Modeling Pond-Water Availability for Fish Culture

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EXTENDED ABSTRACT

Water availability has been identified as a key environmental factor that influences the potential for small-scale freshwater pond aquaculture. Common techniques used in estimating pond-water availability are based on water balance accounting between net gains from inflows from direct rainfall and surface water runoff versus net losses from outflows through soil seepage and percolation. The objective of this study is to estimate pond-water availability for fish culture by developing and applying a simulation model that can express water budget for fish ponds based on prevailing climatic and hydrological conditions. The model captures the key physical elements of the hydrological system influencing the water budget of the pond, but at a level of complexity that is consistent with data limitations encountered in many developing countries

Our simulation model calculates variations in pond-water depth due to the physical processes by starting with the basic climatic water balance involving water gain into the pond from direct rainfall and loss from the pond-water surface through evaporation, and then including potential inflow from surface water runoff from the immediate surroundings of the pond, deep percolation and lateral seepage or inflow. The model result is displayed as a time profile plot of pond-water depth, from which can be determined the pond-water availability period (PWAP) when the water depth in the pond is sufficient for stocking and subsequently grow-out until final harvest of the fish crop.

The simulation model was applied at 15 selected meteorological stations located in the floodplains of the Ganges-Brahmaputra delta in Bangladesh at weekly time steps over five years, 1998-2002. Although Bangladesh is generally well-endowed with water supply from rainfall and river discharge, in many areas experiencing non-uniform rainfall distribution throughout the year, seasonality of pond-water availability constrains annual fish productivity.

The simulation results show that generally pond-water availability is perennial where the annual rainfall exceeds 2000 mm, but this does not constitute a sufficient condition to assure perennial water availability. The most water-deficient situation occurs at Rajshahi in the drought-prone western part, which has the lowest rainfall. With mean annual accumulated surface runoff at 150% of the mean annual rainfall at this station, the maximum PWAP within the five-year period is 33 weeks in 1999-2000 while the minimum 10-week period in 2002, a relatively low-rainfall year, would not permit fish culture. Of the 15 stations, seasonality in pond-water availability occurs at eight stations where there is a clear need for water harvesting strategies to prolong the PWAP, such as lining or deepening the pond, or supplemental irrigation. At the other seven stations, PWAP simulation suggests perennial pond-water availability. At Sylhet station, which records the highest rainfall and is located in the low-lying flood-prone northeastern Bangladesh, the groundwater table is high but even so it generally remains below the pond water level.

The model results were compared with responses obtained from a survey of key informants, i.e. fisheries district officers of the Bangladesh Fisheries Department conducted in 2006. The survey-reported durations fall within the ranges of the PWAP model results at almost all stations that show seasonality of the pond-water availability.

In conclusion, the PWAP model was developed for regional-scale assessment of pond-water availability as a key determinant of pond-aquaculture development potential. The model can be used in an exploratory manner to construct scenarios that help identify possibilities for prolonging pond water availability duration in these areas by enhancing water harvesting and storage under different climatic and topographical conditions. Initially developed for point-based evaluation, the model is being further programmed for evaluation in a GIS environment to generate gridded maps of pond-water availability.

1. INTRODUCTION

In many developing countries, raising fish in household ponds relies heavily on natural sources of water supply. Pond-water availability is therefore a key determinant of the potential for small-scale freshwater pond aquaculture. Techniques commonly used in estimating pond-water availability are based on water balance accounting between net gains from inflows (such as from direct rainfall and surface water runoff) versus net losses from outflows (such as soil seepage and percolation). For example Nath and Bolte (1998) developed a water budget simulation model at the detailed level of individual ponds. In contrast, continental-scale estimations tend to over-simplify model inputs. Aguilar-Manjarrez and Nath (1998) used simplified estimates of the key variables - surface runoff was estimated as a constant proportion (0.1) of the monthly rainfall, while a constant soil percolation rate was applied for the entire African continent. The annual quantum of water (in mm) required for fish culture was estimated, and critical thresholds set for rating and mapping pond aquaculture suitability. In mapping indicators of water-harvest potential at continental scale for Africa, Senay and Verdin (2004) used a more elaborate procedure to estimate annual surface runoff based on the Curve Number (CN) method of the United States Department of Agriculture Soil Conservation Service (SCS, 1985).

