International Journal of Ecology and Environmental Sciences 32(1): 25-40, 2006

Enhancing the Productivity of Small Waterbodies

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ABSTRACT

Most small waterbodies were built for irrigation and/or drinking water storage for humans and livestock, but have also been shown to play an important role in watershed management. Apart from natural lakes, small waterbodies are generally of two types: 1) reservoirs created by damming a river and, 2) ponds built on watersheds to collect and store surface runoff. There are millions of small waterbodies scattered throughout the world, most of which are poorly or not at all managed for fish production. Consequently, the potential positive food security and rural economic impacts that might be achieved through organized exploitation are not being realized. To optimise both productive and economic returns from small waterbodies requires managed stocking, harvest and nutrient dynamics. Manipulation of fish population density and structure, weeds, disease vectors and fertility can increase fish ouput by up to 10 times natural productivity while improving water and environmental quality. A range of private and community management systems have been effectively used to manage small waterbodies, retuning millions of dollars and tons of fish to both rural and urban populations. This paper reviews the salient features of small waterbody fisheries and the key principals of their management as a guide to specialists and policymakers seeking to implement strategies for sustainable watershed management.

Key Words: Reservoirs, Dams, Fishery Management, Stock Enhancement

INTRODUCTION

Small water bodies are found all over the world and although no accurate estimates for their number are available, they most likely number in the millions. Most small waterbodies were built for irrigation and/or water storage for drinking water and livestock, but have also been shown to replenish water tables, decrease the severity of flash-flooding, reduce soil erosion and increase vegetative cover, especially trees (Roggeri 1995). Small waterbodies are generally of two types: 1) reservoirs created by damming a river and, 2) ponds built on watersheds to collect surface runoff. To optimise both productive and economic returns from small waterbodies requires managed stocking, nutrient loading and harvest.

What constitutes a "small" waterbody has been the subject of considerable debate. The WorldFish Centre regards any waterbody of less than 200 ha as small. In reality, this type of definition is artificial because the key feature that differentiates small waterbodies from fishponds and from other, larger, waterbodies is their degree of manageability. Virtually all aspects of fishpond productivity are controllable to one degree or another by the farmer. For larger water-bodies, the level of control is restricted to capture fish-eries management and, possibly, stocking of certain species. Small waterbodies, lying somewhere in-between are likewise intermediate in their amenability to management. Usually, small waterbodies can be at least partially drained, they are normally small enough to be effectively fertilized, water quality can be reliably monitored, catches can be more easily regulated through better-controlled access and more accurate mixed-species stocking programs are feasible. In addition to size, other key features of small waterbodies include fluctuating water levels, seasonal thermoclines and seasonally or permanently flooded marginal vegetation.

STOCKING

Because of the nature of small waterbodies, the species naturally present are generally not well suited to lacustrine environments. Stocking with lacustrine species thus can have a large impact on productivity. For example, typical natural production of lotic ecosystems is in the range of 10-500 kg ha^{-1}, whereas stocked systems produce in the range of 100-1500 kg ha^{-1}.

Stocking is typically of two general types: 1) establishment or enhancement of a sport or commercial food fishery, and 2) to control weeds or aquatic disease vectors. In industrialized countries, value added by sport fishing is generally much higher than for foodfish. Stocking of centrarchids (especially largemouth bass, *Micropterus salmoides*) and salmonids (especially rainbow trout, *Onchorynchus gairdnari*) is widespread in the United States, Europe and Southern Africa. State managed programs in the United States have increased catches by almost 12 times (Davies 1973). Often, sport fish stocking is accompanied by weed control and/or introduction of fish attracting devices (i.e., brush piles) to increase success rates among rod and reel fishers.

More typical in developing countries are efforts to establish or enhance food fisheries. The majority of these introductions have been of just a few species, most of which are littoral. The main species stocked are tilapias of the genera *Sarotherodon, Tilapia* and *Oreochromis* and common carp (*Cyprinus carpio*). Pelagic species are particularly rare in reservoirs, but options also exist. For example, kapenta (*Limnothrissa miodon*) introduced into Lake Kariba (formed by damming the Zambezi River) where it accounts for a 35 000 Mg yr^{-1} fishery. In China, the stocking of the pelagic planktivorous silver (*Aristichthys nobilis*) and bighead (*Hypophthalmichthys molitrix*) carps has increased production from less than 100 kg ha^{-1} to more than 300 kg ha^{-1} (Lu 1992).

In Burkina Faso, stocking small waterbodies in the Sahel with 20 kg (800 fingerlings) of *Oreochromis niloticus* per hectare increased production from 23 to 269 kg ha^{-1} (de Graaf and Waltermath 2003). India reports up to 10 fold increases in yield from stocking programs (Sugunan 1995). Five-fold increases have been reported from Thailand, Indonesia, the Philippines and Malaysia (Fernando 1977). Stocking of oxbow lakes in Bangladesh has increased yields up to nearly 600 kg ha^{-1}, while stocking of shallower floodplain lakes has yielded 2 800 kg ha^{-1} (Welcomme and Bartley 1998). Introduction of the largemouth bass, the red swamp crayfish (*Procambarus clarkii*) and two tilapia species into Lake Naivasha, Kenya have increased the production of food and sport fish from virtually zero prior to the introduction up to 300 tons (under very poor management).

There are two basic strategies for stocking: 1) the establishment of reproducing, balanced, populations and, 2) unbalanced put-and-take fisheries. Reproducing populations can either be internally or externally balanced. In externally balanced systems, fishers remove a certain percentage of the fish, often targeting larger individuals. This is the type of system that is most commonly observed in developing countries where stocking programs are undertaken to address problems of food insecurity or declining capture fisheries. Sometimes, natural predators already in the system supplement fishing pressure. Properly managed, these systems can be highly productive and beneficial to human communities. The majority of the examples cited above are of this type of stocking program. Inappropriate fishing (e.g., overfishing, taking fish that are too small or fishing in the breeding season) can ruin such fisheries and poses a major threat to sustainable management.

Internally balanced systems are comprised of reproducing predators and prey species and are most popular for sport fishery enhancements. As for externally balanced systems, if the exploitation is properly regulated, the fishery is self-sustaining and does not require restocking. However, the ratio of predator and prey species is critical to success and is often difficult to achieve, particularly in areas where food insecurity and poverty create incentives to poach or violate bag limits. Examples include the widely successful stocking programs for mixed centrarchid sport fisheries in the US and Europe (Davies 1973). Such programs stimulate economic growth and generate millions of dollars in fishing fees, tackle and equipment sales, hotel and restaurant revenues and guide services annually and create important recreation opportunities.

