GIS/Spatial Analyses in Fishery and Aquatic Sciences (Vol. 3)
Kam et al – GIS: decision support & domain for small-scale freshwater aquaculture (431-444)

Delineating recommendation domains for small-scale freshwater aquaculture: deploying GIS for decision support

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Abstract

This paper highlights Geographical Information System (GIS) applications in an on-going, three-year project to develop spatial decision-support tools for identifying recommendation domains (places and sets of conditions) that determine the potential and feasibility for adoption of smallholding pond-aquaculture systems to aid strategic aquaculture planning and development. Implemented at sub-national scale, the project is piloted in Bangladesh, Cameroon, China and Malawi. Assessment of aquaculture potential involves evaluation and estimation of many factors, both biophysical and socio-economic. GIS providès tools not only for producing the suitability maps based on some decision-rule algorithm such as multi-criteria evaluation, but also for spatial estimation and mapping of the input factors. In the case of the latter, GIS for aquaculture-planning benefits from applications developed in a variety of other fields. Two specific enhancements of GIS-based methodology

development for factor estimation are described: for estimating pond-water availability by supplementing climatic–soil water-balance estimation with modeling the contribution of groundwater and surface flow; and for developing physical-accessibility indices based on network analysis of origin–destination travel distances and time. An econometric modeling-framework and methodologies are being developed for identifying and quantifying the factors that influence socio-economic adoption of smallholding pond-aquaculture systems. These factors will be incorporated into the GIS modeling of aquaculture potential. To investigate further the implications of the evaluated potential, fish-yield models for mono- and poly-culture of selected species are being developed for use in conjunction with GIS to determine the spatial variability of expected production. Finally, user-friendly interfaces are being developed to facilitate and encourage users who lack GIS skills to use the decision-support tool not only for generating aquaculture-suitability maps but also for structured query and interpretation of the results in meaningful ways to support planning and decision making. These utilities will be web-enabled for wider usage.

Key words

GIS, freshwater pond aquaculture, decision-support tool, aquaculture planning.

1. Introduction

Aquaculture planning and management, like many other natural-resource-based economic activities, is inherently spatial. Therefore geographical information systems (GIS) have a useful role in integrating and analyzing information relevant for supporting aquaculture development. Indeed there has been a history of methodology development for applying GIS in this area; comprehensive reviews are provided by Nath, *et al.* (2000) and Kapetsky (2004). Kapetsky and Aguilar-Manjarrez (2004) pointed out the predominance of GIS applications developed for identifying aquaculture suitability and zoning and to support strategic planning. The main outputs from the GIS modeling in such applications are suitability maps for the targeted aquaculture species or production system(s). The maps indicate the potential—as measured by some suitability rating—of different locations, at geographical scales ranging from continental (e.g. Kapetsky and Nath, 1997, for Latin America; Aguilar-Manjarrez and Nath, 1998, for Africa) to sub-national and local levels (e.g. Kapetsky *et al.*, 1991, for Ghana; Aguilar-Manjarrez and Ross, 1995, for Sinaloa State in Mexico; Paw *et al.*,1994, for Lingayen Gulf in the Philippines; and Salam, *et al.*, 2005, for Barhatta sub district of Netrokona district in Bangladesh).

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1. Introduction

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Such suitability maps provide strategic assessments of potential areas for aquaculture. However, they do not directly address pertinent concerns of planners and development agencies, particularly in the context of promoting aquaculture development for improving livelihoods and alleviating poverty of small-scale farm households that are not necessarily located in the most suitable areas. In promoting appropriate aquaculture systems among new-entrant farmers, or improved aquaculture technologies among practicing farmers for enhancing production, it is important to know not only where and under what circumstances would opportunities exist but also what constrains adoption in less-promising locations. GIS can provide the spatial decision-support, beyond suitability mapping, to answer these questions. Providing the knowledge in an organized and systematic manner to decision makers and planners would help guide national strategies for aquaculture development targeted at the smallholder sector.

