GIS-based models for the development of sustainable aquaculture of native fish species in central Mexico: a catchment level approach for the protection of biodiversity.

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for the degree of Doctor of Philosophy

by

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STATEMENT OF ORIGINALITY

I herby confirm that this is an original piece of work conducted independently by the undersigned and all work contained here has not been submitted for any other degree.

All research material has been duly acknowledge and cited.

Signature of Candidate

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Victor Manuel Peredo Alvarez

Date: 31st March 2011

To my Mom and Dad for always believe in me;

all I am is thanks to you.

And

To my lovely wife Elisa and my niece Renata;

you are my inspiration.

ABSTRACT

Over the last 3 decades, freshwater aquaculture has become one of the most important food industries. However the constant introduction of a reduced number of very successful species for aquaculture has been identified as one of the main activities related to the alarming decline of fish biodiversity worldwide. This issue has raised awareness amongst the scientific community, governmental authorities and the general public towards freshwater fish biodiversity. This new awareness has promoted the development of “green” markets and environmentally friendly strategies, aiming for a reliable production of protein sources. The development of native species aquaculture has been presented as a strong alternative for sustainable aquaculture and the protection of biodiversity. However, it seems clear that unplanned native species aquaculture developments can be as detrimental on local biodiversity as the introduction of exotic fish, if not more dangerous. Therefore, the advantages and disadvantages of native species aquaculture have to be clearly analysed before any aquaculture development.

This study aimed to establish a philosophical background regarding the use of native fish species in aquaculture in contrast to the introduction of exotic species that may compete for a similar niche as food in local markets. The main ecological impacts that exotic fish species may have on natives, such as competition, predation, and hybridization were discussed. In addition, a well planned native species Aquaculture Strategy for the Protection of Biodiversity was produced, at catchment level, within a Geographic Information System (GIS).

For the development of the native species aquaculture strategy in central Mexico, four species of Atherinids (*Chirostoma estor, C. Jordani, C. promelas* and *Atherinella balsana*) and two species of native Ictalurids (*Ictalurus balsanus* and *Ictalurus dugesii*) were included in this study. These six species are relatively new to aquaculture and they were selected on the basis of their importance in local fisheries and markets in their native basins of the Lerma-Santiago and Balsas rivers. Both of these basins are of great importance in central Mexico, not only because of their biodiversity but also because of their high human population densities and socio-economic status.

The use of Geographic Information Systems was a fundamental factor in the development of the native species aquaculture strategy at catchment level, consisting of site suitability models (SSM) for each species in their corresponding native catchments. Overall, SSM identified 13,916 km^2 and 11,178 km^2 highly suitable for aquaculture of the studied Atherinids and Ictalurids respectively, based on Water, Soil and Terrain, Infrastructure and Risk sub-models.

A set of predictive species distribution models (PSDM), which related ecological characteristics for each studied species with relevant environmental and topographic parameters into a GIS, were also produced. Such models were developed for the establishment of potential natural ranges of distribution for each species, as well as their potential to become exotic in new environments, as a potential for invasion model (PI). Based on a partial verification, both PSDM and PI models produced results that were satisfactorily consistent with the known distribution of each modelled species.

The combination of SSM and PSDM produced an Aquaculture Strategy for the Protection of Biodiversity model (ASPB) which identified the most environmentally friendly suitable areas for aquaculture sites. In contrast, the combination of the SSM with PI models into an ASPB model identified the site suitability potential for non-native species that are genetically close to native ones, in an attempt to reduce the known impacts that exotic species have on local biodiversity. In this way the ASPB model identified 7,651 km^2 suitable for aquaculture of *I. balsanus* in its native Balsas basin and 15,633 km^2 suitable for aquaculture of the non-native *I. dugesii.* ASPB models were produced for all the studied species.

The final results were used to produce a set of guidelines for the development of sustainable aquaculture of native species at catchment level that cover genetic and ecological implications, as well as a well planned decision making tool produced in a GIS.

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Introduction to the use of GIS for the development of native fish species aquaculture: a case study in central Mexico.

1.1 General Introduction

Aquaculture has established itself as the strongest animal agriculture industry in the world (Noga, 2011). According to the Food and Agriculture Organization (FAO, 2009) the global production from aquaculture was 64,065,357 tonnes in2008, and more than 31 thousand tonnes, almost 50%, was obtained from freshwater aquaculture (FAO, 2009). Freshwater aquaculture production has been led by Asia which in 2008 was the continent with the largest production at 28,068,676 t, more than 80% of the world total (FAO, 2009). Aquaculture in Latin America falls way behind Asia with a total production of 1,754,059 tonnes, out of which only 23 % was produced by freshwater aquaculture (CONAPESCA 2009; FAO, 2009). In Latin America the most successful industries are in Chile for marine aquaculture and in Brazil for freshwater aquaculture (Table 1.1). Mexico has the third biggest marine aquaculture industry behind Chile and Peru, whilst it is 24th in terms of freshwater aquaculture (FAO, 2009).

According to the FAO statistics (2009) aquaculture grew more than 11,500% between 1950 and 2008. It seems clear that aquaculture’s growth follows the trend set by the increasing population worldwide. According to the Population Reference Bureau (PRB, 2008), human population rose three times in nearly 60 years, reaching 6.7 billion people by 2008. Current estimates are that world population will reach between 9.15 billion and 9.51 billion people by 2050 (Bremner, 2010). This means

that consumption growth will increase even more and with it the global demand for food, over at least the next 40 years (Godfray *et al*., 2010).

Table 1.1 Leaders of Aquaculture production in Latin America

Place	Country	Aquaculture	Species	Production (tones)
1	Chile	Marine	Diadromous fishes	627950
2	Chile	Marine	Molluscs	212,210
3	Brazil	Freshwater	Freshwater fishes	208,706
4	Ecuador	Brackish water	Crustaceans	150,000
5	Mexico	Marine	Crustaceans	124,701
6	Brazil	Marine	Crustaceans	65,000
7	Colombia	Freshwater	Freshwater fishes	45,100
8	Cuba	Freshwater	Freshwater fishes	27,771
9	Honduras	Brackish water	Crustaceans	26,586
0	Ecuador	Freshwater	Freshwater fishes	22,000
:				
24	Mexico	Freshwater	Freshwater fishes	5,631

Adapted from FAO (2009)

The need for reliable sources of food can be reflected in the dramatic change in land use for agriculture, which has accounted for the transformation of nearly

50% of the world's land into grazed land or cultivated crops (Kareiva *et al.,* 2007). Aquatic habitats are also affected by land change, since thousands of hectares of mangroves worldwide have been transformed into milkfish and shrimp ponds (Naylor *et al*., 2000). As a result of this extensive land use conversion, both on land and in water, massive losses in biodiversity can be observed, which may also reflect severe consequences to ecosystem services (Naylor *et al*., 2000; Ranganathan *et al.,* 2008).

One of the main activities that are affecting ecosystem services in aquatic habitats is overfishing. Fishing has caused a general decline in fish biomass, and it is now thought that about 25% of world's fisheries are depleted (Cheung *et al*., 2007; Grafton, 2007). According to Jackson *et al*., (2001) overfishing accounts for more ecological extinctions than any other anthropogenic activity related to coastal ecosystems, including pollution, degradation of water quality, and climate change.

Another way in which ecosystems have been affected by the expansion of the food industries is the introduction of species that potentially provide both a faster and bigger production. This has been noticed in the increasing number of exotic species introduced and the use of genetically improved stocks (FAO, 2009). Aquaculture and fisheries are the two principal activities involved in the introduction of exotic species in aquatic systems. These introductions have played a particularly important role in the development of freshwater aquaculture. For example, tilapia and carp are amongst the most extensively used species in freshwater aquaculture (Frei *et al*., 2006; De Silva *et al*., 2006) and the production of these two species was more than 80% of the global freshwater fish production in 2008 (FAO, 2010). In Latin America, production also increased as a consequence of the decline in local fisheries (Alceste *et al*., 2002). However, the main explanation for the use of tilapia and carp is the importation of a known technology, their high growth rates, adaptability to a range of environments and low cost of production (el-Sayed, 2006; Poot-Lopez *et al*., 2010).

Deliberate introductions of carps and tilapia, and escapes from aquaculture sites have contributed to their establishment in almost every water body in the world (Singh *et al*., 2010). As a matter of fact, fish escapes are one of the main routes for introduction of non-native fish (Naylor *et al*, 2005). The introduction of exotic species is an issue that has raised awareness amongst the scientific community and conservation organisations and introduction of exotic species is considered to be one of the main forces in the reduction of diversity and the change in freshwater systems dynamics (Zambrano *et al*., 2006).

Exotic species can affect biodiversity in different ways. Their presence is a known factor for the change in community composition affecting ecosystem goods or services by directly reducing abundances of useful species (Stuart *et al*., 2000). The most common causes for the reduction of biodiversity are competition, predation and hybridization (Vitule *et al*., 2009). Ironically, most of these introductions are economically driven, although they can simultaneously affect the economic interests of fishing communities by reducing local fish fauna (Perez *et al*, 2003). However, it is believed that the trend of exotic species introductions can be expected to continue as the food demand continues increasing (Gozlan, 2008).

The use of native species in aquaculture has been suggested as an alternative to the introduction of exotic species (Perez *et al*., 2000). This idea suggests that native species can present less danger for wild populations (Vitule *et al*., 2009). This supposition, however, is not accepted by the entire scientific community (Gozlan, 2010). One of the major risks in the use of native species could be the reduction of the natural genetic pool by improved lines (Bekkevold *et al*., 2006). However the dramatic loss of fish biodiversity and the increasing demand for food supply have created a paradox between protection of biodiversity and the much needed increase in production (Silva *et al.,* 2009). This demands actions and solutions that would benefit both sectors and the use of native species under a well planned development strategy, seem to be an excellent approach.

In Mexico, aquaculture is dominated by the production of shrimp and non-native tilapia, carp, trout and catfish (CONAPESCA, 2010). The production of tilapia in 2009 was 73,373 tonnes, just behind shrimp production which was 133,282 tonnes in the same year (CONAPESCA, 2010). However native species aquaculture is almost non-existant. Since 1992, the National Commission for the Use and Understanding of Biodiversity (CONABIO) has been promoting the development of strategies for the sustainable use of biodiversity in Mexico. One of their main goals is the development of management tools for the use of the native resources (CONABIO, 2011). Although aquaculture of native species in Mexico has been encouraged by CONABIO, better management tools are required for the development of aquaculture with the capability to include a varied amount of data related to site selection, risk assessment and conservation.

1.2 Aquaculture Planning and Development in central Mexico

In order for aquaculture to satisfy the growing market demand in a sustainable way, it needs to be managed in ways that are designed to reduce negative impacts on biodiversity (Godfray *et al.,* 2010). The aquaculture of native species represents a solid opportunity to produce enough food for the world population in a more sustainable way (Perez, *et al.,* 2003). To provide solid ground for the development of native species aquaculture in Mexico, this project aimed to develop an Aquaculture Management Strategy for the sustainable use of native species at catchment level within a Geographic Information System.

1.3 Geographic Information Systems

Geographic Information Systems (GIS) are becoming essential tools for management in a great variety of disciplines (Boroushaki and Malczewski, 2010; Anagnostopoulus, 2010; Ehrogtt, 2010). One of its most powerful advantages is its capability to integrate a large amount of information, from different sources and backgrounds into a relatively easy to access system. Arguably site selection models are the most extensively used in GIS for aquaculture; they have been used in marine aquaculture (Ross *et al*., 1993; Pérez *et al*., 2005; Benetti *et al*., 2010), shrimp aquaculture (Salam *et al*., 2003, Hossain and Das, 2010) and freshwater aquaculture (Salam *et al*., 2005; Hossain *et al*., 2007; Ross *et al*., 2010). Site suitability models are powerful tools essential during the planning stages (Longdill *et al*., 2008). They enhance the capability of the decision maker to find the most suitable areas for the development of aquaculture. This is an essential factor for the sustainability of the site (Ross & Beveridge, 1995).

In conservation, GIS is playing a special role. The use of GIS for the prediction of species distribution is known as ecological-niche modelling, a tool with great potential for conservation (Peterson, 2003). Maps of potential distribution use statistical models in combination with GIS to predict the distribution of species (Guisan and Zimmerman, 2000). These models have significant potential for management and conservation of natural resources (Brotons *et al*., 2004). Ecological-niche modelling has been widely used to investigate the effect of climate change on distribution of species, potential areas for species reintroductions, probability of invasion by exotic species and it has also been used to prioritise areas for the conservation of biodiversity (Thomas *et al*., 2004; Martinez-Meyer *et al*., 2006; Peterson *et al*., 2003; Thuiller *et al*., 2005; Ficetola *et al*., 2007; Scot *et al*., 1993; Pearce and Ferrier 2001; Olden *et al*., 2002; Graham *et al*., 2004; Dietz and Czech, 2005; Peterson 2006).

1.4 Modelling framework

The aquaculture management strategy for the development of native species aquaculture in central Mexico, presented in this research, has as geographic target of the basins of the rivers Lerma and Santiago as a single hydrological system (INEGI, 2011) and the basin of the Rio Balsas.

These two catchments are amongst the most important ecological regions in Mexico (CONABIO, 2011). The Lerma-Santiago basins are rich in biodiversity, and in terms of ichthyofauna are particularly recognised for the abundance of native silversides (Miller *et al*., 2005). This area is highly populated and contains an excessive number of industries and highly developed intensive agricultural land which have all contributed to the deterioration of the environment (SEMARNAT, 2008).

The basin of the Balsas is one the biggest catchments in Mexico. Due to its rugged terrain it has a low population density; however its waters are amongst the most polluted in the country (CONAGUA, 2008).

Native species aquaculture in this part of Mexico is of great interest and has been producing some interesting results (Martinez-Palacios *et al*., 2008). Endemic silversides are abundant in central Mexico (Lerma-Santiago basins) but are under severe environmental and fishing pressure (Martínez-Palacios, 2004). Due to their high economic, social, cultural and ecological value, there have been several attempts to establish aquaculture of native silversides but with slow progress (Olvera-Blanco *et al*., 2009) and this production is still in its pilot stages. Probably the greatest achievement in aquaculture of native silversides in Mexico has been observed in the aquaculture of *Chirostoma estor*, the Patzcuaro silverside (Alarcon-Silva *et al*., 2009; Martínez-Palacios *et al*., 2002).

Other species that are of interest for aquaculture in Mexico are native catfish. The strongest catfish aquaculture industry in Mexico is based on *Ictalurus punctatus* which is mainly produced in the northern state of Tamaulipas (Sanchez-Martínez *et al*., 2007). *I. punctatus* is naturally distributed from southern Canada through central United States between the Rocky and

Appalachian mountains, to the east of Mexico (Chihuahua, Chahuila, Nuevo Leon, Tamaulipas and Veracruz), but has been introduced into the basins of the river Lerma, Santiago and Balsas for aquaculture purposes (Miller *et al*., 2005; UMMZ, 2011).

The overall objectives of this study were:

- To develop a systematic methodology based on spatial modelling in order to provide an efficient instrument for planning the development of sustainable native species aquaculture.
- To develop an aquaculture management strategy for native species using an integral approach based on catchment systems.
- To construct an information system that can be consulted, analysed, updated and modelled in order to ensure adequate decision-making, and investments on aquaculture.

The present work was set to develop flexible tools for the sustainable management of native species at catchment level in central Mexico. The following chapters are presented in a publication-ready format. In those chapters the problematic relationships between conventional aquaculture and biodiversity were addressed, and a potential tool for management planning was presented. In Chapter 2 a detailed description of the study area will provide a clear understanding of the region and why it is important to implement sustainable management tools there. Chapter 3 contains the description of the construction process for the Native Fish Aquaculture database, including advantages and problem solving. Then in chapter 4, a complete discussion regarding the use of exotic species and the advantages of native species aquaculture is presented. Chapter 5 explores the use of GIS in site selection and decision making process, essential step for sustainability of the site. Also, in chapter 6 the use of predictive distribution models is presented. Chapter 7 integrates the models presented in chapters 5 and 6, in order to produce an Aquaculture Strategy for the Protection of Biodiversity, finally concluding with a general discussion in chapter 8.

References

Alceste, C.C., Illingworth, J.A., and Jory, D.E. 2001. Tilapia farming industry in Ecuador. *Aquac. Mag*. **27**: 77–82.

Aguilar-Manjarrez, J. & Ross, L.G., 1995. Geographical information system (GIS) environmental models for aquaculture development in Sinaloa State, Mexico.quaculture International, **3**:103-115.

Brotons, L. *et al.,* 2004. Presence-absence versus presence-only modelling methods for predicting bird habitat suitability. *Ecography*, **27**:437-448.

Chapin III, F.S. *et al*., 2000. Consequences of changing biodiversity. *Nature*, **405**:234-242.

Cheung W.W.L. Watson R. Morato T. Pitcher T.J. & Pauly D. 2007. Intrinsic vulnerability in the global fish catch. *Marine ecology Progress Series*. **333**: 1-12

CONAGUA. 2011. Available at: http://www.cna.gob.mx/LermaWeb/ [Accessed: March 22-2011].

CONAPESCA. 2010. Anuario 2009. Available at: http://www.conapesca.sagarpa.gob.mx/wb/cona/anuario_2009_capitulo_i_preliminar [Accessed: March 24-2011]

CONABIO. 2011. Available at: http://www.conabio.gob.mx/ [Accessed: 18-January 2011]

Bekkevold, D., M. Hansen, and E. Nielsen. 2006. Genetic impact of gadoid culture on wild fish populations: predictions, lessons from salmonids, and possibilities for minimizing adverse effects. ICES *Journal of Marine Science* **63**:198-208.

Benetti, D.D. *et al.,* 2010. Site Selection Criteria for Open Ocean Aquaculture. *Marine Technology Society Journal*, **44**:22-35.

Bremner J *et al*. 2010 http://www.prb.org/pdf10/65.2highlights.pdf

Brotons, L. *et al*., 2004. Presence-absence versus presence-only modelling methods for predicting bird habitat suitability. *Ecography*, **27**:437-448.

Dietz, R.W. & Czech, B., 2005. Conservation Deficits for the Continental United States: an Ecosystem Gap Analysis. *Conservation Biology*, **19**:1478-1487.

Egoh, B. *et al*., 2007. Integrating ecosystem services into conservation assessments: A review. *Ecological Economics*, **63**:714-721.

El-Sayed, A.-F.M., 2006. Tilapia culture, CABI.

Ficetola, G.F., Thuiller, W. and Miaud C. 2007. Prediction and validation of the potential global distribution of a problematic alien invasive species- the American bullfrog. *Diversity and Distributions*. **13:** 476-485.

Frei, M. *et al*., 2007. Performance of common carp, *Cyprinus carpio* and Nile tilapia, *Oreochromis niloticus* in integrated rice-fish culture in Bangladesh. *Aquaculture*, **262**:250-259.

Godfray, H.C.J. *et al*., 2010. Food Security: The Challenge of Feeding 9 Billion People. *Science*, **327**:812 -818.

Grafton, R.Q., Kompas, T. & Hilborn, R.W., 2007. Economics of Overexploitation Revisited. *Science*, **318**:1601.

Graham, C.H. *et al*. 2004. New developments in museum-based informatics and applications in biodiversity analysis. *Trends in Ecology & Evolution*, **19**:497-503.

Gozlan, R. E., J. R. Britton, I. Cowx, and G. H. Copp. 2010. Current knowledge on non-native freshwater fish introductions. *Journal of Fish Biology* **76**:751-786.

Gozlan, R. E. 2008. Introduction of non-native freshwater fish: is it all bad? *Fish and Fisheries* **9**:106-115.

Guisan, A. & Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. *Ecological Modelling*, **135**:147-186.

Hossain, M.S. *et al.,* 2007. Multi-criteria evaluation approach to GIS-based land-suitability classification for tilapia farming in Bangladesh. *Aquaculture International*, **15**:425-443.

Hossain, M.S. *et al.,* 2009. Integration of GIS and multicriteria decision analysis for urban aquaculture development *in Bangladesh. Landscape and Urban Planning*, **90**:119-133.

Hossain, M.S. & Das, N.G., 2010. GIS-based multi-criteria evaluation to land suitability modelling for giant prawn (*Macrobrachium rosenbergii*) farming in Companigonj Upazila of Noakhali, Bangladesh. *Computers and Electronics in Agriculture*, **70**:172-186.

Jackson, J.B.C. *et al*., 2001. Historical Overfishing and the Recent Collapse of Coastal Ecosystems. *Science*, **293**:629 -637.

Kareiva, P. *et al*., 2007. Domesticated Nature: Shaping Landscapes and Ecosystems for Human Welfare. Science, **316**:1866 -1869.

Longdill, P.C., Healy, T.R. & Black, K.P., 2008. An integrated GIS approach for sustainable aquaculture management area site selection. *Ocean & Coastal Management*, **51**:612-624.

Martínez-Meyer, E. *et al*., 2006. Ecological Niche Modelling and Prioritizing Areas for Species Reintroductions. *Oryx*, **40**:411-418.

Martínez-Palacios, C.A. *et al*., 2008. Developments in the nutrition of *Menidia estor* Jordan 1880. *Aquaculture Research*, **39**;738-747.

Miller, R.R., Minckley, W.L. & Norris, S.M., 2005. Freshwater Fishes of Mexico. *University of Chicago Press*.

Naylor, R.L. *et al*., 2000. Effect of aquaculture on world fish supplies. *Nature*, **405**:1017-1024.

Noga, E.J., 2010. Fish Disease: Diagnosis and Treatment, John Wiley and Sons.

Olden J.D. Jackson D.A. and Peres-Neto P.R. 2002. Predictive Models of Fish Species Distributions: A Note on Proper Validation and Chance Predictions. *The American Fisheries Society*. **131**: 329-336.

Pearce, J. & Ferrier, S., 2001. The practical value of modelling relative abundance of species for regional conservation planning: a case study. *Biological Conservation*, **98**:33-43.

Perez, J E., C. Alfonsi, M. Nirchio, C. Muñoz, J. A. Gómez. 2003. The introduction of exotic species in aquaculture: a solution or part of the problem? *Interciencia*, **28**:234-238. ISSN 0378-1844.

Pérez, O.M., Telfer, T.C. & Ross, L.G., 2005. Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. *Aquaculture Research*, **36**:946-961.