The objective of this study is to estimate pond-water availability for fish culture by developing and applying a simulation model that can express water budget for fish ponds based on prevailing climatic and hydrological conditions. The model captures the main physical elements of the hydrological system influencing the water balance in the pond, but at a level of complexity that is consistent with data limitations encountered in many developing countries including our case study country, Bangladesh. Instead of estimating annual quanta of pond-water accumulation, the model determines the period that meets the minimal pond-water depth requirement for fish culture, which directly influences annual pond productivity of fish.

2. MODEL DESCRIPTION

In developing our model, we adopted the system identification approach of Jakeman et al. (1994), starting with the key processes and simple assumptions, and refining the model incrementally. The simulation model calculates variations in pond-water depth due to the physical processes depicted in Figure 1.

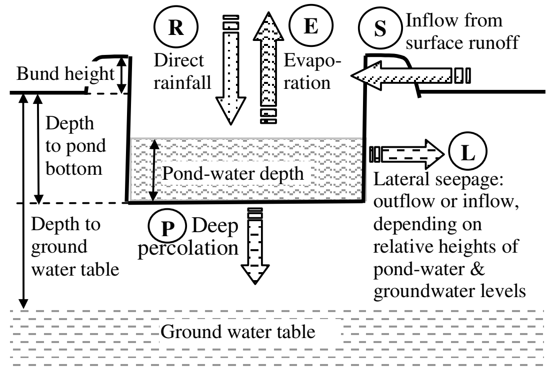

Figure 1. The pond-water budget components.

The main calculation steps are listed in Figure 2.

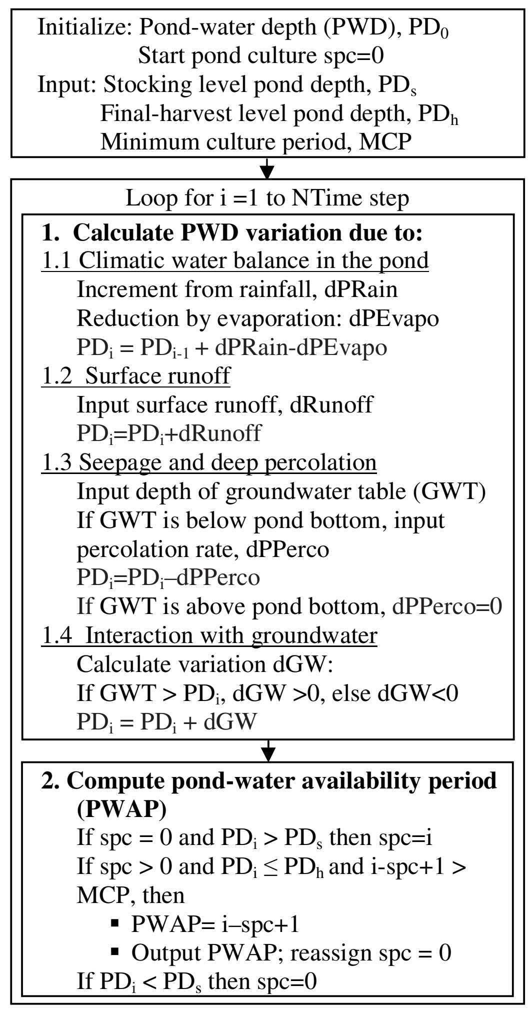

Figure 2. Main processing steps of the Pond Water Availability Period (PWAP) model.

Starting with the basic climatic water balance involving water gain into the pond from direct rainfall, (R in Figure 1), and evaporation loss from the pond-water surface (E), other interactions are added. These include potential inflow from surface water runoff (S) from the immediate surroundings of the pond, and deep percolation and seepage losses (P). Interaction with groundwater is modeled as lateral outflow or inflow (L), depending on whether the groundwater table is lower or higher than the pond-water level. In the latter case, there is also no deep percolation loss from the pond.

