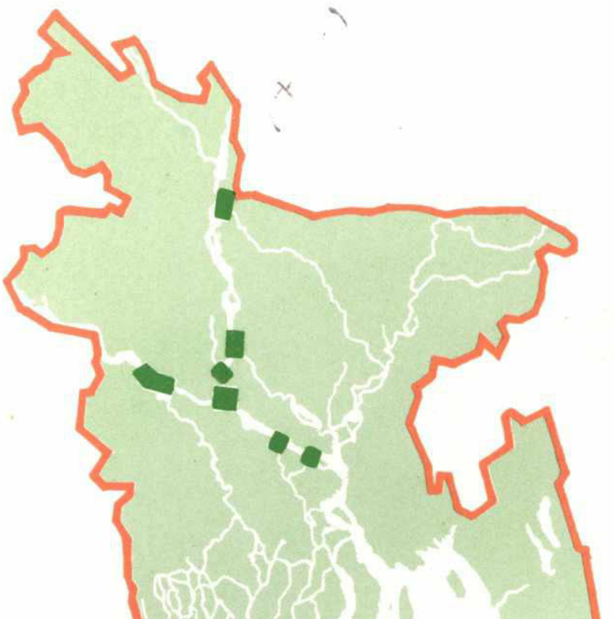
GOVERNMENT OF BANGLADESH
FLOOD PLAN COORDINATION ORGANIZATION

FAP 24 RIVER SURVEY PROJECT

Study Report 5

Qualitative impact assessment of FAP implementation



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Project ALA/90/04 — Commission of the European Communities

Study Report 5

Qualitative impact assessment of FAP implementation

November 1995

FAP 24 **RIVER SURVEY PROJECT**

DELFT-DHI

Flood Plan Coordination Organization

Commission of the European Communities

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March 02, 1996

Mr. M. H. Siddique
Director General
Water Resources Planning Organization (WRPO)
7 Green Road, Dhaka

Attention	:	Afzalur Rahman Principle Scientific Officer
Subject	:	Study Report No. 5
Reference	:	RSP/9.1/1809

Dear Sir,

With pleasure we submit herewith Study Report No. 5 dealing with the qualitative impact assessment of FAP implementation. This assessment was one of the Phase 1 study tasks of the River Survey Project (ToR, Subsection 4.2.7). This Study Report No. 5 is a reprint of our Working Paper No. 2, submitted to you on March 21, 1994. An update of some of our conclusions will be included in our Final Report.

Thanking you.

Yours sincerely

Johan G. Grijsen
Team Leader.

Executive summary

In this report a quantitative assessment of the impact of the implementation of FAP on the main river system is made. The assessment is limited to the hydraulic and morphological impact. Whether or not a certain development is acceptable or even preferable from environmental or socio-economic point of view is not studied here.

The assessment is done on the basis of the present knowledge of the main river system of Bangladesh as laid down in two FAP 24 reports, notably Study Report 1 (Selection of Study Topics Phase 2) and Study Report 3 (Morphological Studies Phase 1), and on the results of the hydraulic simulations carried out by FAP 25, in particular Annex 2 of the Main Report (Analysis of country-wide protection schemes).

The assessment was done in some subsequent stages. Firstly the results presented in FAP 25 were analysed as far as changes in discharges in the main rivers were concerned. Then the so-called Lane's balance was applied to assess the ultimate conditions in the main rivers. Next the intermediate conditions were assessed in a qualitative way. Finally the impact on the distributaries was estimated, together with the possible feedback on the main rivers.

The results demonstrate that the initial increase in stages in some rivers (in particular the Padma, Jamuna and Ganges Rivers) will in due time probably change to a reduction in stages. Rough estimate indicate degradation and lowering of stages of more than 0.6 m, for most of the main rivers apart from the Upper and Lower Meghna Rivers. This degradation will only materialize fully after 50 to 100 years or more. An important finding of the present assessment is that the assessment for the distributaries cannot be fully done in a deterministic way. The development of the distributaries is at least partly determined by phenomena which are varying in time, hence the period and sequence of implementation of the various projects may be important. The present assessment supports the selection of study topics as proposed by FAP 24 and underlines the need to improve the understanding of the behaviour of off-takes.

Finally it is remarked that the present assessment is a very preliminary one only. It should be followed by more detailed assessments in due time, in which also the sequence of projects and possible adaptations should be studied as part of the development of a well-balanced FAP.

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Notation

Symbol	Meaning	Unit
B	Channel width	(m)
C	Chezy's roughness parameter	($m^{1/2}$/s)
D	Bed material size	(mm)
D_{50}	Median Particle diameter	mm
g	Acceleration due to gravity	(m/s^2)
h	Average water depth	(m)
i	River slope	(m/m)
i_v	Valley slope	(m/m)
k	Number of parallel channels of a braided river	(-)
L	Length of river reach	(m)
m	Coefficient in simplified sediment transport formula	(various)
n	Power of velocity in simplified sediment transport equation	(-)
p	Sinuosity, power of particle diameter in simplified sediment transport equation	(-)
Q	River discharge	(m^3/s)
Q_b	Bank full discharge	(m^3/s)
R	Hydraulic radius	(m)
S	Sediment transport	(m^3/s)
s_t	Total sediment transport per unit width	(m^2/s)
s_b	Bed load per unit width	(m^2/s)
t	Time coordinate	(s)
u	Flow velocity	(m/s)
V	Sediment transport integrated over the year	(m^3)
x	Longitudinal coordinate	(m)
z_b	Bed level	(m)
α_Q	Correction for variability of the discharges in a river	(-)
ρ	Density of water	(kg/m^3)
$\triangle$	Relative Density	
ϵ	Porosity	
μ	Ripple factor	
ψ^1	Effective dimensionless shear stress	($\mu\psi$)

Indices

b	bank-full
o	original situation (present state)
1	changed value (after FAP implementation)

1 Introduction

1.1 Rationale

In the Terms of Reference of FAP 24 it is stated that in phase 1 of the project "a preliminary assessment of the morphological characteristics of the rivers, their shifting characteristics and expected response in qualitative terms as different components of the FAP are implemented" has to be made. In the present report this qualitative assessment is presented.

1.2 Phase 2 activities

In the Terms of Reference an indication is given of "the Possible studies that the Consultants may be requested to undertake" for phase 2 and one of the items mentioned specifically there is "a quantitative assessment and evaluation of river response with respect to implementation of various FAP projects". Since the awarding of the contract and in particular during the Workshop on Alluvial Rivers that was held in Dhaka last November, it has become clear that most probably the phase 2 activities related to the impact assessment will be transferred to a new project. Hence the present report could be the only report dealing with impact assessment to be published by FAP 24.

1.3 Relation to other phase 1 activities

Under phase 1 of FAP 24 an assessment of the morphological characteristics of the main river system in Bangladesh was made (see Study Report 1 "Selection of Phase 2 study topics"). Furthermore a more extensive analysis of existing data on the morphological characteristics of the main rivers and the distributaries is provided in Study Report 3("Morphological Studies Phase 1"). Here it is assumed that the reader is familiar with the relevant parts of the contents of these reports.

1.4 Approach

The approach taken here is to accept the results of the analysis by FAP 25 as far as the impact of FAP on hydraulic conditions is concerned. Hence Annex 2 of the FAP 25 Flood Hydrology Study is used here as a basis.

Regarding the morphological changes, which result again in changes of discharges and stages, a distinction is made between the ultimate effects and the intermediate effects. The *ultimate effects* relate to a new equilibrium condition and they will be approached after a long time only. Preliminary estimates on the basis of a 1-dimensional morphological model investigation under the Jamuna Bridge Study (see RPT et al, 1990) indicate that bed degradation and aggradation for the main rivers in Bangladesh due to local changes in the system have a time scale in the order of 50 to 100 years. Changes in plan-form probably have a time scale in the scale of several centuries. This means that only after a fairly long period a new equilibrium will have established. *Intermediate effects* are related to the transition between the present conditions and the new equilibrium. Hence these are of more interest for the coming decades. Ultimate conditions can be determined using Lane's balance (see Annexure 2), in combination with estimates of changes in width and plan-form (number of channels and sinuosity). Intermediate conditions are usually assessed using 1-dimensional morphological models, but here, only some qualitative considerations are given.

Because of the complexity of the system (several bifurcations and confluences), the estimate for the future equilibrium conditions is done in some steps. First estimates are made of the impact of the hydraulic changes on the ultimate slopes of the main rivers using an improved Lane's balance and (in a second step) the consequences for the water and sediment distribution at the main offtakes are assessed. Then also the possible effects on the distributaries are estimated. In first instance the analysis is limited to the ultimate effects, but subsequently also the intermediate effects are indicated. The assessment is completed with a discussion of some elements that can not easily be included in even a qualitative assessment : changes in width and plan-form. Also the possible impact in relation to natural developments are reviewed in the discussion.

1.5 Accuracy of assessment

It should be stressed here that the qualitative assessment made in this report is indeed only a very first estimate to assess the impact of FAP on the river system. This is so for a number of reasons. First of all the understanding regarding the river system, the interaction between the different reaches and the importance of overland flow is still very meagre. This limits the possibilities for making predictions.

Another and even more serious drawback is that more future "equilibrium" conditions may be possible. In that case, the one that will finally materialize depends fully on the intermediate conditions. This can be illustrated by considering the role of the distributaries in the system. If during the intermediate conditions the stages near bifurcations are for some decades larger than they used to be and if at the same time less sediment is entering (e.g. due to a favourable local plan-form), the dying of the distributaries (which was observed in Study Report 1) may be reversed to a distributary increasing in importance again. The same holds for human interference; owing to the implementation of remedial measures, it is possible that the system develops in a slightly different direction. This should be taken into account when evaluating the present assessment of FAP.

2 Frame-work for analysis

2.1 Systems approach

In line with the approach adopted in Study Report 1, here the main river system of Bangladesh is considered as a progress-response system. A process-response system consists of a cascade system, in which water and sediment are cascading downstream and a number of morphological systems. Here these morphological systems are river reaches. These reaches are mutually connected at bifurcation and/or confluences may be split up in more reaches if there is a substantial change in flows, yearly sediment transport or particle diameters. The morphology (the "form" of rivers, hence the river characteristics) of river reaches is determined by the flows they carry, the yearly volume of sediment transport and its size characteristics and conditions (clayey outcrops, previous plan-form and channel conditions, if the river is still adjusting to new conditions).

2.2 Application of Lane's balance for ultimate conditions

The approach adopted here for the qualitative assessment of the ultimate conditions by the application of Lane's balance. This balance, proposed by Lane (1955), is applicable for the ultimate equilibrium conditions in a river. In an adapted form (see Klaassen, 1994 and Annexure 2) for a system with one channel this balance reads :

$$V D^{p} B^{\frac{n-3}{n}} :: \alpha_Q \overline{Q}^{\frac{n}{3}} i^{\frac{n}{3}} \quad (2.1)$$

where V = yearly sediment transport, D = particle size, B = width of river, α_Q = coefficient related to the deviation of the discharges in the river from the average discharge conditions, $\overline{Q}$ = average discharges in the river, and i = slope of the river. The coefficients p and n are representative for the sensitivity of the sediment transport for changes in the velocity and the particle size respectively, where it is assumed that :

$$S = m_1 D^{-p} u^{n} \quad (2.2)$$

where s = sediment transport per unit width and u = average flow velocity. The values of p and n officially still have to be assessed for the various rivers in Bangladesh. It was demonstrated in e.g. Klaassen et al (1988), that the Engelund-Hansen sediment transport predictor holds with some minor adjustments for the Jamuna River. For the time being it is assumed that for all the main rivers in Bangladesh this predictor gives a fair estimate. Hence, as is demonstrated in Annexure 1, p = 1 and n = 5. The value of m_1 is not relevant when comparisons between equilibrium conditions are made.

The response of a river system to changes in e.g. the flow rates in the river, supposing that all the other factors remain the same, can be determined with

Lane's balance. As is shown in Annexure 2, it holds that for a change of Q_0 to Q_1 the slope of the river changes according to :

$$\frac{i_1}{i_0} = \frac{Q_0}{Q_1} \qquad (2.3)$$

If also the width of the river may change, e.g. according to a regime relation (B :: $Q^{0.5}$), then the above Equation (2.3) transforms to :

$$\frac{i_1}{i_0} = \left(\frac{Q_0}{Q_1}\right)^{\frac{n+3}{2n}} \qquad (2.4)$$

This implies in most cases a less serious increase of the ultimate slope of the river, as (for n > 3) the power of Equation (2.4) is less than that of Equation (2.3). Similar relations can be derived for the diversion of water, e.g. for the case a distributary is starting to take more water than before. Lane's balance is used here to make a quantitative assessment of the impact of FAP.

Although the application of Lane's balance has some limitations, it is felt that the results will be fair when applied to the main rivers. For the distributaries it holds however that they are much more dependent on the intermediate conditions (see hereafter) and on the water and sediment distribution at the offtakes (see Section 3.4).

2.3 Intermediate changes

Intermediate changes are changes that occur in the period of transition (until a new equilibrium has established). These changes relate to (i) changes in bed levels and (ii) changes in width and plan-form. As outlined in Section 1.4, these changes have usually different time scales. Hence it may be allowable to assume that during at least the first decades of the transition period the plan-form characteristics of the rivers are not adjusting too much. Hence the application of a 1-dimensional approach may be acceptable for this first period. In this stage the application of such a model does not seem warranted within the present analysis, because as is indicated in the previous chapter the more quantitative assessment of the FAP impact will probably be done within the frame-work of a separate project. Hence here a more qualitative approach is used.