Peterson, A.T., 2003. Predicting the Geography of Species' Invasions via Ecological Niche Modelling. The Quarterly Review of Biology, **78**:419-433.

Peterson, A., 2006. Uses and Requirements of Ecological Niche Models and Related Distributional Models. Available at: https://journals.ku.edu/index.php/jbi/article/viewArticle/29 [Accessed March 13, 2011]

Poot-López, G.R., Hernández, J.M. & Gasca-Leyva, E., 2010. Input management in integrated agriculture-aquaculture systems in Yucatan: Tree spinach leaves as a dietary supplement in tilapia culture. *Agricultural Systems*, **103**:98-104.

Ranganathan, J. *et al*., 2008. Sustaining biodiversity in ancient tropical countryside. *Proceedings of the National Academy of Sciences*, **105**:17852 -17854.

Ross, L.G. & Beveridge, M.C.M., 1995. Is a better strategy necessary for development of native species for aquaculture? A Mexican case study. *Aquaculture Research*, **26**:539-547.

Ross, L.G., Martinez Palacios, C.A. & Morales, E.J., 2008. Developing native fish species for aquaculture: the interacting demands of biodiversity, sustainable aquaculture and livelihoods. *Aquaculture Research*, **39**:675-683.

Ross, L.G. *et al*., 2010. Spatial modelling for freshwater cage location in the Presa Adolfo Mateos Lopez (El Infiernillo), Michoacán, México. *Aquaculture Research*.

Salam, M.A., Ross, L.G. & Beveridge, C.M.M., 2003. A comparison of development opportunities for crab and shrimp aquaculture in southwestern Bangladesh, using GIS modelling. *Aquaculture*, **220**:477-494.

Salam, M., Khatun, N. & Ali, M., 2005. Carp farming potential in Barhatta Upazilla, Bangladesh: a GIS methodological perspective. *Aquaculture*, **245**:75-87.

Sánchez-Martínez, J.G. *et al*., 2007. First detection of channel catfish virus associated with mortality of cultured catfish (*Ictalurus punctatus*, Rafinesque) in Mexico. *Aquaculture Research*, **38:**1428-1431

Scott, J.M. *et al.,* 1993. Gap Analysis: A Geographic Approach to Protection of Biological Diversity. *Wildlife Monographs*, (123): 3-41.

SEMARNAT. 2008. Statistics on Water in Mexico. Pp. 229. Available at: http://www.conagua.gob.mx/english07/publications/SGP-20StatisticsLow.pdf [Accessed : March 01-2011]

Silva, S. S. D., T. T. T. Nguyen, G. M. Turchini, U. S. Amarasinghe, and N. W. bery. 2009. Alien Species in Aquaculture and Biodiversity: A Paradox in Food Production. *AMBIO: A Journal of the Human Environment* **38**:24-28.

da Silva, L.B. *et al*., 2006. Alternative species for traditional carp polyculture in southern South America: Initial growing period. *Aquaculture*, **255**:417-428.

Singh A.K. Pathak A.K. & Lakra W.S. Invasion of an Exotic Fish- Common Carp, *Cyprinus carpio* (Actinopterygii: Cypriniformes: *Cyprinidae*) in the Ganga River, India and its Impacts

Stuart, V., Platt, T. & Sathyendranath, S., The future of fisheries science in management: a remote-sensing perspective. ICES Journal of Marine Science: Journal du Conseil. Available at: http://icesjms.oxfordjournals.org/content/early/2011/01/17/icesjms.fsq200.abstract [Accessed 16:49:10].

Taylor, D.A., 2009. Aquaculture Navigates Through Troubled Waters. , 117(6), p.A252-A254. Thomas, C.D. *et al.,* 2004. Extinction risk from climate change. *Nature*, **427**:145-148.

Thuiller, W. *et al.,* 2005. Niche-based modelling as a tool for predicting the risk of alien plant invasions at a global scale. *Global Change Biology*, **11**:2234-2250.

UMMZ. 2011. Available at: http://www.ummz.lsa.umich.edu/fishes/index.html [Accessed: March 10-2011]

Vitule, J. R. S., C. A. Freire, and D. Simberloff. 2009. Introduction of non-native freshwater fish can certainly be bad. *Fish and Fisheries* **10**:98-108.

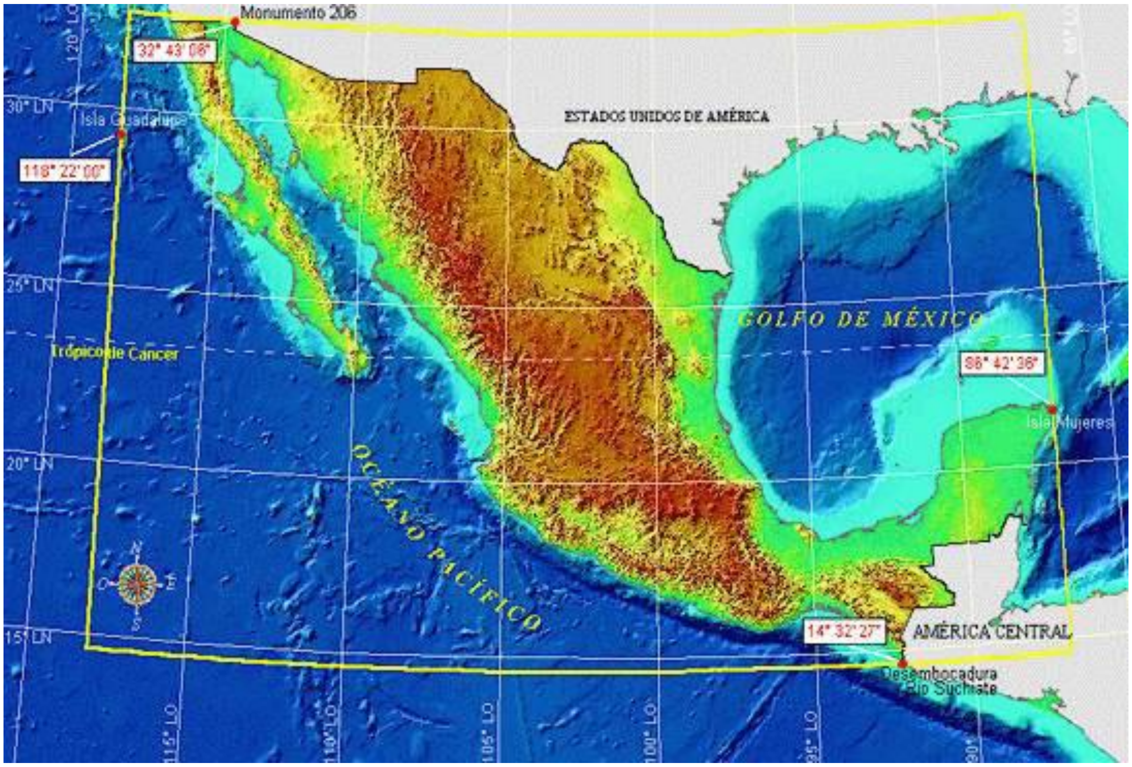
Zambrano, L. *et al*., 2006. Invasive potential of common carp (*Cyprinus carpio*) and Nile tilapia (*Oreochromis niloticus*) in American freshwater systems. Canadian *Journal of Fisheries and Aquatic Sciences*, **63**:1903-1910.

Chapter 2

Studied Area

2.1 Geographic location of Mexico

The Mexican territory is bounded at the South by the coordinates 14° 32´ 27´´ N, at the outlet of the Rio Suchiate on the border with Guatemala; at the North by the coordinates 32° 43´ 06´´ N at the Monument 206 in the border with the United States of America; at the East 86° 42´ 36´´ W, at the southern point of Isla Mujeres; and West by the coordinates 118° 22´ 00´´ W at the “Roca el Elefante” (the Elephant Rock) in the Island of Guadalupe on the Pacific Ocean (INEGI 2011) (fig. 2.1).



INEGI: www.inegi.org.mx

Figure 2.1 Geographic location of Mexico.

The republic of Mexico is divided into 31 states and one Federal District, which is Mexico City (INEGI 2006). Based on its hydrology the Mexican territory is divided into 30 hydrologic regions (HR), which are formed by basins with similar superficial drainage (INEGI 2011 b). For the purpose of this study the area of interest is based on two of the most important hydrological regions, the constituted by the Lerma-Santiago basins (HR 12) and the Balsas basin (HR 18). According to SEMARNAT (2008) two thirds of Mexico's gross Domestic Product (GDP) is concentrated in the Hydrologic systems of the Valley of Mexico, Rio Bravo, Lerma-Santiago and Balsas.

2.2 Lerma-Santiago basins

The hydrologic system number 12, formed by the Lerma-Chapala and Grande de Santiago basins is located between the coordinates 19°03' N and 21°32' N latitude, and 99° 18' W and 03° 46' W longitude. The two basins are connected by the Chapala Lake with a combined catchment area of 116,649 km^2, which represents 16.6% of the national territory (Alcocer and Bernal-Brooks 2010).

The basin of Lerma-Chapala is located in central Mexico along the Mexican Volcanic Belt (FEOW 2011) and crosses the states of Querétaro, Guanajuato, Michoacán, Mexico and Jalisco (Wester et al., 2003) (Fig. 2.2). The basin of the Rio Grande de Santiago lies on the Pacific coast and covers the states of Durango, Nayarit, Jalisco, Zacatecas, Aguascalientes and Guanajuato (INEGI 2011) (Fig. 2.3). Its topography is defined by the mountain chains of the Sierra Madre Occidental and the Trans-Mexican Volcanic belt.

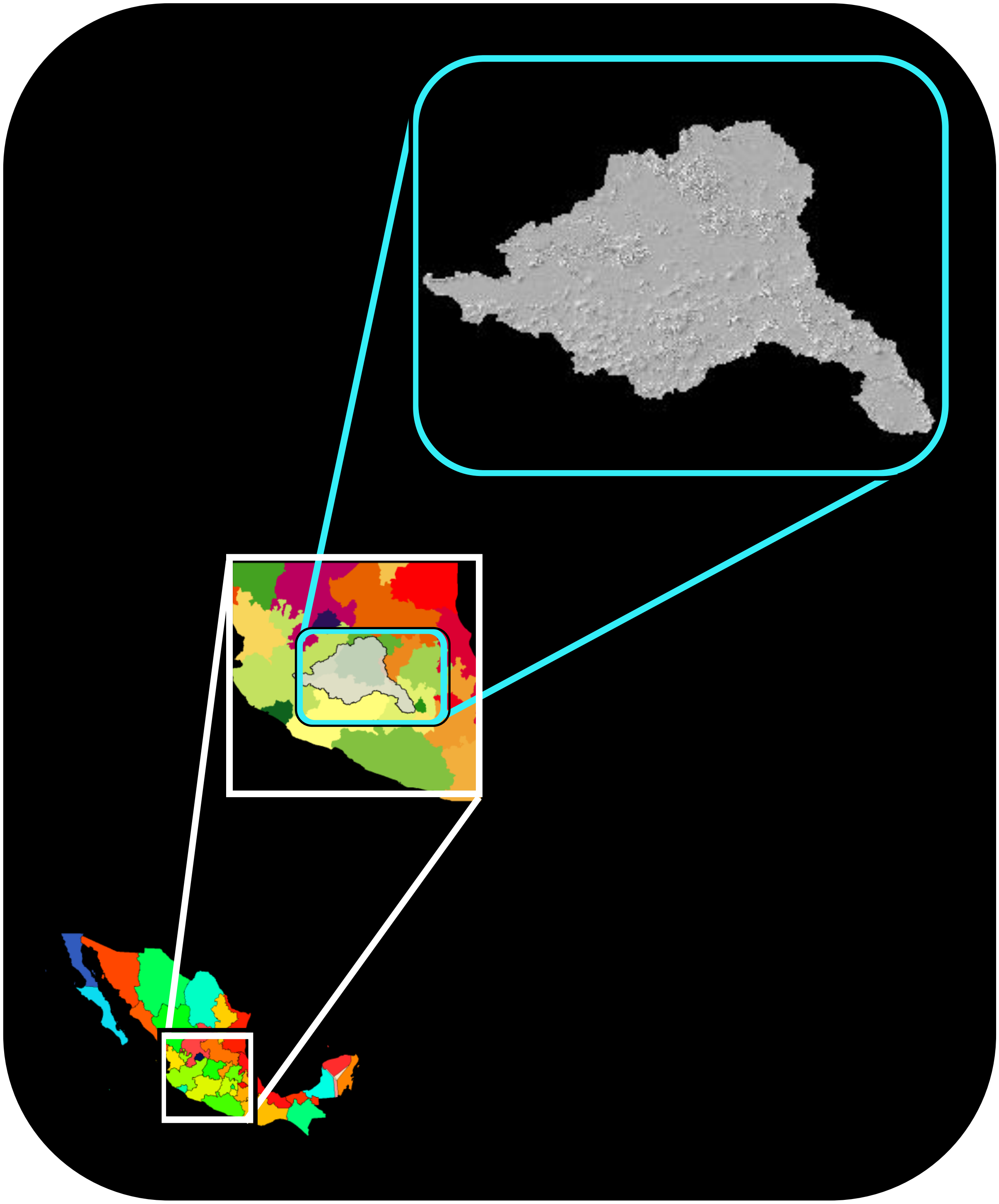


Figure 2.2: The Lerma-Chapala basin in central Mexico. The Basin crossess the states of Querétaro, Guanajuato, Michoacán, Mexico and Jalisco.

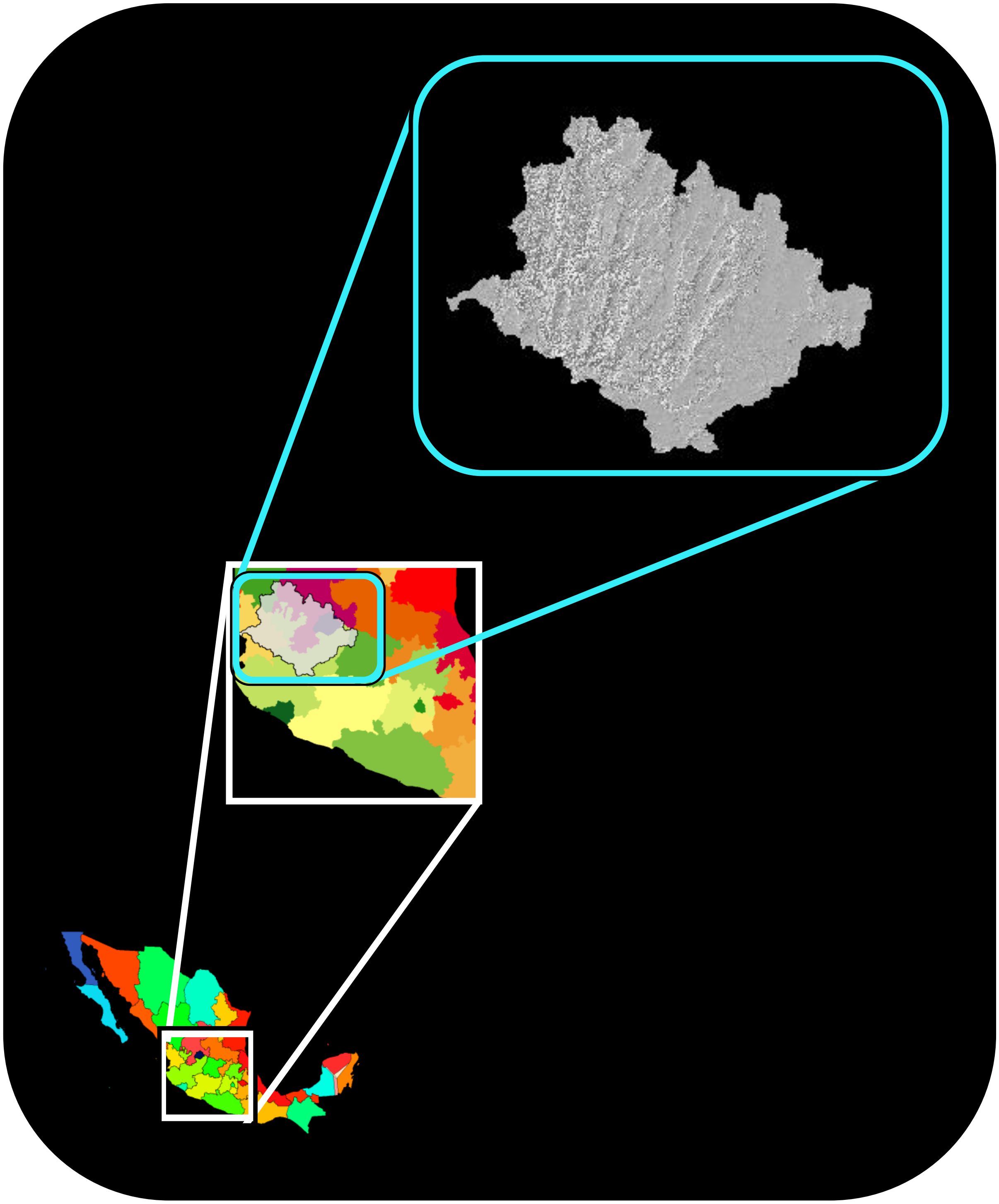


Figure 2.3: The Santiago basin in central Mexico. The Basin crossess the states of Jalisco, Zacatecas, Aguascalientes and Nayarit

The Lerma-Santiago hydrologic system is the second most populated in the country, with more than twenty million inhabitants in 2007, just behind the Valley of Mexico (21,090,206 inhabitants) (SEMARNAT 2008).

2.2.1 Main water resources of the Lerma-Santiago basins.

The Rio Lerma begins its flow at 3,000 m above sea level (masl) at the southeast of Toluca City, in the Central Plateau of Mexico, and it flows through the states of Guanajuato, Michoacan, Jalisco, Mexico and Queretaro (CONAGUA, 2011). The length of the river is more than 700 km and is divided into three subprovinces: the Alto (upper), Medio (middle) and Bajo (lower) lerma (Diaz Pardo et al., 1993). Its main tributaries are the Rio de la Laja, Rio Apaseo, and Rio Turbio (CONAGUA, 2011).

The Lerma-Chapala basin’s contain 40 water bodies of which the main Lakes are the main water bodies are the Lakes Cuitzeo, Patzcuaro, Sirahuen, Chalco, Yuriria and of course Lake Chapala (Schoendube et al., 2002; Cotler, 2004; Levine, 2007) (Table 2.1).

The Rio Lerma ends at Lake Chapala (1,510 masl) (Fig 2.4), which is the biggest natural water body in Mexico, shared by the states of Jalisco and Michoacán (FEOW, 2011). The lake is located between 20°07’ and 20°20’ N and between 102°42’ and 103°25’ N. It has a surface area of approximately 1,100 km^2 and an average depth of 4.5 m (Trujillo-Cardenas et al., 2010). The outlet of the Chapala Lake, the Rio Grande de Santiago, is located at 152 masl and flows westwards

Figure 2.4: Lake Chapala, located between 20°07’ and 20°20’ N and between 102°42’ and 103°25’ N. In between the states of Michoacan and Jalisco.

across the states of Jalisco and Nayarit, draining in to the Pacific Ocean (Mestre-Rodriguez, 1997). The Rio Grande de Santiago's main tributaries are the Rio Verde, Rio Juchipila, Rio Huaynamota in Nayarit, and the Rio Bolaños. The basin also contains the Santa Rosa and the Aguamilpas reservoir.

Table 2.1: Main lakes of the Lerma-Santiago (SEMARNAT, 2007).

Lake	**Catchment area (km^2)**	**Storage Capacity (hectometres^3)**	**State(s)**
Chapala	1,116	8,126	Jalisco and Michoacan
Cuitzeo	306	920	Michoacan
Patzcuaro	97	550	Michoacan
Yuriria	80	188	Guanajauto

In combination the Rio Lerma-Lake Chapala- Rio Santiago, at 1,281 km in length, is the second longest river in Mexico, next to the Rio Bravo(CONAGUA, 2011) (Table 2.2). It is one of the most environmentally endangered basins in the world, due to the excessive extraction of water for human consumption. In 1999, the water extraction from Lake Chapala, exceeded 236,500,000 m^3 to supply for Guadalajara City, the second largest city in Mexico and in consequence the lake nearly dried out losing more than 80% of its volume (Aguirre-Jimenez and Moran Martinez, 2000). According to Vargas-Velazquez (2009) by 2008 the lake had recovered its storage capacity due to above-average rainfall between 2003 and 2008; however he also remarked that Chapala Lake has lost around 80% of its volume twice from 1955 to 2002.

The basins of the Rivers Lerma and Santiago are some of the most polluted basins in the country just behind the water of the Valley of Mexico (including Mexico City) (Sedeño-Diaz and Lopez-Lopez, 2007; CONAGUA, 2008) (Table 2.3).

Table 2.2: Main Rivers in the Lerma-Santiago basins (SEMARNAT, 2008)

River	Mean surface runoff (millions of m^3/year)	Catchment area (km^2)	Length of the river(km)	Maximal stream order
Santiago	7,849	76,416	562	7
Verde	5,937	18,812	342	7
Lerma	4,742	47,116	708	6
Armeria	2,015	9,795	240	5

Table 2.3: Percentage distribution of surface water quality in the Lerma-Santiago basins (CONAGUA, 2008)

Lake	Excellent	Good quality	Acceptable	Polluted	Heavily polluted
BOD_5	40.4	14.4	24.2	19.0	2.0
COD	1.3	14.1	29.5	44.3*	10.8
TSS	40.2	32.3	17.7	7.9	1.9

* Second to The Valley of Mexico including Mexico City

The most polluted water bodies in the Lerma-Santiago basins are the Lake Cuitzeo, the Almoloya del Rio Lagoon, and the Rivers Tamazula, Aguascalientes, Verde, Turbio, Lerma,Mezapa, Tuxcacuesco, La laja and Santiago (SEMARNAT, 2008). In addition, the Lerma-Chapala basin contains two hydro electric power plants, the Salamanca and the Celaya plants. According to UNESCO (2007) the plants generated 1.6 GWh/year and 0.4 GWh/year respectively, with an average annual water extraction of 28.3 hm^3 and 3.7 hm^3. Beside the hydro electric plants, the Basin of Lerma-Chapala contributes to processing and cooling water for an oil refinery, fertilizer, fruit-packing houses, poultry farms, pig farms, tanneries and a massive agriculture sector (INE, 2004). Mean water quality parameters according to Alcocer and Bernal-brooks (2010) are presented for the Lerma-Santiago basins in Table 2.4.

