Better Options for Integrated Floodplain Management: uptake promotion
NRSP Project R8306

Final Technical Report
Annex G

Integrated Floodplain Management Modelling Report

A.S. Halls, Abu Mostafa Kamal Uddin, Amanullah Bin Mahmood and M. Mokhlesur Rahman

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CNRS

MRAG, UK

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Executive Summary

This report contributes two sub-outputs towards the DFID-funded project R8306 logframe outputs 1.3 and 1.4:

Output 1: Integrated floodplain management recommendations. Using an age-structured fish population dynamics model that accounts for the effects of hydrology, Sections 3 and 4 of the report explore potential benefits of implementing: (i) controls over dry season water abstractions for irrigation, (ii) closed seasons and (iii) reserves for fisheries exploiting two beels (Charan and Goakhola) in Bangladesh.

For Charan Beel, the model was first fitted to weekly estimates of landed weight (catches) of *P. sophore* and corresponding fishing effort, measured as man days for the period August 1999-June 2004. Corresponding hydrological conditions (weekly flooded area and volume) were estimated from empirical (power and exponential) models fitted to estimates of water levels in a nearby river and flooded area and volume estimates for the beel described by an earlier study.

A reasonable fit to the data was achieved with the age-structured fisheries model. The correlation between the observed and predicted catches was 0.64. The model poorly predicted the catches in year 4 (June 2002-June 2003) when estimated fishing effort was high, but catches were low.

The fitted model predicted that modest (up to 12%) increases in yield are possible following the removal (de-commissioning) of dry-season irrigation pumps from the Charan Beel site. These improvements in yield arise from improved rates of recruitment arising from larger areas of spawning substrate and slightly lower fishing mortality rates.

However, it is noted that further removals of water caused by **additional pumps** to those already in existence at the site, could lead to significant reductions in flooded areas and volumes which **could threaten the sustainability of the fishery.**

Closures during any month of the year are predicted to improve yields reflecting existing excessive levels of fishing mortality. The greatest gains are achieved by closing the fishery in July or August when fish are still growing rapidly. Currently this fishery is being *growth over-fished* as reflected in the large predicted gains in yield-per-recruit (Y/R). Three-month closures from June to August are predicted to increase yields by as much as 60%, although earlier closures between May and July (also predicted to result in significant increases in yield) may be more acceptable to fishers. Significant gains are also predicted by closing the fishery in April when fish densities are high and fish are vulnerable to capture.

A total dry season reserve area of less than 20 ha is predicted to bring only modest increases in yield. The model predicts that the total reserve area must exceed at least 25 ha before improvements in yield in excess of 10% are achieved. This reflects the fact that currently much of the total fishing effort is expended early in the season giving rise to growth over-fishing (see above).

Goakhola beel was found to virtually dry each year. Given the seasonal nature of this beel and the fact that the population model relies upon recruitment from resident

populations, the model was unable to be fitted to the observed fishery data and therefore to make predictions about the effects of the management interventions. It is likely that external sources of recruitment (immigrating fish) supported the observed catches.

Output 2: Guidelines for determining benefits to the fisheries sector from controlling dry season water abstractions.

The dry season is a period of great stress for floodplain-resident fish populations. Modelling studies have shown that beyond some threshold, the dry season can be more important in determining fisheries yields than the flood season and therefore dry season water abstractions for irrigation can impact on floodplain fisheries and threaten their sustainability.

Section 4 describes guidelines for developing simple empirical models to describe how fish yields respond to dry season conditions. A further empirical relationship, fitted between observations of dry season area and volume, can then be used to predict the effects of controlling water abstractions on fisheries yields and thereby help make decisions concerning the integrated management of floodplains..

These guidelines cover monitoring of catch and effort using catch assessment surveys, hydrological monitoring to estimate flooded areas and volumes and methods to fit non-linear models to estimates of yield in relation to dry season hydrological conditions. These models can be fitted either to a time series of estimates made at one site (water body) or estimates compiled from a number of sites after first normalising catches for differences in waterbody size.

1 Introduction

1.1 Aim

This report seeks to deliver two outputs in relation to the project logframe outputs 1.3 and 1.4:

Output 1: Integrated floodplain management recommendations. Using an age-structured fish population dynamics model that accounts for the effects of hydrology, explore the potential benefits of implementing the following management interventions at two study sites:

- Controls over dry season water abstractions for irrigation
- Closed Seasons
- Reserves

Output 2: Guidelines for determining benefits to the fisheries sector from controlling dry season water abstractions. These should include theoretical background describing how and why fish production is largely dependent upon dry season water volumes and how irrigation abstractions can have a significant impact on fish production. Using this theoretical background, explain what benefits could accrue to fisheries from controlling dry season abstractions for irrigation.

Provide simple guidelines for collecting data to construct an empirical models that can provide the basis for making decisions concerning the control of dry season water abstractions. This should include advice on catch assessment survey methodology with guidance on required sample sizes to adequately monitoring management performance and advice on water body surface area and volume estimation.

1.2 Study Sites

Both outputs were generated on the basis of fisheries and the hydrological studies conducted since 1997 under several DFID funded projects including R7868 and R8306 at two beel sites:

1.2.1 Charan Beel

Charan Beel complex is in the Brahmapatra-Jamuna flood plain covering six mouza (lowest revenue boundary of Bangladesh) in two unions. During the flood season, the area of the beel extends over more than 8km^2.

1.2.2 Goakhola-Hatiara Beel

Goakhola-Hatiara is a beel complex in Narail district, and is one of the IFM (Integrated Floodplain Management) project sites partially covering four Mouza. During the monsoon the complex becomes a single water body covering nearly 2km^2. In the dry season entire area dries up except for one canal and a few deeper pockets. Beside the deeper pockets the complex is under deep-water rice cultivation.

2 Integrated floodplain management recommendations

2.1 Approach

The recommendations described below are developed upon the basis of fisheries and hydrological data collected at Charan and Goakhola Beels under the DFID-funded CBFM Projects and R8306 since August 1996 using an age-structured fisheries model developed under R5953 and later by R7868.

The fisheries model was first fitted to weekly estimates of catch, effort and hydrological data. Having achieved an adequate fit, the effects of management interventions on average yield were then explored.

2.2 The Fisheries Model

An age-structured population dynamics model described by Halls *et al.*. (2001) was used to explore the benefits of alternative integrated floodplain management options. This analytical model assumes that fish growth, natural mortality rates and recruitment are dependent upon fish density driven by both inter-and intra-annual changes in exploitation intensity and flooded area (and volume). The combination of hydrological conditions and age-dependent fishing mortality rates drives changes to numerical and biomass density. These in turn affect rates of recruitment, growth and natural mortality (Figure 1).

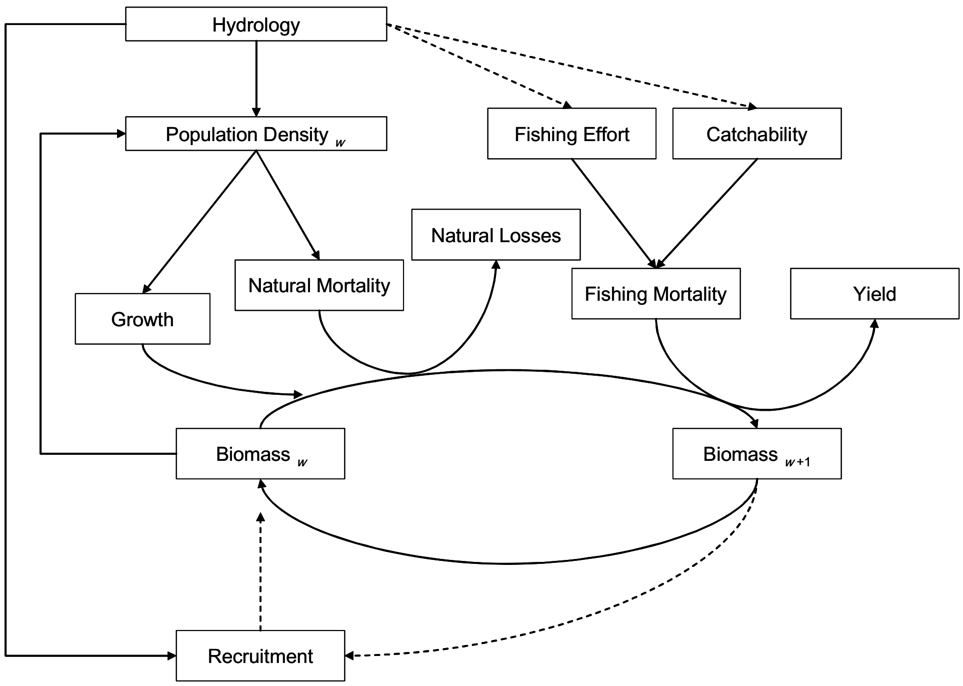

Figure 1 Schematic representation of the population model illustrating the processes by which the biomass in week w becomes the biomass in the following week, w+1. The weekly process is repeated for the 52 weeks of the year, after which recruitment, determined by the surviving spawning stock biomass, is added at the end of week 52. Solid lines indicate direct influences or operations and broken lines indirect influences or occasional operations. Source: Halls *et al*. (2001).