The model result is graphically displayed as a time profile plot of pond-water depth, from which can be determined the time period(s) when the pond-water depth is sufficient for stocking and subsequently grow-out until final harvest of the fish crop. This period, called the pond-water availability period (PWAP), may vary in length over the sequence of consecutive years that the model is applied.

3. IMPLEMENTING THE MODEL

The simulation model was applied for Bangladesh. With much of its land area comprising the Ganges-Brahmaputra delta, Bangladesh is considered to be well-endowed with water supply from rainfall and river discharge. However there are areas that experience non-uniform rainfall distribution, where seasonality of pond-water availability constrains annual fish productivity. The simulation modeling is intended to help determine locations where pond-water availability is seasonal and identify possible pond management interventions that can extend the period of water availability. The PWAP model was evaluated at the point locations of the 15 meteorological stations where the climatic data were collected (Figure 3).

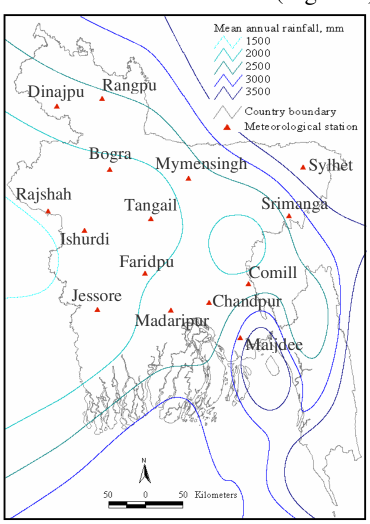

Figure 3. Location of meteorological stations and mean annual rainfall (1998-2002) isohyets, Bangladesh.

The model was run at weekly time steps (as only weekly groundwater depth data were available) for five common years of data availability for all required climatic and hydrological parameters, from 1998 to 2002. The computation and modeling processes to derive the input variables are briefly described below.

3.1. Rainfall and Evaporation

The climatic data used included weekly rainfall records and potential evapo-transpiration (PET) estimates derived from temperature, wind speed, relative humidity and sunshine hours using the Instat software (Stern et al., 2006), based on the Penman-Monteith method. The time series climate data were obtained for 15 meteorological stations from the data archives of the Bangladesh Agricultural Research Council. Evaporation from the free water surface of the pond was estimated by applying a factor of 1.3 to the PET (Aguilar-Manjarrez and Nath, 1998).

3.2. Deep Percolation and Seepage

In the absence of geographically-comprehensive data on seepage and percolation losses, estimates were based on an empirical relationship derived between soil texture and percolation rates using limited field measurements (BARC, 2001) and adjusted for local relief as represented by the land type classification for Bangladesh (FAO, 1988).

3.3. Surface Runoff

Data on surface water runoff is generally lacking in Bangladesh. Because surface runoff arriving at a pond is accumulated from its surroundings, estimation of runoff amounts requires modeling surface water flow over the contributing area. The generation and flow of surface runoff is influenced by local topography, current and preceding rainfall events, soil properties influencing water infiltration and retention, and land cover. It is assumed that runoff inflow is not deterred by the constructed pond bund, but is actually made possible through small inlets to harvest the surface water runoff.

Advances in geo-spatial modeling of surface water flow enable reasonable runoff estimates to be made, using rainfall-runoff relationships such as the SCS-CN method (USDA, 1986). Originally developed for gross runoff estimation at watershed level, the SCS-CN method has been adapted for computing and mapping runoff at grid-cell level, for example the Africa-wide maps of Senay and Verdin (2004). In this study, we advanced their methodology by simulating the accumulation of runoff calculated at individual grid cells over a digital terrain model, using a two-step process. The first step estimates runoff generated at each grid cell using the SCS-CN method, with parameters adapted for South Asian conditions (Pandey, et al., 2005). The second step simulates runoff accumulation over the terrain, represented by a digital elevation model (DEM), using the RUNOFF surface analysis function in IDRISI™ Kilimanjaro. Weekly time-series values read off these accumulated runoff surfaces at the grid cell locations of the meteorological stations were used as inputs for the PWAP model.