Table 2.4: Mean water quality values in the Lerma basin (Alcocer and Bernal-Brooks, 2010)

Basin	**Temperature** (°C)	**O2 (mg l^{-1})**	**pH**	**SO_4 (mg l^{-1})**	**Cl (mg l^{-1})**	**NH_3 (mg l^{-1})**	**$P\text{-}PO_4$ sol (mg l^{-1})**	**$P\text{-}PO_4$ tot (mg l^{-1})**
Lerma	24.4	1.07	7.9	345	92	34.42	9.17	7.01

2.2.2 Fish fauna in the Lerma-Santaigo Basins

The Lerma-Chapala basin contains more than 40 fish species, 30 of them endemic (Abell, 2000; Miller et al., 2005). The most common families that live in the basin are the Cyprinid *Algansea*, the Goodeid family, and the Atherinopsid endemic fishes within genus *Chirostoma* (FEOW, 2011). In comparison to the high degree of endemism that the Lerma-Chapala has, the Santiago basin has a reduced number of species, although several atherinopsid *Chirostoma* and poeciliid *Poeciliopsis*, are abundant there. Common species are the charal (*C. jordani*), largetooth silverside (*C. arge*), shortfin silverside (*C. humboldtianum*), Lerma livebearer (*P. infans*), Sinaloa livebearer (*P. presidionis*), blackstripe livebearer (*P. prolifica*), and chubby livebearer (*P. viriosa*) (FEOW, 2011).

2.2.3 Climate in the Lerma-Santiago basins

The climate of the Lerma-Chapala Basin is semi-arid to sub-humid, with an average temperature of 21°C (Wester et al., 2009). With a mean annual precipitation of 817.9 mm $year^{-1}$, mainly concentrated from May to October (SEMARNAT, 2008). During the rainy season, the mean run-off is of 5.19 km^3 (Sedeño-Diaz and Lopez-Lopez, 2007).

2.3 The Balsas basin

The balsas basin is situated between the mountain chains of the Trans-Mexican Volcanic belt and the “Sierra Madre del Sur”, at 17°00' N and 20°00' N latitude and 97°30' W and 103°15' W longitude (INEGI, 2011). It is extended across the states of Michoacán, Jalisco, Guerrero, Mexico, Morelos, Tlaxcala, Puebla, and Oaxaca (Fig. 2.5). Its average altitude is less than 200 masl but it varies from just 100 masl at the gully of Coahuayutla near the outlet, to its highest point at the Popocatepetl volcano (5,452 masl) in the state of Puebla (19°00' N and 98°37' W) (Zepeda, 2005).

The Basin is also divided into three sub-regions. The Alto (upper) Balsas which includes the cities of Huajapan de Leon in Oaxaca, Puebla, Tlaxcala and Cuernavaca; the Medio (middle) Balsas which includes the cities of Iguala Tasco and Cutzmala in Guerrero, Valle de Bravo in the State of Mexico and Zitacuaro, Michoacan; and finally the Bajo (Lower) Balsas including the cities of Huetamo,Tacambaro, Uruapan, Apatzingan and Tepalcatepec in Michoacan, and Jalisco (INE, 2007) (Table 2.5). The Rio Balsas basin has a total area of 117,406 km^2 and is sparsely populated due to its rough terrain (Toledo, 2003). In 2008

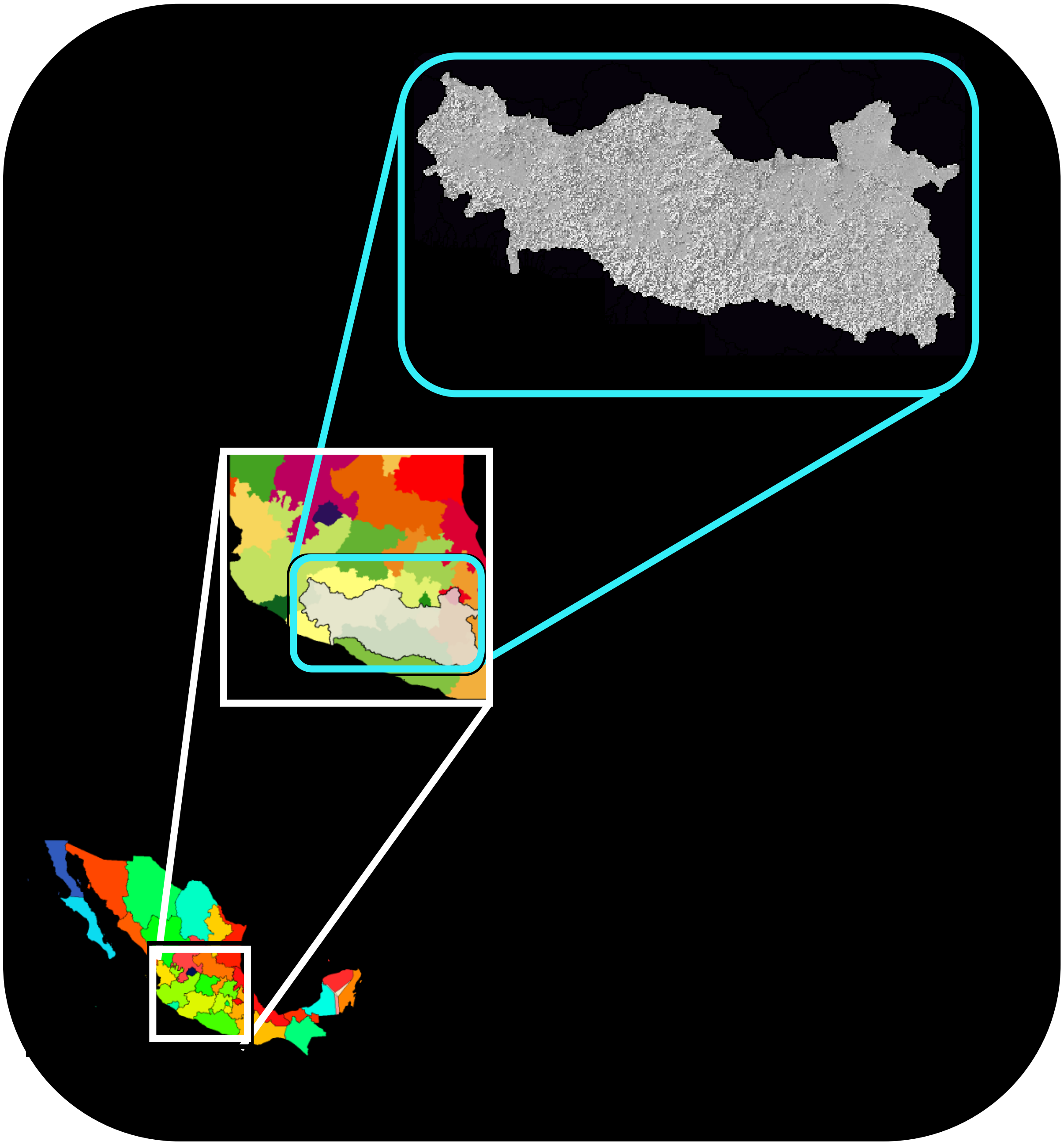


Figure 2.5: The Santiago basin in central Mexico. The Basin crossess the states of Michoacán, Jalisco, Guerrero, Mexico, Morelos, Tlaxcala, Puebla, and Oaxaca

population for the Balsas hydrological-administrative region was 10,581,511 inhabitants and a population density of 89 inhab/km^2, with a Grosse Domestic Product of 11% (SEMARNAT, 2010).

Table 2.5: Political structure and Population of the Balsas Basin

Sub region	**Area (Km ^{2})**	**Municipalities**	**Population (inhab)**	
			1995	**2020**
Upper Balsas	48,600	332	6,258,134	8,836,144
Middle Balsas	36,900	51	1,675,100	2,160,442
Lower Balsas	38,000	38	1,314,621	1,508,102
Total	123,500	421	9,247,855	12,504,688

Modified from INE (2007)

2.3.1 Main water resources of the Balsas basins.

The Rio Balsa has a total length of 770 km and in Mexico it contributes to the biggest freshwater input to the Pacific Ocean (Table 2.6). Other important water bodies in the Balsas basin are the Lakes Tequesquitengo, Coatetelco and Tuxpan (Alcocer and Bernal-Brooks, 2010). The reservoir “Presa el Infiernillo” was created in January 25, 1965 (CFE, 2011) (Fig. 2.6). It is located at 18°16′23″N 101°53′34″W, and is the third reservoir with more capacity in Mexico (INEGI, 2011) (Table 2.7).

The waters of the Balsas basin are amongst the most polluted in Mexico (Table 2.8). According to the National Water Commission in Mexico (CONAGUA, 2008) the water bodies most affected by pollution are the Alseseca River, Atoyac River,

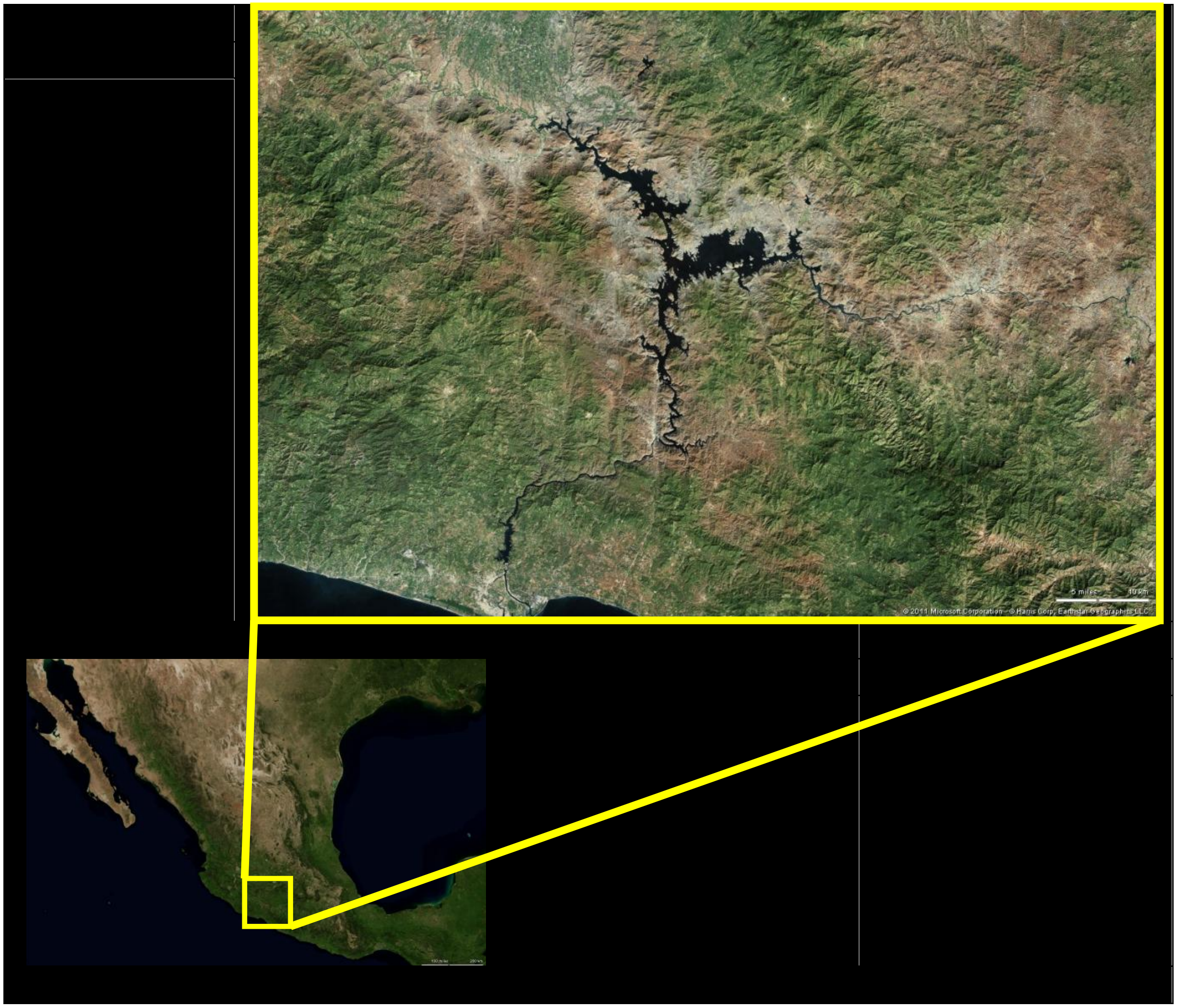


Figure 2.6: The Infiernillo reservoir located at 18°16′23″N 101°53′34″W between the states of Michoacan and Guerrero

Zahuapan River, the Estuary of Balsas River, Balsas River, Mezcala River,Iguala River, Arroyo Salado and the Cuautla River. Almost 77% of the water allocated to thermoelectric plants in Mexico is consumed by thermal-electric plant in Petacalco, near the mouth of the river Balsas (CFE, 2011). Pollution in the basin area comes from the Upper Balsas watershed, agriculture, cattle waste, sedimentation and agrochemicals (Abell et al., 2000). Mean water quality parameters for the Balsas basin are presented in table 2.9

Table 2.6: Rio Balsas characteristics (SEMARNAT, 2010)

River	**Total mean surface runoff (hm^3/year)**	**Catchment area (km^2)**	**Length of the river(km)**	**Maximal stream order**
Balsas	17,057	117,406	770	7

Table 2.7: Area and storage volume of the Balsas basin’s main water bodies (SEMARNAT, 2007).

Lake / reservoir	**Catchment area (km^2)**	**Storage Capacity (hm^3)**	**State(s)**
Tequesquitengo	8	160	Morelos
Infiernillo reservoir	755	118,600	Guerrero and Michoacan

Table 2.8: Percentage distribution of surface water quality in the Balsas basin (SEMARNAT, 2008)

Lake	**Excellent**	**Good quality**	**Acceptable**	**Polluted**	**Heavily polluted**
BOD_5	32.7	20.7	32.8	8.6	5.2*
COD	15.5	17.2	31.0	20.7	15.6*
TSS	27.6	34.5	20.7	8.6	8.6**

* Second to The Valley of Mexico including Mexico City; ** Highest percentage in the country

Table 2.9: Mean water quality values of the Balsas basin (Alcocer and Bernal-Brooks, 2010)

Basin	**Temperature** (°C)	**O_2 (mg l^{-1})**	**pH**	**SO_4 (mg l^{-1})**	**Cl (mg l^{-1})**	**NH_3 (mg l^{-1})**	**P-PO_4 sol (mg l^{-1})**	**P-PO_4 tot (mg l^{-1})**
Balsas	28	6.7	8.0	345	85	0.55	0.28	0.73

2.3.2 Fish fauna

The Balsas basin has a reduced fish biodiversity of only 30 species including those of marine origin (Miller et al., 2005). Seven of them are endemic to the Balsas: Balsas splitfin (*Ilyodon whitei*), the Catarina allotoca (*Allotoca catarinae*), the Balsas livebearer (*Poeciliopsis balsas*), the Balsas molly (*Poecilia maylandi*), the Balsas silverside (*Atherinella balsana*), the Balsas catfish (*Ictalurus balsanus*), and the Balsas shiner (*Hybopsis boucardi*) (Miller et al., 2005; FEOW, 2011).

2.3.3 Climate

Due to its location, the catchment fits into the tropical zone, with annual mean temperature varying according to the altitude from 18° C to 26° C (Zepeda 2005). Precipitation is higher during the rainy season which runs from June to October, with a mean annual precipitation of 963 mm (SEMARNAT, 2011).

2.4 Aquaculture

In Mexico aquaculture is regulated by the National Commission of Aquaculture and Fisheries (CONAPESCA). In 2010, CONAPESCA published Fisheries and Aquaculture statistics, with values of production by state. According to them the most used species for freshwater aquaculture are Tilapia, Carp, Trout, Catfish and Silversides, and those species productions are almost as high as those from fisheries (Table 2.10). It is clear that aquaculture production in the study area is dominated by tilapia, whereas trout and silversides are less exploited by the industry (Table 2.11). Aquaculture is generally considered to have high potential in the areas of study due to the high number of species with high market values. However as Table 2.12 shows, the number of registered fisheries is evidently higher than the number of registered aquaculture sites.

2.10: National aquaculture and fisheries production, 2009 (Tonnes)

Species	**Fisheries**	**Aquaculture**
Shrimp	196,456	133,282
Tilapia	77,009	73,373
Carp	26,659	22,620
Trout	7,969	6,065
Catfish	5,186	3,145
Silversides	2,414	1,876

Modified from CONAPESCA, (2010)

2.11: Number of registered Fisheries and Aquaculture sites by state

State	**Fisheries**	**Aquaculture**
Aguascalientes	11	1
Nayarit	303	64
Jalisco	215	3
Michoacan	306	99
Guerrero	557	22
Oaxaca	588	-
Guanajuato	65	80
Morelos	56	15
State of Mexico	86	206

Puebla	21	45
Tlaxcala	9	-

2.11 (Cont)

State	Fisheries	Aquaculture
Queretaro	31	3
Zacatecas	76	-

Modified from CONAPESCA, (2010)

2.12: Aquaculture production in the site of study, by state (Tonnes)

State	Tilapia	Carp	Trout	Catfish	Silversides
Aguascalientes	291	168	-	24	-
Nayarit	6,034	-	-	5	-
Jalisco	8,073	3,156	6	130	677
Michoacan	9,129	732	308	310	308
Guerrero	1,916	-	-	165	-
Oaxaca	608	-	-	-	3
Guanajuato	1,476	1,303	0	7	34
Morelos	622	-	11	28	-
State of Mexico	925	6,437	3,713	53	365
Puebla	783	3,584	919	-	-
Tlaxcala	38	334	3	-	8
Queretaro	307	167	4	2	-
Zacatecas	1,587	410	-	22	-

Modified from CONAPESCA, (2010)

The basins of the rivers Lerma, Santaigo and Balsas are three of the most important areas for conservation in central Mexico. They provide a wide variety of ecological services essential for the economic development of the region. The accelerated rate at which the natural resources in these basins are deteriorating is alarming. Therefore the development of management tools for the sustainable use of their natural resources is of great relevance for conservation of biodiversity.

References

Abell, R.A. & (U.S.), W.W.F., 2000. *Freshwater ecoregions of North America: a conservation assessment*, Island Press.

Aguirre Jimenez A.A. & Moran Martinez F. 2000 Demanda, Escasez y Transferencias de Agua para la Zona Metropolitana de Guadalajara. *In: Los estudios del agua en la cuenca Lerma-Chapala Santiago.* Ed. Schoendube B.B.

Alcocer, J. & Bernal-Brooks, F.W., 2010. Limnology in Mexico. *Hydrobiologia*, **644**:15-68.

CFE. 2011. Available at: http://www.cfe.gob.mx/QuienesSomos/estadisticas/listadocentralesgeneradoras/Paginas/listadohidroelectricas.aspx [Accessed: March 20-2011]

CONAGUA. 2011. Available at: http://www.cna.gob.mx/LermaWeb/ [Accessed: March 22-2011].

CONAPESCA. 2010. Anuario 2009. Available at: http://www.conapesca.sagarpa.gob.mx/wb/cona/anuario_2009_capitulo_i_preliminar [Accessed: March 24-2011]

Cotler, H., 2004. El manejo integral de cuencas en México: estudios y reflexiones para orientar la política ambiental, Instituto Nacional de Ecología.

Díaz-Pardo, E., Godínez-Rodríguez, M. A., et al. (1993). "Ecología de los peces de la cuenca del Lerma, México" Anales de la Escuela Nacional de Ciencias Biologicas Mexico **37** 104-127.

FEOW. 2011. Freshwater Ecoregions of the World. Available at: http://www.feow.org/ecoregion_details.php?eco=169 [Accessed: March 01-2011].

INE. 2004. Available at: http://www.diputados.gob.mx/USIEG/docts/INEI_industrias%20%20Cuenca%20Lerma-Chapala.pdf [Accessed: March 19-2011]

INE. 2007. Available at: http://www2.ine.gob.mx/publicaciones/libros/402/cuencabalsas.html [Accessed : January 20-2011].

INEGI. 2006. Atlas, Situacion Actual de la Divison Politico-Administrativa Interestatal; Estados Unidos Mexicanos. *INEGI.* 232.

INEGI. 2011. Atlas Nacional Interactivo de Mexico. Available at: http://www.atlasdemexico.gob.mx/ [Accessed: January 15-2011]

INEGI b. 2011. Regiones Hidrologicas de Mexico. Available at: http://mapserver.inegi.gob.mx/geografia/espanol/datosgeogra/basicos/hidrologia/rios/regiones_hidrologicas.cfm?c=519 [Accessed: September 26-2009]

Levine, G., 2007. The Lerma-Chapala river basin: a case study of water transfer in a closed basin. *Paddy and Water Environment*, **5**:247-251.

LUGO, J. (1990) El relieve de la Republica Mexicana, Boletın del Instituto de Geologıa, **9**: 82–111.

Mestre-Rodriguez J.E. 1997. Case study VIII – Lerma-Chapala Basin, Mexico. In Helmer R, Español I ed. Water pollution control a guide to the use of water quality management principles. WHO-UNEP pp 15

Miller, R.R., Minckley, W.L. & Norris, S.M., 2005. Freshwater Fishes of Mexico. *University of Chicago Press*.

Sedeño-Díaz J.E. & López-López E. 2007. Water Quality in the Río Lerma, Mexico An Overview of the Last Quarter of the Twentieth Century. *Water Resource Management*. **21:** 1797-1812.

Schoendube, B.B. Duran-Juarez J.M., Sanchez-Rogriguez.M.S and Torres-Rodriguez A. 2002, *Los estudios del agua en la cuenca Lerma-Chapala-Santiago*, El Colegio de Michoacán A.C.

SEMARNAT. 2008. Statistics on Water in Mexico. Pp. 229. Available at: http://www.conagua.gob.mx/english07/publications/SGP-20StatisticsLow.pdf [Accessed : March 01-2011]

SEMARNAT. 2010. Statistic on Water in Mexico.Pp. 249. Available at: http://www.conagua.gob.mx/english07/publications/EAM2010Ingles_Baja.pdf [Accessed: March 10-2011].

