AN EVALUATION OF THE DESIGN OF THE PROPOSED KEMUNING DIVERSION CHANNEL

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By

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ST JOHN'S NEWFOUNDLAND CANADA

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To:

My mother Ny. K. H. Ali Hamdan

My wife Setianingrum Risqiah, S.H

My daughter Desy Qurrotu Aini

INDONESIA.

Abstract

The construction of the Kemuning Diversion channel is designed to address the flooding problem of the city of Sampang, Indonesia. Under the proposed scheme the Kemuning River, which causes this flooding (drainage area = 345 km^2), will be divided into two channels upstream of the city. The downstream limit for both channels is the Strait of Madura. The diversion channel will carry much of the flood waters away from the old channel through Sampang (population ~ 1,000,000). The proposed design, which was developed by a local engineering consultant, did not include any analysis of possible future channel changes caused by sediment budget imbalances. This thesis is concerned with the analysis of the possible channel changes associated with relatively long periods of operation. The problem was evaluated by using a deductive approach, which involved application of a mobile bed mathematical model of the channel, and an inductive approach, based on regime theory.

Using the deductive approach, estimated channel changes were derived by solving the sediment-continuity equation together with Laursen's and Yang's method for calculating the rate of sediment transport. Initial sediment movement was determined using a critical hydraulic shear stress, estimated from available soil data in and around the proposed channel. Hydraulic computations, which were also used to calculate the rate of sediment transport, were performed using the standard step method and the Manning equation. To simulate twenty years of hypothetical operation, water discharge inflows of interest were selected using the historical flow duration curve, which was set up as a series of discrete discharges.

The estimated channel changes were simulated using mean sea level (MSL) as the downstream boundary condition. The channel bottom was found to exhibit aggradation all along its length.

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Symbol	Description
A	cross-section area of the flow
A_b	amount of change in cross-sectional area
C	sediment concentration
C_b	bed load concentration
C_m	sediment concentration (Laursen's method)
C_t	sediment concentration (Yang's method)
D	water depth
d_{50}	median grain size
d_t	vertical distance from datum to the channel bottom
d	average sediment particle size
e	void ratio
e_t	erosion or deposition depth
F	function
F_b	Blench's bed factor
f_L	Lacey's silt factor
F_s	Blench's side factor
g	gravitational acceleration
h	water depth
H	total head; abbreviation for horizontal
HEC	Hydrologic Engineering Centre
h_e	eddy loss
h_f	friction loss
i	subscript to indicate cross-section
I_p	plasticity index
j	subscript to indicate grain fraction
LL	liquid limit
MSL	mean sea level
n	Manning's roughness coefficient, porosity
OIS	the Office of Irrigation Services

PL	plastic limit
p	percent of a given grain size
P_r	probability
P	wetted perimeter
Q_s	sediment load
Q_{st}	sediment load from a tributary
Q_t	water discharge from a tributary
Q_w	water discharge
R	hydraulic radius
S	sediment storage, channel slope
s	specific gravity of a single sediment grain
S_f	friction slope
S_o	bed slope
S_v	soil shear strength
t	time
TW	top width
U_*	bed shear velocity
V	water velocity; abbreviation for vertical
w	fall velocity
V_o	non-silting velocity
V_t	water velocity at a tributary
W	bottom channel width
W_o	average channel width
W_t	water content
X	coordinate
X_{left}	X coordinate for water surface at left side, looking downstream
X_{right}	X coordinate for water surface at right side, looking downstream
Y	coordinate
Y_{left}	Y coordinate for water surface at left side, looking downstream
Y_{max}	largest Y coordinate
Y_{right}	Y coordinate for water surface at right side, looking downstream
Z	water stage
α	kinetic energy coefficient
α_L	angle of water surface to left bank channel
α_R	angle of water surface to right bank channel
γ	unit weight of water
γ_s	unit weight of sediment particles
ΔA_b	amount of change in cross-sectional area
ΔH	energy loss, expansion or contraction energy loss
Δ_t	time step
Δ_x	length of reach between the sections
θ	internal angle of friction,
μ	dynamic viscosity
ν	kinematic viscosity

τ'	Laursen's bed shear stress due to grain resistance
τ_{*c}	dimensionless critical shear stress
τ_c	critical shear stress, critical hydraulic shear stress
τ_{cj}	critical shear stress for particles of size d_j
ϱ_s	dry density, sediment density
τ_o	mean hydraulic shear stress

1. INTRODUCTION

1.1 Background

Indonesia (Figure 1.1) is a tropical country with two distinct seasons, a wet season and a dry season. The annual variation in flow in Indonesia's rivers is very much affected by this seasonal cycle. River flows usually diminish during the dry season but increase very markedly during the wet season. These conditions tend to create potential flooding problems, which in turn affect the people whose lives are intrinsically tied to the various rivers. The particular river with which this thesis is concerned is the Kemuning River on Madura Island, in the province of East Java.

The Kemuning River flows through the city of Sampang (Figure 1.2) which has experienced flooding problems almost every year on record. An investigation into this problem was conducted by a private engineering firm under the supervision of the Office of Irrigation Services (OIS) for the province of East Java. This investigation found that the interdependent factors contributing to the flooding problems were the hydrologic condition of the Kemuning River basin and hydraulic capacity of the river channel. Based on these findings, the Government of Indonesia implemented a two-stage plan for coping with the problem. This plan involves the construction of diversion channels and the construction of detention basins (reservoirs).

Figure 1.1. Map of Indonesia.

For the first stage, the design of the Kemuning Diversion Channel was undertaken by CV.HIDROS, a local engineering consultant. The proposed design for the diversion channel is summarized in Figure 1.3 and Table 1.1. When the proposed diversion channel is completed, the Kemuning River will flow into two channels before passing through the city of Sampang and then on to the Strait of Madura (Figure 1.4). It is hoped that this will ensure that the maximum safe water level within urban areas will not be exceeded as a result of flooding. In this respect it is noted that the design of the

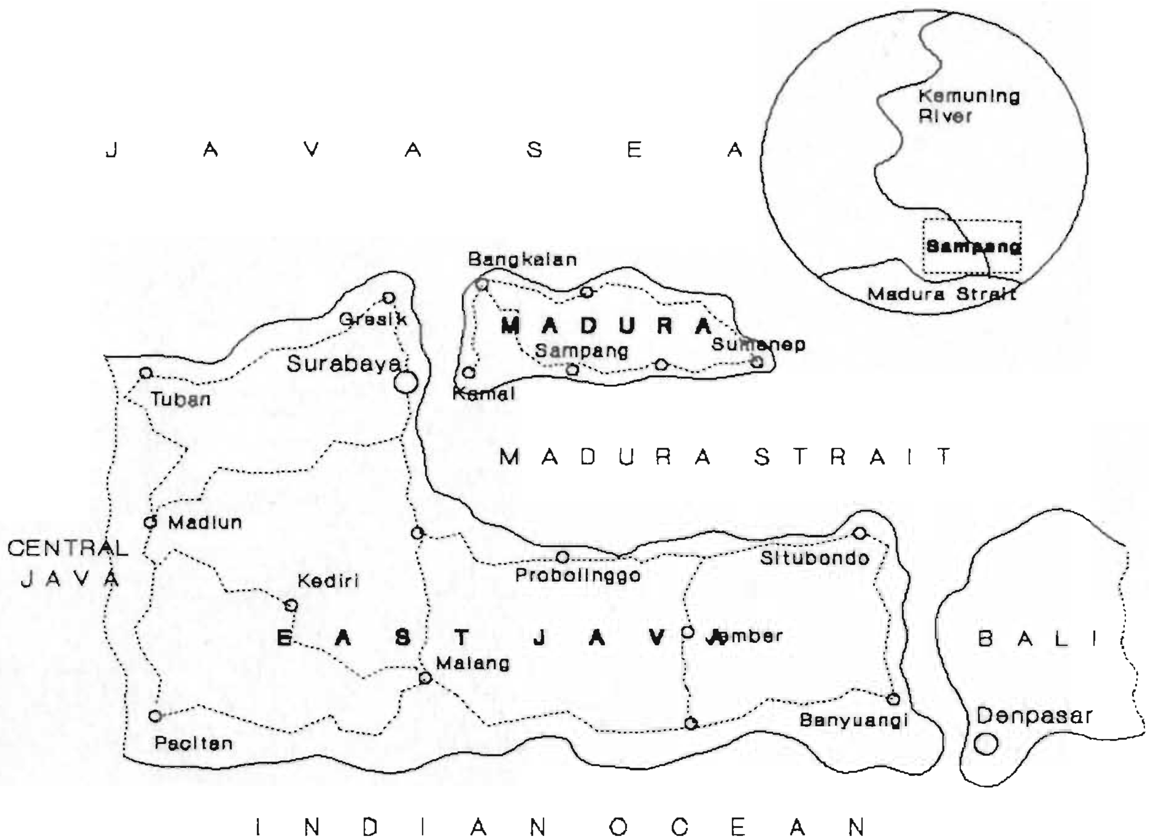


Figure 1.2. East Java and Madura Island.

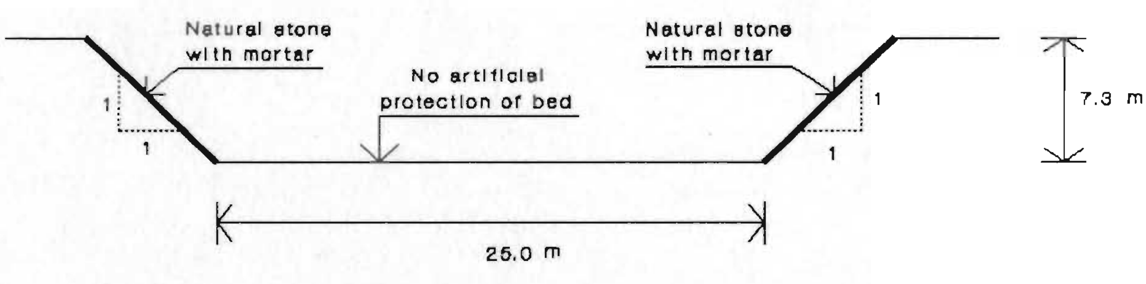


Figure 1.3. Typical cross-section of the proposed diversion channel.

Table 1.1. Summary of Diversion Channel Characteristics

Description	Remark	Description	Remark
Design discharge	311 m^3/s	Bottom width	25 m
Channel shape	trapezoidal	Water depth	5.6 m
Bed slope	0.00032	Free board	1.7 m
Side slope	1V : 1H	Channel length	7131 m

Kemuning Diversion Channel proposed by CV.HIDROS did not include any analysis of possible future channel changes caused by sediment budget imbalances. Such imbalances, if severe, could affect the long term hydraulic capacity of the diversion. Specifically, the water surface elevation in a given reach and for a given water discharge might exceed the height of the banks. In connection with the analysis of possible changes in cross-sectional geometry, data such as discharge records, sediment concentrations, soil properties, channel cross-sections and the channel long-profile were required. These will be discussed in more detail in the next section.

1.2 Available Data

Flow records consisted of 20 years of mean daily discharge. These were obtained at the Pangelen hydrometric station, located approximately 2 km upstream of the area under consideration. Stage measurements were continuously made at this site by the OIS for the province of East Java. For this study, these records were assumed to represent the flow coming from the Kemuning River basin because the station is relatively close to Sampang, being located only 12 km upstream of Sampang. There are no intervening tributaries. The river basin has an area of 345 km^2 and a length of 44 km.

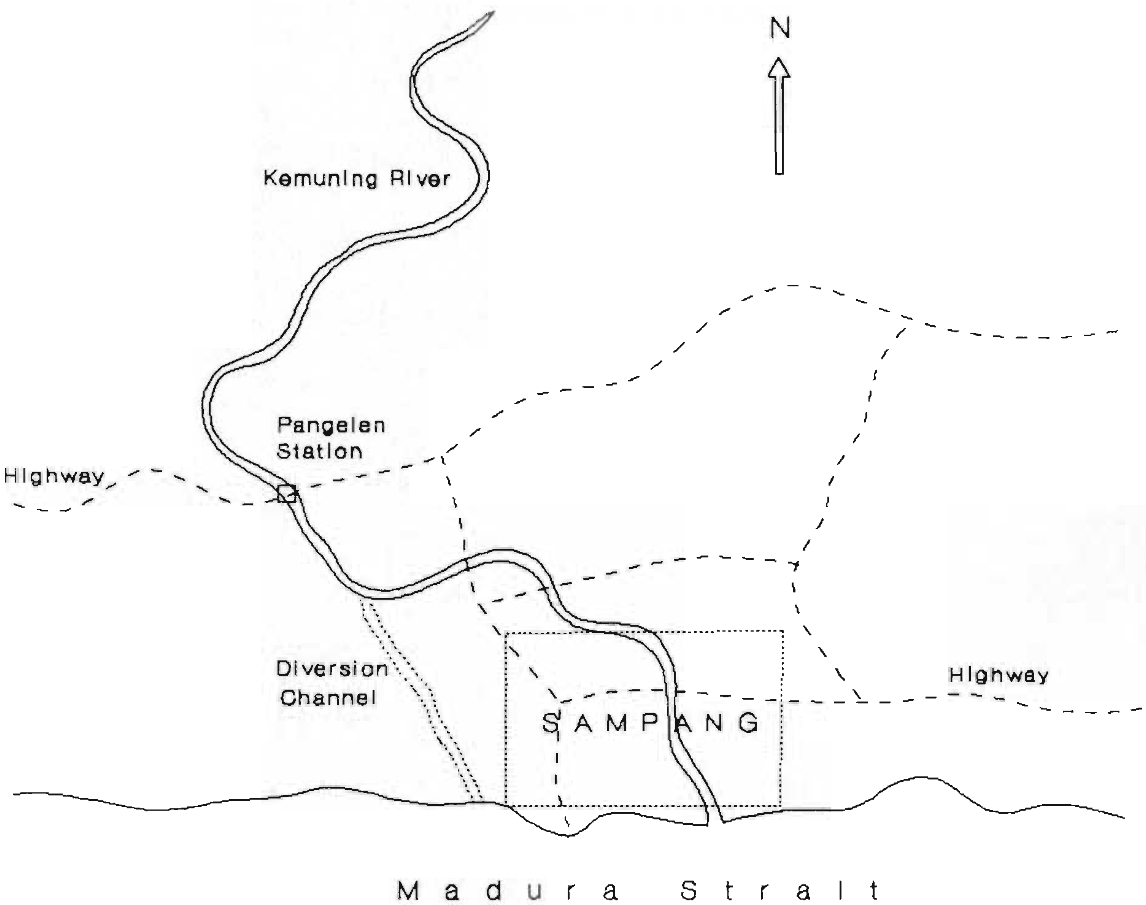


Figure 1.4. Plan view of proposed diversion channel.

Limited sediment concentration records were available. These consisted of six months of daily instantaneous suspended sediment concentration data at the Pangelen station for the period January 1989 to July 1989, inclusive. Although the suspended sediment record was very short, the period sampled did include the two seasons which characterize the Indonesian climate, the dry season and the wet season, ranging from May to October, and from November to April, respectively.

Soil characteristics were investigated in and around the proposed diversion channel. The subsurface investigation was carried out by making borings from which soil samples were recovered for identification and testing. The results of this investigation were available from CV.HIDROS. In addition to this data, the vane shear strength of the soil was directly investigated by this writer in and around the proposed channel. Details on the soil characteristics will be presented in Section 4.

1.3 Objectives of the Study

As previously mentioned, the analysis of the proposed Kemuning Diversion Channel did not consider possible erosion or deposition of the banks and bed of the channel. These might be expected to occur over a long time span. Therefore, the main objective of this thesis was to evaluate possible channel changes associated with a relatively long period of operation.

Two approaches were considered in the context of this evaluation. These were the inductive and deductive approaches. The inductive approach involved regime theory, and the deductive approach involved a mobile bed mathematical model of the channel bed, specifically developed for this research. This thesis emphasized application of the deductive approach. The results of these investigations led to recommendations pertinent to the final design of the Kemuning Diversion Channel.

2. DESCRIPTION OF STUDY AREA

2.1 Location of Study

The Kemuning River basin is about 90 kilometers east of Surabaya, the provincial capital of East Java. The region lies between 7.2° to 7.3° south altitude and 113.2° to 113.4° east longitude. The relief is between 4 and 200 m above sea level. Before flowing into the Strait of Madura, the Kemuning River passes through the city of Sampang, which is located about 2 kilometers from the sea. The planimetric area of the region which is routinely subjected to flooding is about 300 ha. Therefore, in order to lessen the consequences of such floods a design for the bifurcation of the Kemuning River has been proposed at a site 7 kilometers upstream of the city. The resulting diversion channel would be built outside of the city and ultimately reach the strait of Madura, as shown in Figure 1.4. To the north the Kemuning River Basin is bounded by the Tanggulangin mountain range, while on the west it shares a boundary with the Klampis River basin. The eastern boundary is the Selo River basin, and the southern boundary is Madura Strait, into which the Kemuning River flows.

2.2 Topography and Land Use

The Kemuning River basin consists of both lowland and upland areas. The lowland area is on the coast of Madura Island and includes some urban areas. The elevation of the lowland region ranges from 4 meters to 25 meters above sea level. The middle region and the upper regions together comprise an upland area which has elevations ranging from 25 meters to 200 meters. The headwaters of the Kemuning River originate in the Tanggulangin mountain range, in which the highest elevation is 200 meters. The average ground slope of the Kemuning River basin is approximately 25 %. It consists of four sub-basins, as shown in Table 2.1 and Figure 2.1.

Table 2.1. Sub-basins of the Kemuning River basin

No	Sub Basin	Area (km^2)	Length of river (km)	Average width of river (m)
1.	Suren	93	8	10
2.	Serpong	97	10	14
3.	Kelokot	88	12	16
4.	Gn.Maddah	67	14	18

Although the steeply sloping terrain is not well-suited to agriculture, the people inhabiting this basin still pursue a predominantly agrarian-based livelihood. For this reason the Kemuning River basin shows evidence of poor soil conservation and a high degree of deforestation. Agriculture occupies the greatest percentage of land use in this basin, as can be seen in Table 2.2. The land is usually prepared in the wet season for rice paddies and in the dry season for dryland crops such as maize, peanuts, red beans, soybean, cassava and tobacco.

Table 2.2. Land use in the Kemuning River basin

No	Type of land use	Percentage (%)
1.	Agricultural area	75
2.	Forest	20
3.	Residential area / others	5

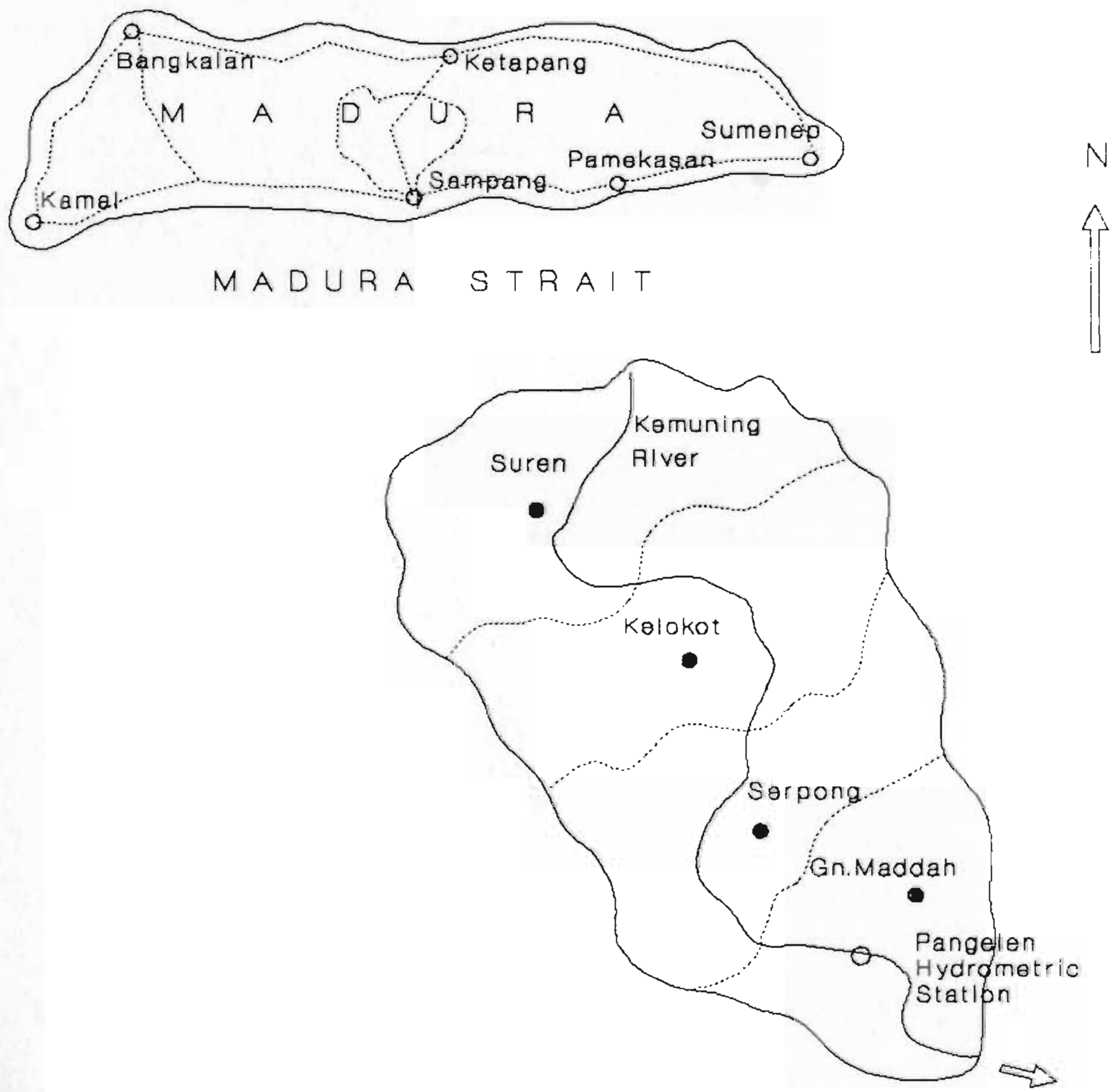


Figure 2.1. Kemuning River sub-basins.

2.3 Climate and Hydrology

A previously discussed, the climate of the Kemuning River basin is tropical. Both the wet and dry seasons are affected by the monsoon cycle. Two types of wind blow during the year. During the months of May to October, a southeast wind blows and shifts direction at the equator. Before reaching Indonesia, this wind passes over the Australian desert and thus carries less moisture, bringing the dry season. By contrast, from November to April, a northwest wind blows, again shifting direction at the equator. This wind picks up a considerable amount of moisture when passing over the South China Sea, bringing the wet season.

The average annual rainfall in the Kemuning River basin ranges from 900 mm to 2400 mm. Annual hydrographs of daily mean discharges for years with reference to wet season and dry season are shown in Figures 2.2, 2.3, 2.4. The following characteristic discharges were based on a flow duration curve based on daily mean flows over twenty years of record (OIS), and on the design flood of the Kemuning Diversion Channel done by CV.HIDROS.

Flow exceeded 1% of time:	60.4 m^3/s
Flow exceeded 30% of time:	6.5 m^3/s
Flow exceeded 50% of time:	4.1 m^3/s
1 in 2 year flood:	160 m^3/s
1 in 20 year flood:	369 m^3/s
1 in 100 year flood:	499 m^3/s

There is only a small variation in solar radiation through the year. During the

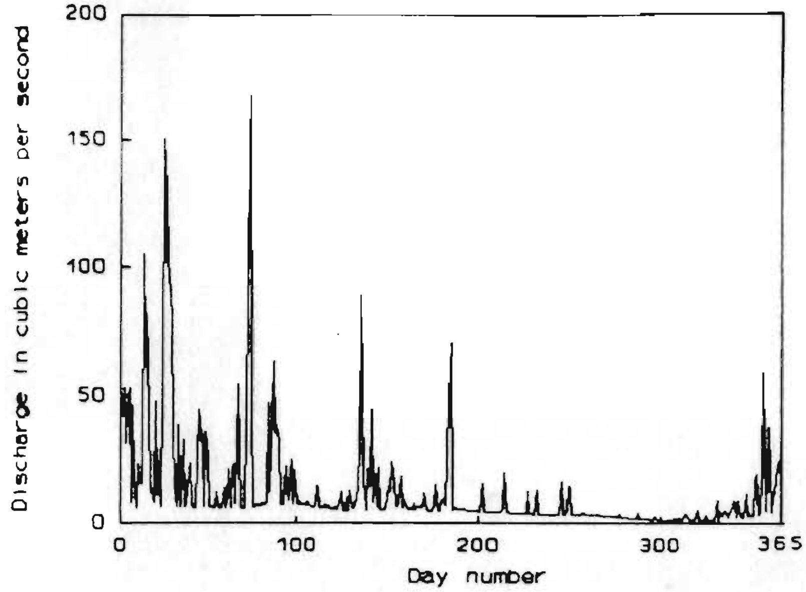


Figure 2.2. Typical hydrograph for a high annual runoff, 1978.

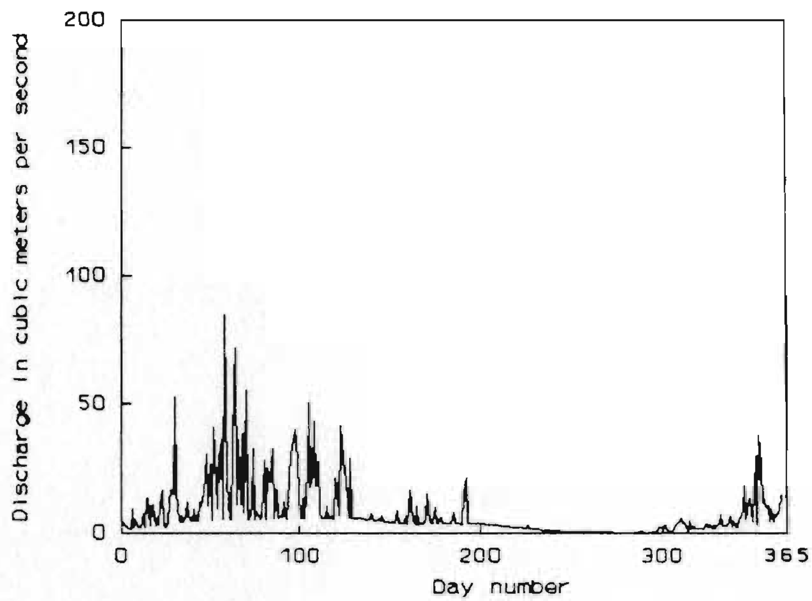


Figure 2.3. Typical hydrograph for an average annual runoff, 1962.

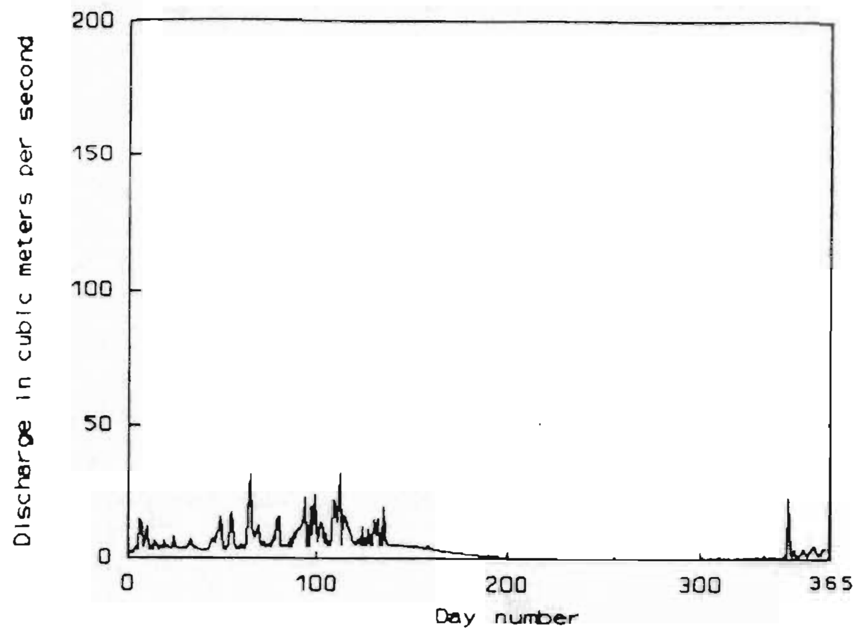


Figure 2.4. Typical hydrograph for a low annual runoff, 1961.

dry season, solar radiation intensity increases, and gradually decreases during the wet season. On average, the ratio of actual to maximum possible sunshine hours is 60 %. In connection with this, daily temperature and humidity fluctuate over the year, with annual averages at 27° C and 86% respectively (Department of Transportation, 1989). Evapotranspiration does not show significant seasonal variation. The average evapotranspiration rate is 3.5 mm/day.

2.4 Sediment Sources

The continuing development of agricultural areas in the Kemuning River basin has accelerated the process of erosion. The primary moving agent of the eroded materials is water, mostly from rainfall. During the wet season, the river flow tends to exhibit a yellowish colour, which indicates a relatively high sediment concentration, while in the dry season the river flow is fairly clear, which is indicative of low sediment transport. This tendency suggests that the fraction of sediment flowing in the river which can be ascribed to the catchment area is relatively high. This high sediment input is aggravated by the soil characteristics of the Kemuning River basin, which consist mainly of fine sand. This soil is very loose and is easily eroded by the flow of water. Based on this writer's experience as an official of the Office of the Irrigation Service for the province of East Java, it is surmised that most of the sediment load of the Kemuning River comes from the catchment area, with as much as 40% - 50% of the sediment being in suspension.

3. LITERATURE REVIEW

The design of an artificial channel is usually based on a single relatively fixed value of water discharge. In natural channels, however, the discharge varies in response to rainfall events which vary both spatially and temporally. The channel geometry adjusts itself in response. The questions of channel stability, optimum cross-section, and the rate of geometric change are relevant to the design of an earth channel.

One method commonly used to evaluate channel geometry "is based on the premise that an observable condition represents events whose recurrence is predictable according to certain mathematical formulae" (Richards 1982). Such a method investigates empirically the possibility of the relationship between the conveyed discharge (of water and of sediments) and the established channel geometry in the soil material by analyzing available data. This method is called the *inductive* or black-box approach. Regime theory makes use of this approach. The second method is based on theoretical considerations which seek to identify the fundamental causal mechanisms involved. The possible relationship between the channel geometry and the discharge is obtained analytically in a rational or physical way by analyzing available data. This method is sometimes called the *deductive* approach. Recently developed mathematical models (HEC-6, MOBED, 1-D SED) of movable bed rivers are examples of this approach.

3.1 The Inductive Approach

The inductive approach is concerned with the concept of a regime flow. This concept is based on an empirical approach to data analysis, particularly to field data, in order to determine relationships between the parameters under consideration. A channel which is designed using relationships of this kind is intended to be stable and capable of avoiding velocities which lead to scour or silting. In order to accomplish this, data have been collected from channels whose water and sediment discharge are in equilibrium and which therefore have no erosion and deposition. The hydraulic relations are generally expressed by three independent equations in terms of width, depth, and slope, respectively. These equations make up the principle components of what is known as regime theory. In the following paragraphs some examples of regime theory will be presented.

Kennedy (1895) pioneered the development of regime theory. He formulated his classic empirical equation (Table 3.1) after rationalizing data which was collected from canals in the Punjab of India. Kennedy thought that canals designed using his equation would have velocities that would not promote either erosion or deposition. However, Kennedy did not characterize the typical channel section as wide-shallow or narrow-deep. This limitation became the subject of much discussion.

Lindley (1919) stated that "the dimensions, depth, width and gradient of a channel to carry a given supply loaded with a given silt discharge are all fixed by nature." He developed a set of empirical relations based on data which was collected from India and Pakistan and which consisted of water surface width, vertical depth and slope. In addition to adjusting the coefficient and exponent of Kennedy's equation, Lindley postulated other hydraulic relations based on these data (Table 3.1). In this way, he was able to more thoroughly express the three empirical equations of regime theory. His equations implied that each channel falling within the regime criteria had a single solution. For a given water depth, channel dimensions could be designed to convey water and sediment discharge such that they caused neither erosion nor deposition. However, Lindley did not mention how a channel was fixed by nature, nor how to apply his equation if the channel being designed varied in both bank and bed conditions; for example, alluvial beds and banks that were either rigid or contained residual soils. This stimulated further contributions to regime theory.

Lacey (1930) reanalysed a set of data which had been studied previously by Kennedy and Lindley, as well as additional data which he collected (Stevens and Nordin, 1987). Lacey expanded his equations and introduced the idea of the interrelatedness of

Table 3.1. Some early regime equations

Kennedy (1895)	Lindley (1919)	Lacey (1930)
$Vo = 0.55\ D^{0.64}$	$V_o = 0.57\ D^{0.57}$	$P = 4.84\ Q_w^{1/2}$
	$V_o = 0.28\ W^{0.36}$	$R = 0.47\ Q_w^{1/3}\ f_L^{-1/3}$
	$W = 7.2\ D^{1.61}$	$V_o = 0.44\ Q_w^{1/6}\ f_L^{1/3}$
		$S_o = 0.0003\ Q_w^{-1/6}\ f_L^{5/3}$
		$f_L = 1.76\ d_{50}^{1/2}$
		$n = 0.022\ f_L^{0.2}$

V_o: Non-silting velocity, m/s

D: Water depth, m

W: Channel width, m

P: Wetted perimeter, m

Q_w: Water discharge, m^3/s.

R: Hydraulic radius, m

S: Bed slope

f_L: Lacey's silt factor, $mm^{1/2}$

d_{50}: median grain size, mm

sediment transport in regime theory, as expressed by a so-called "silt-factor". His equations (Table 3.1) were useful for design purposes because each dependent variable was represented as a function of the water discharge and/or the silt-factor. For a given design discharge and a mean grain size, a channel cross-section free from scouring and silting could be sized. In introducing his equation, Lacey also used a Manning-type resistance equation and his analysis showed that slope was explicitly dependent on sediment grain size, but inversely related to water discharge. Other characteristics showed that the wetted perimeter was independent of the slope, that the hydraulic radius varied with discharge but was inversely related to grain size, and that the velocity was dependent upon discharge and grain size. However, Lacey neglected the rate of sediment transport but introduced instead a silt factor which was proportional to the grain size. Consequently, all geometrically similar canals which had identical velocities had to have same rate and size of sediment transport. This differs from general experience with canal performance in field conditions. Lacey (1930) correlated his silt factor to Manning's n coefficient, $n = 0.022\ f_L^{0.2}$. This condition shows that Lacey's equations are restricted to canals which have n values similar to those values for the canals studied by him. As a further extension, many regime theories have been developed with reference to Lacey's equations. Some later theories have adjusted his original formulation.

Blench (1952) suggested that Lacey's silt-factor be modified by making a distinction between the bed and bank effects on channel adjustment. As a further development, Blench (1969) used field data taken from the same area as Lacey's study and combined this with laboratory data. He considered sediment concentration in his equation (see Table 3.2) and both bank and bed factors were taken into account separately. Blench concluded that his equations were more generally applicable than Lacey's and had greater flexibility than other regime theories because in addition to the field data, the laboratory data supported his equations. However, Blench did mention that his equations were limited to *bed* load concentrations of less than 100 mg/L, and that they were "unreliable" for concentrations greater than 200 mg/L. His equations are also sensitive to the equation which is used to calculate bed load (C_b). Therefore, Blench still recommended field investigations of a given channel reach, and careful determination of both the bank and bed factors when using his equations.

Stevens and Nordin (1987) reexamined Lacey's silt factor from the point of view of the principle of the conservation of mass and on Newton's law of action and reaction. They found that Lacey correlated his silt-factor to channel roughness by using a Manning/Chezy-type resistance equation, with Chezy's C coefficient calculated by the Ganguilet and Kutter equation. In fact the silt factor must be related to sediment concentration. Stevens and Nordin proved that two different silt-factors result from Lacey's equations. The first one (f_{VR}) was obtained when calculated using the equations in terms of velocity and hydraulic radius. The other silt-factor (f_{RS}) was obtained using the equations in terms of hydraulic radius and slope. To compensate for this inconsistency, Stevens and Nordin (1990) developed a formulation based on sediment concentration, in conjunction with the original silt-factor, and proposed a new set of regime equations (see Table 3.2). Their equations are of practical use if sediment concentration data are available. Stevens and Nordin recognized that their equations still have limitations, however: namely, cohesionless sediment sizes between 0.1-0.3 mm, sediment concentrations less than 100 mg/L, and flow velocities ranging from 0.15 to 0.75 m/s.

