Present applications and future needs of meteorological and climatological data in inland fisheries and aquaculture

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Abstract

In 1996 production from capture fisheries and aquaculture in inland waters amounted to more than 23 million t. The amount of fish that can be produced, whether by capture from natural systems, or through aquaculture, depends on water quality and quantity. The most obvious connections between meteorological data and inland fisheries and aquaculture production are via water temperature and the amounts of water available to natural and man-made systems, but there are also more subtle indirect relationships that affect the movement of nutrients and fish behaviour including migrations and reproduction.

A wide range of examples of applications of meteorological data to aquaculture and inland fisheries are provided. They include continental assessments of inland fish farming potential, fishery potential in small water bodies, synoptic loss of fishery potential due to environmental degradation, complex effects of wind on fish production in a large lake and effects of global warming on fish distribution and production.

It is concluded that the meteorological data that serve for agriculture also are relevant for inland fisheries and aquaculture, although the relative importance of parameters and their temporal aptness may be different, and thresholds may be dissimilar. Similarly, if the timeliness, resolution and predictive capabilities for agrometeorological data can be improved, there would be considerable benefits to inland fisheries and aquaculture. Geographically synoptic gridded agrometeorological data sets at 1 km resolution should be a short term objective. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Inland fisheries; Aquaculture; Meteorology; Climatology; Production models; Climate change models

1. Importance of inland water fisheries and aquaculture

In 1996 production from capture fisheries and aquaculture in inland waters amounted to more than 23 million t, with respective contributions of 7.5 and 15.5 million t. Yields from fisheries, especially subsistence fisheries, being greatly under-reported, may be twice the published figures. The bulk of aquaculture production comes from Asia, derived mainly from extensive and semi-intensive farming of lower-value herbivorous and omnivorous fish species. Fisheries yields are highest in Asia, but are also important in Africa. Fishery enhancement techniques, especially stocking of natural and artificial water bodies, are contributing to a major proportion of the catch, particularly in Asia.

Most inland fish production provides significant contributions to animal protein supplies in many rural areas. In some regions freshwater fish represents an essential, often irreplaceable source of high quality,
and inexpensive, animal protein crucial to the balance of diets in marginally food secure communities. Most inland fish produce is consumed locally, marketed domestically, and often contributes to subsistence and livelihood of poor people. The degree of participation, including a significant number of women and children, in fishing and fish farming can be high in some rural communities, and fish production often is undertaken in addition to agricultural or other activities.

2. Inland fish production, weather and climate

The amount of fish that can be produced, whether by capture from natural systems, or through aquaculture, depends on two fundamental characteristics: (1) water quality, and (2) water quantity. A third variable is the productivity of the system. It is the innate productivity for natural systems as well as that added (or lost) through eutrophication and other man-induced changes. In aquaculture it is the amount of feed or fertiliser purposely added that determines the productivity.

Thus, most obvious connections between meteorological data (atmospheric temperature, cloud cover, wind velocity, precipitation) and inland fisheries and aquaculture are:

1. Water temperature as the salient element of physical water quality;
2. Water available to natural and man-made systems (surface area and volume, standing and running);
3. Effects of inclement weather on inland fishing and aquaculture activities.

In fisheries the connections manifest themselves in several ways. Temperature can be a lethal factor. At sub-lethal ranges it controls metabolic rates. It affects not only the rate of growth, but also fish behaviour. Temperature changes trigger fish movements and fish reproduction. Similarly, changes in water quantity, both area and flow, coincide with reproduction and migrations. Seen on a longer time scale, seasonal and inter-annual changes in living space that are characteristic of river-floodplains, shallow lakes, swamps and reservoirs condition fish catch both through the amount of biological production that can take place and via changes in concentration or dispersion of fishes and the efficiency of fishing.

Inclement weather affects fishing activities on inland waters; however, in contrast to seafisheries, the effects are limited mainly to the open waters of the larger lakes and reservoirs. Severe weather, manifest in floods and high winds, can damage aquaculture installations and interrupt operations such as harvesting. In countries with well-organised national weather services timely warnings of impending bad weather can play an important role in making inland fisheries safer and in lowering risk for aquaculture operations. Fundamental to the development and management of inland fisheries and aquaculture is the ability to predict output, or loss of output. Each of the examples set out further uses meteorological and climate data in different ways to achieve estimates of potential gain or loss.

3. Applications of meteorological data to inland fisheries and aquaculture

3.1. Development and management of aquaculture using climate data

The basic questions in aquaculture development are ‘What is the suitability of the site for the culture system and what will be the performance of the organism to be cultured?’ Virtually any scale is relevant and the time frame is that of the expected life of the culture installation.

