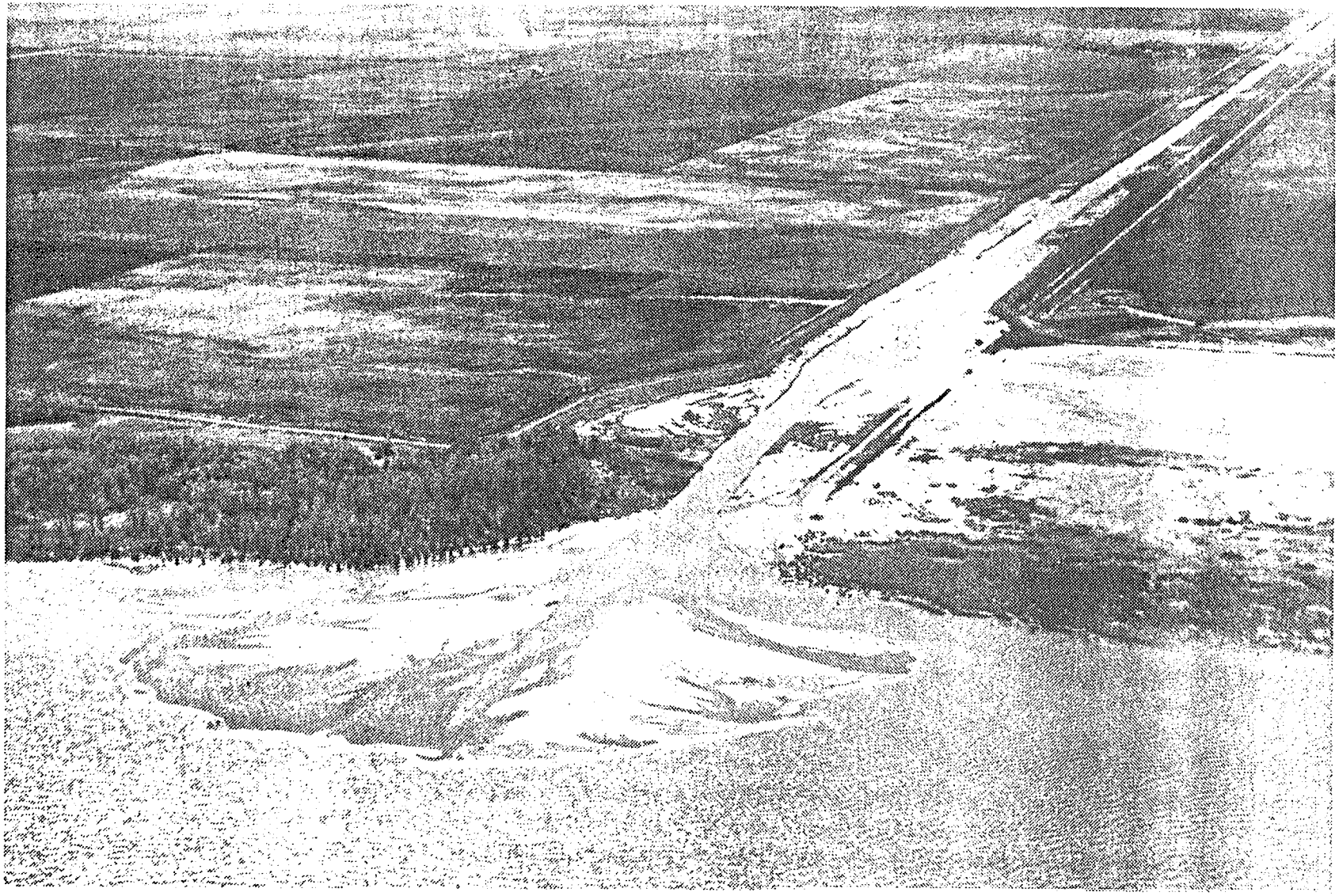


Figure 95 The Edwards Creek delta, June 4, 1954.

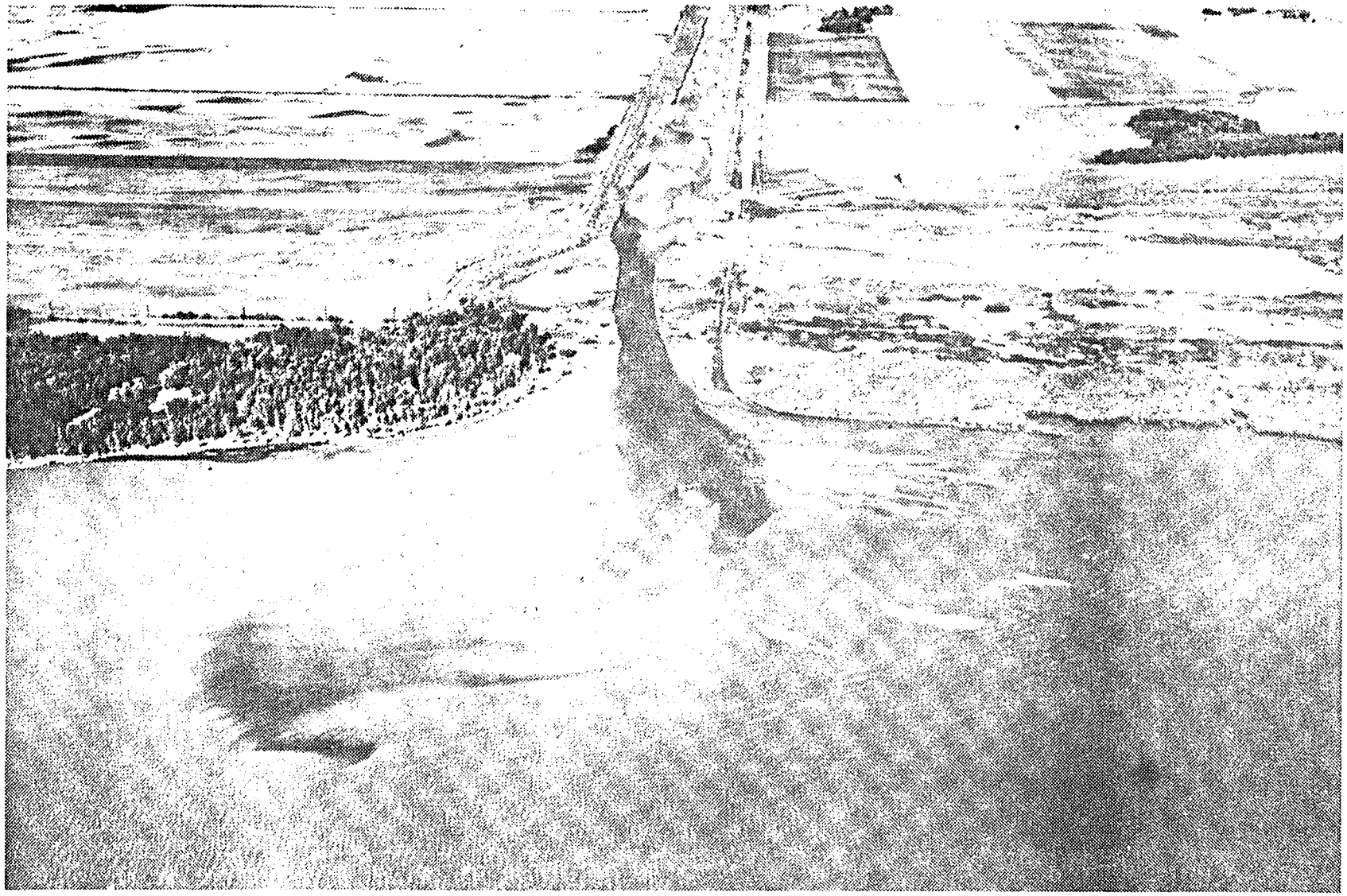


Figure 96 The Edwards Creek delta, August 17, 1956.

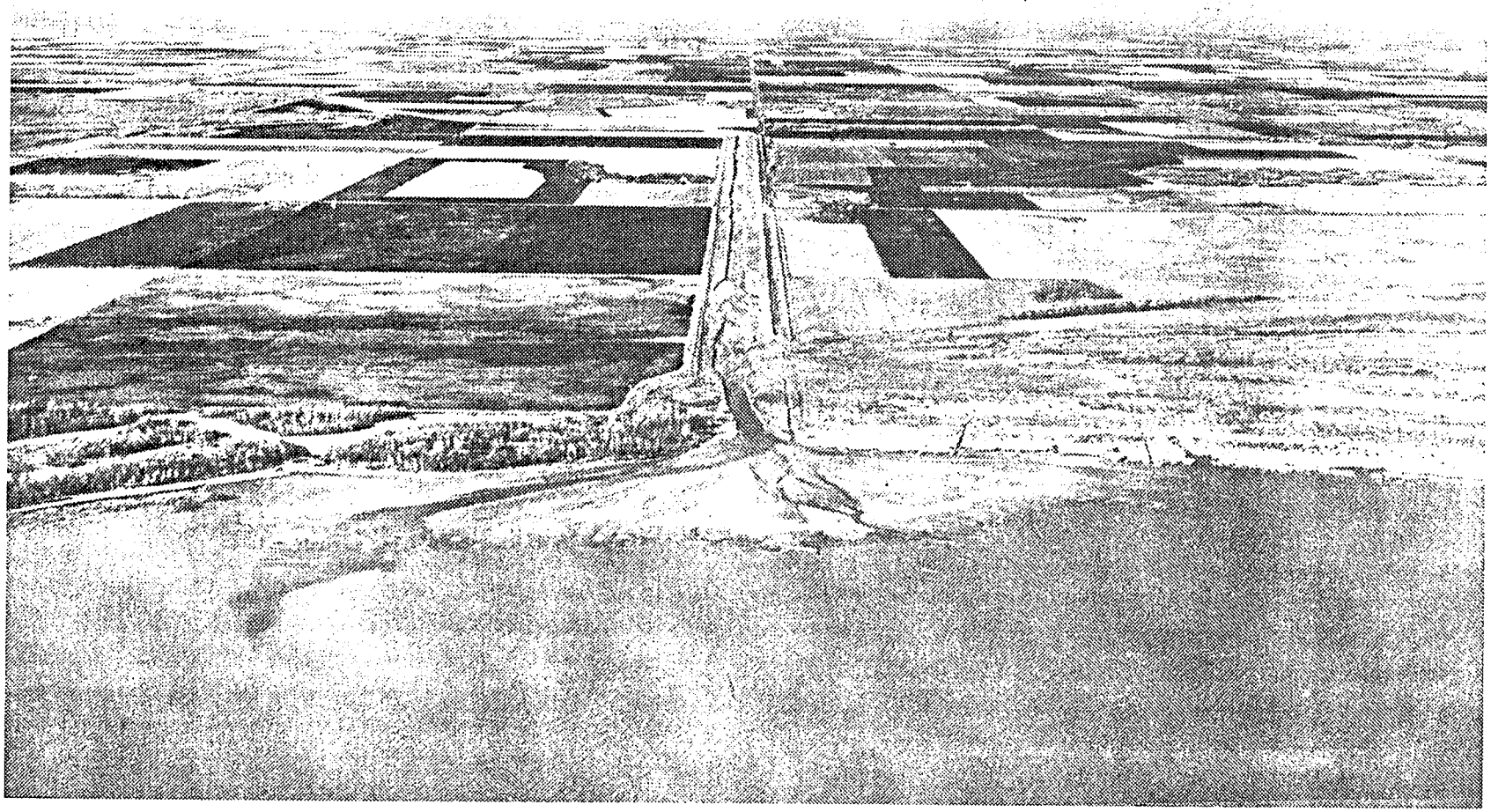


Figure 97 The Edwards Creek delta, October 9, 1957.

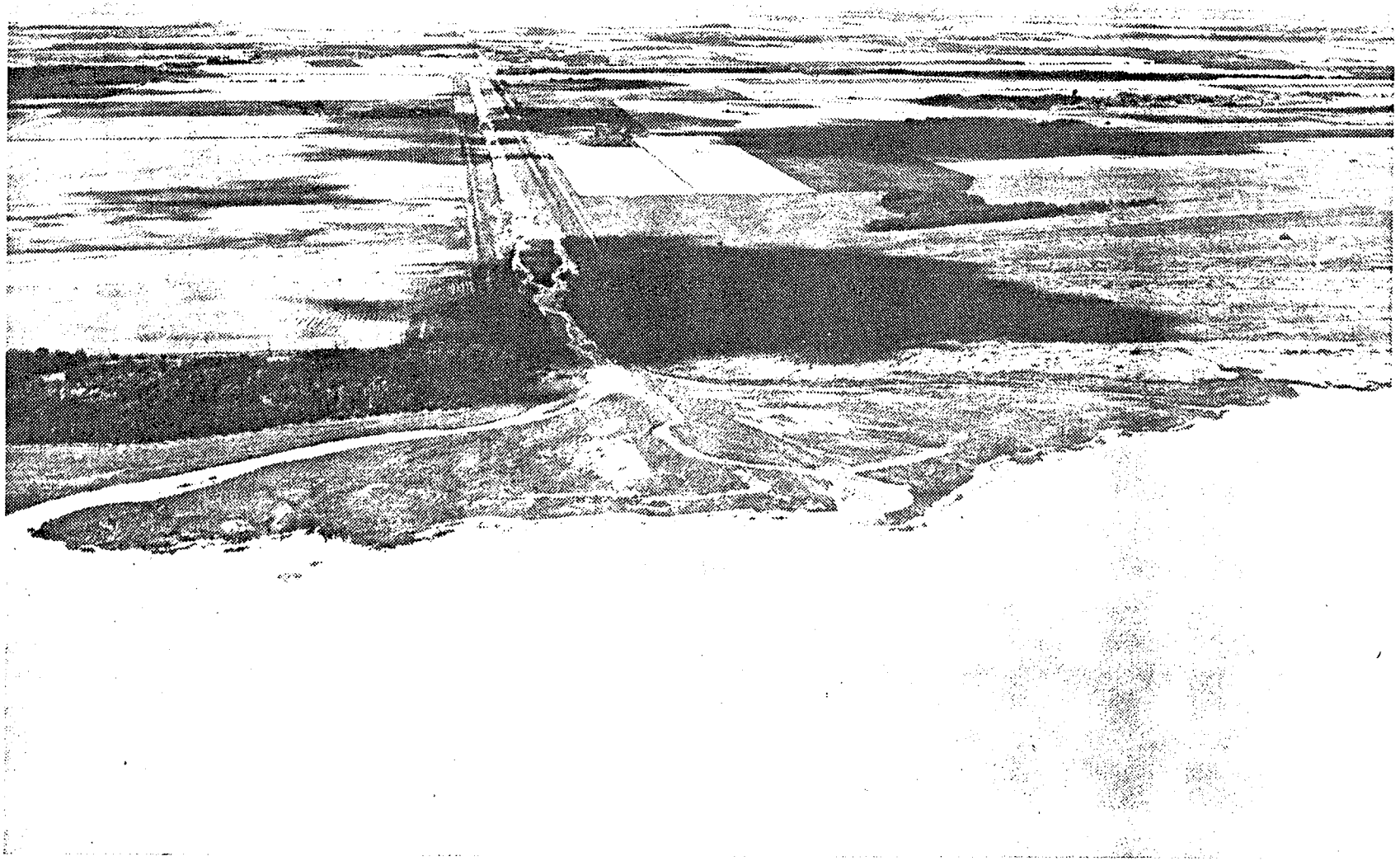


Figure 98 The Edwards Creek delta, August 25, 1959.

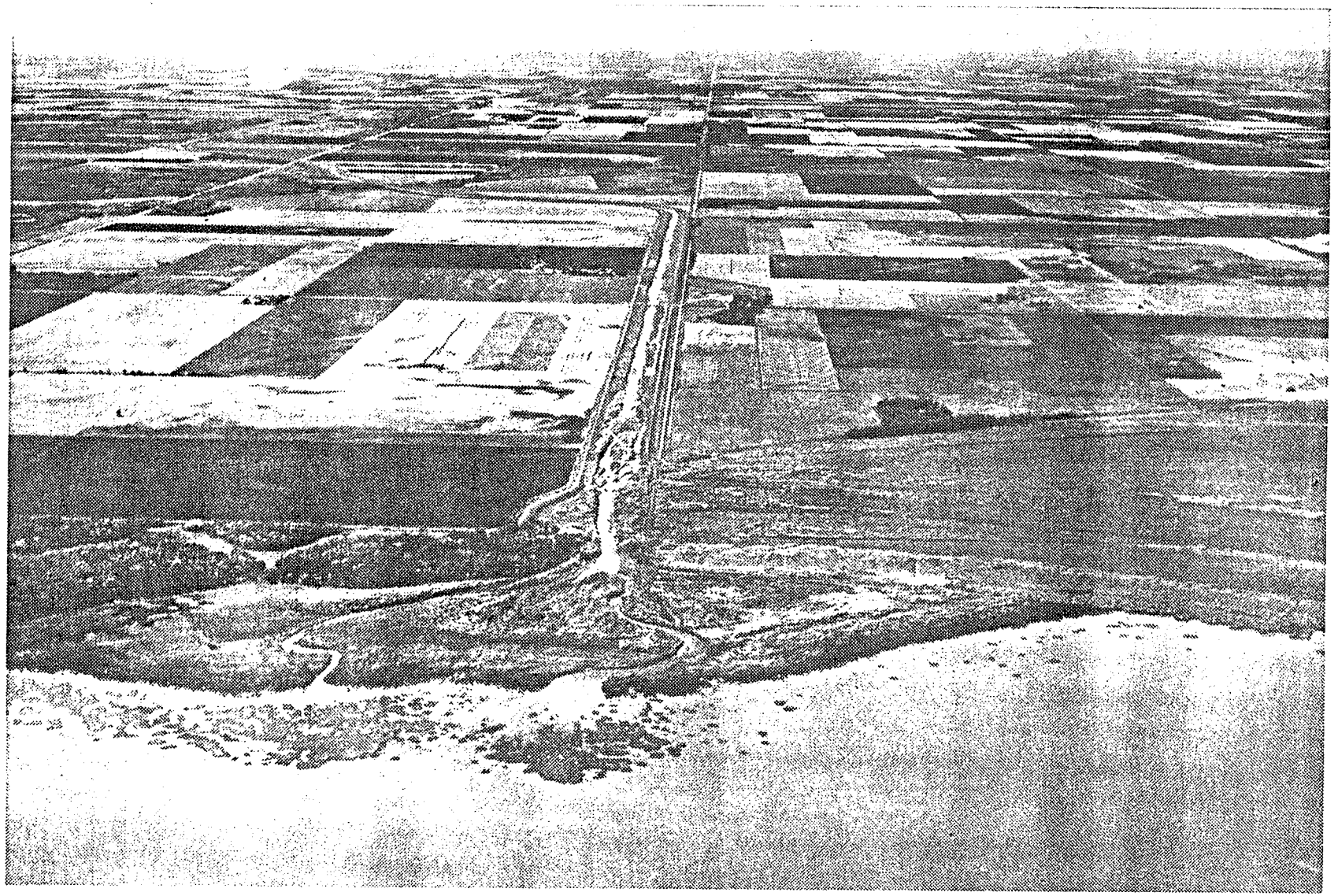


Figure 99 The Edwards Creek delta, September 10, 1963.