The approach taken here is that the results of the analysis by FAP 25 (as laid down in FAP 25 (1993)) are accepted and on that basis the effect on the bed levels and on the discharge and sediment distribution at the bifurcations are assessed. The possible consequences for the development of the distributaries is outlined and in a second step the possible impact on the main rivers is indicated. The possible consequences for the final equilibrium are indicated subsequently together with the effect on the equilibrium stages, discharges and bed levels.

In doing this it will be found that the present system may develop in different directions, depending on the intermediate conditions. Hence it will be found that it is impossible to indicate beyond any doubt the future state of the river system. For more details on these aspects see Section 5.4 and the discussions in Chapter 6.

2.4 Natural changes, effect of other developments and FAP impact

As is outlined in Study Report 1, there are strong indications that the main river system of Bangladesh is still in an adjustment stage as a response to (1) the major change in course of the Brahmaputra River some 200 years ago and possibly (2) recent tectonic movements. Hence the possible impact of FAP will materialize in combination with future adjustments of the river system.

As far as the different river reaches are concerned, the adjustment as a response to natural changes can be summarized as follows :

- The Jamuna River upstream of Sirajganj is still widening and possibly moving in Western direction.

- The plan-form of the Jamuna River South of Sirajganj is still widening and possibly still becoming more braided (increasing braiding index = average number of parallel channels).

- The Padma River near Mawa appears to be constricted (due to clay out-crops ?) and is possibly adjusting its width very slowly. In due time (many centuries ?) its width may become comparable to the Jamuna River (widening from the present 3 km as a minimum to 15 km ?), with a related increase in slope (see Lane's balance and Annexure 1).

- The Upper Meghna River is in a process of adjustment from a braided river to a meandering one.

- Both the Old Brahmaputra and Dhaleswari River seem to loose importance. It could be that in due time (and without human interference) these distributaries are "dying".

Apart from adjustments to natural changes, also other developments may have their effect on the behaviour of the main river system of Bangladesh. These developments, mostly related to human interference with the river and changes in the catchment (also as consequence of human activities) amongst others are:

- Deforestation in the catchment (and more generally changes in land use) that could result in more sediment production and higher flood waves.

- Embankments in the Indian parts of the catchment.

- Major water diversions.

o Sea level rise.

It is worthwhile to note that already some exploring computations regarding the effect of such changes were done under both Jamuna Bridge Study (RPT et al, 1990) and within the frame-work of FAP 1. Although not done here, it is possible to include the outcomes of these exploring studies in an analysis of possible future directions in which the riverine conditions may go. In this respect it was found that the non-linearity of the describing system of equations plays a minor role only, hence that the effect of e.g. sea level rise for a first assessment can simply be added to the outcome of the present analysis. This holds only for aggradation and degradation; width and plan-form changes are much more complex and need special attention in a later stage.

The impact of FAP implementation will be noticeable as superimposed on these "natural" adjustments, which can only be assessed roughly as they belong to almost unpredictable natural behaviour and to developments which can not be foreseen. This makes it more difficult to make estimates of the real future development and subsequent changes in stages, discharges and bed levels in the different branches of the main river system.

3. Main river system of Bangladesh

3.1 General

In Study Report 1 an extensive description of the river system of Bangladesh is included. It is assumed that the reader is familiar with this description and hence with the main river characteristics. The main river system in Bangladesh consists of the lower reaches of the three large rivers that enter into the Bay of Bengal via Bangladesh, notably the Brahmaputra River, the Ganges River and the Meghna River. More specifically the following rivers are considered to belong to the main river system in Bangladesh (see Figure 3.1) :

- o Brahmaputra/Jamuna River,
- o Ganges River,
- o Upper Meghna River,
- o Padma River,
- o Lower Meghna River,
- o Old Brahmaputra River,
- o Dhaleswari River,
- o Gorai River,
- o Dubaldia/Arial Khan Rivers.

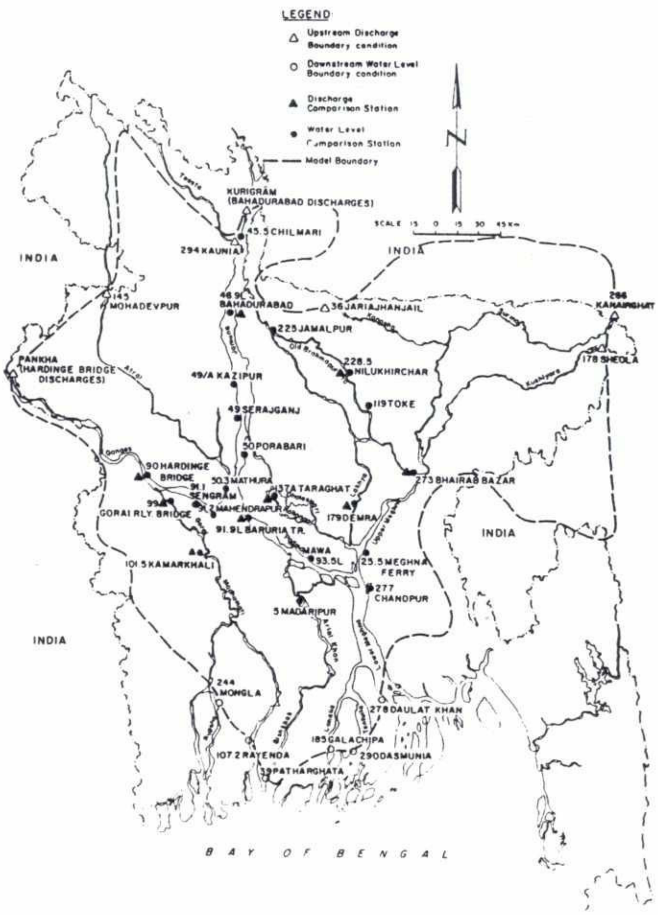


Figure 3.1 Main river system in Bangladesh with key hydrological stations.

Hereafter the main river system is divided into :

- Main rivers,
- Distributaries.

The distributaries branch off from the main rivers and hence depend for their discharge and sediment mainly on these main rivers. Apart from that, they also have a function for local drainage of excess rainfall in the areas adjacent to them.

The main rivers are the first five rivers of the above listing (Brahmaputra/Jamuna River, Ganges River, Upper Meghna River, Padma River and Lower Meghna River) and the distributaries are the remaining four (Old Brahmaputra River, Dhaleswari River, Gorai River and the Dubaldia/Arial Khan Rivers). In line with study Report 1 the Padma and the Lower Meghna River are considered here as one river system. The reasoning behind this is that the Lower Meghna is nowadays more the continuation of the Padma River rather than the lower reach of the Upper Meghna River.

3.2 Main Rivers

The following main rivers belong to the main system in Bangladesh :

- o Brahmaputra/Jamuna River,
- o Ganges River,
- o Upper Meghna River,
- o Padma River,
- o Lower Meghna River,

In the following Table 3.1 the main characteristics of these five rivers are summarized. Note that in particular the characteristics are given which are of relevance for Lane's balance. For the width B the combined width of the channels is given for a braided system.

River	Q average (m^3/s)	α_Q (-)	V ($10^6 m^3$)	D_{50} (mm)	B (km)	i (10^{-3}m/m)
Brahmaputra/Jamuna River	20,400	1.2	206	0.23-0.15	4	0.1-0.06
Ganges River	10,600	1.2	195	0.12	3-5	0.05
Padma River	28,400	1.15	361	0.09	4-10	0.05
Upper Meghna River	4,500	1.2	12.5	0.14	0.5	0.02
Lower Meghna River	n.a.	1.2	n.a.	0.09	2.5-5	0.05

n.a. = not available

Table 3.1 Some characteristics of the main rivers

For the response of these rivers to changes, e.g. as a consequence of FAP, it is important to distinguish the main rivers as to the number of freedoms they have in adjusting to changed conditions. Further on the concept of a river as a cascade system, the imposed variables in a reach are the average discharge Q, α_Q (representing the duration curve), V and D_{50}. The dependent variables in a reach are the number of channels, the width of the channels and the sinuosity of these channels and the slope of the water surface (corresponding to the slope of the river bed for uniform conditions). The water depth is also a dependent variable and varies for varying discharges. Most of the main rivers (and the distributaries) in Bangladesh are fairly simple as they are meandering (implying that the number of channels is 1). Only braided reaches have a large number of freedoms.

The dependent characteristics of the main rivers can be described as follows :

o *Brahmaputra/Jamuna River*
Braided river with a braiding index of 3 upstream and 2 downstream. Sinuosity of the braided channels is about 1.1.

o *Ganges River*
Meandering river with a fairly straight overall course and a sinuosity of about 1.3. Near Hardinge bridge a stable section, but at downstream the river widens again, resulting in the development of alternate bars travelling through the system.

o *Padma River*
Straight river constricted in width probably due to clayey outcrops. If width was free to adjust the river would probably be a braided river with a braiding index of 3. In the constricted reach (near Mawa) alternate bars are travelling through the system.

o *Upper Meghna River*
A river in transition from a braided system to a meandering one. Due to the very low sediment loads (probably as a result of the subsidence of the upstream reaches) this adaptation takes place at a very slow rate.

o *Lower Meghna River*
A fairly straight river, which is quite constricted near Chandpur due to the sharp bend. More downstream the tidal influence is gradually taking over.

As will be shown later only the Brahmaputra/Jamuna system may react in a more complicated way than indicated by Lane's balance. This is due to the fact that a braided river system may change its number of channels as well. It can be shown that an increase in braiding index, together in combination with $B :: Q^{0.5}$ for the individual channels, results in a slight increase in slope of the river (Klaassen, 1994).

3.3 Distributaries

There are four distributaries which belong to the main river system in Bangladesh.

- Old Brahmaputra River,
- Dhaleswari River,
- Gorai River,
- Dubaldia/Arial Khan Rivers.

These distributaries are actually all some kind of overflow rivers. They carry flow in particular during the flood season. The main river from which they "originate" is listed hereafter :

- Old Brahmaputra River	from	Brahmaputra River
- Dhaleswari River	from	Jamuna River
- Gorai River	from	Ganges River
- Dubaldia/Arial Khan Rivers	from	Padma River

The Old Brahmaputra and the Dhaleswari Rivers are connected to the main river system at the downstream end as well. The Old Brahmaputra via the Lakhya to the Upper Meghna and the Dhaleswari River directly to the Upper Meghna River (see figure 3.1).

All distributaries are meandering rivers, although the Old Brahmaputra as the former course of the Brahmaputra River still has some braiding tendencies.

3.4 Off-takes and confluences

The off-takes are important (upstream) links between the main rivers and the distributaries, while the confluences are the (downstream) links between the main rivers mutually or between the main rivers and some of the distributaries. For the development of the distributaries the off-takes are the crucial elements. At an off-take the flow and the sediment transport entering into the distributary are determined by the downstream conveyances, the local geometry of the offtake and the relative size of the bed material : for very fine sediment the geometry of the offtake becomes less important.

In Study Report 1 the importance of the off-takes is discussed extensively. If more sediment is entering into the off-take than can be transported over a longer period, the distributary will start to aggrade. As a consequence less water is entering and hence this may start a self-accelerating process. It has been shown that most off-takes are unstable : either the distributary start to 'die' or gradually the distributary takes the function of the main river. Much about this is still unknown, but in general it can be stated that the flow and sediment distribution is controlled by 2 and even 3 dimensional conditions which can not easily be predicted.

For the present assessment it is important to underline that the off-takes really start to function only during higher stages. Any change in the stages in the main river will affect the flow (and sediment transport) entering into the distributary. In particular a decrease of stages will result in less water entering into the distributary and depending on the quantities of sediment entering the distributary, it will silt up. It may work out the other way around also : degradation of the distributary may result in its increasing importances.

4. FAP Scenario's

4.1 General

To assess the impact of FAP it is of course required to know which plans will be implemented under FAP. A problem is that an integrated plan has not yet been developed for Bangladesh. This also can not be expected in this stage as some of the FAP projects are still under study and an integrated plan is only scheduled to be developed over the coming years. The present preliminary impact assessment should therefore be seen as one of the steps towards the development of such an overall plan, in which costs, benefits and impacts (together with preventive and remedial measures) are included in a balanced way.

Nevertheless some assumptions have to be made to be able to make an assessment as to possible developments. Different scenario's as far as possible developments are concerned (each comprising a selection from the different options of the Flood Action Plan) were developed recently by FAP 25 and these will be considered for acceptance here as well.

4.2 FAP 25 scenario's

Scenario's for development under FAP consists mainly of embankments and bank protection works. Regarding the latter only comprehensive plans have been developed for the Jamuna River within the frame-work of FAP 1 and to some extent for the Lower Meghna River under FAP 9B. Although it may be reasoned that the envisaged bank protection works may (slightly ?) affect the riverine conditions, in particular if the rivers are shifting due to tectonic effects, the effect of river training works is not taken into account here. Hence the development scenario's are limited to embankments. These embankments may have two types of effects :

- o reduction of overland flow;
- o reduction of flood conveyance.

If overland flow is away from the main rivers, embankments will cause the main rivers to carry more flow during the floods. Hence the average discharge increases.

In Annex 2 of the FAP 25 Flood Hydrology Study, in total 8 different scenario's for the construction of embankments have been studied. The characteristics of these 8 scenario's are summarized in Table 4.1. For each of the regional studies (FAP 1 through FAP 6) embankment options proposed are listed in the second column from left. On the right side of the table, different scenario's for possible development are given. They differ from fairly modest ones (Scenario 2 consists of the Brahmaputra Right Embankment - in fact already present - and an embankment along the Lower Meghna River - also already present over large distances - in combination with Ganges LE and embankments along the left side of the Jamuna and along the Dhaleswari) to comprehensive plans like scenario 5 (including the embankments along both sides of almost all the main rivers and distributaries). In Annexure 3 a more extensive discussion is given of the different measures that could be taken. This Annexure is a copy from a part of Annex 2 of the mentioned Flood Hydrology Study (FAP 25, 1993).