Unbalanced, or put-and-take fisheries, are based on species that cannot spawn in the lake or dam environment. The grass, silver and bighead Chinese carps are examples of such species. Trout stocked in dams that have no access to streams are unbalanced. Weed control programs involving grass carp are another example. The advantage of these systems is that they do not rely on any particular level of fishing pressure to maintain balance. However, they must be restocked regularly.

A variant of the put-and-take fishery is "ranching" of migratory species. In these programs juveniles are released, which then move away to feeding grounds, to be recaptured during their spawning runs back to the area of release. This is less important in lakes than it is rivers.

Fingerlings or broodfish for stocking come from two sources, the selection of which depends upon the objectives of management and the type of system (balanced or unbalanced). Hatchery-reared stocks, either of local or exotic origin, require careful genetic management to avoid inbreeding. On the other hand, hatchery stocks can be manipulated to provide exactly the number and size of fish required at the time when they are wanted. Wild-caught fingerlings may only be available at certain times of year, and then only in certain sizes and numbers. These can, however, be very useful in ensuring that any accidental fish escapes will have minimal impact on surrounding aquatic ecosystems. Also, reliance on wild stocks facilitates genetic management by always having a pool of wild fish from which to select new broodfish when restocking.

Knowledge of a fish's reproductive strategy and seasonality contributes substantially to success rates in stocking programs. Programs to enhance the production of red drum (*Sciaenops ocellatus*) in the US have increased the capture of stocked fish from 0.005% to 4.1%, depending upon the season of release (Willis et al. 1995). Introduction of Chinese carps has often failed because stocking programs did not take into consideration the fact that these fish can only reproduce in large rivers. In this latter case, the failure to reproduce can be a good thing, if escape of stocked species into other natural waterbodies is deemed undesirable.

Stocking rate is also a critical factor in success and is generally based on estimates of productivity generated through ecological studies. In general, production rises with increasing stocking density up to a limit determined by the abundance of food organisms, the carrying capacity (Welcomme and Bartley 1998). The number and sizes of fish to stock is based on estimates of carrying capacity, expressed in terms of weight/unit area (see Harvest, below). Within a given carrying capacity, the total weight of fish can either be in the form of many small fish or fewer larger fish. Typically, the number of fish to stock is calculated on the basis of desired fish size and the productivity of the waterbody, simply put:

$$\text{Number to Stock (per ha)} = \frac{\text{Carrying Capacity (kg ha}^{-1}\text{)}}{\text{Minimum Average Weight Desired (kg)}}$$

If mortality and growth rates are known, an inversion of the standard mortality formula can be used to give a more accurate estimate (Welcomme 1976):

$$N_o = N_c^{(z\,(c-o))}$$

where N_o = number to stock, N_c = number of fish desired at age of capture c, o = age at stocking, and z = total mortality.

Naturally occurring species, both of fish and other aquatic fauna or flora, can have strong impacts on the success of small waterbody management. Typically, from the point of view of the manager wishing to increase the yield of desirable (marketable or eatable species) these impacts are negative. Indigenous species compete for food, disrupt nesting/breeding behaviour and can predate stocked fish. By muddying water and uprooting plants, common carp can disrupt foodwebs and render ineffective the stocking of planktivorous species. Stocking of tilapias in Lake Nasser, Egypt to increase production was foiled by the Nile Perch (*Lates niloticus*), which ate the bulk of the stocked fish, often at the point of stocking. Stocking with forage species in cases where natural reproduction occurs, is often superfluous (Welcomme and Bartley1998).

Predators or competitors can be removed through the use of poisons or selective fishing, but the effectiveness of this is directly proportional to the size of the waterbody in question and the degree to which it can be physically manipulated through draining, weed control, etc. When control of unwanted species is not possible, or when multiple users demand different species for different purposes, fish population structure becomes a critical management issue. Balancing species with different ecological niches can be quite complicated and subjective and requires careful control of exploitation intensity and strategy.

Stock Structure

Structured populations can also increase productivity by taking advantage of the multiple food resources available in most waterbodies. For example, Tang (1970) characterized the feeding habits of the main species available for small waterbody culture in Taiwan (Table 1). In general, adults of the main species used in managed reservoirs overlap by less than 10% in terms of dominance within the diet of an individual food item (Tang 1970). From a quantitative comparison of the quantities of the main food items and biomass of fish produced over a period of years, Tang estimated where food items could be added and/or fish species abundance manipulated to optimise productivity. Likewise, Huet (1972) described a subjective indicator, the biogenic capacity, based on the composition of a waterbody's biota. This is a relative value that can provide general guidelines for extrapolation and comparison.

Table 1. Food habits of fish stocked in small water bodies for aquaculture

Species	Food Habit	Stocking Rate ha^{-1}
Silver Carp (*Hypothalmichthys molitrix*)	Planktophagic	400
Grey Mullet (*Mugil cephalus*)	Detritophagic	200
Bighead Carp (*Aristichthys nobilis*)	Zooplanktophagic	15
Grass carp (*Ctenopharyngodon idella*)	Macrophytophagic	80
Common Carp (*Cyprinus carpio*),	Benthophagic	200
Black carp (*Mylopharyngodon piceus*)	Benthophagic	200
Sea perch (*Lateolabrax japonicus*)	Nektophagic	50

A practical method used to manage small impoundments in Malawi was developed by Brummett (1996). This is a three-step process for matching the fish with the local pond environment. The first step is to characterize the pond in terms of available foods. The second step is to characterize the diet of the fish, and the third step is to make meaningful comparisons between various pond/fish combinations and production/economic constraints. Categorization of food resources is based on the intrinsic traits of the foods that effect their "selectivity" by consumers (Ivlev 1961):

I. Plankton (phyto + zooplankton)
II. Macrophytes + Filamentous Algae
III. Benthic Invertebrates and Detritus

To give an indication of how well a particular fish species might fit into the environment, the frequencies of materials from these basic food groups in the stomach and in the pond system are compared on a dry matter basis (Table 2):

Table 2. Proportion of Plankton, macrophytes and benthos/detritus in the food of some fishes

	Plankton	Macrophytes	Benthos/ Detritus
Waterbody (w/out fish)	0.02	0.56	0.42
Barbus paludinosus	0.93	0.07	0.00
Lethrinops furcifer	0.02	0.06	0.92
Oreochromis shiranus	0.67	0.28	0.05
Tilapis rendalli	0.01	0.88	0.11