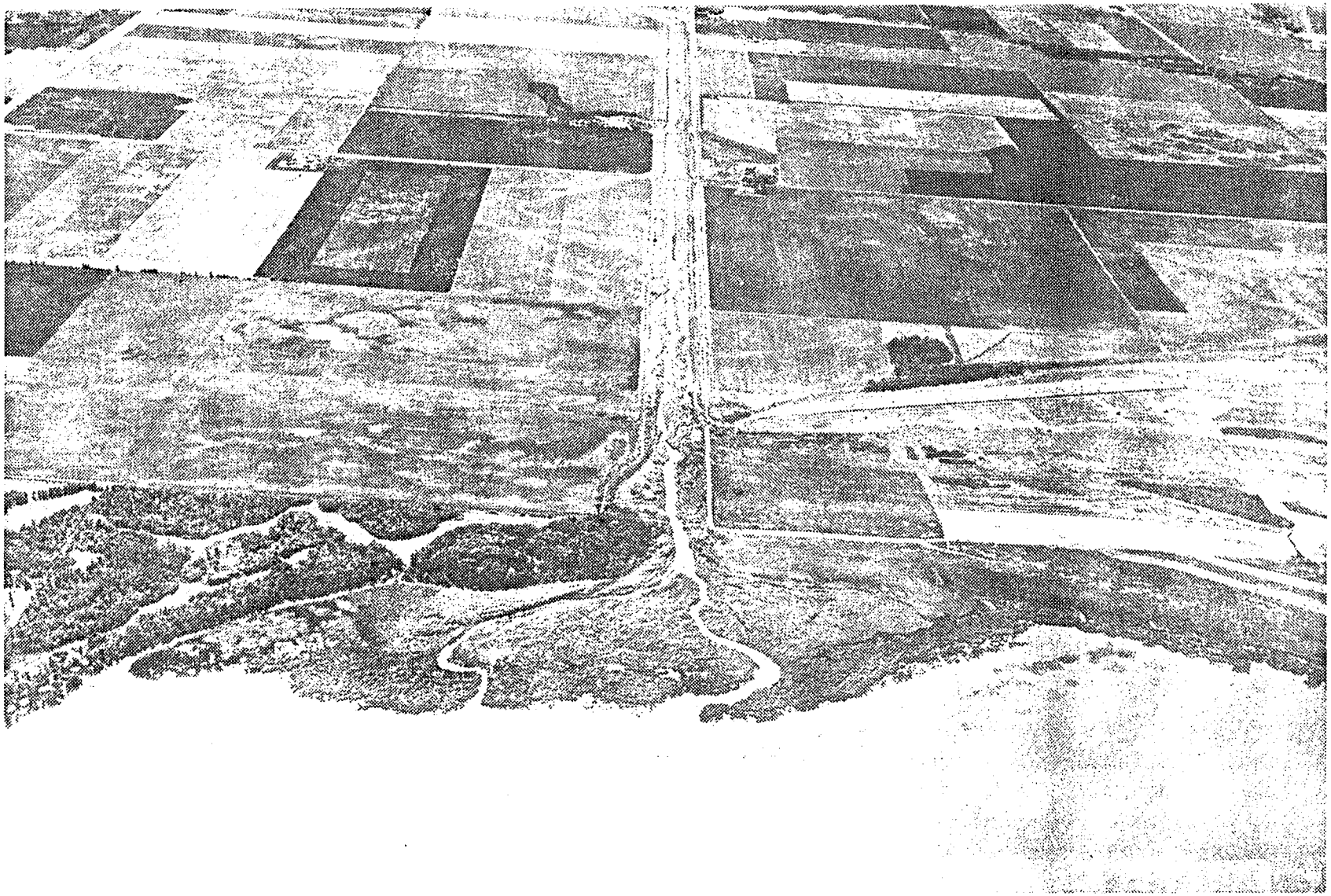


Figure 100 The Edwards Creek delta, July 19, 1968.

while not much evidence of erosion was observed along the channel, the floodway could still have contributed significant amounts of sediment during the two years. While average flow may have been reduced, it is peak events that cause erosion. One large flood in a year may carry a significant load of silt and during the rest of the year very little erosion could occur, with the result that the banks of the creek would have an opportunity to grow vegetation covering any evidence of erosion. An examination of discharge records shows that in 1957, at least one such peak flow event occurred (see figure 86).

However, many people in the federal and provincial governments felt, at the time, that the infilling of Dauphin Lake with sediment was a natural geologic phenomena and that the rate of infilling had not varied due to land use practices (MacKay, 1960). G. H. MacKay (1960) felt that while it was true that part of the problem at the mouth of the Edwards Creek floodway was due to erosion in the drain, the amount of sediment eroded out of the drain was not significantly contributing to the amount of sediment entering the lake. The apparent increase in the size of the delta, from 1957 to 1959, was due to wind induced littoral drift bringing in material or the timing of the soundings (MacKay, 1960). The original soundings described in PFRA (1960) were taken in the summer when wind induced currents may have eroded away

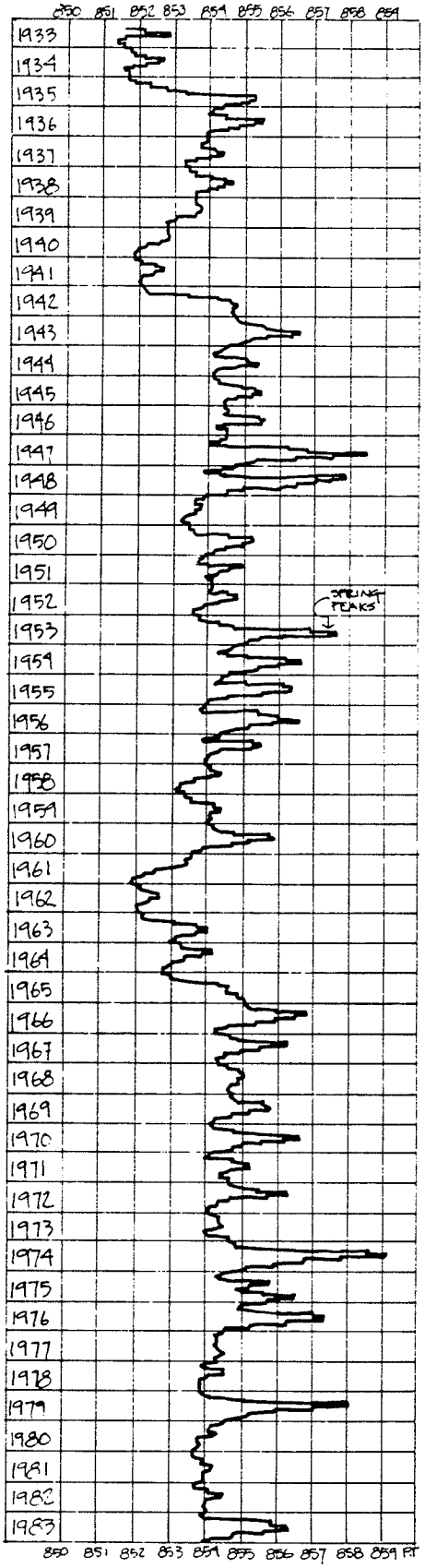


Figure 101 Dauphin Lake waterlevels. Note elevations in feet.

parts of the delta (MacKay, 1960).The second set of soundings were taken in winter when no such currents were active and fine suspended sediments may have been precipitated to the bottom (MacKay, 1960). Since the creek would be solidly frozen, it could not be contributing sediment to the delta in winter and since the precipitation of waterborne sediments would occur over the entire lake bottom, it seems unlikely that 6 inches (0.15 m.) of material would be deposited in this location after freeze up. It is also important to note that these arguments deal only with a 30 month study of the growth of the delta. An examination of the aerial photographs from 1950 to 1959 (see figures 94 to 98) clearly shows that the rapid formation of the delta cannot be attributed solely to in-lake processes.

The PFRA was clearly concerned about the problems along Edwards Creek and at its mouth. In 1960, the agency suggested a number of remedies to the growth of the delta. The first involved the installation of additional grade control structures in the floodway to cause the flattening of slopes in order to prevent the severe scouring flows that had been occurring (PFRA, 1960). The PFRA designed 9 drop structures that were to be placed so as to reduce the slope of the water surface during the design flood to an average of 5.3 feet per mile (1 metre/km.) and to limit velocities in the channel to 5 feet per second (1.5 metres per second) (see figure 102). The design discharge, 3600 cubic feet per second (100 cubic metres per second), which had an estimated frequency of 1%, was developed from an examination of the hydrological records of nearby streams (PFRA, 1960). It was assumed that the areas upstream of the drop structures would fill up naturally over time with sediments from upstream portions of the channel. This process occurred with with the drop structures previously placed in the creek (PFRA, 1960). The cost of this project was estimated at $110,000.00 (PFRA, 1960) only 58% of the cost of drain maintenance for the previous eight years. However, the drop structures would only control erosion occurring in the floodway and would do nothing to reduce the sediment entering the drain from above the siltation basin, upstream of Highway 10 or from Jackfish Creek (PFRA, 1960). Why these two factors were of concern is unclear, since the siltation basin should still have been trapping sediments from the upstream reaches in the escarpment and Jackfish Creek apparently was not experiencing any bank erosion (Inland Waters, 1971).

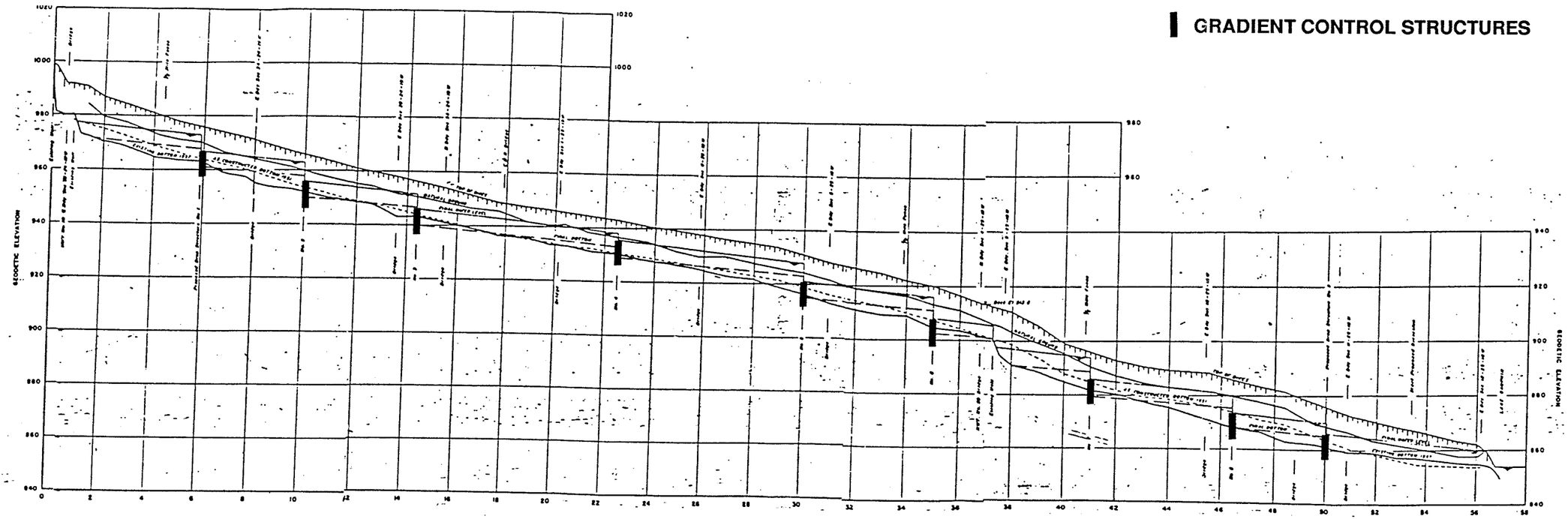


Figure 102 Edwards Creek floodway profile showing drop structures proposed by the PFRA in 1960.

A second possible remedy to the delta problem was suggested by the cottage owners along the beach, who felt that the drain should be diverted north from a point roughly 1 kilometre west of the lakeshore (PFRA, 1960). The marshy areas along the lakeshore would be used as a silting basin (PFRA, 1960). Work that would have to be undertaken to complete this project included plugging the existing drain, excavation of a new drain, raising existing dykes and periodic re-alignment of the ditch to ensure that it would fill the selected areas with silt (PFRA, 1960). Although the diversion of the floodway near the mouth of the drain cost less than the construction of the drop structures, it did not address the problem of erosion in the drain at all, its proper functioning could not be guaranteed and it was, at best, only a temporary solution to sediment entering the lake since sediment would continue to arrive from the channel after it was full (PFRA, 1960).

A third proposal, a less costly alternative to the development of a siltation basin in the marshy areas along the shoreline, was the diversion of the mouth of the channel north through the delta (PFRA, 1960). The discharge entering the lake would not have any less sediment load than it had previously, but the build up of coarse material would be diverted north away from the cottage development (PFRA, 1960). Vegetative or mechanical protection would have to be provided on the outside of the curve to prevent floodwaters from continuing straight east through the delta (PFRA, 1960). A major flood would certainly tend to do this, but just as the new siltation basin would require steering to ensure optimum performance, so would this proposal (PFRA, 1960). This solution would cost approximately $3,000.00 and barring any major floods could be maintained for $500.00 per year (PFRA, 1960).

G. H. Mackay (1960), a hydraulic engineer, discussed these three proposals to decrease the rate of growth of the delta. He felt that building gradient control structures, in an effort to eliminate scour, would not be effective because the structures would not decrease the amount of material brought into the floodway from the upstream portions of the creek, and carried to the lake. He felt that since the floodway had been partially stabilized by mechanical and vegetative means that not much more erosion, in the floodway proper,

would take place. The floodway would continue to bring sediment from upper portions of the creek to the lake in increasing amounts as the siltation basin above Highway 10 filled. The diversion of the outlet towards the Vermillion River, involving the construction of a siltation basin system, would only be a temporary solution that would also not address the problem of sediment entering the lake. Its sole benefit would be to decrease the growth of the delta towards the cottage area. Since only 9 cottages were affected and the beach was only usable at high lake levels, the $170,000.00 cost of this project was far in excess of any expected benefits. The third option, involving a minimum of channel work right in the delta in order to direct the main portion of the flow at this point north rather than east, was the least expensive and would slow the growth of the delta east towards Oaka Beach. MacKay (1960) suggested that if any works were to be undertaken, that this third proposal be the one that should be built. This proposal incidently had absolutely no effect whatsoever on the amount of sediment entering Dauphin Lake, and it is surprising that MacKay would endorse it, in light of the fact that he criticized the other two proposals, which at least temporarily addressed the problem, for not offering long term solutions.

Edwards Creek continued to be a focus of concern regarding erosion problems occurring in the region. A major study, entitled Morphological Study Edwards Creek Watershed was undertaken by the Inland Waters Branch of the federal government in 1971. It examined drainage area characteristics, regime of the channel, flows, suspended sediment loads and the formation of the delta. Based on these investigations, a number of observations regarding the functioning of the channel and a series of recommendations on how to address the erosion problems occurring in the drain were made. These observations and recommendations are described below.

Drainage density analysis of Edwards Creek yielded a value of 1.3 miles per square mile (0.8 km. per square km.). Drainage density is defined as the sum of the channel length of all sizes divided by the drainage basin area. Drainage density is therefore a good indicator of the erosion susceptibility of a drainage basin because channels cannot form without

erosion. A drainage density of 3 to 8 miles per square mile (2 to 5 km./square km.) indicate an erosion resistant basin. Values of 125 or more are indicative of a high sediment producing basin.

Thus, Edwards Creek's drainage density of 1.3 miles per square mile (0.8 km./square km.) was low even for an erosion resistant basin. Inland Waters (1971) had determined the drainage system from topographical maps and aerial photographs. Unfortunately, even with stereoviewing, smaller fingertip tributaries were hard to identify because of the dense vegetative cover in Riding Mountain National Park. However, it was felt that even if a detailed investigation of all the fingertip tributaries was undertaken, the basin would still be within the 3 to 8 miles per square mile (2 to 5 km./square km.) range and would still have to be classified erosion resistant. Slope analysis also showed the basin to be erosion resistant. The creek, in its entirety, had a maximum slope of 4.8% and a mean slope of 1.9%, before channelization. The middle branch had a mean slope of 3.0%, the east branch a mean of 3.4% and the west branch a mean of 2.2 %.

> (The)... low drainage density together with the slope of the basin hypsometric curve (suggested) an erosion-resistant basin. This conclusion (was) supported by the steep slopes of the channel segments in the escarpment, the western tributary being the single exception. (Inland Waters, 1971)

Jackfish Creek, from its source at 2375 feet (735 m.) to the base of the escarpment at 1125 feet (345 m.), also flowed through terrain that was highly resistant to erosion. In 1971, aerial photographs showed the watershed of Jackfish Creek to be heavily vegetated and no indication of channel bank erosion was found.

Based on its analysis, the Inland Waters (1971) concluded that the upper watershed of Edwards Creek was generally erosion resistant. However, isolated reaches running through glacial lake beach deposits and shale beds on the western and eastern tributaries were major sources of the heavy sediment loads discharging into the sediment basin. The

sediment basin was absorbing 100% of the bedload and about 30% of the suspended sediment entering it, from upstream. At the time, 1971, the basin was virtually full and its sediment retention capacity was diminishing quickly. Above normal flows from 1951 through 1960 caused severe channel bed and bank erosion in the floodway. The reaches immediately below the siltation basin and near the junction with Jackfish Creek were affected the most severely. From 1961 to 1969, below normal flows and correspondingly reduced water velocities, promoted channel bed aggradation, especially in reaches whose slopes had been previously reduced through degradation. Based on quantitative analysis from 1951 to 1969, the erosion within the floodway was responsible for approximately 50% of the entire sediment load discharging into Dauphin Lake.