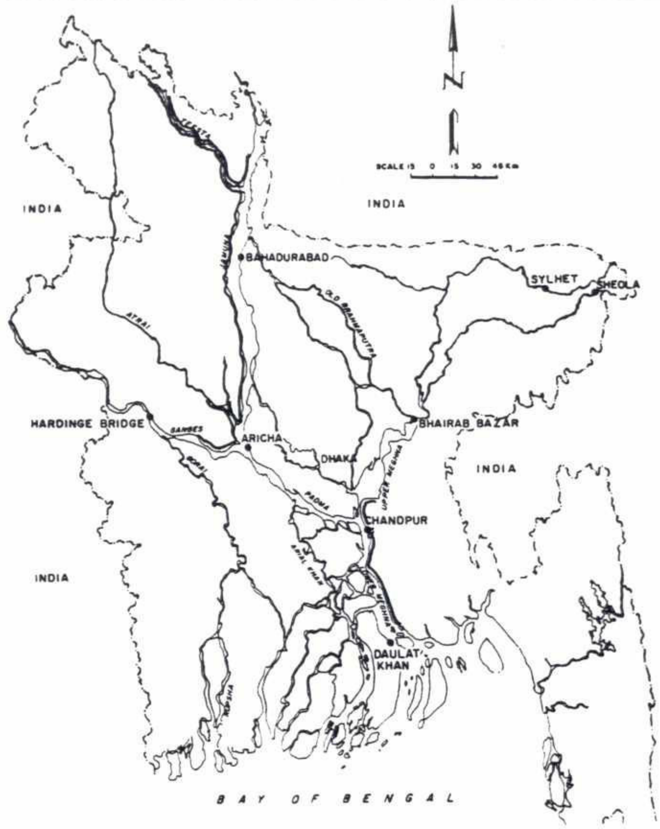
The scenario's not only include FAP components but also some other "miscellaneous" possible developments (Jamuna Bridge and a sea level rise of 0.35 m) are part of some scenario's. According to FAP 25 the Jamuna Bridge causes backwater in the upstream reaches, but it appears that the important constriction scour, which reduces the backwater considerably (Klaassen & Vermeer, 1988), was not taken into account by FAP 25.

FAPs	OPTIONS	SCENARIOS							
		1	2	3	4	5	6	7	8
FAP 1	Brahmaputra RE, present alignment	X	X	X	X	X	X	X	X
FAP 2	Ganges LE		X	X	X	X	X		X
FAP 3 & FAP 3.1	Jamuna LE(N), West of Chatal		X	X	X	X	X		X
	Jamuna LE(S), Western alignment					X	X		
	Dhaleswari LE, to Katalia		X	X	X	X	X		X
	Dhaleswari LE, D/S Katalia					X	X		
	Padma LE					X			
	Dhaleswari RE					X			
	Old Brahmaputra, RE + LE & Lakhya					X	X		
FAP 4	Ganges RE				X	X	X		
	Padma RE					X			
FAP 5	Lower Meghna LE	X	X	X	X	X	X	X	X
FAP 5B	Lower Meghna RE								
FAP 6	Upper Meghna LE					X	X		
	Upper Meghna RE					X			
MISC	Jamuna Bridge at ch. 170.75			X		X	X		X
	Sea Level Rise (+35 cm)							X	

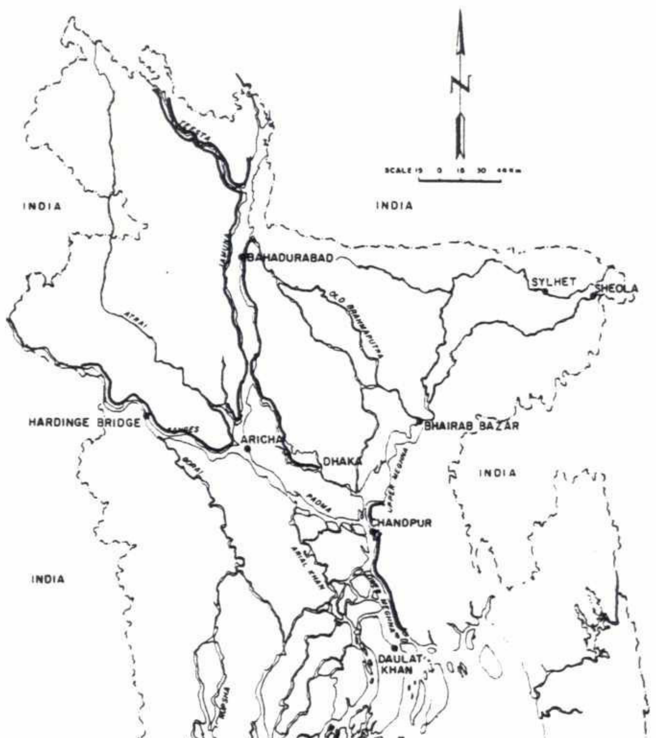
Table 4.1 Scenario's simulated by FAP 25 (FAP 25, 1993)

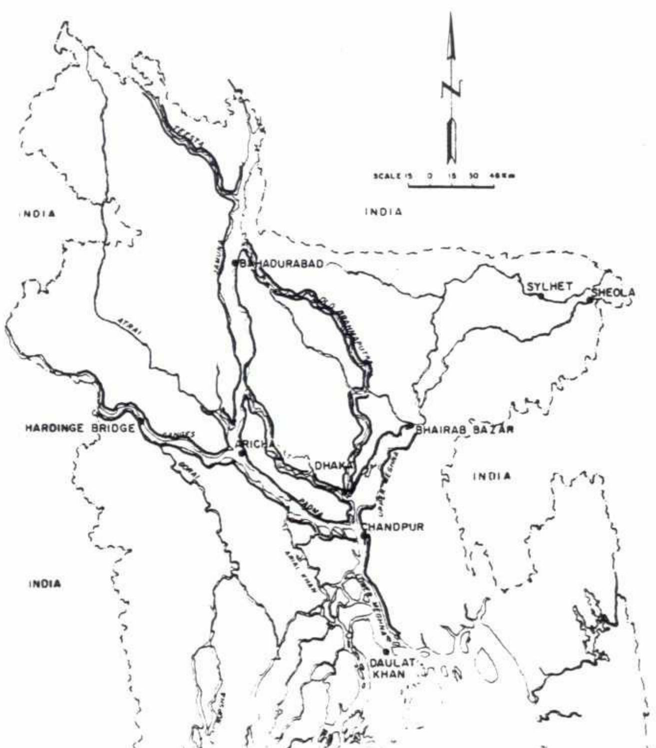
4.3 Selection of scenario's for assessment

As indicated in Section 4.2 in total 8 scenarios's were investigated in the Flood Hydrology under FAP 25. "The simulation programme has been prepared on the basis of discussions with the Flood Plan Coordination Organization (FPCO), FAP



(a) Present condition (Scenario 1)





(b) Scenario 3 (c) Scenario 5

Figure 4.1 Present condition. (a), compared with Scenario's 3(b) and 5(c)

1 and the regional FAP's (FAP 25, 1993). The simulation programme is a slightly adapted version of the programme presented in the Main text of the FAP 25 Flood Hydrology Programme. Also here these 8 scenario's have been accepted for consideration.

For the present assessment it was deemed sufficient to consider only the scenario's 3 and 5. Scenario 3 is the scenario for which a long term simulation (1965-1989) was undertaken for the establishing of hydrological design criteria along the major rivers and is considered as one of the most likely future protection scenario's (FAP 25, 1993).

Scenario 5 is the most severe as far as the implementation of works is concerned. In fact it includes all possible embankments together with Jamuna Bridge. Only sea level rise is not included. Figure 4.1 gives an overview of present conditions and the project components proposed for the scenario's 3 and 5. The other scenario's are probably causing less serious impacts as the related changes in hydraulic conditions are less serious as well.

In principle there is a complicating factor when assessing morphological impacts. Morphological changes are changes that progress both in space (in x-direction for 1-dimensional approaches) and in time (hence in t-direction). The different FAP components as included in Scenario 5 will not be implemented at the same time. It makes however quite some difference whether certain measures are implemented at the same time, or whether the implementation is spread over a period of say 50 years. Hence scenario's for morphological assessment do not only consist of the projects to be implemented but also the moment at which they become effective. A good example of such "morphological scenario's" are the scenario's used under the Jamuna Bridge Study (see RPT et al, 1990).

For the time being it will be assumed that all projects as included in Scenario 5 will be implemented at the same time. This gives probably a "worst case scenario", although due to the complicated interaction between the main rivers and the distributaries, there may be scenario's where time is considered as well that may have more serious consequences. This should be studied in a later stage.

5. Hydraulic and morphological impact

5.1 Introduction

In this chapter a qualitative assessment of the morphological impact of FAP is made. As the morphological changes are triggered by the hydraulic changes, first the hydraulic changes are reviewed. The relevant information, presented in Section 5.2, was derived from the FAP 25 study (FAP 25, 1993). In the subsequent sections the resulting morphological changes are discussed : ultimate changes, the intermediate changes and the possible changes in stages in the main rivers and in the distributaries. As indicated in the previous chapter the assessment is limited to the Scenario's 3 and 5 (referred to hereafter as SCE 3 and SCE 5, respectively), while it is assumed furthermore that all measures as proposed in these scenario's are implemented at the same time : probably be a "worst case" scenario.

5.2 Changes in water distribution and in stages

Here it is of interest to determine the effects of implementation of embankments, according to the two selected scenario's on the water distribution over the main river system and on the stages along the various rivers. For this purpose a comparison should be made between the present and the future conditions.

In the first stage of the FAP 25 a general model of the main river system of Bangladesh was set up and calibrated. As basis the so-called RUN 6 is used, supposedly the best simulation of the present conditions. This run extended over the same period of 25 years (1965-1989) as for which SCE 3 was applied. In Annex 2 of the FAP 25 Flood Hydrology Study relevant results are presented. Mostly as comparisons between RUN 6 and SCE 3, but also some information can be derived from the comparison between RUN 6 and SCE 5. In the following some of this information is summarized. First on the water distribution and next on the stages.

o *Water distribution differences*

Table 5.1 summarizes the computed differences between the simulations SCE 3 and RUN 6 in discharges in five main stations. As can be observed there is hardly any difference in four out of five stations. Only the discharge in Baruria is on the average about 2500 m^3/s higher for SCE 3. Although not indicated this increased discharge occurs also in the lower reach of the Jamuna River.

A similar comparison cannot be derived straightforward from FAP 25 (1993) for the differences between RUN 6 and SCE 5. Some idea about the changes in discharges can be obtained from the changes in stages (see hereafter).

o *Water-level differences*

In Table 5.2 the differences in stages between the simulations RUN 6 and SCE 3 are summarized on the basis of a simulation of the 25 year period 1965-1989.

River	Station	Period			
		May-Jun	Jul-Aug	Sep-Oct	Average May-Oct
Jamuna River	Bahadurabad	22	-26	-29	-11
Ganges River	Hardinge Bridge	0	0	0	0
Padma River	Baruria	2155	4066	1382	2574
Upper Meghna	Bhairab Bazar	3	8	-7	1
Old Brahmaputra	Nilukhirchar	3	19	8	10

Table 5.1 Changes in discharges in m^3/s in the main river system (SCE 3 - RUN 6) over a period of 25 year (1965-1989) (from FAP 25, 1993)

The location of the stations included in this comparison is indicated in Figure 3.1. Inspection of Table 5.2 leads to the following observations :

- Changes are negligible along the Lower Meghna River, the upper reach of the Ganges River and along the Old Brahmaputra River.

- Lowering of the water-level, but only to a small extent (less than 0.05 m), can be observed in the Upper Meghna and the Lakhya River. This probably due to more flow passing through the Dhaleswari and Jamuna-Padma River systems. See Table 5.1.

- Water-levels are higher in the Padma and the lower reach of the Jamuna River due to more water passing through this system (see also the above point). Also the lower reach of the Ganges River is affected by this increased discharge via backwater from the confluence.

- Also in Sirajganj and more upstream a substantial increase in stages is observed. This, however, is not caused by an increase in discharge but it is due to not taking into account the constriction scour under the bridge during floods. Hence this computed increase is not realistic (see Section 4.2) and does not lead to morphological changes other than on a local scale.

- Along the Dhaleswari (Kaliganga) system a substantial increase in stages is observed.