Application of Lacey's (1930), Blench's (1969), and Stevens and Nordin's (1990) equations are presented in Appendix B.

Table 3.2. Some relatively recent regime equations

Blench (1969)	Steven and Nordin (1990)
$W_o = (F_b/F_s)^{1/2}\ Q_w^{1/2}$	$P = 4.84\ Q_w^{1/2}$
$D = (F_s/F_b^2)^{1/3}\ Q_w^{1/3}$	$R = 2.11\ Q_w^{1/3}\ C^{-1/3}$
$S_o = \dfrac{F_b^{5/6}\ F_s^{1/2}\ \nu^{1/4}}{3.63\ g\ Q_w^{1/6}\ (1 + C_b/2330)}$	$V_o = 0.0983\ Q_w^{1/6}\ C^{1/3}$ $S_o = 1/6{,}050{,}000\ Q_w^{-1/6}\ C^{5/3}$
$F_b = 0.58\ d_{50}^{1/2}\ (1 + 0.012\ C_b)$	$A = 10.2\ Q_w^{5/6}\ C^{-1/3}$
F_s = 0.009 (sandy loam) to 0.028 (clay loam)	
$F_s = F_b^2/8$ (gravel-bed rivers)	

W_o: Average of channel width, m F_s: Blench's side factor, m^2/s^3

D: Water depth, m ν: Kinematic viscosity, m^2/s

S_o: Bed slope C_b: Bed load concentration, mg/L

F_b: Blench's bed factor, m/s^2 C: Sediment concentration, mg/L

3.2 The Deductive Approach

An open channel may be considered to be bounded by a non-rigid boundary that can be eroded and transported by flowing water. For any given water discharge, the flow depth will depend on the final adjusted boundary geometry, which is itself dependent upon the value of the given discharge. In response to discharges which vary over relatively short periods of time, channel form tends to remain constant. However, among these varying discharges there has been found a certain range of discharges which manifests the same results as the morphological processes involved in channel formation. This discharge is known as the dominant discharge (Richards 1982). The magnitude of this discharge is much affected by cross-sectional characteristics, such as size and shape. The dimension of cross-sections which are related to the dominant discharge are considered to be located at the bank elevation where overtopping occurs. This is known as a "bankfull" cross-section. For this reason, the dominant discharge usually refers to the bankfull discharge. To estimate this discharge it is necessary to select a representative bankfull cross-section. This usually differs along the channel in accordance with the top of bank elevation. The stage-discharge relationship is then investigated, and the dominant discharge can be calculated. The estimation of this discharge is therefore greatly affected by the accuracy of the determination of the bankfull cross-section. In terms of the return period, its frequency may be different from river to river due to differences in channel and river-basin characteristics, but some investigations have shown that the return period for the dominant discharge ranges from 1 to 2.33 years (Richards 1982).

Hydraulic relations for the condition of equilibrium can be successfully expressed for certain classes of alluvium and sediment concentration by regime theory. Three independent equations relating to the dimensions of width, depth and slope result from this approach. However, regime theory does not consider the adjustment that the channel undergoes due to both hydrological processes and possible sediment transport imbalances. This adjustment process can be predicted mathematically (Dawdy and Vanoni 1986). An analytical solution to the problem of geometric change can be estimated using detailed computations of the flow profile, the sediment transport, and the resistance of the sediment material which forms the flow's boundary. Because of the variety of factors and the time scale involved, the rate of change in the boundary geometry is generally difficult to study in the field. For this reason, many mathematical simulations using mathematical models have been developed. Some examples of the mathematical modelling of movable bed rivers will be described in the following paragraphs. The first are HEC-6 and Fluvial 12, which are coupled models, and the second is Pickup's model which is an uncoupled model. *It is noted that deductive models in which n is adjusted within the model, based on the flow regime, are known as coupled models. Models in which changes in flow regime (usually indicated by the Froude number) do not result in* *a change in n are known as uncoupled models.*

HEC-6 is a computer program package for evaluating scour and deposition in rivers and reservoirs developed by the Hydrologic Engineering Centre, United States Army Corps for Engineers in Davis, California. This program is a one-dimensional model which describes the longitudinal bed profile, longitudinal free surface profile and sediment transport as a function of time and hydraulic flow conditions. The model was originally developed by Thomas (1977). In this model, only the *bed* in the channel is considered mobile, while the horizontal location of the channel banks is assumed to be fixed. The hydrograph input is set up as a series of discrete discharges that occur over specified periods of time. Each discharge is considered to be steady over the time interval. The water surface profile is evaluated section by section, using the standard step method, beginning with the downstream section and going upstream, while the sediment calculations work in the opposite direction. The bed material distributions are represented by size fractions. The channel geometry is adjusted by using the sediment continuity equation, and the equilibrium condition is characterized by a water depth with reference to the grain diameter. By entering a discrete discharge, sediment is routed through the model and the channel geometry adjusted. The entire process is repeated for the next discharge. The water surface elevation and changes in the bed elevation are calculated as functions of both location and time. Thomas (1977) concluded that by using this computer program the geometric changes could indeed be estimated for subcritical flows in channels, rivers, and reservoirs, but not for flow in estuaries and tidal channels.

Fluvial 12 (Chang, 1990) is a computer package developed by H. Chang of the University of San Diego. This program can be used for calculating geometric channel changes due to scour and fill for a channel or river. This program is specifically designed for erodible channels. The mathematical formulation consists of a series of components, including water routing, sediment routing, changes in channel width, changes in channel-bed profile, and changes in geometry due to the curvature effect (a special case). Changes in the channel width are associated with increases or decreases in the energy gradient. The *rate* of width adjustment depends on the sediment transport rate, the bank configuration, and bank erodibility. For such cases, Chang (1990) introduced a bank erodibility factor which ranges from 0 for non-erodible banks to 1 for easily eroded banks. In applying the sediment continuity equation the model also considers *lateral* sediment inflow. The distribution of scour and fill across a section is expressed as a power function of the effective tractive force. The exponent in this power function ranges from 0 for a nearly uniform distribution to 1 for a relatively non-uniform distribution. Using his model, Chang found that during aggradation the river channel tended to widen, and during degradation tended to become narrower. He concluded that an alluvial river will adjust to any change imposed on it, whether natural or man made. The adjustment may involve channel-bed aggradation and/or degradation, width variation, and lateral migration of channel bends.

Pickup (1977) also developed a mathematical simulation of river channel changes. Pickup's model describes changes in channel size and shape, as well as in the longitudinal slope. The model performs a sequential calculation, starting with water surface profile, followed by application of the sediment continuity equation, resulting in changes in channel shape and slope. The entire calculation is repeated for the next input of flow and sediment. Pickup developed his model based on the principle of moving sediment-transport-discontinuities which cause either erosion or deposition, or both, and thus lead to changes in channel geometry. To accomplish, this the model changes channel morphology at one end of a given reach. As a result, a sediment transport discontinuity is created, and this causes the addition of, or reduction in, available sediment at a given location in the bed. Pickup found that geometric changes can be developed through sediment discontinuities, called drop elevations or "knickpoints". Pickup's (1977) simulations showed that the changes which occur in the long profile of a channel reach over time may develop as a result of the *retreat* of knickpoints rather than by *rotation* (see Figure 3.1). In his simulations he assumed that the shape and size of the channel cross-section changed systematically with the depth of the incision.

3.3 Erosion of Cohesive Bed Material

Flaxman (1963) evaluated soil resistance under a range of flows by considering soil permeability and shear strength. His evaluation was based on undisturbed soil samples and was intended to evaluate resistance to erosion in the field. The samples tested were taken together with flow measurements under both eroding and stable channel conditions. A regression analysis showed that the unconfined compressive strength increased as permeability decreased and vice versa. By contrast, the dry density, the percentage of particle finer than 5 microns, and the plasticity index showed only

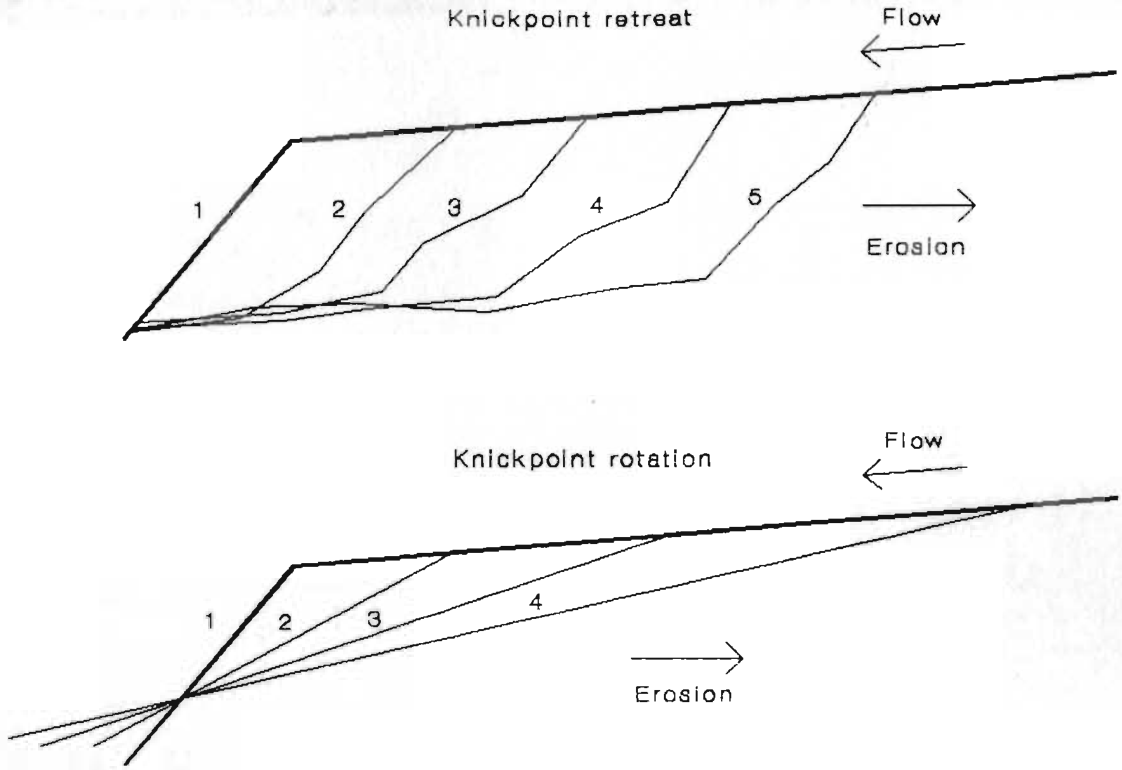


Figure 3.1. Simulated changes in the long profile of an eroding channel with time (after Pickup 1977).

moderate correlation to the unconfined compressive strength. Flaxman found that soils of low permeability and high shear strength showed relatively high resistance to erosion, those of low shear strength and high permeability exhibited less resistance, and those of low shear strength and low permeability were highly dependent upon the permeability characteristics, and therefore might not be stable even under slow flows. However, Flaxman's investigation also indicated that accuracy of prediction was to a large degree dependent on the educational background and experience of the observer in defining each type of channel during soil sampling and flow measurement. For this reason, some soil samples from "stable" channels showed erosion, according to his criteria. It is noted that Flaxman used *non*cohesive criteria in determining the boundary between eroding and non-eroding channels when he plotted his results.

Jaeggi (1986) outlined a method that can be used to analyze shore erosion occurring as a result of a new river mouth at the end of a cutoff. According to Jaeggi's observations of the Reuss River in Switzerland, deposition developed around the new river mouth. To prevent a decrease in canal capacity both the left and right dykes were lengthened into the lake into which the river flowed. This resulted in shore erosion, especially at the shoreline of the old delta, located near the new river mouth. To overcome this problem, Jaeggi (1986) proposed a reduction in the length of the river channel which extended into the lake, followed by the creation of a natural delta. This delta was formed by making river branches in the delta zone such that these branches were directed toward the eroded shore. In this way, Jaeggi expected that a decline in the transport capacity in the former river canal would result in an excess of sediment, which would then flow through the river branches and onto the eroded shore region. According to the interval of time involved, it was predicted that equilibrium would occur between the erosion process and the sediment supply, and a new delta would be created. Jaeggi examined his proposal by hydraulic model testing. The results showed that a natural delta could be created using river branches, and that shore erosion would be halted. However, the success of this design was greatly affected by assumptions about the sediment supply to the river branches, especially of the finer gradations (sand). The sediment sources came from materials from the upstream (eroded) channel and the catchment area. If there was a reduction in the sediment supply rate due to improvement in both the upstream channel and/or catchment area, neither deposition nor establishment of a delta was expected to occur. Instead, erosion was predicted.

Parthenides (1965) investigated the erosion rate of cohesive soil using laboratory flume tests on samples of soil of fine sand, silt and clay, and using water at ocean salinity. Partheniades found that the erosion rate was greatly affected by the hydraulic shear stress but was independent of the suspended (cohesive) sediment concentration and, surprisingly, the shear strength of the bed. He also demonstrated that the critical hydraulic shear stress was not a single value, but was bounded by the condition for eroded materials below which they were deposited, and above which they remained in suspension. Partheniades (1965) found that the bed erosion pattern, which was designated by small, smooth ripples, was a well-defined and relatively straight zone of deep scouring. This pattern did not result in any measurable additional resistance to flow. Cementation of silt and clay on the bed surface did increase erosion resistance, however.

Nicholson and O'Connor (1986) developed a three dimensional model for cohesive sediment transport. This model involved four factors which affected cohesive sediment transport; namely deposition, erosion, flocculation and slump. The model was developed by a numerical solution of the three-dimensional diffusion-advection equation. In application to field problems, the model showed reasonable results, and was considered to be adaptable to a given set of field conditions.

3.4 Special Difficulties

The foregoing discussion has shown that the inductive and deductive approaches to describing mobile bed rivers have limited applicability and cannot cover all possible problems. Several limitations of these methods have created difficulties in terms of their applicability to a particular set of conditions. The following discussion addresses some of these problems.

Regime theory is generally related to so-called independent variables such as width, depth and slope. These are in turn affected by factors such as the flow, the sediment transport rate, and the channel characteristics. The majority of regime equations are supported by limited data which have been collected, for the most part, under special conditions. Most of the data used to develop regime theory originated from canals in the Punjab (India and Pakistan). As a result, such equations might be unsuitable for application to locations other than those in which the particular formulation was developed. As previously discussed, each regime equation was derived using different considerations and assumptions, even though nearly the same data was used. This has resulted in different equations having different limitations, limitations which should be considered before applying any given regime equation. The most important assumptions are probably those pertaining to the rate of sediment *supply*, cohesiveness of the banks, and relative constancy of the flow.

Channel geometric changes are clearly sediment-related problems. Unfortunately, the available methods for calculating sediment discharge are far from completely satisfactory because sediment transport and water flow are complex phenomenon difficult to analyze by mathematical formulation. One possible solution is to consider one or more dominant factors which govern the rate of sediment transport. Through laboratory simulation some of these factors have also been investigated. Finally, the various sediment transport equations have been developed using different independent variables. This means that sediment transport equations are suitable for application to conditions similar to those from which the equations were derived. In general, field conditions are difficult to replicate in the laboratory. This problem affects the accuracy of the mathematical modelling of movable bed rivers. The other problem common to many projects is the dearth of data. To cope with this problem, a model was usually calibrated to the observed data or to laboratory tests. Major items which require calibration include the roughness coefficient and the sediment transport equation. In other words, before applying a mobile bed mathematical model to a given situation, its characteristics and limitations should be as fully understood as possible, especially in relation to the site or problem being investigated.

3.5 Summary

The following important points have emerged from the literature survey. The *inductive* approach (historically associated with "regime theory") shows that hydraulic relations can be formulated describing channel geometry for channels in quasi-equilibrium . These formulations are usually expressed in terms of three independent variables: width, depth, and slope. Such equations were generally derived by analyzing the data associated with a particular set of hydrologic and soil conditions, which leads to limitations to their application. Such equations are limited to conditions similar to those from which the formulations were developed.

The *deductive* approach has shown that the channel geometric changes (with certain difficulties) can be modelled using mathematical models. The applicability and accuracy of a given model depends on the degree to which factors affecting the fluvial process also affect model performance. These factors include the principle of continuity of sediment flux, as well as the flow resistance, the degree of bank stability, and the resistance to erosion of the natural bed material. Such models must be calibrated using observed field data, and/or laboratory data.

In this study, various regime equations were applied, but most of the effort was concentrated on developing and applying a mathematical model as an example of the deductive approach. In the following section, these aspects will be discussed.

4. METHOD

4.1 Application of the Deductive Approach

As previously discussed, various mathematical models are available to calculate the geometric changes in a channel. However, all such models have their own limitations, and cannot be applied to all conditions. The soil in and around the area of the proposed Kemuning Diversion Channel was found to exhibit cohesiveness. For cohesive soil, critical conditions of sediment movement are generally proportional to the shear strength of the sediment (Vanoni 1975). For this reason, the mathematical model which was developed in this study, which resembles the 1-D uncoupled model described by Pickup (1977), used a critical hydraulic shear stress as the threshold of initial sediment movement. This section discusses the following components of the mathematical model developed:

1. Input data requirements,
2. Water surface and applied hydraulic shear stress simulation,
3. Mobile bed simulation,
4. Output data.

The first step in the simulation was a sequential calculation of components 2 and 3, and the entire calculation was repeated for each time step of one day. The model was then run at a given level of discharge for the number of time steps appropriate to that discharge, based on the historical flow duration curve and a 20 year period of interest. The model was written in Quick Basic. A flow chart of the computer program is given in Figure 4.1. The listing of the computer program is given in Appendix A.

4.1.1 Input Data Requirements

The computer program was divided into six sub-programs. The input data format was adjusted to suit each sub-program. In order to simplify the program, the data was represented by two types. The first type was included as part of the computer program, and the second type was available as a file on disk. The first type included critical hydraulic shear stress, water discharge, initial channel width, bed slope, Manning's n, sea level, local datum, water properties, soil properties, and suspended sediment concentration. The second type consisted of channel cross-sectional geometry and the distance between sections.

4.1.1.1 Critical hydraulic shear stress

Critical hydraulic shear stress may be defined as the minimum average value of the tractive hydrodynamic force per unit of wetted area which is able to put a single particle of cohesionless sediment (or an aggregate of particles of a cohesive sediment) in motion under critical or threshold conditions. However, noncohesive and cohesive sediments manifest different types of responses to the hydrodynamic forces which act

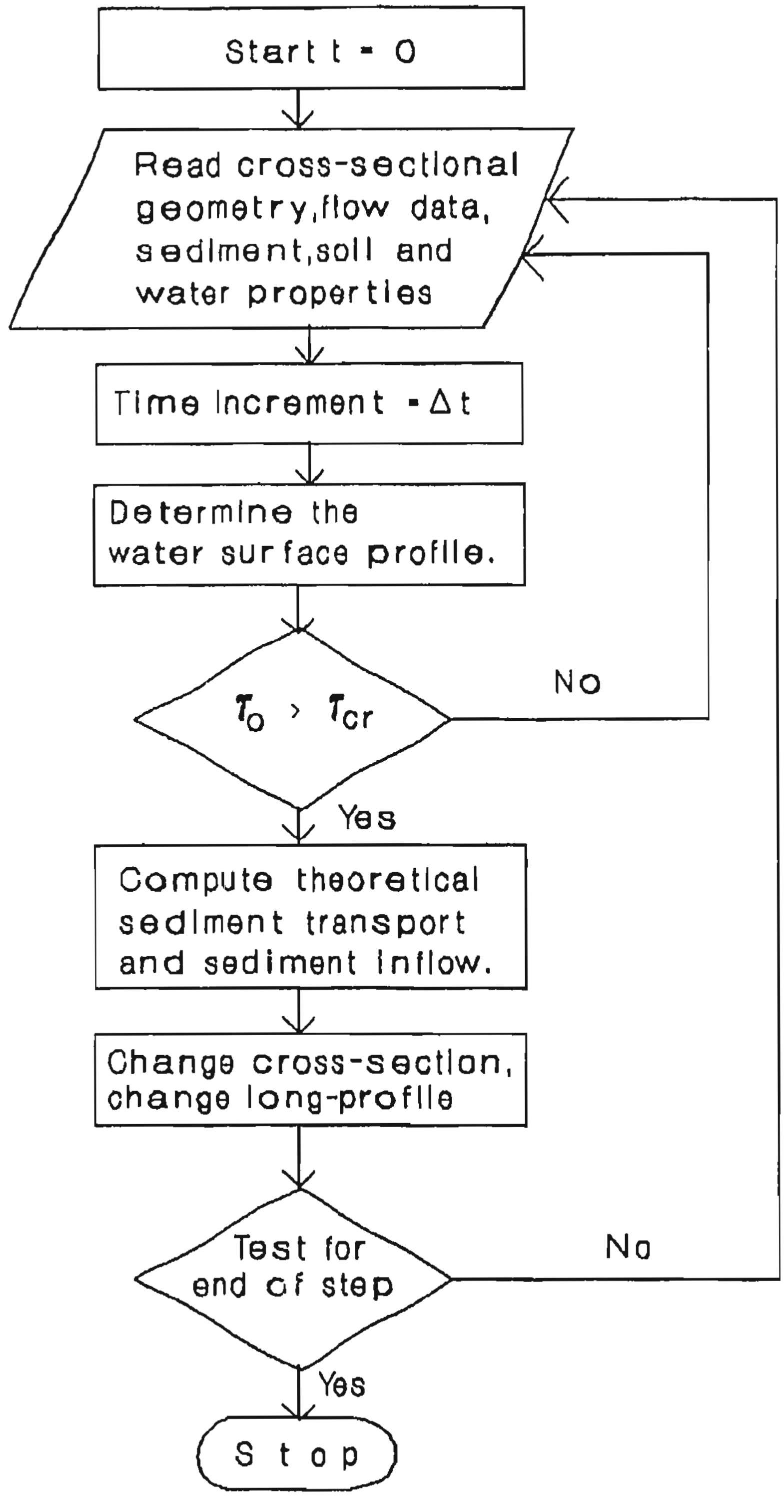


Figure 4.1. Flow chart of computer program developed.

upon them. The ability of noncohesive sediments to resist incipient motion depends on individual particle properties, such as particle shape, size, density, as well as the grain size distribution, the existing sediment concentration in the fluid (related in part to *watershed* supply of sediment), and the relative position or prominence of the particle in relation to other particles (Graf 1984). In general, noncohesive sediments are transported as individual grains. In contrast, the resistance to movement of cohesive sediment depends mainly on the strength of the cohesive bond between particles (Ariathurai and Arulanandan 1978). The process of initial motion initially involves the erosion of the material in the form of chunks, which is followed by its movement as individual grains (Lefebvre *et al* 1985). Furthermore, the critical hydraulic shear stress is usually determined by observation in a laboratory flume test which cannot perfectly replicate field conditions, including details of the turbulence flow and the exact conditions true initial movement in the field (Simons and Şentürk 1976). Hence, the value of such tests for field conditions is limited.

In terms of cohesive sediments, the behaviour of fine sediments which interact with water is a complicated phenomenon and depends on many factors, including the mineral composition and physicochemical environment of the sediment (Chapuis 1986). However, some attempts to examine the critical hydraulic shear stress of cohesive sediments associated with the beginning of sediment motion have been made. Vanoni (1975) has summarized various published criteria regarding the critical hydraulic shear stress for erosion of cohesive materials. Dunn (1959) found the critical hydraulic shear stress to be:

$$\tau_c = 0.001 \ (S_v + 8618.4) \tan (30 + 1.73 I_p) \qquad (4.1)$$

where:

τ_c: critical hydraulic shear stress (Pa),

S_v: soil shear strength using a vane shear device (Pa),

I_p: plasticity index as a percent; argument of the tan function in degrees.

Dunn's equation was based on cohesive sediment samples from several channels ranging from sand to silt clay. Lefebvre *et al* (1985) found that the critical *hydraulic* shear stress was between 3 Pa and 12 Pa for "soft to firm" clays and between 12 Pa and 22 Pa for "stiff" clays.

The soil in and around the area of the proposed Kemuning Diversion Channel (Table 4.1 and Figure 4.2) was found to exhibit properties similar to those studied by Dunn (1959), containing a wide range of material, from sand to silt and clay. Based on a qualitative comparison with soil strengths published by Al-Khafaji and Andersland (1992) it was concluded that this soil could be considered to be a "soft" clay. Table 4.2 shows the results of the application of Equation 4.1, and of the information of Lefebvre *et al* (1985) for the soil under consideration. With reference to these results, the critical hydraulic shear stress of the Kemuning Diversion Channel was considered to be 5 Pa, for the purposes of erodibility considerations in the mathematical model developed.

4.1.1.2 Determination of range of discharges of interest.

The water discharge which would flow into the study reach was summarized in the form of a flow duration curve, based on two decades of daily flow record (see

Table 4.1. Soil data for proposed diversion channel

Property *	Value
Water content W_t (%)	36.59
Dry density ϱ_s (tonnes/m^3)	1.831
Porosity n (%)	51.89
Void ratio e	1.079
Angle repose θ	8
Specific gravity s	2.787
Liquid limit LL (%)	51.49
Plastic limit PL (%)	38.66
Plasticity index I_p (%)	12.83
Mean vane shear strength S_v (Pa) **	2200
Standard Deviation of VSS (Pa)	280
Fine sand content, 0.177 mm (%)	31
Very fine sand content, 0.088 mm (%)	42
Silt and clay content, < 0.062 mm (%)	27

* CV. HIDROS 1990

** average of 6 holes with each 5 point measurements per hole (on site measurement done in Indonesia by the author).

Table 4.2. Estimates of critical hydraulic shear stress

Equation/source	τ_c (Pa)
Dunn (1959)	13
Lefebvre *et al* (1985)	3 - 12

Figure 4.3). In application, this curve was represented as a series of discrete flow levels for various percent-exceedances of interest, as presented in Table 4.3. Using a critical hydraulic shear stress of 5 N/m^2 and mean sea level as the downstream boundary

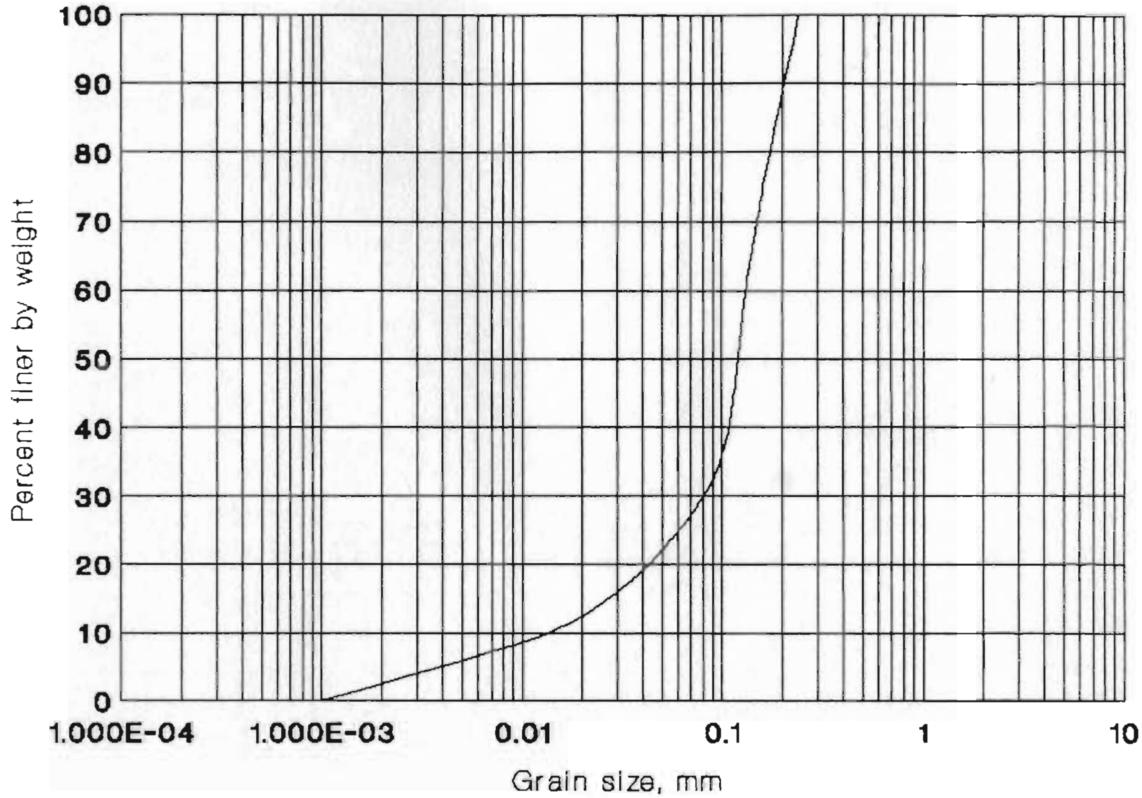
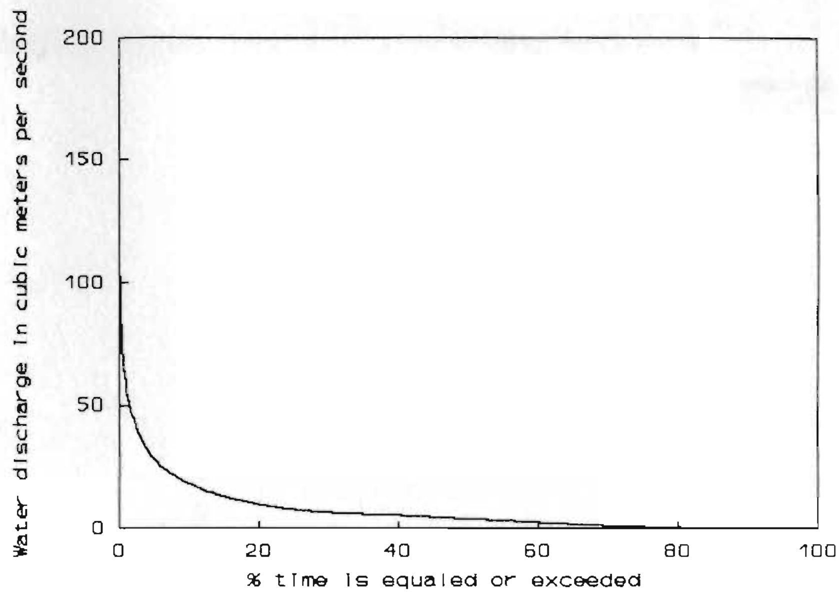
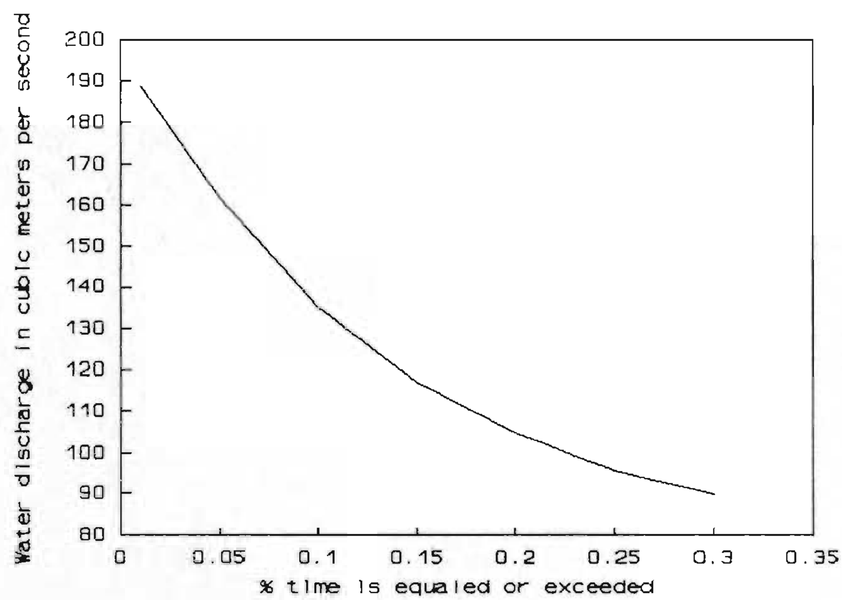


Figure 4.2. Grain size distribution (after CV. HIDROS 1990).

condition, preliminary results showed that erosion would occur everywhere along the channel if the water discharge was greater than 150 m^3/s, and that the channel was stable for all discharges less than 90 m^3/s (Figure 4.4). In accordance with these findings the range of flows used as the primary input data to the hydraulic model were from 90 m^3/s to 188.8 m^3/s (the latter being the maximum flow on record). Six discharges were selected to represent the flows for this part of the flow duration curve and to permit estimation of possible long-term changes in hydraulic geometry. These flows are stated in Table 4.3.



a) Complete flow duration curve.



b) Expansion of flow duration curve for high flows.

Figure 4.3. Flow duration curve based on 20 years of daily mean flow at the Pangelen hydrometric station.

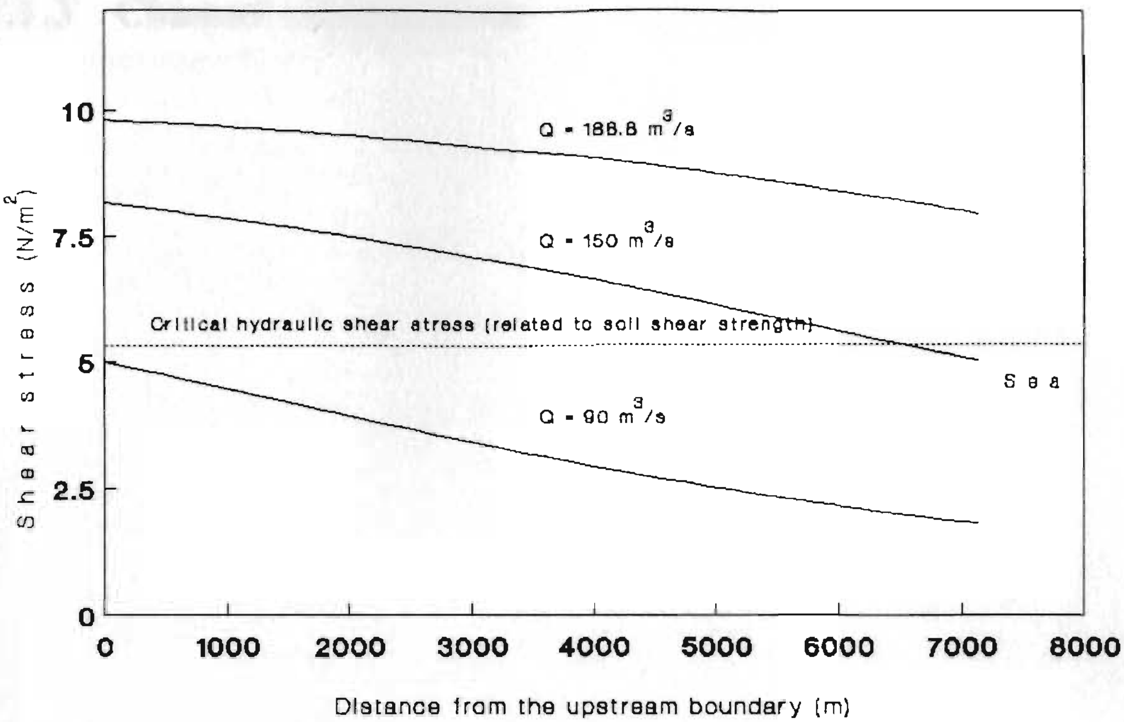


Figure 4.4. Spatial variation in computed hydraulic shear stress.

Table 4.3. Discretization of flow duration curve for the Kemuning River

Q_w (m^3/s)	P_r ($X \geq x$) %	Days in 7092 days *	Mid point of Q_w **	Numbers of day ***
188.8	0.01	1		
159.6	0.05	4	**174.20**	**3**
138.3	0.10	7	**150.45**	**3**
114.8	0.15	11	**128.05**	**4**
101.7	0.20	14	**108.25**	**3**
97.6	0.25	18	**99.65**	**4**
89.9	0.30	21	**93.75**	**3**
			Total	**20**

* 7092 = 20 years

** Used for simulations

*** Used for simulation as numbers of time step

4.1.1.3 Channel cross-sections

The typical cross-section shape for the proposed Kemuning Diversion Channel is trapezoidal (Figure 1.3). For calculation purposes, the channel geometric data used X, Y coordinates (see Appendix D) and were measured with reference to a local origin. The X coordinates had a positive value which increased in a left-to-right direction and the Y coordinates were elevations which were based on a local datum. The value of the Y coordinate increased positively from the bankfull elevation to the channel bottom. For a given water surface elevation the important geometric elements, such as cross-sectional area, wetted perimeter, hydraulic radius, and top width, could then be calculated. The method used to compute the hydraulic parameters is given in Appendix D. By using a series of six points, these calculations were arranged in a computer program and could be developed for any number of coordinate points.