3.4. Groundwater Interaction

Groundwater depth data collected weekly by the Bangladesh Water Development Board were selected for the most "representative" monitoring wells in the vicinity of the meteorological stations. There can be net lateral inflow or outflow of water along the pond wall depending on relative depths of the groundwater and pond-water surfaces (Figure 2). In the absence of lateral flow data for Bangladesh, it was assumed that the lateral flow rate increases linearly from zero at the pond-water surface to a maximum value equal to the deep percolation rate at the pond bottom. Therefore the vertically-averaged lateral flow rate is half the percolation rate. Tsubo, et al. (2004) found vast variations in lateral flow rates in paddies in northeast Thailand; at most locations the mean flow rates were of the same order of magnitude as the percolation rates.

3.5. Pond Dimensions and Operational Characteristics

Ahmed et al. (2004) reported that small-scale fish ponds in Bangladesh are normally dug 2 m below the soil surface, with a 0.5-m bund; and the surface area is on average 200 m^2. Local aquaculture experts advise that farmers would normally start stocking when the pond-water level reaches about 1 m (parameterized as the stocking level); they maintain a minimal pond-water depth of 1.5 m during grow-out of fish (operational level); and carry out the end-of-season harvest when the pond water falls below 1.2 m (final-harvest level). Computationally, a PWAP starts when the pond-water depth exceeds the stocking level, is minimally maintained at the operational level and ends when the pond-water depth falls below the final-harvest level.

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4. RESULTS AND DISCUSSION

4.1 Results and Sensitivity Analysis for Rajshahi Station

The detailed discussion of the modeling results in this section is focused on Rajshahi station, which is located in the drought-prone western part of Bangladesh (Figure 3). Table 1 summarizes the annual climatic and hydrological variables at this station, while Figure 4 shows the weekly rainfall, surface runoff, groundwater depth and simulated pond-water depth profiles for 2001 and 2002 - the two years with annual rainfall below the five-year average.

Table 1. Climatic and hydrological profile of Rajshahi station, Bangladesh.

Year	Rainfall mm	Ground-water depth, m	PET, mm	Surface runoff mm
1998	1,540	4.61	1,196	2,265
1999	1,862	4.87	1,217	3,246
2000	1,670	4.60	1,162	2,273
2001	1,363	5.22	1,226	1,987
2002	1,444	5.37	1,221	1,844
Mean	1,576	4.93	1,204	2,323

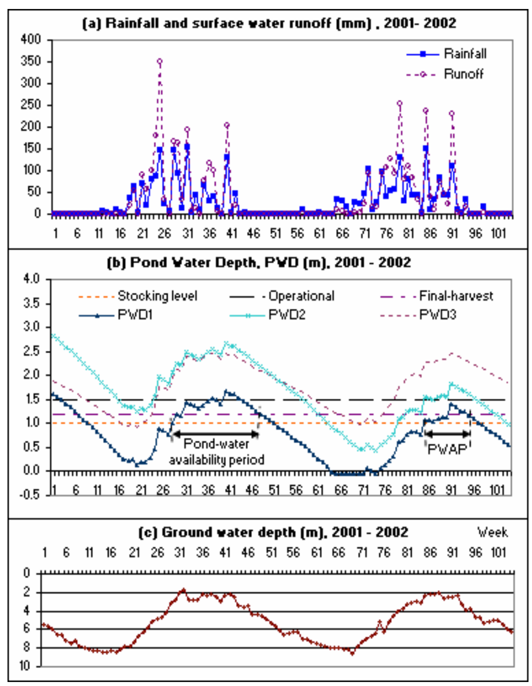

Figure 4. Weekly profiles of (a) rainfall and surface runoff; (b) pond-water depth; and (c) groundwater depth for Rajshahi station, 2001-2002.

The pond-water depth (PWD) values are results from the PWAP model which was run for the five-year period (1998-2002) using the pond parameters described in Section 3.5.

At the sampled location, the annual surface runoff is on average 50% higher than the annual rainfall (Table 1) while the weekly fluctuations correspond with the rainfall pattern, with some response lag following weeks of high rainfall (Figure 4a). The groundwater table at the location is on average almost 5 m below the soil surface or 3 m below the pond bottom (Table 1) but fluctuates seasonally, ranging from 0.5 to 8.5 m, and shows a distinct response lag with the rainfall pattern (Figure 4c).