Delta formation occurred rapidly during the period of high flows and sediment loads from 1951 to 1957. In the period 1957 to 1968 the delta was subject to alternating periods of erosion and deposition, with the overall result of a minor net volume decrease. While it did not significantly change in size or shape, the delta and its distributary channels were stabilized by the natural growth of vegetation. Figure 103 shows the volumes of sediments deposited in and eroded from the delta. It is divided into two categories, the

	DELTA PROPER		LAKE BOTTOM IN VICINITY OF DELTA	
PERIOD CONSIDERED	DEPOSITION (cu. yds.)	EROSION (cu. yds.)	DEPOSITION (cu. yds.)	EROSION (cu. yds.)
1951-1957	430,700		336,300	
1957-1960		25,500	304,400	
1960-1964	27,200			126,700
1964-1969		23,200		341,700
TOTAL	457,900	48,700	640,700	468,400
NET	409,200		172,300	

Figure 103 Edwards Creek delta sediment deposition and erosion volumes.

delta proper and the lake bottom in the vicinity of the delta. Based on an investigation and evaluation of delta bed material and the configuration of the contours, the 851 foot contour was selected as the boundary line between these two areas. The delta area, between the pre-delta shoreline and the contour, received its supply of sediment from the discharge of the floodway. The area outside of the contour, the lake bottom in the vicinity of the delta, may have had its sediment transported there from other parts of the lake through the action of waves and currents.

Figure 103 shows that, in the period from 1951 to 1957, deposition of 430,700 cubic yards (329,000 cubic metres) occurred in the delta. This amount corresponds very closely with the amount of 435,000 cubic yards (332,000 cubic metres) that the PFRA (1958) determined was deposited in the delta in the first eight years of the operation of the floodway. From 1957 to 1960, Inland Waters determined that erosion of 25,500 cubic yards (19,500 cubic metres) occurred, meaning that a net volume of 405,200 cubic yards (309,500 cubic metres) had been deposited in the delta. Examination of the erosion mass curve for the floodway shows that during the same period, 278,000 cubic yards (212,500cubic metres) of material had been eroded out of the channel (see figure 104). This would indicate that erosion in the floodway was the source of 69% of the sediment forming the delta.

Based on these findings, Inland Waters (1971) then made a number of recommendations.

In the upper watershed, the area within Riding Mountain National Park, it was felt that the unstable shale banks in the western and eastern tributaries should be stabilized in order to reduce the amount of sediment entering the siltation basin. The steep banks and frequent slides on the faces of these banks would not allow vegetative stabilization and other conventional methods, such as various types of mattresses, would have required heavy anchoring. It was therefore suggested that the most efficient method for stabilization of the banks in the area would be the placement of retaining walls at the toe of the banks. Wing walls extended into the slope at either end of the construction would seal the unstable portion of the bank off from flood flows, halting erosion.

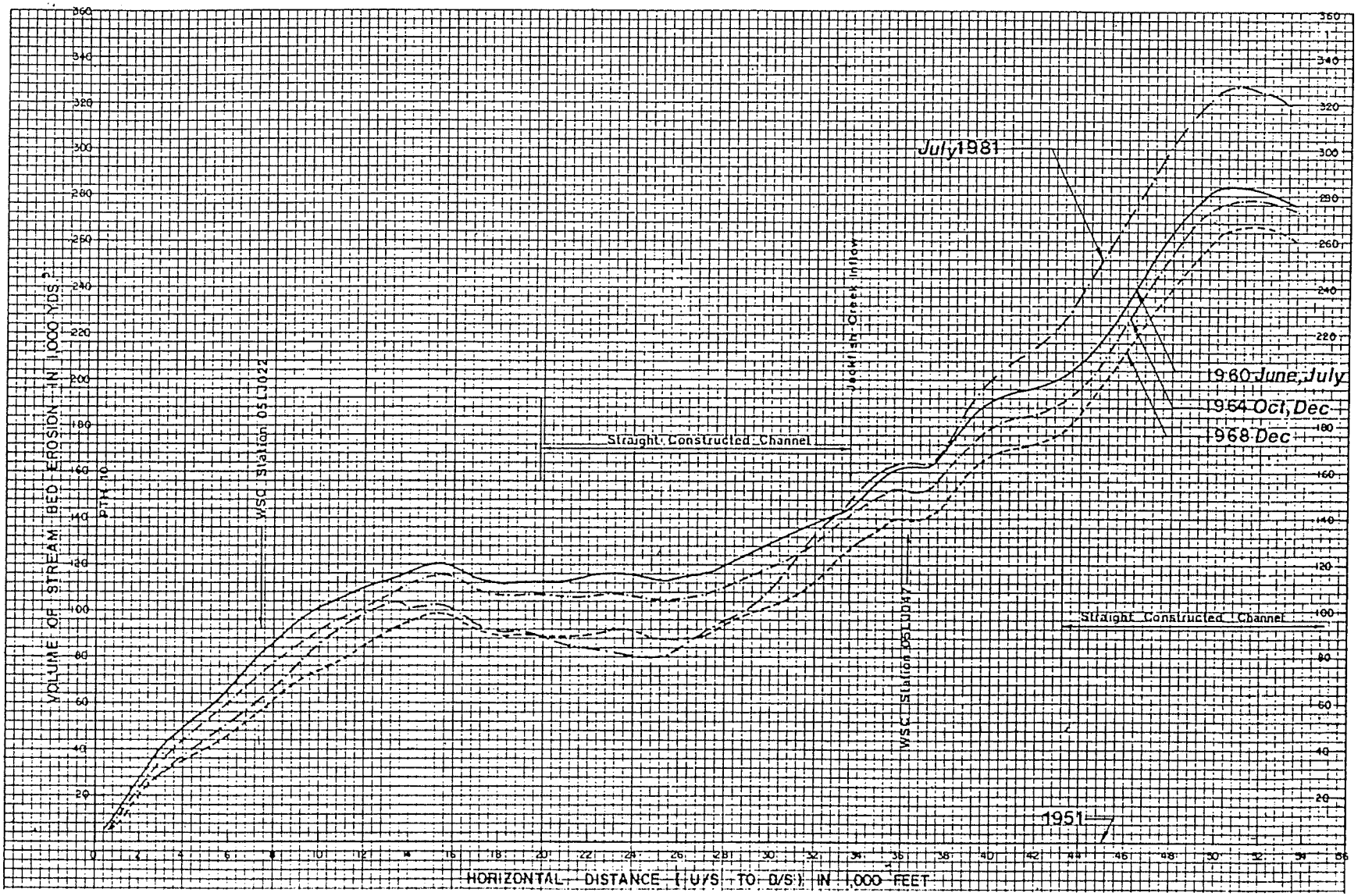


Figure 104 Edwards Creek floodway erosion mass curves.

Since the regime of the Edwards Creek channel, upstream of the siltation basin, is directly dependent on the channel conditions in the headwater areas in the park, reducing the sediment input from these areas would lead to increased bed degradation and lateral erosion in the reach until equilibrium is attained. In order to keep erosion to a minimum while this process was occurring, the banks of the channel in this reach would have to be protected through vegetative and mechanical means. If the bed and banks were not stabilized, the channel gradient would continue to decrease. The flatter slope would lead to aggradation of the channel. Consequently, the channel would be unable to carry large discharges and increased flooding of the land between the siltation basin and the foot of the escarpment would occur.

Without major re-construction, such as dredging or raising the height of the outlet weir and dykes, the siltation basin would no longer be able to perform the function for which it was designed (Inland Waters, 1971). Raising the dykes, increasing capacity in this manner, would lead to a decrease in channel bed gradient, promoting aggradation upstream of the siltation basin. Thus, flooding would be more likely to occur in the area unless the dykes were extended for a considerable length upstream from the head of the basin. As an alternative, dredging of the basin would require the removal of 300,000 cubic yards of material to restore its original capacity. Unfortunately, the dredging would necessitate the removal of most of the existing vegetation in the 110 acre basin. Both solutions are only temporary remedies. If the supply of sediment entering the basin is not reduces, the life expectancy of the project is limited to 20 to 30 years.

The channel was experiencing interrelated cycles of erosion and aggradation and these processes were not controlled, it was felt that meandering of the channel would result. Thus for short term protection, bank stabilization consisting of methods, such as vegetation, riprap or mattresses, would required. For a long term solution, a reduction of the high velocities in the channel was required. The use of grade control structures as described by the PFRA in 1960 offered one possible method. In addition to the grade control structures, to prevent a rapid and continuous aggradation of the channel bed the

amount of bed load entering the channel would also have to be reduced. Since bed load contributes to the volume of flood flows, another long term solution would involve the virtual elimination of the bed load which enters the creek from its head and along its entire length. This solution would initially result in increased channel bed degradation and lateral erosion. The erosion could be controlled through bank stabilization measures, while the bed degradation would continue until a gradient compatible with the dominant discharge would be reached. Eliminating bed load from the floodway would require the continued efficient operation of the siltation basin and control of bed load entering the channel from the surrounding agricultural land. This material which enters the channel through tributaries, drains and ditches, must be controlled through conservation cultivation techniques such as crop rotation, strip cropping, seasonal cover crops, vegetative control of gullies and waterways or through overflow structures at the outlets of tributaries, drains and ditches. This latter method is once again only a temporary solution and sediment would have to be removed from the overflow structures on a regular basis.

The formation and development of the delta was seen to be directly dependent of the sediment supplied by Edwards Creek. The best possible solution to the growth of the delta would entail a combination of the methods already outlined. They include a reduction of the amount of sediment entering the drain from the upstream portions of the watershed through the stabilization of banks in the area, stabilization of the banks of the creek from the foot of the escarpment to the siltation basin, maintaining the sediment entrainment capacity of the siltation basin, protection of the banks along the entire length of the floodway and reduction of flood velocities through the reduction of channel bed gradients or by the elimination of the supply of bed load entering the channel from the surrounding agricultural lands.

Problems with the loss of fish stocks and poor water quality in Dauphin Lake have meant that discussions as to the cause of Edwards Creek's problems have continued to the present. The Manitoba Water Commission (1984) felt that the amount of silt that Edwards Creek contributed to the lake was proportionally small. The creek produces only 10% of

the silt that goes into Dauphin Lake (Manitoba Water Commission, 1984). Unfortunately, this does not give an accurate indication of the condition of the drain. As shown earlier, Edwards Creek has a sediment yield of 663 tons per square mile per year, almost 50 times as much as the Valley River, one of the least channelized watercourses entering Dauphin Lake (see figure 93).

The Manitoba Water Commission's report, Dauphin Lake Regulation and Siltation Study (1984) states that the Inland Waters study (1971) "found that the excessive rate of sedimentation manifest in the settling basin and the delta on Edwards Creek was due to erosion along the escarpment" and based a number of its conclusions and recommendations on the statement. However, an examination of the Inland Waters study (1971) indicated that Edwards Creek in the escarpment area, with the possible exception of the western tributary,was erosion resistant.

> The upper portion of the Edwards Creek Channel from its source in Edwards Lake at a mean elevation of 2225 feet (680 metres) above sea level to just below the junction of the eastern tributary at an elevation of approximately 1400 feet (425 metres) above sea level, has every appearance of erosion resistivity. As shown in Figure (105), the banks and bed of the channel in this reach are paved with boulders and the surrounding are is heavily vegetated. Even during high flow period, the flow is contained in the channel and the vegetation protects the higher levels of the banks. (Inland Waters, 1971)

The Inland Waters study (1971) went on to state that "...from the quantitative evaluations conducted for the period 1951 to 1969, the estimated sediment discharge from the lower watershed amounted to nearly 50 percent of the entire sediment load discharging into Lake Dauphin."

The Manitoba Water Commission (1984) also indicates that while the siltation basin was in operation, it was very effective at removing a portion of the high sediment load entering

Figure 105 Edwards Creek in the upper watershed showing the paving of the creek bank and bed.

the lake. An examination of the aerial photographs detailing the development of the delta (see figures 94 to 100), along with the quantitative analysis (Inland Waters, 1971; see figure 103) shows that the most extensive development of the delta occurred from 1951 to 1959, shortly after the opening of the floodway and the siltation basin. The basin was brand new at this time and should have been operating at optimum efficiency. If it was as effective at removing sediment from the creek flow as the Manitoba Water Commission (1984) indicated then very little sediment eroded out of the escarpment should have been reaching the creek mouth. Since the basin did not fill up until the late 1970's (Marc Gaboury, personal communication, April 6, 1989), it was removing most of the sediment from the escarpment that would otherwise entered the floodway during the period of delta formation. Thus, some other processes must have been responsible for the sedimentation occurring at the creek mouth.

An examination of the cross-sections and profile of Edwards Creek indicates the

considerable erosion has occurred in the channel (see figures 108 and 109 for examples of these sections). The channel has lowered its bed up to 8 feet (2.5 m.) in places and has widened its bank up to 10 feet (3 m.) in an attempt to achieve equilibrium. The erosion mass curves (see figure 104) indicates that large scale erosion is still taking place in the drain today.

The combination of steep slopes, heavy runoff, erodable soils and the use of conventional river engineering techniques often leads to severe erosion in escarpment area watersheds. This erosion has an adverse effect on downstream channels, ecosystems and waterbodies and can lead to reduced agricultural yields and higher drain maintenance costs. As the PFRA recognized in 1957, climate and overall watershed conditions are responsible for these problems and it is unlikely that any substantial change will occur without appropriate conservation planning.

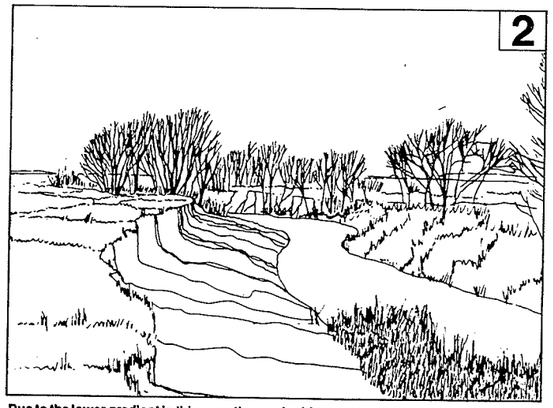
4.3 EXISTING CONDITIONS ALONG EDWARDS CREEK

see figures 106, 107, 108 and 109

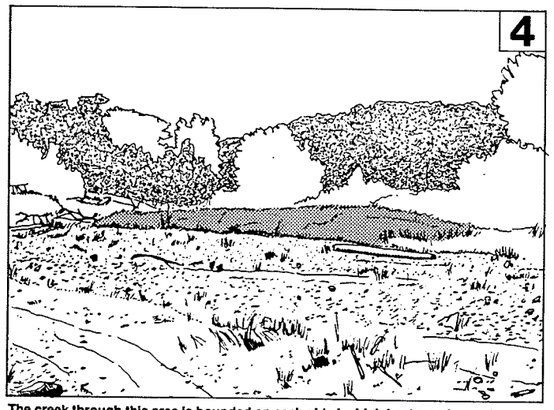
4.4 RECOMMENDATIONS AND DESIGN OF REHABILITATION TECHNIQUES ALONG EDWARDS CREEK

4.4.1 WATERSHED CONSERVATION PRACTICES

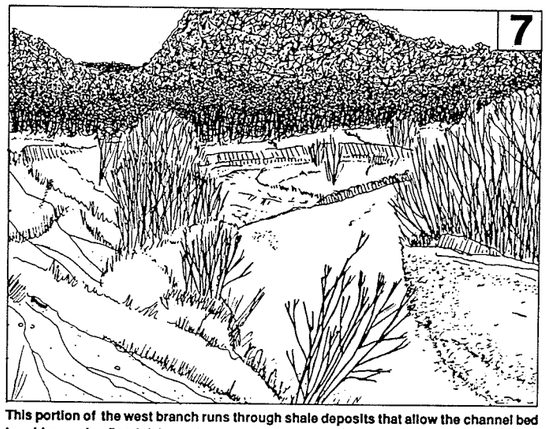
As stated earlier, a waterway is a system composed of two components, the watercourse, consisting of the channel and the immediate riparian zone in the floodplain, and the watershed, consisting of the land surrounding the watercourse that contributes water to the flow in the channel. Since the watercourse and its watershed are inseparable components of a system, changes cannot be made to one part without some impact on the other. Just as the watercourse affects the land surrounding it, the land surrounding the



Due to the lower gradient in this area, the creek widens a great deal and the flow assumes a braided pattern over the channel bed during low flow.



The creek through this area is bounded on each side by high banks and experiences a large amount of aggradation in the upper end of the reach.



This portion of the west branch runs through shale deposits that allow the channel bed to widen and a floodplain to develop. Banks and bed, in this reach, are composed primarily of shale.

1 The sediment basin, built around 1951 and has been full since the early 1960's.

Edwards Creek, downstream of the park is now almost completely and geomorphologically unstable.