The average of the absolute value of the difference between food available and food eaten for each food group is calculated to give a general indication of the fishes "food fit" (F_f) with the dam or pond. Data from Malawi give a general indication of the F_f for some of the main species:

B. paludinosus	(0.02-0.93) + (0.56-0.07) + (0.42-0.00)/3 = 0.61
L. furcifer:	(0.02-0.02) + (0.56-0.06) + (0.42-0.92)/3 = 0.33
O. shiranus:	(0.02-0.67) + (0.56-0.28) + (0.42-0.05)/3 = 0.43
T. rendalli:	(0.02-0.01) + (0.56-0.88) + (0.42-0.11)/3 = 0.21

A perfect fit using this method would be represented by an average F_f of 0.0. A perfect mismatch would give an F_f of 0.66. In this case, *T. rendalli* would be the best candidate of the three, followed by *L. furcifer*, *O. shiranus* and *B. paludinosus*. In addition to guiding species selection for use in various culture systems, the categorization and comparison of food groups also permits the pond manager to make systematic guesses about management strategies for various species. For example, polycultures might be evaluated by generating a group stomach from pooled stomach content data. If 100 *O. shiranus* were stocked together with 100 *T. rendalli*, the polyculture, would have an F_f of 0.32 for the grass-fed pond. If the stocking ratio or average weight of the polyculture were altered so that the standing stock in the pond was 25% *O. shiranus* and 75% *T. rendalli*, the F_f becomes 0.27 as shown below (Table 3):

Table 3. Food fit for different stocking ratios

	Plankton ($g\ m^{-2}$)	Macrophytes ($g\ m^{-2}$)	Benthos/ Detritus ($g\ m^{-2}$)	Food Fit (F_f)
Grass-fed pond	0.02	0.56	0.42	-
O. shiranus Stomach	0.67	0.28	0.05	0.43
T. rendalli Stomach	0.01	0.88	0.11	0.21
(50:50 polyculture)				
Stomach*	0.34	0.58	0.08	0.32
(25 *O. shiranus* :				
75 *T. rendalli*)	0.18	0.73	0.10	0.27

* Polyculture Stomach Content Frequencies =

$$\frac{[(W_{os} \times F_{fos}) + (W_{tr} \times F_{ftr})]}{(W_{os} + W_{tr})}$$

Where W_{os} = weight of *O. shiranus*, W_{tr} = weight of *T. rendalli*, F_{fos} = food frequency in *O. shiranus* stomachs, and F_{ftr} = food frequency in *T. rendalli* stomachs.

It would also be possible to improve the F_f for a species or a polyculture by modifying the environment. For instance, a qualitative examination of imbalances between food needs and availability might be used to design input regimes. A replacement of grass with inorganic fertilizer which increases the relative frequency of dry matter in the form of plankton to 0.25 and decreases that of macrophytes to 0.33, improves the F_f for *O. shiranus* to 0.28.

Removal of unwanted species can be as important as addition of desired species in managing stock structure. Competition for food or space with low-value species or size/age classes can seriously undermine stocking programs (Meronek et al. 1996). In some cases, partial removal of particular age-classes through the selective application of fish poisons (e.g., rotenone) to specific habitats (e.g., spawning beds) within a waterbody can be effective. Likewise, the use of selective fishing gears can help to reduce competition with desired species. Drawing down the water level, when feasible and if carefully timed, can target the removal of certain species when they are on their spawning or nursing grounds. The stocking of predatory species has been used in Israel (Leventer 1981). When these partial measures are not sufficiently effective, more drastic measures such as complete poisoning or desiccation can be considered.

Another way to structure populations is to give selective advantage to certain species through environmental modifications. The placement or cleaning (of sediment) of gravel beds can enhance production of char (*Salvelinus spp*.) and largemouth bass (*Micropterus salmoides*). Construction of shallow marginal areas can increase reproductive success of tilapias and carps. Fish aggregating devices or brush-parks can be installed to provide cover and grazing for desired forage species.

Trophic Cascades

Managing stock structure through manipulation of predators has potential to dramatically modify productivity, but will generally emphasize water quality (i.e., reduction of phytoplankton turbidity) and the production of larger, carnivorous species at the expense of the forage fish most commonly consumed by the rural poor. For example, Zalewski (1992) showed how phytoplankton density could be managed by stocking carnivorous percids. Stocking the zooplanktivorous perch (*Perca fluviatilis*) reduced zooplankton, increasing phytoplankton and lowering water quality. Conversely, stocking the piscivorous zander (*Stizostedion lucioperca*) reduced the number of zooplanktivorous perch and bleak (*Alburnus alburnus*), thus reducing the number of forage species that eat larger zooplankton, which in turn increases zooplankton grazing on phytoplankton, increasing water quality (Figure 1).

Another example comes from Lake Naivasha, Kenya where Mavuti et al. (1996) developed a trophic model showing how lack of a zooplankton predator (Lake Naivasha contains only alien species stocked by man) substantially reduces the productive capacity of the fishery. Actually, these relationships are quite complex, involving important differences in plankton size, zooplankton predator avoidance and, as mentioned below, nutrient recycling as a result of changes in fish foraging pattern (Ramcharan et al. 1996). In a similar vein, Berlanga-Robles et al. (2002) showed how introduction of alien species (*C. carpio, O. niloticus, M. salmoides*) can disrupt food webs and create imbalances in feed utilization and, subsequently, the stability of the lake ecosystem.

NUTRIENTS

Since productivity is generally a function of food organism density, fertilization to increase planktonic and benthic prey species can substantially improve the