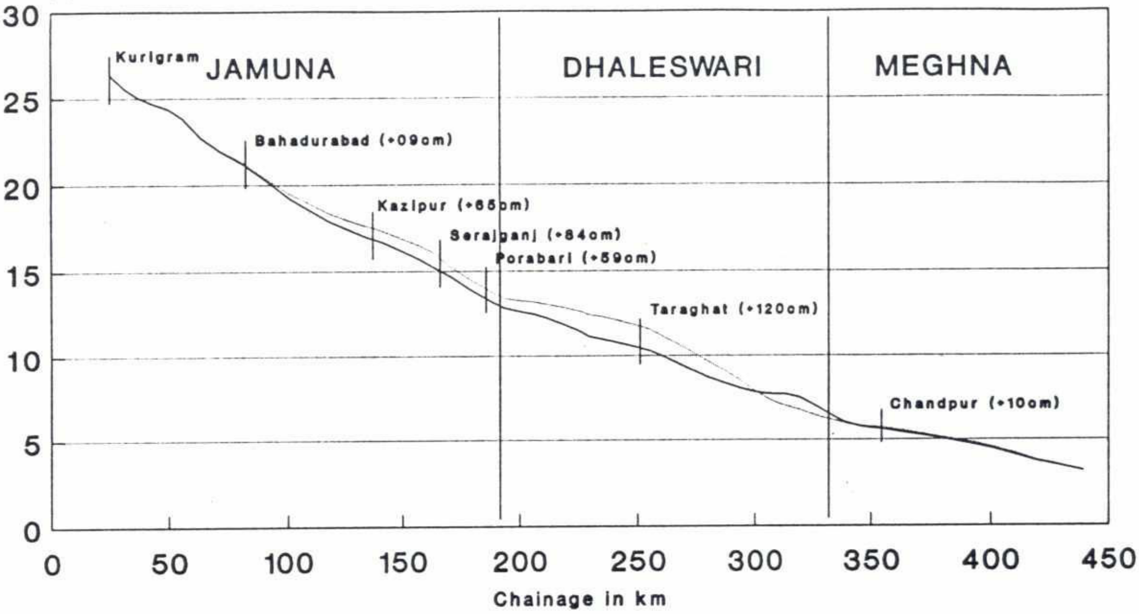
- Negligible changes in the Gorai and in the Dubaldia/Arial Khan Rivers.

River	Station	Period			
		May-Jun	Jul-Aug	Sep-Oct	Average May-Oct
Jamuna River	Bahadurabad	0.02	0.04	0.03	0.03
	Kazipur	0.16	0.21	0.17	0.18
	Serajganj	0.19	0.30	0.23	0.24
	Porabari	0.15	0.22	0.18	0.18
	Mathuria	0.22	0.19	0.12	0.17
Ganges River	Hardinge Bridge	0.01	0.00	0.00	0.01
	Sengram	0.05	0.02	0.01	0.03
	Mahendrapur	0.08	0.03	0.02	0.04
Padma River	Baruria	0.11	0.12	0.09	0.11
	Mawa	0.04	0.07	0.05	0.05
Upper Meghna River	Bhairab Bazar	-0.01	-0.03	-0.03	-0.02
	Meghna Ferry	-0.02	-0.06	-0.05	-0.05
Lower Meghna River	Chandpur	0.00	0.00	-0.01	0.00
Old Brahmaputra River	Jamalpur	0.01	0.02	0.01	0.01
	Nilukhirchar	0.01	0.02	0.01	0.01
	Toke	0.00	-0.02	0.00	0.01
Lakhya River	Demra	-0.03	-0.05	-0.05	-0.04
Kaliganga River	Taraghat	0.33	0.87	0.66	0.62
Gorai River	Gorai Rly. Bridge	0.02	0.01	0.00	0.01
Atrai River	Baghabari	0.14	0.19	0.14	0.16
Arial Khan River	Madaripur	-0.11	0.14	0.07	0.03

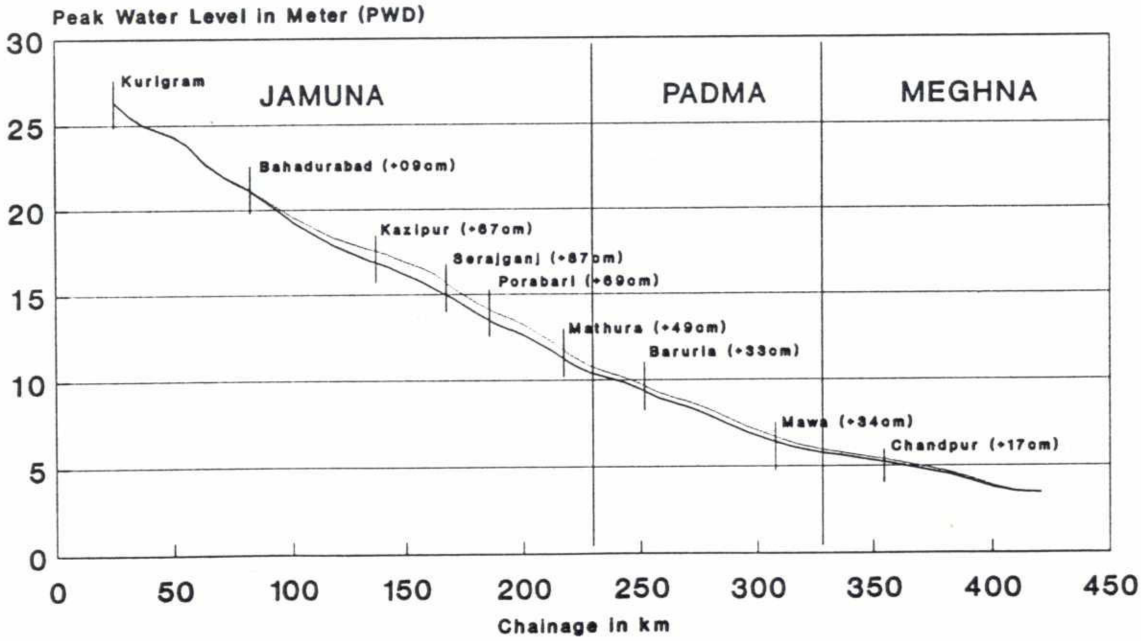
Table 5.2 Water-level differences in m between SCE 3 and RUN 6 for key stations along the main river system over a period of 25 year (1965-1989) (after FAP 25, 1993)

The above yields a picture of more water being discharged via the main channel system which is of course the consequence of the embankments which block overland flow and limit the conveyance of the floodplain.

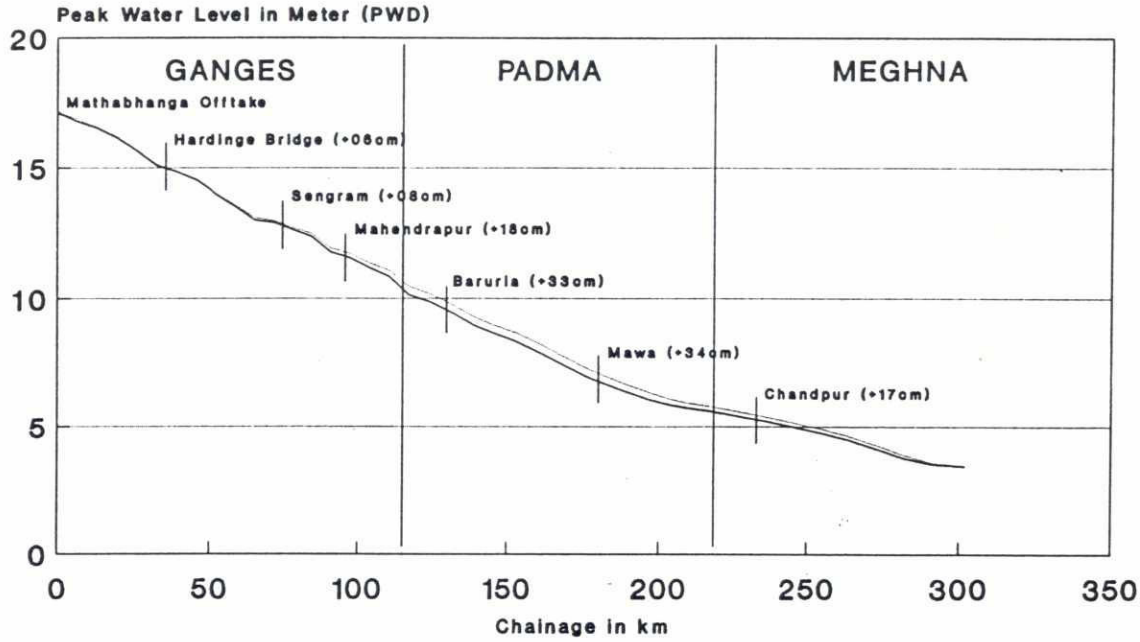
No similar information is available for SCE 5, because SCE 5 was not tested versus a 25 year long period of flow. A simulation was made however of the peak stages in the main river system and the distributaries for the years 1986, 1987 and 1988. The results of the simulation for the year 1988 are presented in Figure 5.1. In addition in Annex 2 of the Flood Hydrology Study (FAP 25, 1993) simulated differences in peak water-levels for the different scenario's for the years 1986,



(a)Jamuna-Dhaleswari-Meghna system



(b)Jamuna-Padma-Meghna system



(C) Ganges-Padma-Meghna system

Figure 5.1 Simulated difference in peak water-levels between SCE 5 and RUN 6 for the year 1988(FAP 25, 1993)

1987 and 1988 are presented. Here in particular the differences between SCE 3 and SCE 5 are relevant. Although the results are difficult to generalize, the main differences for SCE 5 compared to SCE 3 are:

- o slight increase in water-level in the lower reach of the Jamuna River and in the Padma River,
- o substantial increase along the lower reach of the Old Brahmaputra and in the Lakhya River.

For the time being it is concluded that SCE 5 has approximately a slightly more serious effect on the lower reach of the Jamuna and on the Padma River and a more serious effect on the stages in the lower reach of the Old Brahmaputra. Probably on the average the flows in these river reaches are larger than in the present situation and for SCE 3.

5.3 Ultimate morphological changes for the main rivers

In a next step the ultimate morphological consequences of the possible changes according to the scenario's 3 and 5 are assessed. The main effect of these scenario's on the main rivers is an increase in stages in the lower reach of the Jamuna River (see Table 5.2) and an increase in flows in the Padma River (see Table 5.1). Although there are no data on flows in the lower reach of the Jamuna river given in FAP 25 (1993), it is assumed here that in the lower reach of this river (downstream of the Dhaleswari intake) also increased flows will occur. For the time being nothing is known about the effect of the different scenario's on the transport and distribution of bed material, but it is assumed here that this is not affected by the proposed changes.

Hence Lane's balance can be applied assuming that V and D remain the same. Furthermore it is assumed that the analysis can be done on the basis of the average discharge, assuming that the (dimensionless) duration curve does not change (Hence α is assumed to remain the same). Applying Lane's balance under these assumptions, it is found that the application results in a decrease of the ultimate slope of the river, either according to Equation (2.3) if the width B remains constant, or Equation (2.4) if the width B can change as well. As discussed before the width of the *Padma River* is constricted and it is assumed that the increase in average discharge is not all of a sudden leading to a substantial increase in width of this river. Hence Equation (2.3) is more appropriate.

For the *Jamuna River* the situation is more complicated : the river can adjust its slope i, its total width B, its number of channels k and its sinuosity p. If the number of channels would remain the same,then an increase in discharge would lead to a reduction in slope conform Equation (2.3). An (slight) increase in braiding index (= average number of channels k) is plausible, as a consequence of the (slightly) increased Q. It can be shown that an increase in the average number of k results in an increase in slope, but only marginal. For the time being it is assumed that for the Jamuna River Equation (2.3) is applicable as well. If more insight into the response of a braided system as a consequence of an increase in Q is becoming available, possibly a revision of this assumption can be made.

In the other main rivers there are no changes in flows and consequently it can be concluded that the slope of these rivers remains constant. This does not mean that their stages remain the same as well. Due to the reduction of the slope of the Padma and the lower reach of the Jamuna River the stages will reduce in the upstream reaches of these rivers. As a consequence the stages in the Ganges River and in the upper reaches of the Jamuna River will fall as well.

The result of the application of Lane's balance to Scenario 3 is presented in Table 5.3. The following observations can be made :

- Only the slopes in the Padma and the lower reach of the Jamuna River will be affected.

- The reduction of slope is about 6% for the Padma River and about 10% for the Jamuna River.

- No changes in slope in the other main rivers.

River	Reach	Parameter					
		Reach length L (km)	Original average discharge Q_0 (m^3/s)	New average discharge Q_1 (m^3/s)	Original slope i_0 (10^{-5})	New slope i_1 (10^{-5})	Lowering water level upstream (m)
Lower Meghna River	Downstream confluence Upper Meghna River	irrelevant	40,000	40,000	4	4	0.0
Upper Meghna River	Bhairab Bazar confluence Padma River	irrelevant	5,000	5,000	2	2	0.0
Padma River	Confluence Ganges/Jamuna-confluence Upper Meghna R.	100	35,000	37,000	5	4.6	0.4
Jamuna River	Confluence Ganges River-Dhaleswari off-take	85	20,000	22,500	6	5.3	0.6
	Dhaleswari off-take-Bahadurabad	irrelevant	20,000	20,000	8	8	0.0
Ganges River	Upstream confluence of Jamuna River	irrelevant	15,000	15,000	5	5	0.0

Table 5.3 Results of application of Lane's balance to ultimate conditions for Scenario 3

5.4 Intermediate morphological changes in the main rivers

The estimates presented in the preceding section relate to the ultimate conditions, due to occur may be after 50 to 100 years only. In this section some considerations regarding the *intermediate* conditions are presented, hence the conditions directly after implementation until the ultimate conditions have almost been reached.

According to Table 5.4 embankments along the main rivers as assumed under the scenario's 3 and 5 will lead to slope reduction and related degradation of the Padma, Ganges and Brahmaputra/Jamuna Rivers. How quickly reduction in slope will materialize, depends in particular on the sediment transport rates. This underlines the need to know fair accurately the sediment transport predictor that is applicable as one of the important elements of a 1-dimensional morphological model, required to model the behaviour for the intermediate conditions.