By including a hydrological sub-model to describe these changes in hydrological conditions, the model enables the importance of traditional fishery management measures such as fishing effort control and closed seasons to be compared with the management of the hydrological regime either by controlling irrigation abstractions or sluice gate management practices. The model has been used to explore the effects of different dam release strategies on exploitable biomass (Halls & Welcomme 2004), and to determine production trade-offs between fisheries and agriculture (Shanker *et al.* 2004).

Parameter estimates for the model are currently available only for *Puntius sophore*, a small but commonly abundant cyprinid that inhabits most floodplain environments in Bangladesh and other parts of Asia. The model is therefore fitted only to observed catches of this species. In order for the model results to be applicable for the multi-species catch for the whole fishery, it must be assumed that the population dynamics of this species are broadly representative of all the species landed.

For reference, model algorithms and parameter estimates are provided in Annex 1.

2.2.1 Catch ability models

Catchability of gear efficiency is defined as the proportion of the total fish biomass (B) caught, *C* by one unit of effort, *f* (Eq. 1).

$$q = \frac{C}{Bf} \qquad (1)$$

The effect of hydrology on gear catch ability (gear efficiency) is poorly understood. Three alternative density-dependent catch ability sub-models (Figure 2) were used to describe potential effects: a simple linear model (Eq. 2); and asymptotic exponential model (Eq. 3) and a standard exponential model (Eq.4) where α and β are constants.

$$q = \alpha\left(\frac{B}{A}\right) \qquad (2)$$

$$q = 1 - e^{-\alpha\left(\frac{B}{A}\right)} \qquad (3)$$

$$q = \beta e^{\alpha\left(\frac{B}{A}\right)} \qquad (4)$$

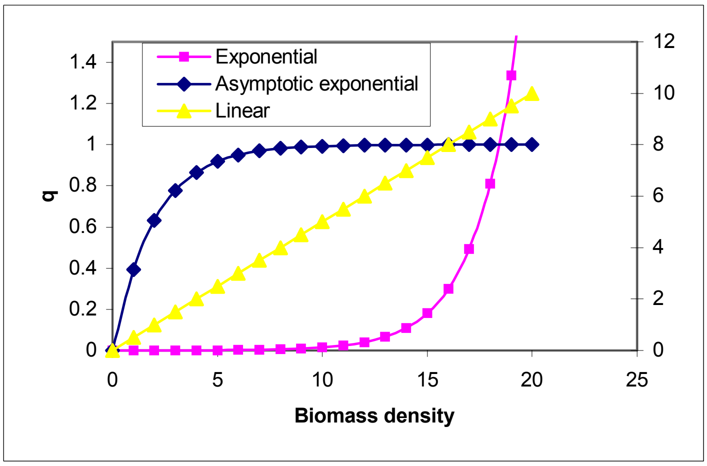

Figure 2 Illustration of the three different catch ability models.

2.3 Fisheries Data

The model was fitted to weekly estimates of landed weight (catches) of *P. sophore* and corresponding fishing effort, measured as man days irrespective of the gear employed, for the period August 1999-June 2004. The sampling methodology to generate these estimates is provided in Annex 3. Four weekly estimates were made for each month providing a total of 48 weekly estimates per year. Because the population model employs a 52 week year, the values were re-estimated for 52 weekly intervals using linear interpolation. Missing data were estimated as average values estimated from observations made in the same week in other years.

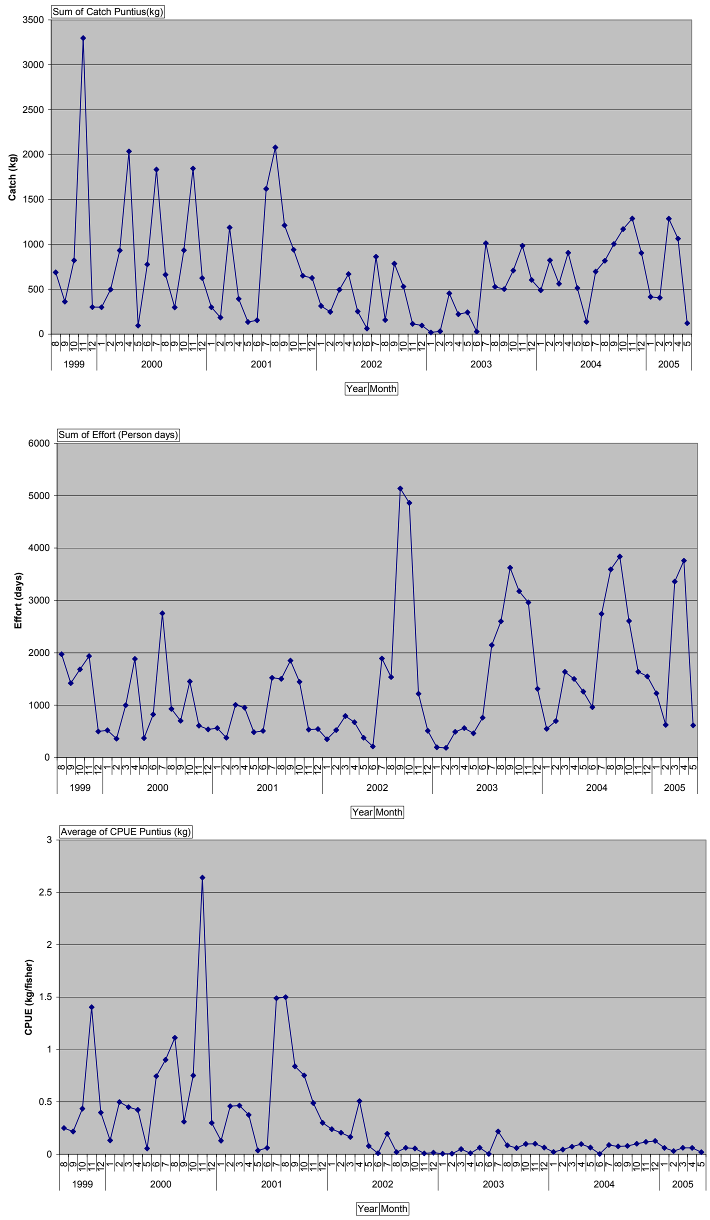

Figure 3 Time series of estimated catch, effort and CPUE of *P. sophore* at Charan Beel.

Examination of the time series estimates show a marked increase in fishing effort after May 2002, a reduction in catch and a corresponding reduction in mean catch per unit effort (CPUE) (Figure 3). These significant changes in catches and fishing effort correspond with a change to the catch and effort sampling methodology employed. It may therefore be that estimates made after May 2002 are biased.

2.4 Hydrological Data and Models

2.4.1 Charan Beel Hydrology

Weekly water area and volume estimates provided for this modeling exercise were estimated from monthly observations of flooded area and depth recorded by Barr (2000) for the period September 1997-September 1998. To generate weekly estimates for the period January 1996- November 2004, these observed monthly estimates were divided by water height observations recorded in the same months for the Kwaljani river which is connected to the beel during part of the year (June-November). For these months, the resulting monthly calibration factors where applied to the observed weekly water heights in the Kwaljani river to give weekly flooded area (and volume) estimates in Charan beel for the period January 1996- November 2004. For those months when the beel and river are no longer connected (January-May), weekly water area and volumes in the beel were estimated from the observed monthly estimates reported by Barr (2000). These were adjusted for differences in rainfall and abstractions for irrigation, but no account was taken of losses arising from evaporation and evapotranspiration and seepage. Further details of the estimation methods are described in other project documentation.

The resulting time series (Figure 4) shows almost no inter-annual variation in dry season water volumes (and areas). This is likely to reflect the relatively small variation in the low levels of rainfall typically recorded during this period and the relative small volumes of water abstracted for irrigation.