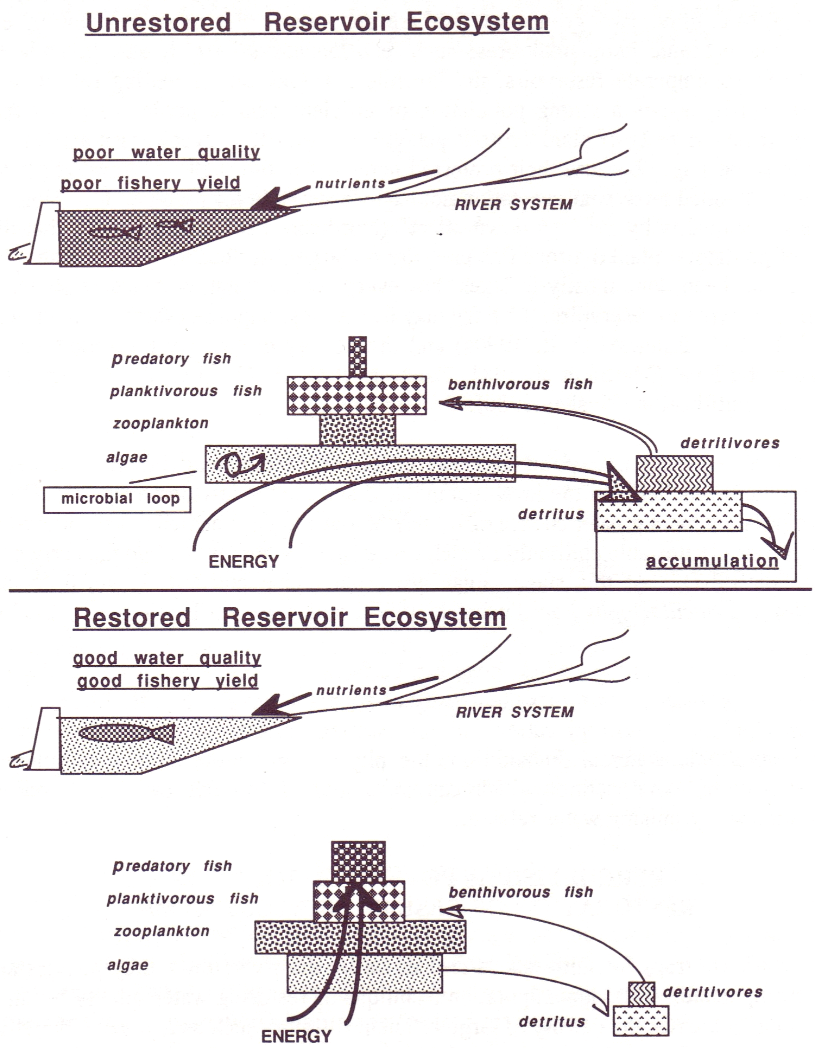

Figure 1. Example of a trophic cascade model of a percid-regulated food web in eastern Europe (Zalewski 1992).

catches (Bíró 1995). Sources of nutrients can be in the form of organic inputs such as manures or leaves, inorganic (chemical) fertilizers or waste matierals such as agro-industry by-products (e.g., brewery waste) or treated/untreated sewage. Due to the nature of small waterbodies, nutrients in the watershed (e.g., from animal grazing or fertilization of crops can strongly influence water fertility.

There are two principal mechanisms through which nutrients enter the food web: 1) dissolved forms (often inorganic fertilizers) are taken up by primary producers which then convert them into usable food, or 2) organic matter is decomposed by bacteria which then are either eaten directly or, when they die and breakdown, release dissolved nutrients into the water column.

In China, yields have been increased by nine times up to 540 kg ha$^{!1}$ through the application of inorganic fertilizers (Lu 1992). Fertilization rates for small waterbodies are on the order of 3-6 kg ha$^{!1}$ of phosphorus and 10-20 kg ha$^{!1}$ of nitrogen. In Russia, these rates have been shown to increase the density of food organisms by 5 times (Berka 1990). Maximum carbon fixation in the sub-tropics and tropics is on the order of 10 g C m^{-2} day$^{!1}$, but other factors such as turbidity and temperature limit productivity to an average of about 4 g C m^{-2} day$^{!1}$ (Schroeder 1980). To approach maximum fertility without polluting the water, Boyd (1979) recommends maintaining 0.5 mg L^{-1} P and 1.4 mg L^{-1} N dissolved in the water, obtained from regular application of 9 kg ha^{-1} N, 9 kg ha^{-1} P_2O_5 and 2.2 kg ha^{-1} K_2O. Schroeder (1980) recommends that manures be applied at a rate of 120 kg ha^{-1} day^{-1} of dry organic matter (2.5-4% fish biomass day^{-1}). Such nutrient input levels, if properly matched with fish stocking levels, can produce up to 7 000 kg ha^{-1} of fish.

The source of nutrients makes little difference to the food web (Schroeder 1980) so the choice of which inputs to use depends upon other factors. Although price and availability are important considerations, especially in developing countries, it is clear that the use of chemical fertilizers is more efficient in terms of labour and transportation than the bulky and less effective organic fertilizers. Moving and applying whatever nutrient source is a critical factor in usability in small waterbody fertilization. Manures are typically spread on the dry bottom before filling (Bíró 1995) while chemical fertilizers can be applied in a slurry or on a platform (Boyd 1979) to avoid direct contact with bottom sediments.

Depending upon the chemical composition of the water, large amounts of nutrients can be tied up in sediments. This is especially true of phosphorus, typically the most limiting factor in pond fertility, which adsorbes onto aerobic muds, especially under acidic conditions or situations where the mud contains high concentrations of calcium carbonate (Boyd 1979). The introduction of benthic detritivores to these systems such that adsorbed mud is either resuspended by foraging activity (in the case of common carp, for example) or by the digestion and excretion of food particles, can result in recycling of phosphorus back into the water column where it is again available to phytoplankton (Přikryl 1990). Such a phenomenon has been shown to increase dissolved P levels by up to three times (Havens 1993).

Interactions between the bank and the water of small lakes are important determinants of productivity. For example, a major source of nutrients in some small waterbodies is the epiphytic algae, bacteria and invertebrates that grow on the surface of submerged woody vegetation, particularly trees, which effectively increases the shore-line/water interface that to a large extent regulates productivity in natural ecosystems (Lowe-McConnell 1975). Also, substantial nutrient inputs result from regular draw-down and refilling, thus flooding the seasonally vegetated draw-down zone and exposing their accumulated nutrients to decomposition (Karenge and Kolding 1995).

Drawdowns can also have negative consequences, particularly when a fish stock is near carrying capacity. As most reservoirs occupy v-shaped (ex-riverine) valleys, the total surface area, and hence the area of the air-water interface through which much of the oxygen needed for fish respiration is diffused, declines sharply when water levels are lowered, effectively decreasing the size of the waterbody and driving and pushing the existing fish stock over carrying capacity (Costa-Pierce 1997).

