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Development of sector response functions for a water resources decision support system

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Abstract: Currently, the Institute of Water Modelling (IWM) hosts a suite of hydrodynamic models that can simulate river stages and discharge, flood and groundwater levels and water quality parameters for most regions of Bangladesh. In the past 10 years, there has been a growing capacity and capability of numerical modelling in IWM and other organizations in the country. However, there is pressing need to translate the outputs of these models into meaningful information for decision makers. “What is the effect on Aman rice production from an increase in upstream water levels due to a new embankment on the Jamuna River?” “What is the cost of infrastructure damage due to Climate Change induced sea level rise in Chittagong port area?” To address this knowledge gap, researchers at IWM are developing a water resources Decision Support System (DSS) that can use outputs from the numerical models to predict likely impacts on key sectors, such as agriculture, infrastructure, environment, fisheries, navigation, etc. It is envisaged that this DSS will assist policy makers and planners by providing information about likely impacts of water-related projects in Bangladesh. The DSS has also been designed to be a communication and educational tool for non-technical users and key project stakeholders.

In this paper, the sector response functions used in the DSS to estimate various impacts are described. The prototype DSS is GIS-based and primarily data driven. However, it also has features of a model-driven DSS. At the heart of the DSS impact estimates are the sector response functions, which consist of quantitative and qualitative relationships that describe how changes in the state of water resources will affect key sectors. For example, for the agriculture sector, response functions include empirical equations that estimate losses in rice yield depending on rice type, growth stage, water level, duration of inundation and salinity levels. The impacts are presented in terms of yield loss in tonnes and also in monetary units, where relevant price data is available.

For the fisheries sector, one of the response functions estimates the connectivity between a river and an adjacent water body. This module takes into account timing and duration of connection between the river and the adjacent water body. Where sufficient data is available, the DSS user can relate the connectivity measure to fisheries yields. Thus, impacts of changes in the river (and flood) hydrology on fish yields can be estimated.

The development of DSSs is a key feature in IWM’s long-term plan. This involves meeting the growing demand from integrated modelling software to hydroinformatic objects, such as DSSs. This evolution should assist resource managers and decision makers in Bangladesh to adapt better to Climate Change and chronic water-related challenges, such as arsenic contamination in groundwater.

Keywords: *Decision Support System (DSS), water resources, Bangladesh, impact assessment*

1. INTRODUCTION

Term Decision Support System (DSS) is used to describe a wide variety of tools: from spreadsheets to complex GIS-based simulation models. When DSSs are well-designed, they help achieve more informed and effective decision-making (Rizzoli and Young, 1997). More advanced and complex DSSs, integrate environmental, economic, social aspects related to the decisions being made. This is achieved by using different models and datasets to create flexible linkages between the different bio-physical and socioeconomic aspects of a resource system. Thus, a DSS enables its user to quickly analyse and compare alternative courses of actions or strategies under different uncertain developments or scenarios to demonstrate the impacts of different options or alternatives. This can also be coupled with optimization routines incorporating several objectives and criteria (Ascough et al 2002).

In Bangladesh, there have been DSSs developed for particular sectors or specific projects, e.g. in agriculture (Ruanne et al 2008), reservoir management (Ahmed, Hye and Rahman 2001), fisheries (Hossain et al *in press*, CEGISBD 2008, Halls et al 2007), etc. Indeed, the suite of modeling tools used in IWM can be considered as water resources DSSs. However, these tools are for specific applications and geared towards users with a high degree of technical knowledge, typically engineers. The current challenge is to translate the outputs from these models into a form that can be easily understood by other decision makers, who come from a broader range of disciplines, e.g. economists, sociologists, ecologists, etc. These decision makers face pressing questions such as: “What is the effect on Aman rice production from an increase in upstream water levels due to a new embankment on the Jamuna River?”; and “What is the cost of infrastructure damage due to Climate Change induced sea level rise in Chittagong port area?”. Also, the current challenge includes developing a DSS that is robust and can be applied to a wide range of projects and locations. To address this knowledge gap, researchers at IWM are developing an integrated water resources management Decision Support System (DSS) that can use outputs from the numerical models to predict likely impacts on key sectors, such as agriculture, infrastructure, environment, fisheries, navigation, etc. This DSS is being developed to assist policy makers and planners by providing information about likely impacts of water-related projects in Bangladesh. The DSS has also been designed to be a communication and educational tool for non-technical users and key project stakeholders.