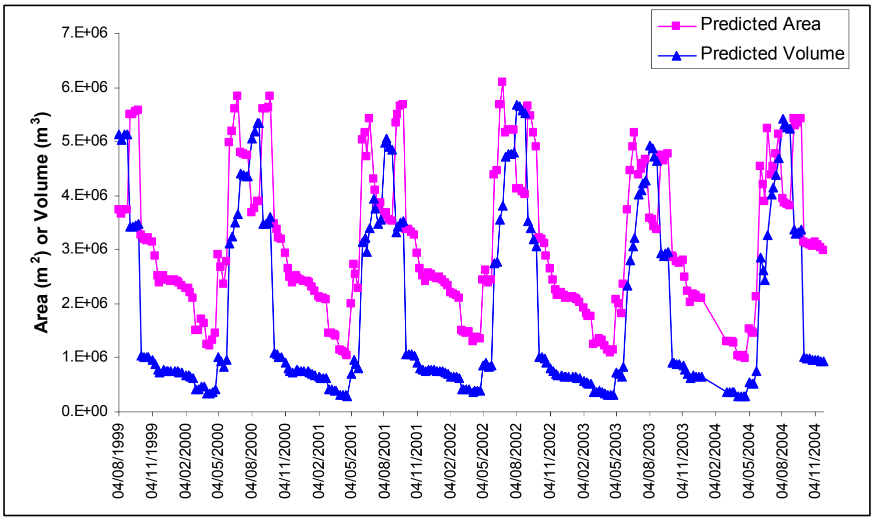

Figure 4 Estimated water areas and volumes in Charan Beel January 1996- November 2004.

An alternative time series was therefore estimated using best-fitting relationships between the month-wise estimates of flooded area and volume in Charan Beel recorded by Barr (2000) and the Kwaljani River levels for the corresponding month and year (Figure 5).

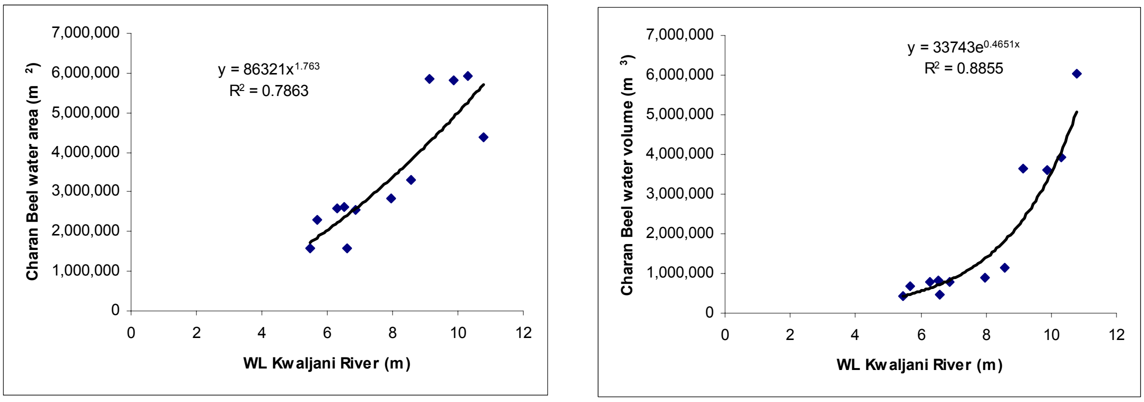

Figure 5 (a) Fitted power relationship between Kwaljani water level and Charan Beel flood area and (b) exponential relationship between Kwaljani water level and Charan Beel flood volume.

These relationships were then used to predict weekly flooded areas and volumes in Charan Beel using the weekly observed Kwaljani River levels for the eight year period (Figures 6 and 7). The 48 weekly estimates per year were then re-estimated for 52 weekly intervals using linear interpolation

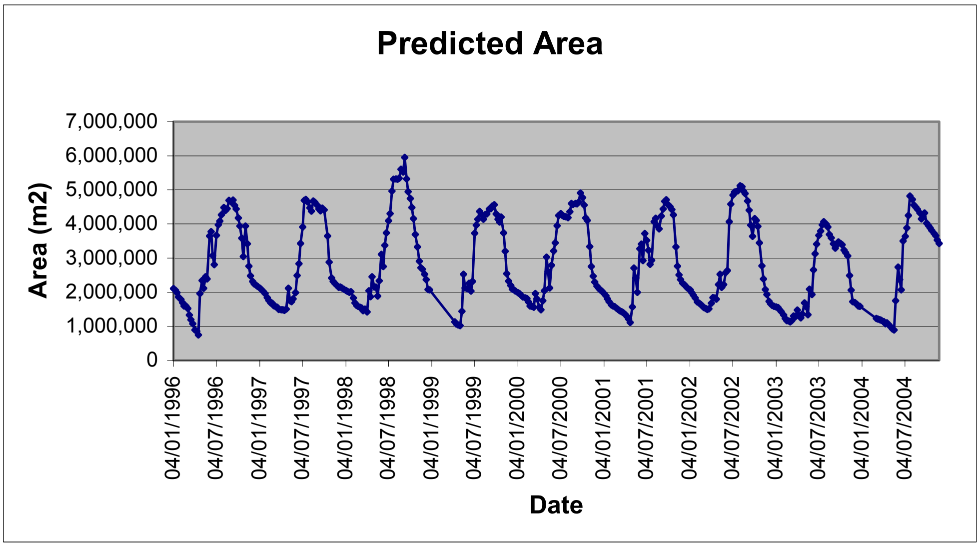

Figure 6 Predicted flooded area estimates in Charan Beel used for the modelling study

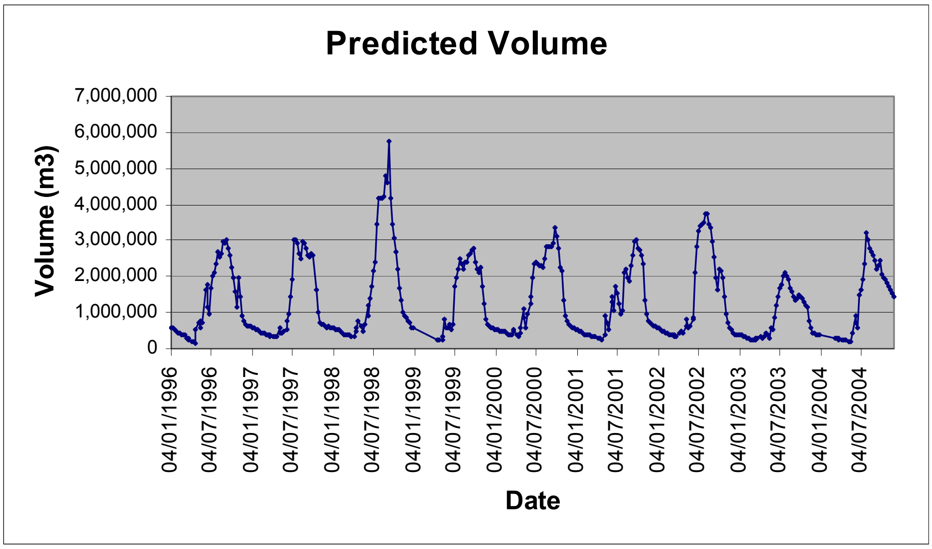

Figure 7 Predicted flooded volume estimates in Charan Beel used for the modelling study

2.4.2 Goakhola Beel

Goakhola Beel showed considerable inter-annual variation in its hydrological characteristics and was found to virtually dry each year. For example in March 2002, it was estimated that only 2.5m^3 of water remained in the beel.

2.5 Fitting and Modeling Procedure

The validity of the model for making management recommendations was first assessed by comparing how well the model was able to predict the observed log$_e$-transformed weekly catch estimates when provided with weekly estimates of fishing effort and flooded areas and volumes. As described in Section 2.2.1, the parameter(s) of the catchability model are not known. These were estimated iteratively using the Solver function in Excel; varying their values to minimize the sum of squared residuals (ssr) between the observed and predicted catches.

Having found the best estimates for the catchability-sub-model parameter, the effect of different management strategies were explored as follows:

2.5.1 Controls of dry season abstraction for irrigation

The benefits to the fisheries sector arising from controls over abstractions of water from Charan Beel for irrigation purposes was examined by adding estimated weekly abstracted irrigation water volumes to the predicted beel volumes during the dry season (January-) used to fit the model.

One pump removes approximately 3500 m^3 (3500 tonnes) of water from the beel per week. Up to 7 pumps may be in operation at any one time removing up to 24,500 m^3 per week equivalent to 0.1million tonnes of water per month. Irrigation has been observed to continue for up to 12 weeks starting December 20.

To model the benefit to the fisheries sector of controlling these abstractions, the total water abstraction capacity of the pumps (number of pumps x pumping capacity) was cumulatively added to the predicted volumes in each week starting Dec 20 for a 12 week period. This cumulative volume at the end of this period was then added to subsequent weeks until the end of the model year (week 52).

The corresponding effects of increased flooded volumes on the flooded area of the beel were estimated from the best fitting logarithmic relationship between flooded volume and area (Figure 8) derived from the observations recorded by Barr (2000). Because we are concerned with predicting areas from volumes during the dry season when volumes rarely exceed 2,000,000 m^3, the poor fit to the data above these volumes is of little concern.