The long profile was represented by the distance of each section to the downstream boundary, denoted section 1 at distance zero (the ocean). There were sixty-five cross sections. The distance between section 1 and section 65 was 7131 meters. A local datum was defined by the bed elevation of the most downstream boundary, namely -4.536 m MSL (CV HIDROS 1990). The Y coordinate increased positively in the direction of the water surface to the channel bottom; hence, the datum was given a positive value of 20.00 m.

For the first time step in the computation, the channel dimensions of the proposed diversion were used as the initial geometric condition. After each time step, the geometric changes were calculated and the new geometry became the condition for the second step. This process was repeated for the necessary number of steps for that particular (discretized) level of the flow duration curve.

4.1.1.4. Rate of sediment inflow to the study reach

The sediment discharge which would flow into the study reach under consideration was summarized in the form of a suspended sediment rating curve, based on six months of daily instantaneous suspended sediment concentration data at the Pangelen hydrometric station. The following formula (Hansen and Bray 1993) was used to compute the suspended sediment rating curve (see Figure 4.5).

$$C = C_f \, a Q_w^b \tag{4.2}$$

where:

$C_f = \frac{1}{n} \sum_{i=1}^{n} 10^{\varepsilon_i}$

ε_i = $\log(C_i) - \log(C)'$,

$\log(C_i)$: $\log_{10}$ of an observation i,

$\log(C)'$: estimated value of log(C) from regression,

n: number of observations = 212

a: constant from regression,

b: exponent of regression.

Q_w: discharge (m^3/s),

C: sediment concentration (mg/L).

Using equation 4.2, the results were:

$$C = 41.0 \, Q_w^{0.53} \tag{4.3}$$

$$Q_s = 3.54 \, Q_w^{1.53} \tag{4.4}$$

where:

Q_s: sediment load (tonnes/day).

The coefficients of the regression were highly significant and from Figure 4.5, the equations developed seem to fit the data points finally well.

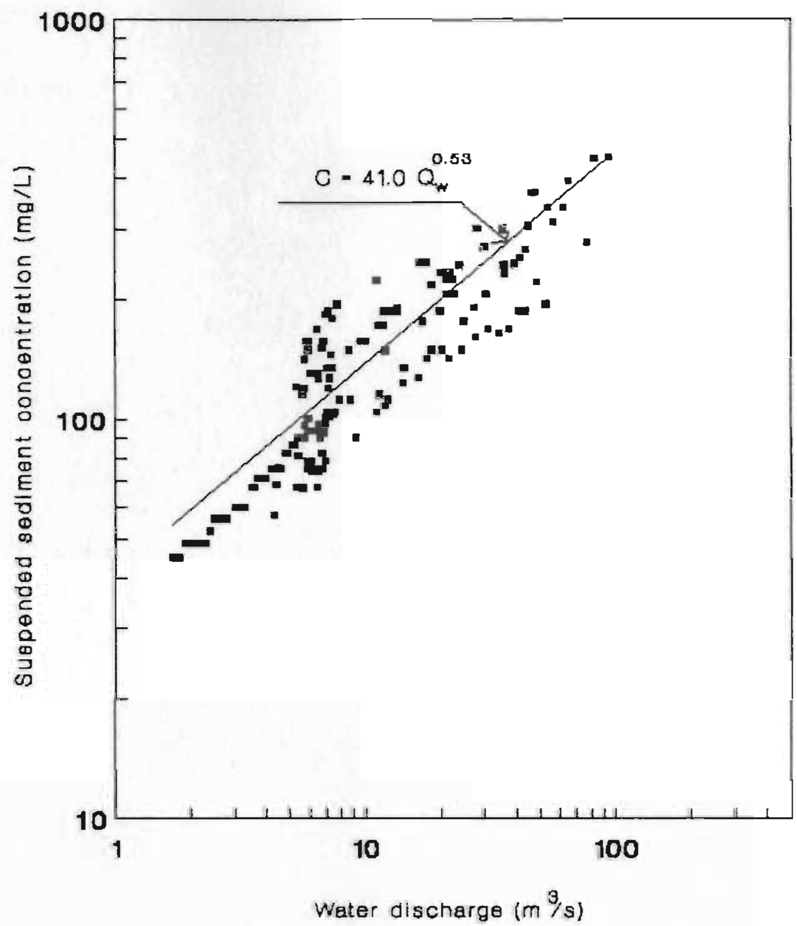


Figure 4.5. Suspended sediment rating curve.

In application, the rate of sediment inflow was accounted for using two assumptions:

1. The river channel upstream of the study reach was stable, and the sediment *demand* at the most upstream study reach was met entirely by the upstream *supply*. In general, this assumption will be satisfactory for relatively large grain sizes in the sediment supply.

2. The river channel upstream of the study reach was stable. The sediment demand at the most upstream study reach was calculated based on an arbitrary fraction of the sediment flux computed using the available suspended sediment rating curve. Based on a heuristic consideration of the land use in the Kemuning River basin, the available soil data in and around the proposed channel, and field observations, this fraction was assumed to be 50 percent. This means that, under this assumed *upstream* boundary condition pertaining to sediment, 50 % of the incoming flux was of such a size that it could interact with the bed in the total study reach. This assumption may be suitable for relatively fine grain sizes. Unfortunately, no information on the grain size distribution of the incoming suspended material was available for this study. Under this assumption, the equation (4.4) reduces to:

$$Q_s = 1.77\, Q_w^{1.53} \tag{4.5}$$

4.1.2 Computation of Water Surface Profiles

Water surface profile computations are a valuable tool in evaluating the hydraulic characteristics of a channel. This evaluation may include problems having downstream variations in water depth due to a fluctuation of sea level (i.e, the downstream boundary condition) and may be extended to consider adjustment in channel shape due to unbalanced sediment transport (Pickup 1977). This study investigated possible channel adjustment based on the water surface profile computation with reference to one particular sea level. The suitable elevation which was considered to represent the sea level over a relatively long period of time was *mean* sea level. The computation of the water surface profile for gradually varied flow was based on numerical solution of the dynamic equation of gradually varied flow. The governing ordinary differential equation for steady gradually varied open channel flow is:

$$\frac{dh}{dx} = \frac{S_o - S_f}{\cos\theta + \alpha\, d(V^2/2g)/dh} \tag{4.6}$$

The most common method of computation of water surface profiles, applicable to either prismatic channels or nonprismatic (natural) channels, is the standard step method (Chow 1959). This method, together with Manning's equation, was the one adopted for use in the present study. The standard step method is solved by determining by successive trials the depth of flow in a given cross-section. The total head at any two sections "1" and "2" are (Figure 4.6):

$$H_1 = dt_1 + D_1 + \alpha_1 \frac{Q_w^2}{2\, g\, A_1^2} \tag{4.7}$$

$$H_2 = dt_2 + D_2 + \alpha_2 \frac{Q_w^2}{2\, g\, A_2^2} \tag{4.8}$$

Equating total energy at section 1 and 2, the equation is:

$$\begin{aligned} H_1 &= H_2 + h_f + h_e \\ &= H_2 + 0.5\, \Delta x\, (\, S_{f1} + S_{f2}\,) + h_e \end{aligned} \tag{4.9}$$

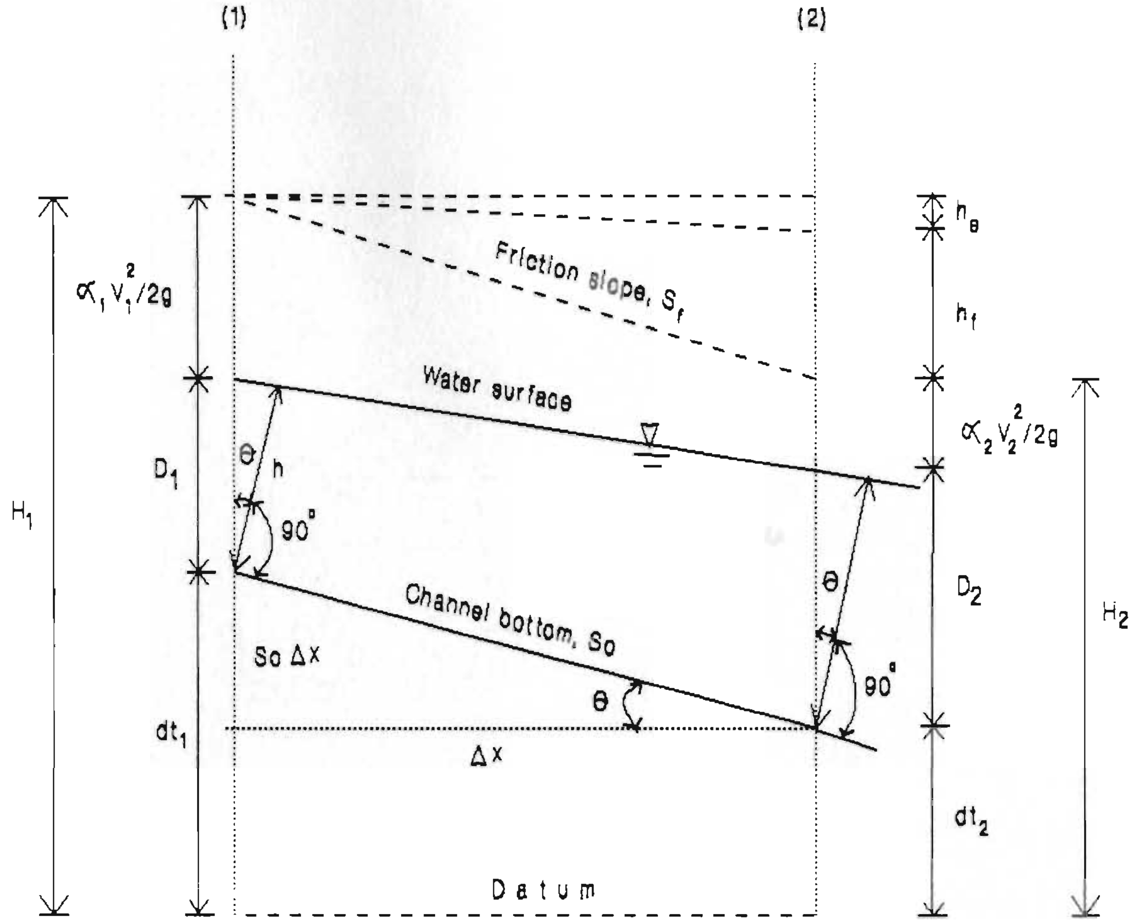


Figure 4.6. Nomenclature for standard step method.

Manning's equation is:

$$S_f = \frac{n^2\ V^2}{R^{2/3}} \tag{4.10}$$

where:

H: total head,

h: depth of flow,

D: vertical depth of flow,

d_t: vertical distance of channel bottom above the datum,

α: kinetic energy coefficient,

V: mean water velocity,

Q_w: water discharge,

A: cross sectional area of the flow,

R: hydraulic radius,

h_f: friction loss,

S_f: friction slope,

h_e: eddy loss,

Δx: length of reach between cross sections,

n: Manning's roughness coefficient,

θ: bottom-slope angle,

g: gravitational acceleration.

The computational procedure was as follows:

1. Calculation of the water surface profile started at section 1 as the downstream boundary (the ocean) and proceeded upstream. Channel dimension of this section was specified to calculate the total head elevation.
2. At the next most upstream section, a trial water surface elevation was used to compute total head using equation 4.7. If this total head was in close agreement with the total head obtained using equation 4.9, the calculation then proceeded to the next most upstream section, and the procedure was repeated.

The energy coefficient α accounts for nonuniform distribution of velocities over the channel cross-section. In general, this coefficient is affected by the shape of the channel section, the channel alignment, the existence of channel bends, and the channel roughness. For relatively straight prismatic channels the energy coefficient tends to be larger for small channels and smaller for large and deep channels. Since the proposed channel is a trapezoidal shape and relatively straight, it may be categorized as a regular channel, and given an energy coefficient equal to 1.15 (Chow 1959). This coefficient was assumed to be constant all along the length of the diversion channel.

The eddy loss is usually calculated as some fraction of the velocity head, and is affected by the existence of expansions or contractions along the channel. The eddy loss is equal to zero if the entire channel is prismatic. Since the proposed design is prismatic the eddy loss was considered to be negligible.

The friction slope was calculated using a rearrangement of Manning's formula, which is actually only valid for uniform flow. This is a very common and well-accepted assumption for flow which is steady (in time) and gradually varied (in depth) in the direction of the long profile (Chow 1959).

The proposed Kemuning Diversion Channel is an excavated channel with a trapezoidal shape, and the soil in and around the channel is comprised of fine sand, silt and clay (see grain size distribution, Figure 4.2). The CV HIDROS company selected a value of Manning's n of 0.025 in their analysis of the diversion. Resistance to flow may be considered to be the sum of the *grain* resistance and *form* resistance (Garde and Ranga Raju 1977). The bed form may change after the beginning of material motion. For fine material less than 0.6 mm, the bed configuration may be ripples (Simons and Richardson 1971; Simons and Şentürk 1976). According to Simons and Richardson (1971),

"Resistance to flow is independent of sand size when the bed configuration is one of ripples because ripple shape is independent of sand size and the effect of grain roughness is small relative to the form roughness. Thus, there is a relative roughness effect produced by the ripple bed."

Simons and Richardson's investigation found that flow over ripples were associated with Manning's n values of between 0.018 to 0.3. Therefore, the use of constant n-value may not be reasonable to compute the estimated channel change for long term periods of interest. However, in order to limit the scope of this study to manageable proportions, and due to the lack of time to include the many factors affecting the n-value, a range of Manning's roughness coefficients was not considered in this model, and it its value was assumed to be constant for the period time of interest (20 years).

4.1.3 Computation of Geometric Changes

An artificial diversion channel will experience fluctuations in the supply of water and sediment such that water and sediment imbalances may occur, resulting in erosion or deposition. Because of these processes, channel geometry will adjust until a new equilibrium is reached. The rate of geometric change depends on the relative erosion and deposition rates, which actually occur in a three-dimensional pattern due to secondary currents. Simulation of this three-dimensional phenomenon is extremely complex (Chiu and Chiou 1986; Yen 1979) and beyond the scope of this study. Even two-dimensional hydraulic models of rivers are rare (Fennema and Chaudhry 1990). The mathematical model which was developed in this study was one-dimensional. Thus, only longitudinal bed profiles, longitudinal water surface profiles, and the 1-D sediment transport as a function of time and flow conditions were modelled. The threshold of sediment motion was the critical hydraulic shear stress. The computation of geometric changes were based on the solution of the equation for the continuity of sediment flux, which assumes that sediment transport is a function of time and the distance along the channel (Pickup 1977):

$$\frac{\partial S}{\partial t} + \frac{\partial Q_s}{\partial x} = 0 \qquad (4.11)$$

where:

S: sediment storage in a given reach,

t: time,

Q_s: Sediment transport rate (units of mass/time),

x: distance along the channel.

Equation 4.11 was expressed in finite difference form between two successive reaches along the channel. The rate of erosion or deposition for each reach at each time step, in a downstream direction, was given by :

$$\frac{\Delta S_i}{\Delta t} + \frac{\Delta Q_{s(i)}/\gamma_s}{\Delta x} = 0 \qquad (4.12)$$

$$\frac{\Delta S_i}{\Delta t} + \frac{(Q_{s(i-1)} - Q_{s(i)})/\gamma_s}{\frac{1}{2}[\Delta x_{(i-1)} + \Delta x_{(i)}]} = 0 \qquad (4.13)$$

$$\Delta S_i = -\frac{2\,\Delta t\,[Q_{s(i-1)} - Q_{s(i)}]}{\gamma_s\,[\Delta x_{(i-1)} + \Delta x_i]} \qquad (4.14)$$

The amount of change in cross-sectional area for each section at each time step was computed using:

$$(1-n)\,\Delta Ab_i = -\frac{2\,\Delta t\,[\,Q_{s(i-1)} - Q_{s(i)}\,]}{\gamma_s\,[\,\Delta x_{(i-1)} + \Delta x_i\,]} \tag{4.15}$$

$$\Delta Ab_i = -\frac{2\,\Delta t\,[\,Q_{s(i-1)} - Q_{s(i)}\,]}{(1-n)\,\gamma_s\,[\,\Delta x_{(i-1)} + \Delta x_i\,]} \tag{4.16}$$

where:

n: porosity of bed material,

Q_s: mass per unit time based on sediment transport rate,

Δt: time step,

γ_s: specific weight of sediment,

i: subscript to indicate cross-section,

$\Delta x_{(i-1)}$: reach length (the distance between section i and the next-most upstream section),

Δx_i: distance between section i and the next-most downstream section,

ΔAb: amount of change in cross-sectional area.

Equation 4.14 describes an *upstream* difference in sediment storage, and is independent of the sediment transport rate at the downstream section. The equation also illustrates the three "stages" of boundary conditions. If the supply rate of the sediment transport $Q_{s(i-1)}$ is greater than the local rate of the sediment transport $Q_{s(i)}$, ΔS_i is positive and deposition occurs. If the local rate of the sediment transport is greater than the supply of sediment, ΔS_i is negative and erosion results. Equilibrium is maintained when both the supply rate and the local erosion rate from the bed (if any) are equal, so that ΔS_i = 0. This means the bed channel is stable. The rate of sediment transport was calculated by using certain sediment transport equations considered appropriate for use with the bed material size distribution in the area of the proposed diversion.

4.1.3.1 Changes of channel shape

The changes in channel geometry and the rate of erosion or deposition are in fact interdependent. Changes in channel geometry, which are caused by erosion or deposition, change the local hydraulic shear stress, which in turn affects the rate of erosion or deposition. In this study, channel cross-sections were assumed to erode or deposit their own material, and the process was considered homogeneous in a given reach. Under this assumption, there are several ways of describing the variation in the cross-sectional area due to erosion or deposition. One is to assume that the channel bed of a given cross-section rises and falls *without* changing the side slope such that erosion or deposition occurs only at the bed (see Figure 4.7a). This assumption requires that the bottom width decreases somewhat for the case of an eroding bed, and increases for a depositing bed. A second is to assume that the bed rises and falls *with* changes in side slope (see Figure 4.7b). Another assumption is that erosion and deposition occur at both the bed and the bank. In such cases that cross-sectional shape remains constant (see Figure 4.7c). There are many factors which affect the nature of this geometric change, including the sediment properties of the bed relative to the bank, the sediment load, and the water discharge flowing through the channel.

The proposed Kemuning Diversion Channel will be maintained by using *bank* protection consisting of natural stone with mortar. Moreover, the soil in and around the proposed channel was found to be cohesive soil, and field observations showed that the Kemuning River upstream of the study reach appears to be in a stable condition (neither eroding nor silting up). In connection with these observations, some reasonable

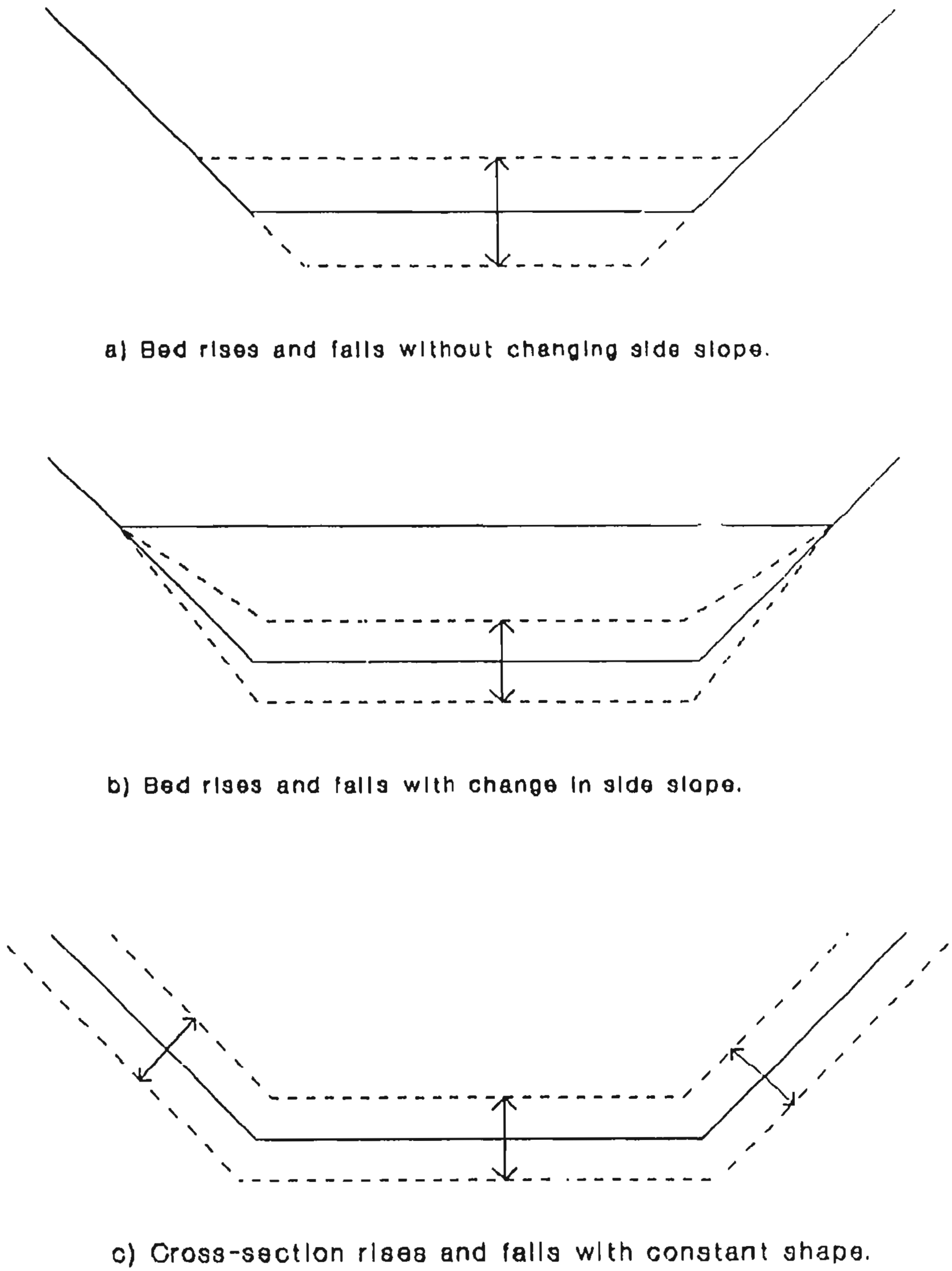


Figure 4.7. Estimation of cross-sectional adjustments.

assumptions were made in order to simulate the changes in channel shape of the proposed design. These are summarized below:

1. During erosion or deposition, the channel *banks* were considered stable. Geometric changes occurred only in the channel bed and the long profile slope.
2. Since the channel alignment was relatively straight (see Figure 1.4), the cross-sections were scoured or deposited homogeneously over any given reach.
3. The formation of an armor layer was not considered.
4. Energy losses due to friction were calculated using Manning's formula. The roughness coefficient was constant, and the energy slope was taken to be an explicit function of the roughness and the other standard hydraulic flow parameters (as opposed to considering possible dune formation, for example).
5. Grain sizes less than 0.06 mm were considered to be wash load, and these were excluded from the erosion and deposition process, being transported to the sea after one time step. This fraction was assumed to be 27 % based on grain size distribution (see Table 4.1 and Figure 4.2). This meant that the aggradation and degradation processes only involved 73 % of the eroded material.

According to these assumptions, the cross-sectional changes (Figure 4.8) for each section at each time step were computed by solving equation 4.16 as:

$$\Delta Ab_i = - \frac{2 \Delta t [Q_{s(i-1)} - Q_{s(i)}]}{(1 - n) \gamma_s [\Delta x_{(i-1)} + \Delta x_i]} \tag{4.16}$$

$$(W' \pm e_t) e_t = \left| \frac{2 \Delta t [Q_{s(i-1)} - Q_{s(i)}]}{(1 - n) \gamma_s [\Delta x_{(i-1)} + \Delta x_i]} \right| \tag{4.17}$$

where:

ΔAb: cross-sectional changes,

e_t: erosion or deposition thickness,

W': bottom channel width resulting from erosion or deposition,

+: representing deposition,

-: representing erosion,

side slope: 45^0.

The channel width and the X Y coordinates which were affected by erosion or deposition were then adjusted to the new dimensions. The bed slope was calculated as the average of the bed slope for each reach.

4.1.3.2 Sediment load

The sediment transport capacity (pertaining to clear water erosion) was computed using two sediment transport equations from the literature. Many equations are available, and all have their own limitations. The soil in and around the area of the proposed channel consists of the fine sand, silt and clay, with a maximum geometric mean diameter of 0.177 mm (Figure 4.2). For this reason, the two methods which were considered to be adequate for computing the bed material load in this study were Yang's method (1972) and Laursen's method (Vanoni 1975; Graf 1984).

Yang's Method

Yang (1972) developed a simple method for the calculation of sediment concentration. He recommended two kinds of equations with reference to the grain size

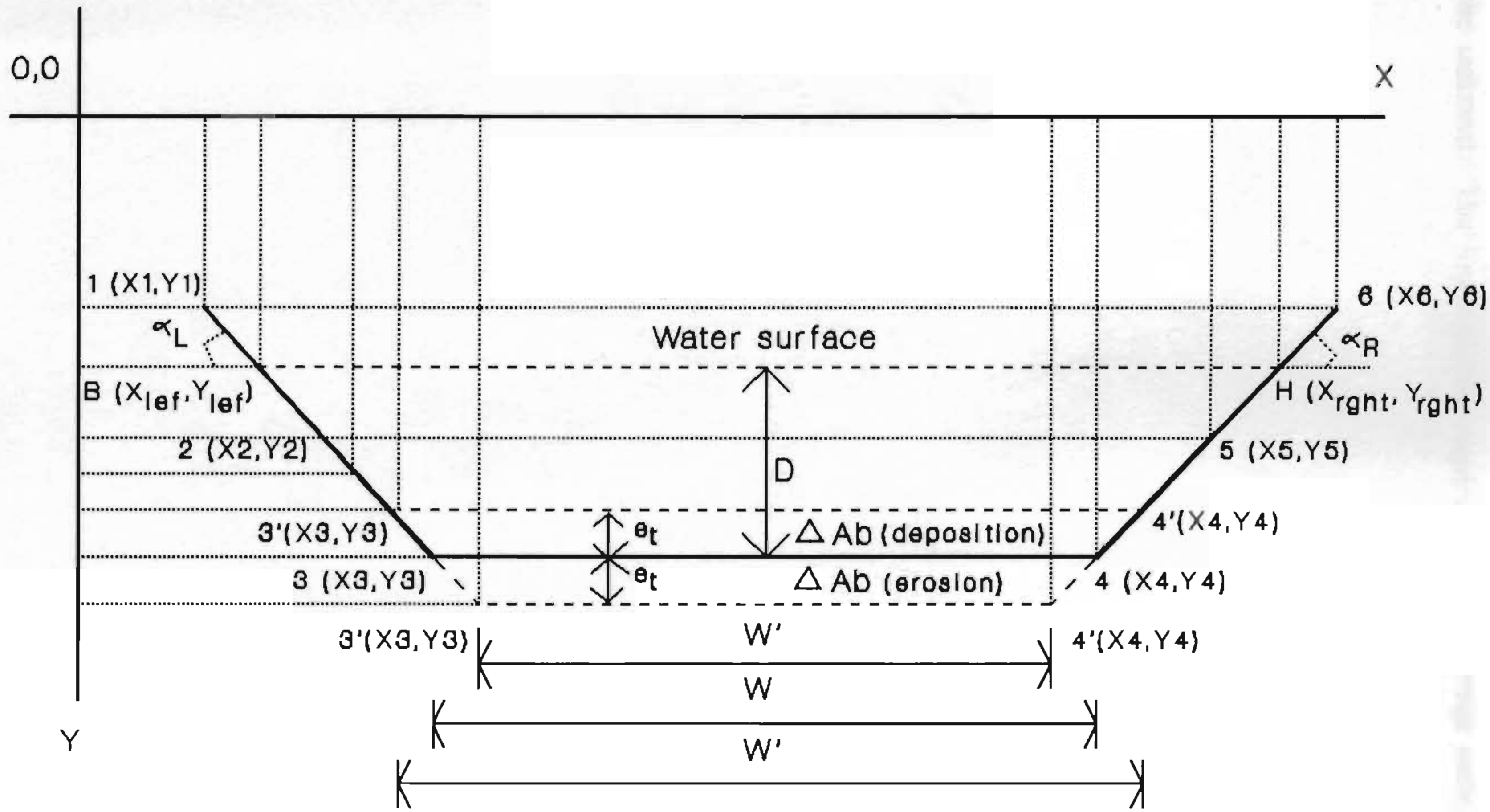


Figure 4.8. Typical changes of a cross-section.

of the sediment. The first equation requires that the average sediment size be less than 2 mm, and the other equation handles sediment greater than 3 mm in mean diameter.

$$\log C_t = (5.913 - 0.255\,\bar{d} - 0.004\,\frac{W}{D}) + (1.257 - 0.005\,\frac{W}{D}) \log (3.281\,V\,S_f) \qquad (4.18)$$

$$Q_s = 0.0864\,C_t\,Q_w \qquad (4.19)$$

where:

C_t: total sediment concentration (mg/L),

$\bar{d}$: average sediment particle size (mm),

W/D: width-to-depth ratio,

V: average water velocity (m/s),

S_f: energy slope,

Q_s: total load (tonnes/day).

Yang developed his equations by analyzing both laboratory flume data and field data of other investigators. Yang (1972) correlated the unit stream power, defined as "the time rate of potential energy expenditure per unit weight of water in an alluvial channel" with the sediment transport, and concluded that his equations can be considered to be quite general. His results showed that there was no significant disagreement between observed and computed sediment concentrations. For this reason, Yang's method was considered suitable for this study, since the sediment size was indeed less than 2 mm (Equations 4.18 and 4.19 have been converted into Système Internationale (SI) units.

Laursen's Method

Laursen's equation (1958) is a total load equation based only on the grain resistance of the bed material. Under this method, it is suggested that the bed material load may be calculated without differentiating between bed load and suspended load because the hydrodynamic forces which result in the motion of bed material and suspended material are identical. At the same time however, Laursen's equation takes into consideration both bed load and suspended load through the parameters included in the equation. Laursen (1958) performed a flume investigation on sediment ranging from 0.011 mm to 4.08 mm. Some field data from small rivers were also used, and good agreement was found. Both the Kemuning River itself and the proposed diversion channel (have mean widths of 18 m and 25 m respectively) may be categorized as "small" rivers. With reference to this condition, as well as to the soil data from in and around the proposed diversion channel, Laursen's method was considered to be a reasonable for application to this study for the calculation of the total load. The following equations (Vanoni 1975) were modified from Laursen's original formulations in order to make them dimensionally homogeneous with any consistent set of units:

$$C_m = 0.01\ \gamma \sum_j p_j \left(\frac{d_j}{D} \right)^{\frac{7}{6}} \left(\frac{\tau_o'}{\tau_{cj}} - 1 \right) f\left(\frac{U_*}{w_j} \right) \tag{4.20}$$

$$\tau_o' = \frac{\rho V^2}{58} \left(\frac{d_{50}}{D} \right)^{\frac{1}{3}} \tag{4.21}$$

$$\tau_{cj} = \tau_{*c} \left(\gamma_s - \gamma \right) d_j \tag{4.22}$$

$$Q_s = 0.0864 \; C_m \; Q_w \tag{4.23}$$

$$w_j = \frac{1}{18\mu} D^2 \left(\rho_s - \rho_w \right) g \tag{4.24}$$

where:

C_m: sediment concentration in weight per unit volume,

Q_w: water discharge,

Q_s: sediment load,

D: water depth,

τ_o': Laursen's bed shear stress due to grain resistance,

τ_{cj}: critical shear stress for particles of size d_j,

U_*: $\sqrt{g R S}$, bed shear velocity,

w_j: fall velocity of particles of mean size d_j in water,

τ_{*c}: dimensionless critical shear stress to be equal 0.039 for sediments ranging from 0.011 mm to 4.08 mm

γ_s: weight density of sediment particles,

γ: unit weight of water,

ρ_s: sediment density,

ρ: water density,

μ: dynamic viscosity,

S: channel slope

g: gravitational acceleration,

d_{50}: median size of sediment,

d_j: particles size of sediment,

p_j: % of sediment of size fraction,

$f(U_*/w_j)$: a function of the ratio of the shear velocity to the settling velocity.

The fall velocity which was calculated by equation 4.24 in cgs units, but C_m and Q_w were in mg/L and m^3/s, respectively, for calculating Q_s (tonnes/day). Both U_* and w_j parameters pertain to the suspended load, and the other parameters directly refer to the bed load. In addition, Laursen assumes that the contribution of each fraction *j* for a given grain size *d* gives the total mean concentration.

4.1.4 Boundary Conditions

Numerical simulation of mobile bed hydraulics requires boundary conditions. In general, there are two types of boundary conditions in modelling problems of this type; the *external* and the *internal* boundary conditions (Cunge *et al* 1986). There are two *external* boundary conditions:

1. The boundary at the upstream end of the reach, in which the water discharge, the sediment load, and river bed elevation are expressed as functions of time.

$$Q_{s(x=0)} = F_1(t) \quad ; \quad Q_{w(x=0)} = F_2(t) \qquad (4.25)$$
$$d_{t(x=0)} = F(t)$$

where:

Q_s: sediment load,

Q_w: water discharge,

t: time,

d_t: river bed elevation to datum,

x: length of reach between sections.

2. The boundary at the downstream end of the reach, in which river *stages* and bed elevations are expressed as functions of time, and in which the stage can be

presented as function of discharge and an imposed downstream water level (in this case, the ocean at MSL).

$$Z_{(x=L)} = F(t) \quad ; \quad D_{(x=L)} = F(Q_w)$$
$$d_{t(x=L)} = F(t) \qquad (4.26)$$

where:

Z: river stage,

d_t: river bed elevation to datum,

D: stage at the downstream boundary,

Q_w: discharge at the downstream boundary.

t: time

There are four *internal* boundary conditions:

1. The boundary condition due to changes in the river cross-section resulting from expansion or contraction. The condition is described in Figure 4.9a. This may be mathematically expressed as:

$$Q_{w(i+1)} = Q_{w(i)} \; ; \; Q_{s(i+1)} = Q_{s(i)}$$
$$Z_{(i+1)} + \frac{V_{(i+1)}^2}{2g} + \Delta H = Z_{(i)} + \frac{V_{(i)}^2}{2g} \qquad (4.27)$$

where:

Q_w: water discharge,

Q_s: sediment load,

Z: river stage,

V: water velocity,

ΔH: expansion or contraction energy loss,

g: gravitational acceleration.

i: subscript to indicate cross-section.

2. The boundary condition due to tributary inflow (see Figure 4.9b). This may be mathematically expressed as:

$$Q_{w(i+1)} = Q_{w(i)} + Q_{wtrib} \quad ; \quad Q_{s(i+1)} = Q_{s(i)} + Q_{strib}$$
$$Z_{(i+1)} + \frac{V_{(i+1)}^{2}}{2g} + \Delta H = Z_{(i)} + \frac{V_{(i)}^{2}}{2g} \tag{4.28}$$

where:

Q_w: water discharge,

Q_s: sediment load,

Q_{wtrib}: water discharge from a tributary,

Q_{strib}: sediment load from a tributary,

i: subscript to indicate cross-section

Z: river stage,

V: water velocity,

ΔH: expansion or contraction energy loss,

g: gravitational acceleration.

In this case, the initial values, Q_{wtrib} and Q_{strib}, must be known or assumed.