This paper describes some of the development activities for a Decision Support System (DSS) for water resources management in Bangladesh. We present preliminary results from prototype DSS testing and consultations with stakeholders. We focus on the response functions developed for agriculture and the capture fisheries sectors. Further details of the DSS development process, stakeholder consultations and case study area are provided in Zaman et al (2009).

2. DSS RESPONSE MODULE CONCEPTUAL APPROACH

The response modules in the IWRM DSS, relates sector wise impact functions (IFs) directly or indirectly to changes in hydrodynamic model outputs (HMOs) with relational impact parameters (IP). As shown in Figure 1, the architecture of the IWRM DSS includes three types of impact calculation methods:

1. Type 1: impact = f(one HMO and one IP), e.g. water supply availability from flow duration curve;

2. Type 2: impact = f(HMOs, IPs), e.g. inundation of crops over several days; and

3. Type 3: impact = g(f(HMOs, IPs), IPs), e.g. converting river stage and duration to fish migration restriction through beel[1] inlet.

For example, impacts on water supply reliability can be classified as a Type 1 estimation procedure. The impact is a direct function of one HMO and one IP. In this case, the HMO is a flow duration curve (for before and after change scenarios) and the IP is the minimum supply reliability. The impact calculation method used in the Agriculture Response Module to estimate crop yield changes is an example of a Type 2 estimation procedure. The impact on crop yield is a direct function of more than one HMO and several IPs. In this case, the HMOs are inundation depths (for before and after change scenarios) and flood duration. IPs include: crop growth stage and critical water depth. The impact calculation method used in Capture Fisheries Module to estimate fish yield changes is an example of a Type 3 estimation procedure. The impact on fish yields are an

[1] ‘Beel’ is a local term referring to freshwater lakes formed in natural, floodplain depressions formed by erosion or other geophysical processes. These lakes can be seasonal or perennial and support capture and culture fisheries, irrigation, domestic water supply, etc. Beels are different to ‘boars’ (ox-bow lakes) and ‘haors’ (large depressions forming freshwater wetlands).

indirect and direct function of more than one HMO and several IPs. In this case, the HMOs are river stage and duration. IPs include: fish growth stage, inlet cutoff depth and critical inlet cross-section area. These modules are discussed in more detail in the following sections.

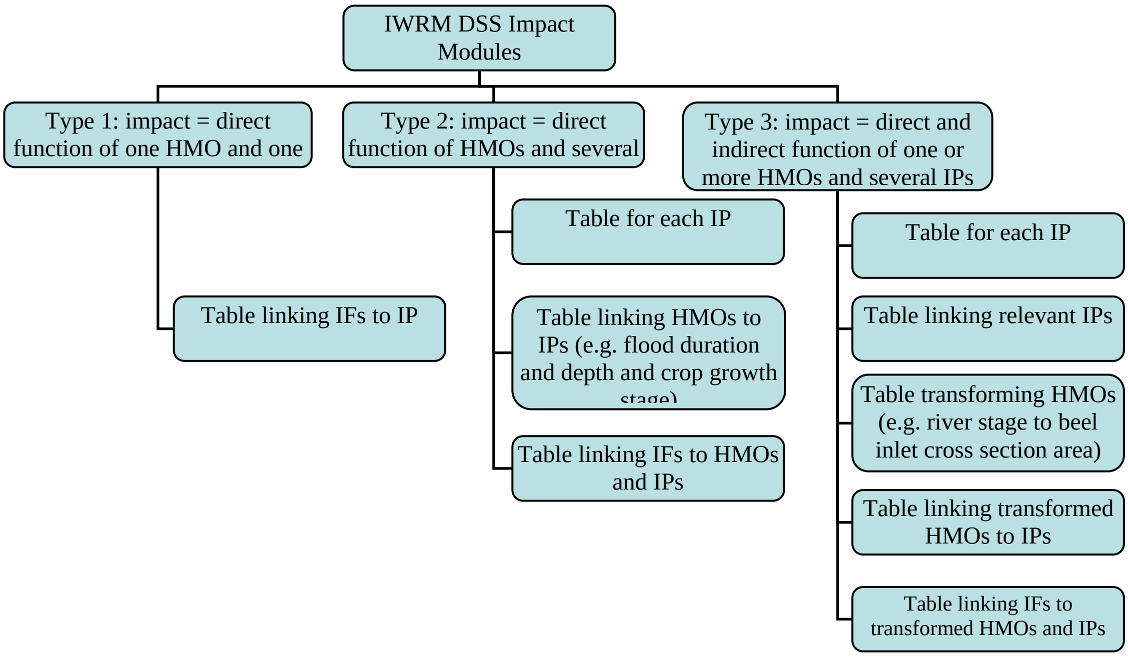

Figure 1. Three types of impact estimation methods in IWRM DSS, categorized by relationship between Impact Function (IF) with Hydrodynamic Model Output (HMO) and Impact Parameters (IP).