Another important aspect of nutrient management in small waterbodies is the role of the thermocline. Decaying organic matter from upper levels descends through the water column and accumulates below the thermocline where they are more or less captured until such time as the thermocline is upset, either due to changes in season or due to activities related to dam management. The subsequent exposure of large quantities of reduced organic matter to oxygen can either provide a big boost to productivity or, if excessive, use up all the dissolved oxygen in the reservoir and cause catastrophic fish kills (Costa-Pierce 1997). Dam design, particularly the location of outlets, can be critically important in management of these turnovers. In situtiaons where nutrients are not limiting, bottom (below the thermocline) outlets can help to reduce build-up of organic matter during periods of high risk for thermocline disruption, increasing the oxygenated portion of the water column and increasing fish production (Costa-Pierce 1997). Use of mechanical aerators has been effective in mediating problems associated with rapid declines in dissolved oxygen due to turnovers or algal blooms (following die off and subsequent oxidation of organic matter), but this is expensive and generally limited to very small or very high-value waterbodies.

HARVEST

Managing the removal of fish may be the most important, and is certainly the most used, method of regulating productivity from both large and small waterbodies. The idea is to optimise individual size and numbers removed for the benefit of fishing communities. In smaller waterbodies or those that are completely drainable, managed strategies for stocking, harvest and restocking are used. In larger or undrainable reservoirs, harvest management generally involves the imposition of bag limits, size restrictions and regulation of fishing gear with or without restocking. Cage aquaculture is a relatively new management option, but in certain cases can present useful options for increasing fish production under minimal management arrangements.

To effectively manage harvest, one needs to understand the concept of carrying capacity. The carrying capacity is the total weight of fish that a waterbody can maintain, determined by nutrient loading, species combinations, etc. For any given waterbody at any point in time, there is a fixed carrying capacity, which can be manifested by a large number of smaller fish or a smaller number of large fish. When a reservoir is first filled and stocked, the fish are small and the total stock is far from carrying capacity. As the fish grow and/or multiply, the fish stock approaches carrying capacity. Once carrying capacity has been reached, fish growth essentially stops. Some system of fish removal will be necessary if the waterbody is to continue producing new or larger fish. Conversely, when the fish stock is much below carrying capacity, nutrients are only being partly exploited for fish growth. The ideal is to keep the pond near carrying capacity, but still growing for as much of the production cycle as possible.

The simplest system is to harvest the total stock all at once and then restock as soon as possible thereafter. Although easy to manage, this system does not effectively take advantage of the waterbody's carrying capacity, as for most of the production cycle, the waterbody is below carrying capacity. Also, having a large quantity of fish all at once complicates fish marketing or consumption. Figure 2 illustrates the yield from such a system, completely harvested twice per year.

Partial harvesting offers more flexible marketing opportunities, while increasing overall yield. Figure 3, for example, illustrates a common system whereby stocking occurs once per year, but part of the fish biomass is removed at some point (as the total approaches carrying capacity) in order to let the remainder continue growing. This method is useful in cases where there are markets for smaller as well as larger fish.

The most efficient systems involve stocking mixed sizes of fish, harvesting each size class as it reaches market size (Figure 4) and/or restocking after each partial harvest (Figure 5). This has the effect of keeping the pond as close as possible, but just below, carrying capacity at all times.

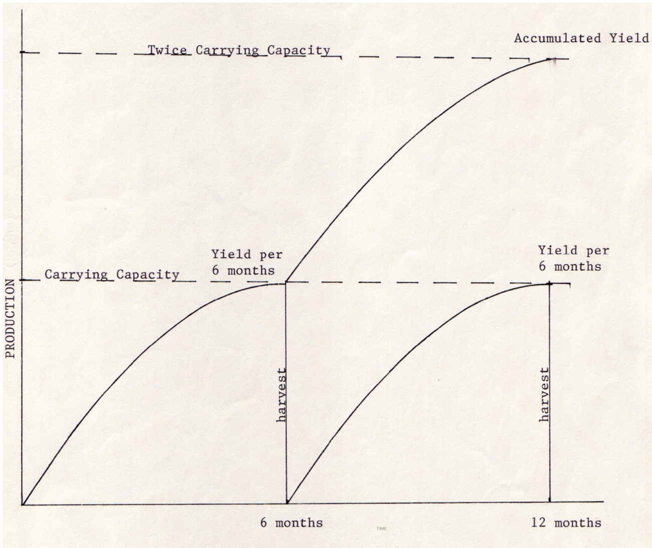

Figure 2. Complete harvesting of a small waterbody twice a year doubles the yield within a fixed carrying capacity.

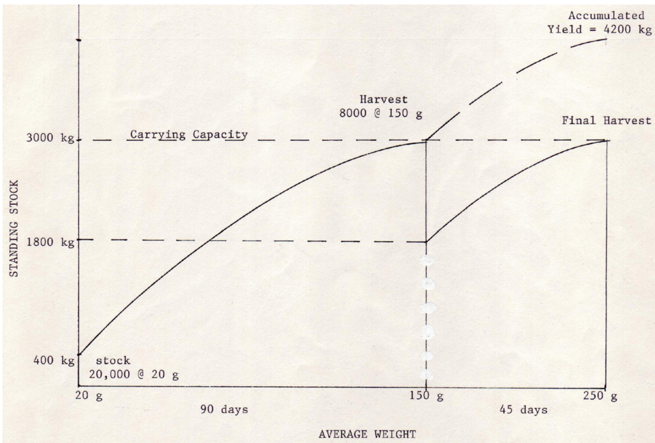

Figure 3. Yield for a system from which part of the fish stock is removed as the population approaches carrying capacity to permit those remaining to continue growing.

In waterbodies for which complete harvest is not an option, stocks must be managed through the establishment and enforcement of bag and size restrictions. This is complicated and generally species-specific, the basic idea being to only remove fish after they have reproduced at least once, thereby protecting the stock from over-exploitation. Such methods as net mesh size limits are common. However, applying inordinate pressure on just larger size classes can have the negative consequence of selecting for earlier maturing, and thus smaller, individuals within the popula-

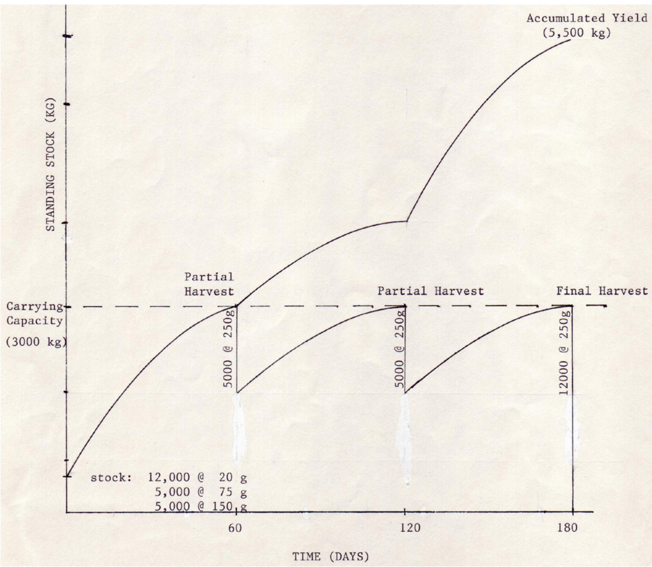

Figure 4. Yield for a system stocked with mixed-size fingerlings. As each group reaches market size, and the population as a whole approaches carrying capacity, it is harvested so the remaining fish can continue growing.