3.1.1. Strategic assessments of inland fish farming potential

Continent-wide estimates of the potential for inland fish farming have recently been completed for Latin America (Kapetsky and Nath, 1997) and for Africa (Aguilar-Manjarrez and Nath, 1998) as well as for the Caribbean Island States (Kapetsky and Chakalall, 1998). Four criteria were used to estimate potential for small-scale fish farming in ponds: water loss, potential for farm gate sales, soil and terrain suitability for ponds and availability of agriculture by-products as feed or fertiliser inputs. A fifth criterion was added in order to estimate potential for commercial fish farming: urban market potential. These criteria were weighted in different ways to make small-scale and commercial fish farming models on the basis of expert advice. Numbers of fish crops (harvests) per year of widely cultured
species, Nile tilapia, *Oreochromis niloticus*, the common carp, *Cyprinus carpio*, the sawtooth catfish, *Clarias gariepinus* or species potentially important for culture, the tambaqui, *Colossoma macropomum*, and the pacu, *Piaractus mesopotamicus*, were predicted based on monthly climatic variables. By varying feeding levels and harvest sizes small-scale and commercial level outputs were simulated. Combining the small-scale and commercial models with the simulations of fish production provided overall suitability ratings for each 5 arc minute grid cell (approximately 9 km × 9 km) in Latin America and the Caribbean and 3 arc minute grid cell (5 km × 5 km) in Africa.

These studies were dependent on grided climate data sets that have been applied in several ways. Air temperature grids for Latin America were prepared by the FAO Agrometeorology Group and for Africa by the Centre for Resource and Environmental Studies (CRES), Australian National University (Hutchinson et al., 1995). The precipitation grid for Latin America was from Corbett (1993) and that for Africa by the CRES.

Water loss: Water loss affects fish farming in several ways: (i) capital costs for ponds in relation to storage capacity, if storage capacity has to be increased due to the seasonality of the availability of water and (ii) operational costs, if water from rainfall has to be supplemented by additional engineering works (e.g. canals) or pumping.

Net annual water loss from ponds was estimated by balancing monthly precipitation with monthly evaporation, the latter taking into account temperature and solar radiation.

**Agricultural by-products as feed and fertiliser inputs:** Small-scale fish farming almost always is integrated with agriculture. Potential availability of agriculture by-products was inferred from crop potential (Alexandratos, 1995), itself derived from length of the growing period (LGP) and crop productivity, except in Africa.

**Fish production:** In general, fish growth is primarily a function of fish size, food availability, photoperiod, temperature, dissolved oxygen and ammonia concentration. These affect growth via food intake. In essence, a bioenergetic model developed by Bolte et al. (1995), taking into account these variables, was parameterised for the species indicated earlier. Simplifying assumptions were made in order to incorporate the spatial dimension. The output was a prediction of the number of crops (fish harvests) per year of each species that could be expected from commercial and small-scale fish farming from each grid cell ‘site’ (Fig. 1.). Because of a lack of grided data sets, only mean temperature and photoperiod were taken into account in Latin America and the Caribbean Islands, but in Africa annual wind velocity also was incorporated.

The aquaculture models described earlier have been implemented using long-term averages, but also could be run to show the effects of extreme conditions such as drought on pond water volumes (related to production costs, growth and survival, and ultimately profitability) and low and high temperatures (growth, number and weight of harvests). Required would be historical grided data sets of the central tendency and extremes.
An important point is that, although the illustration was of a continental approach to estimate fish farming potential, the same data, albeit from the nearest meteorology station, are routinely used for the evaluation of the suitability of individual sites.

3.2. Development and management of inland fisheries using meteorological data

The prediction of catch from inland fisheries can be considered according to purpose:
- ‘Weather-based’ models for single water bodies that are used to predict seasonal and inter-annual variations in catch;
- ‘Climate-based’ models for the same or similar kinds of water bodies that predict average catch potential.

3.3. ‘Weather-based’ models

3.3.1. River floodplain and reservoir hydrological models

Models that describe these relationships in river floodplains were reviewed by Welcomme (1985). For example, annual catches on the Magdalena River floodplain in Colombia have been related to water level in the same year, an expression of efficiency of fishing as a function of water quantity ($r = 0.84$). Water levels from representative gauge stations were the input data. The biological effect of flood size (increased habitat, better growth and survival) on fish catch on the Kafue River floodplain, Zambia has been shown by a good correlation with the flood of the previous year ($r = 0.72$) and 2 years previous ($r = 0.71$). A surrogate for the actual area flooded as input to the model was the area under a representative water level curve. These correlations reflect the fact that in such systems most fishes are caught when 1 and 2 years old. Best fits for three floodplains were obtained by using a combination of flood histories from the two previous years.