These revised weekly flooded area and volume estimates were then included in the model to determine the benefits to the fishery measured in terms of changes to average annual yield.

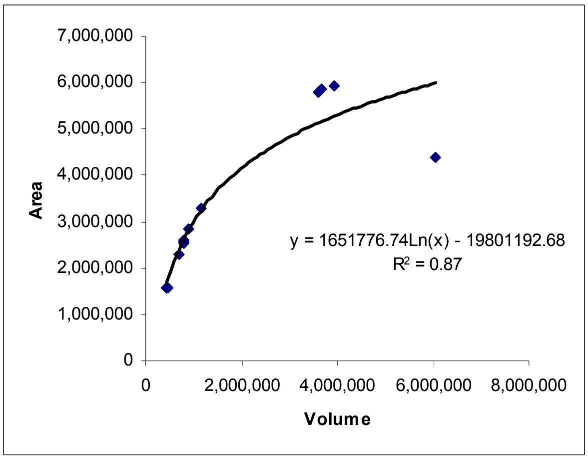

Figure 8 The relationship between flooded volume and area in Charan Beel.

2.5.2 Closed Seasons

The effects of closed seasons (a complete cessation of fishing effort) during individual calendar months were investigated by setting the value of q in the month in question to zero in each year to provide predictions of average changes to annual yield over the five year period.

2.5.3 Dry season Reserves

The effect of reserves of different sizes was determined by reducing fishing mortality (F) during the dry season (December-May) in proportion to the size of the reserve expressed as a proportion of the minimum dry season area observed during the hydrological time series (750,000m^2 or 75ha) (Table 1). Average changes to annual yield over the five year period were then estimated. This approach assumes that fish density and exploitation intensity is spatially uniform.

Table 1 Reductions in fishing mortality rates during the dry season used to simulate the effects of different size reserves in Charan Beel.

Reserve Area (ha)	% of minimum dry season area	% Reduction in F (December- May)
1	1	1
2	2	2
3	4	4
5	6	6
6	8	8
8	10	10
15	20	20
23	30	30
30	40	40
38	50	50
45	60	60
56	75	75

3 Modelling Results

3.1 Model Fits

The one-parameter linear catchability sub-model (Eq. 2) was found to give the best fit between the observed and predicted catches with a value for α=0.23.

3.1.1 Charan Beel

The model was able to predict the observed weekly catches reasonably well over the five year period for which catch and effort estimates were available, particularly during the first three years (July 1999-June 2002) of the time series (Figure 9). Overall, the seasonality of the fishery was well described by the model. The correlation coefficient between the observed and predicted catches was 0.64.

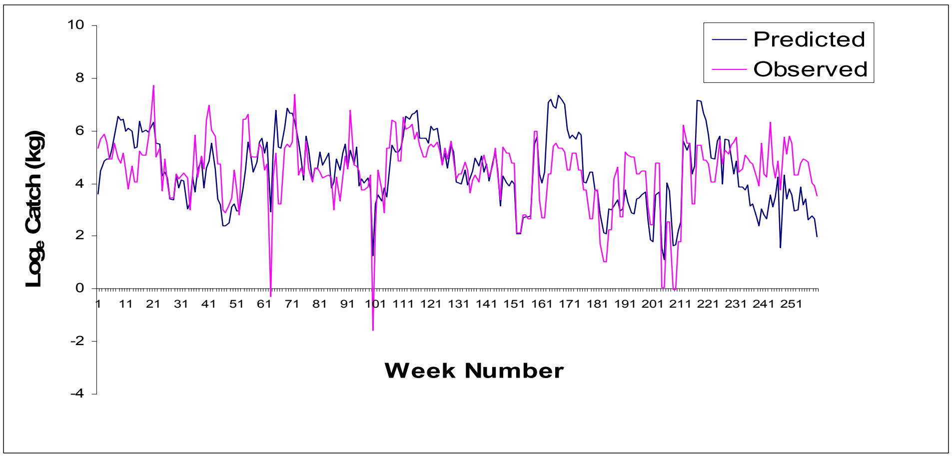

Figure 9 Observed and predicted log-transformed weekly catch estimates for Charan Beel for the period July 1999-June 2004.

A poor fit (Figure 10) was achieved during year 4 (July 2002-June 2003) compared to the final year (July 2003-June 2004).

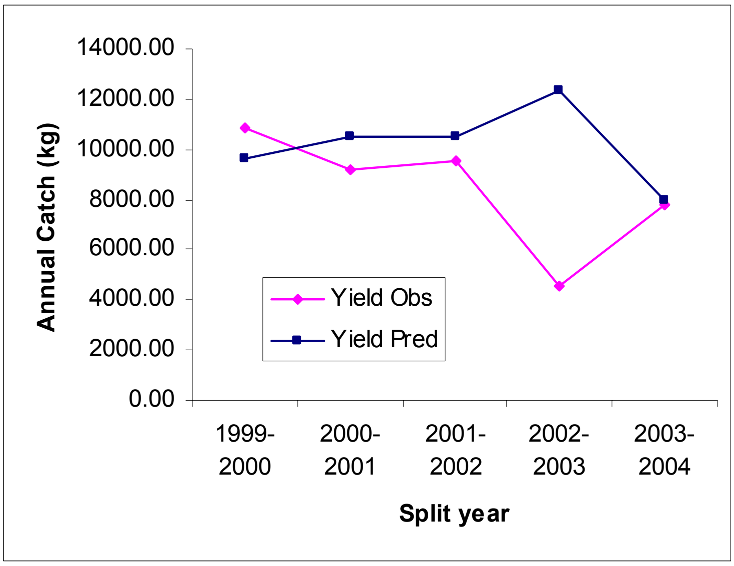

Figure 10 Observed and Predicted annual catches for Charan Beel for the period July 1999-June 2004.

Table 2 Best fitting model predictions

	Recruits	M (y^{-1})	Average Number	Yield Predicted	Yield Observed	F (y^{-1})	Effort Observed
1999-2000	4995481	0.15	1,276,286	9663	10869	3.12	14294
2000-2001	5978034	0.18	1,479,526	10484	9169	2.92	11214
2001-2002	7085732	0.20	1,508,782	10479	9523	2.87	10538
2002-2003	4054767	0.13	1,369,951	12378	4540	3.69	19659
2003-2004	2253675	0.13	903,764	7928	7762	3.73	22464

3.1.2 Goakhola

Given the seasonal nature of this beel and the fact that the population model relies upon recruitment from resident populations, the model was unable to successfully predict the observed catches. The model predicted complete stock collapse during the first extreme dry season period resulting from elevated mortality rates and subsequent impact on the spawning stock. It is therefore likely that external sources of recruitment (immigrating fish) supported the observed catches.

3.2 Controls of dry season abstractions for irrigation

The model predicts that modest increases in yield are possible following the removal (de-commissioning) of pumps from the Charan Beel site. These improvements in yield arise from improved rates of recruitment arising from larger areas of spawning substrate and slightly lower fishing mortality rates (Table 3).

Table 3 Summary of the results of the effects of pump decommissioning on fishery yield and population parameters.

Number of Pumps Removed	Recruits	M (y^{-1})	Predicted Yield (kg)	F (y^{-1})	% Change in Yield
0	4,873,538	0.16	10186	3.27	
1	4,829,207	0.16	10215	3.29	0.3
2	5,117,591	0.16	10514	3.28	3
3	5,351,622	0.16	10759	3.27	6
4	5,549,023	0.16	10965	3.26	8
5	5,719,800	0.16	11143	3.26	9
6	5,870,263	0.16	11300	3.26	11
7	6,004,682	0.16	11438	3.25	12

Improvements in yield are unlikely to be detected until at least four or five pumps have been decommissioned, resulting in a predicted increase in yield in the region of 10% (Figure 11).

It should be borne in mind however, that **further removals of water caused by additional pumps to those already in existence at the site, could lead to significant reductions in flooded areas and volumes**. Preliminary investigations indicate the introduction of an additional two pumps to the site **could reduce flooded areas and volumes to the point of causing recruitment failure and stock collapse**.