Toledo, A., 2003. *Ríos, costas, mares: hacia un análisis integrado de las regiones hidrológicas de México*, Instituto Nacional de Ecología.

Trujillo-Cardenas et al., 2010. Speciation and Sources of Toxic Metals in Sediments of Lake Chapala, Mexico. *J. Mex. Chem. Soc.* **54** :79-87.

UNESCO. 2007. Available at: http://portal.unesco.org/science/es/ev.php-URL_ID=3814&URL_DO=DO_PRINTPAGE&URL_SECTION=201.html [Accessed: March 19-2011].

Vargas-Velazquez. 2009. Aspectos socioeconómicos de la agricultura de riego en la Cuenca Lerma-Chapala. *Economia, Sociedad y Territorio.* **10**: 231-263. Available at: http://fenix.cmq.edu.mx/documentos/Revista/revista32/est_32_8.pdf [Accessed: March 3-20011]

Wester P., Mollard E., Silva-Ochoa P. & Vargas-Velazquez S. 2009. From Half-full to Half-empty: the Hydraulic Mission and Water Overexploitation in the Lerma-Chapala Basin, Mexico. *In: River basin trajectories: societies, environments and development.* Ed. Molle F. & Wester P. **4:** 75-98.

Zepeda, R.V., 2005. *Las regiones climáticas de México 1.2.2*, UNAM.

Chapter 3

Construction, storage and management of large databases for Geographic Information System modelling: a database for Aquaculture of Native Species

"it is virtually impossible to do anything useful with a GIS without devoting major effort to database construction" Goodchild (1993)

3.1 Introduction

Extensive construction of databases is required for the development of Geographic Information Systems (GIS) (Goodchild, 1993). The database development is a lengthy process which includes data input, update, conversion and construction of metadata (Guan et al., 2003). For this project an extensive research of existing databases and related information was conducted in order to gather data and produce a clear, flexible and easy to update database. GIS databases need to be designed in a way that allows easy manipulation of the data. One of the principal objectives of this database is to simplify access to the available information related to native fish species in central Mexico, for its use amongst agencies and stakeholders in general.

3.2 Software

Three different software packages were used in the development of the Native Species Aquaculture Database (NSADb):

- The software selected for the acquisition, storage, analysis and display of geographic data was IDRISI 15, The Andes Edition, developed by Clark Labs, Clark University, Worcester, MA. IDRISI Andes contains almost 250 GIS analysis and image processing functions, and its most innovative element is the Land Change Modeler (LCM) for Ecological sustainability, which was developed by the Conservation International's Andes Centre for Biodiversity Conservation (Hermmann, 2006). The LCM was used for the development of ecological niche-based Predictive Species Distribution and species Potential for Invasion (Chapter 6).

- Microsoft Access was used for database manipulation. Microsoft Access is a relational database management system from Microsoft. It has the potential to import or link directly to different database formats, such as Excel, dBase, Lotus 1-2-3, etc. Microsoft Access is also compatible with IDRISI and can be directly opened through the Idrisi Database Workshop (Eastman et al., 2009).

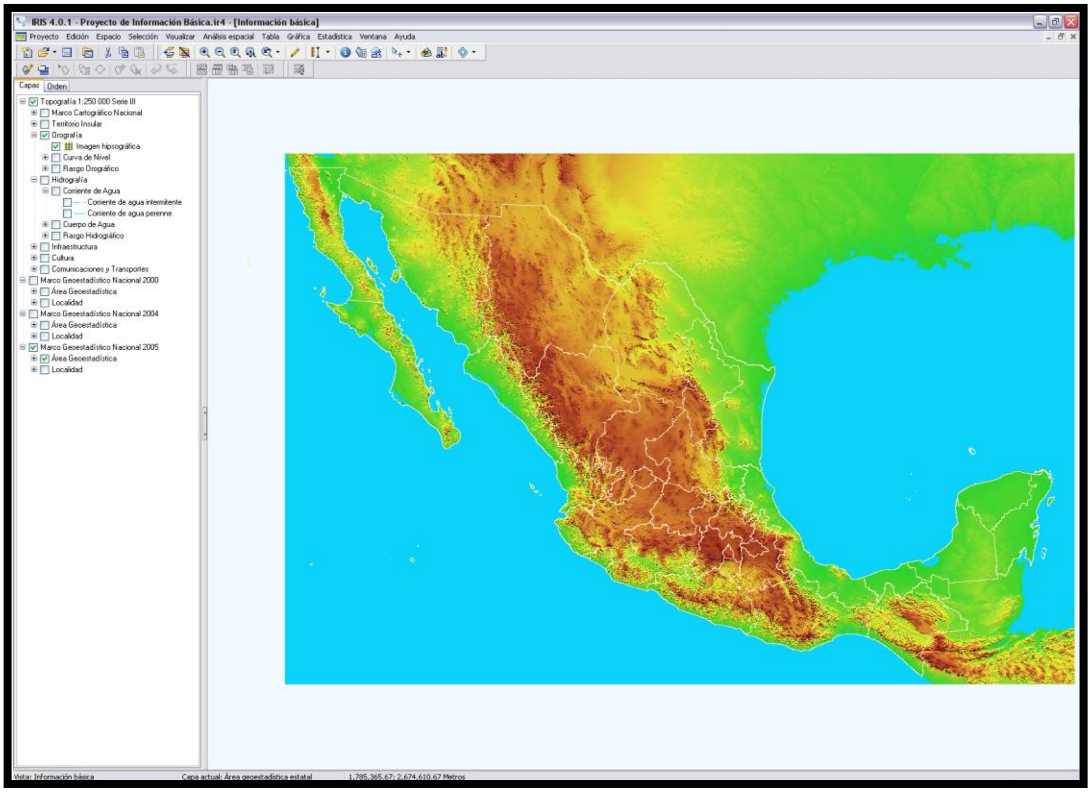
- IRIS 4 was developed in 2006 by the National Institute of Geography and Population in Mexico (INEGI) designed for exploration of Geographic Information Systems. IRIS stands for "*Informacion Referenciada geoespacialmente Integrada en un Sistema"* (Georeferenced Integrated Information System) (Fig 3.1). It relates the available geographic information with statistics developed by INEGI (INEGI, 2011). The potential of the tools within IRIS 4 is limited to identifying spatial and temporal attributes and it was used as. a guide for the identification of geographic features within the study area. However, due to its low capability for modelling and incompatibility with other international software it was decided to stop using IRIS 4.

3.3 Sources of Spatial Data

The majority of spatial variables were obtained from the National Institute of Geography and Population in Mexico (INEGI). The spatial data produced from INEGI is a complete source of information related to the Mexican Territory.

The datasets obtained from INEGI had a shape-file format (.shp) that was then imported into IDRISI Andes. Most of the databases that accompany the vector files were extremely basic and required extended database management. Raster files were obtained from the U.S. Geological Survey (USGS); International Soil Reference and Information Center (ISRIC) which produced the World Soil Database (WSDB); WorldClim which produced a global climate dataset with a spatial resolution of a square kilometre; and the Defence Meteorological Satellite Program- Operational Linescan System, which periodically observes the worlds night light (DMSP-OLS).

In total 16 vector and raster files were initially obtained as the core of the base of the spatial database, from which all calculations developed in the research were produced (Table 3.1).



- ☑ Topografía 1:250 000 Serie III
  - ☐ Marco Cartográfico Nacional
  - ☐ Territorio Insular
  - ☑ Orografía
    - ☑ Imagen hipsográfica
    - ☐ Curva de Nivel
    - ☐ Rasgo Orográfico
  - ☐ Hidrografía
    - ☐ Corriente de Agua
      - ☐ Corriente de agua intermitente
      - ☐ Corriente de agua perenne
    - ☐ Cuerpo de Agua
    - ☐ Rasgo Hidrográfico
  - ☐ Infraestructura
  - ☐ Cultura
  - ☐ Comunicaciones y Transportes
- ☐ Marco Geoestadístico Nacional 2000
  - ☐ Área Geoestadística
  - ☐ Localidad
- ☐ Marco Geoestadístico Nacional 2004
  - ☐ Área Geoestadística
  - ☐ Localidad
- ☑ Marco Geoestadístico Nacional 2005
  - ☑ Área Geoestadística
  - ☐ Localidad

Vista: Información básica
Capa actual: Área geoestadística estatal
1,785,365.67; 2,674,610.67 Metros

Figure. 3.1. IRIS 4 developed by INEGI in 2006

Table 3.1 Spatial database generated

Data	Description	Source	Geographic area	Original Projection	Resolution in meters
Political division	Polygon vector.	INEGI	Mexico	LCC	N/A
Rivers	Line vector	INEGI	Mexico	LCC	N/A
Lakes	Polygon vector	INEGI	Mexico	LCC	N/A
Roads	Line vector	INEGI	Mexico	LCC	N/A
Rail roads	Line vector	INEGI	Mexico	LCC	N/A
Natural Protected areas	Polygon vector	CONABIO	Mexico	LCC	N/A
Watersheds	Polygon vector	INEGI	Mexico	LCC	N/A
Land use	Polygon vector	INEGI	Mexico	LCC	N/A
Populated areas	Polygon vector	INEGI	Mexico	LCC	N/A
Population density 1995	Polygon vector	INEGI	Mexico	LCC	N/A
Population density 2005	Polygon vector	INEGI	Mexico	LCC	N/A
Digital Elevation Map	Raster file elevation	USGS / Hydro k1	World	Lat-Long	90
Soils	Raster file	ISRIC-WSDB	Latin America / World	Lat-Long	90
Precipitation	Raster file	WorldClim	World	Lat-Long	90
Temperature	Raster file	WorldClim	World	Lat-Long	90
Night Lights of the world	Raster file	DMSP-OLS	World	Lat-Long	90

3.4 Spatial Database Processing

All 16 thematic layers were projected with the Lambert Conformal Conic (LCC) geo-reference system. This decision was taken because LCC is the most commonly used projection in Mexico, the United States and Canada. Additionally, most of the used thematic layers in this research, provided by INEGI, had this as their original projection. The use

of LCC as a default georeference projection may simplify the use of the produced results by interested Mexican institutions (table 3.2).

In IDRISI re-projection can be easily achieved with the use of the “PROJECT” module. PROJECT transforms raster files from their original geo-referencing system to a different one (Eastman, 2009).

A 90m resolution was selected for the development of this study. The selection of the correct resolution is a key factor in the development of a spatial database, for it would determine how accurately the results could be theoretically calculated (Longley, 2005). Once the size of grid was established, the studied area was windowed into a grid with 9884 columns and 9422 rows. Windows for all 16 thematic layers were produced with the WINDOW module of IDRISI Andes, which extracts a sub-image from the original to a new one (Eastman, 2009). WINDOW requires the input of geographical position (row/column or X/Y). Geographical X/Y positions for all images were: Min X= 2127034; Max X=3016594; Min Y 473424; and Max Y= 1321404 (Fig. 3.2)

3.5 Attribute Database

This section of the database contains all descriptive data that relates to each pixel of the spatial database (Jenness et al., 2007). Information collected from literature, museum collections and web fish databases was the core for the attribute database. This section of the database had two main components: a Native Fish Species attribute database and a geographic attribute database. The first component included information on meristic and morphometric variables relevant to the project. A section of the Native Fish Database is presented in table 3.3.

More than 70 species were included in the database that covered exotic and native fish species of the Lerma-Santiago and Balsas basins in central Mexico. The geographic attribute database included specific information such as feature names (for example rivers or localities), as well as species distribution and integration of physical and chemical parameters. The major problem of the database development was encountered during the generation of the geographical attribute database, due to lack of compatibility between datasets/databases.

3.6 Database compatibility

Lack of compatibility is a common problem in the development of databases for GIS. Incompatibility commonly results from databases generated by completely different projects. However it can also occur between databases form the same project but created under different circumstances, different time lines or created by different developers. One of the main objectives of the World Soil Database is the

Table 3.2: Lambert Conformal Conic reference system parameters

Parameters	**Values**
ref. system	Lambert Conformal Conic
projection	Lambert Conformal Conic
datum	nAD27
delta WGS84	-12 130 190
ellipsoid	Clark 1866
major s-ax	6378206.4
minor s-ax	6356583.8
origin long	-102.000000
origin lat	12.000000
origin X	2500000
origin Y	0
scale fac	Na
units	M
parameters	2
stand ln 1	17.5
stand ln 2	29.5

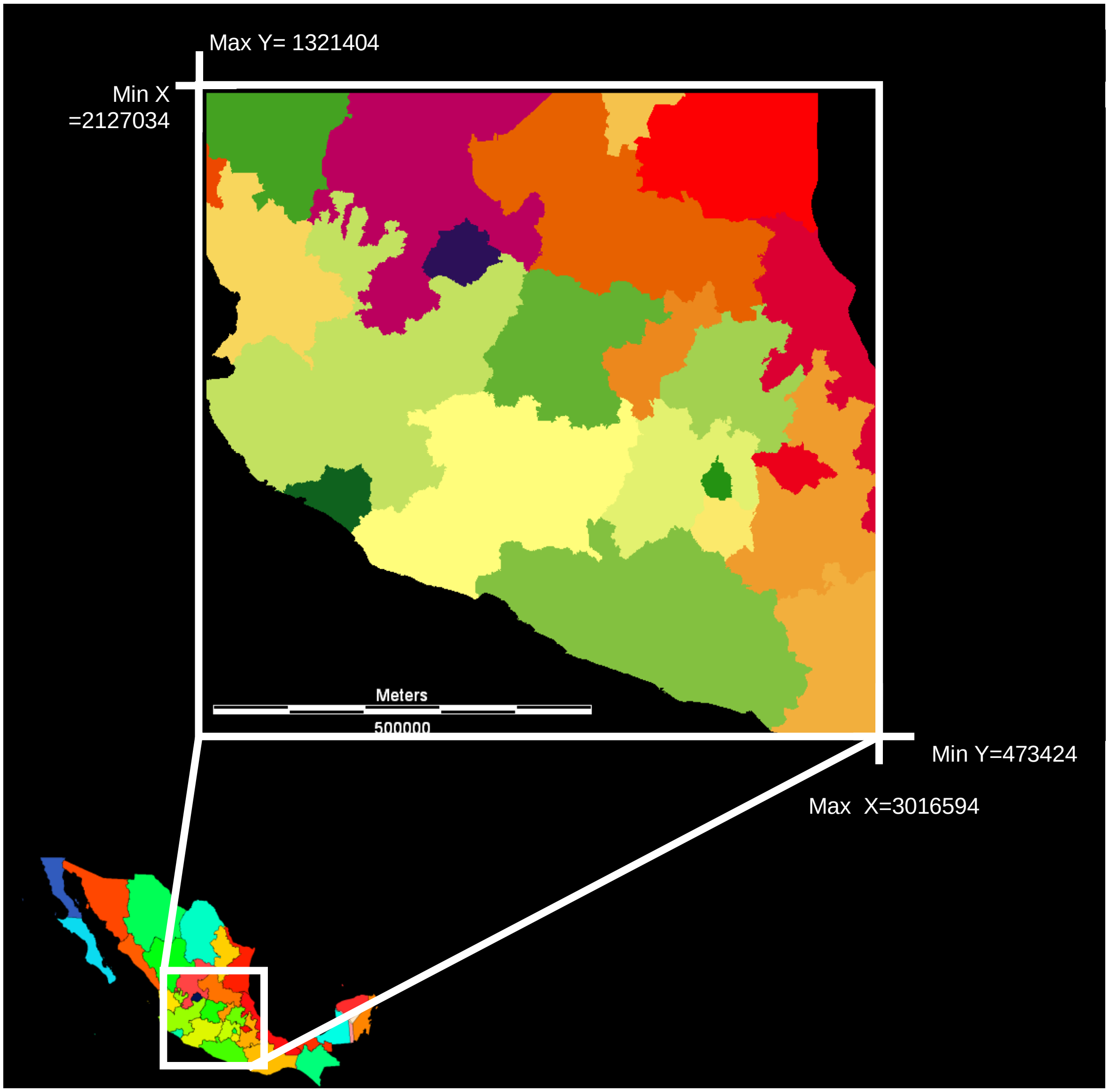


Figure. 3.2: Windowed studied area. The image shows central Mexico.

Table 3.3: Attribute database for native atherinids in the Balsas Basin

Order	Family	Genus	sp	Loc*	Max size	Rep**	use
Atheriniformes	*Atherinopsidae*	*Atherinella*	*balsana*	GRO, MEX, MICH, MOR, PUE	6.5 cm	o	no
Atheriniformes	*Atherinopsidae*	*Chirostoma*	*melanoccus*	MICH	6.5 cm	o	no
Atheriniformes	*Atherinopsidae*	*Chirostoma*	*consocia*	MICH	21.8 cm	o	no
Atheriniformes	*Atherinopsidae*	*Atherinella*	*guatemalensis*	MICH	8.1 cm	o	no

* Location by State

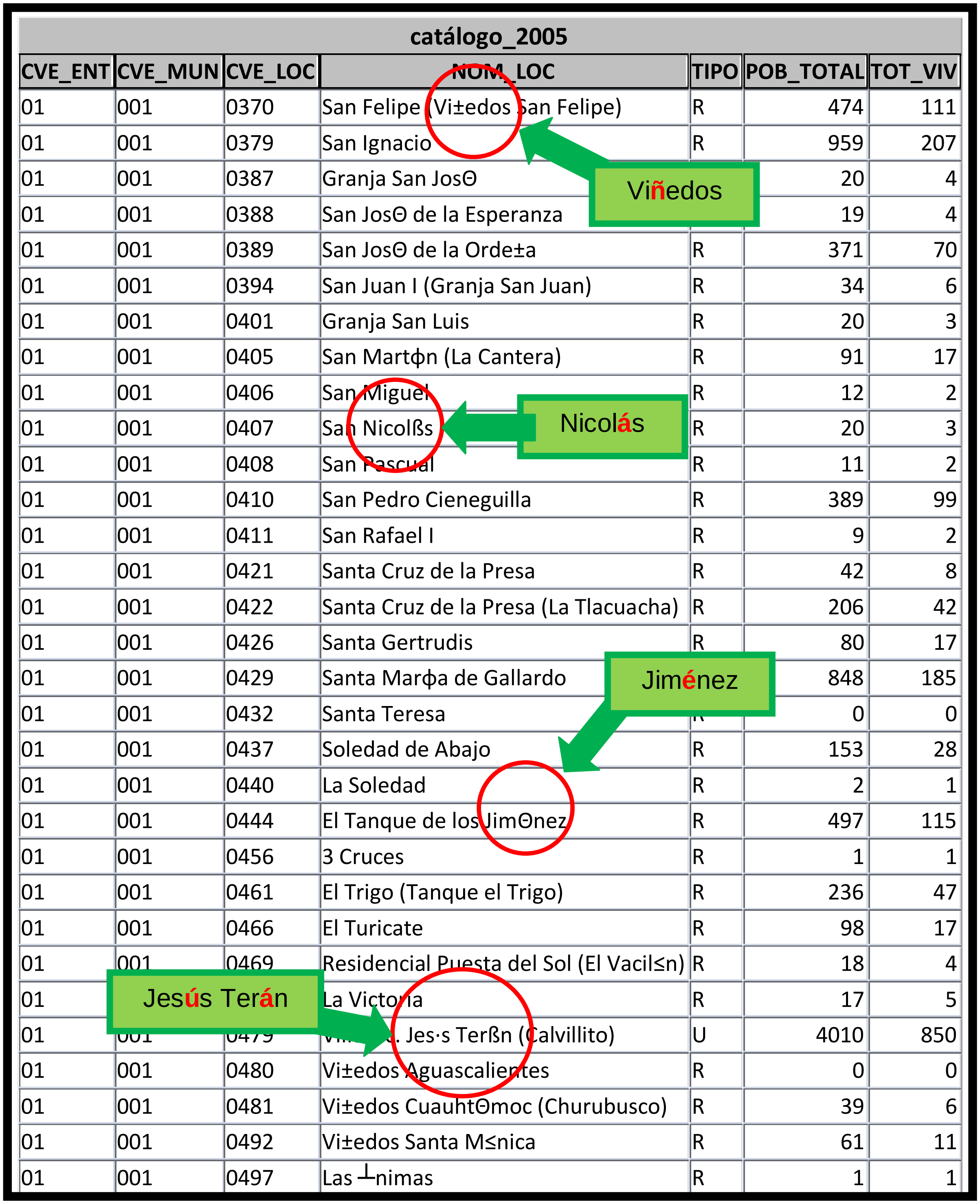
** Type or Reproduction (o=oviparous, v=viviparous)

development of compatible databases between the different available projects developed by ISRIC. However for the use of the different available databases, extensive programming understanding is required.

Datasets are normally composed by an image or a vector file accompanied by an attribute database which is linked to the image/vector by an object identifier code. Often the attribute database linked to an image/vector of interest includes only basic information and in few cases can be incomplete or inaccurate. This was true for specific cases of databases produced by the ISRIC-WSDB and INEGI. Furthermore, both institutions had more complete attribute databases available that had no linked image. However one of the most important traits for a GIS modeller is the capacity to integrate information into new attribute databases. In this way several attribute databases linked to the image/vector of interest were extensively improved and updated for the purpose of this research.

The most time consuming process in the development of the Native fish species database was as a result of a language incompatibility of characters in attribute databases. Specific characters of the Spanish language were replaced by Symbol characters making it necessary to correct thousands of entries in several databases. An example of conflict with river names is presented in figure 3.3.