Furthermore it should be noted that during the intermediate period the behaviour of the river may be quite opposite to the ultimate changes. As an example consider the Ganges River. Initially the stages at the confluence of the Ganges and the Jamuna River are higher, implying that in the Ganges River aggradation will take place. Only later the reduction in stages due to slope reduction will take over and the river will start to degrade. A similar phenomenon takes place in the Lower Meghna and possibly the Upper Meghna and the Padma River. The Jamuna River and to a smaller extent the Padma River will start to degrade. The resulting increased sediment transport leads to (temporary) deposition in the Lower Meghna and possibly the Padma River. This will lead to increased stages at the confluence with the Upper Meghna River. This may induce some aggradation, but it is assumed here that the quantities of sediment transported in the Upper Meghna River are too small to lead to substantial bed level changes. The anticipated bed level changes are indicted in Figure 5.2.

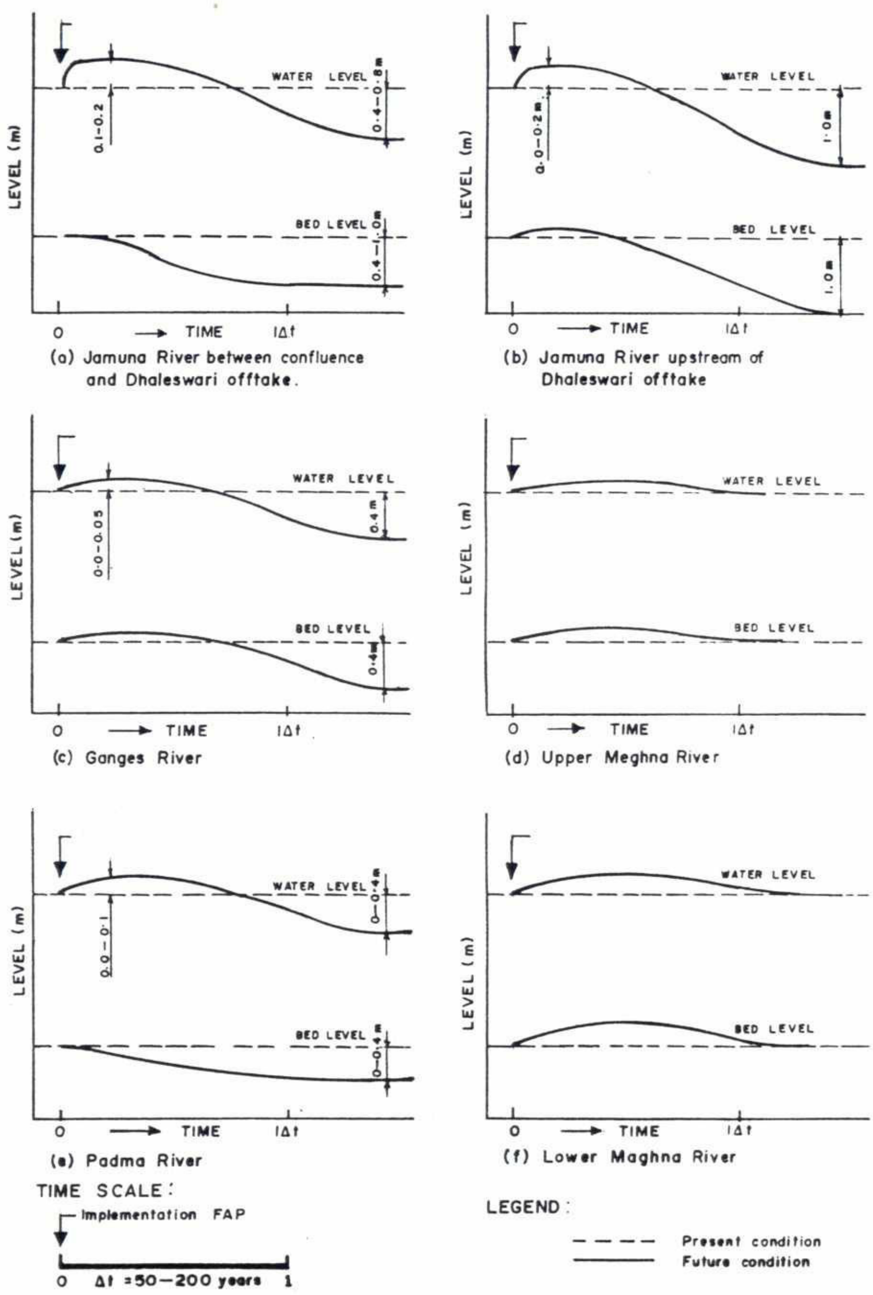


Figure 5.2 Qualitative change of bed levels in the main rivers

5.5 Impact on bed levels and stages in main rivers

From the estimated changes in slope of the river, the lowering of the water-level can also be estimated. It should be recalled in this respect that the water-level changes in the Padma River have their effect on the stages in the Jamuna and the Ganges River as well. The results of this assessment are given in Table 5.4 for a number of key stations. It can be concluded that implementation of Scenario 3 would *ultimately* result in a lowering of the water-levels in the Padma, the Ganges and the Brahmaputra/Jamuna River systems varying from almost zero at the downstream end to about 1.0 m in the Jamuna River.

Station	River	River(s) downstream	Lowering of water stages		
			Effect of slope change in river (m)	Effect of downstream rivers (m)	Total lowering (m)
Bahadurabad	Jamuna River	Jamuna River- Padma River- Lower Meghna River	0.0	1.0	1.0
Serajganj	Jamuna River	Jamuna River- Padma River- Lower Meghna River	0.6	0.4	1.0
Hardinge Bridge	Ganges River	Padma River- Lower Meghna River	0.0	0.4	0.4
Baruria	Padma River	Lower Meghna River	0.4	0.0	0.4
Bhairab Bazar	Upper Meghna River	Lower Meghna River	0.0	0.0	0.0
Chandpur	Lower Meghna River	None	0.0	-	0.0

Table 5.4 Preliminary estimates of lowering of stages for ultimate conditions for Scenario 3

In the preceding section it was demonstrated that the initial and intermediate behaviour may be quite opposite to the ultimate effects. The initial effects are the effects as simulated in the FAP 25 study, because there it was assumed that the bed levels would not change (or rather: were not yet changed). This apparently leads to an increase in the stages in all river reaches. In the intermediate period the stages will gradually lower again as the slope of the river gradually reduces due to the increased discharges.

The general behaviour of the stages in the various river reaches is included in the Figure 5.2 as well. Initially or slightly later the stages are higher than the present ones, but they will gradually lower again and in due time they will be lower than they were initially. The indicated changes will occur over the full range of stages, as they are caused by degradation. This degradation causes the rating curve to shift downwards.

The above analysis was on the basis of SCE 3. SCE 5 has a slightly larger impact. Hence it may be expected that the ultimate effects of SCE 5 are slightly larger.

5.6 Impact on distributaries

In the foregoing sections only the conditions in the main rivers were considered. The different scenario's, however indicate that already initially there will also be some changes in some of the distributaries as well. According to Table 5.2 (see also Figure 5.1 (a) for SCE 5 during peak conditions) in particular in the Dhaleswari system there will be an increased inflow (due to higher stages in the Jamuna River) and local embankments diverting the flow into the distributaries as well. At initial stage the other distributaries will slightly be affected only (see Table 5.2)

Increased flow in the Dhaleswari may lead also here to slope reduction and degradation, but that depends on the sediment entering the Dhaleswari as well. According to Equation (2.1), however, the slope i will decrease only if $V/Q^{n/3}$ decreases. Hence a substantial increase in sediment entering the Dhaleswari may counteract and even lead to continuing aggradation (as is presently occurring, see Study Report 1). The quantities of sediment entering the off-take depend on the relative amount of flow entering, the particle size, the flow conditions and the geometry of the off-take. In particular the latter is difficult to predict, hence the changes during the intermediate conditions can only be predicted in a stochastic way. There is a clear similarity between the stochastic prediction of plan-form (see e.g. FAP 22 reports and/or Klaassen et al. 1993) and the prediction of the future behaviour of the distributaries under the influence of the implementation of FAP. The development of a distributary can only be predicted in terms of a probability of occurrence.

Something similar holds for the ultimate conditions. The ultimate conditions in the distributaries depend on the intermediate conditions as well and hence are difficult to predict in a deterministic way. Still it is felt that the natural tendency for some of the distributaries i.e. gradual silting up will be affected by implementation of the FAP, either by accelerating or by reducing this tendency. Only active interference with the off-takes may allow for the distributaries to remain being important.

Still some qualitative statements regarding the distributaries can be made. Initially the conditions in the *Old Brahmaputra* will hardly change as the backing of the water near Bahadurabad is negligible. Later (after some 50 years ?) the stages will start to lower and hence the flow into the Old Brahmaputra will reduce. This is probably an acceleration of the natural tendency and it will probably lead to the complete dying of this distributary.

Due to the increase of the stages in the Jamuna River, the *Dhaleswari River* and connected rivers like the Buriganga etcetera will initially carry more flow. Depending on the ingress of sediment subsequently the river will start to aggrade or it will degrade. Probably it will be degradation rather than aggradation. Due to this the discharges into the Dhaleswari will increase. In a later stage the lowering of the stages in the Jamuna will exert its influence increasingly, probably leading to the gradual dying of the Dhaleswari.

The *Gorai River* may initially carry some more water, but this tendency will be reversed due to the lowering of the stages in the Ganges River in the intermediate and ultimate conditions.

To predict the future behaviour of the *Dubaldia/Arial Khan River system* is difficult due to the limited knowledge available on this river system. The impact of FAP will be limited as the off-take is near the confluence with the Upper Meghna River where the initial increase in stages and the subsequent degradation are fairly small.

Ultimately there is of course a feed-back from the changes in the distributaries to the main rivers. If some of the distributaries would in due time loose their importance, then the main rivers would have to carry even more discharge with additional slope changes.

Also it should be stated here that SCE 5 probably has larger effects than SCE 3. This, however, has to be checked via a more refined analysis using e.g. a 1-dimensional morphological model. This holds for SCE 3 as well: only the application of such a model may give more quantitative insight.

Finally note that ultimate conditions are meant here in relative terms only. Most bifurcations are not stable over longer periods. Ultimately one of the channels usually silts up. In this respect the possible increase in importance of some of the distributaries should possibly be seen as temporary phenomenon on a time scale longer than some centuries. The impact of FAP could delay the dying of the distributaries, in particular if it would be "guided" (see Chapter 6 for a more extensive discussion on this).

6. Discussion

In the previous Chapter an qualitative assessment was made of the possible impact of implementation of FAP. It was found that probably the initial increase in stage in due time would be reversed into a reduction of the stages due to slope reduction. Also it was found that the probable "fate" of the distributaries of slow dying can be possibly delayed by the impact of FAP, but it can under certain circumstances and for some distributaries be accelerated. Whether these developments are favourable or not has to be assessed during the preparation of an overall plan for the FAP.

It should be stressed however that the present assessment is of a qualitative nature only. To underline this a number of relevant aspects are discussed here briefly. The following aspects are covered hereafter :

1 How accurate are the predictions ?
2 More ultimate conditions ?
3 Time dependency
4 Uncertainties resulting for off-takes
5 Changes in plan-form etc
6 Timing of measures
7 Influence of other developments ?
8 Implications for FAP 24 activities

Re 1 *How accurate are the predictions ?*
Although the present analysis was supposed to be qualitative one, still some figures on changes in stages (and bed levels) are given. The computed changes are subject however to the developments taking place in the distributaries as well. Furthermore the rivers may react in a more complicated way than changing their slope only. Hence the accuracy of the deterministic values in e.g. Table 5.3 are low. Due to different developments the actual values may easily deviated a few decimeter. It is felt however that the general tendency predicted is fair : initially an increase in stages and later a decrease with as ultimate effect an overall lowering.

Re 2 *More ultimate conditions ?*
As indicated before, it is felt that future developments may take different courses depending on elements that could not be included in the present analysis. In particular the (2- and 3-dimensional) conditions at the off-takes and how they vary in time will affect the overall development. Hence predictions on the ultimate developments can only be given together with a probability of occurrence. It is stressed here that application of a 1-dimensional model will not improve this. A model however will be extremely helpful in evaluating the effects of possible variations at the off-takes and in assessing the probability of certain developments.

Re 3 *Time dependency*
The morphological changes, which are quite important for the overall future behaviour of the main river system in Bangladesh, proceed at a certain pace. This time-dependent behaviour is very important as the ultimate conditions will be

reached only after a fairly long period. This underlines the importance of the developing of a 1-dimensional time-dependent morphological model of the whole system, in which the existing knowledge on the river system is introduced and the time-dependent behaviour for various scenario's is simulated (using the probabilistic approach needed).

Re 4 *Uncertainties resulting from off-takes*
The major off-takes play a key role in the development of the main river system over the coming decades. The limited understanding of their characteristics and behaviour in time is a major limitation for any impact assessment (and for any prediction of future developments).

Re 5 *Changes in plan-form etc*
In the previous chapter it was assumed that the main rivers in Bangladesh react on changes in discharges mainly by changing their slope. Braided rivers, however, have more possibilities of adjustment. Further studies on the characteristics of braided river reaches in Bangladesh (and elsewhere) are urgently needed to get more insight in braided rivers and their response to changes. More generally it holds that in this limited study no attention could be paid to plan-form changes due to the implementation of FAP projects. The construction of bank protection woks like envisaged under FAP 1, FAP 9B and FAP 21 may lead to plan-form changes opposite the works and more downstream.

Re 6 *Timing of measures*
In the present analysis it was assumed that all FAP projects would be implemented at the same time. This however is not so realistic. It seems more logic that the different projects will be spread over a period of some decades. This will certainly affect the morphological changes due to FAP implementation.