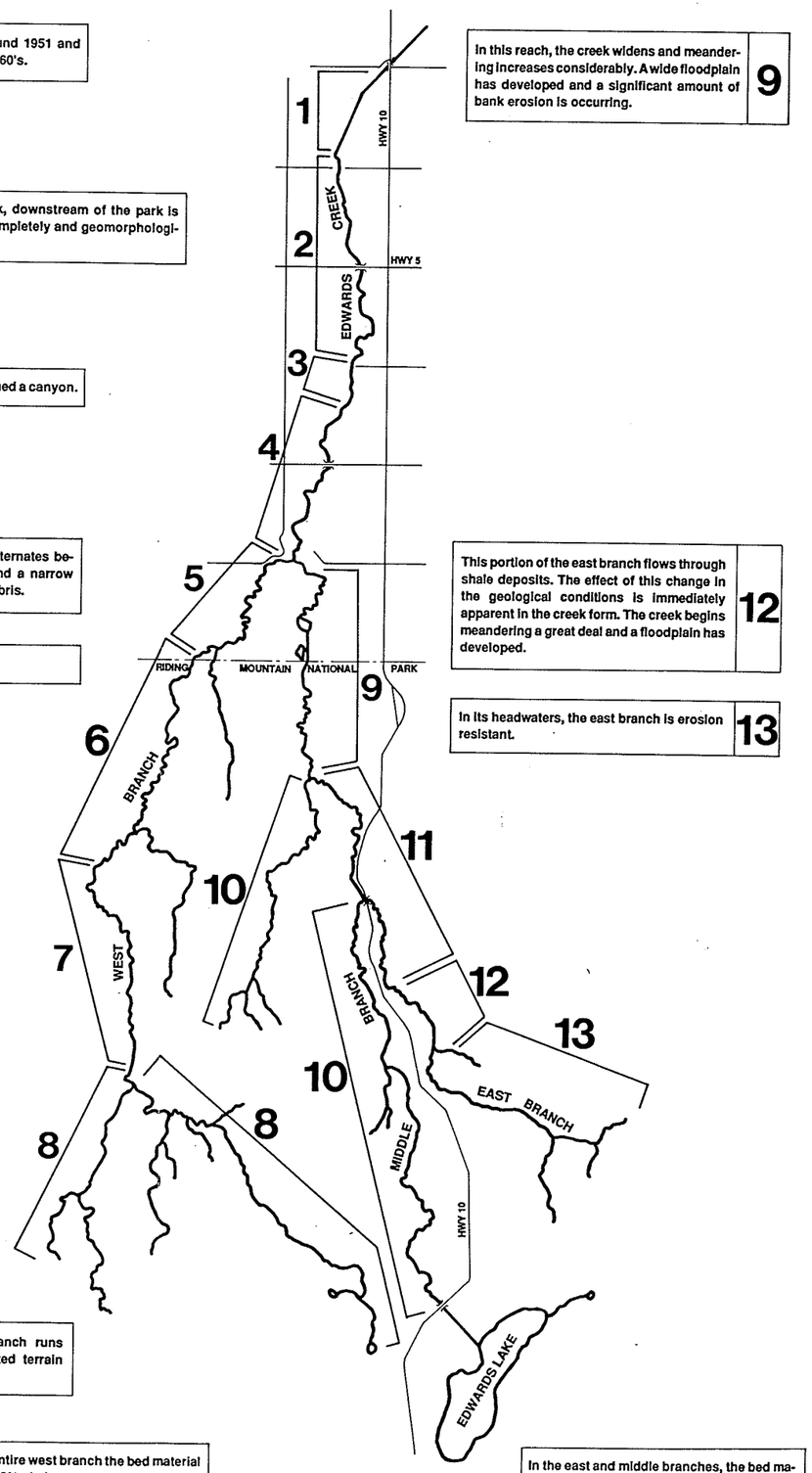
3 Channelized reach that has formed a canyon.

5 In this area, the west branch alternates between a wide, open channel and a narrow banded channel choked with debris.

6 This reach is relatively stable.

8 In its headwaters, the west branch runs through marshy, heavily vegetated terrain with little erosion.

Along the entire west branch the bed material is nearly 100% shale.

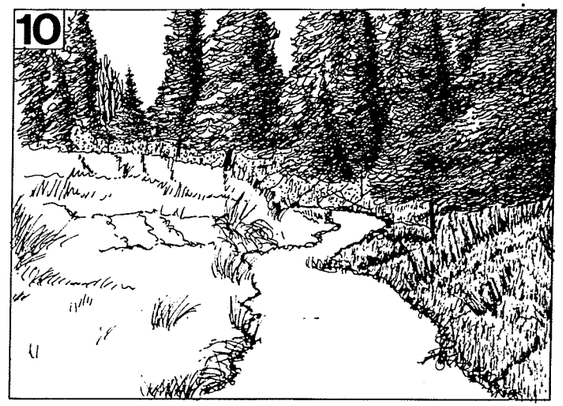


9 In this reach, the creek widens and meandering increases considerably. A wide floodplain has developed and a significant amount of bank erosion is occurring.

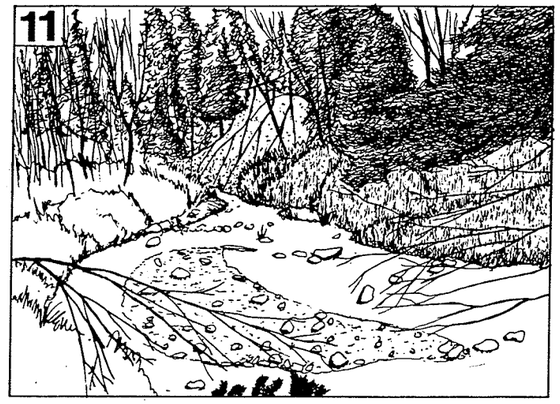
12 This portion of the east branch flows through shale deposits. The effect of this change in the geological conditions is immediately apparent in the creek form. The creek begins meandering a great deal and a floodplain has developed.

13 In its headwaters, the east branch is erosion resistant.

In the east and middle branches, the bed material is mostly gravel and coarse sand.



In its headwater area, the middle branch is erosion resistant.



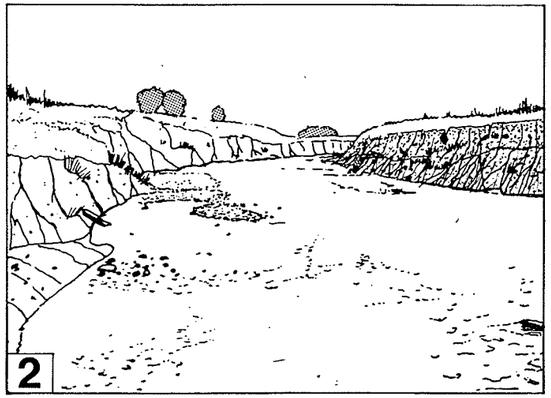
As the east branch leaves shale deposits, it returns to its former regime. Near its junction with the middle branch, there is very little evidence of shale in the bed material.

N

EXISTING CONDITIONS HEADWATERS TO SILTATION BASIN

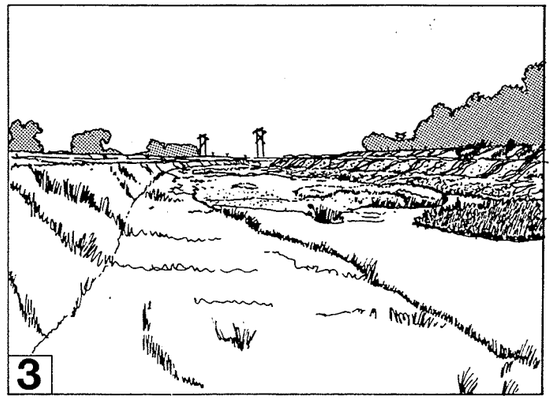
0 1/2 1 mile 1 1/2

FIGURE 106

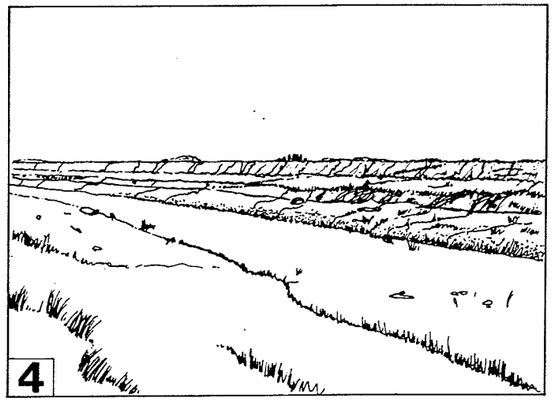


Channel bed aggradation is occurring in this reach. A reduced gradient, as a result of upstream erosion has caused reduced velocities, allowing sediment deposition to occur.

1	From this point downstream, the creek has been channelized and its course altered.

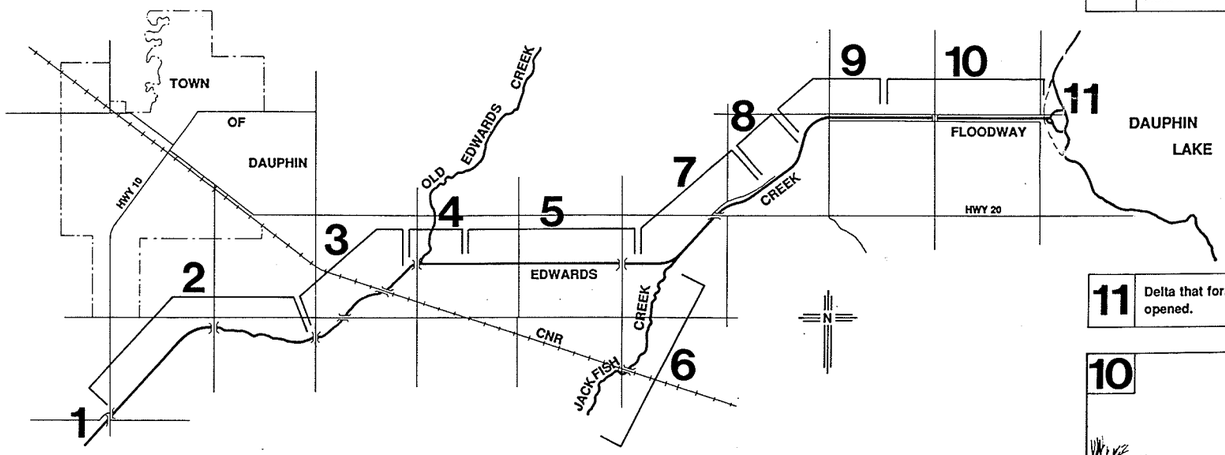


The channel bed is experiencing degradation and lateral erosion is occurring.

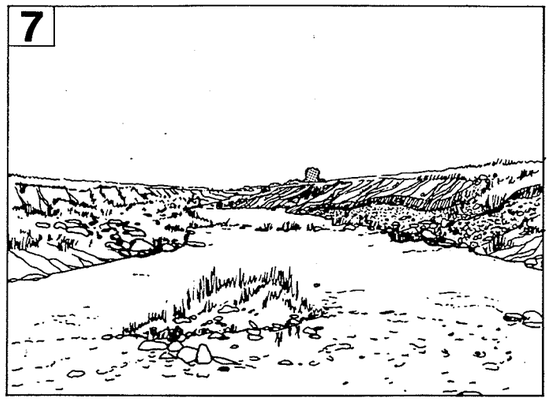


This reach has a low, relatively uniform bed. Aggradation is occurring as a result of sediment inflow from drains and ditches.

5	Due to a steep gradient and increased flow volumes this reach experiences an extremely high rate of bed degradation and lateral erosion.



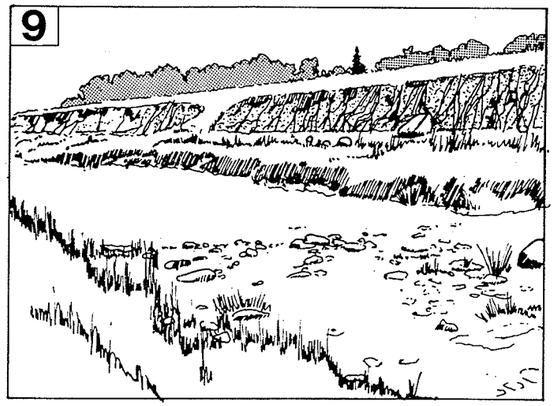
6	Jackfish Creek runs through highly erosion resistant terrain. Although the situation may have changed today, air photo analysis done in 1971 showed no indication of channel bank erosion.



Channel bed degradation and lateral erosion are occurring in response to increased flow with low sediment content from Jackfish Creek. The influence of this factor is felt for a considerable distance upstream as well as downstream.

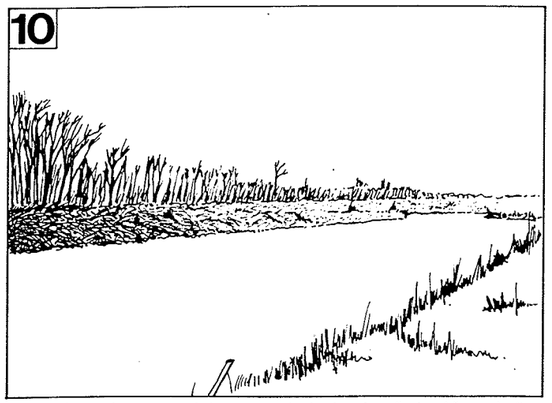
At present, very little in the way of conservation tillage techniques or other methods of soil conservation are practiced on the land in the area. Thus, the cultivated land surrounding the creek contributes significant amounts of sediment to the creek.

8	The channel through this reach is relatively stable.



Due to a steeper grade, and the consequent increase in flow velocity and sediment transport capability, channel bed degradation and lateral erosion are occurring in this reach.

11	Delta that formed shortly after the floodway opened.

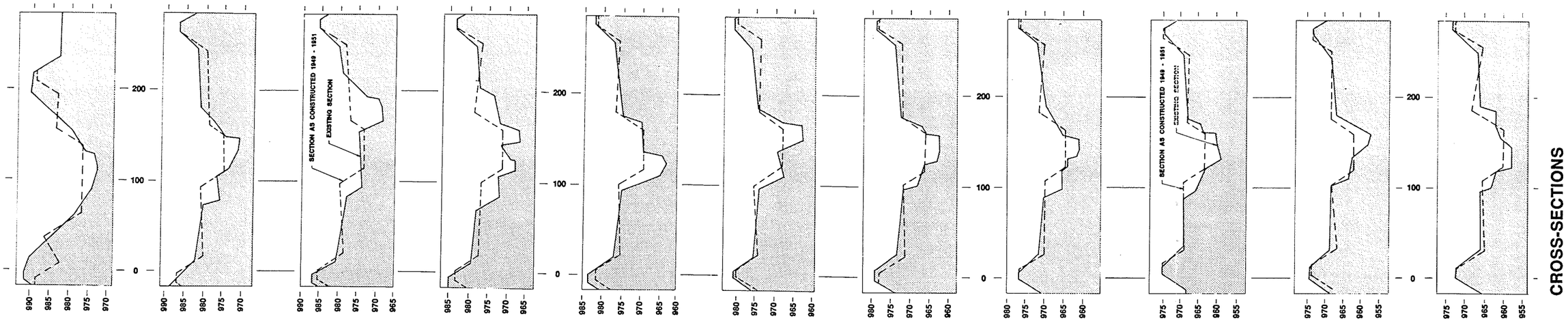


This reach experiences aggradation as a result of reduced gradient and flow velocity.

EXISTING CONDITIONS SILTATION BASIN TO DAUPHIN LAKE

0 1/2 1 mile 1 1/2

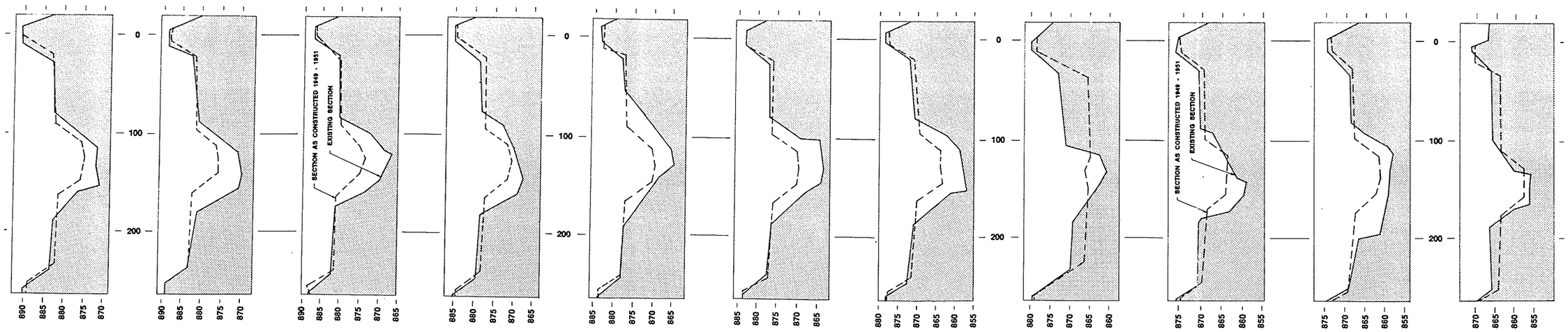
FIGURE 107

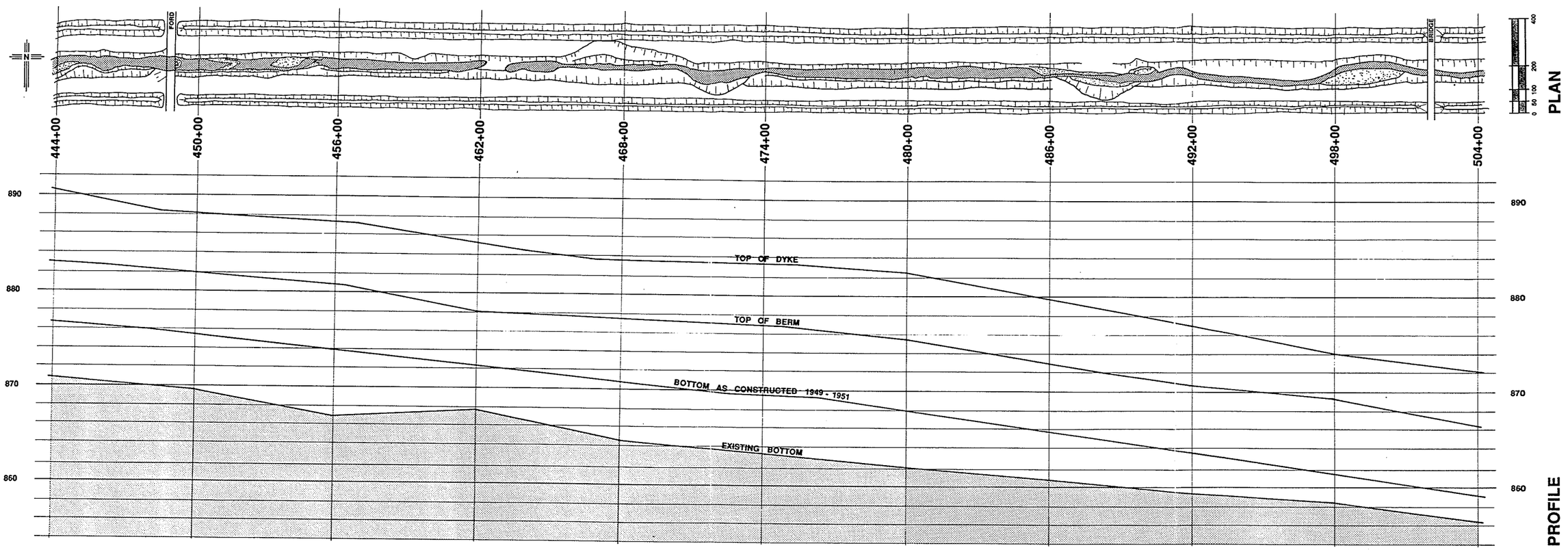


EXISTING CONDITIONS (1981) STATION 6+00 TO 66+00

FIGURE 108

NOTE: ALL DIMENSIONS IN FEET





EXISTING CONDITIONS (1981) STATION 444+00 TO 504+00

FIGURE 109

NOTE: ALL DIMENSIONS IN FEET

watercourse and conditions such as its geology, vegetation and runoff characteristics, have a direct impact on the condition of the watercourse. Therefore, an overall integrated approach to watershed development is necessary if in-channel or riparian works are to function with maximum efficacy and minimum detriment. Thus, recommendations for a series of land based conservation techniques and larger scale stream rehabilitation works are furnished, along with examples of detailed in-channel design solutions.