3. The boundary condition owing to tributary confluence. This is described in Figure 4.9c.

$$Q_{w(i)} = Q_{wtrib1} + Q_{wtrib2} \quad ; \quad Q_{s(i)} = Q_{strib1} + Q_{strib2}$$
$$Z_{(i)} + \frac{V_{(i)}^{2}}{2g} + \Delta H = Z_{trib1} + \frac{V_{trib1}^{2}}{2g} = Z_{trib2} + \frac{V_{trib2}^{2}}{2g} \tag{4.29}$$

where:

Q_w: water discharge,

Q_s: sediment load,

Q_{wtrib1}: water discharge from the tributary 1,

Q_{wtrib2}: water discharge from the tributary 2,

Q_{strib1}: sediment load from the tributary 1,

Q_{strib2}: sediment load from the tributary 2,

i: subscript to indicate cross-section

Z: river stage,

Z_{trib1}: river stage of the tributary 1,

Z_{trib2}: river stage of the tributary 2,

V: water velocity,

V_{trib1}: velocity at the tributary 1,

V_{trib2}: velocity at the tributary 2,

ΔH: expansion or contraction energy loss,

4. The boundary resulting from a control structure. This is represented in Figure 4.9d, and may be expressed as:

$$\begin{gathered} Q_{w(i+1)} = Q_{w(i)} \quad ; \quad Q_{s(i+1)} = F(Q_{s(i)}) \\ Z_{(i)} = F(t) \dashrightarrow Z_i \textit{ calculated by dam's formula} \end{gathered} \tag{4.30}$$

where:

Q_w: water discharge

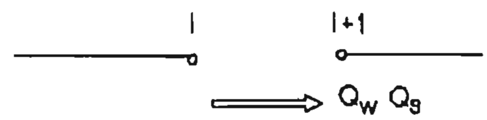
Q_s: sediment load

i: subscript to indicate cross-section

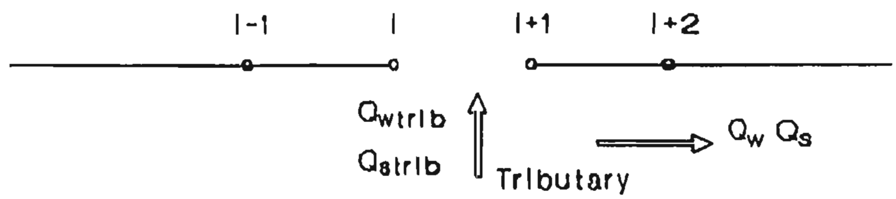
t: Time

Z: river stage

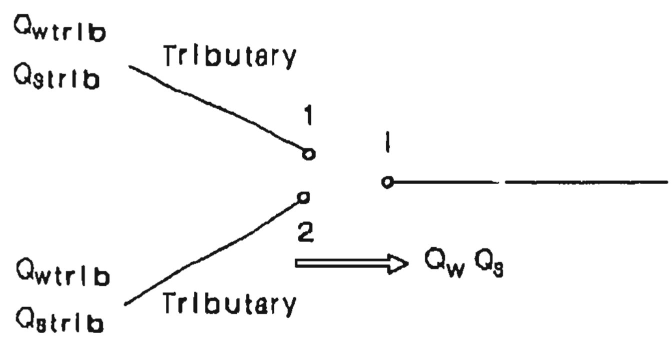
The mathematical model which was developed in this study involved only external boundary conditions because there were no tributaries, expansions or contractions, or control structures which affected the proposed channel.



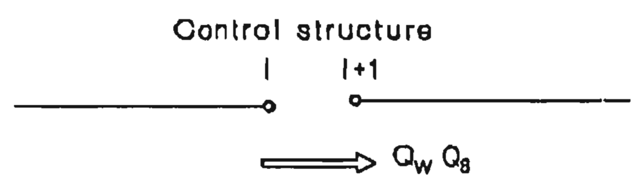
a) Boundary for change in the channel cross-section.



b) Boundary due to tributary inflow.



c) Boundary owing to tributary confluence.



d) Boundary related to a control structure.

Figure 4.9. Internal boundary conditions.

5. RESULTS AND DISCUSSION

This section presents the results of the application of the previously described mathematical model to the evaluation of possible channel changes occurring over relatively long periods of operation of the Kemuning Diversion. These channel changes were simulated using the following options:

1. The sequence of water discharges was assumed to fall into two categories:
   a) A sequence of decreasing discharges starting with 174.2 m^3/s and ending with 93.75 m^3/s.
   b) A sequence of increasing discharges beginning with 93.75 m^3/s and ending with 174.2 m^3/s.
2. Sediment inflow into the reach under consideration was assumed to exhibit two possible characteristics:
   a) Sediment demand at the upstream boundary condition (section 65) was met entirely by the upstream supply.
   b) Sediment demand at the upstream boundary condition was met by a constant percent (assumed to be 50%) of the concentration computed using the available suspended sediment rating curve (see Equation 4.3).

For comparison purposes, the water discharge and sediment inflow were analyzed using the following combinations:

Case L1: Laursen's method combined with options 1a and 2a.

Case L2: Laursen's method combined with options 1b and 2a.

Case L3: Laursen's method combined with options 1a and 2b.

Case L4: Laursen's method combined with options 1b and 2b.

Case Y1: Yang's method combined with options 1a and 2a.

Case Y2: Yang's method combined with options 1b and 2a.

Case Y3: Yang's method combined with options 1a and 2b.

Case Y4: Yang's method combined with options 1b and 2b.

Results for all eight simulations are presented in Appendix C. Typical changes of cross-section for each case are represented by the cross-sections 2, 32, 63 and 64 representing downstream, middle, and upstream reaches, respectively.

For the case of the sequence of decreasing discharges, the application of Laursen's equations, and sediment demand at section 65 met entirely by the upstream supply (case L1), the rise in the channel bed was relatively small, ranging from 0.019 m to 0.057 m, as shown in Figure 5.1 and Appendix C. For the same case but with the discharge sequence reversed (case L2), aggradation ranged from 0.012 to 0.080 m, as shown in Figure 5.2 and Appendix C.

For the case of the application of Yang's equations, the sequence of decreasing discharges, and sediment demand at section 65 fulfilled entirely by the upstream supply (case Y1), the estimated channel changes were again characterized by slight aggradation. The rise of channel bed was between 0.026 and 0.089 m (Figure 5.3 and Appendix C).

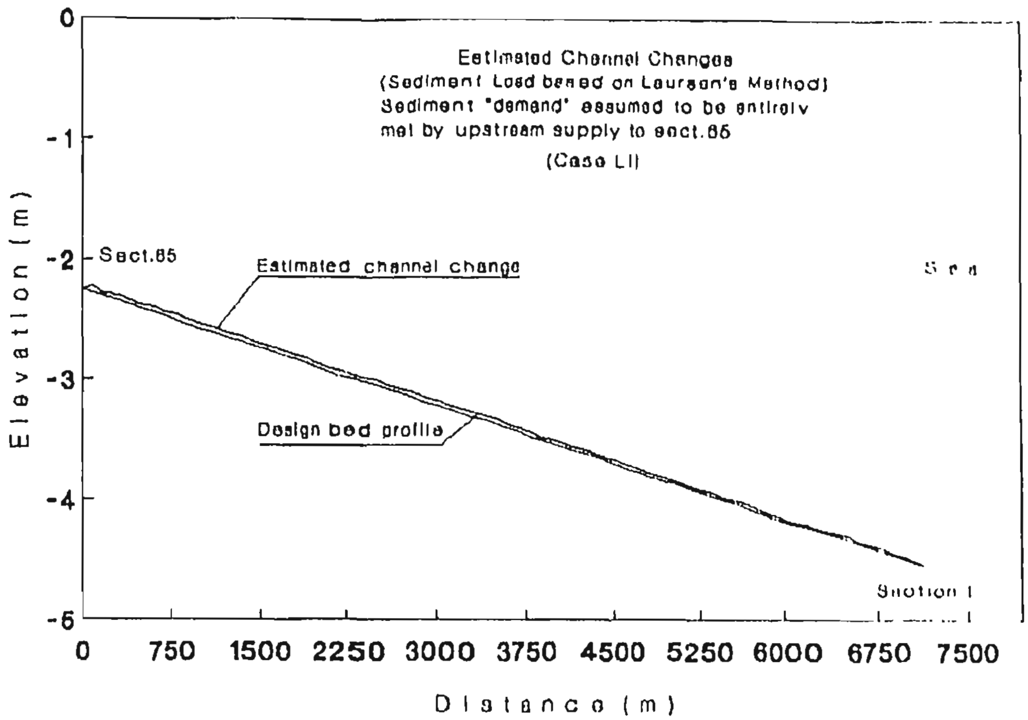


Figure 5.1. Estimated bed-profile change
(20 five steps, corresponds to about 20 years).

For the same case but with the sequence of increasing discharges (case Y2) the simulation showed a small degradation at section 63 (0.009 m) while other sections manifested aggradation ranging from 0.030 m to 0.137 m (see Figure 5.4 and Appendix C).

Different results were found for the scenarios L3, L4, Y3 and Y4. Changes in bed profile were characterized by degradation of certain sections located near the upstream boundary, and then aggradation in a downstream direction.

For the option of the sequence of decreasing discharges, application of Laursen's equations, and 50 % of incoming sediment computed using the available suspended sediment rating curve (case L3), erosion was predicted to occur at section 63 to a depth

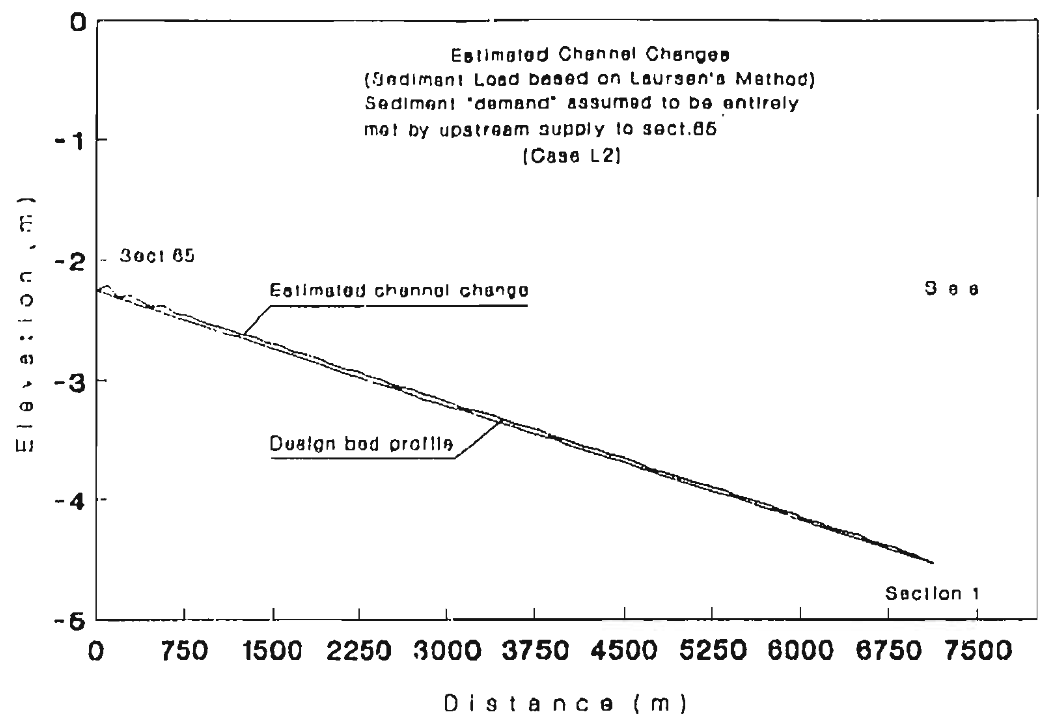


Figure 5.2. Estimated bed profile change
(20 time steps, corresponds to about 20 years).

of 0.104 m while the highest aggradation was 0.857 m for section 64. Aggradation for other sections ranged from 0.019 m to 0.048 m, as shown in Figure 5.5 and Appendix C. A similar scenario with increasing discharges (case L4) showed that sections 61 and 63 manifested erosion as deep as 1.023 and 0.07 m, respectively. The highest aggradation, 1.415 m, occurred in section 64, while in other sections this varied from 0.019 m to 0.454 m (see Figure 5.6 and Appendix C).

For the case of decreasing discharges, and 50 % of incoming sediment and use of Yang's equation (case Y3), degradation was predicted to occur at sections 60, 62 and 64, with section 64 being the highest at 1.635 m degradation. Other sections were found to aggrade with the highest being 0.795 m section 63, and the others ranging from

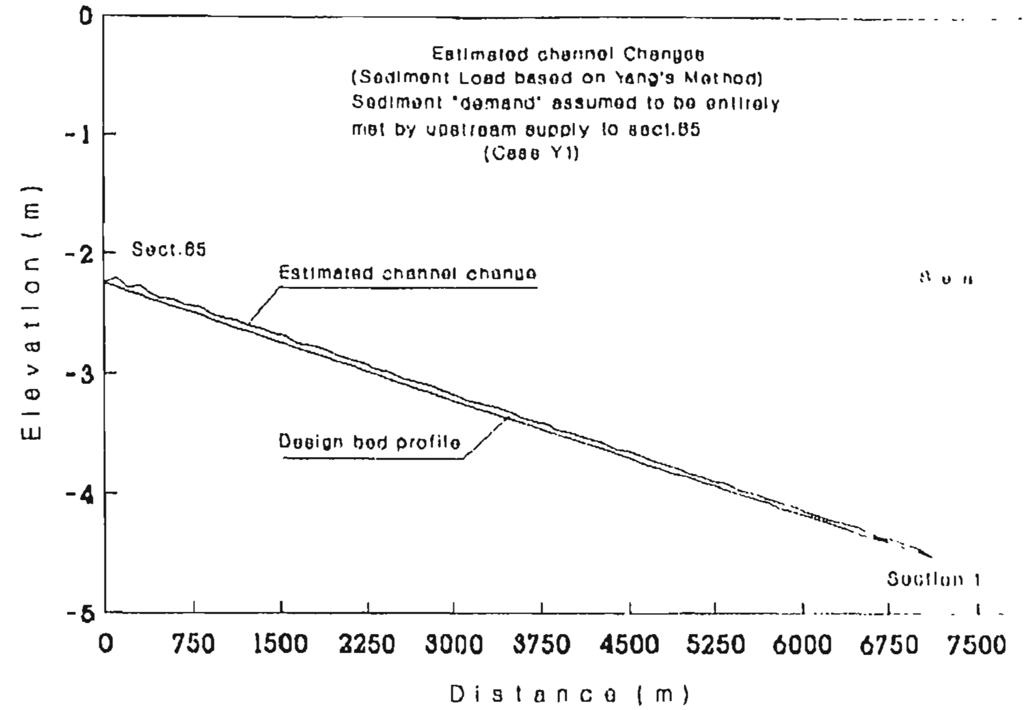


Figure 5.3. Estimated bed-profile change
(20 time steps, corresponds to about 20 years).

0.030 m to 0.070 m, as shown in Figure 5.7 and Appendix C. For the similar scenario but using a sequence of increasing discharges showed degradation in sections 64 and 62 with the former being the highest at 1.795 m, and the latter at 0.124 m. The highest aggradation was estimated to be 0.745 m in section 63, with others ranging from 0.029 m to 0.075 m (see Figure 5.8 and Appendix C).

It can be seen that the river channel changes involved both long profile and bed elevation changes. Taken together, the eight cases showed similar channel changes, characterized by aggradation along the channel except between sections 60 and 65, which were characterized by some erosion for the cases of L3, L4, Y3 and Y4. Similarities and differences in values for the same sections were affected by many factors as will be

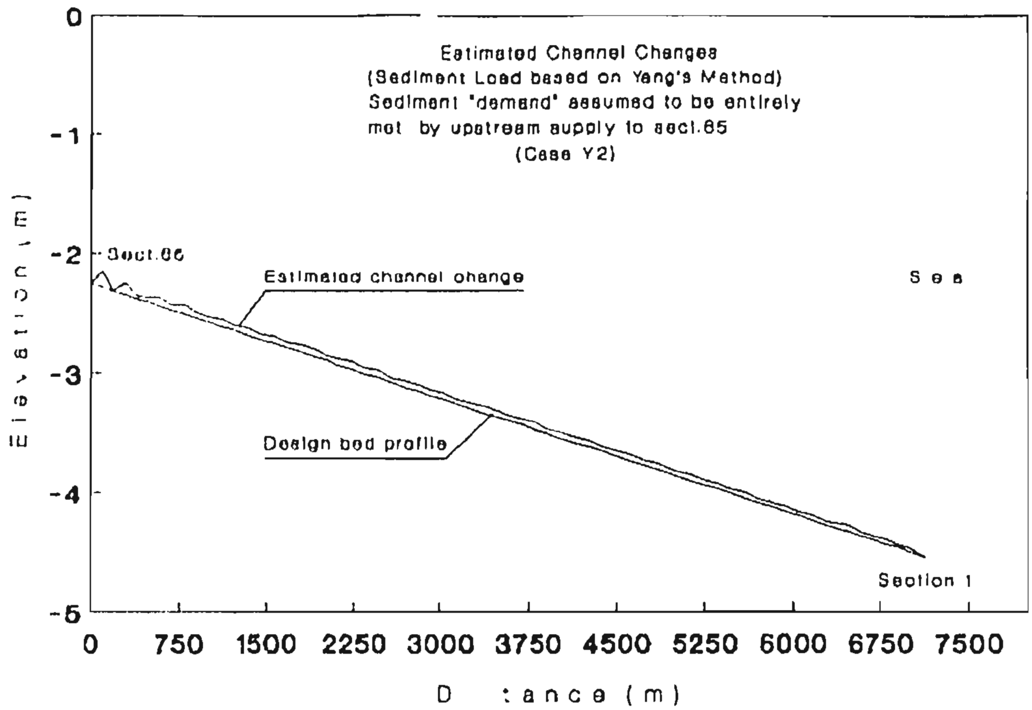


Figure 5.4. Estimated bed-profile change
(20 time steps, corresponds to about 20 years).

discussed in the following section.

5.1 Spatial Variation in Aggradation and Degradation of the Bed

As described in Section 4 the model computed water surface profile computations and applied sediment transport equations to solve the sediment-continuity equation. The variation in the estimated channel changes could be affected by both components of the computations. The following explanation is presented.

For a given section, the sediment transport capacity was calculated based on the hydraulic data, such as local mean shear stress, which resulted from the water surface profile computations. This sediment transport capacity was also used to calculate the

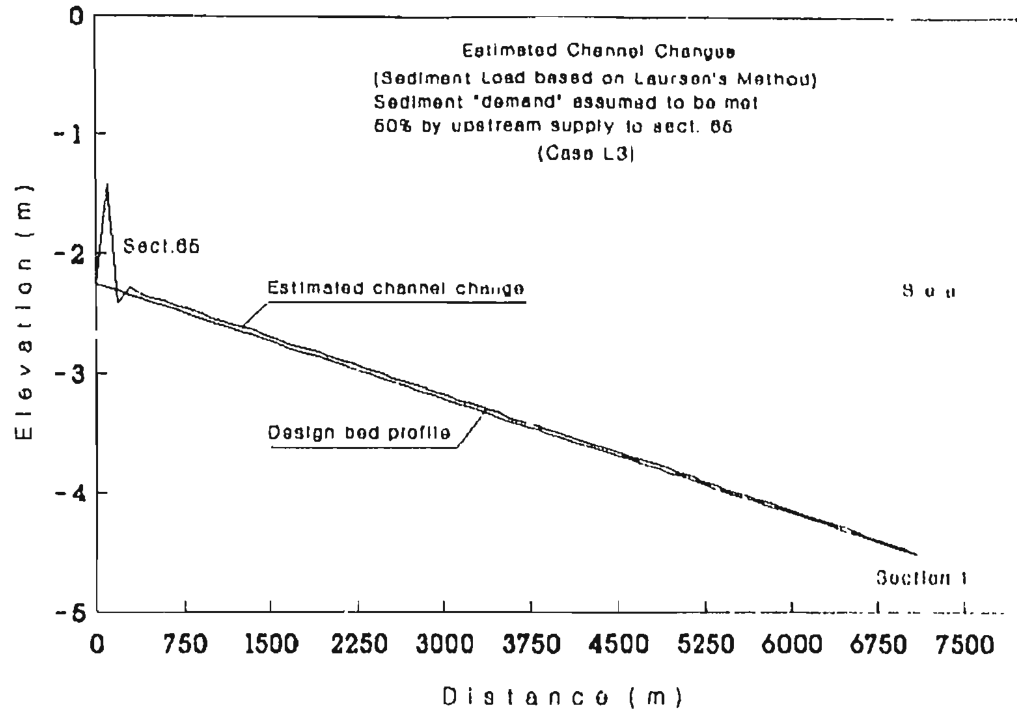


Figure 5.5. Estimated bed-profile change
(20 time steps, corresponds to about 20 years).

amount of aggradation and degradation through the sediment-continuity equation. Dominant factors affecting the water surface profile computation were water discharge and sea level. By using MSL, it was found that all water surface profiles were so-called "back-water" curves, such that the energy slope and velocity gradually increased in an upstream direction. This curve tended to increase the sediment transport rate, in accordance with the simple equilibrium approach suggested by Lane (1955):

$$Q \cdot S_o \propto Q_s \cdot d \tag{5.1}$$

where Q is water discharge; S_o is the bed slope; Q_s is sediment discharge; and d is grain size. During the simulation of one time-step, Q and d were constant. Because energy

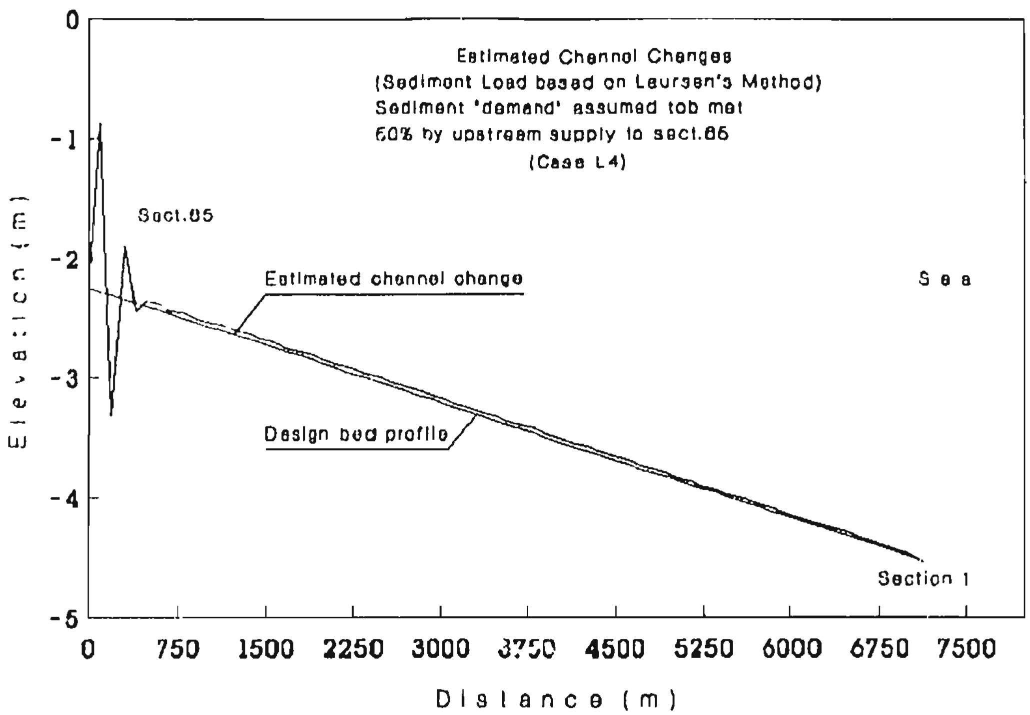


Figure 5.6. Estimated bed-profile change
(20 time steps, corresponds to about 20 years).

slope increased, an increase of Q_s was required. Q_s was calculated using Laursen's and Yang's method. For a given section, the simulations demonstrated that the local rate of sediment transport showed an increase in its magnitude when computation proceeded in an upstream direction. This indicated that the rate of sediment supply might be greater than the *local* rate of sediment removal; thus aggradation occurred. Such conditions were indicated by application of Yang and Laursen's equations, as well as the sequence of decreasing and increasing discharges, and when the sediment demand at the most-upstream was assumed fulfilled by the upstream supply (cases of L1, L2, Y1 and Y2). However, if the sediment budget into the study was a constant fraction (50%) of the computed sediment flux using the available suspended sediment rating curve, the increased

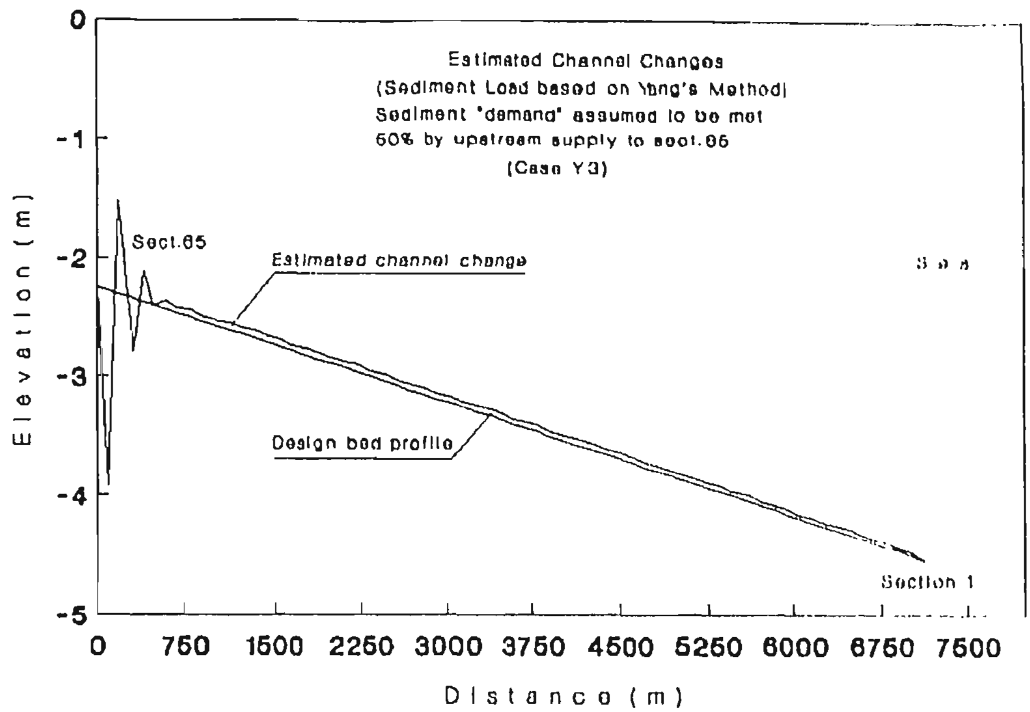


Figure 5.7. Estimated bed-profile change
(20 time steps, corresponds to about 20 years).

transport capacity led to a picking up of material and a decreased transport capacity, causing deposition. This process developed in a downstream direction. This condition was shown by cases of L3, L4, Y3 and Y4. Out of interest, the effect of assuming no sediment supply to the upstream boundary condition (section 65) was also investigated. The results showed a large amount of degradation occurred at the most downstream reach of the upstream boundary and then continued to the next-most downstream reach. This result also showed that variation of the sediment inflow into the reach under consideration had a significant effect on the bed channel changes. In other words, aggradation and degradation process were sensitive to the water surface profile, and their rate was greatly affected by the rate of sediment flux to the reach under consideration.

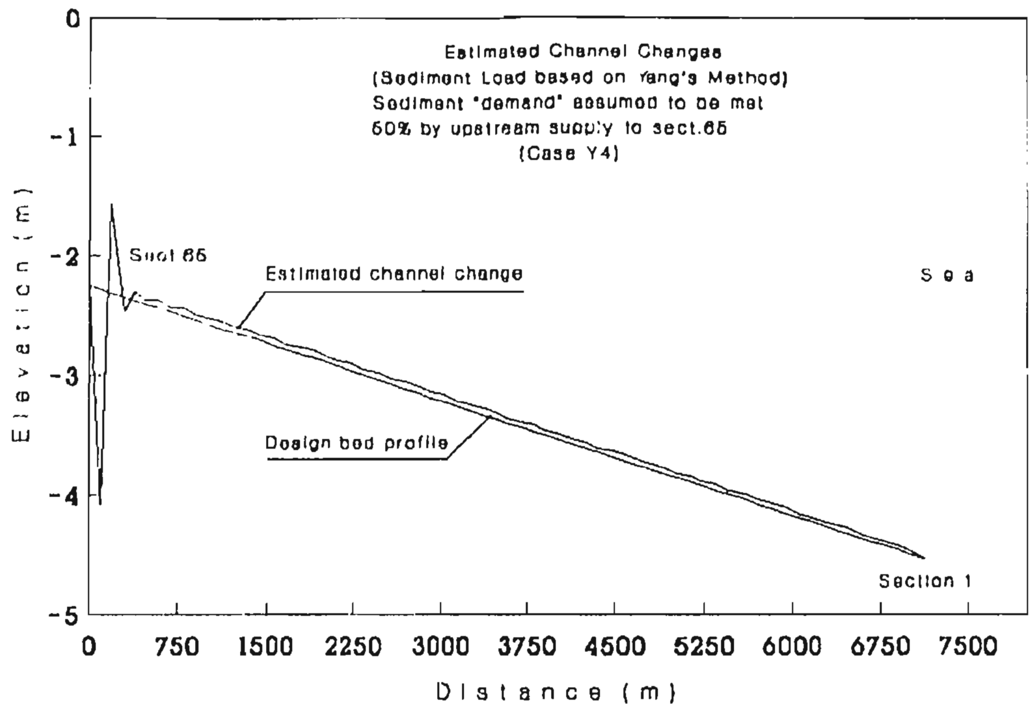


Figure 5.8. Estimated bed-profile change
(20 time steps, corresponds to about 20 years).

The rate of aggradation and degradation was related to the difference between the local rate of sediment removal and the rate of sediment supply (see Equation 4.14). The former is a function of time and distance along the channel. The sediment removal rate was calculated by using a sediment transport equation. Hence, the rate of aggradation or degradation depends entirely upon the sediment transport equation involved. As previously discussed, existing sediment transport equations have been developed using different independent variables. Laursen's method involves hydraulic shear stress and Yang's method uses unit stream power. For this reason, the estimated aggradation and degradation showed different results for the same initial channel and sediment supply specifications. For back-water curves, the hydraulic shear stress and unit stream power tended to increase their magnitudes when calculation proceeded upstream. Hence, sediment transport rate, which was calculated using both methods also increased in value when the calculation proceeded upstream. This indicated agreement with general expression of Lane (1955). This result is confirmed by simulations L1, Y1, L2 and Y2 (application of Laursen and Yang's equation, sequence of decreasing and increasing discharges, and the sediment demand to study reach fulfilled by the upstream supply), and by L3, Y3, L4 and Y4 (application of Laursen and Yang's equation, sequence of decreasing and increasing discharges, and the sediment demand to study reach computed as 50% of the upstream supply). Yang's method showed slightly higher degradation and aggradation amounts for the same reach than did Laursen's method, but the differences were relatively small. In other words, the rate of channel change was found to be sensitive to the sediment removal rate as computed by a sediment transport equation, but at a state of equilibrium the sediment load was found to be less sensitive to the choice of sediment transport equation.

5.2 Spatial Variation in Hydraulic Shear Stress

As previously discussed the hydraulic shear stress tended to increase in upstream direction for the back-water curve, and the geometric channel changes were generally characterized by aggradation. This meant that the aggradation process started at the most downstream reach of the upstream boundary condition and progressed in a downstream direction to the sea. If the aggradation reached the sea and was still in progress, the subsequent process might be expected to depend upon the hydraulic condition of the estuary, which is itself influenced by many factors, including tidal action, the forces of ocean waves and variations in river channel discharges. Unfortunately, these factors were beyond the scope of this study. However, if the tidal action and the wave forces are relatively small factors in the estuary, the aggradation process may develop in two possible directions. First, the aggradation process may progress continuously in a downstream direction, and the sediment may be deposited continuously in the sea. If the aggradation process continues in a downstream direction, the channel slope will tend to increase. Second, if the aggradation reaches the estuary and is still in progress, the aggradation may reverse, to an upstream direction. The bed slope would then decrease. This means that the more aggradation might occur in downstream reaches. For 20 time steps, it was found that the aggradation occurred more in the upstream reaches, so that the aggradation might eventually progress in a downstream direction. However, both types of progressing aggradation could affect the estuary, which might experience shallowing and delta formation over a relatively long period of time.

6. CONCLUSIONS AND RECOMMENDATIONS

This research has demonstrated the application of a mathematical model for the evaluation of the proposed design of the Kemuning Diversion Channel in terms of possible channel changes associated with a relatively long period of operation. This study involved two sediment transport equations: Laursen's equation and Yang's equation. The assumed sequence of inflows was based on the historical flow duration curve, and used two scenarios: an increasing discharge sequence and a decreasing discharge sequence. The rate of sediment inflow into the study under consideration was based on two assumptions:

(i) sediment demand at the most upstream study reach was met entirely by the upstream supply.

(ii) a constant percent (50%) of the concentration computed using the available sediment rating curve (see Equation 4.3). The incoming load was the 50 % of the suspended sediment load, as estimated by a historical suspended sediment rating curve (see Equation 4.5).

6.1 Conclusions

1. Estimated channel changes of the proposed design indicate that future channel

adjustments will be characterized by channel bed *aggradation*. This indicates that the channel will seek equilibrium by slight changes in bed elevation and long profile slope. This finding is based on the assumption that sediment demand at the most upstream study reach is met entirely by the upstream supply.

2. Aggradation and degradation processes were found to be sensitive to the water surface profile, and their respective rates were sensitive to the rate of sediment transport, as calculated by a sediment transport equation. The equilibrium sediment load, on the other hand, was less sensitive to the sediment transport equation.

3. By using the historical flow duration curve and the variation in the sediment inflow into the study reach, it was found that the water surface profile was characterized by backwater curves and the estimated channel change characterized by channel-bed aggradation. For the case where the computed sediment flux into the study reach was assumed to be constant percent of the total concentration, computed using the available sediment rating curve, estimated channel changes tended to show both channel-bed aggradation and degradation.

4. It was found that the highest channel bed aggradation according to Yang's method was less than 0.1 m (see Case Y2 and Figure 5.4). It can therefore be concluded that the proposed design of the Kemuning Diversion Channel is reasonable in terms of possible future channel changes caused by sediment budget imbalances.

5. Assumptions regarding the two categories of sequences of decreasing and increasing discharges did not show significant differences in the computed channel changes. This finding comes cases L1 and L2 (see Figure 5.1 and 5.2), cases Y1 and Y2 (see

Figure 5.3 and 5.4), cases L3 and L4 (see Figure 5.5 and 5.6) as well as cases Y3 and Y4 (see Figure 5.7 and 5.8). However, assumptions regarding the percentage of sediment influx which enters budget from the watershed were found to have a significant effect on the results (see Figure 5.5, 5.6, 5.7 and 5.8).

6. By using regime theory, it was found that the channel tend to widen and flatten. The widening is not expected because both left and right-hand-side along the diversion channel will eventually have human settlements. It can be concluded that bank protection for future maintenance is reasonable.
7. Regarding the bank protection, it was found that regime theory is not completely applicable for evaluation of channel geometry.

6.2 Recommendations

The possible future channel changes of the Kemuning Diversion Channel were analyzed by using both inductive and deductive mathematical models. However, the following suggestions are presented for possible future work on the analysis of possible channel changes:

1. Further investigation into the critical hydraulic shear stress of this particular bed material should be made so that the threshold condition for sediment motion can be represented more accurately.
2. Further investigations should be implemented to provide a better suspended sediment rating curve, together with bed load discharge, into the study reach. More detail and confidence is needed on the nature of these contributions.

3. The rationale for a long-term maintenance strategy, including reaches requiring regular dredging due to the aggradation process, is a possible topic for further analysis.