Re 7 *Influence of other developments ?*
In the foregoing the impact of FAP was discussed as if there are no other influences that may affect the conditions in the main river system. The rivers in Bangladesh, however, are subject to ongoing developments due to neo-tectonics and other changes (partly as a consequence of human activities : water diversions, deforestation, sea level rise etc.). As was explained before, the fate of the distributaries is very much determined by local conditions and how these are developing over time. Hence the impact of FAP cannot be assessed independently without these other developments.

Re 8 *Possibility of influencing the development*
Because of the sensitivity of the system for changes, there possibly are options to influence the development of the system by a phased implementation of the different FAP components. This would imply that the order of implementing projects would be influenced by predictions made regarding the effect. There are however also other boundary conditions that have a bearing on the sequence of implementation (not the least the economic feasibility of the various projects), but still this option could be considered in the development of an overall plan. The same holds for application of FAP 22 techniques. It can be imagined that application of these techniques to influence the conditions at off-takes in some

critical periods may result in a very positive development of the main river system. This should be explored further.

Re 9 *Implications for FAP 24 activities*

The present analysis and the above discussion very much supports the selection of study topics for FAP 24. Emphasis should be on sediment transport, plan-form and how it is affected by the flow and sediment transport in a reach and in particular the conditions at the off-takes. In addition it underlines the importance of using 1-dimensional morphological models to test the present understanding of the systems and to study the sensitivity of the system to changes.

Finally it is remarked that the present assessment is a very preliminary one only. It should be followed by more detailed assessments in due time, in which also the sequence of projects and possible adaptations should be studied as part of the development of a well-balanced FAP.

7. Conclusions and recommendations

The present report presents the results of a first qualitative assessment of the possible impact of FAP on the main river system. The assessment builts on the results of the FAP 25 study (see FAP 25, 1993). In particular the morphological response of the system was explored. This morphological response will take place over a period of 50 to 100 years or more. The present assessment was mainly done for SCE 3 (see Chapter 4 and in particular Table 4.1 and Figure 4.1), but also SCE 5 is briefly considered.

Based on the outcome of this exploring study the following conclusions can be drawn :

- The increase of the stages conform the predictions by FAP 25 due to the implementation of FAP will only occur initially.
- The initial increase in stage would probably in due time be reversed into a reduction of the stages due to slope reduction.
- The "fate" of the distributaries of slowly dying can be possibly delayed by the impact of FAP, but it can under certain circumstances and for some distributaries be accelerated.
- The future conditions can partly be determined deterministically : the complications due to the off-takes induce some probabilistic behaviour as well.
- There may be some scope for influencing the future developments by selecting a certain sequence of projects for implementation under FAP. This may in particular be beneficial for the distributaries.
- The results of the assessment support the selection of study topics for FAP 24.

Based on the above conclusions the following recommendations are made :

- To study in a 1-dimensional morphological model the initial, intermediate and ultimate response of the main river system to implementation of FAP.
- To specifically use this model to explore the stochastic behaviour of the system and to study the influence of possible natural developments and the influence of certain strategies of implementation of the FAP components.
- To concentrate the FAP 24 studies on the already selected topics: sediment transport rates, plan-form characteristics and how they are influenced by changes in flow and sediment transport, and off-takes (in addition to survey techniques).

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Annexure 1

Sediment Predictor

Introduction

It is advantageous to write for the sediment transport in rivers in the following way :

$$s_t = m \cdot u^n$$

Where s = sediment transport per unit width (m^2/s), u = velocity (m/s) and m and n are coefficients. The advantage is mainly that such simplified relationship can be combined with other equations to arrive at analytical expressions that provide increased insight into the behaviour of morphological systems.

Existing sediment transport predictors can be schematized to the above simple relation between s and u. In this annexure this is done for two predictors, notably (i) the total load predictor of Engelund-Hansen (1967) and (ii) the bed load predictor of Meyer-Peter-Muller (1948). This will provide insight in the value of n, which is very important for morphological predictions.

For reasons of comparison with Lane's balance, also occasionally the sediment transport predictor is written as :

$$s_t = m_1 \, D^{-p} \, u^n$$

with

$$m_1 . D^{-p} = m$$

In the last section of this annexure the value of p is discussed.

Value of n

(1) Engelund-Hansen (1967)

The Engelund-Hansen predictor for a wide river reads :

$$s_t = \sqrt{g \Delta D_{50}^3} \cdot \frac{0.05}{1-\epsilon} \cdot \left(\frac{hi}{\Delta D_{50}}\right)^{\frac{5}{2}} \cdot \frac{C^2}{g} \qquad \text{(A1-1)}$$

For uniform flow conditions, the Chezy equation holds. This equation can be written as :

$$h\,i = \frac{u^2}{C^2} \qquad \text{(A1-2)}$$

Also for non-uniform conditions this is a good approximation. Combining these two equations yields :

$$s_t = \sqrt{g \Delta D_{50}^3} \cdot \frac{0.50}{1-\epsilon} \cdot \left(\frac{u^2}{C^2 \Delta D_{50}} \right)^{\frac{5}{2}} \cdot \frac{C^2}{g} \qquad \text{(A1-3)}$$

which can be re-written as :

$$s_t = g^{-\frac{1}{2}} \cdot \Delta^{-2} \cdot D_{50}^{-1} \cdot \frac{0.05}{1-\epsilon} \cdot C^{-3} \cdot u^5 \qquad \text{(A1-4)}$$

Hence the Engelund-Hansen predictor can be written as :

$$s_t = m \cdot u^n$$

with :

$$m = g^{\frac{1}{2}} \cdot \Delta^{-2} \cdot D_{50}^{-1} \cdot \frac{0.05}{1-\epsilon} \cdot C^{-3} \qquad \text{(A1-5)}$$

and

$$n = 5 \qquad \text{(A1-6)}$$

(2) Meyer-Peter/Muller (1948)

The derivation of the value of n for the equation of Meyer-Peter/Muller is slightly more cumbersome. Assuming that :

$$s_b = m \cdot u^n \qquad \text{(A1-7)}$$

it holds that :

$$\frac{ds}{du} = n \cdot m \cdot u^{n-1} \qquad \text{(A1-8)}$$

or :

$$n = \frac{ds}{du} \cdot \frac{u}{s} \qquad \text{(A1-9)}$$

The Meyer-Peter/Muller formula reads as :

$$s_t = \sqrt{g \Delta D_{50}^3} \cdot \frac{8}{1-\epsilon} \cdot \left(\mu \frac{hi}{\Delta D_{50}} - 0.047\right)^{\frac{3}{2}} \qquad \text{(A1-10)}$$

Introducing :

$$\psi' = \mu \cdot \frac{hi}{\Delta D_{50}}$$

it follows that :

$$\frac{ds}{du} = \sqrt{g \Delta D_{50}^3} \cdot \frac{8}{1-\epsilon} \cdot \frac{3}{2} (\psi' - 0.047)^{\frac{1}{2}} \cdot \frac{d(\psi')}{du} \qquad \text{(A1-11)}$$

Furthermore :

$$\frac{d(\psi')}{du} = 2 \cdot \mu \frac{u}{C^2 \Delta D_{50}} = 2 \cdot \frac{\psi'}{u} \qquad \text{(A1-12)}$$

For the power n the following expression is obtained, after introduction of the above results :

$$n = \frac{3\psi'}{(\psi' - 0.047)} \qquad \text{(A1-13)}$$

Apparently n is not constant, but n = f (ψ'). The relationship between n and ψ' is plotted in the below Figure A1-1.

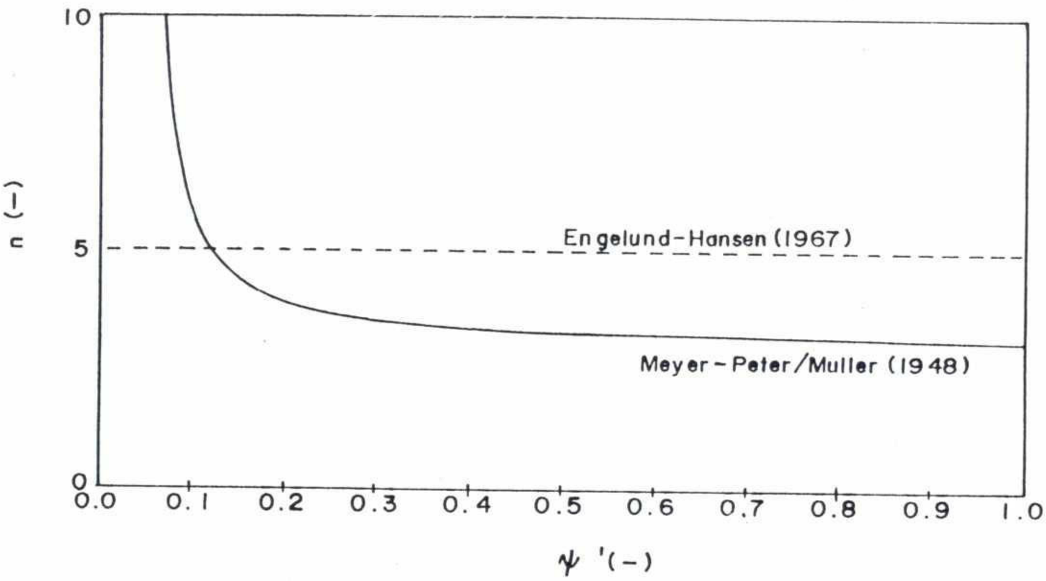

Figure A1-1 Relationship between n and ψ' for the Meyer-Peter/Muller and for the Engelund-Hansen sediment transport predictor

For low values of ψ' (near initiation of motion) the value of n increases rapidly to 8 and more. For high values of ψ' (high sediment transport) the value of n approaches 3. In Figure A1-1 also the value of n according to the Engelund-Hansen formula (constant value of 5 for n) has been drawn.

Value of p

(1) Engelund-Hansen

For the Englund-Hansen (1967) formula the value of p can be obtained directly from Equation (A1-4), which reads as :

$$s_t = g^{-\frac{1}{2}} \cdot \Delta^{-2} \cdot D_{50}^{-1} \cdot \frac{0.05}{1-\epsilon} \cdot C^{-3} \cdot u^5 \qquad \text{(A1-4)}$$

As p is defined as :

$$s_t = m_1 \, D^{-p} \, u^n \qquad \text{(A1-14)}$$

it follows that for Engelund-Hansen (1967) p=1.

(2) Meyer-Peter/Muller (1948)

For the Meyer-Peter/Muller formula again a slightly more cumbersome derivation is needed. By differentiation of Equation (A1-14) it is found that :

$$\frac{ds}{dD} = m_1 \cdot (-p) \cdot D^{-p-1} \cdot u^n \qquad \text{(A1-15)}$$

Hence :

$$\frac{ds}{dD} = -p \cdot \frac{s}{D} \qquad \text{(A1-16)}$$

For the Meyer-Peter/Muller sediment transport predictor it can be shown that :

$$\frac{ds}{dD} = \frac{3}{2}(-0.047)\sqrt{g\Delta}\cdot\frac{8}{1-\varepsilon}\cdot D^{\frac{1}{2}}(\psi'-0.047)^{\frac{1}{2}} \qquad \text{(A1-17)}$$

Introducing this into Equation (A1-16) yields the following expression for p :

$$p = \frac{3}{2}\cdot\frac{0.047}{(\psi'-0.047)} \qquad \text{(A1.18)}$$

The variation of p with ψ' is shown in Figure A1-2. For values of ψ' in the order of 0.1 the value of p is around 1, for smaller values p increases rapidly, while for large values of ψ' p approaches 0. In figure A1-2 also the constant value of p (of p=1) for the Engelund-Hansen sediment transport predictor is introduced.

It can be concluded that according to Engelund-Hansen the relationship between s and D is inversely linear, but according to Meyer-Peter/Muller p varies considerably for smaller values of ψ'.

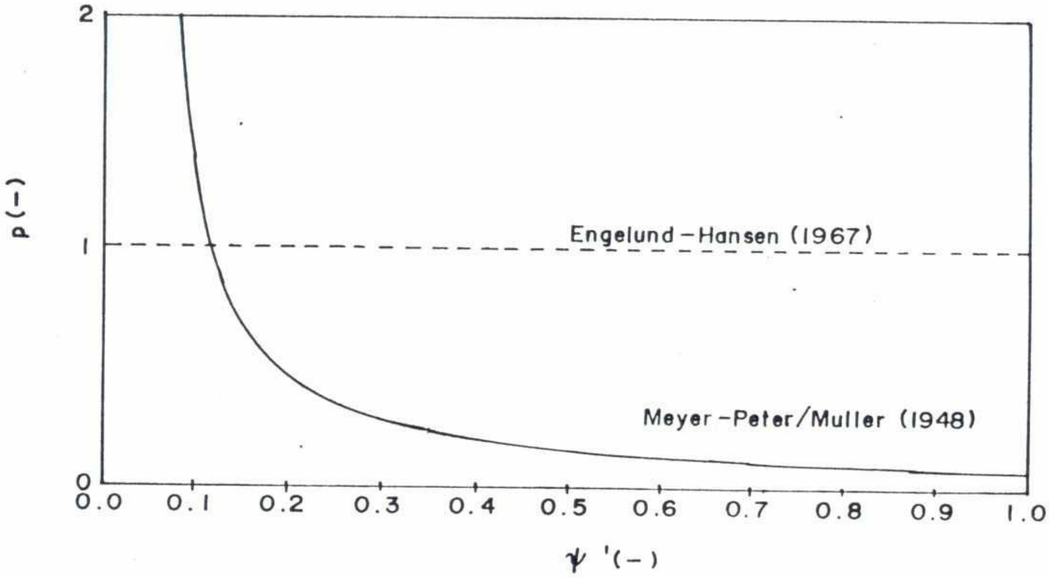

Figure A1-2 Variation of p with ψ' for two sediment transport predictors (Meyer-Peter/Muller and Engelund-Hansen)

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Annexure 2

Improved Lane's balance

Introduction

Predicting the response of a river is a complex task in view of the large number of parameters involved that are interrelated. For rivers with alluvial sediments a very qualitative picture has been proposed by Lane. This relationship reads :

$$S.D::Q.i \qquad \text{(A2-1)}$$

where S = sediment discharge (m^3/s), Q = water discharge (m^3/s), D = grain size (m). and i = slope of energy gradient (m/m).