In the Zimbabwe portion of Lake Kariba reservoir a 7-year decline in the catches of the sardine fishery led to assertions that the fishery had reached its limit and that effort needed to be reduced. A significant negative relationship between catch and catch per unit of effort (CPUE) would be a telltale sign. However, such was not the case for the period 1980–1996. Rather, a strong correlation was found between river inflow and CPUE that linked poor catches to droughts and consequent low inputs of nutrients via rainfall runoff (Marshall, 1982 and Marshall, personal communication).

3.3.2. Winds and fisheries in Lake Tanganyika

Lake Tanganyika (32,000 km$^2$) is the world’s second deepest lake. It supports important pelagic (open water) fisheries that provide some 165,000 t per year. High and steep mountains surround the lake. Gravity winds together with thermal and trade winds create a complicated wind pattern over the lake. Thus, wind patterns have high temporal and spatial variations.

The apparent effects of wind on seasonal and inter-annual catches, the latter affected by ENSO events, have been demonstrated by Plisnier (1997). During a year of high wind speeds from the south, warmer surface water is driven to the north and the water layer with a marked change in temperature (thermocline) there is relatively deep. The return currents in the deeper layers generate a correspondingly strong upwelling in the southern part of the lake. Weak winds have the opposite effect. The internal waves are important for the productivity of the lake because they cause the transport of water rich in nutrients from the depths into the euphotic and oxygenated layers of the epilimnion. In turn, primary production increases, as does biological production and finally, the availability of fishes to the fisheries. Short-term variations in nutrient availability are manifest in catch because the mainstays of the fisheries are two short-lived sardines.

Plisnier (1997) has detected a positive relationship between the southern oscillation index related to el Nino and the catches of the sardines over the period 1963–1993 and a negative one for their predator that appear consistent with the availability of food and feeding habits of these fishes. In addition, he detects evidence for an overall water temperature warming trend that is negatively affecting biological production of fishes because of increased thermal stability leading to decreased rates of release of nutrients into the productive levels of the lake.

In a related study, sedimentation and circulation models were built for Lake Tanganyika by Huttula (1997). Input data were obtained from lakeside meteorological stations that were established at three key
locations around the lake and complementary data were collected during three lakewide hydrodynamics cruises. Similar to the study described by Plisnier (1997), a basic input for model building was wind velocity. Currents at various depths were measured using an Acoustic Doppler Current Profiler. The sedimentation and circulation models are relevant for fisheries on the one hand to estimate the impacts of land use changes on aquatic production and the transportation of pollutants. On the other hand, horizontal transport of larval and juvenile fish and fish-food organisms can be deduced.

Clearly, these relationships open the possibility for short- and long-term fishery forecasting on the lake and by extension, better management of the fisheries, if the supply of meteorological data is reliable.

3.4. ‘Climate-based’ models

3.4.1. Simple models

Looking among systems and across continents, it has been found that a combination of catchment area and rainfall account for about 84% of the variation in catch in tropical lakes and reservoirs (MRAG Ltd., 1995).

By adding mean annual temperature to an earlier yield index based on lake morphology (mean depth) and limnology (total dissolved solids) used regionally, Schlesinger and Regier (1982) expanded the geographic scope of fish yield prediction to North America. They predicted maximum sustainable yield isopleths and showed that mean air temperature explained more of the variance in the continental data set than the morpho-edaphic index.

3.4.2. Fishery potential of small water bodies

In certain combinations of water-holding soil types and seasonal rainfall regimes numerous small water bodies have been constructed to serve as community water supplies for domestic consumption, for watering livestock and for small-scale irrigation. These small multi-purpose water bodies are believed to have good fishery potential, if properly managed, and have the advantage that they often coincide with relatively poor farming communities in areas that are marginal for rain-fed agriculture so that fish could become an important contributor to food security. A relevant question is ‘What is the fishery potential of small water bodies and how does it vary spatially?’