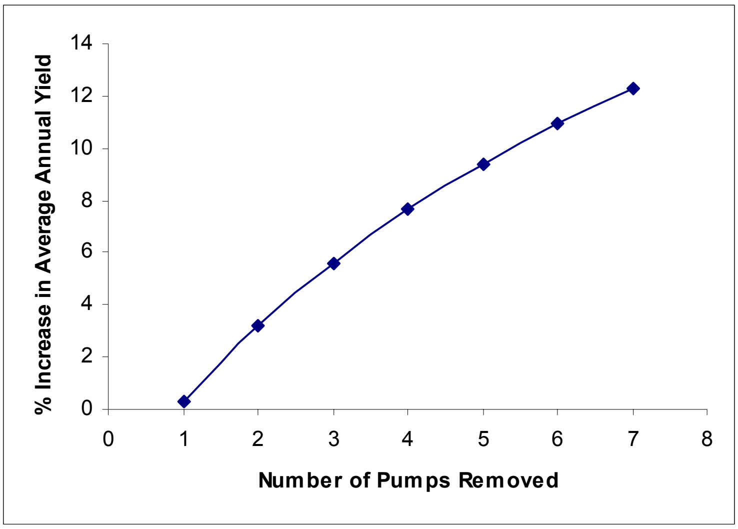

Figure 11 Predicted percentage increases in yield arising from the de-commissioning of pumps at Charan Beel.

3.3 Closed Seasons

Closures during any month are predicted to improve yields reflecting excessive levels of fishing mortality (Table 4). The greatest gains are achieved by closing the fishery in July or August when fish are still growing rapidly. Currently this fishery is being *growth over-fished* as reflected in the large predicted gains in yield-per-recruit (Y/R) when the fishery is closed during this period of rapid fish growth. Significant gains are also predicted by closing the fishery in April when fish densities are high and fish are vulnerable to capture. Improved fish survival increases recruitment to the fishery later in June.

Three-month closures from June to August are predicted to increase yields by as much as 60%, although earlier closures between May and July also predicted to result in significant increases in yield. A closure during this period may be more acceptable to fishers.

Table 4 Model predictions of average recruits, natural mortality, yield, % gain in yield, fishing mortality and yield-per-recruit (Y/R) for monthly closures.

Closed	Recruits	M (y^{-1})	Predicted Yield (kg)	% Gain	F (y^{-1})	Y/R (g)
None	4873538	0.16	10186	0	3.27	2.1
June	5071325	0.16	10436	2	3.24	2.1
July	4947936	0.17	12547	23	3.25	2.5
Aug	5035625	0.17	12577	23	3.25	2.5
Sep	5216786	0.18	11544	13	3.23	2.2
Oct	5403782	0.18	10800	6	3.23	2.0
Nov	5289288	0.18	10529	3	3.23	2.0
Dec	5175803	0.17	10463	3	3.24	2.0
Jan	5149475	0.17	10473	3	3.25	2.0
Feb	5243845	0.17	10559	4	3.25	2.0
March	5693328	0.17	10940	7	3.22	1.9
April	5988554	0.17	11172	10	3.22	1.9
May	5262929	0.16	10466	3	3.23	2.0
Feb-April	8167682	0.20	12809	26	3.13	1.6
April-June	6935067	0.18	11863	16	3.13	1.7
May-July	5588908	0.18	13495	32	3.18	2.4
June-Aug	5325425	0.20	16974	67	3.20	3.2

3.4 Dry season Reserves

A total dry season reserve area of less than 20 ha is predicted to bring only modest increases in yield (Table 5 and Figure 12). The model predicts that reserve area must exceed at least 25 ha before improvements in yield in excess of 10% are achieved. This reflects the fact that currently much of the total fishing effort is expended early in the season giving rise to growth over-fishing (see above). Reserves are predicted to increase recruitment by reducing overall exploitation rates and thereby improving the survival of the spawning stock.

Table 5 Model predictions of average recruits, natural mortality, yield, % gain in yield, fishing mortality and yield-per-recruit (Y/R) for different reserve areas during the dry season (December – May).

Reserve area	% of min area	Recruits	M (y^{-1})	Predicted Yield (kg)	% Gain	F (y^{-1})	Y/R (g)
0	0	4873538	0.16	10186	0	3.27	2.09
1	1	4902654	0.16	10214	0.3	3.26	2.08
2	2	4932120	0.16	10241	1	3.26	2.08
3	4	4992129	0.16	10297	1	3.26	2.06
5	6	5053618	0.16	10353	2	3.26	2.05
6	8	5116642	0.16	10410	2	3.25	2.03
8	10	5181260	0.16	10469	3	3.25	2.02
15	20	5530515	0.17	10774	6	3.23	1.95
23	30	5930338	0.18	11106	9	3.21	1.87
30	40	6392582	0.18	11469	13	3.18	1.79
38	50	6933110	0.19	11868	17	3.16	1.71
45	60	7573621	0.20	12309	21	3.13	1.63
56	75	8792025	0.21	13069	28	3.08	1.49

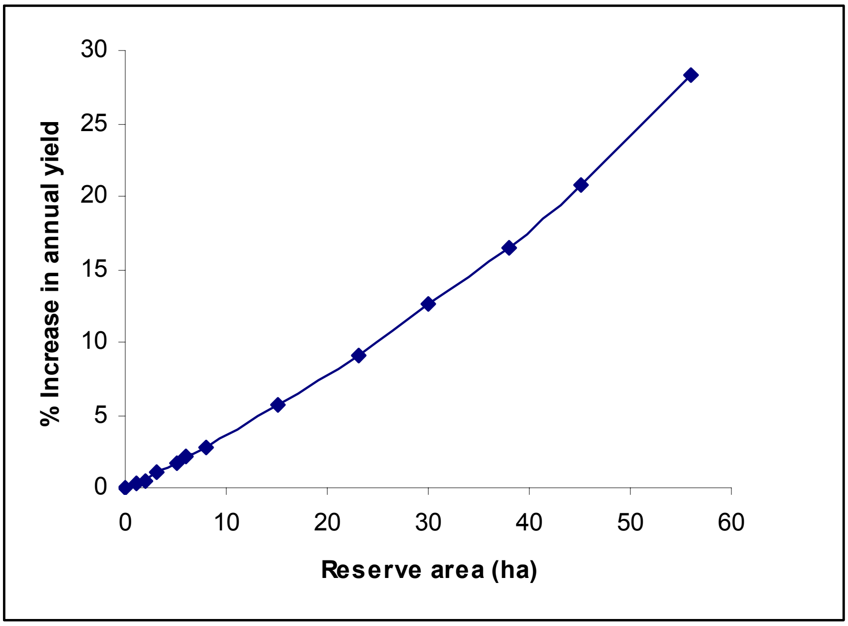

Figure 12 Predicted percentage increases in annual yield plotted as a function of reserve area in Charan Beel.

4 Guidelines for determining benefits to the fisheries sector from controlling dry season water abstractions

4.1 Introduction

The dry season is a period of great stress for floodplain-resident fish populations. During this period these fish must seek refuge in residual waterbodies such as *beels* and *khals* as waters recede from the floodplain back to the main channel. Fish densities increase rapidly leading to increased rates of mortality as fish become more susceptible to predation and exploitation. Natural mortality rates may also increase in response to deteriorating water quality (Welcomme 1985).

Many species also spawn in these residual waterbodies just before they become re-inundated as waters rise in the main channel at the start of the next year. Recruitment in these species will therefore be limited to the amount of available spawning habitat. This habitat availability will be a function of the amount of water remaining on the floodplain in these residual waterbodies.

Indeed modeling investigations (Halls *et al*. 2001; Halls & Welcomme 2004) indicate that fish production and exploitable biomass is more dependent upon available water (flooded areas and volumes) during the dry season, compared to the flood season. Figure 13, illustrates for a constant fishing mortality rate, how, above some flooded area (in this case approximately 9 m), fish yield is dependent almost entirely upon dry season water availability (here measured in terms of water height).

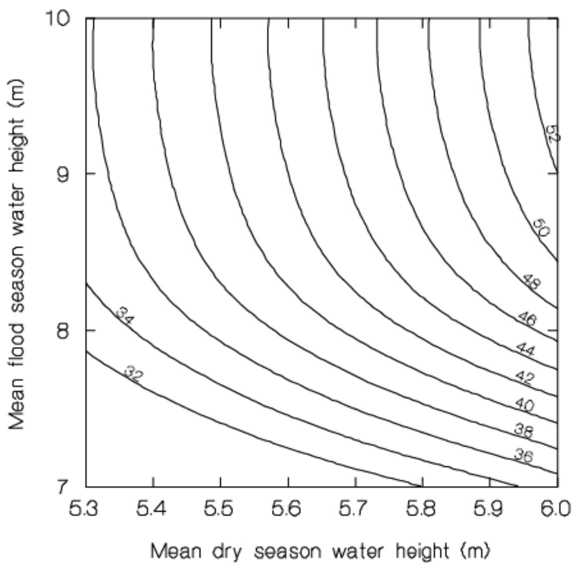

Figure 13 Isopleths of yield (kg $ha^{-1}y^{-1}$) for *P. sophore* in response to different combinations of dry and flood season water levels. Source: Halls *et al*. (2001).