3. AGRICULTURE RESPONSE MODULE

The agriculture response module estimates the impact on crop yield due to flooding. This discussion will focus on rice but can be extended to other crop varieties such as wheat, sugarcane, jute, and vegetables.

The basic assumptions in this module include (Jackson and Ram 2003, Ismail 2006, Oldeman et al 1986):

- Excess water levels damage crops after a critical level is exceeded – the threshold is defined by local farmers, published data from field tests, or simply crop heights;
- Damage increases as inundation duration increases until the total crop yield is lost; and
- The severity of damage depends on crop growth stage.

These factors are combined through interrelated database tables as shown in Figure 2. Flood inundation maps and cropping area maps are input into the DSS as GIS layers and these are combined to identify land parcels that suffer crop damage. This is done by comparing the inundation depth with the critical crop depth at the relevant growth stage. The extent of the damage is calculated based on the time of the year (crop growth stage) and duration of inundation. In this way, the yield reduction for a particular month is calculated for each land parcel (raster pixel or vector object). By comparing the result for two scenarios (e.g. before and after project), the impact on yield is obtained. The impact may be the same, or there may be a positive impact (severity of crop damage is alleviated) or a negative impact.

In the case where the user analyses the impact over several months (e.g. the Monsoon season – May to October), the DSS employs a “time window” approach to estimate the impacts on expected seasonal or annual yield. First the impacts on each land parcel are identified at the start of the time window. Then the cumulative impacts on expected yield are calculated until the end of the time window. The difference between the two values gives the impact for the period of analysis. This value is the compared between the two (or more) scenarios being investigated in the DSS.

After consultation with agronomists, a range of critical depths for each crop growth stage, and growth stage lengths were obtained. Also the agronomists confirmed that the basic approach of the agriculture response module is scientifically sound. However, concerns were expressed that detailed data for the crop response may not be available. As a result we are adapting the design to include range of impact based on uncertainty in the yield reduction values. This functionality was not complete during writing of this paper.

It should be noted that the basic formulation of the agriculture response module is to relate the hydrodynamic model outputs (flood inundation level and duration) to an impact value (crop yield reduction) through a series of relational tables (impact parameters). It is envisaged that a similar approach, where appropriate, will be used to estimate impacts due to other water-related stresses, such as salinity, temperature, drought, etc.

Figure 3 shows a sample output from the agriculture response module.

Crop calendars are specified for different land types (highland, lowland, etc.), identifying growth stages for crops in the study area by calendar month.

Crop Calendars

Month and crop growth stage

			Jan	Feb	Mar	Apr	May	Jun	Jul	Au
CalendarID	CropID	Crop name	1	2	3	4	5	6	7	8
5	1	T.Aman						1	1	2
5	2	HYV Boro	1	2	2	3	3			
5	3	Aus				1	1	2	2	2
5	4	Wheat	2	3	4					
4	1	T.Aman							1	1
4	2	HYV Boro	1	2	2	3	3			
4	3	Aus				1	1	2	2	
4	4	Wheat	2	3	4					

Table listing critical depths for crop type and growth stage. For example, for Transplanted Aman crop stage 1, the critical depth is 0.2m (this is a fictitious value).

Critical Depths by crop and growth stage

Maximum water depth crop can tolerate

CropID	Crop name	1	2	3	4	
1	T.Aman	0.2	0.3	0.4	0.6	
2	HYV Boro	0.4	0.4	0.5		
3	Aus	0.5	0.7			
4	Wheat	0.3	0.4	0.5	0.6	

Table listing yield reduction (as %) for each crop growth stage as function of duration of inundation above critical depth. For example, for T.Aman stage 1, duration of 5 days above critical depth (0.2 from above table) leads to 15% reduction in yield. Duration of 10 days leads to further 25% loss and so on.