In this Annexure it is demonstrated that this so-called Lane's balance is indeed good for a first approximation. Furthermore a slightly more refined expression is derived which can also be used for more quantitative predictions. Next this more refined expression is used to develop formulae for the effect of a water diversion, sediment withdrawal and narrowing on the slope and the water depth of an alluvial river. These derivations are done for steady conditions. In a final section the extension to a river with varying discharges is explored.

Derivation for steady discharge conditions

The derivation is done for a schematized reach of a river and for a schematized regime. Initially it is assumed that :

- o the discharge in the considered reach is constant in time (steady conditions),
- o the discharge Q, the yearly volume to be transported V and the size of the bed material D are not varying in longitudinal direction,
- o the river is in equilibrium,
- o hydraulic roughness constant.

It follows that the conditions are steady and uniform conditions.

The basic questions are :

- o Momentum equation which for steady and uniform conditions results in the Chezy equation :

$$Q=BCh^{\frac{3}{2}}i^{\frac{1}{2}} \qquad \text{(A2-2)}$$

- o Sediment transport equation which is schematized to (see Annexure 1) :

$$S=mu^{n} \qquad \text{(A2-3)}$$

Or :

$$s_t = D^{-p} m_1 u^n \tag{A2-4}$$

Introduction of Equation (A2-2) in Equation (A2-4) and multiplying with the width of the river B results in :

$$s_t = D^{-p} m_1 u^n - B D^{-p} m_1 C^n (hi)^{\frac{n}{2}} \tag{A2-5}$$

Equation (A2-5) gives an expression for the transport capacity of the river reach. Integration of this expression over the whole year yields a value that should be equal to the yearly volume of sediment that has to be transported. Hence :

$$V = \int S.dt = \int [B D^{-p} m_1 C^n (hi)^{\frac{n}{2}}] \cdot dt \tag{A2-6}$$

Because it was assumed that Q is constant, it holds that :

$$V = S.365.24.60.60 = 31536000.S = N.S \tag{A2-7}$$

where N (=315360000) corresponds to the number of seconds (in which S is expressed) in a year (in which V is expressed). Thus for steady discharge conditions it can also be written that :

$$\frac{V}{N} = S = B D^{-p} m_1 C^n (hi)^{\frac{n}{2}} \tag{A2-8}$$

This is the expression valid for steady discharge. Together with Equation (A2-2) it can be used to determine expression for the two unknown i and h. Hereafter first the resulting expressions for the energy slope and the water depth will be derived and next the application to different "cases" of human interference will be discussed. All for steady conditions.

Solutions

(a) Solve by eliminating h and thus obtaining an expression for i :

$$Qi = BCh^{\frac{3}{2}} i^{\frac{3}{2}}$$

$$hi = \left(\frac{Qi}{BC}\right)^{\frac{3}{2}}$$

$$SD^{p} = Bm_1 C^{n}\left(\frac{Qi}{BC}\right)^{\frac{n}{3}} = B^{1-\frac{n}{3}} m_1 C^{\frac{2n}{3}} Q^{\frac{n}{3}} i^{\frac{n}{3}}$$

With as ultimate result :

$$SD^{p}B^{\frac{n-3}{3}} = m_1 C^{\frac{2n}{3}} Q^{\frac{n}{3}} i^{\frac{n}{3}} \qquad \text{(A2-9)}$$

which can also be written as :

$$\boxed{S\,D^{p}\,B^{\frac{n-3}{3}} :: Q^{\frac{n}{3}}\, i^{\frac{n}{3}}} \qquad \text{(A2-10)}$$

where the :: sign stands for "is proportional to " and represents the coefficient $m_l.C^{2n/3}$.

(b) Solve by eliminating i and thus obtaining an expression for h:

$$Q = B\,C\,H\,(hi)^{\frac{1}{2}}$$

$$hi = \left(\frac{Q}{B\,C\,h}\right)^{2}$$

$$S = B\,D^{-p}\,m_l\,C^{n}\,(hi)^{\frac{n}{2}} = B\,D^{-p}\,m_l\,C^{n}\left(\frac{Q}{B\,C\,h}\right)^{2}$$

$$S\,D^{p} = B^{n-1}\,m_l\,Q^{n}\,h^{-n}$$

With as ultimate result :

$$S\, D^{p}\, B^{n-1} = m_{l}\, Q^{n}\, h^{-n} \qquad \text{(A2-11)}$$

which again can be written as :

$$\boxed{S\, D^{p}\, B^{n-1} :: Q^{n}\, h^{-n}} \qquad \text{(A2-12)}$$

The Equations (A2-9) and (A2-11) are the quantitative solutions for i and h, respectively, whereas the Equations (A2-10) and (A2-12) provide tendencies alone.

It is of interest to compare Equation (A2-10) to Lane's balance as expressed by Equation (A2-1). It can be concluded that in qualitative terms Equation (A2-1) is quite acceptable. In fact Equation (A2-10) is completely similar for $n=3$ and $p=1$. If n is different from 3 and/or p is different from 1, Equation (A2-9) should be used for quantitative predictions, but still Equation (A2-1) yields the correct tendency (e.g. increase in sediment to be transported for the same D and Q results in an increase in slope).

Applications

The derived equations can now be used to study the effect of human interference in a (simple) river system. Hereafter the following cases are studied : water diversion (without and with change in width), sediment mining, and narrowing. Use is made of the expressions (A2-10) and (A2-12). For all cases a comparison is made between two equilibrium conditions : one before and one after the human interference. The indexes 0 and 1 refer to these two conditions.

(1) *Narrowing*

$B_o \rightarrow B_1$, hence Q, S and D constant :

(a) Change in slope :

$$i^{\frac{n}{3}}\, B^{1-\frac{n}{3}} = constant$$

$$\frac{i_l}{i_o} = \left(\frac{B_l}{B_o}\right)^{\frac{n-3}{n}} \qquad \text{(A2-13)}$$

(b) Change in depth :

$$h^{-n} B^{1-n} = constant$$

$$\frac{h_l}{h_o} = \left(\frac{B_o}{B_l}\right)^{\frac{n-1}{n}} \qquad \text{(A2-14)}$$

(2) Withdrawal of water

$$Q_o \rightarrow Q_o - \Delta Q \quad hence\ S,\ B,\ D\ constant$$

(a) Change in slope :

$$Q\, i = constant$$

$$\frac{i_1}{i_o} = \frac{Q_o}{Q_o - \Delta Q} \qquad \text{(A2-15)}$$

(b) Change in depth :

$$Q^n h^{-n} = constant$$

$$\frac{h_1}{h_o} = \frac{Q_o - \Delta Q}{Q_o} \qquad \text{(A2-16)}$$

(3) Mining of sediment

$$S_o \rightarrow S_o - \Delta S \quad henceQ,\ B,\ D\ constant$$

(a) Change in slope :

$$S :: i^{\frac{n}{3}}$$

$$S\, i^{-\frac{n}{3}} = constant$$

or

$$\frac{i_1}{i_o} = \left(\frac{S_o - \Delta S}{S_o}\right)^{\frac{3}{n}} \qquad \text{(A2-17)}$$

(b) Change in depth :

$$S :: h^{-n}$$

or

$$S\, h^{n} = constant$$

$$\frac{h_1}{h_o} = \left(\frac{S_o}{S_o - \Delta S}\right)^{\frac{1}{n}} \qquad \text{(A2-18)}$$

(4) Water withdrawal including change of width

Decrease of the discharge in a river results in a decrease of the width. This can be included via a regime equation for the width, which reads as :

$$B :: Q_b^{0.5}$$

where Q_b = bankfull discharge. Assuming that both Q_o and Q_1 correspond to Q_b it can also be stated that

$$B_o :: Q_o^{0.5}$$

and

$$B_1 :: Q_1^{0.5}$$

(a) Change in slope:

$$S\, D^{p} :: (Q^{0.5})^{\frac{3-n}{3}}\, Q^{\frac{n}{3}}\, i^{\frac{n}{3}}$$

$$S\,D^{p} :: Q^{\frac{n+3}{6}}\, i^{\frac{n}{3}} \qquad \text{(A2-19)}$$

For water withdrawal $Q_o \rightarrow Q_o - \Delta Q$, hence S and D are constant

$$Q^{\frac{n+3}{6}}\, i^{\frac{n}{3}} = constant$$

$$\frac{i_1}{i_o} = \left(\frac{Q_o}{Q_o - \Delta Q}\right)^{\frac{n+3}{2n}} \qquad \text{(A2-20)}$$

$$For\ n = 5 \rightarrow \frac{i_1}{i_o} = \left(\frac{Q_o}{Q_o - \Delta Q}\right)^{\frac{4}{5}}$$

$$n = 3 \rightarrow \frac{i_1}{i_o} = \left(\frac{Q_o}{Q_o - \Delta Q}\right)$$

(b) Change in depth :

$$S\,D^{p} :: (Q^{0.5})^{1-n}\, Q^{n}\, h^{-n}$$

$$S\,D^{p} :: Q^{\frac{1+n}{2}}\, h^{-n} \qquad \text{(A2-21)}$$

For water withdrawal $Q_o \rightarrow Q_o - \Delta Q$, hence S and D are constant

$$Q^{\frac{1+n}{2}}\, h^{-n} = constant$$

$$\frac{h_1}{h_o} = \left(\frac{Q_o - \Delta Q}{Q_o}\right)^{\frac{1+n}{2n}} \qquad \text{(A2-22)}$$

$$For\ n = 5 \rightarrow \frac{h_1}{h_o} = \left(\frac{Q_o - \Delta Q}{Q_o}\right)^{\frac{3}{5}}$$

$$n = 3 \rightarrow \frac{h_1}{h_o} = \left(\frac{Q_o - \Delta Q}{Q_o}\right)^{\frac{2}{3}}$$

Hence the same tendency as for constant width, but less serious effect, as the value of the power is less than for the case where the width was supposed to be constant.

Table A2-1 summarizes the above results.

Extension to varying discharge

In the above derivations it was assumed that the discharge in the river is constant. The derived equations can be extended fairly easily to include also the varying discharge conditions. This will be done hereafter.

The variation of the discharges can be characterized by the probability distribution p_i,(Q). This probability distribution is derived from the frequency distribution f(Q) (which in itself is obtained by analyzing the hydrograph Q(t), e.g. the time series of daily discharges, when determined over a sufficiently long period (many hydrographs).

Here first an equation for the slope is derived, essentially following the derivation which leads for constant discharge to the Equations (A2-9) and (A2-10). Assuming uniform flow (hence considering a river reach sufficiently far away from the downstream boundary), and using Equation (A2-9) for each discharge class, it holds that:

$$S_i D^p B^{\frac{n-3}{3}} = m_1 C^{\frac{2n}{3}} Q_i^{\frac{n}{3}} i^{\frac{n}{3}} \qquad \text{(A2-23)}$$

This expression can be integrated over the whole year yielding:

$$D^p B^{\frac{n-3}{3}} \int S_i dt = m_1 C^{\frac{2n}{3}} i^{\frac{n}{3}} \int Q_i^{\frac{n}{3}} dt \qquad \text{(A2-24)}$$

For the integral of the discharge to the power n/3 it holds:

$$\int Q_i^{n/3} = N \int P_i Q_i^{n/3} \qquad \text{(A2-25)}$$

While for the integral of the sediment transport corresponds to the volume of sediment that has to be transported yearly, hence:

$$\int S.dt = V \qquad \text{(A2-25)}$$

Hence Equation (A2-24) can also be written as:

$$D^p B^{\frac{n-3}{3}} V = m_1 N.\, C^{\frac{2n}{9}} i^{\frac{n}{3}} \int p_i Q_i^{\frac{n}{9}} .dt \qquad \text{(A2-27)}$$

Assuming again that C is constant this equation can also be written as:

$$V D^p B^{\frac{n-3}{3}} \propto i^{\frac{n}{3}} \int p_i Q_i^{\frac{n}{3}} .dQ \qquad \text{(A2-28)}$$

Where the integration now has to be done over all values of Q. This equation is the equivalent of Equation (A2-10). Instead of S now V is used and the integral takes the place of the (constant) Q in Equation (A2-10). To expand on this similarity slightly more, it is handy to introduce:

$$\alpha_Q = \int p_i \left(\frac{Q_i}{\bar{Q}}\right)^{\frac{n}{3}} .dQ \qquad \text{(A2-29)}$$

and

$$\bar{S} = \frac{V}{N} \qquad \text{(A2-30)}$$

allowing to re-write Equation (A2-28) as:

$$\boxed{\bar{S} D^p B^{\frac{n-3}{3}} \propto \alpha_Q \bar{Q}^{\frac{n}{3}} i^{\frac{n}{3}}} \qquad \text{(A2-31)}$$

This clearly demonstrates the similarity between Equation (A2-10) and the result of the present analysis.