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Appendix - A

Computer Program for Estimating Geometric Channel Changes

This appendix gives the computer coding which was used to estimate geometric channel changes. The program was written using Quick Basic. This program is comprised of set of 27 subroutines for each stage of 6 stages. The input and output files are differentiated for Yang's and Laursen's methods, except for the input for step 1 at stage one. The program is initiated at stage one, which consists of 3 steps. Each stage has different numbers of step (see Table 4.3). For stage two and beyond, stage one is repeated with a different input. The initial input is the output of the last step and the former stage. Yang's and Laursen's methods, are run sequentially. Results (outputs) are presented for both methods in printed and digital form. Final interpretation of results was performed using Lotus 123 (see Appendix-C).

```
'**************************
'Description of variables
'**************************
'Q, water discharge          B, base width          n, Manning coefficient
'So, bed slope               g, gravitation         Eo, datum (+20)
'Z, water surface level      T, water depth         NITER, number of iteration
'D, cumulative distance      dx, distance           H, head velocity
'Hu, head velocity           P, wet perimeter       SF, friction slope
'A, wet area                 V, water velocity      R, hydraulic radius
'SY, sediment load           ss, specific gravity   vv, kinematic viscosity
'Vs, unit stream power       Tn, normal depth       d, diameter (d35)
'Y, ordinate point           m, number of point     ST, hydraulic shear stress
'X, station point            f, side slope          NSEC, number of section
'Qs, sediment inflow         tol, tolerance         CSS, critical hydraulic shear stress
'************
'Subroutines
'************
CLS
GOSUB INITIALIZATION.STAGE.1 'for stage of 1 only
GOSUB INITIALIZATION.1 'exluded stage of 1
GOSUB NORMAL.CRITICAL.DEPTH.1
GOSUB WATERSURFACE.PROFILE.1
GOSUB CTYANG.SEDIMENT.1 'for using Yang's method only
GOSUB LURSEN.SEDIMENT.1 'for using Laursen's method only
GOSUB RESUME.RESULT.1
GOSUB NEW.COORDINAT.1
GOSUB NORMAL.CRITICAL.DEPTH.2
GOSUB WATERSURFACE.PROFILE.2
GOSUB CTYANG.SEDIMENT.2 'for using Yang's method only
GOSUB LAURSEN.SEDIMENT.2 'for using Laursen's method only
GOSUB RESUME.RESULT.2
GOSUB NEW.COORDINAT.2
GOSUB NORMAL.CRITICAL.DEPTH.3
GOSUB WATERSURFACE.PROFILE.3
GOSUB CTYANG.SEDIMENT.3 'for using Yang's method only
GOSUB LAURSEN.SEDIMENT.3 'for using Laursen's method only
GOSUB RESUME.RESULT.3
GOSUB NEW.COORDINAT.3
GOSUB NORMAL.CRITICAL.DEPTH.4
GOSUB WATERSURFACE.PROFILE.4
GOSUB CTYANG.SEDIMENT.4 'for using Yang's method only
GOSUB LAURSEN.SEDIMENT.4 'for using Laursen's method only
GOSUB RESUME.RESULT.4
GOSUB NEW.COORDINAT.4
GOSUB PRINT.STEP
END
'***********
'Input data
'***********
CLS
DIM Hu1(65), H1(65), Z1(65), SF1(65), P1(65), ST1(65)
```

```
DIM R1(65), D(70), AFR1(65), A1(65), T1(65), V1(65)
DIM SY1(70), RASY1(70), ErY1(70), B1(65), T2(65), BSY1(65)
REM $DYNAMIC
DIM na1(15), nb1(15), nc1(15), bmc1(15), fcn1(15), B(65)
DIM ca1(15), cb1(15), cc1(15), bkc1(15), fcc1(15)
DIM X(70, 70), Y(70, 70), X1(70, 70), Y1(70, 70), MAX(65)
READ Q, n, So, g, f, Eo, NITER, Z1(1), T1(1), ss 'general input
DATA 174.2,0.025,0.00032,9.81,1,20.00,1000,15.464,4.536,2.787
nsec = 65: m = 6: : det = 1: tol = .001 'section number
dk = .000088: dg = .000177: dms = .00012: ik = .42: ig = .31 'grain size
vv = .000001007#: pct = .6: CSS = 5: pros = .51 'soil and sediment
vvd = .00998: Qs = 3.5425 * (Q ^ 1.5279) 'sediment rating curve
INITIALIZATION.STAGE.1:
OPEN "B:DATAK1.PRN" FOR INPUT AS #1 'input file
OPEN "B:WIDTH.PRN" FOR INPUT AS #2 'input file
OPEN "B:Cardinat.PRN" FOR INPUT AS #3 'input file
FOR i = 1 TO nsec
INPUT #1, D(i)
INPUT #2, B(i)
FOR j = 1 TO m
INPUT #3, X(i, j), Y(i, j)
NEXT j
NEXT i
CLOSE #1
CLOSE #2
CLOSE #3
RETURN
INITIALIZATION.1:
OPEN "B:DATAK1.PRN" FOR INPUT AS #4 'input file
OPEN "B:UYANG3A.PRN" FOR INPUT AS #5 'input-output file for Yang's method only
OPEN "B:Y93S3U.PRN" FOR INPUT AS #6 'input-output file for Yang's method only
OPEN "B:UYANG3B.PRN" FOR INPUT AS #7 'input-output file for Yang's method only
OPEN "B:URSEN3A.PRN" FOR INPUT AS #5 'input-output file for Laursen's method only
OPEN "B:L93S3U.PRN" FOR INPUT AS #6 'input-output file for Laursen's method only
OPEN "B:URSEN3B.PRN" FOR INPUT AS #7 'input-output file for Laursen's method only
FOR i = 1 TO nsec
INPUT #4, D(i)
INPUT #5, B(i)
FOR j = 1 TO m
INPUT #6, X(i, j), Y(i, j)
NEXT j
NEXT i
CLOSE #4
CLOSE #5
CLOSE #6
INPUT #7, So, Eo, T1(1)
CLOSE #7
RETURN
'***********************************
'Normal and critical depth, step 1
'***********************************
```

```
NORMAL.CRITICAL.DEPTH.1:
FOR ii = 1 TO 15
IF ii = 1 THEN
na1(ii) = .1: nb1(ii) = 8: nc1(ii) = 1 / 2 * (na1(ii) + nb1(ii))
fa1 = n ^ 2 * Q ^ 2 * (B(1) + 2 * na1(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f1a = So * (((B(1) + f * na1(ii)) * na1(ii)) ^ (10 / 3))
fan1 = 1 - fa1 / f1a
fb1 = n ^ 2 * Q ^ 2 * (B(1) + 2 * nb1(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f1b = So * (((B(1) + f * nb1(ii)) * nb1(ii)) ^ (10 / 3))
fbn1 = 1 - fb1 / f1b
fc1 = n ^ 2 * Q ^ 2 * (B(1) + 2 * nc1(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f1c = So * (((B(1) + f * nc1(ii)) * nc1(ii)) ^ (10 / 3))
fcn1(ii) = 1 - fc1 / f1c
ca1(ii) = .1: cb1(ii) = 8: cc1(ii) = 1 / 2 * (ca1(ii) + cb1(ii))
f1ca = Q ^ 2 * (B(1) + 2 * ca1(ii) * f)
fc1a = g * ((B(1) + f * ca1(ii)) * ca1(ii)) ^ 3
fca1 = 1 - f1ca / fc1a
f1cb = Q ^ 2 * (B(1) + 2 * cb1(ii) * f)
fc1b = g * ((B(1) + f * cb1(ii)) * cb1(ii)) ^ 3
fcb1 = 1 - f1cb / fc1b
f1cc = Q ^ 2 * (B(1) + 2 * cc1(ii) * f)
fc1c = g * ((B(1) + f * cc1(ii)) * cc1(ii)) ^ 3
fcc1(ii) = 1 - f1cc / fc1c
ELSEIF ii > 1 THEN
IF fan1 * fcn1(ii - 1) <= 0 THEN nb1(ii) = nc1(ii - 1): na1(ii) = na1(ii - 1)
IF fbn1 * fcn1(ii - 1) <= 0 THEN na1(ii) = nc1(ii - 1): nb1(ii) = nb1(ii - 1)
nc1(ii) = 1 / 2 * (na1(ii) + nb1(ii))
fc1 = n ^ 2 * Q ^ 2 * (B(1) + 2 * nc1(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f1c = So * (((B(1) + f * nc1(ii)) * nc1(ii)) ^ (10 / 3))
fcn1(ii) = 1 - fc1 / f1c
IF fca1 * fcc1(ii - 1) <= 0 THEN cb1(ii) = cc1(ii - 1): ca1(ii) = ca1(ii - 1)
IF fcb1 * fcc1(ii - 1) <= 0 THEN ca1(ii) = cc1(ii - 1): cb1(ii) = cb1(ii - 1)
cc1(ii) = 1 / 2 * (ca1(ii) + cb1(ii))
f1cc = Q ^ 2 * (B(1) + 2 * cc1(ii) * f)
fc1c = g * ((B(1) + f * cc1(ii)) * cc1(ii)) ^ 3
fcc1(ii) = 1 - f1cc / fc1c
END IF
bmc1(ii) = ABS(nb1(ii) - nc1(ii))
IF bmc1(ii) <= tol THEN Yn1 = nb1(ii)
bkc1(ii) = ABS(cb1(ii) - cc1(ii))
IF bkc1(ii) <= tol THEN Yc1 = cb1(ii)
NEXT ii
RETURN
'*******************************
'Water surface profile, step 1
'*******************************
WATERSURFACE.PROFILE.1:
A1(1) = (B(1) + f * T1(1)) * T1(1): P1(1) = (B(1) + 2.8284 * T1(1))
R1(1) = A1(1) / P1(1): V1(1) = Q / A1(1)
AFR1(1) = ((Q ^ 2 * (B(1) + 2 * T1(1))) / (g * A1(1) ^ 3)) ^ .5
SF1(1) = (V1(1) ^ 2) * (n ^ 2) / (R1(1) ^ (4 / 3))
```

```
bb1 = 1.15 * (V1(1) ^ 2) / (2 * g): ST1(1) = 9789 * R1(1) * SF1(1)
H1(1) = Z1(1) - bb1: Hu1(1) = H1(1): tol = .001: incr = .0001
FOR i = 2 TO nsec
i1 = i - 1
dx = D(i) - D(i1)
sum = 0
FOR c = 1 TO NITER
sum = sum + incr: Z1(i) = Z1(i1) - sum
T1(i) = Eo - Z1(i) - So * D(i)
IF T1(1) <= Yn1 THEN
IF T1(i) > Yn1 THEN T1(i) = .99 * Yn1
ELSEIF T1(1) > Yn1 THEN
IF T1(i) < Yn1 THEN T1(i) = 1.01 * Yn1
END IF
MAX(i) = Y(i, 1)
FOR j = 1 TO m - 1
IF MAX(i) < Y(i, j) THEN MAX(i) = Y(i, j)
NEXT j
j = 2
DO UNTIL Y(i, j) >= (MAX(i) - T1(i))
j = j + 1
LOOP
k = m - 1
DO UNTIL Y(i, k) >= (MAX(i) - T1(i))
k = k - 1
LOOP
yLEFT = MAX(i) - T1(i)
IF Y(i, j) <> yLEFT THEN
SLOPE.LEFT = (Y(i, j) - Y(i, j - 1)) / (X(i, j) - X(i, j - i))
xLEFT = X(i, j) - ((Y(i, j) - yLEFT) / SLOPE.LEFT)
ELSE
xLEFT = X(i, j)
END IF
yRIGHT = yLEFT
IF Y(i, k) <> yRIGHT THEN
SLOPE.RIGHT = (Y(i, k) - Y(i, k + 1)) / (X(i, k) - X(i, k + 1))
xRIGHT = X(i, k) - ((Y(i, k) - yRIGHT) / SLOPE.RIGHT)
ELSE
xRIGHT = X(i, k)
END IF
P1(i) = SQR((X(i, j) - xLEFT) ^ 2 + (Y(i, j) - yLEFT) ^ 2)
P1(i) = P1(i) + SQR((xRIGHT - X(i, k)) ^ 2 + (yRIGHT - Y(i, k)) ^ 2)
FOR L = j TO k - 1
P1(i) = P1(i) + SQR((X(i, L) - X(i, L + 1)) ^ 2 + (Y(i, L) - Y(i, L + 1)) ^ 2)
NEXT L
A1(i) = (X(i, j + 1) - xLEFT) * (Y(i, j) - (MAX(i) - T1(i))) / 2
A1(i) = A1(i) + (xRIGHT - X(i, k - 2)) * (Y(i, k - 1) - (MAX(i) - T1(i))) / 2
FOR L = j TO k - 3
A1(i) = A1(i) + (X(i, L + 2) - X(i, L)) * (Y(i, L + 1) - (MAX(i) - T1(i))) / 2
NEXT L
TPW = xRIGHT - xLEFT: AFR1(i) = ((Q ^ 2 * TPW) / (g * A1(i) ^ 3)) ^ .5
```

```
R1(i) = A1(i) / P1(i): V1(i) = Q / A1(i): Vi2 = 1.05 * (V1(i)) ^ 2
Wi = Vi2 / (2 * g): H1(i) = Z1(i) - Wi
SF1(i) = (V1(i) ^ 2) * (n ^ 2) / (R1(i) ^ (4 / 3))
asf = .5 * (SF1(i) + SF1(i1)): Dasf = dx * asf: Hu1(i) = Hu1(i1) - Dasf
dif = ABS(H1(i) - Hu1(i))
IF dif <= tol THEN
H1(i) = H1(i): SF1(i) = SF1(i): Hu1(i) = Hu1(i): Z1(i) = Z1(i)
T1(i) = T1(i): P1(i) = P1(i): A1(i) = A1(i): R1(i) = R1(i): V1(i) = V1(i)
AFR1(i) = AFR1(i)
GOTO 50
END IF
NEXT c
50 AKU = 0
NEXT i
RETURN
'**********************************
'Sediment transport rate of step 1
'**********************************
CTYANG.SEDIMENT.1:
CLS
FOR i = 1 TO nsec
ayk = 5.913 - .255 * 1000 * dk - .004 * (B(i) / T1(i))
ayg = 5.913 - .255 * 1000 * dg - .004 * (B(i) / T1(i))
byk = 1.257 - .005 * (B(i) / T1(i))
byg = 1.257 - .005 * (B(i) / T1(i))
Cyk = 10 ^ (ayk + byk * (.434295 * LOG(3.281 * V1(i) * SF1(i))))
Cyg = 10 ^ (ayg + byg * (.434295 * LOG(3.281 * V1(i) * SF1(i))))
SY1(i) = (Cyk + Cyg) * Q * .0864
'IF i = nsec THEN SY1(i) = pct * Qs 'for constant sediment inflow
NEXT i
RETURN
LAURSEN.SEDIMENT.1:
CLS
tcr = .039
FOR i = 1 TO nsec
Usl = (3.281 ^ 2 * g * R1(i) * So) ^ .5
wlk = (1822.78 * (dk) ^ 2 * (ss - 1) * g) / vvd
wlg = (1822.78 * (dg) ^ 2 * (ss - 1) * g) / vvd
rlk = Usl / wlk
rlg = Usl / wlg
IF rlk >= .01 AND rlk <= .6 THEN flk = 10.60499 * rlk ^ .240737
IF rlk > .6 AND rlk <= 2.5 THEN flk = 15.68325 * rlk ^ .982138
IF rlk > 2.5 AND rlk <= 30 THEN flk = 6.078651 * rlk ^ 2.167448
IF rlk > 30 AND rlk <= 100 THEN flk = 245.1002 * rlk ^ 1.050231
IF rlk > 100 THEN flk = 6946.656 * rlk ^ .307833
IF rlg >= .01 AND rlg <= .6 THEN flg = 10.60499 * rlg ^ .240737
IF rlg > .6 AND rlg <= 2.5 THEN flg = 15.68325 * rlg ^ .982138
IF rlg > 2.5 AND rlg <= 30 THEN flg = 6.078651 * rlg ^ 2.167448
IF rlg > 30 AND rlg <= 100 THEN flg = 245.1002 * rlg ^ 1.050231
IF rlg > 100 THEN flg = 6946.656 * rlg ^ .307833
tlk = tcr * 62.4 * (ss - 1) * dk * 3.281
```

```
tlg = tcr * 62.4 * (ss - 1) * dk * 3.281
toak = (1.94 * (3.281 * V1(i)) ^ 2 * (dms / T1(i)) ^ (1 / 3)) / 58
toag = (1.94 * (3.281 * V1(i)) ^ 2 * (dms / T1(i)) ^ (1 / 3)) / 58
Cmk = ((dk / T1(i)) ^ (7 / 6)) * (toak / tlk - 1) * flk
Cmg = ((dg / T1(i)) ^ (7 / 6)) * (toag / tlg - 1) * flg
tCm = .01 * 62.4 * (Cmk + Cmg)
SY1(i) = tCm * Q * 385.75 'to t/day (3.281 ^ 3) * .4536 * 86400 / 1000
'IF i = nsec THEN SY1(i) = pct * Qs 'for constant sediment inflow
NEXT i
RETURN
'*********************************
'change of channel bed of step 1
'*********************************
RESUME.RESULT.1:
OPEN "B:UYANG1A.PRN" FOR OUTPUT AS #50 'input-output file for Yang's method only
OPEN "B:URSEN1A.PRN" FOR OUTPUT AS #50 'input-output file for Laursen's method only
FOR i = 1 TO nsec
ST1(i) = 9789 * R1(i) * SF1(i)
BSY1(i) = SY1(i + 1) - SY1(i)
IF ST1(i) <= CSS THEN
IF i = 1 THEN RASY1(i) = 0
IF i > 1 THEN
IF BSY1(i) <= 0 THEN RASY1(i) = 0
IF BSY1(i) > 0 THEN RASY1(i - 1) = 0
RASY1(i) = BSY1(i) / (.5 * (D(i + 1) - D(i - 1)))
END IF
ELSEIF ST1(i) > CSS THEN
IF i = 1 THEN RASY1(i) = 0
IF i > 1 THEN RASY1(i) = BSY1(i) / (.5 * (D(i + 1) - D(i - 1)))
END IF
IF i = nsec THEN RASY1(i) = 0: BSY1(i) = 0: PQsY1 = SY1(i) / Qs
IF RASY1(i) <= 0 THEN ErY1(i) =-(B(i)-(B(i)^2-(4*det*ABS(RASY1(i))/(ss*(1-pros))))^.5)/2:
B1(i) = B(i) + 2 * ErY1(i)
IF RASY1(i) > 0 THEN ErY1(i) =(-B(i)+(B(i)^2+(4*det*ABS(RASY1(i))/(ss*(1-pros))))^.5)/2:
B1(i) = B(i) + 2 * ErY1(i)
WRITE #50, B1(i)
NEXT i
CLOSE #50
RETURN
'****************************************
'New cross-section coordinat of step 1
'****************************************
NEW.COORDINAT.CTYANG.1:
OPEN "B:UYANG1B.PRN" FOR OUTPUT AS #51 'input-output file for Yang's method only
OPEN "B:Y174S1U.PRN" FOR OUTPUT AS #52 'input-output file for Yang's method only
OPEN "B:URSEN1B.PRN" FOR OUTPUT AS #51 'input-output file for Laursen's method only
OPEN "B:L174S1U.PRN" FOR OUTPUT AS #52 'input output file for Laursen's method only
FOR i = 1 TO nsec
FOR j = 1 TO m
IF i >= 1 THEN
IF j >= 1 AND j < 3 THEN X1(i, j) = X(i, j): Y1(i, j) = Y(i, j)
```

```
IF j >= 3 AND j < 4 THEN X1(i, j) = (X(i, j) - ErY1(i)): Y1(i, j) = (Y(i, j) - ErY1(i))
IF j >= 4 AND j < 5 THEN X1(i, j) = (X(i, j) + ErY1(i)): Y1(i, j) = (Y(i, j) - ErY1(i))
IF j >= 5 THEN X1(i, j) = X(i, j): Y1(i, j) = Y(i, j)
IF j >= 1 THEN Sola = (Y1(1, 3) - Y1(20, 3)) / (D(20) - D(1)):
Solb = (Y1(20, 3) - Y1(40, 3)) / (D(40) - D(20)):
Solc = (Y1(40, 3) - Y1(nsec, 3)) / (D(nsec) - D(40)):
Sol = (Sola + Solb + Solc) / 3: Eol = Y1(1, 3): T2(1) = Eol - Z1(1)
END IF
NEXT j
NEXT i
FOR i = 1 TO nsec
WRITE #51, Sol, Eol, T2(1)
WRITE #52, X1(i, 1), Y1(i, 1), X1(i, 2), Y1(i, 2), X1(i, 3), Y1(i, 3),:
X1(i, 4), Y1(i, 4), X1(i, 5), Y1(i, 5), X1(i, 6), Y1(i,6)
NEXT i
CLOSE #51
CLOSE #52
RETURN
'************************************
'Normal and critical depth of step 2
'************************************
NORMAL.CRITICAL.DEPTH.2:
ERASE na1, nb1, nc1, bmc1, fcn1, ca1, cb1, cc1, bkc1, fcc1
ERASE X, Y, MAX, B
DIM Hu2(65), H2(65), Z2(65), SF2(65), P2(65), ST2(65), R2(65), AFR2(65)
DIM A2(65), T3(65), V2(65), SY2(70), RASY2(70), ErY2(70), B2(65), BSY2(65)
REM $DYNAMIC
DIM na2(15), nb2(15), nc2(15), bmc2(15), fcn2(15)
DIM ca2(15), cb2(15), cc2(15), bkc2(15), fcc2(15)
DIM X2(70, 70), Y2(70, 70), MAX1(65)
FOR ii = 1 TO 15
IF ii = 1 THEN
na2(ii) = .1: nb2(ii) = 8: nc2(ii) = 1 / 2 * (na2(ii) + nb2(ii))
fa2 = n ^ 2 * Q ^ 2 * (B1(1) + 2 * na2(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f2a = Sol * (((B1(1) + f * na2(ii)) * na2(ii)) ^ (10 / 3))
fan2 = 1 - fa2 / f2a
fb2 = n ^ 2 * Q ^ 2 * (B1(1) + 2 * nb2(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f2b = Sol * (((B1(1) + f * nb2(ii)) * nb2(ii)) ^ (10 / 3))
fbn2 = 1 - fb2 / f2b
fc2 = n ^ 2 * Q ^ 2 * (B1(1) + 2 * nc2(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f2c = Sol * (((B1(1) + f * nc2(ii)) * nc2(ii)) ^ (10 / 3))
fcn2(ii) = 1 - fc2 / f2c
ca2(ii) = .1: cb2(ii) = 8: cc2(ii) = 1 / 2 * (ca2(ii) + cb2(ii))
f2ca = Q ^ 2 * (B1(1) + 2 * ca2(ii) * f)
fc2a = g * ((B1(1) + f * ca2(ii)) * ca2(ii)) ^ 3
fca2 = 1 - f2ca / fc2a
f2cb = Q ^ 2 * (B1(1) + 2 * cb2(ii) * f)
fc2b = g * ((B1(1) + f * cb2(ii)) * cb2(ii)) ^ 3
fcb2 = 1 - f2cb / fc2b
f2cc = Q ^ 2 * (B1(1) + 2 * cc2(ii) * f)
fc2c = g * ((B1(1) + f * cc2(ii)) * cc2(ii)) ^ 3
```

```
fcc2(ii) = 1 - f2cc / fc2c
ELSEIF ii > 1 THEN
IF fan2 * fcn2(ii - 1) <= 0 THEN nb2(ii) = nc2(ii - 1): na2(ii) = na2(ii - 1)
IF fbn2 * fcn2(ii - 1) <= 0 THEN na2(ii) = nc2(ii - 1): nb2(ii) = nb2(ii - 1)
nc2(ii) = 1 / 2 * (na2(ii) + nb2(ii))
fc2 = n ^ 2 * Q ^ 2 * (B1(1) + 2 * nc2(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f2c = So1 * (((B1(1) + f * nc2(ii)) * nc2(ii)) ^ (10 / 3))
fcn2(ii) = 1 - fc2 / f2c
IF fca2 * fcc2(ii - 1) <= 0 THEN cb2(ii) = cc2(ii - 1): ca2(ii) = ca2(ii - 1)
IF fcb2 * fcc2(ii - 1) <= 0 THEN ca2(ii) = cc2(ii - 1): cb2(ii) = cb2(ii - 1)
cc2(ii) = 1 / 2 * (ca2(ii) + cb2(ii))
f2cc = Q ^ 2 * (B1(1) + 2 * cc2(ii) * f)
fc2c = g * ((B1(1) + f * cc2(ii)) * cc2(ii)) ^ 3
fcc2(ii) = 1 - f2cc / fc2c
END IF
bmc2(ii) = ABS(nb2(ii) - nc2(ii))
IF bmc2(ii) <= tol THEN Yn2 = nb2(ii)
bkc2(ii) = ABS(cb2(ii) - cc2(ii))
IF bkc2(ii) <= tol THEN Yc2 = cb2(ii)
NEXT ii
RETURN
'*********************************
'Water surface profile of step 2
'*********************************
WATERSURFACE.PROFILE.2:
Z2(1) = Z1(1): A2(1) = (B1(1) + f * T2(1)) * T2(1): P2(1) = (B1(1) + 2.8284 * T2(1))
R2(1) = A2(1) / P2(1): V2(1) = Q / A2(1): SF2(1) = (V2(1) ^ 2) * (n ^ 2) / (R2(1) ^ (4 / 3))
AFR2(1) = ((Q ^ 2 * (B1(1) + 2 * T2(1))) / (g * A2(1) ^ 3)) ^ .5
bb2 = 1.15 * (V2(1) ^ 2) / (2 * g): ST2(1) = 9789 * R2(1) * SF2(1)
H2(1) = Z2(1) - bb2: Hu2(1) = H2(1): tol = .001: incr = .0001
FOR i = 2 TO nsec
i1 = i - 1
dx = D(i) - D(i1)
sum = 0
FOR c = 1 TO NITER
sum = sum + incr: Z2(i) = Z2(i1) - sum
T2(i) = Eo1 - Z2(i) - So1 * D(i)
IF T2(1) <= Yn2 THEN
IF T2(i) > Yn2 THEN T2(i) = .99 * Yn2
ELSEIF T2(1) > Yn2 THEN
IF T2(i) < Yn2 THEN T2(i) = 1.01 * Yn2
END IF
MAX1(i) = Y1(i, 1)
FOR j = 1 TO m - 1
IF MAX1(i) < Y1(i, j) THEN MAX1(i) = Y1(i, j)
NEXT j
j = 2
DO UNTIL Y1(i, j) >= (MAX1(i) - T2(i))
j = j + 1
LOOP
k = m - 1
```

```
DO UNTIL Y1(i, k) >= (MAX1(i) - T2(i))
k = k - 1
LOOP
yLEFT = MAX1(i) - T2(i)
IF Y1(i, j) <> yLEFT THEN
SLOPE.LEFT = (Y1(i, j) - Y1(i, j - 1)) / (X1(i, j) - X1(i, j - 1))
xLEFT = X1(i, j) - ((Y1(i, j) - yLEFT) / SLOPE.LEFT)
ELSE
xLEFT = X1(i, j)
END IF
yRIGHT = yLEFT
IF Y1(i, k) <> yRIGHT THEN
SLOPE.RIGHT = (Y1(i, k) - Y1(i, k + 1)) / (X1(i, k) - X1(i, k + 1))
xRIGHT = X1(i, k) - ((Y1(i, k) - yRIGHT) / SLOPE.RIGHT)
ELSE
xRIGHT = X1(i, k)
END IF
P2(i) = SQR((X1(i, j) - xLEFT) ^ 2 + (Y1(i, j) - yLEFT) ^ 2)
P2(i) = P2(i) + SQR((xRIGHT - X1(i, k)) ^ 2 + (yRIGHT - Y1(i, k)) ^ 2)
FOR L = j TO k - 1
P2(i) = P2(i) + SQR((X1(i, L) - X1(i, L + 1)) ^ 2 + (Y1(i, L) - Y1(i, L + 1)) ^ 2)
NEXT L
A2(i) = (X1(i, j + 1) - xLEFT) * (Y1(i, j) - (MAX1(i) - T2(i))) / 2
A2(i) = A2(i) + (xRIGHT - X1(i, k - 2)) * (Y1(i, k - 1) - (MAX1(i) - T2(i))) / 2
FOR L = j TO k - 3
A2(i) = A2(i) + (X1(i, L + 2) - X1(i, L)) * (Y1(i, L + 1) - (MAX1(i) - T2(i))) / 2
NEXT L
TPW = xRIGHT - xLEFT: AFR2(i) = ((Q ^ 2 * TPW) / (g * A2(i) ^ 3)) ^ .5
R2(i) = A2(i) / P2(i): V2(i) = Q / A2(i): Vi2 = 1.05 * (V2(i)) ^ 2
Wi = Vi2 / (2 * g): H2(i) = Z2(i) - Wi: SF2(i) = (V2(i) ^ 2) * (n ^ 2) / (R2(i) ^ (4 / 3))
asf = .5 * (SF2(i) + SF2(i1)): Dasf = dx * asf: Hu2(i) = Hu2(i1) - Dasf
dif = ABS(H2(i) - Hu2(i))
IF dif <= tol THEN
H2(i) = H2(i): SF2(i) = SF2(i): Hu2(i) = Hu2(i): Z2(i) = Z2(i)
T2(i) = T2(i): P2(i) = P2(i): A2(i) = A2(i): R2(i) = R2(i): V2(i) = V2(i)
AFR2(i) = AFR2(i)
GOTO 60
END IF
NEXT c
60 AKU = 0
NEXT i
RETURN
'*********************************
'Sediment transport rate of step 2
'*********************************
CTYANG.SEDIMENT.2:
CLS
FOR i = 1 TO nsec
ayk = 5.913 - .255 * 1000 * dk - .004 * (B1(i) / T2(i))
ayg = 5.913 - .255 * 1000 * dg - .004 * (B1(i) / T2(i))
byk = 1.257 - .005 * (B1(i) / T2(i))
```

```
byg = 1.257 - .005 * (B1(i) / T2(i))
Cyk = 10 ^ (ayk + byk * (.434295 * LOG(3.281 * V2(i) * SF2(i))))
Cyg = 10 ^ (ayg + byg * (.434295 * LOG(3.281 * V2(i) * SF2(i))))
SY2(i) = (Cyk + Cyg) * Q * .0864
'IF i = nsec THEN SY2(i) = pct * Qs 'for constant sediment inflow
NEXT i
RETURN
LAURSEN.SEDIMENT.2:
CLS
tcr = .039
FOR i = 1 TO nsec
Usl = (3.281 ^ 2 * g * R2(i) * Sol) ^ .5
wlk = (1822.78 * (dk) ^ 2 * (ss - 1) * g) / vvd
wlg = (1822.78 * (dg) ^ 2 * (ss - 1) * g) / vvd
rlk = Usl / wlk
rlg = Usl / wlg
IF rlk >= .01 AND rlk <= .6 THEN flk = 10.60499 * rlk ^ .240737
IF rlk > .6 AND rlk <= 2.5 THEN flk = 15.68325 * rlk ^ .982138
IF rlk > 2.5 AND rlk <= 30 THEN flk = 6.078651 * rlk ^ 2.167448
IF rlk > 30 AND rlk <= 100 THEN flk = 245.1002 * rlk ^ 1.050231
IF rlk > 100 THEN flk = 6946.656 * rlk ^ .307833
IF rlg >= .01 AND rlg <= .6 THEN flg = 10.60499 * rlg ^ .240737
IF rlg > .6 AND rlg <= 2.5 THEN flg = 15.68325 * rlg ^ .982138
IF rlg > 2.5 AND rlg <= 30 THEN flg = 6.078651 * rlg ^ 2.167448
IF rlg > 30 AND rlg <= 100 THEN flg = 245.1002 * rlg ^ 1.050231
IF rlg > 100 THEN flg = 6946.656 * rlg ^ .307833
tlk = tcr * 62.4 * (ss - 1) * dk * 3.281
tlg = tcr * 62.4 * (ss - 1) * dk * 3.281
toak = (1.94 * (3.281 * V2(i)) ^ 2 * (dms / T2(i)) ^ (1 / 3)) / 58
toag = (1.94 * (3.281 * V2(i)) ^ 2 * (dms / T2(i)) ^ (1 / 3)) / 58
Cmk = ((dk / T2(i)) ^ (7 / 6)) * (toak / tlk - 1) * flk
Cmg = ((dg / T2(i)) ^ (7 / 6)) * (toag / tlg - 1) * flg
tCm = .01 * 62.4 * (Cmk + Cmg)
SY2(i) = tCm * Q * 385.75 'to t/day (3.281 ^ 3) * .4536 * 86400 / 1000
'IF i = nsec THEN SY2(i) = pct * Qs 'for costant sediment inflow
NEXT i
RETURN
'********************************
'change of channel bed of step 2
'********************************
OPEN "B:UYANG2A.PRN" FOR OUTPUT AS #53 'input-output file for Yang's method only
OPEN "B:URSEN2A.PRN" FOR OUTPUT AS #53 'input-output file for Laursen's method only
RESUME.RESULT.2:
FOR i = 1 TO nsec
ST2(i) = 9789 * R2(i) * SF2(i)
BSY2(i) = SY2(i + 1) - SY2(i)
IF ST2(i) <= CSS THEN
IF i = 1 THEN RASY2(i) = 0
IF i > 1 THEN
IF BSY2(i) <= 0 THEN RASY2(i) = 0
IF BSY2(i) > 0 THEN RASY2(i - 1) = 0
```

```
RASY2(i) = BSY2(i) / (.5 * (D(i + 1) - D(i - 1)))
END IF
ELSEIF ST2(i) > CSS THEN
IF i = 1 THEN RASY2(i) = 0
IF i > 1 THEN RASY2(i) = BSY2(i) / (.5 * (D(i + 1) - D(i - 1)))
END IF
IF i = nsec THEN RASY2(i) = 0: BSY2(i) = 0: PQsY2 = SY2(i) / Qs
IF RASY2(i) <= 0 THEN ErY2(i) = -(B1(i) (B1(i)^2-(4*det*ABS(RASY2(i))/(ss * (1 - pros))))^.5)/2:
B2(i) = B1(i) + 2 * ErY2(i)
IF RASY2(i) > 0 THEN ErY2(i) = (-B1(i)+(B1(i)^2+(4*det*ABS(RASY2(i))/(ss*(1 - pros))))^.5)/2:
B2(i) = B1(i) + 2 * ErY2(i)
WRITE #53, B2(i)
NEXT i
CLOSE #53
RETURN
'*************************************
'New cross-section coordinat of step 2
'*************************************
NEW.COORDINAT.CTYANG.2:
OPEN "B:UYANG2A.PRN" FOR OUTPUT AS #54 'input-output file for Yang's method only
OPEN "B:Y174S2U.PRN" FOR OUTPUT AS #55 'input-output file for Yang's method only
OPEN "B:URSEN2A.PRN" FOR OUTPUT AS #54 'input-output file for Laursen's method only
OPEN "B:L174S2U.PRN" FOR OUTPUT AS #55 'input-output file for Laursen's method only
FOR i = 1 TO nsec
FOR j = 1 TO m
IF i >= 1 THEN
IF j >= 1 AND j < 3 THEN X2(i, j) = X1(i, j): Y2(i, j) = Y1(i, j)
IF j >= 3 AND j < 4 THEN X2(i, j) = (X1(i, j) - ErY2(i)): Y2(i, j) = (Y1(i, j) - ErY2(i))
IF j >= 4 AND j < 5 THEN X2(i, j) = (X1(i, j) + ErY2(i)): Y2(i, j) = (Y1(i, j) - ErY2(i))
IF j >= 5 THEN X2(i, j) = X1(i, j): Y2(i, j) = Y1(i, j)
IF j >= 1 THEN So2a = (Y2(1, 3) - Y2(20, 3)) / (D(20) - D(1)):
So2b = (Y2(20, 3) - Y2(40, 3)) / (D(40) - D(20)):
So2c = (Y2(40, 3) - Y2(nsec, 3)) / (D(nsec) - D(40)):
So2 = (So2a + So2b + So2c) / 3: Eo2 = Y2(1, 3): T3(1) = Eo2 - Z2(1)
END IF
NEXT j
NEXT i
FOR i = 1 TO nsec
WRITE #54, So2, Eo2, T3(1)
WRITE #55, X2(i, 1), Y2(i, 1), X2(i, 2), Y2(i, 2), X2(i, 3), Y2(i, 3),:
X2(i, 4), Y2(i, 4), X2(i, 5), Y2(i, 5), X2(i, 6), Y2(i,6)
NEXT i
CLOSE #54
CLOSE #55
RETURN
'*************************************
'Normal and critical depth of step 3
'*************************************
NORMAL.CRITICAL.DEPTH.3:
ERASE na2, nb2, nc2, bmc2, fcn2, ca2, cb2, cc2, bkc2, fcc2
ERASE X1, Y1, MAX1
```

```
DIM Hu3(65), H3(65), Z3(65), SF3(65), P3(65), ST3(65), R3(65), AFR3(65)
DIM A3(65), T4(65), V3(65), SY3(70), RASY3(70), ErY3(70), B3(65), BSY3(65)
REM $DYNAMIC
DIM na3(15), nb3(15), nc3(15), bmc3(15), fcn3(15)
DIM ca3(15), cb3(15), cc3(15), bkc3(15), fcc3(15)
DIM X3(65, 65), Y3(65, 65), MAX2(65)
FOR ii = 1 TO 15
IF ii = 1 THEN
na3(ii) = .1: nb3(ii) = 8: nc3(ii) = 1 / 2 * (na3(ii) + nb3(ii))
fa3 = n ^ 2 * Q ^ 2 * (B2(1) + 2 * na3(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f3a = So2 * (((B2(1) + f * na3(ii)) * na3(ii)) ^ (10 / 3))
fan3 = 1 - fa3 / f3a
fb3 = n ^ 2 * Q ^ 2 * (B2(1) + 2 * nb3(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f3b = So2 * (((B2(1) + f * nb3(ii)) * nb3(ii)) ^ (10 / 3))
fbn3 = 1 - fb3 / f3b
fc3 = n ^ 2 * Q ^ 2 * (B2(1) + 2 * nc3(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f3c = So2 * (((B2(1) + f * nc3(ii)) * nc3(ii)) ^ (10 / 3))
fcn3(ii) = 1 - fc3 / f3c
ca3(ii) = .1: cb3(ii) = 8: cc3(ii) = 1 / 2 * (ca3(ii) + cb3(ii))
f3ca = Q ^ 2 * (B2(1) + 2 * ca3(ii) * f)
fc3a = g * ((B2(1) + f * ca3(ii)) * ca3(ii)) ^ 3
fca3 = 1 - f3ca / fc3a
f3cb = Q ^ 2 * (B2(1) + 2 * cb3(ii) * f)
fc3b = g * ((B2(1) + f * cb3(ii)) * cb3(ii)) ^ 3
fcb3 = 1 - f3cb / fc3b
f3cc = Q ^ 2 * (B2(1) + 2 * cc3(ii) * f)
fc3c = g * ((B2(1) + f * cc3(ii)) * cc3(ii)) ^ 3
fcc3(ii) = 1 - f3cc / fc3c
ELSEIF ii > 1 THEN
IF fan3 * fcn3(ii - 1) <= 0 THEN nb3(ii) = nc3(ii - 1): na3(ii) = na3(ii - 1)
IF fbn3 * fcn3(ii - 1) <= 0 THEN na3(ii) = nc3(ii - 1): nb3(ii) = nb3(ii - 1)
nc3(ii) = 1 / 2 * (na3(ii) + nb3(ii))
fc3 = n ^ 2 * Q ^ 2 * (B2(1) + 2 * nc3(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f3c = So2 * (((B2(1) + f * nc3(ii)) * nc3(ii)) ^ (10 / 3))
fcn3(ii) = 1 - fc3 / f3c