Crop yield reduction by crop stage and inundation duration

Days of inundation above critical depth and yield reduction (%)

Crop name	1	3	5	10	14	21	28
T.Aman-1	10	12	15	25	30	70	100
T.Aman-2	10	15	20	30	50	90	100
T.Aman-3	14	20	25	50	70	100	100
T.Aman-4	20	30	50	100	100	100	100
HYV Boro-1	15	20	25	30	50	80	100
HYV Boro-2	30	40	50	70	90	100	100
HYV Boro-3	35	45	60	80	100	100	100
Aus-1	15	20	25	30	50	80	100
Aus-2	17	25	27	60	80	90	100

Figure 2. Key Tables in Agriculture Response Module (fictitious values shown)

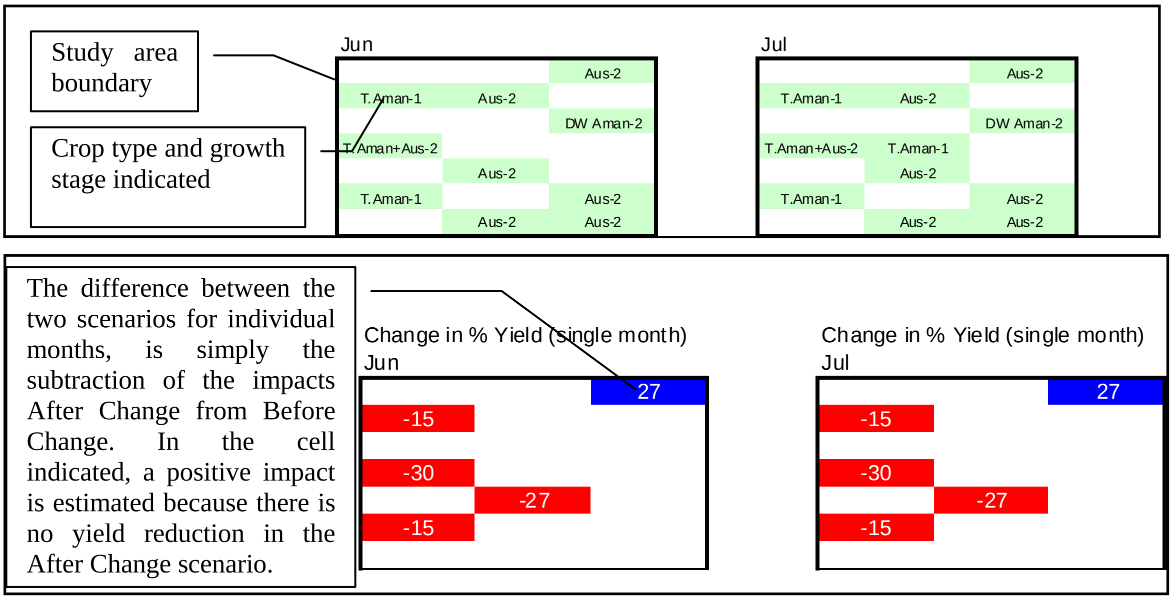

Figure 3. Example Outputs from Agriculture Response Module

4. FISHERIES RESPONSE MODULE

The fisheries sector of Bangladesh is quite complex, with large number of species, capture and culture fisheries, migratory ("white") and floodplain resident ("black") fishes, etc. Therefore, from an early stage in the DSS design, it was envisaged that several response modules would be required. We have focused on developing response modules for the capture fisheries sector, as this has been considerably impacted by flood defense and irrigation projects over the past few decades (FPCO 1992, Nishat and Bhuiyan 1997, etc.). Indeed there seems to be conflicts and tradeoffs between agricultural and fisheries yield (Shankar et al 2004). One of the major impacts is the change in connectivity[2] between natural water bodies (like beels and hoars) to their connecting rivers, which has major implications for white and black fishes.

Currently, two impact models have been incorporated in the fisheries response module of the DSS. One model focuses on beel-river connectivity; the other expands on this by including a density dependent fish population model. Due to space constraints, only the first model is described in this paper.

4.1. Conceptual River-Beel Connection

In Figure 4, a simple conceptual river-beel connection is shown. The key parameters include beel cutoff depth, mean river bank level for the inlet, and river stage versus inlet cross-section area relationship. In this connection setup, changes in river hydrology will affect the four dimensions of river-beel connectivity. Thus, when comparing two or more scenarios, the DSS outputs differences in these connectivity measures.

In Figure 5, example outputs from this module are shown. The user can quickly see the difference between the scenarios in terms of beel-river connectivity.