A major problem for the implementation of such fisheries is that inventory and characterisation information on small water bodies is very often lacking (Haight, 1994; Verheust, 1998). Therefore, it was reasoned that the occurrence of small water bodies can be estimated globally on the basis of the spatial distribution of mean annual rainfall (Kapetsky, 1998; grided precipitation data from Leemans and Cramer, 1990; Fig. 2) in the same way as was carried out for ponds in Africa by Kapetsky (1994). Precipitation thresholds were assigned that relate to the risk of the water body going dry, or of requiring cost-adding modifications in order to support fisheries.

Fig. 2. Risk for fisheries in small water bodies in relation to annual precipitation.
The cost of management of fisheries can be minimised, if the small water bodies are in a temperature regime where the stock can reproduce naturally. Similarly, maximum output can be obtained where growth is continuous the year around. One of the most widely introduced and commercially important food fishes of warm inland waters is the Nile tilapia. It is a good candidate for this purpose and the global distribution of its continuous growth and reproduction using air temperature is illustrated in Fig. 3 (Kapetsky, 1998; grided precipitation data from Leemans and Cramer, 1990).

Combining the continuous growth regime of Nile tilapia with the occurrence of small water bodies shows that only about 1% of the land surface encompasses conditions where these coincide at low risk of the water body drying out while an additional 12% combines the continuous growth regime with very low risk of the water body going dry (Fig. 4).

3.4.3. Regional global warming

Prediction of the effects of global warming provides another example of the use of climate data for fishery purposes over large areas. Global warming will affect freshwater fishes, fisheries and aquaculture and thereby the global food supply. An approach for modelling fisheries dynamics in order to reduce the uncertainty of the predicted changes and to allow economic planning has been put forward by DeAngelis...
and Cushman (1990). Climatic change could lead to warming of inland waters, changes in stream flows and decreases in physical mixing in standing waters by increasing thermocline strength, thus decreasing nutrient movement from lower to upper waters. These changes, in turn, could manifest themselves in alterations in timing of reproduction, larval distribution and survival, migration and feeding rates. Additionally, trophic levels lower than fishes are bound to be affected thereby changing food availability to fishes. From the standpoint of one species in relation to all others, there will be changes in predators and competitors. Different changes can be considered if caused by long-term trends in climate, or by greater seasonal and annual variations.

The approach advocated is to pursue causal links and to consider hydrodynamic and ecosystem simulation models, as well as fish process (behavioural and physiological) models and population models that bring in climate, or climate-related variables. Given the state of knowledge and of experience with modelling, the objective should be to generate ranges of possible outcomes rather than definite predictions.

Three types of ecological linkages, water temperature, water quantity and water quality, have been used by Regier and Meisner (1990) to assess the effects of climate change on freshwater fishes and their habitat. The relationship between these is basin-specific, depending on such characteristics as physiography, topography and slope. Thus, fisheries workers will require relatively fine-scale estimates of these meteorological variables to assess the effects of climate change. Similarly, in a study that used a reservoir water quality model to simulate global climate change effects on fish habitat Chang et al. (1992) noted the problems of using generally coarse resolution grid cell output of atmospheric general circulation models to assess small scale impacts.

Minns and Moore (1992) developed a practical application of a regional model predicting the spatial distribution of fish yield capability with and without climate change of three species in lakes in eastern Canada. They established the distribution of the three species within the tertiary watersheds, then assigned the 30-year mean annual air temperature to each watershed. The Global Climate Model (GCM) of the Goddard Institute for Space Studies (GISS) was used to create a temperature increase map. Equations relating fish yield to mean annual temperature in lakes were used to estimate yield capability.

The GISS-GCM predicted temperature increases of 2.5–7.7°C with a mean of 4.5°C in eastern Canada. The regional model predicted substantial spatial distribution of fishery capabilities. It was concluded that without special efforts to prevent temperature increases, or major efforts to redistribute fishes, Canadian freshwater fisheries would suffer large disruptions, given GISS-GCM increases.

Two trends are evident in the estimation of the effects of global climate change on inland fisheries. One is a proliferation of interest exemplified by incorporating it as a session topic in a recent American Fisheries Society symposium. Another is the increasing diversification of effects taken into account and the sophistication of the simulations. For example, with regard to the latter, Frissel et al. (1996) brings out the importance of exchange of flow between surface and subsurface hyporheic compartments as a means of mediating water temperatures. This, in turn, calls attention to protection and restoration of forests as a way to conserve the relatively cool thermal signature of hyporheic-orgin water in order to resist adverse effects of climate warming. With regard to the former, Stefan et al. (2000) simulated climate change impacts on fish habitat in lakes of the Temperate Zone by taking into account not only temperature, but also dissolved oxygen requirements of fishes and trophic states of the lakes. The simulations were driven by daily weather data inputs. The model output consisted of daily profiles of water temperature and dissolved oxygen concentration for 19 years. A database of 3002 lakes gave a decrease in good growth habitat for cold-water fish by about 40% and an increase in cool- and warm-water fish habitat by about 20 and 50%, respectively.