2. Recommendation domains for smallholding aquaculture and the role of GIS

The GIS-based work described in this paper constitutes a core component of an on-going project that attempts to organize, analyze and present information aimed at addressing the key aquaculture planning and management issues discussed above. Led by the WorldFish Center (WFC) working in close collaboration with national partners in four countries—Bangladesh, Cameroon, China and Malawi—the three-year project, which started in November 2004, is developing a decision-support system that would help in:

- identifying where and under what circumstances would desired freshwater, pond-aquaculture systems be feasible and conducive for sustained smallholder adoption;
- determining what measures or interventions are needed to realize the aquaculture potential and overcome constraints existing in different locations; and
- estimating what levels of impact on people can be expected from widespread adoption of the target systems in meeting food needs and improving livelihoods.

This body of knowledge constitutes the "recommendation domains" for aquaculture systems targeted for smallholders. The main outputs of the project include:

- methodologies developed for identifying and evaluating key factors influencing adoption of target aquaculture-production systems for smallholders;

- a suite of analytical and decision-support tools for delineating and characterizing recommendation domains for these production systems; and

- integrated biophysical and socio-economic data sets (including GIS data) and knowledge base for target pilot areas in the four partner countries.

Target stakeholders include government and non-government agencies responsible for aquaculture development and donor agencies concerned with investment priorities for poverty alleviation. Therefore, the project also places emphasis on close collaboration with and building the capacity of, national partners (mainly the authoritative government line-agencies) for continued use of the project outputs for their aquaculture planning and management purposes.

The use of GIS is integral to the development of the decision-support tool and has a role in:

- providing spatial analytical functions for generating indicator maps of key factors influencing aquaculture potential (e.g. estimating pond-water availability, market accessibility);

- mapping out the potential for selected pond-aquaculture production systems or technologies, based on biophysical and socio-economic spatially-explicit influencing or adoption factors; and

- allowing dynamic spatial querying of the limiting factors contributing to the suitability rating of the output maps.

3. GIS modeling for resource evaluation and suitability mapping

Methodologies that have been developed to determine suitable areas for aquaculture essentially use a resource-evaluation framework modeled after the FAO land-use-evaluation approach (FAO, 1976). Generically the framework consists of the following steps:

- The key determinant factors for the target resource use (in this case, aquaculture) are identified. Early applications of aquaculture-suitability analysis started with modeling of biophysical parameters-such as climate, terrain, soil and water properties-that affect productivity (Meaden and Kapetsky, 1991). Later applications featured methodological refinements that take into consideration socio-economic factors such as prices of inputs, demand for outputs, infrastructure and technical/extension support (e.g. Aguilar-Manjarrez and Nath, 1998);

- Indicators are developed and mapped for these factors. Thresholds for the individual factors may be set based on knowledge or assumption of the underlying response-function of aquaculture potential to the determinant factor; and

- Decision-rule-based techniques are used to combine these factors to determine the potential or suitability. A commonly used technique is multi-criteria evaluation, whereby variables representing multiple criteria (i.e. the relevant factors) are included in a weighted linear combination to yield results that are interpreted as suitability ratings. The factor weights may be set in consultation with experts and stakeholders.

If implemented in a GIS modeling environment whereby the criteria are input map layers, the results are suitability maps indicating areas of differing potential for aquaculture. Geographical masks may be included in the GIS-based modeling to confine the evaluation outside of "exclusion" areas, i.e. where it is not possible for aquaculture to be carried out—such as built-up areas, national parks and forest reserves.

Evaluating the potential of technologies as complicated as pond aquaculture involves many different factors, both biophysical and socio-economic. Rather than model a single weighted linear combination of numerous factors, it is more sensible to adopt a hierarchical modeling scheme (Kapetsky, 2004). Factors are thematically grouped—for example, those influencing ease of pond construction, water availability and market access. Each thematic grouping may be separately evaluated as sub-models that produce outputs that are then combined to evaluate the overall aquaculture suitability. This approach is generically applicable within the resource-evaluation and suitability-assessment framework described above.

4. Building upon past GIS work for determining recommendation domains

In this project we adopt the basic approach of using multi-criteria evaluation for spatial analysis of the potential for aquaculture and develop nested sub-models for separately evaluating groups of factors or criteria. This corresponds well with the organization of the research in this project into thematic components that investigate the agro-ecological factors (e.g. climatic and hydrological influences on pond water availability), the socio-economic factors influencing adoption and enabling institutional factors (including accessibility to markets and extension support). These thematic components identify the key driving factors influencing the potential and adoption of target aquaculture-production systems and where possible, develop and estimate spatially-explicit indicators for these factors as sub-modules in the GIS modeling.