The Native Fish Species database contains information relevant to the project and is presented in an easy to access format. With the use of this database it was possible to generate the GIS models that contribute to the Aquaculture Strategy for the Protection of Biodiversity. In total six main sub models, two models and one overall model were created during this research (table 3.4).



catálogo_2005						
CVE_ENT	**CVE_MUN**	**CVE_LOC**	**NOM_LOC**	**TIPO**	**POB_TOTAL**	**TOT_VIV**
01	001	0370	San Felipe (Vi±edos San Felipe)	R	474	111
01	001	0379	San Ignacio	R	959	207
01	001	0387	Granja San JosΘ		20	4
01	001	0388	San JosΘ de la Esperanza		19	4
01	001	0389	San JosΘ de la Orde±a	R	371	70
01	001	0394	San Juan I (Granja San Juan)	R	34	6
01	001	0401	Granja San Luis	R	20	3
01	001	0405	San Martφn (La Cantera)	R	91	17
01	001	0406	San Miguel	R	12	2
01	001	0407	San Nicolßs	R	20	3
01	001	0408	San Pascual	R	11	2
01	001	0410	San Pedro Cieneguilla	R	389	99
01	001	0411	San Rafael I	R	9	2
01	001	0421	Santa Cruz de la Presa	R	42	8
01	001	0422	Santa Cruz de la Presa (La Tlacuacha)	R	206	42
01	001	0426	Santa Gertrudis	R	80	17
01	001	0429	Santa Marφa de Gallardo		848	185
01	001	0432	Santa Teresa	R	0	0
01	001	0437	Soledad de Abajo	R	153	28
01	001	0440	La Soledad	R	2	1
01	001	0444	El Tanque de los JimΘnez	R	497	115
01	001	0456	3 Cruces	R	1	1
01	001	0461	El Trigo (Tanque el Trigo)	R	236	47
01	001	0466	El Turicate	R	98	17
01	001	0469	Residencial Puesta del Sol (El Vacil≤n)	R	18	4
01			La Victoria	R	17	5
01	001	0479	Vi[illegible]. Jes·s Terßn (Calvillito)	U	4010	850
01	001	0480	Vi±edos Aguascalientes	R	0	0
01	001	0481	Vi±edos CuauhtΘmoc (Churubusco)	R	39	6
01	001	0492	Vi±edos Santa M≤nica	R	61	11
01	001	0497	Las ┴nimas	R	1	1

Figure 3.3. Language conflict and incompatibility of characters. The image shows a section of a records database that included 289,689 river names. More than ¾ of the database had character conflicts

Table 3.4: Sub models and models characteristics.

Sub-models	**Main Components**	**Characteristics**
Water availability	Water availability	Boolean image of all the water bodies of the region.
	Proximity to Water source	Distance in meters, from all water sources
	Water Balance	WB Formula: ((Precipitation mm x 1.1) – (Evapotranspiration x 1.3) – (soil permeability))
Water quality	Precipitation	Mean monthly precipitation from the last 30 years
	Temperature	Temperature obtained form the mean monthly air temperature of the last 30 years
	Dissolved Oxygen	DO Formula: ((P-U) x 0.678) / (35+t) where, t= temperature, P= Atmospheric pressure y U= saturated vapour pressure.
	Pollution	Anthropogenic impact in water quality
Soil and Terrain	Slope Soil texture	The terrain sub model incorporates slope and soil texture into an MCE to identify suitable areas for the construction of pond aquaculture. Considering topography suitability for aquaculture ponds Identify suitable soils for aquaculture ponds
Infrastructure	Accesses Roads Urban Markets Rural Markets	An infrastructure layer was incorporated to the final model. This layer identifies distance to and access points Models distance from all access roads and distance to potential markets

Table 3.4 (Cont)

Sub-models	**Main Components**	**Characteristics**
Risk	Human Influence Index	The Human Influence Index was calculated for the region, following the methodology proposed by (Sanderson et al., 2002). This model was then used as a proxy for the influence that humans posed to the ecosystems. From this methodology it is also possible to deduce areas with no anthropogenic impact for their used as constraints (Last of the wild).
Constraints	Last of the wild Protected areas Roads-railroads	A layer with constraints for the development of aquaculture was created identifying areas where the construction of pond aquaculture is not possible, such as roads and railroads, protected areas, and those areas identified from the HII as undisturbed by humans. Identified areas with no human influence Boolean image of the protected areas Boolean image of roads and railroads
Site Suitability Model	Water sub model Soil and terrain Infrastructure sub Risk sub model Constraints	The model integrates all four sub models with the use of a Multi-Criteria Evaluation. Including Constraints
Species Distribution and Potential for Invasion Models	Rivers and Water bodies Fish distribution records	The model identifies potential distribution of the targeted species based on climatic and topographic variables. The Potential for invasion is a derivate of the Species Distribution Model, that identifies the potential o a species to distribute on specific basins in the event of introduction
Aquaculture Strategy for the Protection of Biodiversity	Site Suitability Model Species Distribution and Potential for Invasion Models	Integrates the overall models into a management strategy for the development of native species aquaculture.

References

Eastman, J.R. 2009. IDRISI ANDES. Manual. Clark Laboratories for Cartographic Technology and Geographic Analysis. Clark University, Worcester, MA, USA

Goodchild, M.F., 1993. *Environmental modeling with GIS* B. O. Parks & L. T. Steyaert, eds., Oxford University Press US.

Guan W. Turner. L.J. and Lostal S.L. 2003. Development of a Database for Lake Ecosystem Studies: Linking GIS with RDBMS. In *Gis for Water Resources and Watershed Management EdLyon J.G.* **12:**129-140.

Hermann J.T. 2006. IDRISI Andes Edition Enhances Modules, Adds Land Change Modeler. *Earth Imaging Journal*. Available at: http://www.clarklabs.org/products/loader.cfm?url=/commonspot/security/getfile.cfm&pageid=2450 [Accessed: March 2-2011].

INEGI. 2005. Guia para la Interpretacion de Cartografia; Topografia. *INEGI.* Pp 7.

INEGI, 2011. IRIS 4. Available at: http://mapserver.inegi.gob.mx/geografia/espanol/prodyserv/iris3/seccion/introduccion.cfm?c=698 [Accessed: March 2- 2011]

Jenness J. Dooley J. Aguilar-Manjarrez J. and Riva C. 2007. African Water Resource Database. *FAO.* Pp.165

Longley, P., 2005. *Geographic information systems and science*, John Wiley and Sons.

Sanderson, E. W., Jaiteh M. Levy, M.A. Redford, K.H. Wannebo, A.V. Woolmer, G. 2002. The human footprint and the last of the wild. *BioScience,* **52**:891-904.

Chapter 4

Pro-biodiversity Aquaculture: a philosophical framework

VM Peredo-Alvarez, Trevor C Telfer and Lindsay G Ross.

This chapter analyses the relationship between aquaculture and the loss of biodiversity. The introduction of exotic fish species and the effects that they have on freshwater biodiversity is widely discussed. Additionally this essay describes the use of native fish species as an approach for the conservation of biodiversity and describes case scenarios in Latin America.

The body of the text is presented as a publication-ready manuscript.

The main author, **VM Peredo-Alvarez**, developed all the research. Trevor C Telfer and Lindsay G Ross provided supervisory and editorial support throughout the whole study.

This manuscript will be submitted to **Conservation Biology**; an international journal focused on key issues contributing to the science and practice of conserving Earth's biological diversity.

Pro-biodiversity Aquaculture: a philosophical framework

V. M. Peredo-Alvarez, T.C. Telfer, and L.G. Ross

Abstract

The growth of human population in the last 500 years has forced the food industries to new levels of production. In developing countries, where the need for sustainable protein sources represents a significant problem, aquaculture of fast growing fish species, such as tilapia and carps, has been widely promoted as one solution for food security. This has resulted in an increase in fish production over the last few decades that has shown aquaculture as a very successful industry. However, the side-effects of aquaculture success have not been so pleasant and the constant introduction of exotic species for aquaculture has been paying its toll on biodiversity. The use of native fish species in aquaculture has been suggested in recent years as an alternative answer to food security and especially for the protection of biodiversity. This idea raises new questions: is the use of native fish species for aquaculture a realistic idea? And, is it risk free? Here we review the negative ecological impacts that exotic species have on biodiversity as a result of aquaculture activities. Then the advantages and disadvantages of using native species instead, are discussed, using case scenarios from Latin America to illustrate. We also present the necessary steps to support the development of "environmentally friendly" aquaculture using native fish species.

Keywords: Aquaculture, native species, exotic species, catchment.

4.1 Aquaculture in developing countries

Aquaculture in developing countries has been promoted since the 1970's by international organizations such as FAO and the World Development Bank as an alternative source of food and consistent employment opportunities, (Perez *et al*., 2003). Aquaculture became one of the fastest growing food supply industries in the 1980's largely due to the decline of marine fisheries (Naylor *et al*., 2001; De Silva *et al*., 2009). At this time its economic impact started to become apparent. Now provides for nearly 50% of fish for human consumption worldwide (FAO 2010a). However, most efforts for producing an affordable source of protein for rural communities in developing countries, through aquaculture, have historically used a reduced number of fish species. This has resulted in limited development of technologies for the culture of the same handful of species all over the world (Tapia and Zambrano, 2003). Furthermore, over the years aquaculture has become the principal vector for exotic fish introductions in the wild either intentionally, as it the case of extensive aquaculture or accidentally, as a result of escapes from semi intensive or intensive aquaculture (Zambrano *et al*., 2006). As a consequence, those few exotic species used for aquaculture are now well established in natural water bodies throughout the world.

Estimates indicate that with the continued decline of native fisheries production, socio-economic pressures and subsequent increase in aquaculture, the number of fish introductions will keep increasing (Gozlan, 2008; Gozlan *et al*., 2010). Along with this the associated ecological risks and biodiversity loss will also increase. As a result, in recent years there has been considerable concern about the effects that exotic species have on local biodiversity, not only regarding direct competition between exotic and native species but also on genetic interactions such as hybridization (Martinez-Palacios *et al*., 2008).

4.2 The effect of exotic fish introductions on wild populations

According to Sagoff (2007), the impact that exotic species have on fish biodiversity is still ambiguous. For Gozlan (2008, 2010), the use of non-native fish in aquaculture has to be encouraged, arguing that not all exotic fish introductions have had negative effects on biodiversity. He also points out the advantages of introducing highly marketable species with “low environmental risk”, while prohibiting poor value species with high environmental risk. However, compelling reports on the negative consequences resulting from the interaction between exotic and native species that in severe cases have led to local extinctions, surely suggest that introduction of exotic species cannot be considered positive, ecologically speaking (Ryman *et al*., 1995; Moyle & Light, 1996; Masood, 1997; Beardmore *et al*., 1997; McDowall, 2006; Pelicice & Agostihnio, 2009; Cambray, 2003; Alves *et al*., 2007; Kopp *et al*., 2009; Badiou & Goldsborough, 2010). Furthermore, in response to Gozlan (2008), Vitule *et al.,* (2009) provided several real case scenarios of freshwater fish introduction, with catastrophic consequences on fish biodiversity. The authors discussed worldwide case scenarios of the highly marketable Nile perch, Common carp, Tilapia, Catfishes, and Zebra mussel species, and classified Gozlan’s views of confrontation between conservationists and aquaculturists as “inaccurate”.

Freshwater ecosystems are especially susceptible to the arrival of exotic species due to the restricted natural distribution and reduced ability for inter-basin movement of many freshwater species (Moyle & Light 1996; Minns and Cooley, 2000; Unmack, 2001; Magurran, 2009). For many endemic freshwater species distribution can be very restricted due to geographic isolation. This poses a great risk to many of those species, as species with the smallest geographical range tend to be more vulnerable to extinction (Dickman *et al*., 2007). This is due to their incapability of migrating and redistributing when dramatic changes in their habitat have taken place.

It has been considered that freshwater fishes are the most endangered aquatic vertebrates after amphibians (Pascual *et al*., 2002). However, aquaculture or other reasons for non-native species introduction cannot be blamed for all cases of fish biodiversity loss. The most significant reason for biodiversity loss in freshwater habitats is still through other human activities that modify the environment producing physical, chemical and biological changes. Examples of this include construction of dams, the use of natural reservoirs’ water for human consumption, or pollution (Degerman *et al*., 2010; Sato *et al.,* 2010). However, it is accepted that one of the most important causes of species extinction is through introduction of exotic species (Canonico *et al*., 2005). Even though not all introductions may have negative impacts on biodiversity, long term results are unpredictable (Gozlan, 2010), especially in parts of the world where the native fauna is poorly known and where exotic species are becoming increasingly common (Pascual *et al*., 2002).

It is clear that the introduction of exotic fish species can affect native fish biodiversity both directly and indirectly; we will refer to the former as direct ecological impacts (DEI), and the latter as indirect ecological impacts (IEI). DEIs refer to the interactions between the invasive and the local species. The most common DEIs, in aquatic systems, are competition, predation, and genetic introgression, natural processes that are enhanced by introduction practices, such as aquaculture. A clear example of severe DEI happened in Lake Victoria, where predation by Nile perch on native haplochronime cichlids, accompanied by competition and hybridization between native species of tilapiines, *Oreochromis esculentus* and O*reochromis variabilis*, and the introduced *Oreochromis niloticus*, led to a dramatic loss of biodiversity (Nijru *et al.,* 2010).

4.2.1 Direct Ecological Impacts (DEI)

Competition and predation are natural processes that can be exacerbated as a result of the direct encounter between non coevolved species. Such species can compete for resources such as food or space, and diet overlap between exotic and native species can result in habitat shifts. This problem is intensified when the main source of food gets depleted as a consequence of more voracious behaviour from the introduced species (Zambrano *et al.,* 2010). The feeding behaviour of some species with a low trophic position such as the omnivorous tilapia and the benthivorous carps, have a massive predatory effect on higher trophic positioned species, by feeding on eggs and small larvae (Zambrano *et al.,* 2010).

Loss of genetic diversity is an important topic in relation to conservation. The consistent inclusion of non-native alleles into the related species' local gene pools may result in the loss of native's genetic variation, which can reduce productivity by decreasing individual fitness and the ability of sub-populations to evolve in the future (Allendorf, 2008; Ludwig *et al.,* 2009). Hybridization, which is the most rapid genetic threat to endangered populations, can also occur between closely related species, particularly when they share the same reproductive niches and timing (Wolf *et al*., 2001; Alves *et al*., 2007). This process leads to introgression, fitness reduction and displacement of native species, when hybrids mate with parent species (Scribner and Avise, 1993; Scribner *et al*., 2000; Ludwig *et al.,* 2009; Sato *et al*., 2010).

4.2.2 Indirect Ecological Impacts (IEI)

An IEI occurs when the introduced species modifies the environment. Such changes tend to be fast alterations, for which the native species may not be evolutionary prepared for. Habitat modifications are strongly related to dramatic changes in water quality parameters. Carps are well known for increasing water turbidity in shallow systems by re-suspending sediments in the water column, and hence changing the local community dynamics (Zambrano *et al.,* 2001, Badiou & Goldsborough, 2010)

The IEI most related to aquaculture is the introduction of new strains of parasites or diseases. The increase of fish pathogens and diseases in the wild is associated with the rapid development of aquaculture. Movement of stocks and subsequent escapes of non-native species are factor for the introduction of new disease strains (Naylor, 2001; Daszak *et al*., 2001). Under certain conditions exotic parasites or diseases may lead to the virtual extinction of indigenous hosts as native populations often lack a co-evolved host-pathogen resistance or benign resistance to the new pathogens (Hindar *et al*., 1991; Utter and Epifanio, 2002). For example, in Britain when the North American crayfish *Pacifastacus leniusculus*, was introduced through an aquaculture project, a vector for crayfish plague *Aphanomyces astaci*, caused significant impact on populations of the white-clawed crayfish through disease (Guan and Wiles, 1997; Macdonald *et al*., 2007).

It is true that these ecological interactions are all natural processes that determine the evolution of species; it is however the accelerated rate of biodiversity loss due to human activities, such as the introduction of exotic species, that raises concern amongst the scientific community.

4.3 Food security and conservation of biodiversity

According to the UN Population Division (2009) human population is expected to exceed 9 billion individuals, most of them enlarging developing countries' population size to 7.9 billion by the year 2050. In 1995 it was estimated that 20% of the population was living within the biodiversity hotspots and population growth rate between then and the year 2000 was 1.8% yr^{-1} (Cincotta and Engelman, 2000). That is why addressing food security is so important but it also highlights the danger that biodiversity is still to face in years to come from over fishing of native species and introduction of exotic species for aquaculture.

Worldwide freshwater fish culture produced nearly 33 million tonnes for human consumption in 2008 (FAO 2010b). This was largely based on intentionally introduced species of tilapias, carps and catfishes, dispersed widely outside their natural ranges of distribution (Arthur *et al*., 2010). It is clear that most of those exotic species have many economical advantages such as rapid growth or low production cost and have provided an important source of protein in developing countries. However fisheries of native species that support many communities have been severely compromised by the inclusion of exotic species changing the way of life of the people that make their living from the activity. In developing countries, freshwater fisheries for native species have a considerable social value due to their artisanal practices that have been used for generations and are, in many cases, close to extinction.

The conflict between food security for a constantly growing human population, and the rapid reduction of biodiversity, is evident. However because of the clear danger that biodiversity faces, *ergo* human food resources, we must reconsider the path. Aquaculture's and species conservation's goals, which are often in conflict and little understood by practitioners of both activities (Utter and Epifanio, 2002), need to be clearer and improved. For that, the relative costs and advantages of each activity need to be compared and recognized in order for those to co-exist (Feber *et al*., 2007).

The dilemma is simple; we need to find a way of producing enough food without endangering biodiversity. The risk from overfishing of native species is more than evident, and the use of exotic species for aquaculture, and how they affect biodiversity, has been explained. Perhaps the shift from fisheries of native species to fisheries of the well established introduced species can help to reduce those populations and with that the impacts their introduction has on the environment. Alternatively the use of native species to achieve food security has been suggested. The question now is, is aquaculture of native species a sustainable way for the protection of biodiversity?

4.4 Aquaculture of native species as a sustainable way for protection of biodiversity

We believe that responsible planning of native species aquaculture has the potential to mitigate many of the ecological impacts previously discussed, for example, unwanted exotic pathogens and parasites, while other factors like inter-species predation, competition, and hybridization can be significantly limited. If native fish species are used for aquaculture, indigenous fish are more likely to have natural immunity or defences against the particular strains of pathogens and parasites released from aquaculture activities. In addition, enhanced predation, competition and hybridization cannot occur even if native cultured fish escape into the wild.

However aquaculture of natives is not the panacea. The developing process can be long and expensive (Ross and Martinez-Palacios*,* 2008), and the risks of using native species, although unknown, can be suggested. Growing fish in higher than natural stocking densities would increase the chances of infection transfer and effect even between native species but the highest risk of all would be the genetic implications that come from selective breeding for aquaculture. Normal practices in aquaculture aim to increase production by accelerating the reproductive maturity process, raising the production of eggs, increasing weight and maintaining consistency in size, shape, and color of fish (Law 2000; Gjedrem 2000). And even without the application of selective breeding programmes, the effect of random genetic drift, what is known as domestication selection, can be expected (Bekkevold, *et al.,* 2006). It can be assumed that improved lines can be more voracious than the wild organisms, and that the breeding improvement process may contribute to a reduction in the natural genetic variability. Escaped native cultured fish may impact wild populations given that the smaller genetic pool of these domesticated lines can reduce fitness and natural genetic variability (McGinnity *et al.,* 2003).

Even so, aquaculture of native species should represent a lower risk to the environment than exotic species, but it requires thorough planning in order to prevent negative genetic impacts on existing wild populations and the introduction of new exotic fish as result from translocations. The correct genetic management of broodstocks can be suggested to minimize the ecological impact of escapees on biodiversity. The major consideration for environmentally friendly culture of native species would be the establishment of restrictions to maintain geographical isolation, as fish species must be cultured accordingly to their natural range of distribution, e.g. each river basin should have its own native cultivated stock for each species. Catchment level planning seems the most suitable option, as river catchments are the natural constraints for fish distribution and such a measure would prevent translocation of native species into new environments. A properly developed genetic plan for broodstocks combined with catchment-related aquaculture will help prevent negative effects from aquaculture on biological diversity.

We strongly suggest that in order to minimize the negative effects on biodiversity, the development of sustainable aquaculture for native species' should follow three steps: 1, identification of species suitable for aquaculture; 2, appropriate genetic consideration; 3, establishment of aquaculture sites within the natural range of fish distribution.

1) Identification of native species suitable for aquaculture

In general, native species suitable for aquaculture must be cost-efficient in terms of production, and resistant to environmental stressors; knowledge on culture technologies is also required. However, it is largely accepted that for native species aquaculture, the limiting factor is the development of new culture technologies (Perez *et al*., 2003). As a first step though, existing technologies for related species could be employed or adapted for use with local species.

2) Genetic management

Appropriate genetic management of local, native broodstock is of considerable importance to reduce genetic impacts from escaped farmed fish on local populations (Alves *et al.*, 2007). A healthy broodstock can be obtained from a founder stock containing a high genetic diversity, with systematic tagging of the first generation for the correct management of pedigree records and, if possible, the establishment of gene banks to maintain genetic variability (Philippart 1995; Sriphairoj *et al*., 2007; Frankham *et al*., 2009).

In addition, sterile triploid offspring (organisms with three sets of homologous chromosomes) can be induced (using a “hydrostatic pressure shock” technique) in order to minimize interaction with escaped cultured fish. This has been employed for genetic containment of farmed fish such as Grass carp and Atlantic salmon, of shellfish (Piferrer *et al*., 2009; Powell *et al*., 2009; Anderson, 2010).

3) Establishment of aquaculture sites within the natural range of fish distribution.

Many native freshwater species are naturally confined to catchments that prevent fish from spreading to other geographic locations; a process known as geographic isolation. One natural consequence of geographic barriers is the reproductive isolation that prevents related species from interbreeding (Sobel *et al*., 2010), ultimately leading to speciation (Mayr 1963). Aquaculture of each native species within its correspondent river basin, maintains the natural process of isolation, avoiding ecological interactions between species that did not evolve together.

Identification of areas, where genetic isolation of fish species is likely, represents an important part of the process of development of aquaculture of native species. There are a number of ways of achieving this, one of the strongest being the use of Geographic Information Systems, which allow the efficient storage, management, analysis and subsequent use of spatial and non-spatial data (Kapetsky *et al*., 1987). Such an advantage makes GIS a powerful tool for decision support for responsible aquaculture. Assessments of natural distribution ranges of native species candidates for aquaculture and the creation of predictive models of species distribution for establishment and protection strategies for rare species can be achieved through GIS modelling. It is also possible to predict distributions and impacts of exotic species for the establishment of fisheries. Such assessments can be used in effective site selection for aquaculture operations, in order to enhance the success and sustainability of the culture system as well as solving conflicts between different competing activities such as agriculture (Hossain & Das, 2010)**.**

Translocation of native species with economic potential is a common activity. Therefore it could be expected that the successful development of new species in aquaculture can result in further introductions (Lopez-Rojas and Bonilla-Rivero 2007). The establishment of aquaculture sites within the natural range of the targeted species distribution will represent a safety measure for the protection of biodiversity.