This suggests that yields can be improved by retaining more water during the dry season. At the same time it indicates that removing water from residual waterbodies during the dry season for irrigation purposes can negatively impact on fish yields. In other words, controlling irrigation water abstractions offers a means to improve fish yields and improve sustainability.

To further illustrate the potential impact of dry season irrigation abstractions on fish yields, Figure 14 shows the results of model predictions reported by Shanker *et al.* (2004). The figure shows how fish yield, measured in terms of catch per unit area (CPUA) is predicted to respond to the area of boro rice irrigated at three different schedules; low, medium and high. Notice how initially, the effects on yield are marginal. However, beyond some threshold, yield begins to decline rapidly, ultimately leading to recruitment failure and stock collapse.

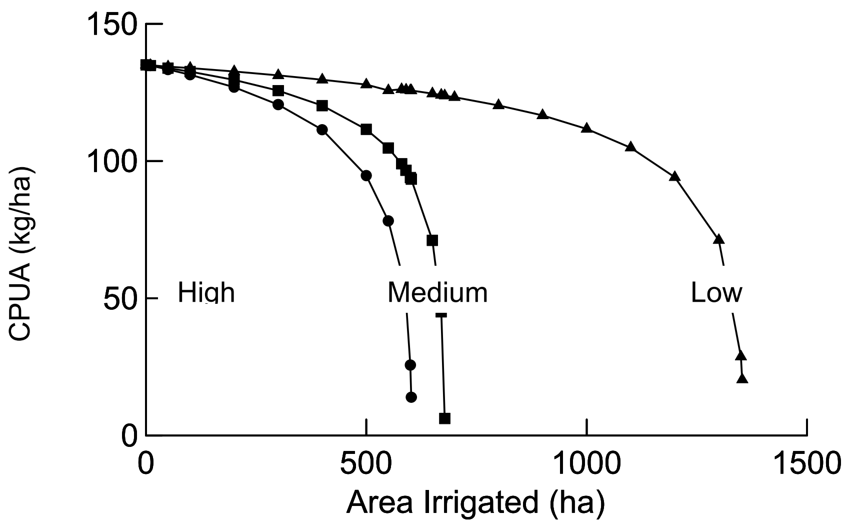

Figure 14 Predicted response of catch per unit area (CPUA) to changes in the area of land irrigated for dry season Boro rice cultivation for low (▲); intermediate (■); and high (●) irrigation schedules in the Pabna flood control and irrigation compartment, Bangladesh. Source: Shanker *et al*. (2004).

Halls & Welcomme (2004) further explored the importance of dry season hydrology. They found that that exploitable biomass varied non-linearly in response to dry season area expressed as a proportion of the maximum flood season area or flooded area ratio (FAR):

$$FAR = \frac{Minimum\ flooded\ area}{Maximum\ flooded\ area} \quad (5)$$

This response (Figure 15) was found to be robust to both variation in flood-season duration and to the density-dependent assumptions underlying the simulation model used.

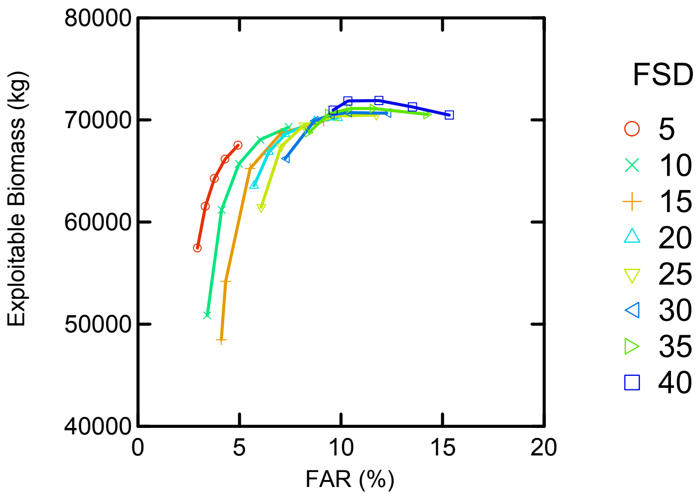

Figure 15 Predicted response of exploitable biomass to the FAR for different flood season durations ranging from 5 to 40 weeks. Source: Halls & Welcomme (2004).

These types of model outputs can provide managers with guidance on how abstractions should be managed to maintain fisheries production.

Generating these types of outputs for specific sites can, however, be both costly and time consuming. The construction of empirical models (models based upon observations) can offer managers with an alternative approach (see below).

4.2 Guidelines for Constructing Empirical Yield-FAR Models

To construct an empirical Yield-FAR model, managers will require several years of observations of total annual yield (catch) from the fishery and corresponding estimates of minimum and maximum flooded areas to calculate the FAR.

Instead of attempting to generate a time series of observations at a single site, opportunities may, however, exist to construct the Yield-FAR model using data collected from a number of nominally similar sites (e.g. floodplain or beels) in different locations. It may be possible to compile these observations over a regional or even national scale to construct a generally applicable model. When comparing yields among sites in this way it will be necessary to normalize the catches among sites by dividing the estimated total annual catch by the maximum area of the site or waterbody. This will give estimates of yield or catch per unit area (CPUA).

This *among-site* comparative approach may be particularly suited to co-managed fisheries where networks for information sharing already exist. For further guidance on developing data collection and sharing programmes for co-managed fisheries see Halls *et al*. (in press).

Having compiled observations of annual yield and FAR, a suitable model could then be fitted to describe the relationship (Figure 16). In this example, an asymptotic model similar to the VBGF (Eq. 6) has been fitted but other models (e.g. logarithmic) may also be applicable.

$$Yield = Max\,Yield\left(1-e^{-\alpha(FAR)}\right) \qquad (6)$$

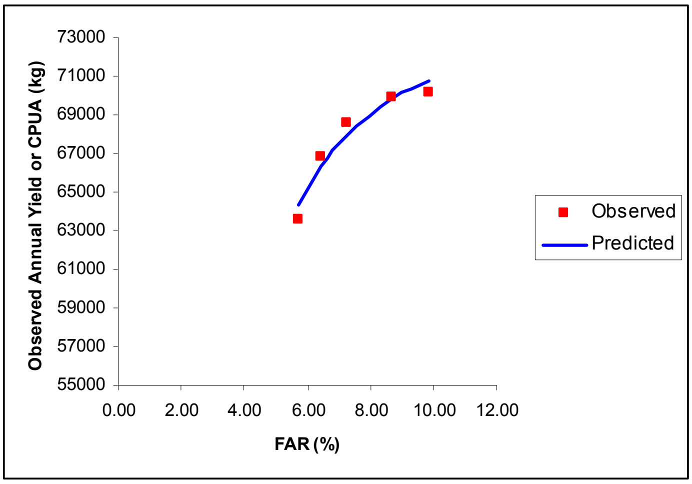

Figure 16 Observed yield or CPUA plotted as a function of FAR with fitted asymptotic model.

These types of non-linear models can be easily fitted to the observations using non-linear least squares. The Solver function in Excel can be used to find the best combination of Yield Max and *α* values that minimize the sum of squared residuals between the observed and predicted yields i.e. minimize $\sum(observed\ yield - predicted\ yield)^2$. For further advice on fitting non-linear models using spreadsheets see Haddon (2001).

It may not be necessary to fit a mathematical model to the data to predict how yields are likely to change with FAR. Simple visual examination of the plotted data should provide managers with a guide to how yields are likely to respond to FAR.

As further observations become available either through time or from other sites, the plots and models can be updated to improve their predictive capacity.

Note that there may be significant deviations from the predicted response described in Section 5.1 if significant variation in exploitation intensity exists either inter-annually (if constructing a model for a single site), or between sites (if among site comparisons are used to construct a model). In these cases it may be necessary to use the analytical model described by Halls *et al*. (2001), to make predictions about how yield will respond to both changes in minimum dry season areas and exploitation rates.

4.2.1 Predicting the benefits of controlling dry season abstractions for irrigation.

To predict the benefits to the fisheries sector of controlling dry season abstractions, it will be also necessary to have the capacity to predict the effects of abstractions on dry season water volumes and areas in order to first predict changes to the FAR.

This will require estimates of flooded area and volume for each location and a model to describe the relationship between the two variables. An example of such a model is given in Figure 8 in Section 2.5.1 above. These types of models can be fitted in the same manner as described above using the Solver Function in Excel. Methodologies for estimating flooded area and volume are provided in Annex 2.

The area-volume model can now be used to determine to what extent flooded areas will increase in response additional volumes of water remaining during the dry season following abstraction controls.

The additional volume of water remaining following the controls can be estimated from the number of pumps removed (controlled) multiplied by their daily pumping capacity and the number of days they are typically in operation during the dry season.

The new FAR can then be estimated from the new volumes to predict how yield will increase. Various abstraction control scenarios can be examined to produce figures similar to Figure 11 in Section 3.2 to guide decision-making.