PRIMARY RECOMMENDATIONS

1) Designation of a Stream Conservation Corridor

A buffer strip to protect the stream from adjacent existing or potential land uses should be established. The size may vary but a minimum width of 400 feet (120 m.) should be maintained (see figure 110). A stream conservation corridor would provide adequate space for long term channel changes, and permit a variety of conservation measures to take place including re-vegetation of riparian woodlands, maintenance of dykes outside the forested area for flood and erosion control, and the development of grass or meadow

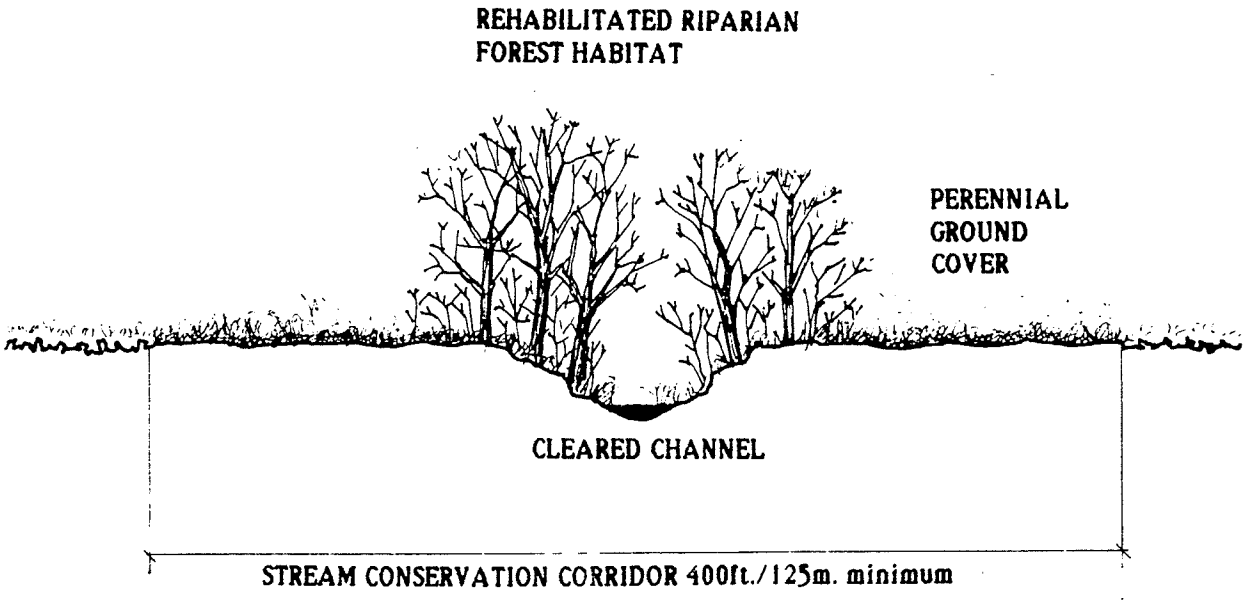


Figure 110 Cross-section of the proposed stream conservation corridor.

strips to act as a vegetative sponge to intercept nutrients and silt from agricultural runoff (see figure 111). Through the development of these measures, the conservation corridor would also provide increased size and diversity of wildlife habitat and improved water quality and aquatic habitat.

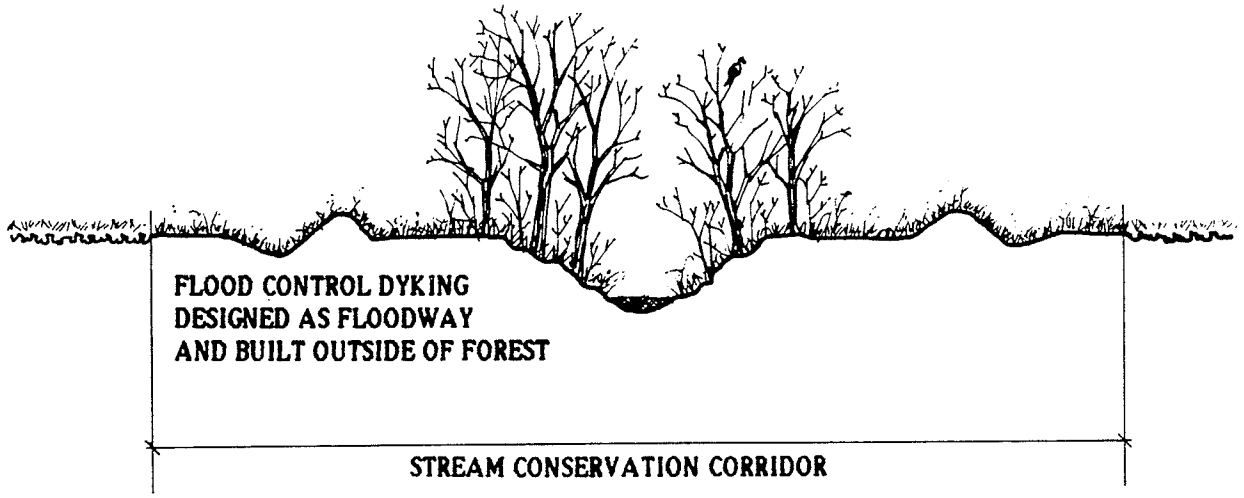


Figure 111 Placement of the dykes within the corridor.

Woody vegetation, along the watercourse, is especially effective at reducing rill and gully erosion and prevents cultivation right up to the edge of the streambank, a practice which weakens the top of the bank and contributes to bank failure (Bruce, 1984). The vegetative buffer would protect water quality and downstream conditions from adjacent landuse. Similar practices could be carried out in all ditches and drains entering the creek (see figure 112). Planting of alfalfa and other perennial forage crops could provide some agricultural production while maintaining a protective corridor (McLachlan, 1986).

In areas where cattle are grazed along the creek, the animals should have their own trough or dugout away from the waterway. Cattle tend to defecate directly into the water, adversely

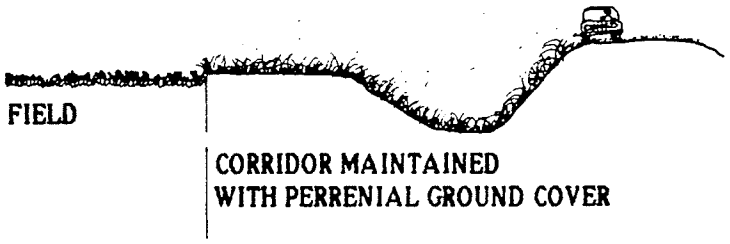


Figure 112 Proposed agricultural drain corridor.

affecting water quality and their hooves cut the bank and bed of the waterway augmenting other erosional processes. To control access fencing should be a minimum of 10 feet (3 m.) back from the top of the bank of the waterway. Unfortunately, while the fencing will reduce erosion, excess nutrients will still be able to reach the waterway with the runoff from the adjacent land. A recent report, on cattle grazing along drains, indicated that more study of this problem is required and that until the effects of cattle access to waterways is better understood, rather than completely excluding livestock, riparian grazing should be delayed until mid- to late summer. If cattle must cross the watercourse or if absolutely no other access to water is available, special cattle crossings should be constructed to protect the channel and floodplain from erosion and compaction caused (see figure 113).

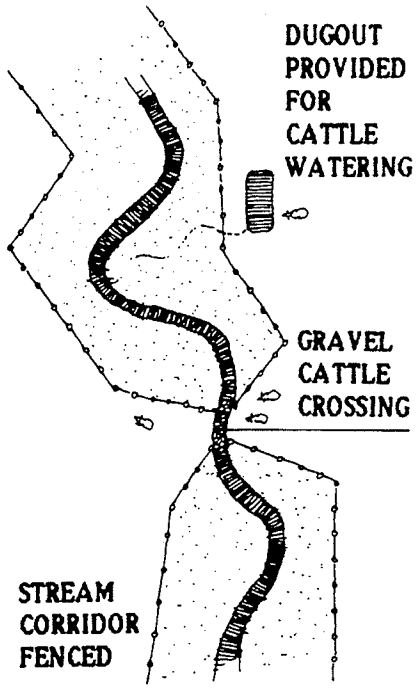


Figure 113 Layout of cattle fencing to preserve the creek

2) Development of an Integrated System of Shelter belts

A shelter belt system is important for controlling wind erosion and snow. The lack of overall windbreak strategy in the watershed means that only Edwards Creek has provided a windbreak in the area and as a result has experienced excessive snow loading in its channel, clogging the drain (see figure 114). This problem has in the past caused the drain

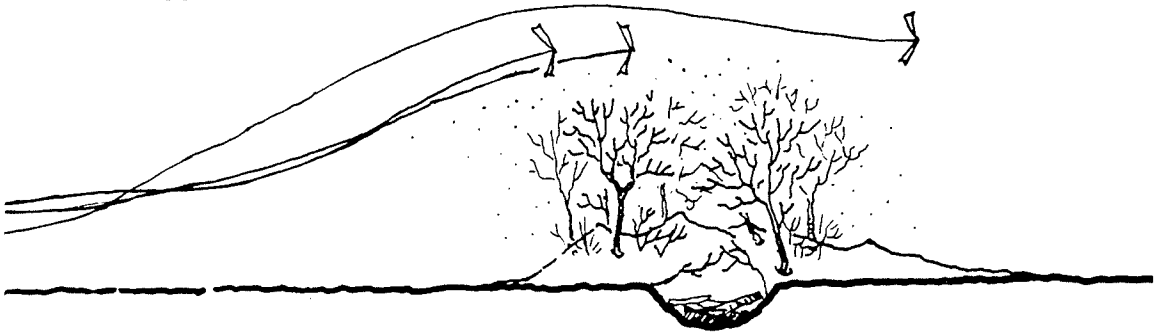


Figure 114 Problems with snow drifting in forested portions of Edwards Creek.

to remain frozen later in the spring producing severe flood problems (PFRA 1960). Therefore, it appears that the re-constructed portions of the channel have been designed without vegetation so as not to not intercept the wind (McLachlan, 1986). An integrated system of vegetation along the stream corridor combined with an on-farm shelter belt system would reduce the problem (see figure 115). The trees would act as a wind sponge filtering out harsh summer winds and allowing a more even distribution of snow (McLachlan, 1986). The creek would not become clogged with snow and as an ancillary benefit, the snowdrifts on the fields would provide extra moisture for crop germination in the spring.

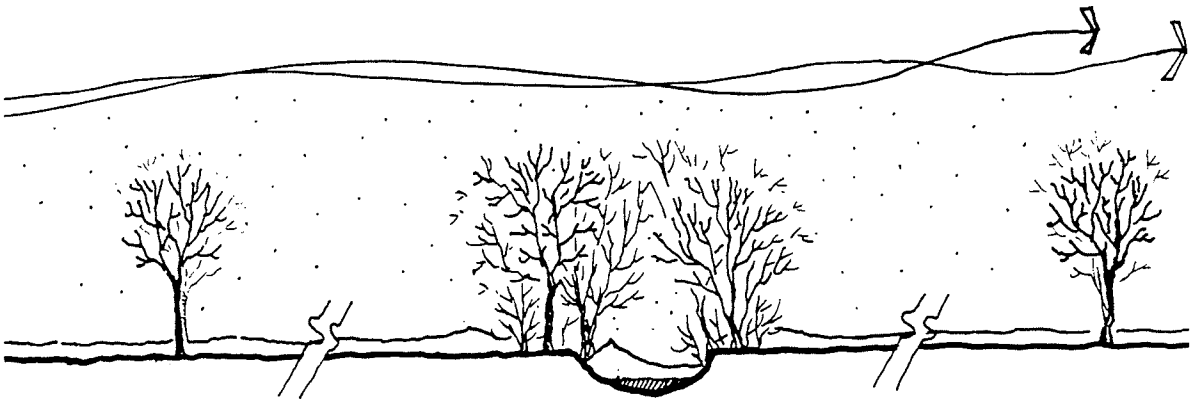


Figure 115 Proposed windbreak network.

Mackling (1987) researched shelter belts and made a number of observations regarding their effectiveness and suggestions for their design. Shelter belts perform poorly on rolling or poorly drained fields and therefore their use is only recommended on relatively flat areas. Shelter belts protect the land lying within a distance of about 12 times the height of the trees. The length of the belts should be a minimum of 24 times the height of the trees.

Unfortunately, shelters belts do have disadvantages. Most evident are land loss, division of fields and increased cultivation difficulties. Shelter belts may also provide a haven for weeds and pests. However, weed control in shelter belts is crucial not only for its own sake but also because the presence of grass and weeds can adversely affect shelter belt condition . Large snowdrifts trapped by the belts have in the past caused delays seeding

in the spring, but new design criteria has reduced this problem. Old belts, planted a 4 to 5 feet (1.2 to 1.5 m.) on centre with caragana between each tree, were too dense. Existing shelter belts of this type should be thinned and pruned. New belts should be planted as 5 to 6 feet (1.5 to 1.8 m.) on centre. These dimensions do not cause the drift problems, provided that the lower branches are pruned.

Possible variations on tree shelter belts, that, unfortunately, do not offer as permanent a solution, include the use of strips of flax or crested wheatgrass to shield the soil. The strips should be spaced 25 to 50 feet (8 to 15 m.) apart and should be several rows wide. Since wheatgrass is a perennial care must be taken not to kill it with herbicide or tillage.

Another possible variation is stubble shaping. This technique consists of the attachment a deflector to the swather, so that a row of tall stubble is left on the field. Tall rows, one swath width apart, then occur over the entire field perpendicular to the erosive winds. The tall straw slows the wind and captures snow, which forms a protective layer against strong winter winds and traps moisture over the field that will be released during the spring melt. The stubble may be plowed into the ground in spring. Stubble shaping can be used on no till fields and with forage crops that are not harvested until late fall. Crop loss with method is extremely small amounting to only 0.2%.

3) Improvement of the Network Grassed Waterways (Mackling, 1987)

Grassed waterways are one of the most basic conservation techniques designed to carry water safely from the field to the drain. Grass or legume sod lines the waterway, decreasing the velocity of the water, resisting gullying and erosive scouring, increasing infiltration and trapping sediment and nutrients. The cost is small, only $1.00 to $3.00 per lineal foot ($0.30 to $1.00 per metre). While already widely practiced, this method should be developed on any swales that are at present experiencing erosion problems. These waterways should if possible follow natural drainageways, so that runoff flows naturally

to the drain and good soil depth and moisture availability are assured. There is a great deal of literature available on the specifics of the design and construction of these waterways which should be consulted before installation.

Grassed waterways can be hayed at the regular haying time, but should not be grazed for the first two years. Maintenance of the cover in good condition is very important. When a grassed waterway is wet and soft, animal traffic should be restricted. Also, to ensure continued effectiveness, complimentary soil conservation practices should be utilized to prevent infilling of the waterway as a result of field erosion. In existing ditches and waterways experiencing severe erosion, live brush and comb constructions should be built across the channel.

SECONDARY RECOMMENDATIONS

A variety of other farmland conservation techniques have been described by Mackling (1987) and should be used in combination with the three described above, to further reduce land based erosion problems. The decision of the proper method to be used in each field should be based on an examination of local conditions.

1) Buffer Strips

Buffer strips consist of strips of vegetation at the edges of fields and are composed of forage or cereal crops, which may be rotated to maintain vitality. This method stabilizes field borders, reduces slumping into drains, traps sediments that would wash into the drains and protect against the scouring action of floods when the drains are overtopped. If the strips are properly managed there are no problems with weeds or pests.

The buffer strips may also be composed of brush or woody plantings. While brush and woody plants are very good at protecting against wind and water erosion, it does trap large

amounts of snow and insulates it from the sun in the spring. Because this material would stay frozen while upper portions of the drain thaw, this problem could cause the drains to back up during spring runoff. Thus, it is recommended that this method only be used in the upper portions of the drain, while a forage buffer is used in the rest of the watershed.

2) Conservation Tillage, Zero Till and Continuous Cropping

Generally, the aim of these practices is to reduce tillage. Reduced tillage refers to a reduction in the number of times that machinery, especially tillage equipment, passes over a field. Each pass reduces surface residue and uses fuel and time. If tillage is only reduced by one pass, cost effectiveness is questionable. However, farmers often feel that they are practicing conservation tillage and that their fields are not eroding, when in fact very little trash is left on fields that are actively eroding. On highly erodable soils, a 50% trash cover reduces erosion by 65% compared to a bare field. An 80% cover reduces erosion by 90%.

Unfortunately, the term "conservation tillage" is loosely defined in the literature and requires a concise definition. The best definition is an array of reduced tillage and cultivational practices that protect the soil by leaving a mulch residue on the soil surface. Minimum tillage refers to the least amount of tillage operations to create proper soil conditions for germination and plant growth. If sufficient crop residue is left on the soil surface, erosion is reduced and conservation tillage is being practiced. If no summer fallow is practiced, if crops are rotated or if some other system is used that maintains plants on the field, continuous cropping is in effect. Zero tillage involves planting crops directly into untilled stubble land with a minimum of soil disturbance and chemical weed control. This method leaves 90% of the crop residue intact. A secondary benefit of zero tillage is improved duck production, which may be increased almost 4 times on zero till small grain farms compared to conventional farms.

While extremely effective, these methods do require some special management skills. Timing of various operation becomes much more critical. Planting must not be done too

early, as soil under cover can remain 8 to 10°F cooler in the spring. As well, since in conventional tillage mistakes are repaired by another pass and this option is not available in conservation tillage, the operation must be effective the first time.