In addition, the number of cultured fish at one time needs to be carefully controlled. Such a strategy may minimize the ecological impact from escapees interfering with the natural ecosystem balance or be forced, due to their high numbers, to occupy niches which are not naturally theirs. Controlling the production can also reduce the risks from diseases and pathogens related to high fish densities in aquaculture.

4.5 Native Species Aquaculture in Latin America

Aquaculture of native species has been discussed in recent years by a number of authors (Utter and Epifanio, 2002; Perez *et al*., 2003; Alves *et al.,* 2007; Magurran, 2009, Vitule *et al.,* 2009). In Latin America there is a considerable and increasing interest in using native species for aquaculture for the food industry and as a measure for the protection of biodiversity (Saint-Paul, 2002; Ross *et al.*, 2008). There are two clear activities where the need for food security has affected fish biodiversity in Latin America: overexploitation of native fisheries and aquaculture of exotic species. In these processes, native fish populations declined due to overfishing whilst deliberate and accidental introduction of exotics increased. The existence of established fisheries is indicative of the profitable condition of some native species, whereas overexploitation reflects the high demand for it in the market: both are excellent reasons for their development as new aquaculture candidate species. Incidentally in many locations where exotic species have been introduced by aquaculture, native populations of closely related species often occur, question being: *if there is a market for the cultured exotic species, why not for a cultured native one instead?*

While still in its pilot stages, aquaculture of native fish in Latin America is promoting constant development of new aquaculture and fisheries technologies. Currently more than 64 aquatic species are farmed in Brazil with a considerable variety of native fish species being used, particularly from the Amazon basin. Successful industries for the culture of native catfish *Pseudoplatystoma fasciatum* and *Pseudoplatystoma coruscans* have been developed, and other native species such as *Arapaima gigas, Brycon cephalus,* and *Brycon orbignyanus* have shown some potential (FAO, 2010c).

Aquaculture for many other fish species, native to Latin America, is undergoing constant expansion and technological improvement. For example, aquaculture of pejerrey (*Odontesthes argentinensis* and *O. bonariensis*) can be found in Argentina, southern Brazil, Uruguay and Chile and its aquaculture is considered of regional importance (Colautti *et al*., 2006; Miranda *et al*., 2006; Sampaio, 2006). A program for the development of pejerrey aquaculture in Argentina started in 2001 and has produced considerable scientific advances for its culture (Somoza *et al*., 2008).

4.6 New native species for aquaculture in Mexico

In Mexico there are more than 500 freshwater fish species, 271 of which are endemic (Contreras-Balderas *et al*., 2002; Miller *et al.,* 2005; Contreras-Balderas *et al*., 2008). However, food production from freshwater fisheries and aquaculture is dominated by exotic species, with 62% of the production being tilapia (*Oreochromis niloticus*) and 29% being different species of carp (Conapesca, 2010). Only a few native fish species are included in the remaining production, such as catfish (*Ictarulus sp*) and the silver side (*Chirostoma* sp.) (FAO, 2010a).

The catfish, *Ictarulus punctatus*, which is distributed from southern Canada to the north of Mexico, has a successful commercial production based in Tamaulipas, northern Mexico (Miller *et al.,* 2005). High human consumption throughout Mexico has led to its translocation to other river catchments such as Lerma, Santiago and

Balsas in the centre of the Mexican republic. As a consequence, hybridization of *I. punctatus* with *I. dugesii* (native to the Lerma and Santiago basins), and *I. balsanus* (endemic to the Balsas basin) have been reported. *I. dugesii* and *I. balsanus* can be successfully introduced to aquaculture within their respective catchments for they share many genetic characteristics in common with the translocated species. Also, the available technology for *I. punctatus* can be transferred to *I. dugesii* and *I. balsanus* as a first step.

The introduction of exotic species and overfishing in the Lerma basin has led to a decline in the populations of native atherinids (Ross *et al*., 2008). Endemic to the basin of Lerma, *Chirostoma estor* is an endanger species of the Atherinopsidae family, with a strong influence on the cultural environment and the economy of the local human population of the region due to its very high prices in local markets (40-80 USD kg^{-1}). There have been significant advances in the development of biotechnology for this species with regard to its culture (Martinez-Palacios *et al*., 2002; Martinez-Palacios *et al*., 2004; Ross *et al*., 2006; Rios-Duran *et al*., 2006; Ross *et al.,* 2007; Martinez-Palacios *et al*., 2008). This technology, for the culture of *C. estor estor*, can be used for other members of the same genera, such as the smaller species belonging to the *Agre* group. Also known as “charales”, the members of the *Agre* group are endemic to the Lerma basin, and are a highly marketable fish with considerable potential for aquaculture.

4.7 Conclusion

Many native fish species that support local freshwater fisheries are now endangered due to overexploitation and the lack of appropriate protection tools. However a number of native species with no economic value are likely to disappear as a consequence of the introduction of exotics. The big difference is that those species with low economic value tend to be neglected as they have no interest for humans. The use of key native species in aquaculture may indirectly benefit these species with less or non economical value as the impact of aquaculture will be reduced. In the same way, aquaculture of native species that are at the moment overfished will help to avoid local extinctions and will provide financial support to local communities. However the establishment of native fish aquaculture needs to be planned carefully in order to minimize the ecological impacts related to aquaculture.

As shown in Argentina, Brazil and Mexico, there are many native species with considerable potential for aquaculture, which have not been exploited to date. It is clear that introduced species have better qualities for aquaculture than native species of the same genera; this will support the argument of many aquaculturists that exotic species will have a higher economical impact than a similar native species. However this can be a misconception. Farming systems that have the aggregated value of providing environmental benefits, while meeting high social, animal welfare and food safety standards, are increasingly and successfully being marketed (Feber *et al*., 2007).

As highlighted by Perez *et al*., (2003), international agencies need to incorporate more programs for the development of new technologies for aquaculture of native species. For this to succeed, the collaboration of governments, the food industry and the scientific community is essential. The lack of new technologies represents a constraint for the development of native species' aquaculture; therefore, we strongly recommend the generation of technologies for the culture of native species. We also suggest that, although the removal of the established exotic species is an unrealistic process, the establishment of fisheries for these species should be recommended. The shift from aquaculture to fisheries of exotics, and the shift from fisheries to a responsible planned aquaculture of native species is the best option to ensure food security whilst protecting biodiversity.

References

Allendorf, F. W., P. R. England, G. Luikart, P. A. Ritchie, and N. Ryman. 2008. Genetic effects of harvest on wild animal populations. *Trends in Ecology & Evolution* **23**:327-337.

Alves, C., F. Vieira, A. Magalhães, and M. Brito. 2007. Impacts of Non-Native Fish Species in Minas Gerais, Brazil: Present Situation and Prospects. Pages 291-314 in *Ecological and Genetic Implications of Aquaculture Activities*

Anderson, J. D. 2010. Mitochondrial DNA Dosage Effects in Triploid Grass Carp. *North American Journal of Aquaculture* **72**:177-183.

Arthur RI, Lorenzen K, Homekingkeo P, Sadavong K, Sengvilaikham B, Garaway CJ (2010) Assessing impacts of introduced aquaculture species on native fish communities: Nile tilapia and major carps in SE Asian freshwaters. *Aquaculture* **299**: 81–88

Badiou, P. H. J., and L. G. Goldsborough. 2010. Ecological Impacts of an Exotic Benthivorous Fish in Large Experimental Wetlands, Delta Marsh, *Canada. Wetlands* **30**:657-667.

Beardmore, J. A., G. C. Mair, and R. I. Lewis. 1997. Biodiversity in aquatic systems in relation to aquaculture. *Aquaculture Research* **28**:829-839.

Bekkevold, D., M. Hansen, and E. Nielsen. 2006. Genetic impact of gadoid culture on wild fish populations: predictions, lessons from salmonids, and possibilities for minimizing adverse effects. ICES *Journal of Marine Science* **63**:198-208.

Cambray, J. 2003. Impact on indigenous species biodiversity caused by the globalisation of alien recreational freshwater fisheries. *Hydrobiologia* **500**:217-230.

Canonico, G. C., A. Arthington, J. K. McCrary, and M. L. Thieme. 2005. The effects of introduced tilapias on native biodiversity. Aquatic Conservation*: Marine and Freshwater Ecosystems* **15**:463-483.

Cincotta, R., and R. Engelman. 2000. Biodiversity and population growth. Issues in *Science and Technology* **16**:80-81.

Colautti, D., M. Lenicov, and G. Berasain. 2006. A standard weight equation to assess the body condition of pejerrey Odontesthes bonariensis. *Biocell* **30**:131-135.

CONAPESCA, 2010. July 20. Anuario 2010, Retrieved July 20 from http://www.conapesca.sagarpa.gob.mx/wb/cona/anuario_2010

Contreras-Balderas, S., P. Almada-Villela, M. de Lourdes Lozano-Vilano, and M. García-Ramírez. 2002. Freshwater fish at risk or extinct in México. Reviews in *Fish Biology and Fisheries* **12**:241-251.

Contreras-Balderas, S., G. Ruiz-Campos, J. J. Schmitter-Soto, E. Diaz-Pardo, T. Contreras-McBeath, M. Medina-Soto, L. Zambrano-Gonzalez, A. Varela-Romero, R. Mendoza-Alfaro, C. Ramirez-Martinez, M. A. Leija-Tristan, P. Almada-Villela, D. A. Hendrickson, and J. Lyons. 2008. Freshwater fishes and water status in Mexico: A country-wide appraisal. *Aquatic Ecosystem Health & Management* **11**:246-256.

Daszak, P., A. A. Cunningham, and A. D. Hyatt. 2001. Anthropogenic environmental change and the emergence of infectious diseases in wildlife. *Acta Tropica* **78**:103-116.

Degerman, E., J. Hammar, P. Nyberg, and G. Svärdson. 2001. Human impact on the fish diversity in the four largest lakes of Sweden. *Ambio* **30**:522-528.

Dickman C.R., S.L Pimm and M. Cardillo. 2007. The pathology of biodiversity loss: the practice of conservation. *In* Key topics in conservation biology / edited by David W. Macdonald, Katrina Service. *Blackwell, Malden, Massachusetts*. pp. 1-16.

FAO, 2010a, July 26. FAO Fisheries & Aquaculture - Aquaculture. Retrieved July 26, 2010, from http://www.fao.org/fishery/aquaculture/en

FAO, 2010b, July 29. FAO Fisheries & Aquaculture Global Aquaculture Production, Overview. Retrieved July 29, 2010, from http://www.fao.org/fishery/statistics/global-aquaculture-production/en

FAO, 2010c, July 29. National Aquaculture Sector Overview, Brazil. Fisheries and Aquaculture Department 2010, Retrieved July 29 from http://www.fao.org/fishery/countrysector/naso_brazil/en.

Feber, R.E., E.J. Asteraki and L.G. Firbank. 2007. Can farming and wildlife coexist? *In* Key topics in conservation biology / edited by David W. Macdonald, Katrina Service. Blackwell, Malden, *Massachusetts*. 239-252.

Frankham, R., J. Ballou, and D. Briscoe. 2009. Introduction to Conservation Genetics. Cambridge University Press.

Gjedrem, T. 2000. Genetic improvement of cold-water fish species. *Aquaculture Research* **31**:25-33.

Gozlan, R. E., J. R. Britton, I. Cowx, and G. H. Copp. 2010. Current knowledge on non-native freshwater fish introductions. *Journal of Fish Biology* **76**:751-786.

Gozlan, R. E. 2008. Introduction of non-native freshwater fish: is it all bad? *Fish and Fisheries* **9**:106-115.

Guan, R., and P. R. Wiles. 1997. Ecological Impact of Introduced Crayfish on Benthic Fishes in a British Lowland River. Impacto Ecologico de un Langostino de Rio Introducido en Poblaciones de Peces Bentonicos de un Rio de las Tierras Bajas Britanicas. *Conservation Biology* **11**:641-647.

Hindar, K., K. Ryman, and F. Utter. 1991. Genetic-effects of cultured fish on natural fish populations. *Canadian Journal of Fisheries and Aquatic Sciences* **48**:945-957.

Hossain, M. S., and N. G. Das. 2010. GIS-based multi-criteria evaluation to land suitability modelling for giant prawn (*Macrobrachium rosenbergii*) farming in Companigonj Upazila of Noakhali, Bangladesh. *Computers and Electronics in Agriculture* **70**:172-186.

Kapetsky, J.M., L. McGregor and H. Nanne E. 1987. A geographical information system and satellite remote sensing to plan for aquaculture development: a FAO-UNDP/GRID cooperative study in Costa Rica. *FAO Fish.Tech.Pap.,* 287:51.

Kopp, D., J. Syväranta, J. Figuerola, A. Compin, F. Santoul, and R. Céréghino. 2009. Environmental effects related to the local absence of exotic fish. *Biological Conservation* **142**:3207-3212.

Law, R. 2000. Fishing, selection, and phenotypic evolution. ICES Journal of Marine Science: *Journal du Conseil* **57**:659 -668.

Lopez-Rojas, H., and A. Bonilla-Rwero. 2007. Introduction of exotic species and transplantation of native species across river basins in Venezuela. *Ecological and Genetic Implications of Aquaculture Activities* **6**:279-289.

Ludwig, A. *et al.,* 2009. First evidence of hybridization between endangered sterlets (*Acipenser ruthenus*) and exotic Siberian sturgeons (*Acipenser baerii*) in the Danube River. *Biological Invasions*, **11**:753-760.

Macdonald D.W., C.M. King, and R. Strachan. 2007. Introduced species and the line between biodiversity conservation and naturalistic eugenics *In* Key topics in conservation biology / edited by David W. Macdonald, Katrina Service. Blackwell, Malden, Massachusetts. pp. 186-205.

Magurran, A. 2009. Threats to Freshwater Fish. Science **325**:1215-1216.

Martinez-Palacios, C., J. Morte, J. Tello-Ballinas, M. Toledo-Cuevas, and L. Ross. 2004. The effects of saline environments on survival and growth of eggs and larvae of *Chirostoma estor estor* Jordan 1880 (Pisces : Atherinidae). *Aquaculture* **238**:509-522.

Martinez-Palacios, C., M. Rios-Duran, J. Madrigal, M. Cuevas, A. Lopez, and L. Ross. 2008. Developments in the nutrition of *Menidia estor* Jordan 1880. *Aquaculture Research* **39**:738-747.

Martinez-Palacios, C., E. Tovar, J. Taylor, G. Duran, and L. Ross. 2002. Effect of temperature on growth and survival of *Chirostoma estor estor*, Jordan 1879, monitored using a simple video technique for remote measurement of length and mass of larval and juvenile fishes. *Aquaculture* **209**:369-377.

Masood, E. 1997. Aquaculture: a solution, or source of new problems? *Nature* **386**:109.

Mayr, E. 1963. Animal Species and Evolution. Cambridge, Massachusetts: *Belknap Press of Harvard University Press*, 797.

McDowall, R. 2006. Crying wolf, crying foul, or crying shame: alien salmonids and a biodiversity crisis in the southern cool-temperate galaxioid fishes? Reviews in *Fish Biology and Fisheries* **16**:233-422.

McGinnity, *et al*., 2003. Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon. Proceedings of the Royal Society B: *Biological Sciences* **270**:2443-2450.

Miller, R.R., Minckley, W.L. & Norris, S.M., 2005. Freshwater Fishes of Mexico. *University of Chicago Press*.

Minns, C.K., and J. M. Cooley. 2000. Intentional introductions: Are the incalculable risks worth it? *In* Nonindigenous freshwater organisms. *Lewis Publishers, New York.* 57–60.

Miranda, L., G. Berasain, C. Velasco, Y. Shirojo, and G. Somoza. 2006. Natural spawning and intensive culture of pejerrey *Odontesthes bonariensis* juveniles. B*iocell* **30**:157-162.

Moyle, P. B., and T. Light. 1996. Fish invasions in California: Do abiotic factors determine success? *Ecology (Washington D C)* **77**:1666-1670.

Naylor, R. L. 2001. Aquaculture--A Gateway for Exotic Species. *Science* **294**:1655-1656.

Njiru, M., Mkumbo, O.C. and van der Knaap, M., 2010. Some possible factors leading to decline in fish species in Lake Victoria. *Aquatic Ecosystem Health & Management*, **13**:.3-10.

Pascual, M., P. Macchi, J. Urbanski, F. Marcos, C. Riva Rossi, M. Novara, and P. Dell'Arciprete. 2002. Evaluating Potential Effects of Exotic Freshwater Fish From Incomplete Species Presence–absence Data. *Biological Invasions* **4**:101-113.

Pelicice, F., and A. Agostinho. 2009. Fish fauna destruction after the introduction of a non-native predator (*Cichla kelberi*) in a Neotropical reservoir. *Biological Invasions* **11**:1789-1801.

Perez, J E., C. Alfonsi, M. Nirchio, C. Muñoz, J. A. Gómez. 2003. The introduction of exotic species in aquaculture: a solution or part of the problem?. *Interciencia*, vol.28, no.4, p.234-238. ISSN 0378-1844.

Philippart, J. C. 1995. Is captive breeding an effective solution for the preservation of endemic species? *Biological Conservation* **72**:281-295.

Piferrer, F., A. Beaumont, J. Falguière, M. Flajshans, P. Haffray, and L. Colombo. 2009. Polyploid fish and shellfish: Production, biology and applications to aquaculture for performance improvement and genetic containment. *Aquaculture* **293**:125-156.

Powell, M., M. Jones, and M. Lijalad. 2009. Effects of skeletal deformities on swimming performance and recovery from exhaustive exercise in triploid Atlantic salmon. *Diseases of Aquatic Organisms* **85**:59-66.

Ríos-Durán, M. G., A. R. Hernández-Téllez, C. A. Martínez-Palacios, and L. G. Ross. 2006. The effect of transportation stress on tissue ascorbic acid levels of Mexican silverside (*Chirostoma estor estor* Jordan, 1979). *Biocell*: *Official Journal of the Sociedades Latinoamericanas De Microscopía Electronica* **30**:149-155.

Ross, L., J. Blanco, C. Martinez-Palacios, I. Racotta, and M. Cuevas. 2007. Anaesthesia, sedation and transportation of juvenile *Menidia estor* (Jordan) using benzocaine and hypothermia. *Aquaculture Research* **38**:909-917.

Ross, L., C. Martinez-Palacios, M. Valdez, M. Beveridge, and M. Sanchez. 2006. Determination of feeding mode in fishes: the importance of using structural and functional feeding studies in conjunction with gut analysis in a selective zooplanktivore *Chirostoma estor estor* Jordan 1880. *Journal of Fish Biology* **68**:1782-1794.

Ross, L.G., Martinez-Palacios, C.A., and Morales E.J., 2008. Developing native fish species for aquaculture: The interacting demands of biodiversity, sustainable aquaculture and livelihoods. *Aquaculture Research*. **39**: 675-683.

Ryman, N., F. Utter, and L. Laikre. 1995. Protection of intraspecific biodiversity of exploited fishes. *Reviews in fish biology and fisheries* **5**:417-446.

Sagoff, M. 2007. Are nonnative species harmful? *Conservation Magazine* **8**, 20-21.

Saint-Paul, U. 1992. Status of aquaculture in Latin America. *Journal of Applied Ichthyology* **8**:21-39.

Sampaio, L. 2006. Production of "pejerrey" *Odontesthes argentinensis* fingerlings: A review of current techniques. *Biocell* **30**:121-123.

Sato, M. *et al.,* 2010. A review of the research on introduced freshwater fishes: new perspectives, the need for research, and management implications. *Landscape and Ecological Engineering*, **6**:99-108.

Scribner, K. T. and Avise, J. C. (1993). Cytonuclear genetic architecture in mosquito fish populations and the possible roles of introgressive hybridization. *Mol Ecol*, **2**: 139–149.

Scribner, K. T., K. S. Page, and M. L. Bartron. 2000. Hybridization in freshwater fishes: a review of case studies and cytonuclear methods of biological inference. *Reviews in Fish Biology and Fisheries* **10**:293-323.

Silva, S. S. D., T. T. T. Nguyen, G. M. Turchini, U. S. Amarasinghe, and N. W. Abery. 2009. Alien Species in Aquaculture and Biodiversity: A Paradox in Food Production. *AMBIO: A Journal of the Human Environment* **38**:24-28.

Sobel, J. M., G. F. Chen, L. R. Watt, and D. W. Schemske. 2010. The biology of speciation. *Evolution* **64**:295-315.

Somoza, G. M., L. A. Miranda, G. E. Berasain, D. Colautti, M. R. Lenicov, and C. A. Strüssmann. 2008. Historical aspects, current status and prospects of pejerrey aquaculture in South America. *Aquaculture Research* **39**:784-793.

Sriphairoj, K., W. Kamonrat, and U. Na-Nakorn. 2007. Genetic aspect in broodstock management of the critically endangered Mekong giant catfish, *Pangasianodon gigas* in Thailand. *Aquaculture* **264**:36-46.

Tapia, M., and L. Zambrano. 2003. From aquaculture goals to real social and ecological impacts: Carp introduction in rural Central Mexico. *AMBIO* **32**:252-257.

UN Population Division 2009. Jun 25. World Population Prospects. The 2008 revision. Retrived Jun 25 from http://www.un.org/esa/population/publications/wpp2008/wpp2008_highlights.pdf

Unmack, P. J. 2001. Biogeography of Australian freshwater fishes. *Journal of Biogeography* **28**:1053-1089.

Utter, F., and J. Epifanio. 2002. Marine aquaculture: Genetic potentialities and pitfalls. *Reviews in Fish Biology and Fisheries* **12**:59-77.

Vitule, J. R. S., C. A. Freire, and D. Simberloff. 2009. Introduction of non-native freshwater fish can certainly be bad. *Fish and Fisheries* **10**:98-108.

Wolf, D. E., N. Takebayashi, and L. H. Rieseberg. 2001. Predicting the Risk of Extinction through Hybridization. *Conservation Biology* **15**:1039-1053.

Zambrano, L., E. Martínez-Meyer, N. Menezes, and A. T. Peterson. 2006. Invasive potential of common carp (*Cyprinus carpio*) and Nile tilapia (*Oreochromis niloticus*) in American freshwater systems. *Canadian Journal of Fisheries and Aquatic Sciences* **63**:1903-1910.