4.2.2 Catch assessment surveys (CAS) and Management Performance Monitoring

Catch assessment surveys (CAS) are used to provide estimates of catch and effort. Most catch assessment surveys (CAS) sample a proportion (fraction) of the population (fishers) each month for their catches (and in some cases also gear effort). A mean monthly catch rate is then estimated and multiplied by the total number of fishers or gears operating in each month to give estimates of total monthly catches (and effort).

The CAS methodology employed by this project is described in Annex 3. Guidelines for designing and implementing catch assessment surveys, particularly in the context of co-management are given by Halls *et al.* (in press).

Managers will be interested to know whether their catches or exploitable biomass have responded to their management interventions, in this case, dry season water abstraction controls.

To do so they will need to compare their baseline (pre-intervention) estimates of catch or CPUE (an index of biomass) with estimates made following the implementation of the interventions (post intervention estimates). Because gear catchability (efficiency) varies seasonally, it is appropriate to make comparisons for the same seasons or months between years.

The ability to detect significant differences between two mean catch or CPUE estimates (assuming they are unbiased i.e. accurate), depends upon the precision with which their true (population) values have been (or can be) estimated. Sample variance is used as a measure of this precision. If samples used to estimate the mean are highly variable (high sample variance), then differences between means will be hard to detect. As the sample variance increases, the minimum detectable difference (MDD) between two means increases.

When designing sampling programmes to monitor management performance, managers must therefore decide what minimum detectable difference in mean values of catch or CPUE is acceptable. This will depend largely upon the anticipated size of the management intervention effect. For example, if it is believed that an intervention might have only a small effect on CPUE (e.g. bring about a10% increase), then the minimum detectable difference should be 10% or less.

Having established the acceptable MDD, managers can now determine how many samples they will require to determine significant differences in mean values of 10% based upon the sample variance using Eq. 7. This approach assumes that the two samples compared have equal variance (Zar 1984):

$$n = \frac{2S_p^{\ 2}}{\delta^2}(t_{\alpha,\nu} + t_{\beta(1),\nu})^2 \qquad (7)$$

Where $S_p^{\ 2}$ is the pooled variance of the two samples, *t* is the Student's *t* statistic, *α* is the significance level (typically 0.05), *β* is the power of the test (typically set to 80-90%), *δ* is the minimum detectable difference between the two means, and *v* is the degrees of freedom (=2(*n*-1)).

The equation must be solved iteratively. The Solver function in Excel can be used for this purpose. An accompanying Excel spreadsheet has been programmed to calculate *n* for different values of $S_p^{\ 2}$, *α*, *β* and *δ.*

The table below summarises the results of an analysis to determine the required monthly sample size for detecting differences in mean monthly CPUE for gillnets based upon data collected monthly from Charan Beel during 2000 and 2001.

Table 6 Required sample sizes for detecting differences in month-wise gillnet CPUE for Charan Beel based upon monthly CPUE observations during 2000 and 2001. *α* =0.05, *β=0.1* (power of at least 90%).

		Difference in mean CPUE							
Current *n*	**Month**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**
29	1	270	60	27	16				
24	2	3500	894	398	224	144	100	74	57
34	3	21000	5200	2320	1300				
28	4	18300	4600	2030	1142				
50	8	1355	339	151	86	55			
55	9	845	212	95	54				
75	10	1329	333	149	84	54			
47	11	528	133	60	34				
50	12	414	104	47	27				

In this example the required sample sizes to detect 10% or smaller differences in CPUE between consecutive years varies from 270 to 21000 samples per month.

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Annex 1 Fish population model algorithms and parameter estimates

From Halls *et al.* (2001):

The yield, Y in year k is given by:

$$Y_k = \sum_{i=0}^{i=t_l} \sum_{w=1}^{w=52} \left([\frac{F_{k,i,w}}{F_{k,i,w} + M'_{k,w}}][1 - \exp(-(F_{k,i,w} + M'_{k,w}))]\, N_{k,i,w} \cdot \overline{W}_{k,i,w} \right)$$

where t_l is the species longevity, integer years (1,2,3...); w is the week number (1,2,3...52); i is the age of fish in integer years (0,1,2,....); $F_{k,i,w}$ is the weekly instantaneous fishing mortality rate during week w of year k on age i fish; $M'_{k,w}$ is the weekly instantaneous density-dependent natural mortality rate during week w of year k ; $N_{k,i,w}$ is the number of age i individuals at the start of week w in year k; and $\overline{W}_{k,i,w}$ is the mean weight in week w of year k for age i fish.

If R_k is the number of recruits in year k, recruiting at age 0 at the beginning of week 1, then the numbers of age i fish at the start of week w in year k is given by:

$$N_{k,0,1} = R_k \qquad \text{for } i = 0, w = 1$$

$$N_{k,i,w} = R_{k-i} \exp[- \sum_{x=k-i}^{x=k-1} \sum_{y=0}^{y=i-1} \sum_{z=1}^{z=52} (F_{x,y,z} + M'_{x,z})] \exp[- \sum_{z=1}^{z=w-1} (F_{k,i,z} + M'_{k,z})] \qquad if\ i \geq 1$$

and

$$N_{k,0,w} = R_k \exp[- \sum_{z=1}^{z=w-1} (F_{k,0,z} + M'_{k,z})] \qquad for\ i = 0, w > 1$$

The number of recruits in year k is determined by floodplain system fertility measured in terms of nitrate concentration (N), flooded area (A) and the density of eggs (S) produced by the spawning stock in the last week (week 52) of the previous year. The relationship is described by an extended form of the Ricker stock-recruitment model:

$$R_k = (\alpha S_{k-1,52}\, e^{-\beta S_{k-1,52} + cN_{k-1,52}})\, A_{WH\,52}$$

where α, β, and c are parameters of the extended Ricker stock-recruitment model; $N_{k,52}$ is the nitrate concentration (mg / 100 litres) in week 52 of year k ; A_{WH52} is the flooded area for water height (WH) at week 52; and $S_{k,52}$ is the number of eggs m^{-2} produced by the spawning stock in week 52 of year k.

The density of eggs produced in week 52 is a combination of the numbers of spawning individuals and their mean fecundity:

$$S_{k,52} = \frac{\sum_{i=t_m}^{i=t_l} N_{k,i,52} \overline{F}_{k,i,52}}{A_{WH52}}$$

where t_m is the age at maturity, integer years (0,1,2,....) and $\overline{F}_{k,i,52}$ is the mean fecundity of age i fish in week 52 of year k.

The mean fecundity is given by:

$$\overline{F}_{k,i,w} = d\,(\overline{L}_{k,i,w})^{e}$$

where e , d are parameters of the length-fecundity relationship, and $\overline{L}_{k,i,w}$ is the mean length of age i fish in week w of year k. The relationship is described by the seasonally oscillating von Bertalanffy growth function (Pitcher, Macdonald 1973). The asymptotic length is dependent upon biomass density after Lorenzen (1996):

$$\overline{L}_{k,i,w} = L_{\infty B,k,w}\left(1 - e^{-K\left[(i+\frac{w}{52}-t_0)+\frac{C\sin(2\pi(i+\frac{w}{52}-t_\omega))}{2\pi}\right]}\right)$$

where K is the von Bertalanffy growth parameter, t_0 is the age at length zero, C is the amplitude of seasonal growth oscillation in growth rate (0-1), t_ω is the starting (winter) point of growth oscillation, and $L_{\infty B,k,w}$ is the asymptotic length in week w of year k.

This asymptotic length is dependent upon the biomass density B in the previous week given by:

$$L_{\infty B,k,w} = L_{\infty L} - g.B_{k,w-1} \qquad \text{for w = 2,3,....52,}$$

$$L_{\infty B,k,w} = L_{\infty L} - g.B_{k-1,52} \qquad \text{for w = 1,}$$

where $L_{\infty L}$ is the limiting asymptotic length, g is the competition coefficient, and $B_{k,w}$ is the biomass density in week w of year k._Biomass density is described by:

$$B_{k,w} = \frac{\sum_{i=0}^{i=t_l} N_{k,i,w} \overline{W}_{k,i,w}}{V_{k,w}}$$

where $V_{k,w}$ is the volume of water upon the floodplain in week *w* of year *k*. The mean weight, $\overline{W}$, of age *i* fish in week *w* of year *k*, is given by:

$$\overline{W}_{k,i,w} = a\,(\overline{L}_{k,i,w})^{b}$$

where *a* and *b* are parameters of the length-weight relationship.