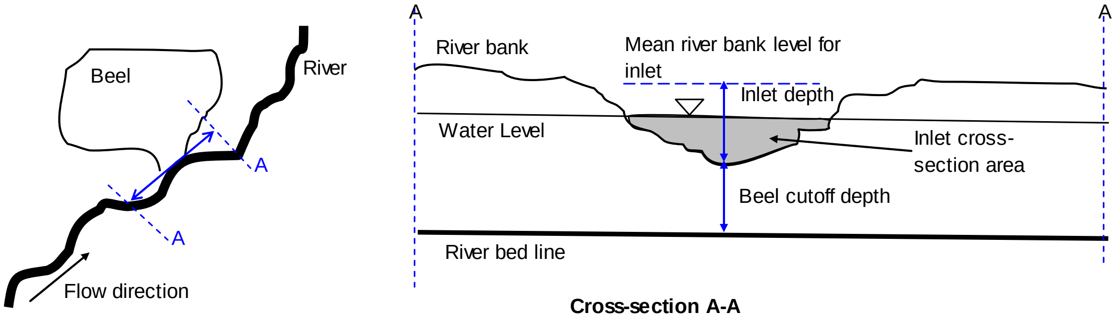

Figure 4. Parameters of the Conceptual Beel-River Connection Model

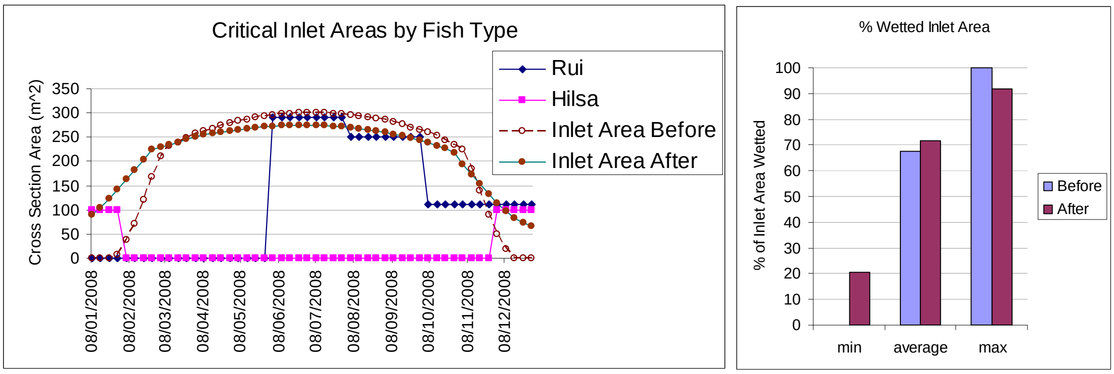

Figure 5. Example output from Fish Response Module – River-Beel Connectivity (Rui and Hilsa are different fish species

4.2. Fish Yield Response Curves

When suitable data is available, the fish yield response due to changed beel-river connectivity can be estimated in the DSS. This is done by relating the inlet cross-section area with floodplain fish yields. Several relational tables (impact parameters) are required as shown in Figure 6. First the user needs to specify how the inlet cross-section area varies with river stage (similar to a stage-discharge relationship). The user can

[2] Connectivity means frequency, duration, flow and depth of river water at the beel inlet.

define more than one inlet area – river stage relationship for a given location, which can be used to examine impact of changes to inlet cross-section profiles (due to siltation, embankments, etc.). Then the critical area for each fish species, at relevant growth stages, need to be specified (similar to critical depths for crop growth stage in the agricultural response module). The final table required is the extent of fish yield reduction due to the critical area not being met over different durations (typically weeks).

Table of Inlet Cross-section area (m^2) For Different Fish Locations

FLID	Location Name	CrossSectionID	Maximum Intake X-section Area (m^2)	Cutoff Depth (m)	Mean River Bank Level (m)	Mean inlet depth (m)	River stage (m) 0	1	2	3
1	Location 1	1	500	4	8	4	0	50	100	250
2	Location 2	1	400	3	6	3	0	32	60	180
2	Location 2	2	400	3	6	3	0	20	40	100
3	Location 3	1	300	2	10	8	0	60	150	225
3	Location 3	2	200	1	10	9	0	16	30	90

In this table, the user defines the relationship between river stage and beel inlet area.