Zambrano, L., M. Scheffer, and M. Martinez-Ramos. 2001. Catastrophic response of lakes to benthivorous fish introduction. *Oikos* **94**:344-350.

Zambrano, L., E. Valiente, and M. J. Vander Zanden. 2010. Food web overlap among native axolotl (*Ambystoma mexicanum*) and two exotic fishes: carp (*Cyprinus carpio*) and tilapia (*Oreochromis niloticus*) in Xochimilco, Mexico City. *Biological Invasions* **12**:3061-3069.

Chapter 5

Aquaculture of Native Fish Species at Catchment Level in Central Mexico; GIS-based Decision Support for the Culture of Native Species

VM Peredo-Alvarez, Trevor C Telfer and Lindsay G Ross.

This chapter describes the application of GIS as an analytical approach for development of native species aquaculture resource management that can identify appropriate site locations in Central Mexico for sustainable development. This has been recognized as an important requisite stage and sets the base line from which the rest of the sub-models in the study will follow.

The body of the text is presented as a publication-ready manuscript.

The main author, **VM Peredo-Alvarez**, developed all sub models and the final model. Trevor C Telfer and Lindsay G Ross provided supervisory and editorial support throughout the whole study.

This manuscript will be submitted to, **Aquaculture Research**, an international journal committed to the scientific advance and understanding of the various research topics relating to aquaculture production.

Chapter 5

Aquaculture of Native Fish Species at Catchment Level in Central Mexico: GIS-based Decision Support for the Culture of Native Species

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Abstract

The growing interest in aquaculture of native fishes worldwide requires robust and dynamic planning instruments for responsible management in order to minimise introductions of exotics and to ensure sustainability of biodiversity. This paper outlines the development of GIS-based tools at catchment level which address the culture of three species of native Atherinids (*Chirostoma estor, C. jordani* and *Atherinella balsana*) and two species of native Ictalurids (*Ictalurus balsanus* and *Ictalurus dugesii*) within a group of Mexican catchments. A species attribute database, and a GeoSpatial database were constructed with 90m resolution. A series of multi-criteria models were then created to assess site suitability for the development of native species aquaculture. From fourteen thematic layers, standardized to a scale from 0 – 1 using fuzzy set membership functions, four outcomes were generated: a Water sub-model (including physicochemical parameters and water availability), a Terrain sub-model used to identify suitable soils for pond construction, an Infrastructure sub-model that recognizes available markets and roads for transportation of goods, and a Risk sub-model showing areas that may be hazardous for the species. A constraint layer excluded unsuitable areas such as roads and railroads. Importantly, areas with no human influence were identified and included as constraints in order to avoid the growth of the industry in these natural places. The model results clearly identified 13,916 km^2 highly suitable for native silverside aquaculture and 11,178 km^2 suitable for native catfish aquaculture.

5.1 Introduction

Worldwide, the aquaculture industry continues growing, and with it the number of fish introductions. As a result there are increased efforts in the search for suitable new species for domestication and more environmentally friendly practices. The need to domesticate new aquatic species has been recognized, and it is a process in constant development (Duarte *et al*., 2007). So far, the number of cultured fish species is rather small and most of aquaculture’s production comes from only a handful of species (Ross and Beveridge 1995; Tapia and Zambrano 2003). According to Holmer *et al*., (2008) out of nearly 3000 species used for human consumption only 450 species are being cultured. The great majority of those species are being used in marine aquaculture, whereas freshwater practices still rely on just a few species with the best economical advantages such as tilapias, carps and prawns (Dey *et al*., 2005). The rate at which this small number of freshwater species has been introduced worldwide for aquaculture has doubled in the last 3 decades, a trend that can be expected to continue (Gozlan *et al*., 2010). This trend is becoming one of the major threats to freshwater biodiversity in the form of species homogenization (Ribeiro *et al*., 2009).

Concerns have been growing about the impact that non-native species have on biodiversity and it is a topic that has been widely discussed (Irons *et al*., 2007, Yonekura *et al*., 2007, Pelicice and Agostinho 2008, Gozlan, *et al*., 2010). Silva *et al*., (2009) called the relationship between aquaculture and biodiversity a paradox in food production, referring to the necessity for increasing the supply of aquatic food products and the impact that this has on biodiversity. However it has been suggested that the development of aquaculture technologies for native species can be a more environmentally friendly practice and should be encouraged in place of the continued introduction of few exotic species (Ross and Beveridge 1995, Perez *et al*., 2003, Magurran 2009, Vitule *et al*., 2009).

The freshwater fish fauna of Mexico is highly diverse; it includes around 500 species and has a very high degree of endemism with 311 species of freshwater fishes known solely from Mexico (Miller *et al*., 2005; FishBase 2011). However freshwater fish populations in Mexico are becoming depleted as a result of interactions with introduced species and overfishing (Lyons *et al*., 2000). According to the FAO (2010) by 2008 freshwater fish production in Mexico was 110,189 t of which only 4,653 t came from aquaculture. Furthermore, most of aquaculture's production in Mexico is dominated by introduced tilapia spp and Asian carp (CONAPESCA 2010), whereas the aquaculture of native freshwater fish is scarce. By 2008, the production of tilapia spp was 3,689 t, accounting for more than 79% of the total production for that year (FAO 2010). In an effort to protect Mexican biodiversity without compromising national food security, the National Commission for the Understanding and Use of Biodiversity (CONABIO) has promoted the diversification of resources and the commercialization of sustainable "green markets"; a strategy that encourages the use of native species (Ross *et al*., 2006). Even though this strategy has been encouraged by CONABIO since the end of the last century, the lack of sufficient information on native fish species and the development of appropriate culture techniques has proved challenging.

5.1.1 GIS in Aquaculture

The responsible development of new aquaculture species in Mexico requires a complex range of information structured in a logical way. Geographical information systems (GIS) are proving to be a useful tool for assembling the required spatial and non-spatial information for decision making in aquaculture (Ross and Beveridge 1995; Kapetsky *et al*., 1988; Wilson and Fotheringham 2007; Radiarta *et al*., 2008).

For all types of aquaculture, there is a strong necessity for location suitability issues to be considered in the planning stages (Longdill *et al*., 2008). Failure to address this factor often results in the selection of inferior sites, which can be reflected in unsuccessful aquaculture developments and stressed ecosystems (Londgill *et al*., 2008). The development of spatial databases for aquaculture sites allow the use of GIS as a decision support tool, which can help the aquaculture developers and the government regulator in assessing and managing such sites (Simms 2002). The use of GIS for aquaculture has increased in the last ten years, and its planning potential has been widely discussed elsewhere (Nath *et al*., 2000; Kapetsky and Aguilar-Manjarrez 2007; Radiarta *et al*., 2008).

Site selection for semi-intensive aquaculture should be one of the most important decisions in aquaculture development. Site selection is a basic function for GIS technology (Fei *et al*.,, 2009) and has been widely applied to marine cage aquaculture (Perez *et al*., 2005; Benetti *et al*., 2010), shrimp aquaculture (Salam *et al*., 2003, Hossain and Das 2010), and bivalves (Arnold *et al*., 2000; Radiarta *et al*., 2008). In this paper we explore the site suitability for semi-intensive aquaculture of six native Mexican fish species, from the Atherinopsidae and the Ictaluridae families.

5.2 Study Area

The basins of the rivers Lerma and Grande de Santiago (fig 5.1, a, b) are located in central Mexico, between the coordinates 19°03' N and 21°32' N latitude, and 99° 18' W and 03° 46' W longitude. They are connected by Chapala Lake, the largest natural water body in Mexico, and together form one of the 23 hydrologic systems within the Pacific watershed (Alcocer and Bernal-Brooks, 2010). The Lerma-Santiago hydrologic system has a catchment area of 132,724 km^2, covering almost 7% of the Mexican territory. Its average annual temperature fluctuates between 18 to 22°C (Kwak *et al*., 2009). It is a densely populated area that by 2000 had reached 9.5 million inhabitants, mostly distributed in the city of Toluca and in what is known as the industrial corridor, streching more than 200 km between the cities of Leon and Queretaro (Cotler 2004). The Lerma basin is one of the most endangered in the world due to its excessive water extraction for agriculture and human consumption (Wester *et al*., 2001).

The Rio Balsas' basin (fig 5.1, d) is situated in south-central Mexico and it also forms part of the Pacific watershed. It is flanked by the mountain chains of the "Eje Neovolcanico Transversal" and the "Sierra Madre del Sur", between the 17°00' N and 20°00' N latitude and 97°30' W and 103°15' W longitude. It occupies an approximated hydrologic surface area of 117,406 km^2 (Toledo 2003). Its altitude varies from 100 meters above sea level (masl) at the gully of Coahuayutla near the outlet, to 5 452 masl at the Popocatepetl volcano; its average altitude is less than 200 masl (Zepeda 2005). Due to its location, the catchment fits into the tropical zone, with annual mean temperature varying according to the altitude from 18° C to 26° C (Zepeda 2005). Regardless of the Rio Balsas basin's size (almost as big as the Lerma and Santiago basins together), it is scarcely populated due to its rough terrain (Toledo 2003); it also produces considerably less water ($\sim 1.2 \times 10^{10}$ m^3) and is home to only 30 native species (Miller *et al*., 2005).

Figure 5.1: The three major basins in central Mexico selected for this study; the hydrological region No. 12 formed by the Lerma (a) and Santiago (b) basins and the Balsas basin (d) which contributes to the biggest fresh water output to the west coast. Also in this image is Chapala Lake (c) which connects the Lerma and Santiago basins and is the largest water body in the country, and Mexico City (d) the largest city in Mexico.

5.2.1 Targeted Native Species for Aquaculture in Central Mexico

Six fish species native to the basins of Lerma-Santiago and Balsas can be considered as suitable candidates for aquaculture (Table 5.1). Four of these species belong to the Atherinopsidae family, three of them (*Chirostoma estor, C. promelas* and *C. jordani*) native to the Lerma-Santiago basins, and *Atherinella balsana* native to the Balsas' basin. Two more species belong to the Ictaludae family; one is native to the Lerma-Santiago (*Ictalurus dugesii*) and another to the Balsas basin (*I. Balsanus*).

The Lerma basin has a considerable number of native atherinids, many of them endemic to the region. They are divided into the Jordani group, consisting of larger species known locally as 'pescados blancos', and the Arge group, consisting of the smaller species known collectively as 'charales' (Martinez-Palacios *et al*., 2008). These species of fish are highly consumed and even considered a delicacy. The Mexican Silverside *C. estor* (Jordan 1880), a member of the Jordani group, is the principal species in the artisanal fishery in Lake Patzcuaro due to its tradition, aspect, flavour, exclusivity and very high market value (Martinez-Palacios *et al*., 2007b). However, fisheries for this species have been collapsing in recent years (Lyons *et al*., 2007) and fisheries of "charales" have grown as a response. Furthermore, due to the difficulty in taxonomic differentiation between adults of charal and juveniles of the bigger species, it has been suggested that fishing is still one of the many reasons for the reduction of *C. estor* populations in Patzcuaro lake, along with declines in water quantity and quality (Badillo and Garcia, 2009).

The economic value of *C. estor* is high, with a seasonally sensitive price in regional markets of 40-80 USD kg^{-1} (Martinez-Palacios *et al*., 2002). Although aquaculture of this species is still in the prototype stages, many advances in its development have occurred in the last few years (Martinez-Palacios *et al*., 2004; Ross *et al*., 2006; Toledo-Cuevas *et al*., 2006; Martinez-Palacios *et al*., 2007a; Martinez-Palacios 2007b, Ross *et al*., 2007; Martinez-Palacios 2008).

Charales also have a big market. Dried charales are widely distributed throughout central Mexico and they are easy to find in the major stores. Due to this large market and the impact that fisheries may have on the environment, aquaculture of the charales *C. jordani* and the related species of *Atherinella balsana* would also make a worthwhile project.

In Mexico, channel catfish are common in both the Pacific and Atlantic slopes and there are at least 9 species of *Ictalurus* (Miller *et al*., 2005). The consumption of channel catfish, (especially *I. punctatus)* is high in Mexico, due to the appreciation of its flesh and flavour (Sanchez-Martinez *et al*., 2007). In 2008 aquaculture produced 970 t of *Ictalurus* sp; most of it coming from the production of the channel catfish *I. punctatus* (FAO 2010). Aquaculture of *I. punctatus* is strongest in the northern state of Tamaulipas where it is endemic, but its highest demand occurs in the states of Jalisco, Michoacan, and Guerrero (all of them in the basins of Lerma-Santiago and/or Balsas). For this reason the species has been introduced for aquaculture in these basins. The Pacific slope species *I. dugesii* and *I. balsanus* are very similar in most biological parameters to *I. punctatus*, which makes them strong candidates for aquaculture of native species. In addition, both species are included in the AFS Endangered Species Committee list of imperilled freshwater and diadromous fish of North America, with the status of vulnerable (Jelks *et al*., 2008).

5.3 Methods

The principal GIS software used for this study was IDRISI 15.0 the ANDES Edition, developed at Clark University, USA. The models for semi–intensive aquaculture of native species were created following the Weighted Multicriteria Evaluation technique (Kapetsky and Aguilar-Manjarrez 2007; Store, 2009). Four main sub-models (Water quality and Availability, Soil and Terrain, Infrastructure and Risk) were developed in order to provide relevant information into the final model. A final layer of constraints was also included to identify those areas where the development of aquaculture would be unsuitable. The modelling procedure for native fish species in central Mexico is described in fig 5.2. An Attribute database was created with information collected from literature, museum collections and web-based fish databases. The principal database contains information related to fish species in the area of study covering life history, morphometric measures, distribution, reference, etc. Additionally a Spatial database was created with a set of

Table 5.1: New native fish species, candidates for aquaculture at catchment level in central Mexico.

Specie	**Family**	**Basin**	**Known Location**	**Aquaculture**	**Common name**	**Reference**	**Available technology**
Ictalurus dugesii	Ictaluridae	Lerma	Bajo Lerma; Rio Ameca: Rio Grande de Santiago; Rio Verde;Rio Turbio: Chapala Lake	No	Lerma Catfish	Meek 1904; UNAM IdB	*I. punctatus*
Chirostoma estor	Atherinopsidae	Lerma	Lake Patzcuaro; Lake Zirahuen; Lake Chapala	Pilot	Silverside	De Buen 1945a	*Menidia esto sp*
Chirostoma promelas	Atherinopsidae	Lerma	Lake Chapala; Rio Grande de Santiago: Rio Salto de Juanacatraln	Pilot	Blacknose Silverside	Barbour 1973 a, b& Chernoff 1985;UNAM IdB	*Menidia esto sp*
Chirostoma jordani	Atherinopsidae	Lerma	Widely spread in the Lerma-Santiago Basins	No	Charal	Barbour, 1973a	*Menidia esto sp*
Ictalurus balsanus	Ictalurdae	Balsas	Balsas river and tributaries	No	Balsas Catfish	Jordan and Snyder 1899; Meek 1904	*I. punctatus*
Atherinella balsana	Atherinopsidae	Balsas	Pacific slope, Rio Balsas	No	Plateado del Balsas	Chernoff 1986a,b	*Menidia esto sp*

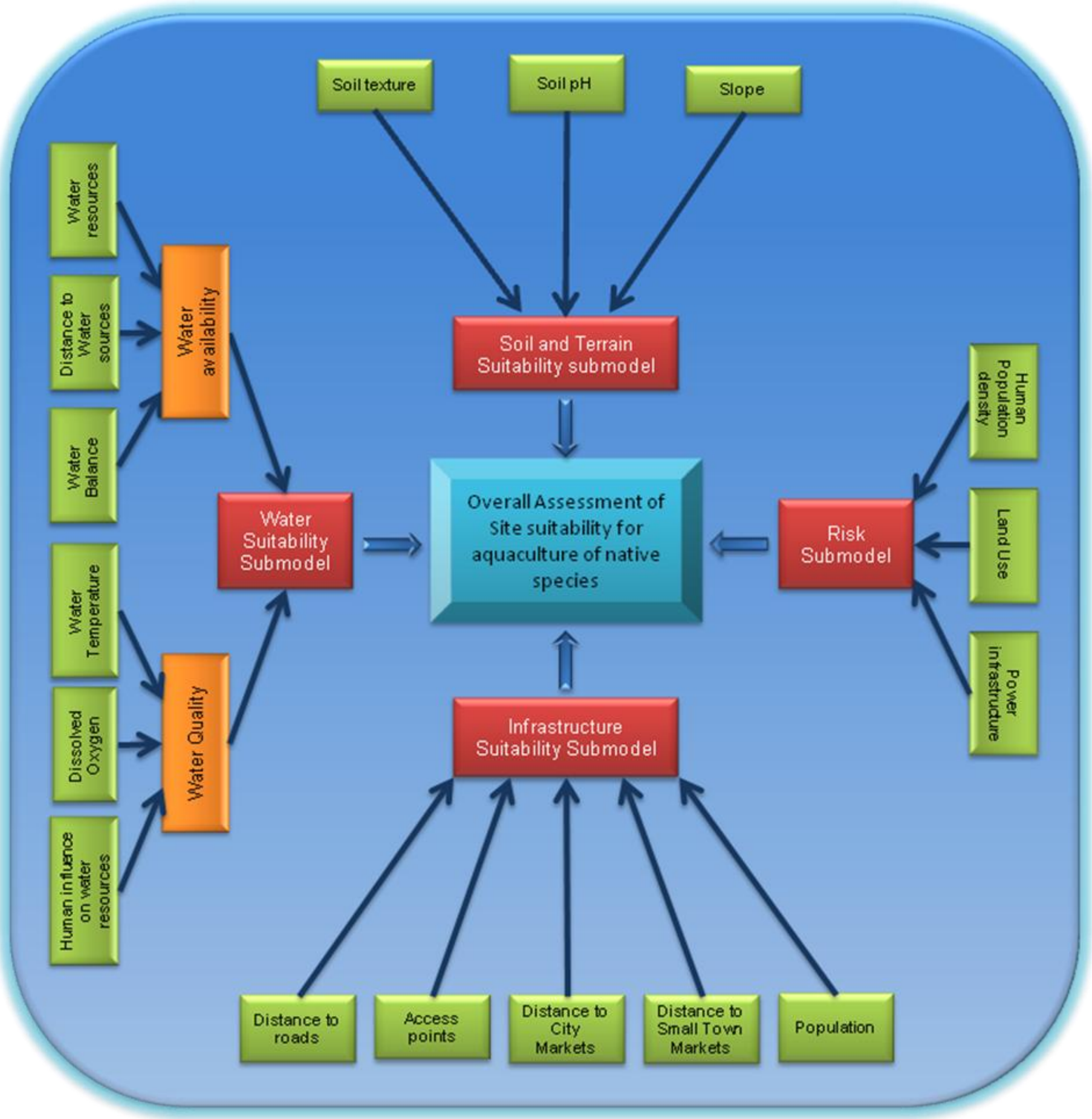


Figure 5.2: Modeling procedure for site suitability for aquaculture of Mexican native species.

thematic layers obtained from the Mexican Institute of Geography (INEGI), the USGS hydro 1k data set, CONABIO (Mexico), and the Landsat program. All Thematic layers were projected in Lambert Conformal Conic georeference, with a 90 m resolution. The employed data includes Monthly Mean Air Temperature, Monthly Mean Precipitation, DEM, Land Use, Soil texture, Soil pH, Rivers, Lakes, Roads and Rail roads, Stable lights, and 2005 Population density

5.3.1 Classification

Using the FUZZY module within the IDRISI environment, all thematic layers were reclassified to a suitability scale from 0 to 1. Fuzzy set classification, evaluates the degree of membership of each pixel in all classes under consideration. This method is commonly used to reclassify parameters where the transition between membership and non-membership in the set is gradual (Robinson 2003). From a range of options, the Sigmoidal and Linear membership functions were selected according to the type of factors to be reclassified. IDRISI ANDES requires the input of four membership function constant points (*a*, *b*, *c*, and *d*) as inputs for the calculations (fig 5.3), the assigned values to each point being based on the limiting and optimum values of the parameter to be reclassified. The order of the inputs depends on the type of function to be used. For "monotonically increasing" or "monotonically decreasing" functions only two control points are required to define the fuzzy set membership function, that is points *a* and point *b*, or point *c* and point *d* respectively. Whereas symmetric curves require the four control points to be input in the following order: *a*, *b*, *c*, and *d* (Eastman 2009) (fig 5.3 b,c).

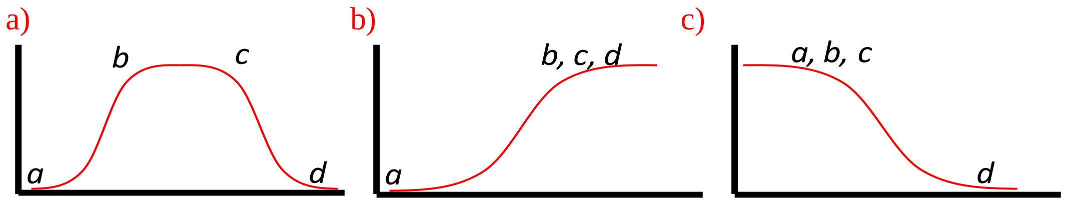


Figure 5.3: Sigmoidal (s-shape) membership functions, where: *a*= membership rises above 0; *b*= membership becomes 1; *c*= membership falls below 1; and *d*= membership becomes 0.

For the sigmoidal membership function, the following formula was used:

$$\mu = \cos^2 \alpha \qquad \textbf{[Equn 1]}$$

where, for a monotonically decreasing function:

$$\alpha=(x- \text{point } c)/(\text{point } d - \text{point } c) * pi/2 \qquad \textbf{[Equn 2]}$$

When x < pointc, $\underline{m}$ =1. A monotonically increasing function:

$$\alpha=(1-(x- \text{point } a)/(\text{point } b - \text{point } a)) * pi/2 \qquad \textbf{[Equn 3]}$$

When x > pointc, $\underline{m}$ =1.

Dissolved oxygen (DO), and Temperature were the two factors that were species specific. However, since these studied native species are relatively new to aquaculture, the factors were reclassified accordingly to the known requirements of related species.

In the case of the studied Atherinids, culture parameters where obtained from the known technology of *Chirostoma estor* aquaculture and from the well established culture of *Ictalurus punctatus* for the two Ictalurid species. The remaining factors were reclassified accordingly to standardized methodologies (Table 5.2).