The plot of the simulated pond-water depth (PWD1 in Figure 4b) relative to the user-specified stocking, operational and final-harvest levels illustrates the pond-water availability period (PWAP). The maximum PWAP within the five-year period is 33 weeks, occurring in 1999-2000 when the highest annual rainfall of 1862 mm was recorded. The PWAP values for 2001 and 2002 (Figure 2) show that the effect of rainfall hinges not on the annual quantum but its temporal distribution. The annual rainfall in 2001 was marginally higher (6%) than in 2002; yet the PWAP is 20 weeks in 2001, twice longer than in 2002 because of the higher rainfall early in the 2001 season, amplified by higher surface runoff.

The effect of pond depth is illustrated by comparing the PWD profiles in Figure 4. PWD1 is the profile for a 2.5-m pond depth (including bund height of 0.5 m). PWD2 shows the situation if the pond is deep enough to capture all the available water. The simulated PWD is highest at 3.7 m in 1999, which effectively doubles the PWAPs for 2001 and 2002, suggesting that increasing pond depth (in this case by a higher bund) would give greater assurance of ample water in a dry year like 2002. However the greater difficulty of maintaining a deep pond and harvesting fish from it would need to be weighed against alleviating the risk of missing fish crops during the dry years.

PWD3, simulated for the same 2.5m pond depth as PWD1, depicts the situation if the model omits lateral flow interaction with groundwater, as has been applied in other studies (Aguilar-Manjarrez and Nath, 1998; Senay and Verdin, 2004). It presents an optimistic scenario of pond-water levels. In fact the PWAP model is highly sensitive to lateral flow rate. The vertically-averaged lateral flow rate used for producing profile PWD1 is 15.2 mm per m^2 per week, based on the soil type at that location. This value falls within the range of field-measured lateral flow rates reported by Tsubo et al. (2004). Halving this value yields a maximum PWAP value of 41 weeks (compared with 33 weeks), while the values for 2001 and 2002 are 32 and 22 weeks (compared with 20 and 10 weeks); suggesting the benefit of reducing the permeability of the pond walls and pond bottom.

PWD1 in Figure 4b is the result of PWAP modeling at the exact grid cell location of the Rajshahi station, where the estimated runoff is generally higher than rainfall, on average 50% higher. Simulations run for five locations in the vicinity of the station, i.e. at selected grid cells in the accumulated runoff surfaces, illustrate the range of PWAP estimates obtained for different runoff scenarios, indicated by the ratio of average annual runoff to average annual rainfall (Table 2).

Table 2. Simulated pond-water availability periods (PWAP) for Rajshahi station for different surface runoff-rainfall scenarios.

Case/ location	Runoff: Rainfall ratio	Modeled PWAP No.	Min (weeks)	Max (weeks)
1	1	3	17	30
2	1.2	3	21	31
3	1.5	5	10	33
4	2.1	5	26	35
5	2.9	5	28	38

Where the accumulated surface runoff is about equal in magnitude as the direct rainfall (location 1), there are only three periods of pond-water sufficiency for fish culture within the five-year period, indicating there is insufficient pond water for fish culture in the drier years. There are five PWAPs at location 3, one for each year; however the minimum (10-week) period in 2002 is too short for the commonly-cultured fish species to grow to marketable size. The higher runoff-rainfall ratios at locations 4 and 5 increase the estimated PWAP for the five yearly-periods, but pond-water availability remains seasonal. There is a clear need for water harvesting strategies to prolong the duration for fish culture, such as lining or deepening the pond, or supplemental irrigation.

4.2 Comparison of Results Across Sites

Table 3 summarizes the PWAP modeling results, i.e. the number and range of PWAPs over the 1998-2002 period, for the 15 selected stations. At the station locations, the mean annual accumulated surface runoff ranges from 60% to 150% of the mean annual rainfall. Stations 1-5 are located in the drier western part of Bangladesh, with mean annual rainfall below 2000 mm (Figure 3). The most water-deficient situation occurs at Rajshahi.