IF fca3 * fcc3(ii - 1) <= 0 THEN cb3(ii) = cc3(ii - 1): ca3(ii) = ca3(ii - 1)
IF fcb3 * fcc3(ii - 1) <= 0 THEN ca3(ii) = cc3(ii - 1): cb3(ii) = cb3(ii - 1)
cc3(ii) = 1 / 2 * (ca3(ii) + cb3(ii))
f3cc = Q ^ 2 * (B2(1) + 2 * cc3(ii) * f)
fc3c = g * ((B2(1) + f * cc3(ii)) * cc3(ii)) ^ 3
fcc3(ii) = 1 - f3cc / fc3c
END IF
bmc3(ii) = ABS(nb3(ii) - nc3(ii))
IF bmc3(ii) <= tol THEN Yn3 = nb3(ii)
bkc3(ii) = ABS(cb3(ii) - cc3(ii))
IF bkc3(ii) <= tol THEN Yc3 = cb3(ii)
NEXT ii
RETURN
'*********************************
'Water surface profile of step 3
'*********************************
```

```
WATERSURFACE.PROFILE.3:
Z3(1) = Z1(1): A3(1) = (B2(1) + f * T3(1)) * T3(1)
P3(1) = (B2(1) + 2.8284 * T3(1)): R3(1) = A3(1) / P3(1)
V3(1) = Q / A3(1): SF3(1) = (V3(1) ^ 2) * (n ^ 2) / (R3(1) ^ (4 / 3))
AFR3(1) = ((Q ^ 2 * (B2(1) + 2 * T3(1))) / (g * A3(1) ^ 3)) ^ .5
hh3 = 1.15 * (V3(1) ^ 2) / (2 * g): ST3(1) = 9789 * R3(1) * SF3(1)
H3(1) = Z3(1) - hh3: Hu3(1) = H3(1): tol = .001: incr = .0001
FOR i = 2 TO nsec
i1 = i - 1
dx = D(i) - D(i1)
sum = 0
FOR c = 1 TO NITER
sum = sum + incr: Z3(i) = Z3(i1) - sum
T3(i) = Eo2 - Z3(i) - So2 * D(i)
IF T3(1) <= Yn3 THEN
IF T3(i) > Yn3 THEN T3(i) = .99 * Yn3
ELSEIF T3(1) > Yn3 THEN
IF T3(i) < Yn3 THEN T3(i) = 1.01 * Yn3
END IF
MAX2(i) = Y2(i, 1) '= Mx2(i)
FOR j = 1 TO m - 1
IF MAX2(i) < Y2(i, j) THEN MAX2(i) = Y2(i, j)
NEXT j
j = 2
DO UNTIL Y2(i, j) >= (MAX2(i) - T3(i))
j = j + 1
LOOP
k = m - 1
DO UNTIL Y2(i, k) >= (MAX2(i) - T3(i))
k = k - 1
LOOP
yLEFT = MAX2(i) - T3(i)
IF Y2(i, j) <> yLEFT THEN
SLOPE.LEFT = (Y2(i, j) - Y2(i, j - 1)) / (X2(i, j) - X2(i, j - 1))
xLEFT = X2(i, j) - ((Y2(i, j) - yLEFT) / SLOPE.LEFT)
ELSE
xLEFT = X2(i, j)
END IF
yRIGHT = yLEFT
IF Y2(i, k) <> yRIGHT THEN
SLOPE.RIGHT = (Y2(i, k) - Y2(i, k + 1)) / (X2(i, k) - X2(i, k + 1))
xRIGHT = X2(i, k) - ((Y2(i, k) - yRIGHT) / SLOPE.RIGHT)
ELSE
xRIGHT = X2(i, k)
END IF
P3(i) = SQR((X2(i, j) - xLEFT) ^ 2 + (Y2(i, j) - yLEFT) ^ 2)
P3(i) = P3(i) + SQR((xRIGHT - X2(i, k)) ^ 2 + (yRIGHT - Y2(i, k)) ^ 2)
FOR L = j TO k - 1
P3(i) = P3(i) + SQR((X2(i, L) - X2(i, L + 1)) ^ 2 + (Y2(i, L) - Y2(i, L + 1)) ^ 2)
NEXT L
A3(i) = (X2(i, j + 1) - xLEFT) * (Y2(i, j) - (MAX2(i) - T3(i))) / 2
```

```
A3(i) = A ' ) + (xRIGHT - X2(i, k - 2)) * (Y2(i, k - 1) - (MAX2(i) - T3(i))) / 2
FOR L = j TO k - 3
A3(i) = A3(i) + (X2(i, L + 2) - X2(i, L)) * (Y2(i, L + 1) - (MAX2(i) - T3(i))) / 2
NEXT L
TPW = xRIGHT - xLEFT: AFR3(i) = ((Q ^ 2 * TPW) / (g * A3(i) ^ 3)) ^ .5
R3(i) = A3(i) / P3(i): V3(i) = Q / A3(i): Vi2 = 1.05 * (V3(i)) ^ 2
Wi = Vi2 / (2 * g): H3(i) = Z3(i) - Wi
SF3(i) = (V3(i) ^ 2) * (n ^ 2) / (R3(i) ^ (4 / 3)): asf = .5 * (SF3(i) + SF3(i1))
Dasf = dx * asf: Hu3(i) = Hu3(i1) - Dasf: dif = ABS(H3(i) - Hu3(i))
IF dif <= tol THEN
H3(i) = H3(i): SF3(i) = SF3(i): Hu3(i) = Hu3(i): Z3(i) = Z3(i)
T3(i) = T3(i): P3(i) = P3(i): A3(i) = A3(i): R3(i) = R3(i): V3(i) = V3(i)
AFR3(i) = AFR3(i)
GOTO 70
END IF
NEXT c
70  AKU = 0
NEXT i
RETURN
'**********************************
'Sediment transport rate of step 3
'**********************************
CTYANG.SEDIMENT.3:
CLS
FOR i = 1 TO nsec
ayk = 5.913 - .255 * 1000 * dk - .004 * (B2(i) / T3(i))
ayg = 5.913 - .255 * 1000 * dg - .004 * (B2(i) / T3(i))
byk = 1.257 - .005 * (B2(i) / T3(i))
byg = 1.257 - .005 * (B2(i) / T3(i))
Cyk = 10 ^ (ayk + byk * (.434295 * LOG(3.281 * V3(i) * SF3(i))))
Cyg = 10 ^ (ayg + byg * (.434295 * LOG(3.281 * V3(i) * SF3(i))))
SY3(i) = (Cyk + Cyg) * Q * .0864
'IF i = nsec THEN SY3(i) = pct * Qs 'for constant sediment inflow
NEXT i
RETURN
LAURSEN.SEDIMENT.3:
CLS
tcr = .039
FOR i = 1 TO nsec
Usl = (3.281 ^ 2 * g * R3(i) * So2) ^ .5
wlk = (1822.78 * (dk) ^ 2 * (ss - 1) * g) / vvd
wlg = (1822.78 * (dg) ^ 2 * (ss - 1) * g) / vvd
rlk = Usl / wlk
rlg = Usl / wlg
IF rlk >= .01 AND rlk <= .6 THEN flk = 10.60499 * rlk ^ .240737
IF rlk > .6 AND rlk <= 2.5 THEN flk = 15.68325 * rlk ^ .982138
IF rlk > 2.5 AND rlk <= 30 THEN flk = 6.078651 * rlk ^ 2.167448
IF rlk > 30 AND rlk <= 100 THEN flk = 245.1002 * rlk ^ 1.050231
IF rlk > 100 THEN flk = 6946.656 * rlk ^ .307833
IF rlg >= .01 AND rlg <= .6 THEN flg = 10.60499 * rlg ^ .240737
IF rlg > .6 AND rlg <= 2.5 THEN flg = 15.68325 * rlg ^ .982138
```

```
IF rlg > 2.5 AND rlg <= 30 THEN flg = 6.078651 * rlg ^ 2.167448
IF rlg > 30 AND rlg <= 100 THEN flg = 245.1002 * rlg ^ 1.050231
IF rlg > 100 THEN flg = 6946.656 * rlg ^ .307833
tlk = tcr * 62.4 * (ss - 1) * dk * 3.281
tlg = tcr * 62.4 * (ss - 1) * dk * 3.281
toak = (1.94 * (3.281 * V3(i)) ^ 2 * (dms / T3(i)) ^ (1 / 3)) / 58
toag = (1.94 * (3.281 * V3(i)) ^ 2 * (dms / T3(i)) ^ (1 / 3)) / 58
Cmk = ((dk / T3(i)) ^ (7 / 6)) * (toak / tlk - 1) * flk
Cmg = ((dg / T3(i)) ^ (7 / 6)) * (toag / tlg - 1) * flg
tCm = .01 * 62.4 * (Cmk + Cmg)
SY3(i) = tCm * Q * 385.75 'to t/day (3.281 ^ 3) * .4536 * 86400 / 1000
'IF i = nsec THEN SY3(i) = pct * Qs 'for constant sediment inflow
NEXT i
RETURN
'********************************
'change of channel bed of step 3
'********************************
RESUME.RESULT.3:
OPEN "B:UYANG3A.PRN" FOR OUTPUT AS #56 'input-output file for Yang's method only
OPEN "B:URSEN3A.PRN" FOR OUTPUT AS #56 'input-output file for Laursen's method only
FOR i = 1 TO nsec
ST3(i) = 9789 * R3(i) * SF3(i)
BSY3(i) = SY3(i + 1) - SY3(i)
IF ST3(i) <= CSS THEN
IF i = 1 THEN RASY3(i) = 0
IF i > 1 THEN
IF BSY3(i) <= 0 THEN RASY3(i) = 0
IF BSY3(i) > 0 THEN RASY3(i - 1) = 0
RASY3(i) = BSY3(i) / (.5 * (D(i + 1) - D(i - 1)))
END IF
ELSEIF ST3(i) > CSS THEN
IF i = 1 THEN RASY3(i) = 0
IF i > 1 THEN RASY3(i) = BSY3(i) / (.5 * (D(i + 1) - D(i - 1)))
END IF
IF i = nsec THEN RASY3(i) = 0: BSY3(i) = 0: PQsY3 = SY3(i) / Qs
IF RASY3(i) <= 0 THEN ErY3(i) = -(B2(i)-(B2(i)^2-(4*det*ABS(RASY3(i))/(ss*(1 - pros))))^.5)/2:
B3(i) = B2(i) + 2 * ErY3(i)
IF RASY3(i) > 0 THEN ErY3(i) = (-B2(i)+(B2(i)^2+(4*det*ABS(RASY3(i))/(ss*(1 - pros))))^.5)/2:
B3(i) = B2(i) + 2 * ErY3(i)
WRITE #56, B3(i)
NEXT i
CLOSE #56
RETURN
'**************************************
'New cross-section coordinat of step 3
'**************************************
NEW.COORDINAT.CTYANG.3:
OPEN "B:UYANG3B.PRN" FOR OUTPUT AS #57 'input-output file for Yang's method only
OPEN "B:Y174S3U.PRN" FOR OUTPUT AS #58 'input-output file for Yang's method only
OPEN "B:URSEN3B.PRN" FOR OUTPUT AS #57 'input-output file for Laursen's method only
OPEN "B:L174S3U.PRN" FOR OUTPUT AS #58 'input-output file for Laursen's method only
```

```
FOR i = 1 TO nsec
FOR j = 1 TO m
IF i >= 1 THEN
IF j >= 1 AND j < 3 THEN X3(i, j) = X2(i, j): Y3(i, j) = Y2(i, j)
IF j >= 3 AND j < 4 THEN X3(i, j) = (X2(i, j) - ErY3(i)): Y3(i, j) = (Y2(i, j) - ErY3(i))
IF j >= 4 AND j < 5 THEN X3(i, j) = (X2(i, j) + ErY3(i)): Y3(i, j) = (Y2(i, j) - ErY3(i))
IF j >= 5 THEN X3(i, j) = X2(i, j): Y3(i, j) = Y2(i, j)
IF j >= 1 THEN So3a = (Y3(1, 3) - Y3(20, 3)) / (D(20) - D(1)):
So3b = (Y3(20, 3) - Y3(40, 3)) / (D(40) - D(20)):
So3c = (Y3(40, 3) - Y3(nsec, 3)) / (D(nsec) - D(40)):
So3 = (So3a + So3b + So3c) / 3: Eo3 = Y3(1, 3): T4(1) = Eo3 - Z3(1)
END IF
NEXT j
NEXT i
FOR i = 1 TO nsec
WRITE #57, So3, Eo3, T4(1)
WRITE #58, X3(i, 1), Y3(i, 1), X3(i, 2), Y3(i, 2), X3(i, 3), Y3(i, 3),:
X3(i, 4), Y3(i, 4), X3(i, 5), Y3(i, 5), X3(i, 6), Y3(i,6)
NEXT i
CLOSE #57
CLOSE #58
RETURN
'************************************
'Normal and critical depth of step 4
'************************************
NORMAL.CRITICAL.DEPTH.4:
ERASE na3, nb3, nc3, bmc3, fcn3, ca3, cb3, cc3, bkc3, fcc3
ERASE X2, Y2, MAX2
DIM Hu4(65), H4(65), Z4(65), SF4(65), P4(65), R4(65), A4(65), AFR4(65)
DIM V4(65), SY4(70), ST4(65), RASY4(65), ErY4(70), B4(65), T5(65), BSY4(65)
REM $DYNAMIC
DIM na4(15), nb4(15), nc4(15), bmc4(15), fcn4(15)
DIM ca4(15), cb4(15), cc4(15), bkc4(15), fcc4(15)
DIM X4(70, 70), Y4(70, 70), MAX3(65)
FOR ii = 1 TO 15
IF ii = 1 THEN
na4(ii) = .1: nb4(ii) = 8: nc4(ii) = 1 / 2 * (na4(ii) + nb4(ii))
fa4 = n ^ 2 * Q ^ 2 * (B3(1) + 2 * na4(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f4a = So3 * (((B3(1) + f * na4(ii)) * na4(ii)) ^ (10 / 3))
fan4 = 1 - fa4 / f4a
fb4 = n ^ 2 * Q ^ 2 * (B3(1) + 2 * nb4(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f4b = So3 * (((B3(1) + f * nb4(ii)) * nb4(ii)) ^ (10 / 3))
fbn4 = 1 - fb4 / f4b
fc4 = n ^ 2 * Q ^ 2 * (B3(1) + 2 * nc4(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f4c = So3 * (((B3(1) + f * nc4(ii)) * nc4(ii)) ^ (10 / 3))
fcn4(ii) = 1 - fc4 / f4c
ca4(ii) = .1: cb4(ii) = 8: cc4(ii) = 1 / 2 * (ca4(ii) + cb4(ii))
f4ca = Q ^ 2 * (B3(1) + 2 * ca4(ii) * f)
fc4a = g * ((B3(1) + f * ca4(ii)) * ca4(ii)) ^ 3
fca4 = 1 - f4ca / fc4a
f4cb = Q ^ 2 * (B3(1) + 2 * cb4(ii) * f)
```

```
fc4b = g * ((B3(1) + f * cb4(ii)) * cb4(ii)) ^ 3
fcb4 = 1 - f4cb / fc4b
f4cc = Q ^ 2 * (B3(1) + 2 * cc4(ii) * f)
fc4c = g * ((B3(1) + f * cc4(ii)) * cc4(ii)) ^ 3
fcc4(ii) = 1 - f4cc / fc4c
ELSEIF ii > 1 THEN
IF fan4 * fcn4(ii - 1) <= 0 THEN nb4(ii) = nc4(ii - 1): na4(ii) = na4(ii - 1)
IF fbn4 * fcn4(ii - 1) <= 0 THEN na4(ii) = nc4(ii - 1): nb4(ii) = nb4(ii - 1)
nc4(ii) = 1 / 2 * (na4(ii) + nb4(ii))
fc4 = n ^ 2 * Q ^ 2 * (B3(1) + 2 * nc4(ii) * ((1 + f ^ 2) ^ .5)) ^ (4 / 3)
f4c = So3 * (((B3(1) + f * nc4(ii)) * nc4(ii)) ^ (10 / 3))
fcn4(ii) = 1 - fc4 / f4c
IF fca4 * fcc4(ii - 1) <= 0 THEN cb4(ii) = cc4(ii - 1): ca4(ii) = ca4(ii - 1)
IF fcb4 * fcc4(ii - 1) <= 0 THEN ca4(ii) = cc4(ii - 1): cb4(ii) = cb4(ii - 1)
cc4(ii) = 1 / 2 * (ca4(ii) + cb4(ii))
f4cc = Q ^ 2 * (B3(1) + 2 * cc4(ii) * f)
fc4c = g * ((B3(1) + f * cc4(ii)) * cc4(ii)) ^ 3
fcc4(ii) = 1 - f4cc / fc4c
END IF
bmc4(ii) = ABS(nb4(ii) - nc4(ii))
IF bmc4(ii) <= tol THEN Yn4 = nb4(ii)
bkc4(ii) = ABS(cb4(ii) - cc4(ii))
IF bkc4(ii) <= tol THEN Yc4 = cb4(ii)
NEXT ii
RETURN
'*********************************
'Water surface profile of step 4
'*********************************
WATERSURFACE.PROFILE.4:
Z4(1) = Z1(1)
A4(1) = (B3(1) + f * T4(1)) * T4(1): P4(1) = (B3(1) + 2.8284 * T4(1))
R4(1) = A4(1) / P4(1): V4(1) = Q / A4(1): SF4(1) = (V4(1) ^ 2) * (n ^ 2) / (R4(1) ^ (4 / 3))
AFR4(1) = ((Q ^ 2 * (B3(1) + 2 * T4(1))) / (g * A4(1) ^ 3)) ^ .5
bb4 = 1.15 * (V4(1) ^ 2) / (2 * g): ST4(1) = 9789 * R4(1) * SF4(1)
H4(1) = Z4(1) - bb4: Hu4(1) = H4(1): tol = .001: incr = .0001
FOR i = 2 TO nsec
i1 = i - 1
dx = D(i) - D(i1)
sum = 0
FOR c = 1 TO NITER
sum = sum + incr: Z4(i) = Z4(i1) - sum
T4(i) = Eo3 - Z4(i) - So3 * D(i)
IF T4(1) <= Yn4 THEN
IF T4(i) > Yn4 THEN T4(i) = .99 * Yn4
ELSEIF T4(1) > Yn4 THEN
IF T4(i) < Yn4 THEN T4(i) = 1.01 * Yn4
END IF
MAX3(i) = Y3(i, 1)
FOR j = 1 TO m - 1
IF MAX3(i) < Y3(i, j) THEN MAX3(i) = Y3(i, j)
NEXT j
```

```
j = 2
DO UNTIL Y3(i, j) > = (MAX3(i) - T4(i))
j = j + 1
LOOP
k = m - 1
DO UNTIL Y3(i, k) > = (MAX3(i) - T4(i))
k = k - 1
LOOP
yLEFT = MAX3(i) - T4(i)
IF Y3(i, j) < > yLEFT THEN
SLOPE.LEFT = (Y3(i, j) - Y3(i, j - 1)) / (X3(i, j) - X3(i, j - 1))
xLEFT = X3(i, j) - ((Y3(i, j) - yLEFT) / SLOPE.LEFT)
ELSE
xLEFT = X3(i, j)
END IF
yRIGHT = yLEFT
IF Y3(i, k) < > yRIGHT THEN
SLOPE.RIGHT = (Y3(i, k) - Y3(i, k + 1)) / (X3(i, k) - X3(i, k + 1))
xRIGHT = X3(i, k) - ((Y3(i, k) - yRIGHT) / SLOPE.RIGHT)
ELSE
xRIGHT = X3(i, k)
END IF
P4(i) = SQR((X3(i, j) - xLEFT) ^ 2 + (Y3(i, j) - yLEFT) ^ 2)
P4(i) = P4(i) + SQR((xRIGHT - X3(i, k)) ^ 2 + (yRIGHT - Y3(i, k)) ^ 2)
FOR L = j TO k - 1
P4(i) = P4(i) + SQR((X3(i, L) - X3(i, L + 1)) ^ 2 + (Y3(i, L) - Y3(i, L + 1)) ^ 2)
NEXT L
A4(i) = (X3(i, j + 1) - xLEFT) * (Y3(i, j) - (MAX3(i) - T4(i))) / 2
A4(i) = A4(i) + (xRIGHT - X3(i, k - 2)) * (Y3(i, k - 1) - (MAX3(i) - T4(i))) / 2
FOR L = j TO k - 3
A4(i) = A4(i) + (X3(i, L + 2) - X3(i, L)) * (Y3(i, L + 1) - (MAX3(i) - T4(i))) / 2
NEXT L
TPW = xRIGHT - xLEFT: AFR4(i) = ((Q ^ 2 * TPW) / (g * A4(i) ^ 3)) ^ .5
R4(i) = A4(i) / P4(i): V4(i) = Q / A4(i): Vi2 = 1.05 * (V4(i)) ^ 2
Wi = Vi2 / (2 * g): H4(i) = Z4(i) - Wi
SF4(i) = (V4(i) ^ 2) * (n ^ 2) / (R4(i) ^ (4 / 3)): asf = .5 * (SF4(i) + SF4(i1))
Dasf = dx * asf: Hu4(i) = Hu4(i1) - Dasf: dif = ABS(H4(i) - Hu4(i))
IF dif < = tol THEN
H4(i) = H4(i): SF4(i) = SF4(i): Hu4(i) = Hu4(i): Z4(i) = Z4(i)
T4(i) = T4(i): P4(i) = P4(i): A4(i) = A4(i): R4(i) = R4(i): V4(i) = V4(i)
AFR4(i) = AFR4(i)
GOTO 80
END IF
NEXT c
80 AKU = 0
NEXT i
RETURN
'**********************************
'Sediment transport rate of step 4
'**********************************
CTYANG.SEDIMENT.4:
```

```
CLS
FOR i = 1 TO nsec
ayk = 5.913 - .255 * 1000 * dk - .004 * (B3(i) / T4(i))
ayg = 5.913 - .255 * 1000 * dg - .004 * (B3(i) / T4(i))
byk = 1.257 - .005 * (B3(i) / T4(i))
byg = 1.257 - .005 * (B3(i) / T4(i))
Cyk = 10 ^ (ayk + byk * (.434295 * LOG(3.281 * V4(i) * SF4(i))))
Cyg = 10 ^ (ayg + byg * (.434295 * LOG(3.281 * V4(i) * SF4(i))))
SY4(i) = (Cyk + Cyg) * Q * .0864
'IF i = nsec THEN SY4(i) = pct * Qs 'for constant sediment inflow
NEXT i
RETURN
LAURSEN.SEDIMENT.4:
CLS
tcr = .039
FOR i = 1 TO nsec
Usl = (3.281 ^ 2 * g * R4(i) * So3) ^ .5
wlk = (1822.78 * (dk) ^ 2 * (ss - 1) * g) / vvd
wlg = (1822.78 * (dg) ^ 2 * (ss - 1) * g) / vvd
rlk = Usl / wlk
rlg = Usl / wlg
IF rlk >= .01 AND rlk <= .6 THEN flk = 10.60499 * rlk ^ .240737
IF rlk > .6 AND rlk <= 2.5 THEN flk = 15.68325 * rlk ^ .982138
IF rlk > 2.5 AND rlk <= 30 THEN flk = 6.078651 * rlk ^ 2.167448
IF rlk > 30 AND rlk <= 100 THEN flk = 245.1002 * rlk ^ 1.050231
IF rlk > 100 THEN flk = 6946.656 * rlk ^ .307833
IF rlg >= .01 AND rlg <= .6 THEN flg = 10.60499 * rlg ^ .240737
IF rlg > .6 AND rlg <= 2.5 THEN flg = 15.68325 * rlg ^ .982138
IF rlg > 2.5 AND rlg <= 30 THEN flg = 6.078651 * rlg ^ 2.167448
IF rlg > 30 AND rlg <= 100 THEN flg = 245.1002 * rlg ^ 1.050231
IF rlg > 100 THEN flg = 6946.656 * rlg ^ .307833
tlk = tcr * 62.4 * (ss - 1) * dk * 3.281
tlg = tcr * 62.4 * (ss - 1) * dk * 3.281
toak = (1.94 * (3.281 * V4(i)) ^ 2 * (dms / T4(i)) ^ (1 / 3)) / 58
toag = (1.94 * (3.281 * V4(i)) ^ 2 * (dms / T4(i)) ^ (1 / 3)) / 58
Cmk = ((dk / T4(i)) ^ (7 / 6)) * (toak / tlk - 1) * flk
Cmg = ((dg / T4(i)) ^ (7 / 6)) * (toag / tlg - 1) * flg
tCm = .01 * 62.4 * (Cmk + Cmg)
SY4(i) = tCm * Q * 385.75 'to t/day (3.281 ^ 3) * .4536 * 86400 / 1000
'IF i = nsec THEN SL4(i) = pct * Qs 'for constant sediment inflow
NEXT i
RETURN
'********************************
'change of channel bed of step 4
'********************************
RESUME.RESULT.4:
OPEN "B:UYANG4A.PRN" FOR OUTPUT AS #59 'input-output file for Yang's method only
OPEN "B:URSEN4A.PRN" FOR OUTPUT AS #59 'input-output file for Laursen's method only
FOR i = 1 TO nsec
ST4(i) = 9789 * R4(i) * SF4(i)
BSY4(i) = SY4(i + 1) - SY4(i)
```

```
IF ST4(i) <= CSS THEN
IF i = 1 THEN RASY4(i) = 0
IF i > 1 THEN
IF BSY4(i) <= 0 THEN RASY4(i) = 0
IF BSY4(i) > 0 THEN RASY4(i - 1) = 0
RASY4(i) = BSY4(i) / (.5 * (D(i + 1) - D(i - 1)))
END IF
ELSEIF ST4(i) > CSS THEN
IF i = 1 THEN RASY4(i) = 0
IF i > 1 THEN RASY4(i) = BSY4(i) / (.5 * (D(i + 1) - D(i - 1)))
END IF
IF i = nsec THEN RASY4(i) = 0: BSY4(i) = 0: PQSY4 = SY4(i) / Qs
IF RASY4(i) <= 0 THEN ErY4(i) = -(B3(i)-(B3(i)^2-(4*det*ABS(RASY4(i))/(ss * (1 - pros))))^.5)/2:
B4(i) = B3(i) + 2 * ErY4(i)
IF RASY4(i) > 0 THEN ErY4(i) = (-B3(i)+(B3(i)^2+(4*det*ABS(RASY4(i))/(ss * (1 - pros)))^.5)/2:
B4(i) = B3(i) + 2 * ErY4(i)
WRITE #59, B4(i)
NEXT i
CLOSE #59
RETURN
'*************************************
'New cross-section coordinat of step 4
'*************************************
NEW.COORDINAT.CTYANG.4:
OPEN "B:UYANG4B.PRN" FOR OUTPUT AS #60 'input-output file for Yang's method only
OPEN "B:Y174S4U.PRN" FOR OUTPUT AS #61 'input-output file for Yang's method only
OPEN "B:URSEN4B.PRN" FOR OUTPUT AS #60 'input-output file for Laursen's method only
OPEN "B:L174S4U.PRN" FOR OUTPUT AS #61 'input-output file for Laursen's method only
FOR i = 1 TO nsec
FOR j = 1 TO m
IF i >= 1 THEN
IF j >= 1 AND j < 3 THEN X4(i, j) = X3(i, j): Y4(i, j) = Y3(i, j)
IF j >= 3 AND j < 4 THEN X4(i, j) = (X3(i, j) - ErY4(i)): Y4(i, j) = (Y3(i, j) - ErY4(i))
IF j >= 4 AND j < 5 THEN X4(i, j) = (X3(i, j) + ErY4(i)): Y4(i, j) = (Y3(i, j) - ErY4(i))
IF j >= 5 THEN X4(i, j) = X3(i, j): Y4(i, j) = Y3(i, j)
IF j >= 1 THEN So4a = (Y4(1, 3) - Y4(20, 3)) / (D(20) - D(1)):
So4b = (Y4(20, 3) - Y4(40, 3)) / (D(40) - D(20)):
So4c = (Y4(40, 3) - Y4(nsec, 3)) / (D(nsec) - D(40)):
So4 = (So4a + So4b + So4c) / 3: Eo4 = Y4(1, 3): T5(1) = Eo4 - Z4(1)
END IF
NEXT j
NEXT i
FOR i = 1 TO nsec
WRITE #60, So4, Eo4, T5(1)
WRITE #61, X4(i, 1), Y4(i, 1), X4(i, 2), Y4(i, 2), X4(i, 3), Y4(i, 3),:
X4(i, 4), Y4(i, 4), X4(i, 5), Y4(i, 5), X4(i, 6), Y4(i,6)
NEXT i
CLOSE #60
CLOSE #61
RETURN
```

```
'*******************
'Output of stage 1
'*******************
PRINT.STEP:
LPRINT "USING CTYANG'S METHOD" 'for Yang's method only
LPRINT
LPRINT "USING LAURSEN'S METHOD" 'for Laursen's method only
LPRINT
LPRINT "STEP 1, TIME STEP (DT) = 1 DAY "
LPRINT
LPRINT "HYDRAULIC GEOMETRY Q = "; Q; "m3/s"; "; So = "; So; "; %Qs65 to inflow = "; PQsY1
LPRINT "--------------------------------------------------------------------------------------------------------"
LPRINT " Sec  Z(m)  T(m)  H(m)  Hu(m)  P(m)  A(m2)  R(m)  V(m/s)  SF "
LPRINT "--------------------------------------------------------------------------------------------------------"
D1$ = "## ##.### #.### ##.### ##.### ##.### ###.### #.### #.### #.#######"
OPEN "B:A174S1U.PRN" FOR OUTPUT AS #1 'input-output file for Yang's method only
OPEN "B:C174S1U.PRN" FOR OUTPUT AS #1 'input-output file for Laursen's method only
FOR i = 1 TO nsec
LPRINT USING D1$; (i); Z1(i); T1(i); H1(i); Hu1(i); P1(i); A1(i); R1(i); V1(i); SF1(i)
PRINT #1, USING D1$; (i); Z1(i); T1(i); H1(i); Hu1(i); P1(i); A1(i); R1(i); V1(i); SF1(i)
NEXT i
CLOSE #1
LPRINT
LPRINT "THE SED.LOAD, THE ER(-) & DP(+) RATE, WIDTH, E/D DEPTH FOR Q = "; Q; " m3/s"
LPRINT "--------------------------------------------------------------------------------------------------------"
LPRINT " Sec  ST  QS.L'SEN  DELTA QS  ER.RATE  ER(-)DP(+)  WIDTH  FROUD.N  "
LPRINT "  (N/m2)  (t/d)  (t/d)  (t/d)  (m)  (m)  "
LPRINT "--------------------------------------------------------------------------------------------------------"
D2$ = " ## ##.### ######.## ####.## ###.##  #.###  ##.### ##.###  "
OPEN "B:B174S1U.PRN" FOR OUTPUT AS #2 'input-output file for Yang's method only
OPEN "B:D174S1U.PRN" FOR OUTPUT AS #2 'input-output file for Laursen's method only
FOR i = 1 TO nsec
LPRINT USING D2$; (i); ST1(i); SY1(i); BSY1(i); RASY1(i); ErY1(i); B1(i); AFR1(i)
PRINT #2, USING D2$; (i); ST1(i); SY1(i); BSY1(i); RASY1(i); ErY1(i); B1(i); AFR1(i)
NEXT i
CLOSE #2
LPRINT
LPRINT "STEP 2, TIME STEP (DT) = 1 DAY "
LPRINT
LPRINT "HYDRAULIC GEOMETRY Q = "; Q; " m3/s"; " So = "; So1; "; %Qs65 to inflow = "; PQsY2
LPRINT "--------------------------------------------------------------------------------------------------------"
LPRINT " Sec  Z(m)  T(m)  H(m)  Hu(m)  P(m)  A(m2)  R(m)  V(m/s)  SF "
LPRINT "--------------------------------------------------------------------------------------------------------"
D3$ = "## ##.### #.### ##.### ##.### ##.### ###.### #.### #.### #.#######"
OPEN "B:A174S2U.PRN" FOR OUTPUT AS #3 'input-output file for Yang's method only
OPEN "B:C174S2U.PRN" FOR OUTPUT AS #3 'input-output file for Laursen's method only
FOR i = 1 TO nsec
LPRINT USING D3$; (i); Z2(i); T2(i); H2(i); Hu2(i); P2(i); A2(i); R2(i); V2(i); SF2(i)
PRINT #3, USING D3$; (i); Z2(i); T2(i); H2(i); Hu2(i); P2(i); A2(i); R2(i); V2(i); SF2(i)
NEXT i
CLOSE #3
```

```
LPRINT
LPRINT "THE SED.LOAD, THE ER(-) & DP(+) RATE, WIDTH, E/D DEPTH FOR Q = "; Q; " m3/s"
LPRINT "-----------------------------------------------------------------------------------------------"
LPRINT " Sec  ST   QS.L'SEN  DELTA QS  ER.RATE   ER(-)DP(+)  WIDTH  FROUD.N    "
LPRINT "      (N/m2)  (t/d)      (t/d)      (t/d)       (m)        (m)          "
LPRINT "-----------------------------------------------------------------------------------------------"
D4$ = " ## ##.### ######.## ####.## ###.##    #.###   ##.### ##.###   "
OPEN "B:B174S2U.PRN" FOR OUTPUT AS #4 'input-output file for Yang's method only
OPEN "B:D174S2U.PRN" FOR OUTPUT AS #4 'input-output file for Laursen's method only
FOR i = 1 TO nsec
LPRINT USING D4$; (i); ST2(i); SY2(i); BSY2(i); RASY2(i); ErY2(i); B2(i); AFR2(i)
PRINT #4, USING D4$; (i); ST2(i); SY2(i); BSY2(i); RASY2(i); ErY2(i); B2(i); AFR2(i)
NEXT i
CLOSE #4
LPRINT
LPRINT "STEP 3, TIME STEP (DT) = 1 DAY "
LPRINT
LPRINT "HYDRAULIC GEOMETRY Q ="; Q; " m3/s"; " So ="; So2; "; %Qs65 to inflow ="; PQsY3
LPRINT "-----------------------------------------------------------------------------------------------"
LPRINT " Sec  Z(m)  T(m)   H(m)  Hu(m)   P(m)   A(m2)  R(m)  V(m/s)    SF "
LPRINT "-----------------------------------------------------------------------------------------------"
D5$ = " ## ##.### #.### ##.### ##.### ##.### ###.### #.### #.### #.#######"
OPEN "B:A174S3U.PRN" FOR OUTPUT AS #5 'input-output file for Yang's method only
OPEN "B:C174S3U.PRN" FOR OUTPUT AS #5 'input-output file for Laursen's method only
FOR i = 1 TO nsec
LPRINT USING D5$; (i); Z3(i); T3(i); H3(i); Hu3(i); P3(i); A3(i); R3(i); V3(i); SF3(i)
PRINT #5, USING D5$; (i); Z3(i); T3(i); H3(i); Hu3(i); P3(i); A3(i); R3(i); V3(i); SF3(i)
NEXT i
CLOSE #5
LPRINT
LPRINT "THE SED.LOAD, THE ER(-) & DP(+) RATE, WIDTH, E/D DEPTH FOR Q = "; Q; " m3/s"
LPRINT "-----------------------------------------------------------------------------------------------"
LPRINT " Sec  ST   QS.L'SEN  DELTA QS  ER.RATE   ER(-)DP(+)  WIDTH  FROUD.N    "
LPRINT "      (N/m2)  (t/d)      (t/d)      (t/d)       (m)        (m)          "
LPRINT "-----------------------------------------------------------------------------------------------"
D6$ = " ## ##.### ######.## ####.## ###.##    #.###   ##.### ##.###   "
OPEN "B:B174S3U.PRN" FOR OUTPUT AS #6 'input-output file for Yang's method only
OPEN "B:D174S3U.PRN" FOR OUTPUT AS #6 'input-output file for Laursen's method only
FOR i = 1 TO nsec
LPRINT USING D6$; (i); ST3(i); SY3(i); BSY3(i); RASY3(i); ErY3(i); B3(i); AFR3(i)
PRINT #6, USING D6$; (i); ST3(i); SY3(i); BSY3(i); RASY3(i); ErY3(i); B3(i); AFR3(i)
NEXT i
CLOSE #6
LPRINT
LPRINT "STEP 4, TIME STEP (DT) = 1 DAY "
LPRINT
LPRINT "HYDRAULIC GEOMETRY Q ="; Q; " m3/s"; " So ="; So3; "; %Qs65 to inflow ="; PQsY4
LPRINT "-----------------------------------------------------------------------------------------------"
LPRINT " Sec  Z(m)  T(m)   H(m)  Hu(m)   P(m)   A(m2)  R(m)  V(m/s)    SF "
LPRINT "-----------------------------------------------------------------------------------------------"
D7$ = " ## ##.### #.### ##.### ##.### ##.### ###.### #.### #.### #.#######"
```

```
OPEN "B:A174S4U.PRN" FOR OUTPUT AS #7 'input-output file for Yang's method only
OPEN "B:C174S4U.PRN" FOR OUTPUT AS #7 'input-output file for Laursen's method only
FOR i = 1 TO nsec
LPRINT USING D7$; (i); Z4(i); T4(i); H4(i); Hu4(i); P4(i); A4(i); R4(i); V4(i); SF4(i)
PRINT #7, USING D7$; (i); Z4(i); T4(i); H4(i); Hu4(i); P4(i); A4(i); R4(i); V4(i); SF4(i)
NEXT i
CLOSE #7
LPRINT
LPRINT "THE SED.LOAD, THE ER(-) & DP(+) RATE, WIDTH, E/D DEPTH FOR Q ="; Q; " m3/s"
LPRINT "--------------------------------------------------------------------------------------------------------------"
LPRINT " Sec   ST    QS.L'SEN   DELTA QS  ER.RATE   ER(-)DP(+)  WIDTH   FROUD.N    "
LPRINT "       (N/m2)  (t/d)      (t/d)     (t/d)       (m)        (m)             "
LPRINT "--------------------------------------------------------------------------------------------------------------"
D8$ = " ## ##.### ######.##  ####.##  ###.##     #.###   ##.###   ##.###   "
OPEN "B:B174S4U.PRN" FOR OUTPUT AS #8 'input-output file for Yang's method only
OPEN "B:D174S4U.PRN" FOR OUTPUT AS #8 'input-output file for Laursen's method only
FOR i = 1 TO nsec
LPRINT USING D8$; (i); ST4(i); SY4(i); BSY4(i); RASY4(i); ErY4(i); B4(i); AFR4(i)
PRINT #8, USING D8$; (i); ST4(i); SY4(i); BSY4(i); RASY4(i); ErY4(i); B4(i); AFR4(i)
NEXT i
CLOSE #8
RETURN
```

Appendix - B

Application of Regime Theory (Inductive Models)

This appendix gives the application of Lacey's, Blench's, and Stevens and Nordin's equations. Calculation were based on a dominant discharge of 160 m^3/s (Q_2, see chapter 2) and a median grain size of 0.12 mm, representing the soil in and around the proposed channel. Unfortunately, no information on the bedload sediment concentration of the incoming sediment inflow was available for this study. Therefore, in application of Blench's equation, as well as the Stevens and Nordin's equations, the sediment concentration computed is based on the maximum limitation of both equations of 100 mg/L, or 17%, of the computed suspended sediment rating curve.