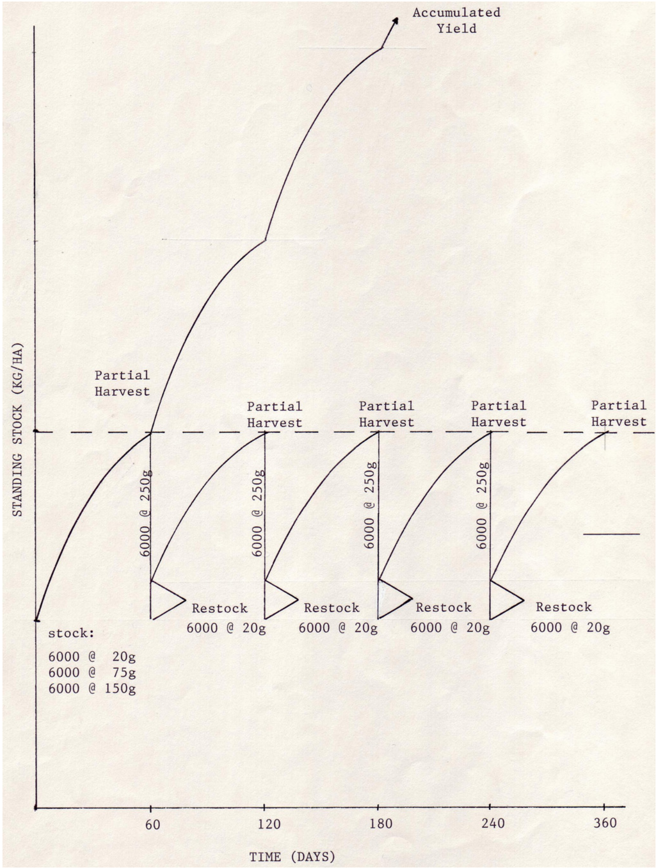

Figure 5. Accumulated yield from a system restocked after each partial harvest with small fingerlings in order to keep the production system going. This type of system would only work if the fish do not reproduce in the lake.

tion ultimately reducing the individual sizes of fish captured even while increasing total catch (Gwahaba 1973). For some species, such as sturgeon, window size limits are used, whereby only fish above and below certain total lengths can be retained.

An increasingly popular approach to fish production in both small and large waterbodies in the introduction of aquaculture cages (Figure 6). Provided there is sufficient water movement (e.g., currents, wind) the carrying capacity of cages within a reservoir can approximate that of the entire waterbody. Very high yields are thus possible from these cages. In lake Kariba, Zimbabwe, for example, tilapia are being cultured in 500 m^3 cages at a stocking density of 50 kg m^{-3}. Costa Pierce (1997) reports standing stocks of 200 kg m^{-3} of carp and tilapia in cages in Saguling Reservoir, West Java, Indonesia. It should be noted that feed inputs to fish cages will result in increasing fertility in the surrounding water. This can be a good thing when capture fisheries are suffering from inadequate nutrients (as in Lake Kariba) or a bad thing if water quality for domestic or other uses is a critical consideration.

Figure 9. Common carp cages placed in the Tishreen Dam, Syria.

NON-FISH OUTCOMES

In addition to producing fish, small waterbodies can provide additional benefits to communities. Many dams have irrigation and livestock watering as design features, but mud turbidity, plankton blooms, incorrect stock structure or weed infestations can impair function and reduce access and lifespan. Unplanned usage often includes extraction for household management, particularly laundering. Contact between humans (often children) and stagnant water creates ideal conditions for disease transmission. The regulation of water quality in general is a desirable outcome of small waterbody management. The other main, non-fish outcomes are weed and disease vector control.

Water Quality

Water quality is generally defined in terms of turbidity. Turbidity can be of two general types: 1) phytoplankton and, 2) suspended solids. Problematic phytoplankton blooms are normally the result of excessive nutrient loading. Suspended solids are the result of sediment entering the water column through erosive runoff from the watershed, or the activities of fish and livestock, which stir up bottom sediments.

Phytoplankton can be managed with applications of copper sulphate, but this chemical is dangerous to the environment and, anyway, expensive applications need to be repeated as long as excess nutrients exist in the system (Leventer 1981). More durable is phytoplankton management through trophic manipulations. Although complex, such manipulations can work as demonstrated by Zalewski (1992) and Ramcharan et al. (1996). Conversely, sediments contain 100-1000 times the concentration of nutrients as the water column (Bíró 1995). PÍikryl (1990) found that most changes in phytoplankton abundance were associated with resuspension of benthic nutrients rather than direct predation on plankton.

On the other hand, Lu et al. (2002) showed that high concentrations of filter-feeding silver carp can significantly reduce phytoplankton concentration, albeit not as efficiently as zooplankton. However, since zooplankton is seldom of interest as a commercial or food crop, the introduction of more planktivorous fish as opposed to just a few (which in fact appear to increase phytoplankton abundance), might be a way to increase fish and decrease phytoplankton biomass.

Several species have been used to influence various parameters in the management of water quality in the Israeli national water carrier system (Leventer 1981) (Table 4).

Table 4. Fish species used in Israel for improving water quality (from Leventer 1981)

Species	Introduced to control	Reproducing?
Oreochromis aureus	organic matter in sediments	Yes
Liza ramada (*Mugil capito*)	organic matter in sediments	No
Aristichthys nobilis	zooplankton	No
Hypophthalmichthys molitrix	phytoplankton	No
Sarotherodon galilaeus	phytoplankton	Yes
Ctenopharyngodon idella	aquatic weeds	No
Mylopharyngodon piceus	snails	No
Cyprinus carpio	snails	Yes

Within their extensive system of reservoirs and canals, three basic types of small waterbody have been described:

A. Reservoirs with low storage capacity, continuous flow through and stable water levels. Main biotic forms include: attached algae, submerged plants, snails, shrimps and insect larvae.
B. Reservoirs with frequent discharge and refilling and highly variable water levels. Main biotic forms are: attached algae, snails and insect larvae.
C. Reservoirs in which water is held for long periods and only replaced annually, thus water levels rise and fall slowly but significantly. The upper layers of these reservoirs are rich in zoo and phytoplankton. Lower layers are thinly populated and often anaerobic.