The weekly instantaneous density-dependent natural mortality rate $M'_{k,w}$ during week *w* of year *k* is a function of the numerical density ρ (Nm^{-3}) in the previous week given by:

$$M'_{k,1} = \gamma + \delta.\rho_{k-1,52} \qquad \text{for } w = 1,$$

$$M'_{k,w} = \gamma + \delta.\rho_{k,w-1} \qquad \text{for } w = 2,3,....52,$$

where γ and δ are parameters of the mortality-density relationship.

The numerical density $\rho_{k,w}$, is defined by:

$$\rho_{k,w} = \frac{\sum_{i=0}^{i=t_l} N_{k,i,w}}{V_{k,w}}$$

The weekly instantaneous fishing mortality rate on age *i* fish during week *w* of year *k* is given by:

$$F_{k,i,w} = f_{k,w}.q_{k,i,w}$$

where $f_{k,w}$ is the fishing effort during week *w* of year *k*, and $q_{k,i,w}$ is the catchability coefficient for age *i* fish during week *w* of year *k* defined as:

$$q_{k,i,w} = bB_{k,w}$$

where *b* is the slope coefficient.

Annex 2 Methodology to estimate flooded areas and volumes

To generate estimates of flooded area and volume through time, a digital elevation model (DEM) of the waterbody is required. The following 13 stage process has been developed by CNRS for this purpose.

Step – 1: Create a grid for the waterbody of 50 m by 50 m pixel.

Step–2: Geographical location (latitude and longitude) of grid points should be recorded using GPS (Global Positioning System) receiver. The GPS values should be triangulated and calibrated using the GPS receiver to record geographical positions of 5 known points (i. e. bridge, nodal point etc.).

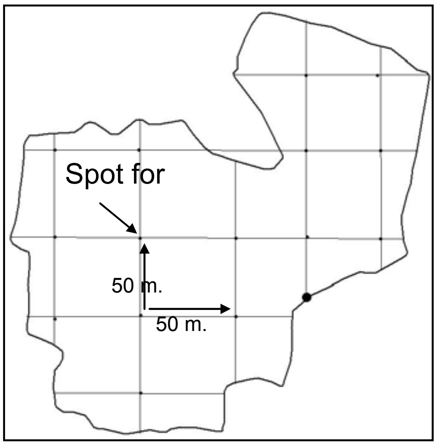

Fig – 1: 50 m. interval grid line

Step – 3: Record water levels at some fixed point (eg sluice gate) and the depth of water at grids on the same day.

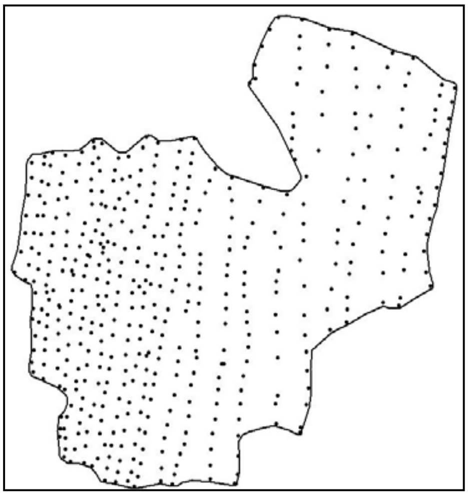

Fig – 2 : Water depth collecting points

Step – 4: Enter all data i. e. water depth, latitude (y), longitude (x) and water depth in tabular format using MS Excel 2000 software and create two table one is location and other is water depth. The format is as below;

Spot ID	Latitude (Y)	Longitude (X)

Spot ID	Water Depth (Z)

Step – 5: Convert this data from Excel to CSV (Comma delimited text) format and generate a point coverage by using Arc/Info NT software (GIS Software)

Step – 6: Project this point coverage using BTM (Bangladesh Transverse Marcetor) projection using Arc/Info NT software.

Step – 7: Spot heights of the grids were water level minus water depth at specific grid points (for example where water depth at a grid point was 0.36 m. and water level was 2.84 m, spot height of this point is 2.84 – 0.36 = 2.48 m.).

Step – 8: Merge the spot height data with the location point coverage by using ArcView GIS 3.3 software.

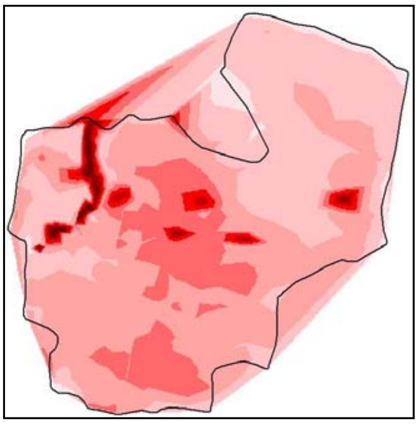

Fig – 4 : DEM of Beel bed

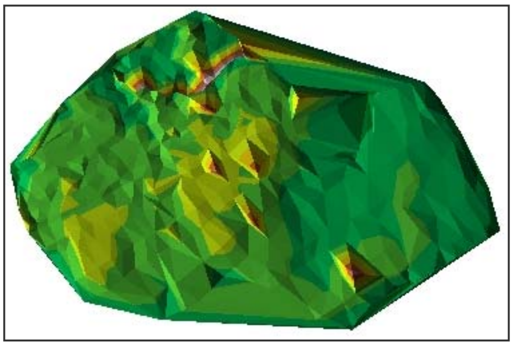

Fig – 3 : 3D view of *Beel* bed

Step – 9: Generate a TIN (Triangulated Irregular Network) form the spot height by using the software ArcView Spatial Analyst ver. 1.1 and ArcView 3D Analyst

Step – 10: Interpolate GRID from TIN fixing cell size 5 m.

Step – 11: For determine the volume and water extent within the waterbody first create a grid file depend on the water level of a certain day. It is showing only water level (for example in June 06, 2003 water level of beel was 1.5 m. create the GRID theme of 1.5 m water level). Then the created grid theme overlaying on the DEM and perform Cut Fill operation from surface analysis of ArcView 3D Analyst (CutFill operation one of the operation of ArcView 3D Analyst for determining the volume and extent of any phenomena i. e. water volume, soil volume). After performing this operation result showing the gain and loses from the given value (water volume of a certain day). Gain showing the area and volume more than of water level of given value, these area actually dry and more than high of 1.5 m and loss show the area and volume of equal and less than 1.5m actually the flooded area.

Step – 13: Water volume and extent has been calculated at two weeks interval.

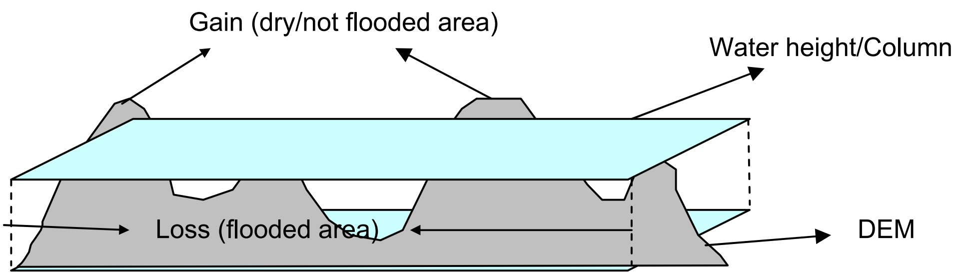

Fig – 5: Thematic view of CutFill operation

Annex 3. CAS methodology employed by the project

Data collection for fish catch assessment in the Charan beel started in August'1999 continued till April'2002 under CBWM project. From May '2002 till date data collection continues under CBFM2. For data collection structured form was developed and used.

Data collection protocol

1998 August to April 2002 under CBWM

- Data are collected separately from beel, floodplain and canals once each week
- Around 30 to 40 % (minimum three gears of each operated types) of operated gears by types are monitored on the monitoring day.
- Catch estimates of at least three gears of each type are collected.
- Gears are enumerated by type on the monitoring day.
- Monitoring continues from early morning to 5 pm of the monitoring day.
- *katha* catch is considered as a gear type

2002 may onwards Under CBFM2

- Total Charan beel is divided into 3 parts and data is collected from middle part of beel and floodplain area (2002 may onwards)
- Around 30 to 40 % (minimum three gears of each operated types) of operated gears by types are monitored on the monitoring day.
- Catch estimates of at least three gears of each type are collected.
- Monitoring continues from early morning to 5 pm of the monitoring day.
- Gears are enumerated by type on the monitoring day.
- Selected *Kathas* are monitored separately when *katha* owner lands fish.

Assessment matrix

MS Access based software was used to store and analyze data. Using standard protocol data quality was validated. Average catch of each gear type on the monitoring day was raised by the numbers of operated gears on the sample day. The sum of all catches of all gear types provides an estimate of the total daily catch. This is then raised to give the catch by month and year. In case of CBWM, Katha catches were treated as a separate gear type. Under the CBFM2 project, a separate monitoring programme was used to estimate catches for this gear types.