Some remarks on the coefficient α_Q :

- o The coeffcicient α_Q is a measure of how much the river flows may deviate from average conditions. As such it is in fact a reflection of both the duration curve and the sensitivity of the river for these deviations via the power n/3. Hence α_Q is different for all rivers.
- o For n = 3 the coefficient $\alpha_Q = 1$.
- o If the discharge is constant also then it follows that $\alpha_Q = 1$.
- o If e.g. a reservoir is constructed and no water is diverted, the reservoir will

influence the value of α_Q. As a reservoir tends to "flatten" the hydrograph, also the value of α_Q will become lower. The effect is (for the same V,D,B and Q that the slope i of the river has to increase. The more the deviation from the average conditions the easier can the river transport its sediment.

The above equations were derived for the slope of the river, assuming that this slope would not vary through the year. This assumption is logic considering the large quantities of sediment that have to be moved for slope changes.

For steady flow it was also possible to derive a similar expression for the water depth. Here, however, because the discharge is varying and the slope is assumed to remain constant, the water depth is varying as well. Hence there is no equivalent for the equations (A2-11) and (A2-12).

Applications for varying discharge

Similar to what was done for constant discharge it is now possible to derive expressions for the response of the river to changes in the independent variables, e.g. due to human interventions. Here this is done for the three basic cases considered before (narrowing, water withdrawal and sediment mining). In addition the effect of a change in the duration curve is studied here. Use is made of Equation (A2-28). The elaboration is similar to what was done for the steady case and will not be given here. The following results are obtained for the change in slope (see also Table A2-2):

(1) Narrowing :

$$\frac{i_1}{i_o} = \left(\frac{B_1}{B_o}\right)^{\frac{n-3}{n}} \qquad \text{(A2-32)}$$

(2) Water withdrawal:

Here it the diversion ΔQ may be different for each Q :

$$\frac{i_1}{i_o} = \left(\frac{\int P_i . Q_i^{\frac{n}{3}} . dQ}{\int P_i (Q_i - \Delta Q_1)^{\frac{n}{3}} . dQ}\right) \qquad \text{(A2-33)}$$

(3) Sediment withdrawal

$$\frac{i_1}{i_o} = \left(\frac{S_o - \Delta S}{S_o}\right)^{\frac{3}{n}} \qquad \text{(A2-34)}$$

Human intervention		Effect on: Slope	Effect on: Water depth
Q constant	Narrowing/ widening $B_o \rightarrow B_1$	$\frac{i_1}{i_o} = \left[\frac{B_1}{B_o} \right]^{\frac{n-3}{n}}$	$\frac{h_1}{h_o} = \left[\frac{B_o}{B_1} \right]^{\frac{n-1}{n}}$
	Water withdrawal (constant width) $Q_o \rightarrow Q_1 = Q_o - \Delta Q$	$\frac{i_1}{i_o} = \frac{Q_o}{Q_o - \Delta Q}$	$\frac{h_1}{h_o} = \frac{Q_o - \Delta Q}{Q_o}$
	Sediment mining $S_o \rightarrow S_1 = S_o - \Delta S$	$\frac{i_1}{i_o} = \left[\frac{S_o - \Delta S}{S_o} \right]^{\frac{3}{n}}$	$\frac{h_1}{h_o} = \left[\frac{S_o}{S_o - \Delta S} \right]^{\frac{1}{n}}$
	Water withdrawal $(B :: Q^{0.5})$ $Q_o \rightarrow Q_1 = Q_o - \Delta Q$	$\frac{i_1}{i_o} = \left[\frac{Q_o}{Q_o - \Delta Q} \right]^{\frac{n+3}{2n}}$	$\frac{h_1}{h_o} = \left(\frac{Q_o - \Delta Q}{Q_o} \right)^{\frac{n+1}{2n}}$

Table A2-1 Effect of human intervention on channel slope and depth for constant discharge

Q variable	Narrowing $B_o \rightarrow B_1$	$\frac{i_1}{i_o} = \left[\frac{B_1}{B_o}\right]^{\frac{n-3}{n}}$	Where flow is uniform: $\left(\frac{h_1}{h_0}\right)_i = \left(\frac{i_0}{i_1}\right)^{\frac{1}{3}}$ elsewhere non-uniform flow profile
	Water withdrawal (B constant) $Q_{io} \rightarrow Qi_1 = Qi_o - \Delta Q_i$	$\frac{i_1}{i_0} = \left(\frac{\int p_i \cdot Q_i^{\frac{n}{3}} .dQ}{\int p_i \cdot (Q_i - \Delta Q_i)^{\frac{n}{3}} .dQ}\right)^{\frac{3}{n}}$	Where flow is uniform: $\left(\frac{h_1}{h_0}\right)_i = \left(\frac{i_0}{i_1}\right)^{\frac{1}{3}}$ elsewhere non-uniform flow profile
	Sediment mining $S_o \rightarrow S_1 = S_o - \Delta S$	$\frac{i_1}{i_o} = \left[\frac{S_o - \Delta S}{S_o}\right]^{\frac{3}{n}}$	Where flow is uniform: $\left(\frac{h_1}{h_0}\right)_i = \left(\frac{i_0}{i_1}\right)^{\frac{1}{3}}$ elsewhere non-uniform flow profile
	Change in probability density function $p_0(Q) \rightarrow p_1(Q)$	$\frac{i_1}{i_0} = \left(\frac{\int p_{0i} \cdot Q_i^{\frac{n}{3}} .dQ}{\int p_{1i} \cdot Q_i^{\frac{n}{3}} .dQ}\right)^{\frac{3}{n}}$	Where flow is uniform: $\left(\frac{h_1}{h_0}\right)_i = \left(\frac{i_0}{i_1}\right)^{\frac{1}{3}}$ elsewhere non-uniform flow profile

Table A2-2 **Effect of human intervention on channel slope and depth for varying discharge**

(4) Change in hydrograph/duration curve :

$$\frac{i_1}{i_o} = \left(\frac{\int P_{o1} . Q_i^{\frac{n}{3}} . dQ}{\int P_{li} Q_i^{\frac{n}{3}} . dQ} \right)^{\frac{3}{n}} \qquad \text{(A2-35)}$$

or :

$$\frac{i_1}{i_o} = \left(\frac{(\alpha_Q)_o}{(\alpha_Q)_1} \right)^{\frac{3}{n}}$$

As was explained there is no comparable equation for the water depth as the water depth is varying with the discharge. In a uniform reach, hence far away from the downstream boundary, it holds (according to the Chezy equation) for any Q_i :

$$h_1^{\frac{3}{2}} . i_1^{\frac{1}{2}} = h_o^{\frac{3}{2}} . i_o^{\frac{1}{2}}$$

Hence for any Q_i :

$$\left(\frac{h_1}{h_o} \right)_i = \left(\frac{i_o}{i_1} \right)^{\frac{1}{3}}$$

To use this equation first the change in slope has to be computed with one of the previous equations and next the change in h can be determined.

Combinations

It can easily be shown that for combinations of interventions, the effects have to be multiplied. Hence e.g. for water withdrawal in combination with some sediment withdrawal, it holds that :

$$\left(\frac{i_1}{i_o}\right) waterwithdrawal + sedimentwithdrawal = \left(\frac{i_1}{i_o}\right) waterwithdrawal * \left(\frac{i_1}{i_o}\right) sedimentwithdrawal$$

or :

$$\frac{i_1}{i_o} = \left(\frac{Q_o}{Q_o - \Delta Q}\right)\left(\frac{S_o}{S_o - \Delta S}\right)^{\frac{1}{n}}$$

Similar expression can be derived for other combinations. The most general expression reads :

$$\frac{i_1}{i_o} = \left(\frac{B_1}{B_o}\right)^{\frac{n-3}{n}} \cdot \left(\frac{Q_o}{Q_o - \Delta Q}\right) \cdot \left(\frac{S_o - \Delta S}{S_o}\right)^{\frac{1}{n}} \cdot \left(\frac{(\alpha_Q)_o}{(\alpha_Q)_1}\right)^{\frac{3}{n}}$$

Annexure 3

Embankments considered in the various regional plans

Brahmaputra Right Embankment (BRE)

In the existing situation (scenario 1) as well as for the future scenarios a watertight RRE has been assumed along its present alignment. It has assumed along its present alignment. It starts from Kaunia and ends at Hurasagar. The embankment has setback distances from nil to about 1 km at various locations. Upstream of the Teesta outfall the present embankment of the Kurigram project is included. Similarly, downstream of Hurasagar the existing embankment of the Pabna IRD projects, also extending up along the Ganges left bank, is modelled.

Jamuna Left Embankment (North)

In the existing situation (scenario 1), the FAP 25-GM includes the existing and Food for Work (FFW) embankments west of Chatal river. Excluding a few gaps here and there, the left bank up to Dhaleswari off-take near Porabari appears fully dyked. The alignment corresponds to the recommendations of FAP 3 and FAP 3.1. During high river stage a considerable flow enters the left bank flood plains as overbank spill or through the said gaps. In the FAP 25-GM this situation is modelled through inclusion of a distributary channel (Jamuna-FP) in the Jamuna left bank flood plain. This channel has its off-take in the Jamuna downstream of Old Brahmaputra at chainage 100.5 km and it joins the Dhaleswari approximately 20 km upstream of its confluence with the Lakhya. The channel is linked with the Jamuna through three artificial channels and with the Dhaleswari upstream of the Kaliganga bifurcation through one artificial channel.

For the future scenarios a full Jamuna Left Embankment is modelled by cutting off these artificial channels. There is no flow in the Jamuna-FP channel. The distance between embankments on the two bank varies from 10-20 km under present and future scenarios, except at Jamuna Bridge location where it is less than 5 km (Figure 4.1 b).

Jamuna Left Embankment (South) - Western Alignment :

At present, there is no continuous embankment except some piecemeal works up to Harirampur. In the existing situation (scenario 1) the FAP 25-GM morphological cross sections extend to the highest point along the left bank, which is also considered to represent the alignment for the future protection scenarios, except for a few km downstream of the Dhaleswari off-take.

Ganges Left Embankment

At present, there are embankments along the Ganges left bank from Rajshahi upto Pabna embankment. In all scenarios the existing alignment is considered as solid.

There are no embankment along the Ganges from the Indo-Bangladesh border to Rajshahi. Along this stretch the FAP 25-GM uses simplified artificial cross-section in the existing as well as the future scenarios.

Ganges Right Embankment

Today, there are high grounds and FFW embankments along the Ganges right bank down to the right bank of the Padma. These existing embankments are represented in FAP 25-GM, scenario 1.

However, for the future protection scenarios 4-6 new embankments are assumed at a few locations resulting in lesser river width. These new locations are based upon the nearby sections with a view to obtaining smooth width transitions along the entire length of the river.

Padma Left Embankment

At present, there are no continuous embankments along the Padma left bank. In the existing situation (scenario 1), the morphological cross-sections extend to the highest point on the bank from Harirampur up to the confluence with the Meghna, (see Figure 4.1 c). This is also the case for the future protection scenarios 5.

Padma Right Embankment

FFW embankments exist along the Padma right bank up to the off-take of the upper Arial Khan. Also, a number of spill channels exists along this stretch. During high flood large flood flows escape through the spill channels and flood plains into the distributary channel approximately 20 km upstream of the Arial Khan off-take.

In the future protection scenario 5, (see Figure 4.1 c), the Padma Right Embankment is considered watertight and the artificial distributary channel is cut off. The upper Arial Khan and the Arial Khan off-takes remain open. Width of the Padma is the same as in the existing situation and varies from 9 to 17 km.

Old Brahmaputra Embankments

In the existing situation embankments exist at places along the right bank and together with the existing railway line, prevent flood flow from entering into the North-Central region. There are no embankments along the left bank of Old Brahmaputra. Along the Lakhya embankments exist near its off-take and close to the outlet to the Dhaleswari, where the Dhaka-Narayanganj-Demra project is located along the right bank.

In the future scenarios 5 and 6, FAP 25-GM cuts off all flood plains along the Old Brahmaputra and the Lakhya. The distance between the embankments along the Old Brahmaputra varies between 2 km to 5 km while along the Lakhya, it is approximately 2 km.

Dhaleswari Left Embankment

At present there are no embankments along the Dhaleswari left bank and the observed spill between the Dhaleswari left bank and the Jamuna left bank flood plains is modelled through an artificial link channel. The FAP 25-GM morphological cross-sections are not extended into the flood plains and stop at the highest point in the existing as well as the future situation.

In the future scenarios 2-6 the Dhaleswari Left Embankment is thus modelled merely by cutting off the artificial spill channel.

Dhaleswari Right Embankment

In the existing situation the right bank has large flood plains and the morphological cross-sections are extended into these flood plains.

In the future scenario 5, (see Figure 4.1 c), the Dhaleswari Right Embankment cuts off these flood plains. The FAP 25-GM assumes a typical width of 4 to 6 km along the Dhaleswari and 2 km along the Kaliganga between the embankments.

Upper Meghna Left Embankment

In the existing situation, there are FFW embankments at a few locations. In the future when Gumti Phase II comes up, a continuous embankment is expected along the Upper Meghna left bank.

In the FAP 25-GM the morphological cross-sections are extended up to the highest point in the existing as well as the future scenarios.

Upper Meghna Right Embankment

At present there are no embankments along the Upper Meghna right bank. In the FAP 25-GM the morphological cross-sections are extended into the flood plains.

For the future scenario 5, an embankment has been assumed which starts from Bhairab Bazar and proceeds to the outfall of Upper Meghna, (see Figure 4.1 c). The distance between the left and right embankments is typically 10 to 15 km.

Lower Meghna Left Embankment

Today embankments exist from the Meghna-Donagoda to Chandpur Irrigation projects with a break above Chandpur. All scenario runs assume continuous embankment, (see Figure 4.1 c).

Lower Meghna Right Embankment

Today no embankments exist along the right bank. All scenarios are identical and assume no embankments even for the future scenarios.