Although these methods are very effective, they may not be enough to completely control erosion and may require combination with other techniques.

3) Contour Tillage

Contour tillage involves tillage and cropping across the slope, roughly parallel to the contour, rather than up and down slope. Tillage up and down the slope creates furrows that concentrate the water and convey it quickly off the field, increasing the potential for erosion. In contour tillage furrows and wheel tracks across the slope act as small barriers that hold back the soil and water.

Contour tillage can reduce soil loss by up to 50%. While it is generally inexpensive to set up, the costs increase where the topography is variable and large scale machinery is used. In the escarpment and sub-escarpment areas of the study area, the topography is highly variable and each field usually contains a variety of slopes. Gullies also often divide the fields such that only short runs following the contours are possible, requiring more turning of equipment. But where field size and configuration permit, the use of this technique is recommended.

While this method is generally effective, it too is not adequate as the sole means of protection. The effectiveness of this technique may be further reduced by the intense summer rainstorms experienced in the area.

4) Contour Cropping

This method consists of planting strips of erosion resistant crops running across the slope roughly along the contour. Erosion prone crops are planted between the strips. The

erosion resistant strips, usually forage crops such as alfalfa, check the flow of water down the slope by reducing runoff velocity and may also reduce the amount of flow by allowing increased infiltration. The degree, length and complexity of the slope as well as soil texture, determine the exact width and arrangement of the strips, which are in most cases 5 to 15 metres wide. Since the amount of erosion is proportional to the length of the slope, this method's effectiveness is based on reducing the effective length of the slope. It can reduce soil loss by 70 to 75%.

5) Cover Crops

These are crops that are planted on land that would otherwise remain fallow. Instead of summer fallowing, a crop is planted and plowed back into the soil. The cover crops help to prevent erosion, add organic matter to the soil, improve soil health, increase water absorbing capabilities and infiltration and can also improve nitrogen levels. Cover crops planted in the fall reduce runoff, prevent leaching of nitrates, help conserve moisture, prevent excessive erosion and may provide winter and spring grazing.

6) Rotational Grazing

Rotational grazing involves moving cattle from one field to another over the course of the season to ensure that overgrazing does not occur. Maintaining adequate vegetation on a field decreases the amount of erosion likely to occur. The use of tame forage, since it grows faster than wild forage and can be grazed earlier, is important to the success of this type of operation. While this method requires more management and labour by the farmer than traditional practices, the extra effort is offset by reduced erosion and optimum forage utilization. Other benefits include improved wildlife opportunities due to increased cover and reduced parasite populations. Permanent fencing is not required if electricity is available. Lightweight posts with 2 strands of electric fencing is enough to confine the cattle. This fencing is very flexible and can easily be moved around.

7) Block Planting

This method is recommended for parts of fields that cultural methods will not stabilize. Trees and brush are re-established on land that should not have been cleared and is prone to erosion or on land that will not produce grain crops. On poor eroding land, the trees stabilize the soil and tap nutrients and moisture deep in the ground. Since many species of trees may be planted, determination of the types to be used should be based on local site conditions.

8) Land Retirement

This, the most drastic measure of land conservation, consists of the permanent conversion of land from agriculture to a more natural state. It has already been used in the Riding Mountain area where 10,000 acres (4,405 ha.) of scarp face and 3350 acres (1,359 ha.) of slopes have been retired at a cost of $508,839.00. Most of the cultivated land was converted to permanent hay, where no grazing is allowed, but harvesting is often permitted. The remainder of the land was planted to trees or allowed to return to a naturalized state. Once actively eroding lands are now stable and productive. This land has a greater capacity to store water leading to decreased runoff and downstream flooding, as well as an increased capacity for wildlife production and recreational activities.

4.4.2 WATERCOURSE WORKS

4.4.2.1 OVERALL FRAMEWORK

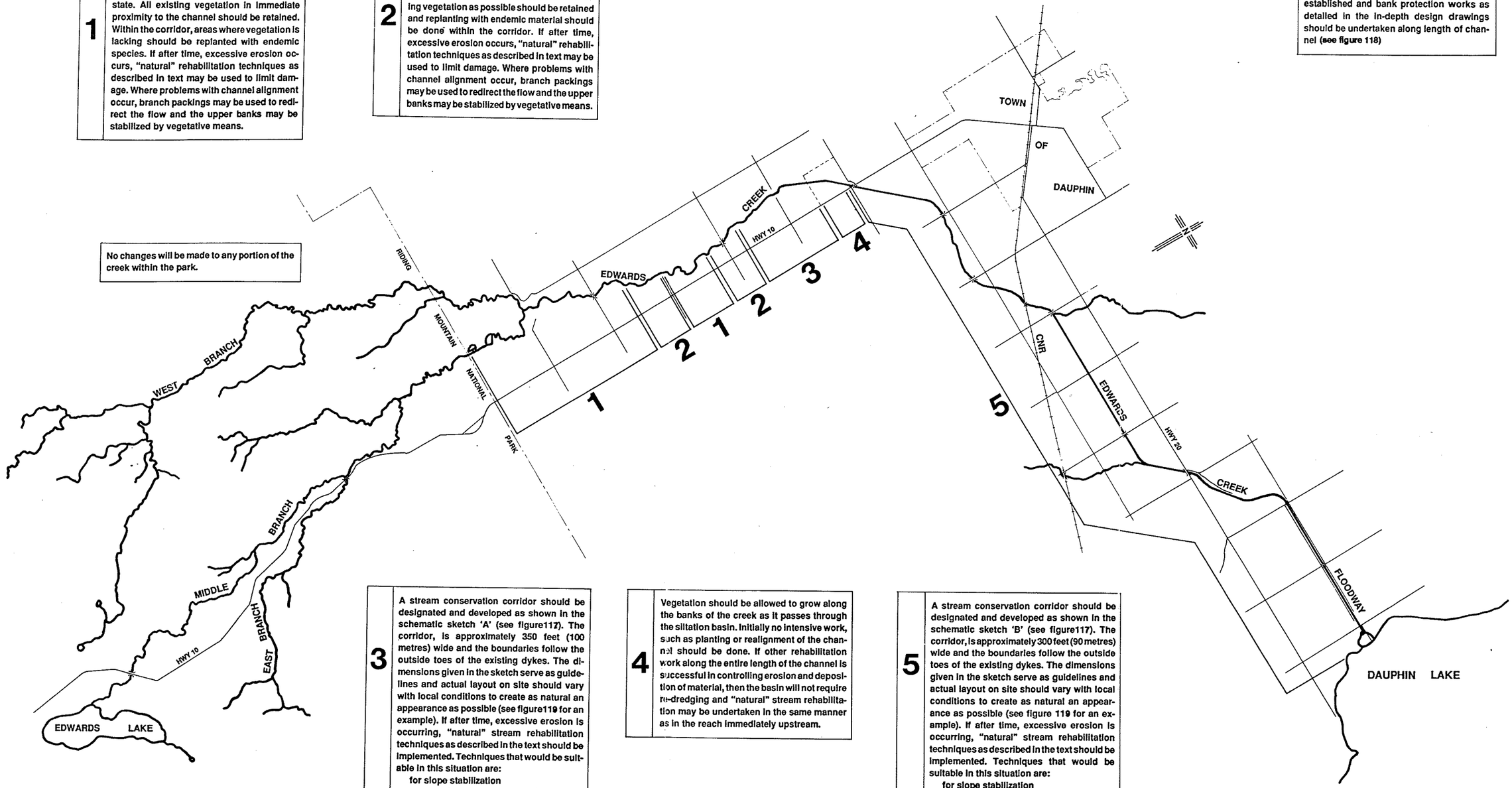
An overall framework for the development of watercourse works pertaining to the rehabilitation of Edwards Creek is illustrated in figure 116. Schematic sketches illustrate the generalized dimensions of the proposed channel form at two locations (see figure 117). These dimensions are then manipulated to create the more variable forms appearing in the detailed design examples.

1 The width of the existing vegetation in these reaches allows the designation of a stream conservation corridor of sufficient width [minimum 600 feet (180 metres)] to accommodate long term channel alignment changes. Therefore, the stream may be left in its natural state. All existing vegetation in immediate proximity to the channel should be retained. Within the corridor, areas where vegetation is lacking should be replanted with endemic species. If after time, excessive erosion occurs, "natural" rehabilitation techniques as described in text may be used to limit damage. Where problems with channel alignment occur, branch packings may be used to redirect the flow and the upper banks may be stabilized by vegetative means.

2 Within these previously channelized reaches, meanders should be re-introduced. Grade control structures and bank protection should be placed as required to maintain the channel within a minimum width [400 feet (120 metres)] stream conservation corridor. As much existing vegetation as possible should be retained and replanting with endemic material should be done within the corridor. If after time, excessive erosion occurs, "natural" rehabilitation techniques as described in text may be used to limit damage. Where problems with channel alignment occur, branch packings may be used to redirect the flow and the upper banks may be stabilized by vegetative means.

If works of this sort cannot be implemented, then as a minimum, grade control structures such as those suggested in the 1960 PFRA report "Edwards-Jackfish Creeks Floodway Lake Dauphin Silting Problem" should be established and bank protection works as detailed in the in-depth design drawings should be undertaken along length of channel **(see figure 118)**

No changes will be made to any portion of the creek within the park.



3 A stream conservation corridor should be designated and developed as shown in the schematic sketch 'A' (see figure117). The corridor, is approximately 350 feet (100 metres) wide and the boundaries follow the outside toes of the existing dykes. The dimensions given in the sketch serve as guidelines and actual layout on site should vary with local conditions to create as natural an appearance as possible (see figure119 for an example). If after time, excessive erosion is occurring, "natural" stream rehabilitation techniques as described in the text should be implemented. Techniques that would be suitable in this situation are:

- for slope stabilization
  - brush mattress construction.
- for blowouts
  - live siltation barriers with log brush barriers
- for severe problems where live siltation barriers are insufficient
  - rock fill with live branch layering
  - rock placing with joint planting
  - as a last resort, crib walls with live branch packings.

4 Vegetation should be allowed to grow along the banks of the creek as it passes through the siltation basin. Initially no intensive work, such as planting or realignment of the channel should be done. If other rehabilitation work along the entire length of the channel is successful in controlling erosion and deposition of material, then the basin will not require re-dredging and "natural" stream rehabilitation may be undertaken in the same manner as in the reach immediately upstream.

5 A stream conservation corridor should be designated and developed as shown in the schematic sketch 'B' (see figure117). The corridor, is approximately 300 feet (90 metres) wide and the boundaries follow the outside toes of the existing dykes. The dimensions given in the sketch serve as guidelines and actual layout on site should vary with local conditions to create as natural an appearance as possible (see figure 119 for an example). If after time, excessive erosion is occurring, "natural" stream rehabilitation techniques as described in the text should be implemented. Techniques that would be suitable in this situation are:

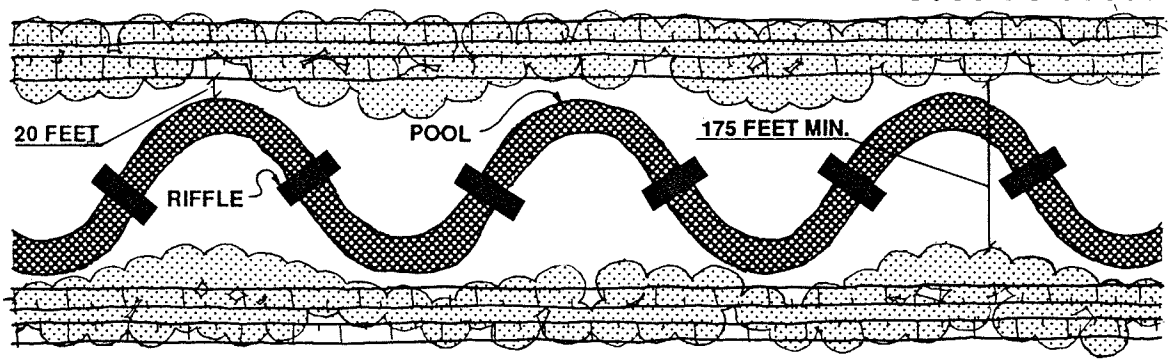
- for slope stabilization
  - brush mattress construction.
- for blowouts
  - live siltation barriers with log brush barriers
- for severe problems where live siltation barriers are insufficient
  - rock fill with live branch layering
  - rock placing with joint planting
  - as a last resort, crib walls with live branch packings.

WATERCOURSE WORKS OVERALL FRAMEWORK

0 1/2 1 mile 1 1/2

FIGURE 116

SKETCH 'A' **6+00 TO 66+00**



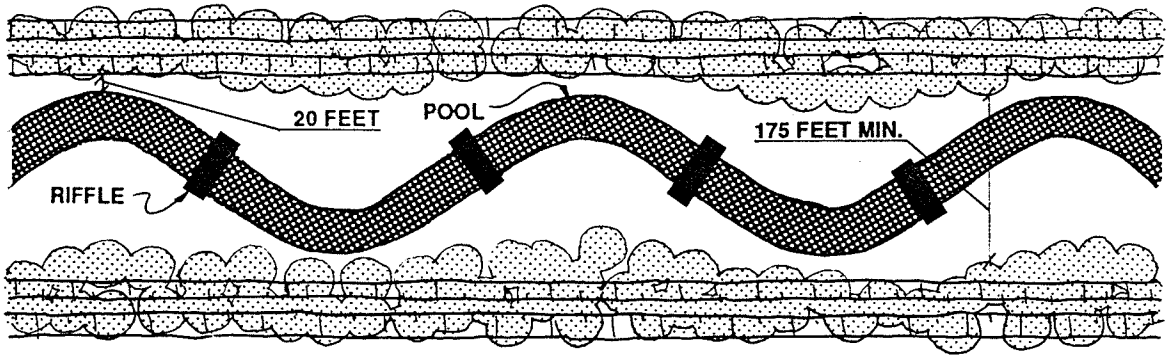
λ = 375 FEET (115 METRES) R_c = 85 FEET (25 METRES)

L = 520 FEET (158 METRES) WIDTH = 33 FEET (10 METRES)

520/375 = 1.4 DEPTH = 1.5 FEET (0.5 METRES)

PLACING VEGETATION IN CHANNEL RIGHT OF WAY WILL REDUCE CAPACITY, BUT SINCE THE ORIGINAL CHANNEL WAS DESIGNED FOR APPROXIMATELY 100 YEAR FLOOD, THE VEGETATION WILL ONLY REDUCE CAPACITY TO APPROXIMATELY A 50 YEAR FLOOD, WHICH IS WELL ABOVE 2 TO 5 YEAR FLOOD REQUIREMENT OF AGRICULTURAL DRAINS AND EQUAL TO REQUIREMENT FOR EXPENSIVE STRUCTURES SUCH AS DAM SPILLWAYS.

SKETCH 'B' **444+00 TO 504+00**



λ = 500 FEET (150 METRES) R_c = 115 FEET (35 METRES)

L = 620 FEET (190 METRES) WIDTH = 45 FEET (13 METRES)

620/500 = 1.24 DEPTH = 2.5 FEET (0.7 METRES)

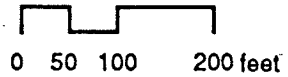


Figure 117 Schematic sketches showing the general dimensions of the proposed Edwards Creek channel in two locations (see figure 116 for locations).

4.4.2.2 DETAILED DESIGN EXAMPLES

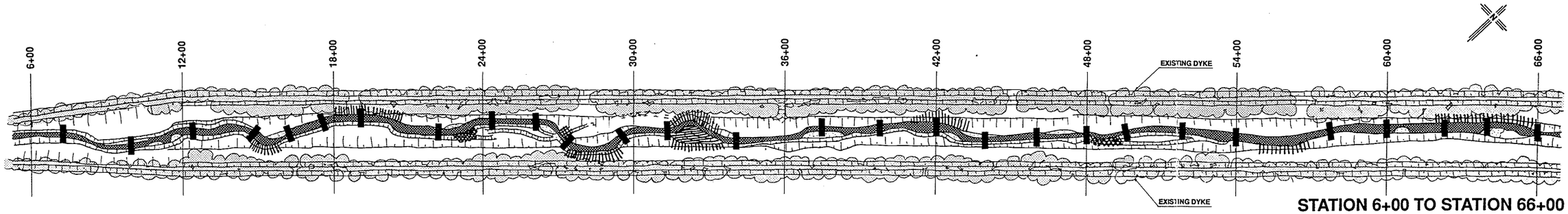
Two sites along Edwards Creek, that are presently experiencing severe erosion, have been chosen to illustrate the range of possible solutions that could be implemented. Three types of solutions, a minimal intervention, a complete realignment of the channel with machinery and a re-direction of the flow to create the new channel, have been demonstrated. The decision regarding which solution is to be implemented would based on public will, political interests, economic conditions and environmental concerns.

ALTERNATIVE ONE - MINIMAL INTERVENTION

(see figure 118)

This solution shows the amount of work that, as a minimum, should be undertaken to achieve, at least, a partial rehabilitation of the creek. The channel is not realigned and gradient control structures have been put in place to reduce erosion and stabilize the low flow channel bed. All the proposed channel works have been kept within the existing channel right of way. so as to minimize the project's impact on the surrounding agricultural land. The gradient control structures have been located to complement the existing bends in the channel, where pools have formed naturally and "artificial" pools have been created by developing riffle pairs in which two gradient control structures are placed 60 to 100 feet (20 to 30 m.) apart. The pools, thus created, improve fish spawning and habitat conditions.

To maintain the channel alignment in its existing location, live siltation barriers, with complementary log brush barriers, have been placed where major blowouts of the channel have occurred. Brushmattress construction has been undertaken in locations where the low flow channel approaches the berms closely and very steep banks occur. The bank slope will be reduced in these areas and the brushmattress will help to stabilize the slope against further erosion. All banks along the pilot channel should be re-graded at 5:1 and seeded to prevent further slippages. Some form of temporary erosion control will likely be necessary to allow the vegetation to take root.



STATION 6+00 TO STATION 66+00

NOTES

THIS SOLUTION INVOLVES MINIMAL INTERVENTION IN THE EXISTING CONDITIONS OF THE CREEK. ONLY RIFFLE STRUCTURES ARE PUT IN PLACE AND SOME VEGETATION IS PLANTED ALONG THE RIGHT OF WAY. NO CHANNEL REALIGNMENT IS UNDERTAKEN. RIFFLE STRUCTURES STABILIZE THE CHANNEL BED REDUCING EROSION AS WELL AS PROVIDING IMPROVED FISH SPAWNING AND HABITAT CONDITIONS.