To be relevant for national needs, the assessment is done at sub-national level, at varying spatial resolutions for the different target areas within the four participating countries, as identified by the national partners and also taking into consideration data availability (Table 1). A sub-national focus provides opportunities for refining the methodological approaches and factor estimations of continental-scale models. To meet the requirements and challenges of determining recommendation domains as defined for the project, we identified a number of methodological refinements and software-utility enhancements that need to be developed and that build on various experiences gained with aquaculture-oriented GIS studies. These endeavors may be categorized into the four main aspects described below:

4.1 More rigorous socio-economic analysis for identification of key adoption factors

While it is widely recognized that socio-economic considerations largely dominate technology-adoption decisions by farmers, incorporating socio-economic factors into spatial modeling of aquaculture potential still faces methodological challenges. Attempts have been made to incorporate the more spatially explicit variables such as market access, availability of support services and labor availability (Salam, *et al.*, 2005 for a sub district), but geographically comprehensive data sets are generally lacking at high spatial resolution for important socio-economic variables. One of the few attempts at gathering socio-economic data for incorporating into GIS modeling of suitability was done in Mexico (Perez-Sánchez and Muir, 2003).

Table 1. Collaborating countries, related characteristics and research partners.

Country	BANGLADESH	CAMEROON	CHINA	MALAWI
Geographical coverage (area)	Whole country (147 570 km^2)	Seven southern provinces (301 540 km^2)	Henan province (160 000 km^2)	Southern Region (35 400 km^2)
Grid-cell resolution	300 m	500 m	500 m	250 m
Smallest administrative unit	Sub-district (Upazila)	Division (Département)	County	Traditional Authority
Pond-culture intensity	Extensive and improved extensive	Extensive	Semi -intensive to intensive	Extensive to semi-intensive
Pond-culture system	Poly-culture of carps; monoculture of carps, monosex tilapia and prawns	Poly-culture of carps and tilapia, integrated with agricultural activities	Shift from poly-culture to poly-culture/ monoculture	Mainly poly-culture of native tilapias and carps in integrated agriculture–aquaculture systems
Principal national partner	Department of Fisheries	Institut de Recherche en Agriculture pour le Developpement	Information Center, Chinese Academy of Fisheries Sciences	Fisheries Department
Other collaborating institution	Bangladesh Agricultural Research Council	WorldFish Center, Cameroon	Freshwater Fisheries Research Centre, Henan Fisheries Bureau	WorldFish Center, Malawi

(m—metres; km^2—square kilometers)

Socio-economic driving factors tend to be more context specific, in comparison with biophysical factors (e.g. climatic, terrain, soils) which are more universally applicable. Certain socio-economic factors may highly influence adoption of particular aquaculture production systems in a country or situation but may be irrelevant in a different context. This in fact underscores the importance of incorporating socio-economic factors in sub-national level assessments of aquaculture potential. The team of socio-economists in the project has developed a methodological framework based on the use of econometric modeling for identifying key factors for successful adoption of target aquaculture technologies at micro level, followed by development of indicators at meso level to generate geo-referenced data sets as inputs for GIS modeling.

4.2 Refining the evaluation of key factors and estimation of indicators

Estimation of spatial indicators for key influencing factors, whether biophysical or socio-economic, has its own set of research challenges and requirements for specific GIS techniques. This calls for the creative use and adaptation of models and data that have been produced for applications in other fields. Two specific examples involving GIS analysis and modeling are described below (4.2.1; 4.2.2).

4.2.1 Pond-water availability

Available pond water is a key factor especially for small-scale farms that do not have the benefit of well-organized water distribution systems. Modeling of pond-water availability developed for continental-scale estimation by Aguilar-Manjarrez and Nath (1998) is based on climatic water balance whereby accumulations from rainfall (adjusted by a run-off factor) are reduced by losses from evaporation and seepage. Constrained by data availability, the model assumes a constant run-off factor and seepage loss over space, which lacks reality.

Furthermore, in practice, water for pond aquaculture accumulates not only from direct rainfall but is tapped from accumulated surface runoff and from streams and rivers—particularly in areas with distinct topographical variation such as many parts of Cameroon and Malawi—and from rising groundwater, particularly in low-lying areas such as the deltaic floodplains of Bangladesh and the riverine floodplains of the Yellow River in Henan province of China where our studies are conducted. Indeed, we found that our preliminary estimates of the duration of water availability for fish ponds for Bangladesh are too conservative. These estimates were based entirely on climate-soil water balance.