B.1 Input data for calculation of the channel dimension.

Q_w: 160 m^3/s — Shape: Trapezoidal

d_{50}: 0.12 mm — Side slope: 1V : 1H

g: 9.81 m/s^2 — C: 41.0009 $Q^{0.5279}$ mg/L

ν: 0.000001007 m^2/s

B.2 Results

Table B.1. Channel dimensions using Lacey's equations (1930)

Regime equation						Trapezoidal channel dimensions		
f_L	P(m)	R(m)	A(m^2)	V(m/s)	So	D(m)	A(m^2)	W(m)
0.61	61.22	3.01	184.22	0.87	0.000056	3.34	184.28	51.76

Table B.2. Channel dimensions using Blench's equations (1969)

Regime equation						Trapezoidal channel dimensions	
C_b=%C	C_b	F_b	D(m)	W_o	So	D(m)	W(m)
17	101.58	0.45	2.83	50.47	0.000139	2.83	47.65

Table B.3. Channel dimensions using Stevens and Nordin's equations (1990)

Regime equation						Trapezoidal channel dimensions		
C	P(m)	R(m)	A(m)	V(m/s)	So	D(m)	A(m^2)	W(m)
100	61.22	2.47	151.09	1.06	0.000153	2.68	151.10	53.63

Table B.4. Trapezoidal channel dimensions

Description	Water depth D(m)	Bottom width W(m)	Bed slope S_o
Proposed design	5.60	25.00	0.000320
Lacey's equations	3.34	51.76	0.000056
Blench's equations	2.83	47.65	0.000139
Stevens and Nordin's equations	2.68	53.63	0.000153

The results of applying the Lacey and Blench equations, as well as the Stevens and Nordin equations, were that the computed channel widths were all wider than the proposed design. Slopes were also flatter. Also, the computed long profiles were flatter slope than the design slope. These result indicate that the channel should tend to widen and flatten in order to achieve of the state of equilibrium (if the regime equations are completely applicable). However, both left and right-hand-side along the diversion channel will eventually have human settlements, so that the proposed design cannot be wider than 25 m. To overcome the possible widening of the channel dimensions, this diversion will be maintained by bank protection using natural stone with mortar. By this means the channel *bed* may be expected to rise or fall in the adjustment process.

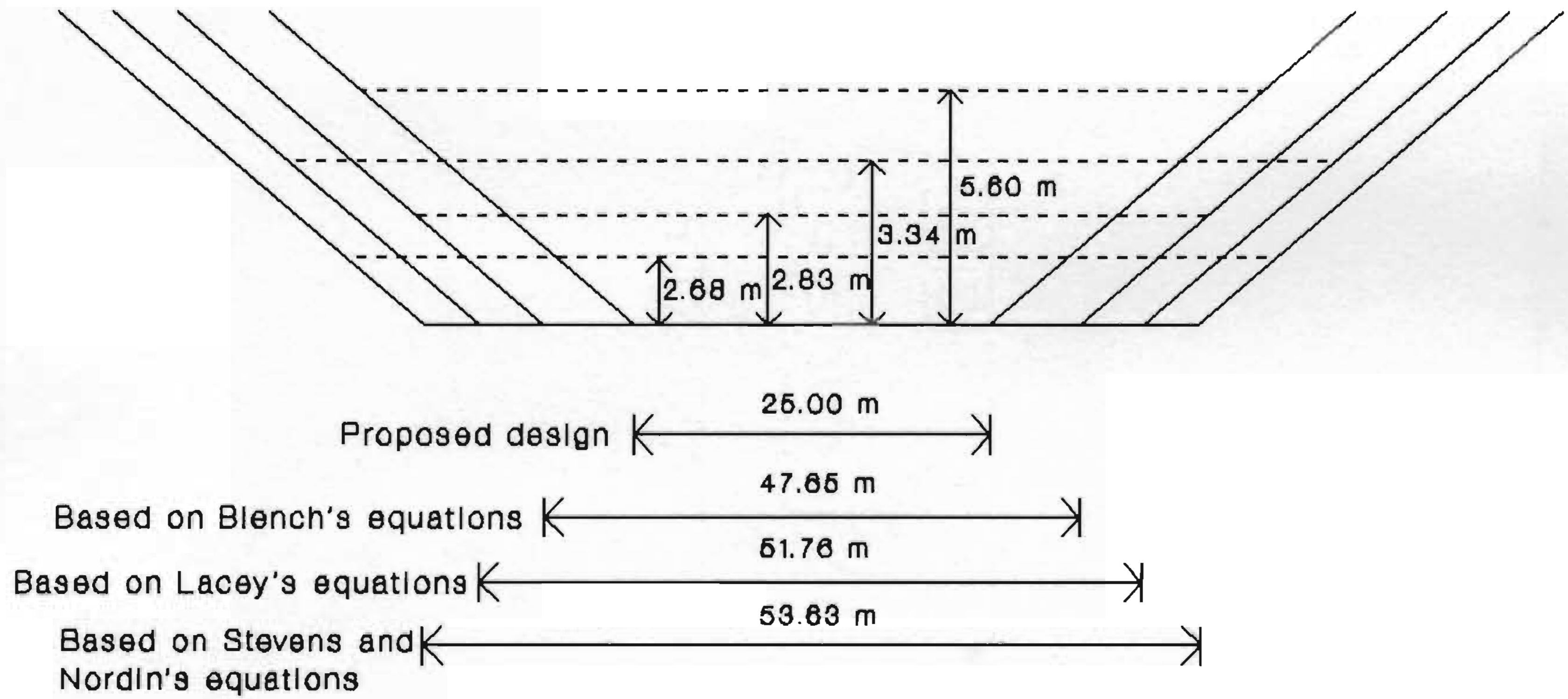

Figure B.1. Channel dimensions based on Regime Theory.

Appendix - C

Results of the Simulation of Channel Changes associated with 20 years of Operation

The appendix gives the long profile and certain cross-sectional changes resulting from the application of the (deductive) mathematical model. These results are presented in Tables C.1 to C.12. Typical changes for 20 time steps (corresponding to about 20 years of flow record) for the cross-section in each case are represented by cross-sections 2 (most downstream), 32 (middle), 63 and 64 (most upstream). The estimated changes for these cross-sections are shown in Figures C.1 to C.8.

Table C.1. Estimated long-profile change after 20 time steps, cases L1 and Y1

Design				Case L1			Case Y1		
Sec	Distance	Bed El.	Width	Bed El.	Ag,Deg *	Width	Bed El.	Ag,Deg *	Width
1	7131	-4.536	25.000	-4.536	0.000	25.000	-4.536	0.000	25.000
2	7002	-4.495	25.000	-4.476	0.019	25.038	-4.465	0.030	25.060
3	6892	-4.460	25.000	-4.441	0.019	25.039	-4.430	0.030	25.060
4	6796	-4.429	25.000	-4.404	0.025	25.049	-4.390	0.039	25.078
5	6676	-4.390	25.000	-4.370	0.020	25.040	-4.359	0.031	25.063
6	6576	-4.358	25.000	-4.337	0.021	25.042	-4.327	0.031	25.063
7	6481	-4.328	25.000	-4.297	0.031	25.063	-4.278	0.050	25.099
8	6296	-4.269	25.000	-4.249	0.020	25.039	-4.239	0.030	25.060
9	6163	-4.226	25.000	-4.203	0.023	25.047	-4.190	0.036	25.073
10	6040	-4.187	25.000	-4.166	0.021	25.043	-4.155	0.032	25.065
11	5941	-4.155	25.000	-4.127	0.028	25.055	-4.112	0.043	25.086
12	5822	-4.117	25.000	-4.092	0.025	25.050	-4.078	0.039	25.079
13	5705	-4.080	25.000	4.052	0.028	25.056	-4.044	0.036	25.073
14	5597	-4.045	25.000	-4.014	0.031	25.063	-3.996	0.049	25.097
15	5454	-3.999	25.000	-3.977	0.022	25.043	-3.967	0.032	25.064
16	5353	-3.967	25.000	-3.936	0.031	25.061	-3.920	0.047	25.094
17	5231	-3.929	25.000	-3.904	0.025	25.050	-3.892	0.037	25.075
18	5133	-3.897	25.000	-3.868	0.029	25.058	-3.853	0.044	25.088
19	5033	-3.865	25.000	-3.840	0.025	25.051	-3.828	0.037	25.075
20	4949	-3.838	25.000	-3.806	0.032	25.064	-3.790	0.048	25.096
21	4847	3.805	25.000	-3.773	0.032	25.065	-3.756	0.049	25.097
22	4729	-3.767	25.000	-3.738	0.029	25.059	-3.724	0.043	25.087
23	4615	-3.731	25.000	-3.699	0.032	25.064	-3.684	0.047	25.095
24	4491	-3.691	25.000	-3.659	0.032	25.064	-3.643	0.048	25.096
25	4365	-3.651	25.000	-3.624	0.027	25.053	-3.613	0.038	25.076
26	4265	-3.619	25.000	-3.582	0.037	25.074	-3.564	0.055	25.110
27	4133	-3.577	25.000	-3.544	0.033	25.065	-3.529	0.048	25.097
28	4003	-3.535	25.000	-3.505	0.030	25.060	-3.491	0.044	25.089
29	3897	-3.501	25.000	-3.475	0.026	25.053	-3.464	0.037	25.074
30	3815	-3.475	25.000	-3.434	0.041	25.082	-3.414	0.061	25.121
31	3699	-3.438	25.000	-3.405	0.033	25.066	-3.389	0.049	25.097
32	3591	-3.403	25.000	-3.372	0.031	25.062	-3.359	0.044	25.089
33	3495	-3.372	25.000	-3.334	0.038	25.076	-3.317	0.055	25.110
34	3379	-3.335	25.000	-3.297	0.038	25.077	-3.279	0.056	25.112
35	3246	-3.293	25.000	-3.260	0.033	25.066	-3.245	0.048	25.096
36	3132	-3.256	25.000	-3.225	0.031	25.062	-3.212	0.044	25.087
37	3035	-3.225	25.000	-3.185	0.040	25.080	-3.166	0.059	25.119
38	2917	-3.188	25.000	-3.148	0.040	25.080	-3.138	0.050	25.101
39	2803	-3.151	25.000	-3.112	0.039	25.078	-3.095	0.056	25.111
40	2679	-3.111	25.000	-3.075	0.036	25.073	-3.059	0.052	25.105
41	2564	-3.075	25.000	-3.042	0.033	25.065	-3.030	0.045	25.089
42	2465	-3.043	25.000	-2.999	0.044	25.088	-2.980	0.063	25.126
43	2340	-3.003	25.000	-2.968	0.035	25.069	-2.955	0.048	25.096
44	2228	-2.967	25.000	-2.926	0.041	25.082	-2.908	0.059	25.119
45	2106	-2.928	25.000	-2.895	0.033	25.066	-2.882	0.046	25.092
46	2010	-2.897	25.000	-2.861	0.036	25.072	-2.848	0.049	25.098
47	1915	-2.867	25.000	-2.821	0.046	25.091	-2.802	0.065	25.129
48	1787	-2.826	25.000	-2.786	0.040	25.081	-2.769	0.057	25.115
49	1657	-2.784	25.000	-2.751	0.033	25.065	-2.739	0.045	25.089
50	1554	-2.751	25.000	-2.710	0.041	25.081	-2.693	0.058	25.116
51	1447	-2.717	25.000	-2.682	0.035	25.071	-2.669	0.048	25.096
52	1349	-2.686	25.000	-2.643	0.043	25.086	-2.625	0.061	25.122
53	1234	-2.649	25.000	-2.610	0.039	25.077	-2.596	0.053	25.106
54	1118	-2.612	25.000	-2.571	0.041	25.083	-2.554	0.058	25.117
55	996	-2.573	25.000	-2.539	0.034	25.069	-2.526	0.047	25.095
56	896	-2.541	25.000	-2.505	0.036	25.072	-2.493	0.048	25.095
57	799	-2.510	25.000	-2.465	0.045	25.091	-2.445	0.065	25.129
58	681	-2.472	25.000	-2.439	0.033	25.065	-2.429	0.043	25.087
59	580	-2.440	25.000	-2.392	0.048	25.096	-2.377	0.063	25.126
60	468	-2.404	25.000	-2.375	0.029	25.059	-2.365	0.039	25.079
61	387	-2.378	25.000	-2.341	0.037	25.075	-2.331	0.047	25.094
62	298	-2.349	25.000	-2.301	0.048	25.096	-2.278	0.071	25.142
63	184	-2.313	25.000	-2.287	0.026	25.052	-2.287	0.026	25.053
64	96	-2.285	25.000	-2.228	0.057	25.115	-2.196	0.089	25.178
65	0	-2.254	25.000	-2.254	0.000	25.000	-2.254	0.000	25.000

* Ag: aggradation (+)
Dg. degradation (-)

Table C.2. Estimated long-profile change after 20 time steps, cases L2 and Y2

Design				Case L2			Case Y2		
Sec	Distance	Bed El.	Width	Bed El.	Ag,Deg *	Width	Bed El.	Ag,Deg *	Width
1	7131	-4.536	25.000	-4.536	0.000	25.000	-4.536	0.000	25.000
2	7002	-4.495	25.000	-4.476	0.019	25.038	-4.465	0.030	25.061
3	6892	-4.460	25.000	-4.441	0.019	25.038	-4.431	0.029	25.059
4	6796	-4.429	25.000	-4.404	0.025	25.050	-4.390	0.039	25.079
5	6676	-4.390	25.000	-4.370	0.020	25.040	-4.359	0.031	25.061
6	6576	-4.358	25.000	-4.338	0.020	25.041	-4.328	0.030	25.060
7	6481	-4.328	25.000	-4.296	0.032	25.064	-4.277	0.051	25.102
8	6296	-4.269	25.000	-4.250	0.019	25.039	-4.239	0.030	25.060
9	6163	-4.226	25.000	-4.202	0.024	25.047	-4.189	0.037	25.074
10	6040	-4.187	25.000	-4.166	0.021	25.042	-4.156	0.031	25.061
11	5941	-4.155	25.000	-4.127	0.028	25.056	-4.112	0.043	25.086
12	5822	-4.117	25.000	-4.092	0.025	25.050	-4.077	0.040	25.079
13	5705	-4.080	25.000	-4.052	0.028	25.056	-4.045	0.035	25.080
14	5597	-4.045	25.000	-4.013	0.032	25.064	-3.995	0.050	25.101
15	5454	-3.999	25.000	-3.978	0.021	25.042	3.969	0.030	25.061
16	5353	-3.967	25.000	-3.936	0.031	25.062	-3.919	0.048	25.096
17	5233	-3.929	25.000	-3.904	0.025	25.050	-3.892	0.037	25.073
18	5133	-3.897	25.000	-3.868	0.029	25.059	-3.852	0.045	25.090
19	5033	-3.865	25.000	-3.840	0.025	25.050	3.830	0.035	25.071
20	4949	-3.838	25.000	-3.806	0.032	25.064	-3.790	0.048	25.096
21	4847	-3.805	25.000	-3.772	0.033	25.065	-3.756	0.049	25.098
22	4729	-3.767	25.000	-3.738	0.029	25.058	-3.724	0.043	25.086
23	4615	-3.731	25.000	-3.699	0.032	25.064	-3.684	0.047	25.095
24	4491	-3.691	25.000	-3.658	0.033	25.065	-3.641	0.050	25.099
25	4365	-3.651	25.000	-3.626	0.025	25.051	3.616	0.035	25.080
26	4265	-3.619	25.000	-3.581	0.038	25.075	3.563	0.056	25.112
27	4133	-3.577	25.000	-3.544	0.033	25.066	3.528	0.049	25.097
28	4003	-3.535	25.000	-3.505	0.030	25.061	-3.489	0.046	25.092
29	3897	-3.501	25.000	-3.477	0.024	25.049	-3.470	0.031	25.062
30	3815	-3.475	25.000	-3.433	0.042	25.083	-3.412	0.063	25.127
31	3699	-3.438	25.000	-3.405	0.033	25.067	-3.389	0.049	25.099
32	3591	-3.403	25.000	-3.373	0.030	25.060	-3.361	0.042	25.084
33	3495	-3.372	25.000	-3.334	0.038	25.076	-3.317	0.055	25.109
34	3379	-3.335	25.000	-3.296	0.039	25.078	-3.277	0.058	25.115
35	3246	-3.293	25.000	-3.260	0.033	25.066	-3.244	0.049	25.098
36	3132	-3.256	25.000	-3.226	0.030	25.060	-3.216	0.040	25.079
37	3035	-3.225	25.000	-3.186	0.039	25.078	-3.164	0.061	25.123
38	2917	-3.188	25.000	-3.147	0.041	25.081	-3.139	0.049	25.097
39	2803	-3.151	25.000	-3.112	0.039	25.079	-3.095	0.056	25.113
40	2679	-3.111	25.000	-3.074	0.037	25.074	3.056	0.055	25.109
41	2564	-3.075	25.000	-3.045	0.030	25.060	-3.036	0.039	25.077
42	2465	-3.043	25.000	-2.998	0.045	25.091	-2.975	0.068	25.135
43	2340	-3.003	25.000	-2.970	0.033	25.067	-2.958	0.045	25.089
44	2228	-2.967	25.000	-2.924	0.043	25.086	-2.904	0.063	25.126
45	2106	-2.928	25.000	-2.896	0.032	25.065	2.882	0.046	25.092
46	2010	-2.897	25.000	-2.864	0.033	25.067	2.854	0.043	25.085
47	1915	-2.867	25.000	-2.821	0.046	25.093	-2.801	0.066	25.132
48	1787	-2.826	25.000	-2.784	0.042	25.084	-2.765	0.061	25.123
49	1657	-2.784	25.000	-2.753	0.031	25.061	-2.744	0.040	25.080
50	1554	-2.751	25.000	-2.709	0.042	25.084	-2.689	0.062	25.123
51	1447	-2.717	25.000	-2.684	0.033	25.067	-2.675	0.042	25.085
52	1349	-2.686	25.000	-2.642	0.044	25.088	-2.622	0.064	25.127
53	1234	-2.649	25.000	-2.611	0.038	25.075	-2.599	0.050	25.101
54	1118	-2.612	25.000	-2.569	0.043	25.086	-2.550	0.062	25.124
55	996	-2.573	25.000	-2.539	0.034	25.068	-2.525	0.048	25.097
56	896	-2.541	25.000	-2.509	0.032	25.065	-2.502	0.039	25.077
57	799	-2.510	25.000	-2.460	0.050	25.100	-2.436	0.074	25.148
58	681	-2.472	25.000	-2.447	0.025	25.050	-2.438	0.034	25.068
59	580	-2.440	25.000	-2.385	0.055	25.110	2.367	0.073	25.147
60	468	-2.404	25.000	-2.377	0.027	25.055	-2.367	0.037	25.073
61	387	-2.378	25.000	-2.346	0.032	25.063	-2.347	0.031	25.063
62	298	-2.349	25.000	-2.292	0.057	25.114	-2.255	0.094	25.188
63	184	-2.313	25.000	-2.301	0.012	25.024	-2.322	-0.009	24.981
64	96	-2.285	25.000	-2.205	0.080	25.160	-2.148	0.137	25.275
65	0	-2.254	25.000	-2.254	0.000	25.000	2.254	0.000	25.000

* Ag: aggradation (+)
Dg: degradation (-)

Table C.3. Estimated long-profile change after 20 time steps, cases L3 and Y3

Design				Case L3			Case Y3		
Sec	Distance	Bed El.	Width	Bed El.	Ag,Deg *	Width	Bed El.	Ag,Deg *	Width
1	7131	-4.536	25.000	-4.536	0.000	25.000	-4.536	0.000	25.000
2	7012	-4.495	25.000	-4.476	0.019	25.038	-4.465	0.030	25.060
3	6892	-4.460	25.000	-4.441	0.019	25.039	-4.430	0.030	25.060
4	6796	-4.429	25.000	-4.404	0.025	25.049	-4.390	0.039	25.078
5	6676	-4.390	25.000	-4.370	0.020	25.040	-4.359	0.031	25.063
6	6576	-4.358	25.000	-4.337	0.021	25.042	-4.327	0.031	25.063
7	6481	-4.328	25.000	-4.297	0.031	25.063	-4.278	0.050	25.099
8	6296	-4.269	25.000	-4.249	0.020	25.039	-4.239	0.030	25.060
9	6163	-4.226	25.000	-4.203	0.023	25.047	-4.190	0.036	25.073
10	6040	-4.187	25.000	-4.166	0.021	25.043	-4.155	0.032	25.065
11	5941	-4.155	25.000	-4.127	0.028	25.055	-4.112	0.043	25.086
12	5822	-4.117	25.000	-4.092	0.025	25.050	-4.078	0.039	25.079
13	5705	-4.080	25.000	-4.052	0.028	25.056	-4.044	0.036	25.073
14	5597	-4.045	25.000	-4.014	0.031	25.063	-3.996	0.049	25.097
15	5454	-3.999	25.000	-3.977	0.022	25.043	-3.967	0.032	25.064
16	5353	-3.967	25.000	-3.936	0.031	25.061	-3.920	0.047	25.094
17	5233	-3.929	25.000	-3.904	0.025	25.050	-3.892	0.037	25.075
18	5133	-3.897	25.000	-3.868	0.029	25.058	-3.853	0.044	25.088
19	5033	-3.865	25.000	-3.840	0.025	25.051	-3.828	0.037	25.075
20	4949	-3.838	25.000	-3.806	0.032	25.064	-3.790	0.048	25.096
21	4847	-3.805	25.000	-3.773	0.032	25.065	-3.756	0.049	25.097
22	4729	-3.767	25.000	-3.738	0.029	25.059	-3.724	0.043	25.087
23	4615	-3.731	25.000	-3.699	0.032	25.064	-3.684	0.047	25.095
24	4491	-3.691	25.000	-3.659	0.032	25.064	-3.643	0.048	25.096
25	4365	-3.651	25.000	-3.624	0.027	25.053	-3.613	0.038	25.076
26	4265	-3.619	25.000	-3.582	0.037	25.074	-3.564	0.055	25.110
27	4133	-3.577	25.000	-3.544	0.033	25.065	-3.529	0.048	25.097
28	4003	-3.535	25.000	-3.505	0.030	25.060	-3.491	0.044	25.089
29	3897	-3.501	25.000	-3.475	0.026	25.053	-3.464	0.037	25.074
30	3815	-3.475	25.000	-3.434	0.041	25.082	-3.414	0.061	25.121
31	3699	-3.438	25.000	-3.405	0.033	25.066	-3.389	0.049	25.097
32	3591	-3.403	25.000	-3.372	0.031	25.062	-3.359	0.044	25.089
33	3495	-3.372	25.000	-3.334	0.038	25.076	-3.317	0.055	25.110
34	3379	-3.335	25.000	-3.297	0.038	25.077	-3.279	0.056	25.112
35	3246	-3.293	25.000	-3.260	0.033	25.066	-3.245	0.048	25.096
36	3132	-3.256	25.000	-3.225	0.031	25.062	-3.212	0.044	25.087
37	3035	-3.225	25.000	-3.185	0.040	25.080	-3.166	0.059	25.119
38	2917	-3.188	25.000	-3.148	0.040	25.080	-3.138	0.050	25.101
39	2803	-3.151	25.000	-3.112	0.039	25.078	-3.095	0.056	25.111
40	2679	-3.111	25.000	-3.075	0.036	25.073	-3.059	0.052	25.105
41	2564	-3.075	25.000	-3.042	0.033	25.065	-3.030	0.045	25.089
42	2465	-3.043	25.000	-2.999	0.044	25.088	-2.980	0.063	25.126
43	2340	-3.003	25.000	-2.968	0.035	25.069	-2.955	0.048	25.096
44	2228	-2.967	25.000	-2.926	0.041	25.082	-2.908	0.059	25.119
45	2106	-2.928	25.000	-2.895	0.033	25.066	-2.882	0.046	25.092
46	2010	-2.897	25.000	-2.861	0.036	25.072	-2.848	0.049	25.098
47	1915	-2.867	25.000	-2.821	0.046	25.091	-2.802	0.065	25.129
48	1787	-2.826	25.000	-2.786	0.040	25.081	-2.769	0.057	25.115
49	1657	-2.784	25.000	-2.751	0.033	25.065	-2.739	0.045	25.089
50	1554	-2.751	25.000	-2.710	0.041	25.081	-2.693	0.058	25.116
51	1447	-2.717	25.000	-2.682	0.035	25.071	-2.669	0.048	25.096
52	1349	-2.686	25.000	-2.643	0.043	25.086	-2.625	0.061	25.122
53	1234	-2.649	25.000	-2.610	0.039	25.077	-2.596	0.053	25.106
54	1118	-2.612	25.000	-2.571	0.041	25.083	-2.554	0.058	25.117
55	996	-2.573	25.000	-2.539	0.034	25.069	-2.526	0.047	25.095
56	896	-2.541	25.000	-2.505	0.036	25.072	-2.493	0.048	25.095
57	799	-2.510	25.000	-2.465	0.045	25.091	-2.445	0.065	25.129
58	681	-2.472	25.000	-2.440	0.032	25.065	-2.430	0.042	25.085
59	580	-2.440	25.000	-2.392	0.048	25.096	-2.370	0.070	25.141
60	468	-2.404	25.000	-2.375	0.029	25.058	-2.414	-0.010	24.980
61	387	-2.378	25.000	-2.340	0.038	25.075	-2.107	0.271	25.543
62	298	-2.349	25.000	-2.289	0.060	25.120	-2.793	-0.444	24.111
63	184	-2.313	25.000	-2.417	-0.104	24.793	-1.518	0.795	26.590
64	96	-2.285	25.000	-1.428	0.857	26.713	-3.920	-1.635	21.729
65	0	-2.254	25.000	-2.254	0.000	25.000	-2.254	0.000	25.000

* Ag: aggradation (+)
Dg: degradation (-)

Table C.4. Estimated long-profile change after 20 time steps, cases L4 and Y4

Sec	Design			Case L4			Case Y4		
	Distance	Bed El.	Width	Bed El.	Ag.Deg *	Width	Bed El.	Ag.Deg *	Width
1	7131	-4.536	25.000	-4.536	0.000	25.000	-4.536	0.000	25.000
2	7002	-4.495	25.000	-4.476	0.019	25.038	-4.465	0.030	25.061
3	6892	-4.460	25.000	-4.441	0.019	25.038	-4.431	0.029	25.059
4	6796	-4.429	25.000	-4.404	0.025	25.050	-4.390	0.039	25.079
5	6676	-4.390	25.000	-4.370	0.020	25.040	4.359	0.031	25.063
6	6576	-4.358	25.000	-4.338	0.020	25.041	-4.328	0.030	25.060
7	6481	-4.328	25.000	-4.296	0.032	25.064	-4.277	0.051	25.102
8	6296	-4.269	25.000	-4.250	0.019	25.039	-4.239	0.030	25.060
9	6163	-4.226	25.000	-4.202	0.024	25.047	-4.189	0.037	25.074
10	6040	-4.187	25.000	-4.166	0.021	25.042	-4.156	0.031	25.063
11	5941	-4.155	25.000	-4.127	0.028	25.056	-4.112	0.043	25.086
12	5822	-4.117	25.000	-4.092	0.025	25.050	-4.077	0.040	25.079
13	5705	-4.080	25.000	-4.052	0.028	25.056	-4.045	0.035	25.070
14	5597	-4.045	25.000	-4.013	0.032	25.064	-3.995	0.050	25.101
15	5454	-3.999	25.000	-3.978	0.021	25.042	-3.969	0.030	25.061
16	5353	-3.967	25.000	-3.936	0.031	25.062	-3.919	0.048	25.096
17	5233	-3.929	25.000	-3.904	0.025	25.050	-3.892	0.037	25.073
18	5133	-3.897	25.000	-3.868	0.029	25.059	-3.852	0.045	25.090
19	5033	-3.865	25.000	-3.840	0.025	25.050	-3.830	0.035	25.071
20	4949	-3.838	25.000	-3.806	0.032	25.064	-3.790	0.048	25.096
21	4847	-3.805	25.000	-3.772	0.033	25.065	-3.756	0.049	25.098
22	4729	-3.767	25.000	-3.738	0.029	25.058	-3.724	0.043	25.086
23	4615	-3.731	25.000	-3.699	0.032	25.064	-3.684	0.047	25.095
24	4491	-3.691	25.000	-3.658	0.033	25.065	-3.641	0.050	25.099
25	4365	-3.651	25.000	-3.626	0.025	25.051	-3.616	0.035	25.070
26	4265	-3.619	25.000	-3.581	0.038	25.075	-3.563	0.056	25.112
27	4133	-3.577	25.000	-3.544	0.033	25.066	3.528	0.049	25.097
28	4003	-3.535	25.000	-3.505	0.030	25.061	3.489	0.046	25.092
29	3897	-3.501	25.000	-3.477	0.024	25.049	-3.470	0.031	25.062
30	3815	-3.475	25.000	-3.433	0.042	25.083	-3.412	0.063	25.127
31	3699	-3.438	25.000	-3.405	0.033	25.067	-3.389	0.049	25.099
32	3591	-3.403	25.000	-3.373	0.030	25.060	3.361	0.042	25.084
33	3495	-3.372	25.000	-3.334	0.038	25.076	-3.317	0.055	25.109
34	3379	-3.335	25.000	-3.296	0.039	25.078	-3.277	0.058	25.115
35	3246	-3.293	25.000	-3.260	0.033	25.066	-3.244	0.049	25.098
36	3132	-3.256	25.000	-3.226	0.030	25.060	-3.216	0.040	25.079
37	3035	-3.225	25.000	-3.186	0.039	25.078	-3.164	0.061	25.121
38	2917	-3.188	25.000	-3.147	0.041	25.081	-3.139	0.049	25.097
39	2803	-3.151	25.000	-3.112	0.039	25.079	-3.095	0.056	25.113
40	2679	-3.111	25.000	-3.074	0.037	25.074	-3.056	0.055	25.109
41	2564	-3.075	25.000	-3.045	0.030	25.060	-3.036	0.039	25.077
42	2465	-3.043	25.000	-2.998	0.045	25.091	-2.975	0.068	25.135
43	2340	-3.003	25.000	-2.970	0.033	25.067	-2.958	0.045	25.089
44	2228	-2.967	25.000	-2.924	0.043	25.086	-2.904	0.063	25.126
45	2106	-2.928	25.000	-2.896	0.032	25.065	-2.882	0.046	25.092
46	2010	-2.897	25.000	-2.864	0.033	25.067	-2.854	0.043	25.085
47	1915	-2.867	25.000	-2.821	0.046	25.093	-2.801	0.066	25.132
48	1787	-2.826	25.000	-2.784	0.042	25.084	-2.765	0.061	25.121
49	1657	-2.784	25.000	-2.753	0.031	25.061	-2.744	0.040	25.080
50	1554	-2.751	25.000	-2.709	0.042	25.084	-2.689	0.062	25.123
51	1447	-2.717	25.000	-2.684	0.033	25.067	-2.675	0.042	25.085
52	1349	-2.686	25.000	-2.642	0.044	25.088	-2.622	0.064	25.127
53	1234	-2.649	25.000	-2.611	0.038	25.075	-2.599	0.050	25.101
54	1118	-2.612	25.000	-2.569	0.043	25.086	-2.550	0.062	25.124
55	996	-2.573	25.000	-2.539	0.034	25.068	-2.525	0.048	25.097
56	896	-2.541	25.000	-2.509	0.032	25.065	-2.502	0.039	25.077
57	799	-2.510	25.000	-2.460	0.050	25.100	-2.436	0.074	25.148
58	681	-2.472	25.000	-2.447	0.025	25.051	-2.438	0.034	25.068
59	580	-2.440	25.000	-2.387	0.053	25.107	-2.366	0.074	25.147
60	468	-2.404	25.000	-2.360	0.044	25.088	-2.372	0.032	25.063
61	387	-2.378	25.000	-2.448	-0.070	24.859	-2.303	0.075	25.150
62	298	-2.349	25.000	-1.895	0.454	25.908	-2.473	-0.124	24.752
63	184	-2.313	25.000	-3.336	-1.023	22.953	-1.568	0.745	26.490
64	96	-2.285	25.000	-0.870	1.415	27.829	4.040	-1.795	21.410
65	0	-2.254	25.000	-2.254	0.000	25.000	-2.254	0.000	25.000