Table 3. Rainfall-runoff characteristics and pond-water availability periods (PWAP) at 15 selected stations, Bangladesh.

Station	Mean annual rainfall (mm)	Runoff: Rainfall ratio	Modeled PWAP No.	Modeled PWAP Range	Reported duration
				(week)	
1 Rajshahi	1576	1.5	5	10-33	26
2 Ishurdi	1614	1.0	4	21-32	30
3 Jessore	1700	0.6	2	22-35	26
4 Tangail	1759	1.1	4	31-47	35
5 Bogra	1891	1.3	4	23-49	48
6 Faridpur	1943	0.7	1	260	17
7 Madaripur	2152	0.7	1	260	30
8 Comilla	2200	0.7	1	260	35
9 Mymensingh	2224	1.0	4	28-46	9
10 Chandpur	2230	0.8	1	260	26
11 Dinajpur	2240	1.4	4	29-38	26
12 Rangpur	2424	0.7	3	66-144	30
13 Srimangal	2643	0.8	1	260	30
14 MaijdeeCourt	3166	0.8	1	260	35
15 Sylhet	3835	0.6	1	260	30

Generally pond-water availability is perennial (a single PWAP of 260 weeks as indicated in Table 3) where the annual rainfall exceeds 2000 mm, but this does not constitute a sufficient condition to assure perennial water availability. This is illustrated by the results for Mymensingh, Dinajpur and Rangpur stations, where seasonality in rainfall distribution tends to be more marked despite the high annual means.

In contrast to the drought-prone situation at Rajshahi, Sylhet in the low-lying flood-prone northeastern Bangladesh records the highest rainfall, with a five-year mean of 3835 mm (Table 3). Accumulated surface runoff at the sampled location is generally lower than rainfall amounts (5-year annual mean of 2340 mm). The ground-water table is high, with depths averaging 1.1 m; reaching the soil surface in the rainy season and dropping to 2.8 m during the dry season. PWAP simulation suggests that the pond is perennially water-filled, and the groundwater table remains lower than the pond-water level except during pond-filling (should the pond be drained) when it is higher, to a maximum of 0.3 m. The contribution of a higher groundwater table to raising pond-water level is minimal, estimated to be 17 mm at a vertically-averaged lateral flow rate of 5.8 mm m^{-2} within a week interval. Doubling the lateral flow rate increases the rise in pond-water level to 22 mm, but this is low compared with the outflow losses when the groundwater table is lower than the pond bottom, as encountered at most other stations.

4.3. Comparison of Model Results with Farmer Field Reports

The last column in Table 3 offers a comparison of the simulated PWAPs with responses obtained from a 2006 survey involving district-based officers from the Bangladesh Fisheries Department. The survey, conducted at sub-district level, asked for the month of the year, on average, that pond water starts to reach sufficient level for fish culture and the end month when it becomes insufficient. The survey-reported durations fall within the ranges of the model results for stations that show seasonality of the PWAPs, except for Mymensingh. None of the survey responses indicated perennial water availability, even for areas in north-eastern Bangladesh that are known to receive sufficient water throughout the year. The survey responses seem to reflect pond-water situations under common farmer practice of pond draining in between fish crops (to maintain water quality and fish health), rather than the actual duration of water availability in these areas.

5. CONCLUSIONS

The PWAP model was developed for regional-scale assessment of pond-water availability as a key determinant of pond-aquaculture development potential. Its intended use is to inform, encourage and guide feasibility studies for the planning, design and management of fish ponds. The analysis and interpretation of model results suggest that although most of the western half of Bangladesh has perennial water supply from natural sources, seasonality in the drought-prone areas in the western part does introduce an element of inter-annual uncertainty in water availability for fish culture in ponds. The PWAP model can be used in an exploratory manner to construct scenarios that help identify possibilities for prolonging pond water availability duration in these areas by enhancing water harvesting and storage under different climatic and topographical conditions. Initially developed for point-based evaluation, the model is being further programmed for evaluation in raster mode to generate maps of pond-water availability duration.

6. ACKNOWLEDGMENTS

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