Each type of reservoir has slightly different water quality problems and so for each type a different fish stock management strategy has been implemented. For type A reservoirs *O. aureus, L. ramada, C. idella, M. piceus* and *C. carpio* are stocked to control the abundant benthic fauna. In type B reservoirs, *L. ramada, H. molitrix, C. idella, M. piceus* and *C. carpio* (males only) are stocked to control snails and aquatic plants. In type C reservoirs, *A. nobilis* and *H. molitrix* control plankton.

An interesting variant of trophic manipulation of water nutrients was presented by Gliwicz (1992), who hypothesized that the use of alarm substances such as purines, pterines or histamine-like compounds that are released by fish when their skin is ruptured, might be introduced to certain parts of a lake, thus "chasing" forage fishes that target algae-grazing zooplankton and in turn reducing phytoplankton blooms. In a study in Lake Ros, zooplanktivorous smelt density in areas where "alarm substances" were splashed were reduced to 25% of pre-treatment levels. Likewise, the introduction of chemical signals that influence the dormancy of certain types of algae might be useful in direct prevention of noxious blooms.

Abundant macrophytes compete with planktonic algae for both light and nutrients and can significantly improve water clarity (Boyd 1979, Hanson and Butler 1994).

Weed Control

As many dams were build for irrigation, evapotranspirative water losses and clogging of intake pipes as a result of heavy aquatic macrophyte infestation are major issues. Water losses due to evapotranspiration by emergent weeds can reach 500 m^3 ha^{-1} day^{-1} in the tropics. Heavy weeds can also limit the accessibility to sport fish and decrease the usability of reservoirs for other recreational uses such as swimming and boating. Common macrophyte weed species in reservoirs include (Applied Biochemists 1979):

- Water hyacinth (*Eichornia crassipes*)
- Water lettuce (*Pistia stratioties*)
- Cattails (*Typha* spp)
- Water lily (*Nymphaea* spp)
- Bulrush (*Scirpus* spp)
- *Salvinia* spp
- Water primrose (*Polygonum* spp)
- Pondweed (*Potamogeton* spp)
- Naiad (*Najas* spp)
- Duck weeds (Lemnaceae)
- Water Millfoil (*Myriophyllum* sp.)
- Coontail (*Ceratophyllum demersum*)
- *Elodea* sp.
- *Hydrilla* sp.
- *Utricularia* sp.
- *Hydrilla* sp.
- Filamentous algae (*Spirogyra, Cladophora, Rhizoclonium, Mougeotia, Zygnema, Hydrodictyon*)
- Attached algae (*Chara, Nitella*)

Weed control is a major objective of reservoir managers. Methods include:

- stocking of herbivorous fishes such as grass carp (*Ctenopharyngodon idella*) and red-breasted tilapia (*Tilapia rendalli*)
- chemical spraying
- mechanical control by hand or with floating weed harvesters.
- periodic draw-down to dessicate marginal weed beds.
- Use of biological control agents, the most notable of these being the weevils that have been introduced all over the globe to constrain the growth of water hyacinth

None of these methods is without negative consequences. The use of chemical methods can effect the usability of both water and fish by humans or for irrigation, most often necessitating delays between application and use of between 1 and 365 days. The most commonly used aquatic herbicides are based on copper which kills all plant life, including beneficial phytoplankton that form the basis of the food web (thus lowering overall productivity) and forms carbonates in water that accumulate in sediments and can render them sterile for aquatic life. In addition, both chemical and mechanical control require frequent and repeated treatment and so are expensive.

Grass carp and tilapias are alien in most of the places where they are introduced and thus risk the negative environmental impacts of escapement. To address this problem, some agencies employ only sterile triploid grass carp, produced through pressure treatment of eggs and subsequent screening, making this technique quite expensive.

Drawdown can not only kill marginal weeds, but can also negatively affect fish reproduction which often occurs in shallow water, particularly among weed beds. In addition water losses from the irrigation system due to draw down can be substantial. On the other hand, drawing down the lake level can allow access by livestock, which can leave behind substantial amounts of nutrients in the form of dung (Kolding 1994, Skarpe 1997).

Phytoplankton can also be weedy, creating problems primarily with water quality leading to either massive fish kills during deoxygenation events or dynoflagellate blooms (red tides), and off-flavours in foodfish. High concentrations of cyanophytes (e.g., *Anabena, Anacystis, Aphanizomenon, Nostoc, Nodularia, Gleotrichia, Gomphosphaeria*) have been associated with deaths among watering livestock, and may also be dangerous for humans. Phytoplanktivorous fish species such as silver carp (*Aristichthys nobilis*), bighead carp

(*Hypothalmichthys molitrix*) and Galilee tilapia (*Sarotherodon galilaeus*) have been successfully used to reduce phytoplankton in Israel (Leventer 1981).

Disease Vector Control

Disease vectors, especially mosquitoes (malaria, yellow fever) and snails (bilharzia) are common in some standing waters and theoretically can pose serious health risks to humans in cases where lakes and reservoirs are in proximity to villages or towns. Chemical control with natural or synthetic insecticides or molluscicides is common and can be effective, but is also expensive and can damage natural food webs, lowering overall productivity (Ndamba and Chandiwana 1992). Preferred in many places has been the introduction of fish that eat mosquito larvae such as members of the poecilidae, especially mosquito fish (*Gambusia affinis*) and guppies (*Poecilia reticulata*).

On the other hand, studies in India, Sri Lanka, Tanzania and West Africa have shown that, though communities living near small waterbodies suffer from very high mosquito densities, they enjoy lower than average malaria transmission (Klinkenberg et al. 2003). According to Teuscher (pers. comm., Bouake, Côte d'Ivoire, 1999) this is due to the stability of predator : prey relationships within the ecosystem. In seasonally wet areas, mosquitoes and their main predator, dragonflies (Odonata), die back during the dry season. When rains begin, mosquitoes rapidly increase in number ahead of the dragonflies resulting in a peak in malaria. As the wet season wears on, dragonfly populations catch up to the mosquitoes and eventually reach a density where they effectively shorten the mosquito's life span to less than the required two weeks for malaria transmission. In areas where permanent water protects the natural balance between predators and prey, the overall density of insects remains high throughout the year, but their individual life spans are shorter, thus reducing malaria.