* Ag: aggradation (+)
Dg: degradation (-)

Table C.5. Estimated change of cros-section 2, cases L1, L2, L3, L4

Design		Estimated cross-section changes, Laursen's method after 20 steps							
Any section		Case L1, section 2		Case L2, section 2		Case L3, section 2		Case L4, section 2	
X	Y	X	Y	X	Y	X	Y	X	Y
0.000	2.800	0.000	2.800	0.000	2.800	0.000	2.800	0.000	2.800
4.745	-1.945	4.745	-1.945	4.745	-1.945	4.745	-1.945	4.745	-1.945
7.295	-4.495	7.276	-4.476	7.276	-4.476	7.276	-4.476	7.276	-4.476
32.295	-4.495	32.314	-4.476	32.314	-4.476	32.314	-4.476	32.314	-4.476
34.845	-1.945	34.845	-1.945	34.845	-1.945	34.845	-1.945	34.845	-1.945
39.590	2.800	39.590	2.800	39.590	2.800	39.590	2.800	39.590	2.800

Table C.6. Estimated change of cross-section 32, cases L1, L2, L3, L4

Design		Estimated cross-section changes, Laursen's method after 20 steps							
Any section		Case L1, section 32		Case L2, section 32		Case L3, section 32		Case L4, section 32	
X	Y	X	Y	X	Y	X	Y	X	Y
0.000	3.892	0.000	3.892	0.000	3.892	0.000	3.892	0.000	3.892
4.745	-0.853	4.745	-0.853	4.745	-0.853	4.745	-0.853	4.745	-0.853
7.295	-3.403	7.264	-3.372	7.265	-3.373	7.264	-3.372	7.265	-3.373
32.295	-3.403	32.326	-3.372	32.325	-3.373	32.326	-3.372	32.325	-3.373
34.845	-0.853	34.845	-0.853	34.845	-0.853	34.845	-0.853	34.845	-0.853
39.590	3.892	39.590	3.892	39.590	3.892	39.590	3.892	39.590	3.892

Table C.7. Estimated change of cross-section 63, cases L1, L2, L3, L4

Design		Estimated cross-section changes, Laursen's method after 20 steps							
Any section		Case L1, section 63		Case L2, section 63		Case L3, section 63		Case L4, section 63	
X	Y	X	Y	X	Y	X	Y	X	Y
0.000	4.982	0.000	4.982	0.000	4.982	0.000	4.982	0.000	4.982
4.745	0.237	4.745	0.237	4.745	0.237	4.745	0.237	4.745	0.237
7.295	-2.313	7.269	-2.287	7.283	-2.301	7.399	-2.417	8.318	-3.336
32.295	-2.313	32.321	-2.287	32.307	-2.301	32.191	-2.417	31.272	-3.336
34.845	0.237	34.845	0.237	34.845	0.237	34.845	0.237	34.845	0.237
39.590	4.982	39.590	4.982	39.590	4.982	39.590	4.982	39.590	4.982

Table C.8. Estimated change of cross-section 64, cases L1, L2, L3, L4

Design		Estimated cross-section changes, Laursen's method after 20 steps							
Any section		Case L1, section 64		Case L2, section 64		Case L3, section 64		Case L4, section 64	
X	Y	X	Y	X	Y	X	Y	X	Y
0.000	5.010	0.000	5.010	0.000	5.010	0.000	5.010	0.000	5.010
4.745	0.265	4.745	0.265	4.745	0.265	4.745	0.265	4.745	0.265
7.295	-2.285	7.238	-2.228	7.215	-2.205	6.438	-1.428	5.880	-0.870
32.295	-2.285	32.352	-2.228	32.375	-2.205	33.152	-1.428	33.710	-0.870
34.845	0.265	34.845	0.265	34.845	0.265	34.845	0.265	34.845	0.265
39.590	5.010	39.590	5.010	39.590	5.010	39.590	5.010	39.590	5.010

Table C.9. Estimated change of cross-section 2, cases Y1, Y2, Y3, Y4

Design		Estimated cross-section changes, Yang's method after 20 steps							
Any section		Case Y1, section 2		Case Y2, section 2		Case Y3, section 2		Case Y4, section 2	
X	Y	X	Y	X	Y	X	Y	X	Y
0.000	2.800	0.000	2.800	0.000	2.800	0.000	2.800	0.000	2.800
4.745	-1.945	4.745	-1.945	4.745	-1.945	4.745	-1.945	4.745	-1.945
7.295	-4.495	7.265	-4.465	7.265	-4.465	7.265	-4.465	7.265	-4.465
32.295	-4.495	32.325	-4.465	32.325	-4.465	32.325	-4.465	32.325	-4.465
34.845	-1.945	34.845	-1.945	34.845	-1.945	34.845	-1.945	34.845	-1.945
39.590	2.800	39.590	2.800	39.590	2.800	39.590	2.800	39.590	2.800

Table C.10. Estimated changes of cross-section 32, cases Y1, Y2, Y3, Y4

Design		Estimated cross-section changes, Laursen method's after 20 steps							
Any section		Case Y1, section 32		Case Y2, section 32		Case Y3, section 32		Case Y4, section 32	
X	Y	X	Y	X	Y	X	Y	X	Y
0.000	3.892	0.000	3.892	0.000	3.892	0.000	3.892	0.000	3.892
4.745	-0.853	4.745	-0.853	4.745	-0.853	4.745	-0.853	4.745	-0.853
7.295	-3.403	7.251	-3.359	7.253	-3.361	7.251	-3.359	7.253	-3.361
32.295	-3.403	32.339	-3.359	32.337	-3.361	32.339	-3.359	32.337	-3.361
34.845	-0.853	34.845	-0.853	34.845	-0.853	34.845	-0.853	34.845	-0.853
39.590	3.892	39.590	3.892	39.590	3.892	39.590	3.892	39.590	3.892

Table C.11. Estimated change of cross-section 63, cases Y1, Y2, Y3, Y4

Design		Estimated cross-section changes, Yang's method after 20 steps							
Any section		Case Y1, section 63		Case Y2, section 63		Case Y3, section 63		Case Y4, section 63	
X	Y	X	Y	X	Y	X	Y	X	Y
0.000	4.982	0.000	4.982	0.000	4.982	0.000	4.982	0.000	4.982
4.745	0.237	4.745	0.237	4.745	0.237	4.745	0.237	4.745	0.237
7.295	-2.313	7.269	-2.287	7.304	-2.322	6.500	-1.518	6.550	-1.568
32.295	-2.313	32.321	-2.287	32.286	-2.322	33.090	-1.518	33.040	-1.568
34.845	0.237	34.845	0.237	34.845	0.237	34.845	0.237	34.845	0.237
39.590	4.982	39.590	4.982	39.590	4.982	39.590	4.982	39.590	4.982

Table C.12. Estimated change of cross-section 64, cases Y1, Y2, Y3, Y4

Design		Estimated cross-section change, Yang's method after 20 steps							
Any section		Case Y1, section 64		Case Y2, section 64		Case Y3, section 64		Case Y4, section 64	
X	Y	X	Y	X	Y	X	Y	X	Y
0.000	5.010	0.000	5.010	0.000	5.010	0.000	5.010	0.000	5.010
4.745	0.265	4.745	0.265	4.745	0.265	4.745	0.265	4.745	0.265
7.295	-2.285	7.206	-2.196	7.158	-2.148	8.930	-3.920	9.090	-4.080
32.295	-2.285	32.384	-2.196	32.432	-2.148	30.660	-3.920	30.500	-4.080
34.845	0.265	34.845	0.265	34.845	0.265	34.845	0.265	34.845	0.265
39.590	5.010	39.590	5.010	39.590	5.010	39.590	5.010	39.590	5.010

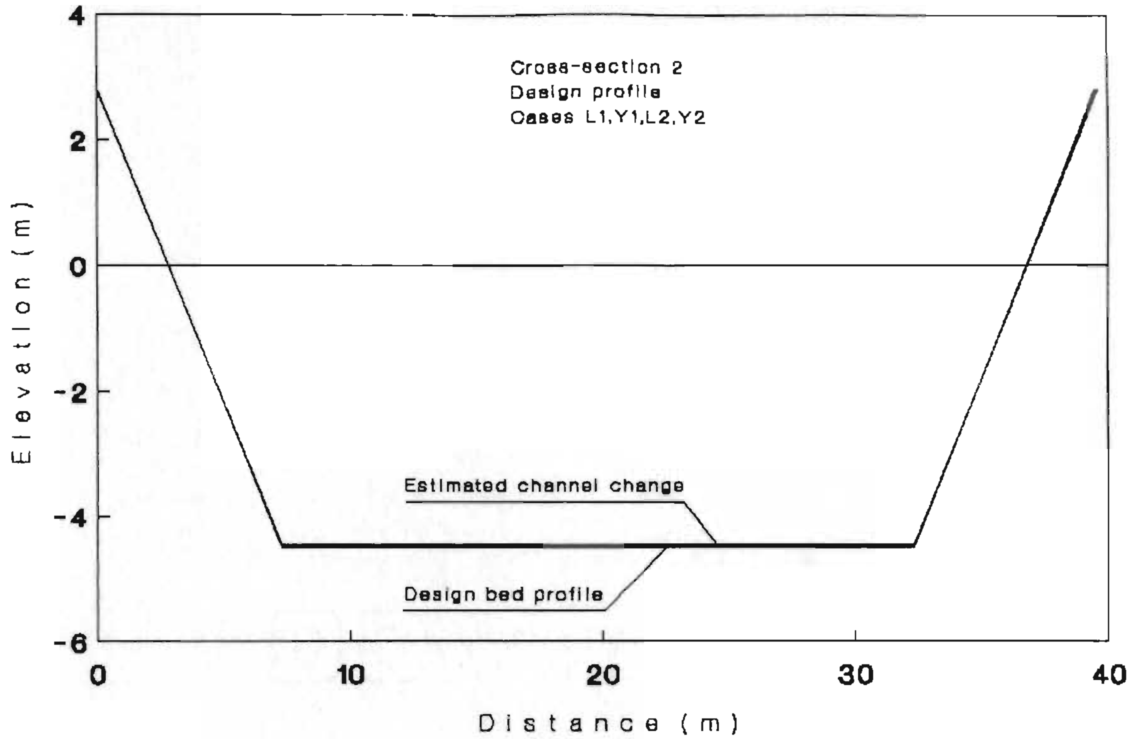

Figure C.1. Estimated changes in cross-section 2.

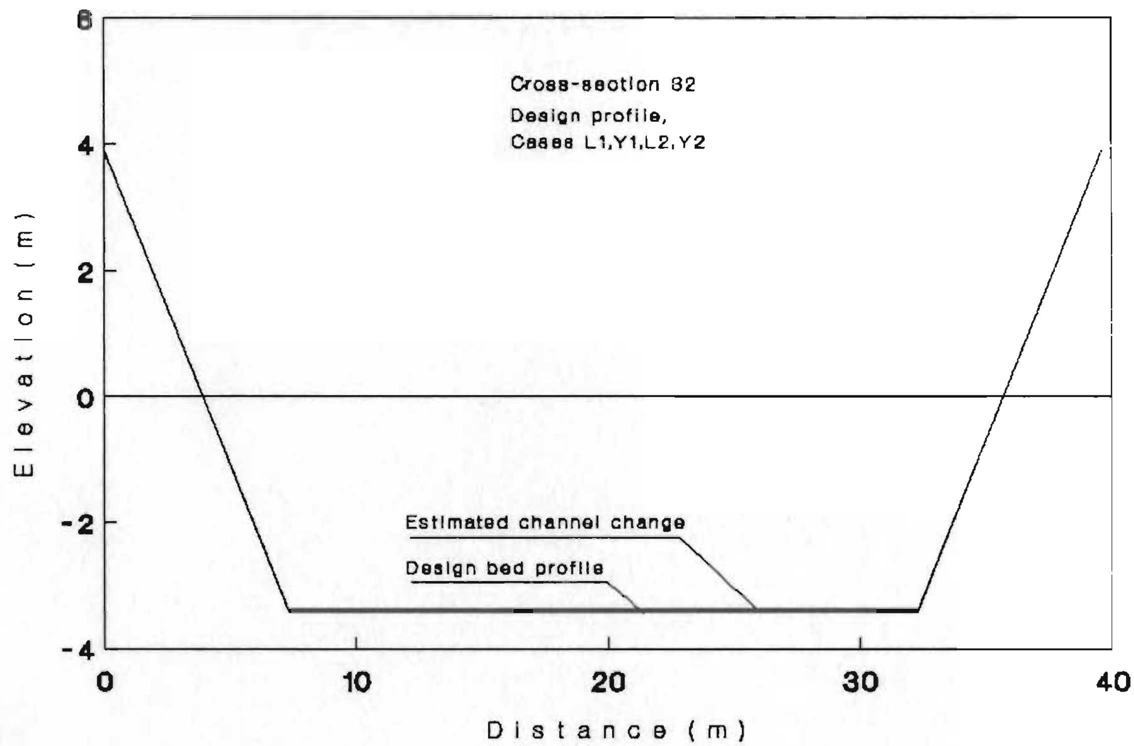

Figure C.2. Estimated changes in cross-section 32.

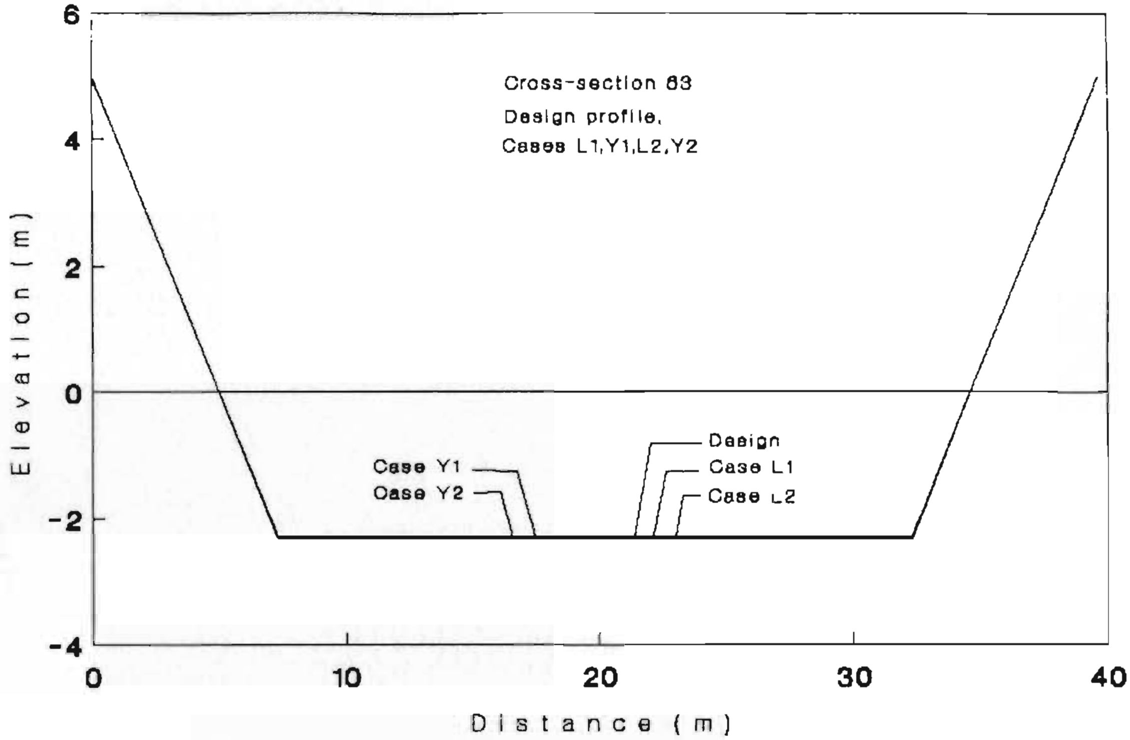

Figure C.3. Estimated changes in cross-section 63.

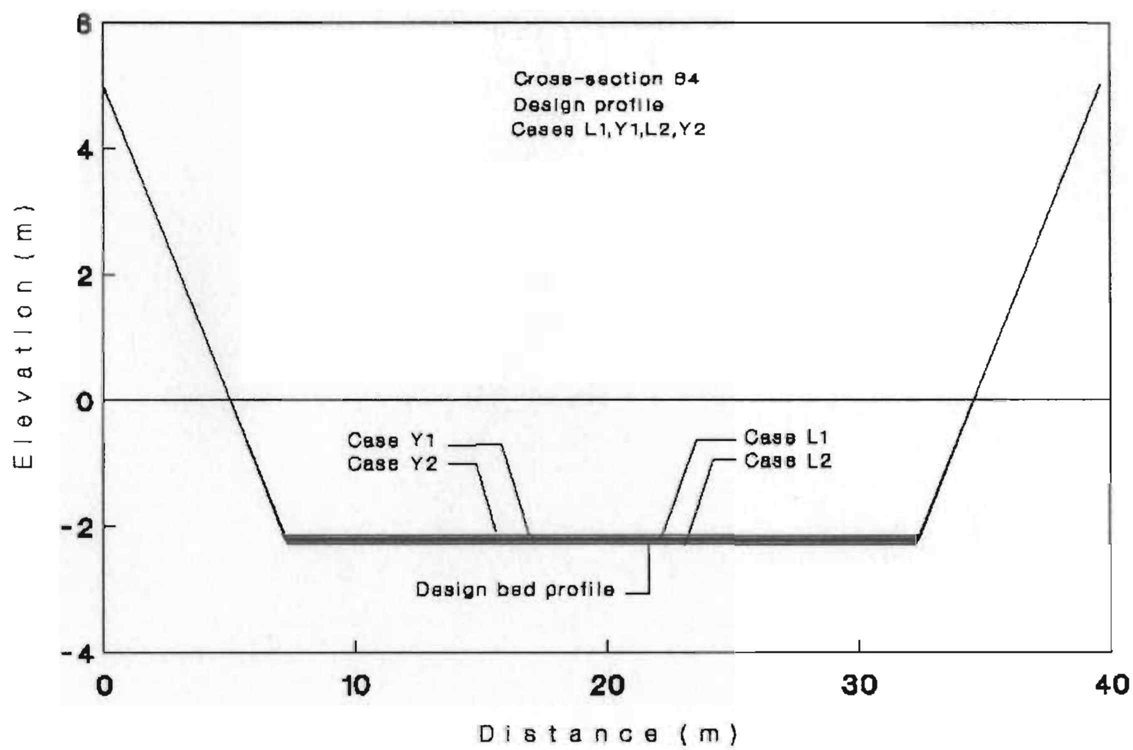

Figure C.4. Estimated changes in cross-section 64.

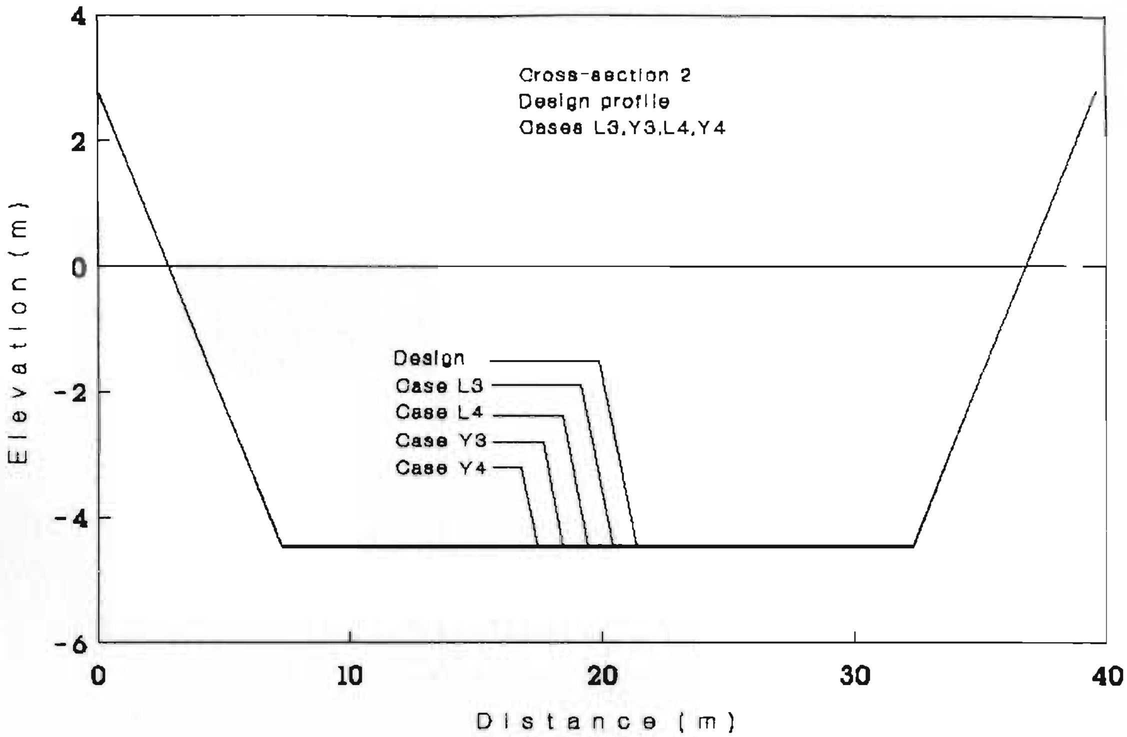

Figure C.5. Estimated changes in cross-section 2.

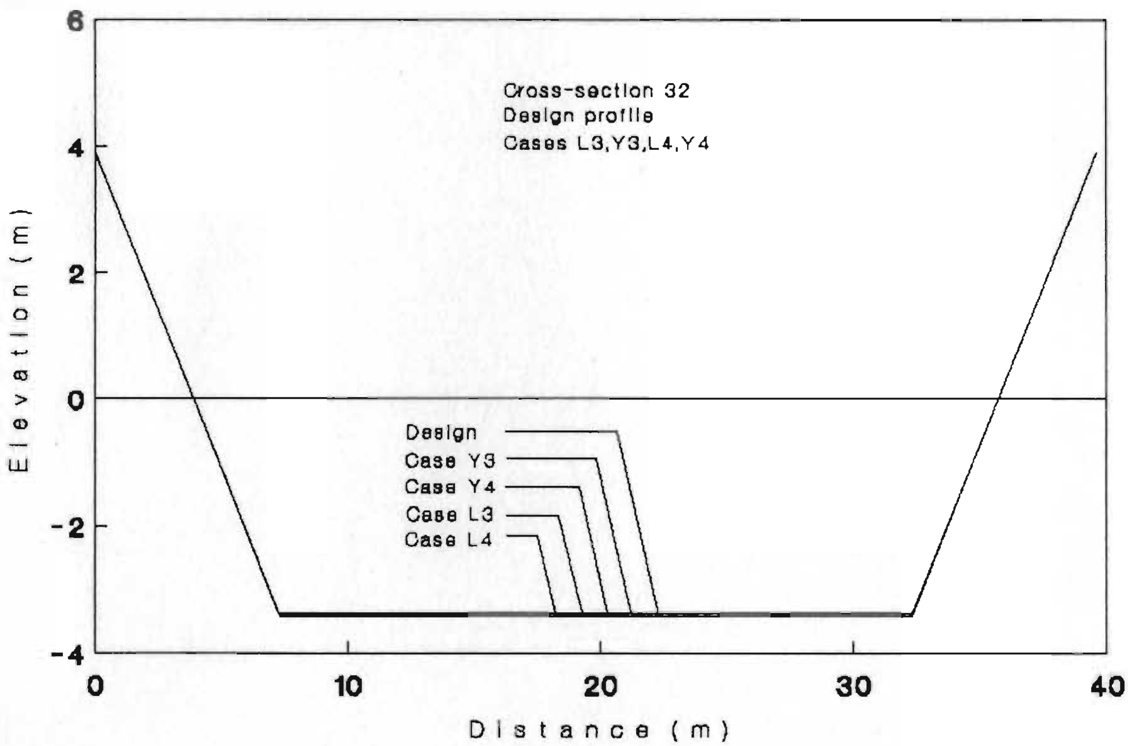

Figure C.6. Estimated changes in cross-section 32.

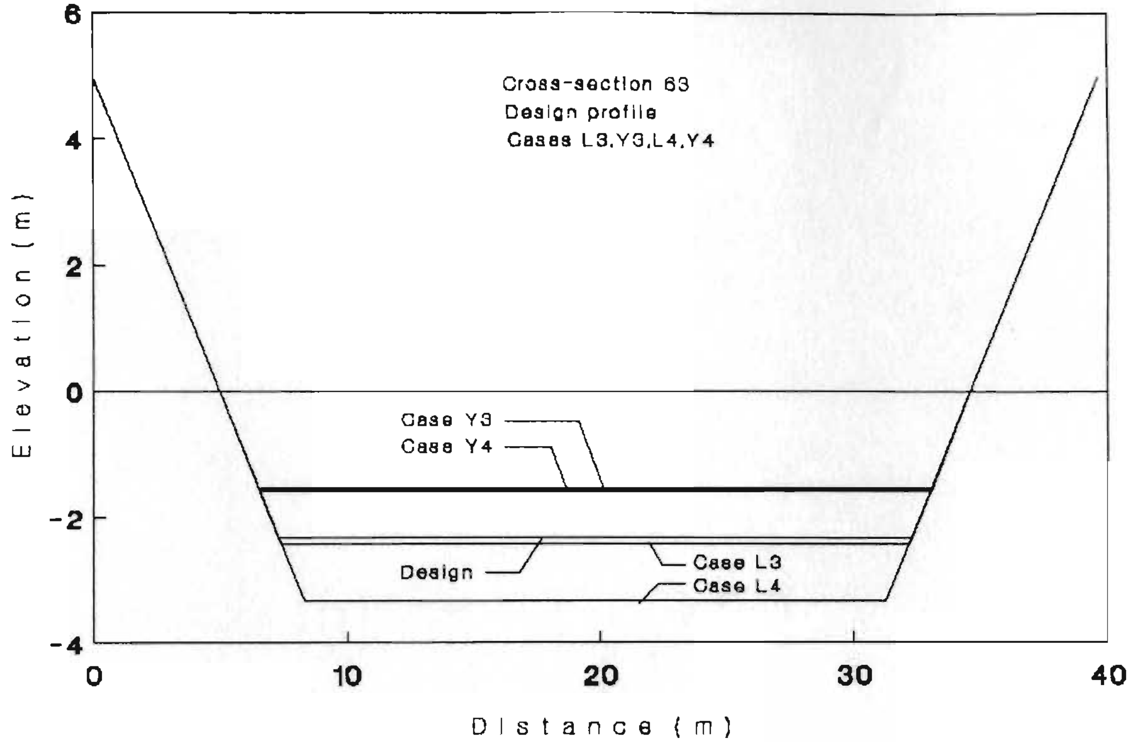

Figure C.7. Estimated changes in cross-section 63.

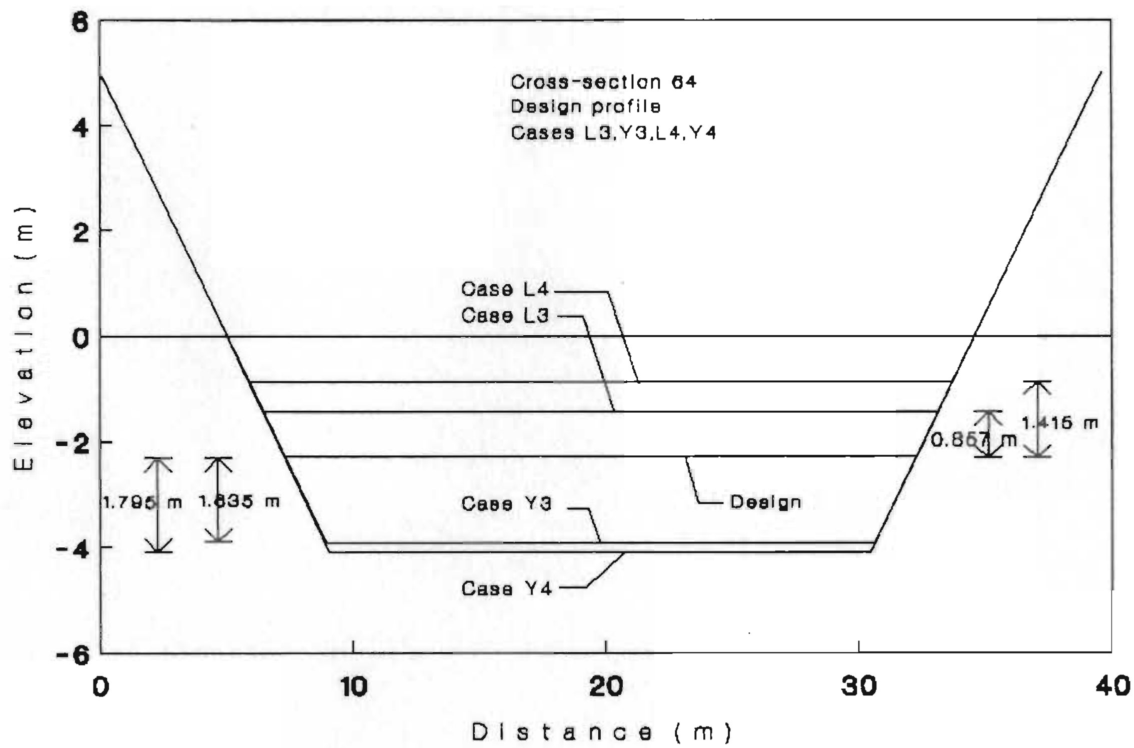

Figure C.8. Estimated changes in cross-section 64.

Appendix - D

Equations used for Hydraulic Geometry Calculations

This appendix gives the computation of the geometric elements using X,Y coordinates. The geometric elements are cross-sectional area, wetted perimeter, hydraulic radius, and top width (see Figure D.1).

There were two possible conditions for the intersection of the water surface with the channel banks. The first intersection was located at either the coordinate point at the left bank (point 1, and 2), the right bank (point 5, and 6) or both. The second possible intersection was between two coordinate points such that the calculation of their geometric elements was solved by interpolation. The calculation of the geometric elements are summarized as follows:

The wetted perimeter P was calculated as the summation of the distances between adjoining coordinate points, from water level at left bank to water level at right bank.

$$P: \{(Y_2 - Y_{lef})^2 + (X_2 - X_{lef})^2\}^{1/2} + \{(Y_3 - Y_2)^2 + (X_3 - X_2)^2\}^{1/2} + \{(Y_4 - Y_3)^2 + (X_4 - X_3)^2\}^{1/2} + \{(Y_5 - Y_4)^2 + (X_5 - X_4)^2\}^{1/2} + \{(Y_{rght} - Y_5)^2 + (X_{rght} - X_5)^2\}^{1/2} \quad (D.1)$$

The cross-sectional area A was taken as the total area of the series of triangles B2E, C3F, E4G, and F5H.

$$A:\ 1/2\ \{ (X_3 - X_{lef})(Y_2 - Y_{lef}) \} + 1/2\ \{ (X_4 - X_2)(Y_3 - Y_{lef}) \} + 1/2\ \{ (X_5 - X_3)(Y_4 - Y_{lef}) \} + 1/2\ \{ (X_{rght} - X_4)(Y_5 - Y_{lef}) \} \quad (D.2)$$

The hydraulic radius R and width of top surface width TW were calculated as:

$$R:\ A/P \quad (D.3)$$

$$TW:\ X_{rght} - X_{lef} \quad (D.4)$$

where:

Y_{max}: the largest Y coordinate, in this case, Y3

D: water depth,

Y_{lef}: Y_3 - D,

Y_{rght}: Y_{lef},

$$\tan \alpha_L = \frac{Y_2 - Y_1}{X_2 - X_1} \qquad \tan \alpha_R = \frac{Y_5 - Y_6}{X_6 - X_5}$$

$$X_{lef} = X_2 - \frac{Y_2 - Y_{lef}}{\tan \alpha_L} \qquad Y_{rght} = X_6 - \frac{Y_{rght} - Y_6}{\tan \alpha_R}$$

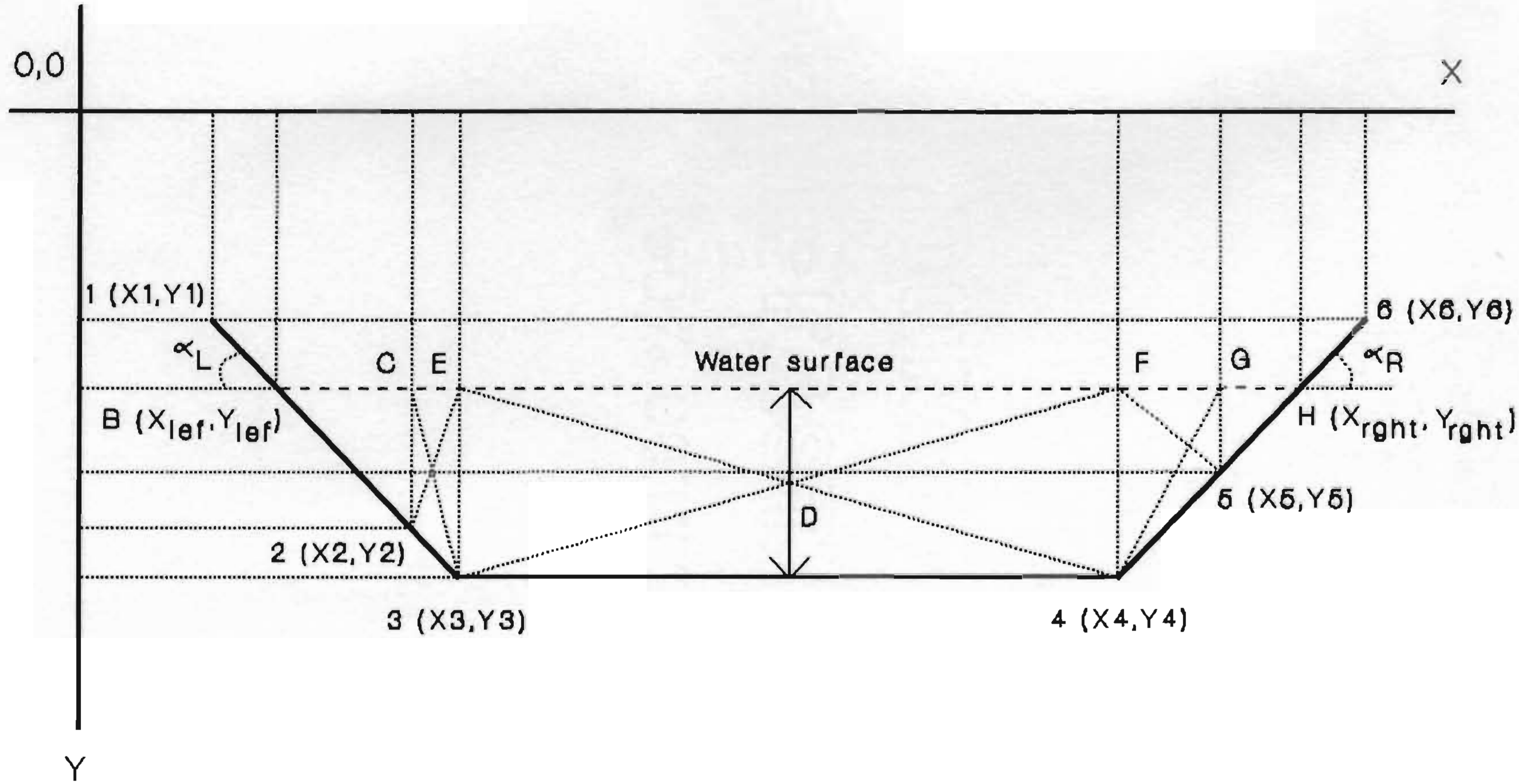

Figure D.1. Local cross-section coordinate system.