Therefore in the modeling of pond-water availability, we identified three distinct sub-components. The first sub-component models climate-soil water-balance to estimate the time period when water in the ponds would be sufficient to support operational levels for fish culture. The second sub-component estimates the additional contribution that a rise in groundwater level provides in extending the period of available pond water. The third sub-component estimates the additional contribution from surface runoff, which is modeled using terrain analysis of watersheds. The availability of the 90-metre Shuttle Radar Topography Mission digital elevation model provides sufficient spatial resolution for such regional-level analysis. The second and third sub-components are based on hydrological analysis of potential water supply from groundwater and surface flow. Studies are on-going to adapt models developed for other applications—for example, irrigation water supply.

4.2.2 Physical accessibility

An important factor that influences the adoption of aquaculture, especially the promulgation of small-scale aquaculture in remote areas, is physical accessibility of farms to markets and sources of supplies. GIS techniques for accessibility analysis range from simple buffer analysis of roads to more sophisticated network analysis of travel distances and time. The choice of approach is largely determined by data availability. For Bangladesh, we carried out detailed estimations based on network analysis, taking advantage of the availability of a rich database of the Local Government and Engineering Department. The database includes a road inventory (the network of road types, quality and estimated travel speeds of different vehicle types) and location and types of village settlements and market facilities. These are used to compute origin–destination travel distances and times, using an approach similar to that of Castella, *et al.*, (2005). These estimates are then used for computing various accessibility indices (after Deichmann, 1997) including the equity index (the shortest travel time to the nearest facility, e.g. market), the covering index (the number of facilities that can be reached from a village within a certain time period—say one hour) and average travel time from a village to a number of facilities (for example, the two closest local markets and the sub-district headquarters).

4.3 Estimating the potential and impacts of smallholding aquaculture development

Leading on from the delineation and characterization of the spatial domains, the potential for aquaculture development within these domains will be estimated. Potential fish yields are modeled based on the agro-ecological conditions that define the aquaculture technology potential. The emphasis is on developing simple yet robust fish-yield models that can be estimated and mapped using a minimum number of parameters, rather than on developing detailed deterministic models. Most fish-yield models have been developed for individual species, while many pond-aquaculture production systems involve poly-culture of different fish species. The challenge that the yield-modeling team faces is to model and estimate yields from fish poly-culture.

Besides potential production, expected production will be estimated using available information on socio-economic conditions and prevailing or alternative scenarios of market demand, input-output delivery systems, institutional capacity for diffusion and the prevailing policy environment. If the producer profile is known, then the impacts of the anticipated production and associated benefits for different producer profiles may be estimated.

4.4 Developing user-friendly tools for implementing the GIS model and investigating the results

The project places importance on further exploratory analysis and interpretation of the outputs from GIS mapping of aquaculture potential. While it is useful to know where locations of high potential are, having user-friendly tools for querying the output maps would facilitate more in-depth interpretation that is relevant to the user. The same rating of low potential at two locations may be due to different sets of limitations. Knowing the nature of limitations at specific locations will help in determining what is needed to overcome them. Some situations may require technological solutions, while others may need socio-economic and policy interventions.

For the convenience of target users, we are customizing user-friendly interfaces to the GIS software being used to develop the decision-support system—IDRISI Kilimanjaro (IDRISI Kilimanjaro is the trademark of the Clarks Laboratory, USA.)—for such specialized queries. The query function allows the user to drill down from the output maps through the input layers to pick up the factors or criteria that are most limiting. The drill-down query of multiple map layers (i.e. the output suitability map and its component input maps) can only be conducted on a pixel-by-pixel basis 'on the fly' in IDRISI. We developed IDRISI-compatible query tools customized for global, hierarchical tracking of map values in the underlying layers that were used in producing particular outcomes of the output suitability map. This will enhance the utility of the decision-support tool for prioritizing strategies in aquaculture-development planning and management.