3.4.4. Synoptic fishery potential

Increased production and value can be attained from inland fisheries by implementing a variety of enhancements in order to improve outputs. These include introductions of new species, periodic stocking to favour certain species, fertilisation to raise productivity and engineering of the environment to improve vital habitat. A fundamental question is “What amount of benefits can be expected?” In order to answer, it is necessary to be able to estimate natural (baseline) fishery potential. Given that the most serious threat
to inland fisheries is degradation of the environment, not overfishing, it is increasingly important to be able to address ‘What potential is being lost through degradation of the environment?’

‘Spatial Modelling for the Assessment and Management of Inland Fisheries’ is a current pilot activity of the FAO Inland Fisheries Programme. It aims to improve on existing models that predict catch and to create new ones. The approach is to expand on the numbers and kinds of parameters that are known to affect inland fishery productivity, in particular spatial parameters. The expanded models take into account:

1. The characteristics of water bodies themselves (e.g. type, surface area, shoreline development);
2. The ‘natural’ characteristics of the water bodies’ catchments (e.g. soil fertility, precipitation, temperature);
3. Factors that modify aquatic productivity (e.g. population density, crop cover, road density);
4. Kinds and magnitudes of fishery enhancements (e.g. stocking, fertilisation).

The modelling process uses catchments as a spatial framework. Spatial parameters are estimated through the use of a geographical information system. The nominal resolution is 1 km. Clearly, the most dynamic parts of the proposed models are precipitation and temperature. With predictions of temperature and precipitation rather than averages, forecasting, albeit crude, could be implemented.

4. Discussion and conclusions

4.1. General

The examples provided underline the fact that weather and climate data are essential for the management and development of inland fisheries and aquaculture. Temperature is an especially important variable because of its key role, ultimately, in determining fish production rates. For modelling over large geographic areas, particularly in developing countries, air temperature is the indispensable surrogate for water temperature. This is because there are insufficient water temperature observations on which to base and test models and, most importantly, on which to apply the models once built.

In fisheries there are a variety of applications that span seasonal and annual time scales extending to long-term climate change. The applications range from single water bodies to global aggregations of lakes, reservoirs and rivers. Similarly, in aquaculture, it has been stated that meteorological data are required in order to properly evaluate the safety of operations and profitability of the enterprise, whether from the perspective of a single site, or a continental assessment of fish farming potential.

The same meteorological data that serve for agriculture also are relevant for inland fisheries and aquaculture, although the relative importance of parameters and their temporal aptness may be different, and thresholds may be dissimilar. Therefore, if the timeliness, resolution and predictive capabilities for agrometeorological data can be improved, there would be a considerable carry-over of benefits to inland fisheries and aquaculture.

A specific need is for better prediction of water temperature from weather and climate data.

4.2. Needs for aquaculture

The fundamental requirements for aquaculture for the prediction of site suitability and management are for climate data that provide measures of central tendency and of extremes for the prediction of future conditions. Obviously, the higher the resolution and the greater the accuracy of the data, the better the prediction of site suitability.

Another need is for warning of impending disasters, for example, exceptionally cold, dry, or destructive weather conditions such as storms and floods.

4.3. Needs in inland fisheries

In individual inland water bodies the linkages already have been defined in order to predict catch seasonally and interannually. However, such relationships are not common, especially for water bodies in developing countries. In contrast, among water bodies of the same or similar types there is a ‘generic’ capability to predict average catch over the long term. Given the timely availability of input data, it would be possible to extrapolate the generic capability to make seasonal and inter-annual predictions of fish catch.
and 2 years ahead. The predictions would depend on measures of water availability and on temperature. Precipitation, if estimated by remote sensing, would meet the criteria of timeliness and would provide synoptic geographic coverage. Results would be best for shallow systems that usually fluctuate in surface area. Although the results would be only indicative, they could be useful in the context of a ‘Fishery Early Warning System’ as a supplement to existing Famine Early Warning Systems.

Finally, 1 km resolution for climate parameter predictions is a realistic goal in order to match the resolution of other important data sets such as soil characteristics, land cover, Digital Chart of the World layers, digital elevation models and drainage basin definitions.

Acknowledgements

The paper benefited from the comments of two anonymous reviewers.

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