THE DOUBLE RIFFLES CREATE 'ARTIFICIAL' POOLS WHICH FISH MAY USE FOR SPAWNING.

BANK STABILZATION UNDERTAKEN TO MAINTAIN THE CHANNEL IN ITS EXISTING LOCATION.

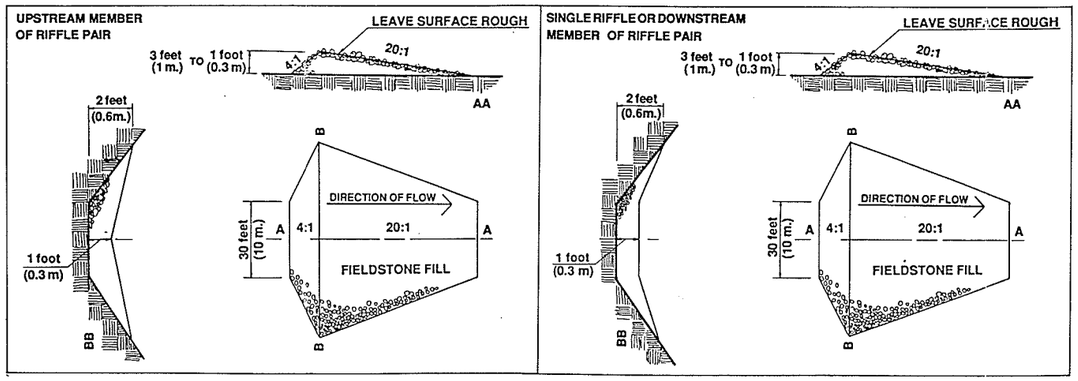
VEGETATION HELPS TO CREATE A MORE NATURAL APPEARING FLOODPLAIN AND RIPARIAN AREA AND IMPROVES FISH AND WILDLIFE HABITAT, ALLOWING MORE ANIMAL ACTIVITY TO TAKE PLACE ALONG THE CREEK.

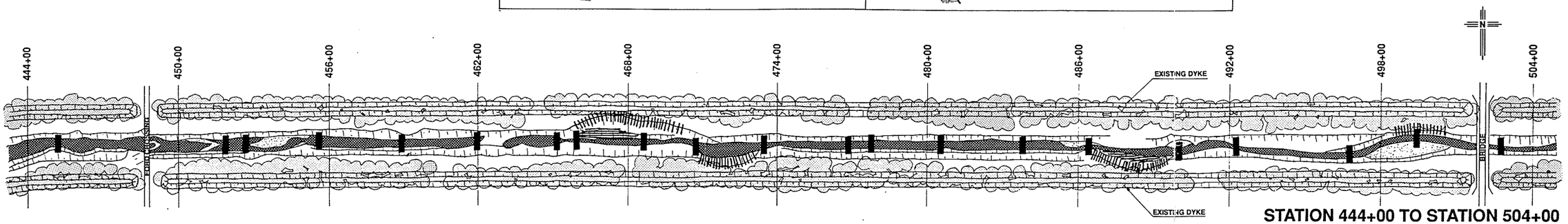
THE VEGETATION ALSO PROVIDES SOME SHADE FOR THE WATER DECREASING ITS TEMPERATURE AND FALLEN LEAVES PROVIDE FOOD FOR A VARIETY OF MICRO-ORGANISMS.

ALL BANKS SHOULD BE RE-GRADED AT 5:1 AND SEEDED AND MULCHED.

PROPOSED CHANNEL HAS CAPACITY ACCOMMODATE A FIFTY YEAR FLOOD. FOR CALCULATIONS, SEE APPENDIX II.

SCHEMATIC 'C'





STATION 444+00 TO STATION 504+00

LEGEND

- EXISTING CHANNEL
- PROPOSED VEGETATION
- SINGLE RIFFLE STRUCTURE SEE SCHEMATIC 'C'
- DOUBLE RIFFLE STRUCTURE SEE SCHEMATIC 'C'
- RIPRAP
- BRUSHMATTRESS CONSTRUCTION
- LIVE SILTATION CONSTRUCTION WITH LOG BRUSH BARRIERS

MINIMAL INTERVENTION

0 50 100 200 feet 400

FIGURE 118

The vegetation associated with the bank stabilization measures and the trees that have been placed on the berms or along the edges of the floodway help to give the channel a more natural appearing floodplain and riparian area. The vegetation also provides some shade for the water, decreasing its temperature and fallen leaves provide food for a variety of micro-organisms. Thus, fish, bird and wildlife habitat is improved and the recreational potential of the creek is increased.

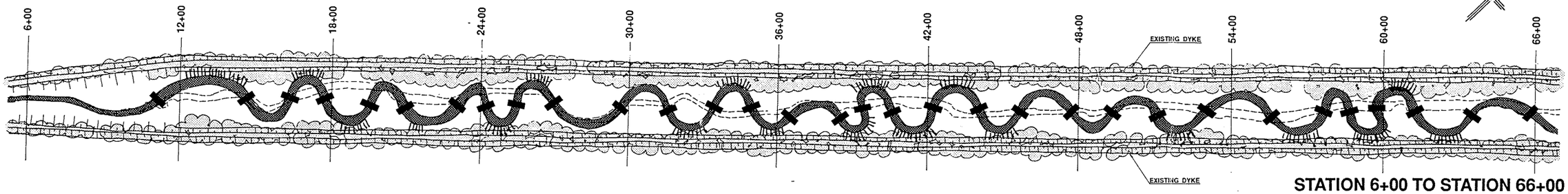
While the capacity of the channel has been reduced slightly, it can still accommodate at least a 50 year flood. This is much greater than the 5 to 10 year capacity of agricultural drains and is equivalent to the capacity of expensive structures, such as dam spillways, that may be damaged by flood flows. For calculations showing the capacity of the proposed channel, see appendix II.

ALTERNATIVE TWO - PROPOSED CHANNEL CONSTRUCTED

(see figure 119)

This solution, in which the creek has been developed to have a more natural appearance, has all the attributes of the minimal intervention solution, plus a few more beneficial aspects. The sinuous course of the proposed pilot channel increases the channel's length, decreasing the gradient of the bed and reducing the erosive power of the water. Since the form of the meander is determined from an examination of other natural watersheds in the area and the form of the original creek, the re-designed channel should be relatively stable. The sinuous course also promotes the development of pools on the outside of the bends, providing improved fish spawning grounds and habitat, rendering the construction of double riffles unnecessary. For calculations relating to the design of the meander forms, see appendix I.

Small gradient control dams have been placed in the pilot channel, where riffles would occur in a natural creek. These structures hold back some water in the creek, complementing the pools that have developed as a result of the curves. Bank stabilization, consisting of brushmattress constructions has been placed, so that on sharp curves, erosion is



STATION 6+00 TO STATION 66+00

NOTES

IN THIS CASE THE CREEK HAS BEEN DEVELOPED TO HAVE A MORE NATURAL APPEARANCE.

ALL PROPOSED CHANNEL WORKS ARE KEPT WITHIN THE EXISTING RIGHT OF WAY SO AS TO MINIMIZE THE PROJECTS IMPACT ON THE SURROUNDING AGRICULTURAL LAND.

VEGETATION HELPS TO CREATE A MORE NATURAL APPEARING FLOODPLAIN AND RIPARIAN AREA AND IMPROVES FISH AND WILDLIFE HABITAT, ALLOWING MORE ANIMAL ACTIVITY TO TAKE PLACE ALONG THE CREEK.

THE VEGETATION ALSO PROVIDES SOME SHADE FOR THE WATER DECREASING ITS TEMPERATURE AND FALLEN LEAVES PROVIDE FOOD FOR A VARIETY OF MICRO-ORGANISMS.

THE SINUOUS COURSE OF THE PROPOSED PILOT CHANNEL REDUCES THE GRADIENT BY INCREASING LENGTH. SINCE THE FORM OF THE PROPOSED CHANNEL IS DETERMINED FROM THE BEHAVIOUR OF NATURAL WATERWAYS, THE RE-DESIGNED CHANNEL SHOULD BE IN EQUILIBRIUM AND RELATIVELY STABLE.

THE CURVES ALSO PROMOTE THE DEVELOPMENT OF POOLS ON THE OUTSIDE OF THE BENDS, PROVIDING MPROVED FISH SPAWNING GROUNDS AND HABITAT.

FOR CALCULATIONS RELATING TO THE DEVELOPMENT OF THE MEANDER FORMS, SEE APPENDIX I.

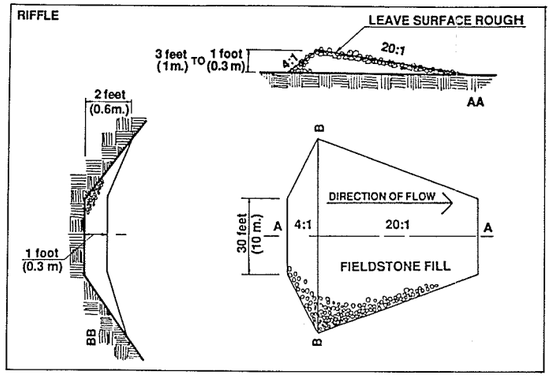
BANK STABILIZATION UNDERTAKEN TO ENSURE THAT, WHERE THE CHANNEL APPROACHES THEM CLOSELY, NO DAMAGE WILL OCCUR TO THE DYKES.

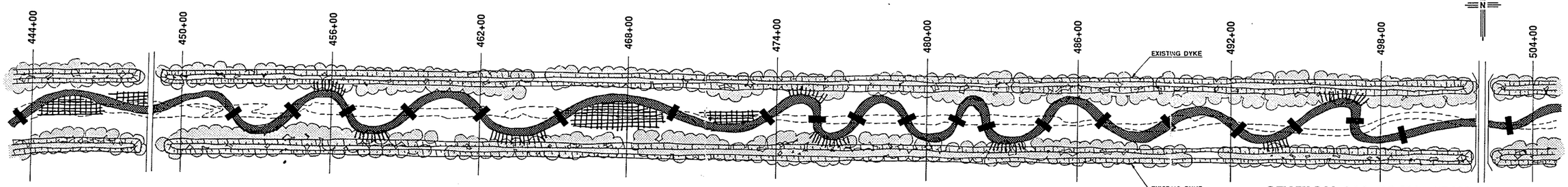
RIFFLE STRUCTURES STABILIZE THE CHANNEL BED REDUCING EROSION AS WELL AS PROVIDING IMPROVED FISH SPAWNING AND HABITAT CONDITIONS.

PROPOSED CHANNEL HAS CAPACITY ACCOMMODATE A FIFTY YEAR FLOOD. FOR CALCULATIONS, SEE APPENDIX II.

WHILE ALL THESE WORKS HELP TO STABILIZE THE CHANNEL, THE IMPROVED AESTHETIC QUALITIES AND FISH AND WILDLIFE HABITAT INCREASE RECREATIONAL OPPORTUNITIES ALONG THE CREEK.

SCHEMATIC 'D'





STATION 444+00 TO STATION 504+00

LEGEND

- EXISTING CHANNEL
- PROPOSED CHANNEL
- PROPOSED VEGETATION
- RIFFLE STRUCTURE SEE SCHEMATIC 'D'
- BRUSHMATTRESS CONSTRUCTION
- BRANCH PACKINGS

PROPOSED CHANNEL CONSTRUCTED

0 50 100 200 feet 400

FIGURE 119

controlled and the risk of damage to the dykes is minimized. While the vegetation plays the same role as in the minimal intervention solution, creating more natural conditions, shading the water and providing improved habitat for fish, birds and wildlife, it is in this proposal more effective because it comes in closer contact with the pilot channel, more often.more natural appearing floodplain and riparian area.

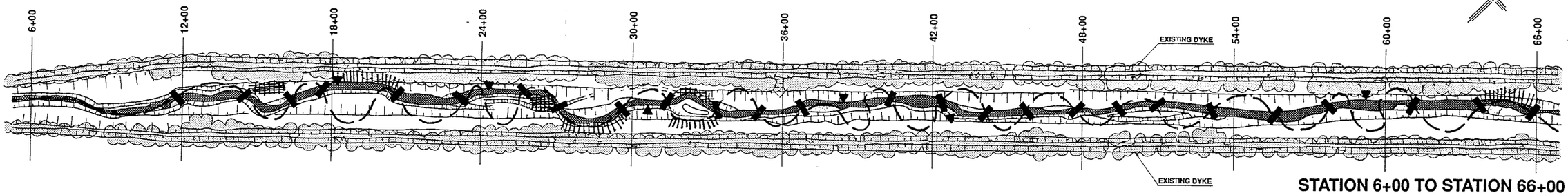
While all the works suggested in this solution help to create a more geomorphologically stable channel, the variety of flow patterns, the increased channel length and more natural general condition of the creek, allow greater opportunities for biological activity as compared to the minimal intervention solution. The increase in fish, bird and wildlife habitat and the improved aesthetic qualities of the land and waterscape, also create much improved recreational opportunities.

ALTERNATIVE THREE - PROPOSED CHANNEL CREATED BY THE RE-DIRECTION OF FLOW

(see figure 120)

This solution is a more experimental proposal that seeks to work with the processes occurring naturally in the creek. An examination of the existing low flow channel shows that incipient meanders have developed. Since erosion is already occurring in the channel, gradient control structures are positioned and their tops angled to concentrate the flow in the desired direction, allowing erosion to create the desired channel form and achieve a more stable result. Branch packings and current deflectors are also positioned to help direct this process. As the channel creates its new form, bank protection may have to be put in place to ensure that the channel stays within the desired limits and that no damage occurs to the dykes. In areas where the proposed channel follows the existing channel path close to the dykes, some stabilization should be undertaken immediately.

This solution reduces the initial construction costs and since the bank stabilization works are only put in as needed, it ensures that "over-design" will not occur and that the construction costs are spread out over time. Since the final form of this solution is



STATION 6+00 TO STATION 66+00

NOTES

THIS SOLUTION SEEKS TO WORK WITH THE PROCESSES OCCURRING NATURALLY IN THE CREEK. FLOWS ARE RE-DIRECTED TO ALLOW EROSION TO CREATE THE DESIRED FORM OF THE PILOT CHANNEL.

ALL PROPOSED CHANNEL WORKS ARE KEPT WITHIN THE EXISTING RIGHT OF WAY SO AS TO MINIMIZE THE PROJECTS IMPACT ON THE SURROUNDING AGRICULTURAL LAND.

THE SINUOUS COURSE OF THE PROPOSED PILOT CHANNEL REDUCES THE GRADIENT BY INCREASING LENGTH. SINCE THE FORM OF THE PROPOSED CHANNEL IS DETERMINED FROM THE BEHAVIOUR OF NATURAL WATERWAYS, THE RE-DESIGNED CHANNEL SHOULD BE IN EQUILIBRIUM AND RELATIVELY STABLE.

FOR CALCULATIONS RELATING TO THE DEVELOPMENT OF THE MEANDER FORMS, SEE APPENDIX I.

AS THE CHANNEL CREATES ITS NEW FORM, BANK PROTECTION MAY HAVE TO BE UNDERTAKEN TO ENSURE THAT IT STAYS WITHIN THE EXISTING RIGHT OF WAY AND THAT NO DAMAGE OCCURS TO THE DYKES. IN AREAS WHERE THE EXISTING CHANNEL ALREADY APPROACHES THE DYKES, SOME STABILIZATION MEASURES WILL HAVE TO BE PUT IN PLACE AT THE OUTSET OF THE PROJECT.

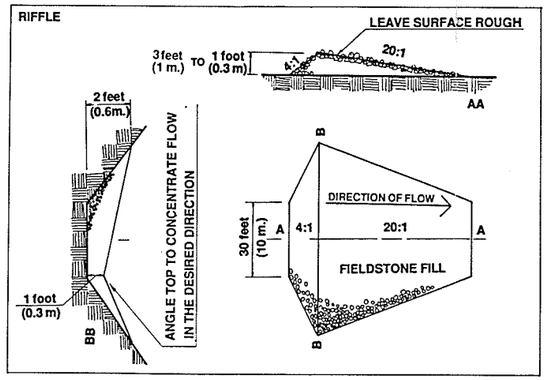
RIFFLE STRUCTURES STABILIZE THE CHANNEL BED REDUCING EROSION AS WELL AS PROVIDING IMPROVED FISH SPAWNING AND HABITAT CONDITIONS.

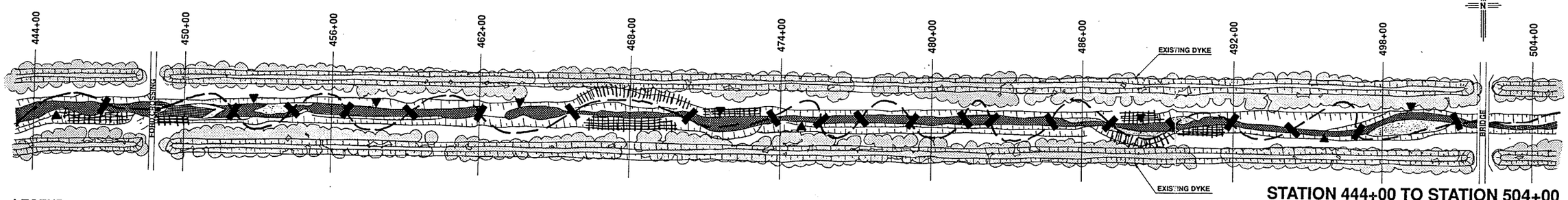
PROPOSED CHANNEL HAS CAPACITY ACCOMMODATE A FIFTY YEAR FLOOD. FOR CALCULATIONS, SEE APPENDIX II.

WHILE ALL THESE WORKS HELP TO STABILIZE THE CHANNEL, THE IMPROVED AESTHETIC QUALITIES AND FISH AND WILDLIFE HABITAT INCREASE RECREATIONAL OPPORTUNITIES ALONG THE CREEK.

THIS SOLUTION REDUCES INITIAL CONSTRUCTION COSTS AND SINCE STABILIZATION WORKS ARE ONLY PUT IN PLACE AS THEY ARE NEEDED, EXPENSES ASSOCIATED WITH THESE WORKS ARE SPREAD OUT OVER TIME.