Normal Fish Yields by Location and Species and Critical Inlet Cross-Section area (m^2) required for Fish movement through Beel inlet by Fish growth stage

FLID	FishID	Fish Name	Normal Yield (t)	Growth stage 1	2	3	4	
1	1	Rui	4	50	40	0	0	
1	3	Catla	3	30	0			
1	4	Silver Carp	5	0	40	50	60	
2	2	Hilsa	3	60	60	60		
2	5	Prawn	6	40	30	20	10	
3	1	Rui	3	60	50	10	10	
3	3	Catla	2	40	0			

In this table, the user defines the critical inlet areas for fish species and growth stage.

Fish yield reduction by growth stage and duration of critical period

Weeks of migration restriction and yield reduction (%)

Fish name and stage	1	2	3	4	6	8	10
Rui-1	10	12	15	25	30	70	100
Rui-2	10	15	20	30	50	90	100
Rui-3	14	20	25	50	70	100	100
Rui-4	20	30	50	100	100	100	100
Hilsa-1	15	20	25	30	50	80	100
Hilsa-2	30	40	50	70	90	100	100
Hilsa-3	35	45	60	80	100	100	100
Catla-1	15	20	25	30	50	80	100
Catla-2	17	25	27	60	80	90	100

In this table, the user specifies how fish yield varies with duration of stress (inlet area below critical value).

Figure 6. Relational tables in Fisheries Response Module to Estimate Impacts on Fish Yields

Example outputs from this part of the Fisheries Response Module are shown in Figure 7. The sample results show that due to a change in the river stage profile, there are some benefits in fish yields at various parts of the year.

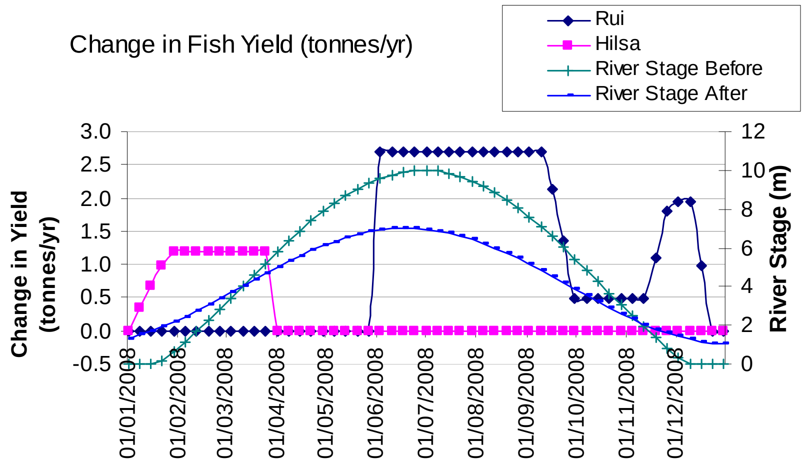

Figure 7. Example output from Fisheries Response Module – Fish Yields

During consultations, fisheries experts have expressed concern that suitable data may not be available to implement this approach. Furthermore, they are concerned that fish yields are a function of a large number of variables (not just inlet area) and that there are also population dynamics effect which this approach does not take into account. Fish population dynamics become particularly important if the impact is calculated over several years. These comments have been taken on board during the DSS design and development. As mentioned earlier, a fish population dynamics model is being incorporated into this module. However, the approach described above still has some usefulness. Firstly, it shows that if a decision (or policy) maker wants to quantify impacts on fish yields, then the type of data required is clearly identified. Secondly, the above approach is a specific example of how to relate fish yield impacts to hydraulic variables. In essence, the above approach is similar to the method employed in the agriculture response module and the beel-river connectivity model, except there is an additional step (table), where the hydraulic variable (river stage) is translated into another variable (inlet cross-section area), which is directly related to fish yields. When the DSS users understand this process they can develop their own impact modules.

5. DISCUSSION AND CONCLUSIONS

In Bangladesh, there is now a clear need to develop hydroinformatics objects, such as DSSs, that can improve integrated water resources management (IWRM). In this paper, several sector response modules, which are at the heart of a prototype IWRM DSS developed by IWM, have been described. This DSS helps estimate direct impacts of changes in water resources systems.

In the agriculture response module, crop damage is estimated as a direct relationship between flood water level, duration and crop growth stage. In the fisheries response module, changes to beel-river connectivity are estimated using a simple conceptual model, which relates river stage to beel inlet area. The module can also estimate impacts on fish yields by the user specifying how yields vary directly or indirectly to hydraulic variables. These response functions and the DSS in general are currently being field tested in a floodplain area in northwest Bangladesh.

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