In addition to snails, bilharzia transmission depends upon contamination of water bodies with human excreta. This disease could be easily controlled through public education and health campaigns, with available drug therapy (Blas et al 1992). Surveys conducted in the Lake Chilwa floodplain of Malawi, where bilharzia is a major public health problem, found that managed waterbodies contain large numbers of snails, but when the local population was not discharging human waste into the water, none of these contained cercariae (Chiotha 1994).

Attempts to introduce snail-eating fishes such as the black carp (*Mylopharyngodon piceus*) to control bilharzias-transmitting snails has been attempted in a number of places without much success, due largely to the snails' habit of sheltering amongst aquatic weeds where they are generally inaccessible to fish predation. When weeds are not a major problem, black carp can be effective. For example, within the Israeli national water carrier system, snail densities of 237 per m^2 were reduced to zero (Leventer 1981). Suppression of bilharzia intermediate host snails by a competitor snail, *Thiara granifera*, has been observed in the Caribbean (Sodeman 1992), while red swamp crayfish (*Procambarus clarkii*) have been shown to effectively control schistosome transmitting snails in Kenya (Lokker et al. 1992, Mkoji et al. 1992), although the translocation of this highly invasive alien species should only be considered in extreme cases (Lokker et al. 1992).

MANAGEMENT

Typically, dams and other water control structures are created by governments and allocated to communities for collective management and use with little or no fish management strategy (Sugunan 1997). Ignoring the high potential for managed fisheries in small dams has lowered overall productivity and efficiency of resource use. In Zimbabwe, for example, over 10,000 dams have been constructed for irrigation, domestic water supply and stock watering. The vast majority of these are currently unmanaged for fisheries, but have the potential to produce over 12 million kilograms of fish per year (Ersdal 1994). If properly managed, the runoff holding and groundwater recharge capacity of these dams is sufficient to supply water to a population some 4-6 times the current level (Sugunan 1997). Low incentives to maintain the physical infrastructure of water control structures can be attributed to low returns on investment and conflicts over ownership of benefits. Enhanced fish production and organized management, optimised around stated objectives of landowners and/or communities, could resolve many of these problems and return substantial benefits to local communities.

In general, management is much easier and more effective in smaller lakes and reservoirs. Fertilization, for example can increase production from the typical 10-500 kg ha^{-1} up to 1000-5000 kg ha^{-1}, but is generally not practical in large reservoirs. Likewise, control of illegal fishing becomes more difficult as the size of the reservoir increases. Managed dams have been shown to produce substantial quantities of fish and revenues if their management can be balanced against the needs of irrigation and other uses (Renwick 2001).

Co-management Vs Community-Based Management (adapted from Cofad 2002)

Central government is usually not capable of taking and enforcing adequate management decisions for a specific waterbody. The involvement of stakeholders, in particular local institutions and traditional authorities, appears to be the only way to manage inland fisheries.

Options include community-based management (CBM) or co-management of resources. Both entail the involvement of communities, but differ in that community CBM gives full responsibility to a community, while co-management creates a partnership arrangement between government and one or more communities. As the degree of government involvement in co-management varies, CBM can be seen as a form of co-management with minimal direct government participation.

Co-management appears to be the most suitable option where larger waterbodies are concerned, where a sizeable number of stakeholders have access to a resource, where different ethnic groups or nations are involved or where the state has a particular interest in a resource (e.g., biodiversity conservation). Where resources are delimited and utilised by only one or a very few stakeholder groups, CBM appears to be the better option. In African inland capture fisheries, it is usually traditional communities that represent most stakeholders. To devolve management functions to these communities has several advantages:

- Institutions exist and can be "utilised" with little or no cost.
- Their acceptance is generally high.
- They have appropriate methods to mediate in case of conflicts.
- They have effective mechanisms of enforcement.

However, to rely solely on traditional communities for resource management is, in most cases, neither viable nor realistic. Successful co-management requires government support, in particular by providing an appropriate legal framework and officially acknowledging traditional institutions. Also, community management could require the adaptation of existing, or the creation of new, institutions and/or management bodies. If traditional authorities and institutions are fully integrated into such structures, the advantages of traditional management could be maintained.

A 10-year effort in Bangaladesh to introduce community-based fisheries management of waterbodies (40-500 ha) has produced improvements in productivity of between 25 and 70%, and new institutional arrangements that have been used to implement season closures, access restrictions, installation of fish aggregating devices and the establishment of protected areas for the benefit of local communities (Thompson et al. 1999). Exclusivity of ownership, transferred from the government (public) to local management entities that are comprised of, and operate on behalf of, fishing communities, was found to be a critical factor in success. In a review of traditional inland fisheries management systems in Africa, COFAD (2002) identified exclusivity of access and "a locally evolved and collectively owned cognitive base and established, accepted and functioning local institutions" as key elements of success.

Workers in Burkina Faso found that simple management strategies for seasonal dams could increase fish standing stock from 60 to over 600 kg ha^{-1} (Baijot et. al 1994). In Malawi, local management entities have proven themselves capable of managing seasonal waterbodies for fish production (Chikafumbwa et al. 1998). What started as a micro-project with two villages has, over the last five years, expanded to over 12 villages with no additional external input and has been so successful that demand for fingerlings to stock the ever-increasing number of community lakes in the area has become a serious constraint.

In Burkina Faso, training and group formation for fisheries management committees helped to develop flexible management plans for a range of small waterbodies (de Graaf and Waltermath 2003). Some of the key issues in regard to the development of sustainable local management strategies are shown in Table 5. As in Bangladesh, the main finding being that exclusive access is a critical component of improved management.

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Table 5. Management issues for a range of small waterbodies in Burkina Faso (de Graaf and Waltermath 2003).

Large (20-700 ha)	Medium (5-20 ha)	Small (1-5 ha)
• Management and ownership by more than one village • People view management as the business of the government • Difficult to obtain exclusive access for local management entities • Impact of investments in management are difficult to monitor • Inequitable distribution of benefits among stakeholders • Management generally not sustainable outside of a project context	• Management and ownership by only one village • Local management is possible in cases where legal framework exists • Exclusive access can be organized • Impacts of investments are relatively easy to monitor • Benefits more equitably distributed among stakeholders • Can be sustainable if developed under a proper legal framework	• Management and ownership by one (extended) family group • Distribution of benefits regulated locally through traditional mechanisms • Access rights are normally exclusive to the family group • Impacts of investments obvious to owners • Benefits distributed according to family norms • Highly sustainable

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