SCHEMATIC 'E'





STATION 444+00 TO STATION 504+00

LEGEND

- EXISTING CHANNEL
- DESIRED CHANNEL LOCATION
- PROPOSED VEGETATION
- RIFFLE STRUCTURE SEE SCHEMATIC 'E'
- CURRENT DEFLECTOR
- BRUSHMATTRESS CONSTRUCTION
- BRANCH PACKINGS

PROPOSED CHANNEL CREATED BY RE-DIRECTION OF FLOW

0 50 100 200 feet 400

FIGURE 120

approximately the same as that of Alternative Two - Proposed Channel Constructed, the end results should be more or less the same. The overall length of the channel is increased and the gradient of the bed is decreased, reducing the erosive power of the water. The curves and gradient control structures promote the development of pools, improving fish spawning grounds and habitat. The vegetation helps to stabilize the channel and to create a more natural appearing riparian zone providing more and better bird and wildlife habitat. These improved conditions also vastly improve the recreational potential of the creek.

5 CONCLUSION

The development of more channelization projects is likely to continue in the near future (Keller, 1980). Projects, such as highway construction and maintenance, and flood control development, and processes such as urbanization, in existence today, will continue to occur and will steadily exert more and more pressure on waterways. As the world population grows, the demand for food will increase and more land will likely be brought under cultivation. As development increases, more channelization projects will be deemed necessary. Thus development interests must be reconciled with environmental concerns.

In order to create a strategy to reduce environmental degradation associated with channelization, several concepts must be recognized (Keller, 1980):

1) The stream and floodplain constitute a system. Channelization reduces water storage in the floodplain and encourages inappropriate landuse by providing a false sense of protection against floods.
2) A more balanced approach to water development projects is required. All costs and benefits must be evaluated and full consideration must be given to environmental values.
3) Priorities must be set. Consideration must be given to future generations. Thus

an inventory should be undertaken and some streams that will not be modified should be set aside and permanently protected from alterations.

4) More research must be undertaken so that a more precise understanding of the behaviour of natural waterways may be achieved. Long term post channelization evaluations should be undertaken, so that the potential impacts of channelization projects may be better recognized and considered.
5) More priority should be given to alternatives that maximize the overall benefits of channelization projects, while minimizing environmental degradation.

This outline of concepts points to the need for an integrated approach to the design of channelization projects. All factors, cost and benefits, both in the watercourse and in the watershed must be considered in determining first the necessity of the project and secondly the design of the works. This practicum attempts to illustrate some of the potential problems with conventional channelization techniques that are used improperly or without an understanding of the consequences of their use. It discusses the way in which natural water systems work and illustrates a variety of techniques, so that selection of the most appropriate method to solve a particular problem can be made from a range of known techniques. This process is demonstrated on Edwards Creek. A range of possible solutions, each of which could be implemented based on political interests, public will, economic conditions and environmental concerns of the time, is illustrated.

It is important to note that many of the problems that Edwards Creek has experienced are a result of its original design. In the 1940's and 1950's, when the channel was designed, information regarding large scale projects of this type was scarce. Therefore, it was likely designed in the best manner possible given the political, technical and economic constraints of the time. In the past 40 years, much more information has become available regarding the planning and design of such projects. Knowledge about relationships between factors such as drainage area, discharge, channel morphology, slopes, soil characteristics and erosion have been introduced into and accepted by the professions responsible for the design and maintenance of channelization works, leading to ever

improving designs. This practicum seeks to add to that knowledge base and to perpetuate improvements in design. While in this case, natural stream landscaping techniques have been applied to Edwards Creek, an existing channel, to improve its geomorphological and ecological condition, these same techniques may and should be applied to the design of new channelization projects to ensure maximum effectiveness with a minimum of environmental disruption.

APPENDIX I

DETERMINATION OF PROPOSED EDWARDS CREEK CHANNEL DIMENSIONS

TEMPLATE FOR A CHANNEL BASED ON THE NATURAL DIMENSIONS OF STREAMS IN THE RIDING MOUNTAIN AREA: DRAINAGE ARE USED AS INDEPENDENT VARIABLE AS IT IS VERY EASILY MEASURED. ALL CALCULATIONS DONE IN METRIC & CONVERTED TO IMPERIAL BECAUSE EQUATIONS & MOST BASE INFORMATION IN METRIC.

$CWbf = 1.7\ DA^{0.36}$ (Chapman, 1987a)

$CWbf$ = bankfull width (m)

DA = drainage area (km^2)

$\lambda = 11.03 CWbf^{1.01}$ (based on Leopold et al, 1964)

$CWbf$ = bankfull width (m)

λ = meander wavelength (m)

from above 2 calculations:

$\lambda = 11.03 CW_{bf}^{1.01}$ & $CW_{bf} = 1.7\ DA^{0.36}$

$\therefore \lambda = 11.03 (1.7\ DA^{0.36})^{1.01}$

$= 18.85\ DA^{0.3636}$

$\lambda = 4.59\ Rc^{0.98}$ (based on Leopold et al, 1964)

λ = meander wavelength (m)

Rc = mean radius of curvature (m)

from above 2 calculations:

$\lambda = 18.85\ DA^{0.3636}$ & $\lambda = 4.59\ Rc^{0.98}$

$\frac{18.85\ DA^{0.3636}}{4.59} = \frac{4.59\ Rc^{0.98}}{4.59}$

$\sqrt[0.98]{4.1\ DA^{0.3636}} = \sqrt[0.98]{Rc^{0.98}}$

$4.2 \sqrt[0.98]{DA^{0.3636}} = Rc$

$R_c = 4.2 D_A^{0.37}$

$L = 1.3\lambda = 4\lambda$ (Leopold & Langbein, 1966)

L = length of channel (m)

λ = meander wavelength (m)

$d_{bf} = 0.12 D_A^{0.30}$ (Chapman, 1987a)

d_{bf} = bankfull depth (m)

D_A = drainage area (km^2)

CHANNEL MORPHOLOGY OF EDWARDS CREEK NEAR DAUPHIN.

$D_A = 142 km^2$

$d_{bf} = 1.7 D_A^{0.36}$
$= 1.7(142^{0.36})$
$= 10.12 m$ (33.2')

$d_{bf} = 0.12 D_A^{0.30}$
$= 0.12(142^{0.30})$
$= 0.53 m$ (1.7')

$\lambda = 18.85 D_A^{0.3636}$
$= 18.85(142^{0.3636})$
$= 114.26 m$ (375')

$R_c = 4.2 D_A^{0.37}$
$= 4.2(142^{0.37})$
$= 26.28 m$ (86')

$L = 1.3\lambda$ to 4λ
$= 1.3(114.26)$ to $4(114.26)$
$= 148.5 m$ (487') to $457 m$ (1450')

CHANNEL MORPHOLOGY OF EDWARDS CREEK BELOW JACKFISH CREEK:

$D_A = 311\ km^2$

$CW_{bf} = 1.7(311^{0.56})$
$= 13.42m\ (44')$

$d_{bf} = 0.12(311^{0.30})$
$= 0.67m\ (2.2')$

$\lambda = 18.85(311^{0.3636})$
$= 152\ m\ (499')$

$R_c = 4.2(311^{0.37})$
$= 35.12m\ (115')$

$L = (1.3)(152)$ to $4(152)$
$= 197.6m\ (648')$ to $608m\ (1995')$

THESE DIMENSIONS APPEAR TO BE FAIRLY CONSISTENT WITH THE ORIGINAL DIMENSIONS OF THE CREEK BEFORE CHANNELIZATION, WHEN MEANDER WAVELENGTH (λ) = 132m (432'), AVERAGE CHANNEL WIDTH MEASURED FROM AIR PHOTOS = 7m. (23') BASED ON MEANDER CHANNEL LENGTH (L) WIDTH (CW) = 14m (46') TO 21m (69')

THESE CALCULATIONS HAVE BEEN USED TO CREATE A PLAN SHOWING THE GENERALIZED DIMENSIONS OF THE EDWARDS CREEK CHANNEL. SEE FIGURE 117 FOR THESE PLANS.

APPENDIX II

CALCULATION OF PROPOSED EDWARDS CREEK CHANNEL CAPACITY

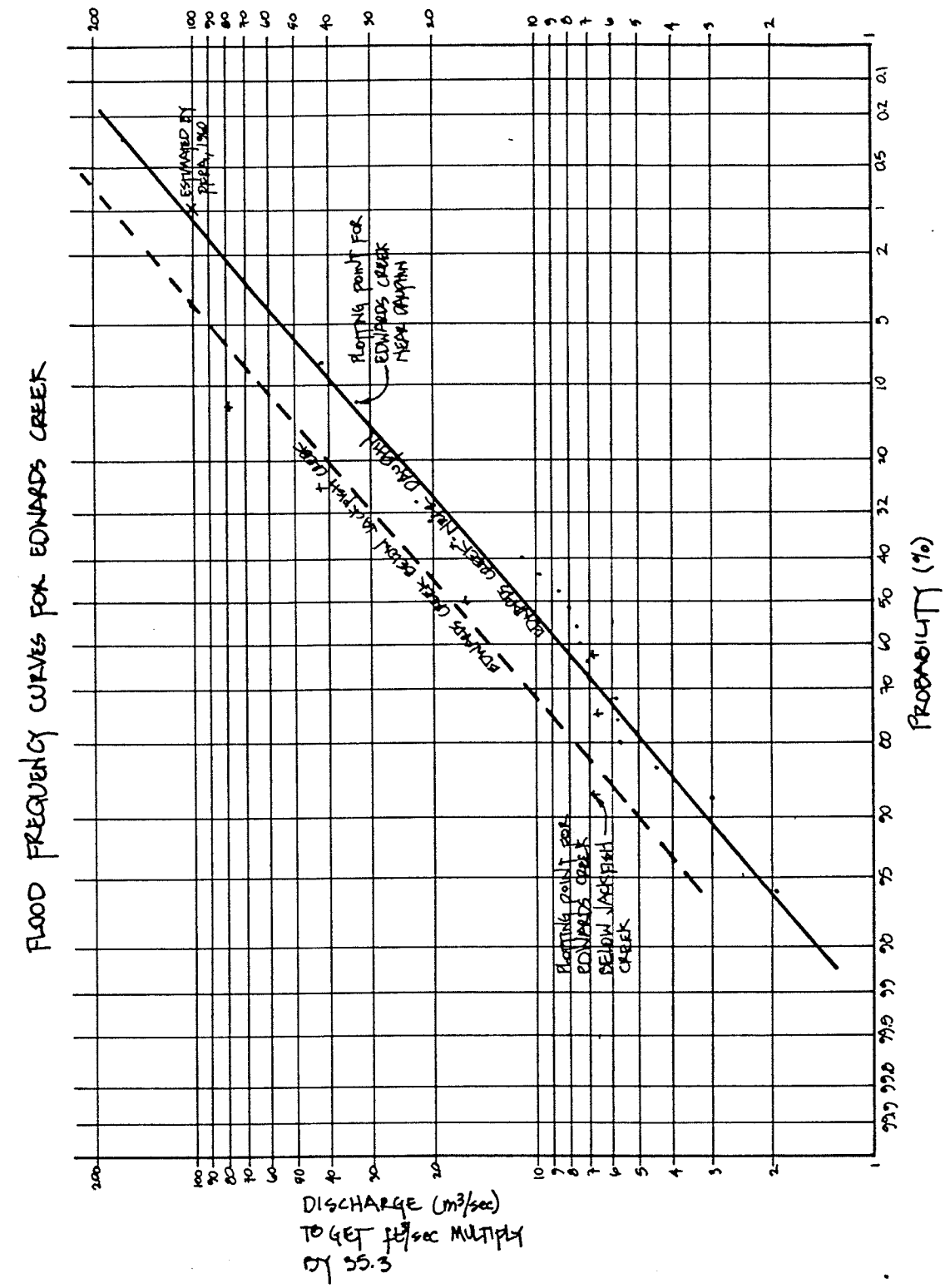
PROPOSED CHANNEL CAPACITY

CHANNEL DESIGNED FOR 1% OR 3600 cfs (102 m^3/sec) ACCORDING TO PFRA; 1960.

SO IF I LESSEN IT TO 2% OR 50 YEAR FLOOD = 2930 cfs (83 m^3/sec). SEE PLOTTING POSITION TABLE BELOW AND FLOOD FREQUENCY CURVE ON FOLLOWING PAGE.

PLOTTING POSITION TABLE

Q (m^3/sec)	RANK	PLOTTING POSITION 100 m/n+1.
102	1	4
41.6	2	8
32.8	3	12
29.5	4	16
26.2	5	20
25.0	6	24
22.3	7	28
20.4	8	32
17.3	9	36
10.9	10	40
9.57	11	44
8.33	12	48
7.90	13	52
7.40	14	56
7.36	15	60
6.97	16	64
6.91	17	68
5.72	18	72
5.66	19	76
5.55	20	80
4.36	21	84
2.94	22	88
2.71	23	92
1.91	24	96


FLOOD FREQUENCY CURVES FOR EDWARDS CREEK
ESTIMATED BY PFRA, 1980
PLOTTING POINT FOR EDWARDS CREEK NEAR CAYUGA
EDWARDS CREEK NEAR CAYUGA
EDWARDS CREEK BELOW JACKFISH CREEK
PLOTTING POINT FOR EDWARDS CREEK BELOW JACKFISH CREEK
DISCHARGE (m³/sec)
TO GET ft³/sec MULTIPLY BY 35.3
PROBABILITY (%)

$Q = VA$ Q = discharge, V = velocity, A = cross-sectional area

$V = \frac{1.49 R^{2/3} S^{1/2}}{n}$ R = hydraulic radius S = channel slope n = roughness coefficient

$\therefore Q = \frac{1.49 R^{2/3} S^{1/2} A}{n}$

DISCHARGE THROUGH MIDDLE PORTION OF CHANNEL:

R = 5' (height of dykes)
S = 0.0023 (average slope of channel from siltation basin to Dauphin Lake)
A = 875 (175 × 5)
(175 = minimum clear width from plan; 5 = ht. of dykes)
n = 0.07 (from Barnes, 1967: irregular banks with fairly heavy growth of 2" to 6" trees on the banks. A high value has been chosen to allow a margin of error.)

$$Q = \frac{1.49(5^{2/3})(0.0023^{1/2})(875)}{0.07}$$

= 2612 cfs (74 m³/sec) not the required 2930 cfs (83 m³/sec) but some water will flow through the trees on the sides of the channel.

to get Q of 50 year flood 2930 − 2612 = 318 cfs (9 m³/sec) must go through trees.

DISCHARGE THROUGH SIDES OF CHANNEL:

R = 5' (height of dykes)
S = 0.0023 (average slope of channel from siltation basin to Dauphin Lake)
A = 210 (5 · (217 − 175))
(217 − 175 = width of channel at toe minus width of clear centre portion of channel. Still some capacity as dyke slopes back to top.; 5 = ht of dykes.)

n= 0.15 (from Chow; 1959: very poor channel, very crooked course, irregular side slopes, uneven bottom. Many roots, trees & bushes, large logs & other drift on bottom. This is an extremely high value representing the worst conditions illustrated by Barnes or Chow. It is unlikely that the vegetated areas will be so rough but this value was chosen to allow a margin of error.)

$$Q = \frac{1.49(5^{2/3})(0.0023^{1/2})(210)}{0.15}$$

$= 292$ cfs ($8.27\ m^3/sec$) This is close to the 318 cfs ($9\ m^3/sec$) required and since the capacity of the low flow channel has not been counted, it is safe to assume the channel has a 50 year capacity.

VELOCITY OF FLOW THROUGH CENTRE PORTION OF CHANNEL:

$$V = \frac{1.49(5^{2/3})(0.0023^{1/2})}{0.07}$$

$= 3$ ft/sec (0.9 m/sec) slower than the 5 ft/sec (1.5 m/sec) suggested by PFRA; 1960.

ALL CALCULATIONS ABOVE FOR EDWARDS CREEK NEAR DAUPHIN. MORE FLOW IN CREEK BELOW JACKFISH CREEK. SEE PLOTTING POSITION TABLE AND FLOOD FREQUENCY CURVE. CURVE PLOTTED FOR EDWARDS CREEK BELOW JACKFISH CREEK PARALLEL TO CURVE FOR CREEK NEAR DAUPHIN BECAUSE PORTIONS OF THE SAME CREEK SHOULD HAVE SIMILAR FLOW PATTERNS.

PLOTTING POSITION TABLE

Q (m^3/sec)	RANK	PLOTTING POSITION 100m/n+1
79.5	1	12.5
42.0	2	25
17.3	3	37.5
16.3	4	50
6.97	5	62.5
6.51	6	75
6.50	7	87.5

∴ 50 YEAR FLOOD IN THIS PORTION OF THE CREEK = 3600 cfs (102 m^3/sec)

DISCHARGE THROUGH MIDDLE PORTION OF CHANNEL:

R = 5.75' (ht of dykes)
S = 0.0023 (average slope of channel from siltation basin to Dauphin Lake.)
A = 1006.25 (5.75 × 175)
(5.75: ht. of dykes; 175: minimum clear width from plan)
n = 0.07 (from Barnes; 1967! see above for description)

$$Q = \frac{1.49(5.75^{2/3})(0.0023^{1/2})(1006.25)}{0.07}$$

$= 3297$ cfs (93 m^3/sec)

to get Q of 50 year flood 3600 − 3297 = 303 cfs (8.6 m^3/sec) must go through trees.

DISCHARGE THROUGH SIDES OF CHANNEL:

R = 5.75' (ht. of dykes)
S = 0.0023 (average slope from siltation basin to Dauphin Lake)
A = 241.5 (5.75 · (217 − 175)) Width of channel at toe minus centre portion
(5.75: ht. of dykes)

$n = 0.15$ (from Chow; 1959: see above for description)

$$Q = \frac{1.49(5.75^{2/3})(0.0023^{1/2})(241.5)}{0.15}$$

$= 369$ cfs ($10.4\ m^3/sec$) This value is more than the 303 cfs ($8.6\ m^3/sec$) required! Therefore, the Edwards Creek channel below Jackfish Creek has a capacity larger than the 50 year flood.

VELOCITY OF FLOW THROUGH CENTRE PORTION OF CHANNEL:

$$V = \frac{1.49(5.75^{2/3})(0.0023^{1/2})}{0.07}$$

$= 3.3$ ft/sec (1.0 m/sec) slower than the 5 ft/sec (1.5 m/sec) suggested by the PFRA, 1960.

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