We are also customizing user interfaces for the IDRISI modeling tool that would allow the user to change input parameters and thresholds and rerun the multi-criteria evaluation models iteratively in an exploratory manner. Hence users can assess aquaculture potential based on their own entries of factors and the weights they place on each factor to reflect different scenarios of technological and other interventions (e.g. improvements to market access and advisory services). The development of the user-friendly interfaces is to encourage use of the decision-support tool by subject specialists who are not conversant with GIS software. To the extent possible, selected components of the GIS-based modeling and query tools will be web-enabled for wider user access.

5. Design considerations

The aquaculture planning context within which the decision-support tool is intended to serve has implications for the tool's conceptualization and design—it needs to be able to handle multidisciplinary components of modeling. GIS provides the spatial context as well as a platform for integrative analysis and modeling. However as many important adoption factors, particularly socio-economic variables, are either not explicitly spatial or impractical to map, characterization of the recommendation domains is not entirely spatial. Therefore, one major design consideration is to ensure that GIS component of the decision-support tool links well with other non-spatial aspects of the decision-support system, e.g. evaluating the enabling institutional factors for aquaculture adoption.

End users who are unfamiliar with GIS software prefer that the decision-support system is easy to use but at the same time expect the models to be sufficiently sophisticated in representing real-world problems. There is a trade-off between providing analytical versatility and customizing user-friendly interfaces. The development of the GIS-based enhancement tools described above has been made in the context of the following considerations (5.1-5.4).

5.1 Modular approach

The GIS modeling needs to be carried out in an incremental and modular manner, tailored for different levels of analytical complexity. This modularity gives the flexibility for the addition of components to accommodate increasing complexity in the modeling as needed. This flexibility also allows the user to include or omit modules to suit different case-study needs and situations of data availability.

5.2 Linkage with non-spatial characteristics

The GIS models need to be coupled with other non-spatial modeling and analytical components to facilitate the transfer of analyzed outputs.

5.3 Querying results

Simple-to-use query tools are needed to facilitate the tracking and the analysis of limiting factors that contribute to the suitability ratings of the output maps.

5.4 User-friendly interfaces

To encourage the target users (planners/extensionists) to use the decision-support tool, the GIS modeling tool needs to be easy to manipulate, especially for repeated evaluations using different input parameters in the model.

6. Operational considerations

Emphasis is placed on the involvement of target users in the development of the decision-support system in order that the project produces relevant outputs that they will continue to use. From the early stages of the study, national partners and stakeholders are involved in identifying the target study areas and aquaculture technologies and the corresponding data requirements. Data gathering, processing and analysis within the component disciplines in this multi-disciplinary study are carried out by subject specialists comprising national and international partners. The availability of data at the corresponding spatial scales is uneven across sectors and countries; hence, sourcing the relevant data and reconciling spatial data from disparate sources are major tasks in the project and the involvement of national partners is crucial. In the process, national partners receive training on specific methodologies and techniques that are new to them. At various stages of the modeling, target stakeholders are consulted for providing local expert knowledge as well as feedback on model results and their interpretative analysis.

7. Conclusions

Adapting continental-scale aquaculture-potential assessment approaches to sub-national-scale evaluation involves more than refining the mapping scale. While the generic resource-evaluation framework still applies, many of the methodological approaches developed for continental-scale evaluation—whereby generic indicators that are applicable and comparable across countries are used—would not be suitable at sub-national level. By necessity, higher-resolution data are required for sub-national assessments. Accordingly, to be meaningful, modeling and estimation of key factors need refinement as well—hence our attempts at a more rigorous assessment of pond-water availability that takes into account terrain conditions and hydrological processes and our focus on socio-economic modeling to identify key adoption factors.

Also at the sub-national level, relevance to specific conditions and national priorities assume a greater importance. In the case of small-scale aquaculture development for poverty alleviation and livelihood improvement, strategic issues relate less to finding suitable locations but more to understanding what limitations occur where and what it takes to enhance the potential by overcoming the limitations to encourage adoption by new and existing pond operators. Suitability maps indicating potential (or lack of potential) per se are of limited use. However, the map outputs, the accumulated knowledge base and the tools can further serve and support strategic decision making for aquaculture planning and development—hence our emphasis on active engagement of national partners and building their capacity and our attempts at making the GIS-based decision support system user-friendly without compromising its analytical power.

Acknowledgments

We acknowledge the funding support of the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH to the project.

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