5.3.2 Multi-Criteria Evaluation (MCE) analysis

The application of a Multi-Criteria Evaluation allows the combination of several parameters into an aggregated evaluation matrix and the investigation os alternatives in the light of multiple criteria and conflicting objectives (Voogd, 1983). Weights were assigned based on a pairwise comparison matrix with a 9 point continuous rating scale from 1/9 (extremely least important) to 9 (extremely more important) (Saaty 1977). It has been suggested that the assignment of weights during a MCE can be partially subjective (Aguilar-Manjarrez, 1995; Nath *et al*., 2000; Hossain & Dass, 2010); to address this issue, a group of 8 aquaculture experts from the Department of Aquaculture of the Institute of Natural Resources (IIAF) in Michoacan Mexico, and from the Institute of Aquaculture of the University of Stirling were invited to rank selected factors in order of relevance. The consistency ratios (*CR*) obtained for all models were within those recommended by Saaty (1977) of equal or less than 0.10.

Table 5.2: Membership function's constant points, for reclassification of variables.

Factor	**Unit**	**Atherinids**				**Ictalurids**				**Membership function**	**Reference**
		Membership Function's Constant Points									
		a	***b***	***c***	***d***	***a***	***b***	***c***	***d***		
Temperature	°C	5	23	26	34	5	25	28	42	Symmetric Sigmoidal	Martinez-Palacios *et al.*,, (2002), Buentello *et al.*, (2000), Pearson and Green (2006)
DO	mg/l	0	2	2	2	0	5	5	5	Monotonically increasing Sigmoidal	Buentello *et al.*, (2000), Martinez-Palacios *et al.*,, (2006), Francais, Pearson and Green (2006)
Distance to water	m	500	500	500	3000	500	500	500	3000	Monotonically increasing Sigmoidal	McLeod *et al.*, (2002)
pH aqua-soil	pH	4.5	7.2	8.5	10	4.5	7.2	8.5	10	Monotonically decreasing Sigmoidal	Kapetsky and Nath (1997), Boyle (2002)
Stable lights	%	0	0	0	70	0	0	0	70	Monotonically decreasing Sigmoidal	Sanderson *et al.*, 2002
Slope	°	4	4	4	10	4	4	4	10	Monotonically decreasing Sigmoidal	Aguilar-Manjarrez & Nath 1998
Soil texture	Clay %	5	50	50	50	5	50	50	50	Monotonically increasing Sigmoidal	Aguilar-Manjarrez & Nath 1998
Distance to roads	m	1000	1000	1000	3000	1000	1000	1000	3000	Monotonically decreasing J-shaped	Aguilar-Manjarrez & Nath 1998
Distance to potential Rural market	m	1000	1000	1000	4000	1000	1000	1000	4000	Monotonically decreasing Sigmoidal	Modified from Aguilar-Manjarrez & Nath (1997)
Distance to potential Urban market	m	4000	4000	4000	10 000	4000	4000	4000	10 000	Monotonically decreasing Sigmoidal	Modified from Aguilar-Manjarrez & Nath (1997)
Human Footprint	%	0	0	0	100	0	0	0	100	Monotonically increasing linear	Sanderson *et al.*, 2002

5.3.3 Databases and variables

The variables used in the sub models were obtained from different sources. The temperature and precipitation datasets were obtained from the WorldClim – Global Climate Data, which contains mean monthly information over 30 years. The ISRIC World Soil Database was used to obtain relevant soil characteristics; it contains information on several parameters in 5 layers of 20 cm each to a meter depth. The Digital Elevation Map was obtained from the US Geological Center. Roads, railroads, water bodies, land use and population densities were obtained from the Mexican National Institute of Geography and Population.

5.3.4 Water Quality and Availability Sub Model

This sub model consists of two primary components, the Water Availability sub model which includes factors relevant to the existence of the resource, and the Water Quality sub model which is based on the species requirements for aquaculture and water pollution.

For the Water Availability sub model, water sources for aquaculture, proximity to such sources and water balance were integrated into a MCE; the applied weights and *CR* can be seen in Table 5.3. The water sources in the area of study were included as a Boolean thematic layer which shows all water bodies (rivers, lakes and reservoirs) of the region. Proximity to water sources was calculated in meters using the distance module in IDRISI ANDES, and reclassified where

<1km was considered highly suitable and >3 km highly unsuitable. The Water balance was calculated following the formula:

WB = [(Precipitation mm x 1.1) – (Evapotranspiration x 1.3) – (soil permeability)] [Equn 4]

The water quality sub model includes Temperature, Dissolved Oxygen, and Pollution. Mean Monthly Air Temperature over a period of 30 years was used as a proxy for water temperature. Dissolved Oxygen was calculated at saturation level following the formula:

D.O. = ((P-U) x 0.678) / (35+t) [Equn 5]

where, P= atmospheric pressure, U= saturated vapour pressure and t= temperature (Beveridge *et al*., 1985).

Water Pollution was calculated by using the World stable lights (add data source for this) as an indication for industry, population density and land use which were considered the three most important factors that create water pollution (table 5.3). Temperature (°C), Dissolved oxygen (mg/l), and water pollution, where included, in a weighted MCE (table 5.3) to produce a Water Quality sub model.

The water sub model was obtained by combining the two primary sub models of Water Availability and Water Quality, into a weighted MCE. Since the Water Quality sub model was based on the specific requirements of each group of species for aquaculture, a higher weight was given to this factor. The weights applied to this sub model can be seen in table 5.3.

Table 5.3: Weights applied in the Water sub model.

Water quality		**Water availability**		**Water sub model**	
Factor	**Weighting**	**Factor**	**Weighting**	**Factor**	**Weighting**
Temperature	0.6370	Distance to water	0.60	Water quality	0.60
Water Pollution	0.2583	Water balance	0.40	Water availability	0.40
DO	0.1047				
CR	0.03	*CR*	0.00	*CR*	0.00

5.3.5 Soil and Terrain Sub model

The Soil and Terrain sub model incorporates slope, soil texture and pH into an MCE to identify suitable areas for the construction of pond aquaculture. The slope was calculated from a DEM and was reclassified where <4° of inclination was taken as highly suitable (Aguilar-Manjarrez & Nath 1998). Weights and CR are showed in Table 5.4.

Table 5.4. Weights applied in the Soil and Terrain sub model

Factor	**Weighting**
Slope	0.6370
Soil texture	0.2583
pH aqua	0.1047
Consistency Ratio	*0.03*

5.3.6 Infrastructure Sub model

An infrastructure layer was incorporated into the final model. This layer was the output of an MCE that integrated distance to access points and distance to urban and rural markets. Weighting values and *CR* can be observed in table 5.5.

Table 5.5. Weights applied in the Infrastructure sub model.

Factor	**Weighting**
Access	0.6833
Urban Market	0.1998
Rural Market	0.1168
Consistency Ratio	*0.02*

5.3.7 Environmental Risk Sub model

Following the methodology used by Sanderson *et al*., (2002) the Human Foot Print (HFP) was included as an environmental risk factor to consider. Using population density, land use, roads, and the power infrastructure of the region, a human influence index was generated (Sanderson *et al*., 2002). This was then reclassified to a percentage scale to give the Human Foot Print. The higher the score, the more the area is influenced by human activities. It can be assumed that areas with high human influence may have lower quality for aquaculture. It can also be assumed that the development of aquaculture in areas with the lowest human activity may affect the environment. Therefore those areas with 0% of human impact were included in the constraints layer as a way of preventing aquaculture from developing in these areas and preserve its state of wilderness.

5.3.8 Constraints

A layer with constraints for the development of aquaculture was created identifying areas where the construction of pond aquaculture would not be possible, such as roads and railroads, protected areas, and those areas identified from the HFP as undisturbed by humans.

5.3.9 Site suitability model for semi-intensive aquaculture of native fish species

The final site suitability models were created using a weighted MCE in which each of the initial four sub models was weighted to indicate relative importance. The calculated weights and *CR* can be seen in table 5.6.

Table 5.6: Weights applied in the site suitability model.

Factor	**Weighting**
Infrastructure Sub model	0.5078
Water Sub model	0.3241
Soil and terrain Sub model	0.1025
Risk Sub model	0.0656
Consistency Ratio	*0.02*

5.3.10 Suitability score Interpretation

Areas with > 0.8 of membership in the scale of suitability have been selected as suitable for aquaculture, based on observation that in all variables 0.8 represented the lower range of the recommended parameters after reclassification. Based on those observations, areas with 0.7 to 0.8 were considered as marginally suitable.

For the final model a mean monthly suitability layer was calculated. We also produced a Boolean layer for each month of the year, where values > 0.8 = 1 and values < 0.8 = 0. A simple calculation of the sum of all 12 months Boolean layers was used to produce a final result showing the areas with high suitability throughout the full year. Values of 11 or less showed that suitability was not constant every month and therefore these areas were not included as highly suitable for aquaculture.

5.4 Results

5.4.1 Water quality and availability sub model

The overall sub model of Water Quality and Availability for both groups of fish shows a clear distinction in seasonality, with higher suitability observed over the entire studied area between the months of June and October and lower suitability during the months of November to May. This is the greatest limiting factor for the development of semi intensive aquaculture (Fig 5.4 and 5.5).

5.4.1.1 Water Quality and Availability sub model for Atherinids

The model results show clear differences between the hydrologic systems of Lerma-Santiago and Balsas, with higher overall suitability year around in the Balsas catchment area (Fig 5.4). However, the highest suitability was observed in the Lerma-Santiago's major water bodies during the months of June to September. This coincides with the natural distribution of the majority of the members of this family.

5.4.1.2 Water Quality and Availability sub model for Ictalurids

The model results for *I. dugesii* and *I. balsanus*, showed higher suitability near water bodies of both hydrologic systems during the rainy season (June to September) (Fig 5.5). A clear influence of highly populated areas can be identified, since year around suitability is lower around these areas regardless of changes in seasonality.

5.4.2 Soil and Terrain Sub model

The Soil and Terrain sub model identified 67,031.78 km^2 of highly suitable (>0.8) area in the Lerma-Santiago system, along with 4,943.11 km^2 of marginal suitability (0.7-0.8). Whilst for the Balsas' basin, 29,039.44 km^2 of highly suitable areas (>0.8), and 3,740.74 km^2 of marginal suitability where identified (Fig 5.6).

5.4.3 Infrastructure Sub model

The Infrastructure sub model shows the highest suitability near roads and access points that are close to urban and rural markets. It was found that there were 36,298.1 km^2 of highly suitable areas and 15,112 km^2 of marginal suitability in the Lerma-Santiago basins, and 31,826.19 km^2 of highly suitable area and 10,781 km^2 of marginally suitable areas in the Balsas basin (Fig. 5.7).

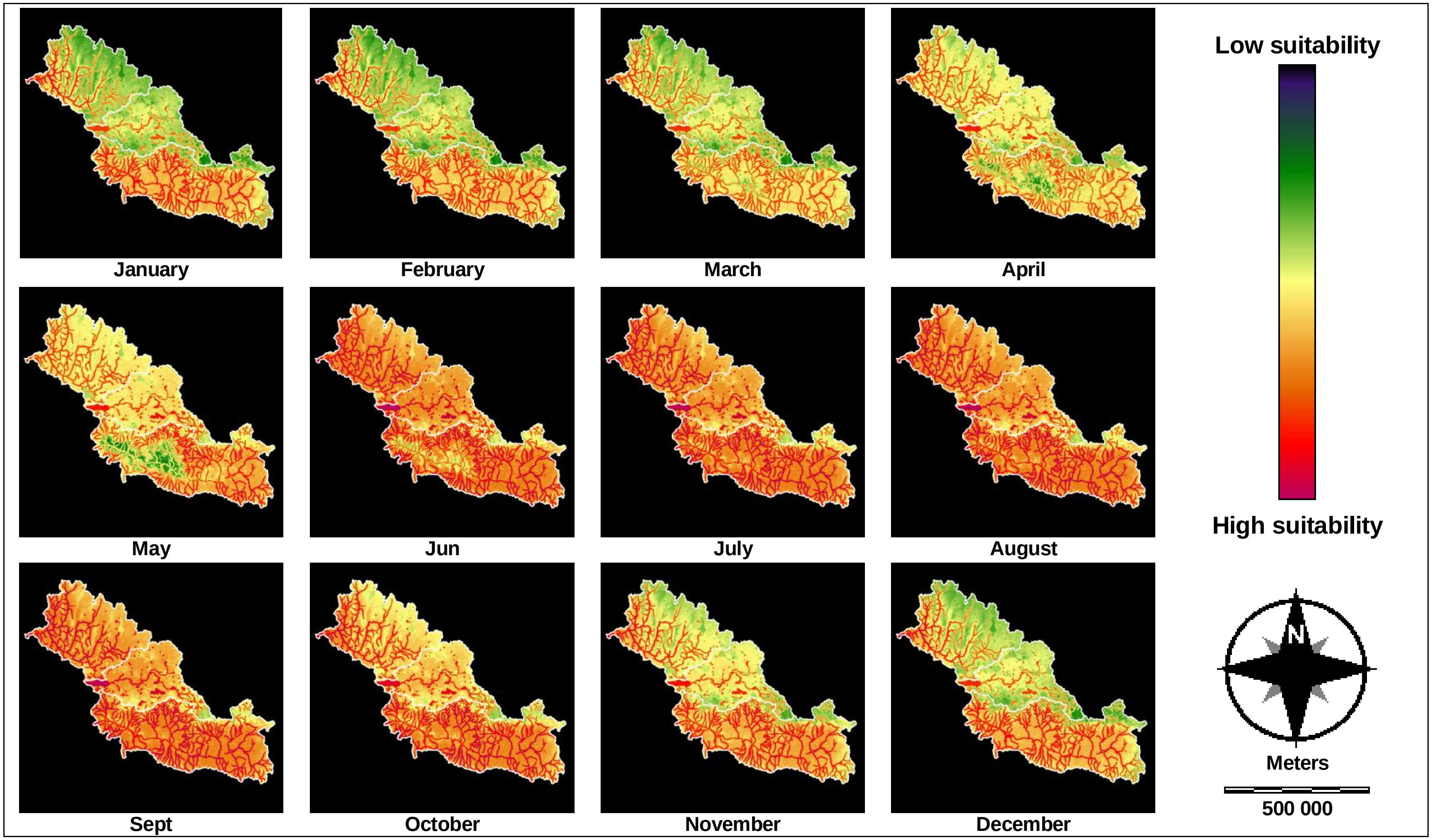


Figure. 5.4: Water sub model for aquaculture of *C. estor, Ch. promelas, C. jordani* and *A. Balsana* over 12 months.

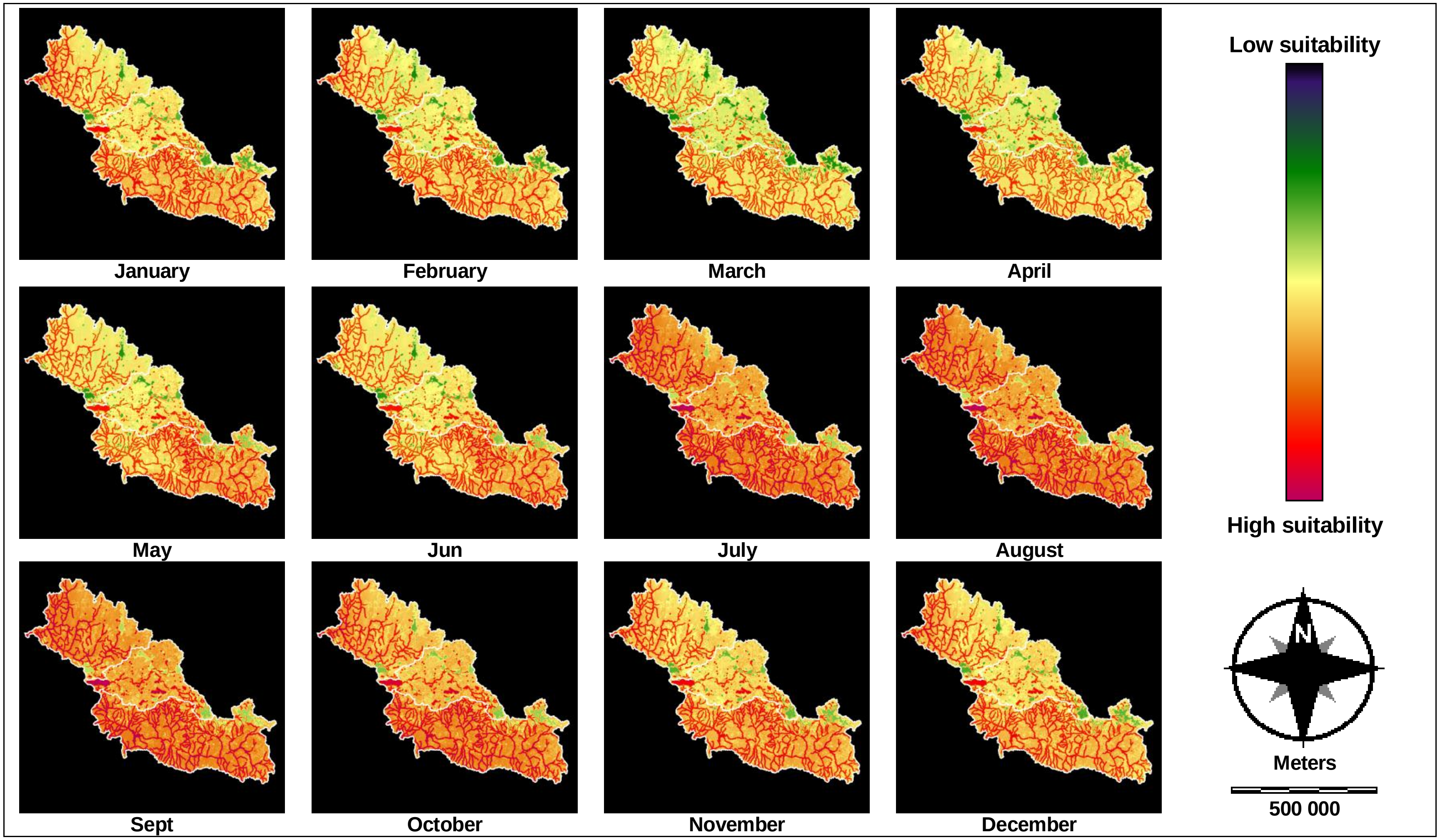


Figure. 5.5 Water sub model for aquaculture of *I. dugesii* and *I. balsanus* over 12 months.

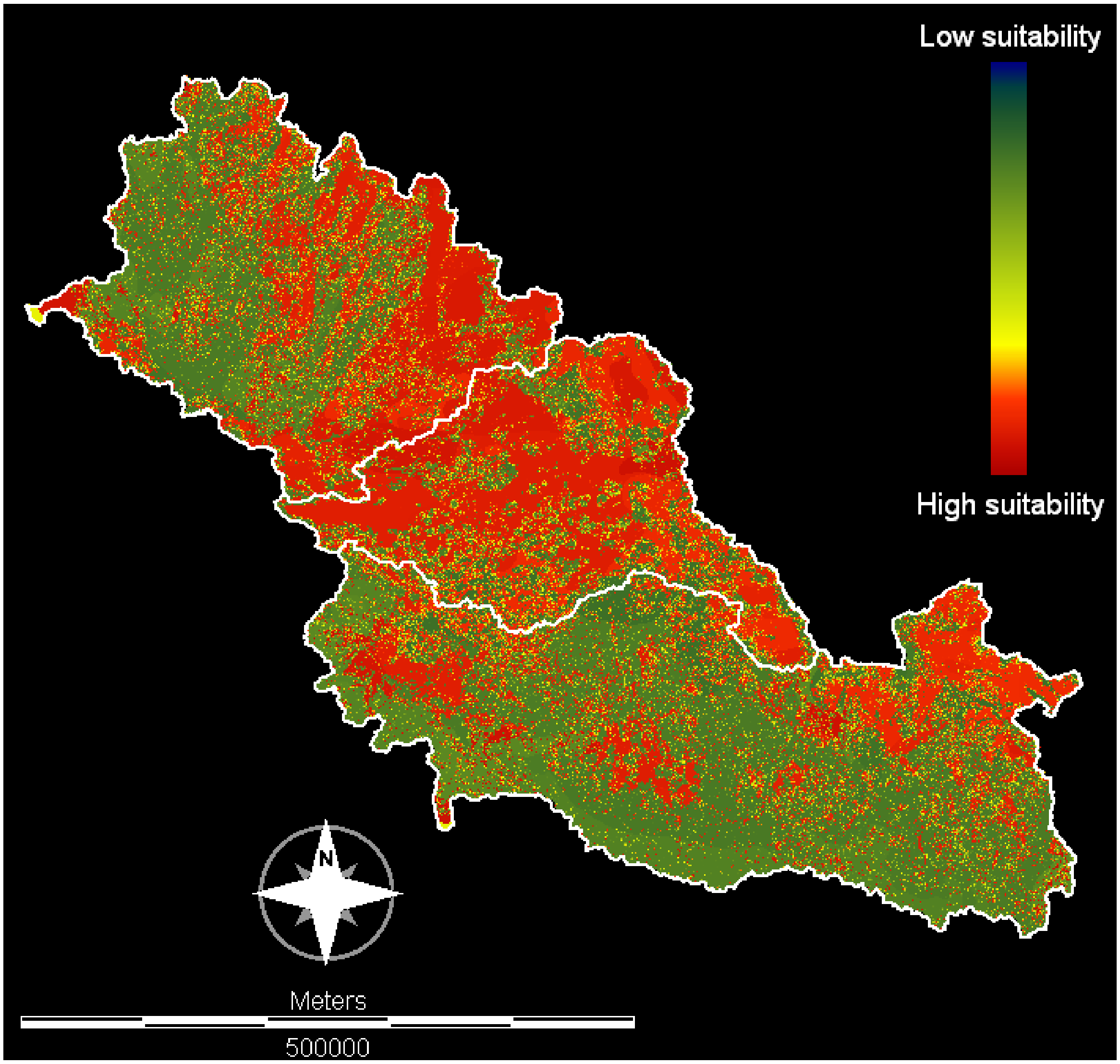


Figure. 5.6: Soil and terrain sub model for semi-intensive aquaculture in the basins of Lerma-Santiago and Balsas.

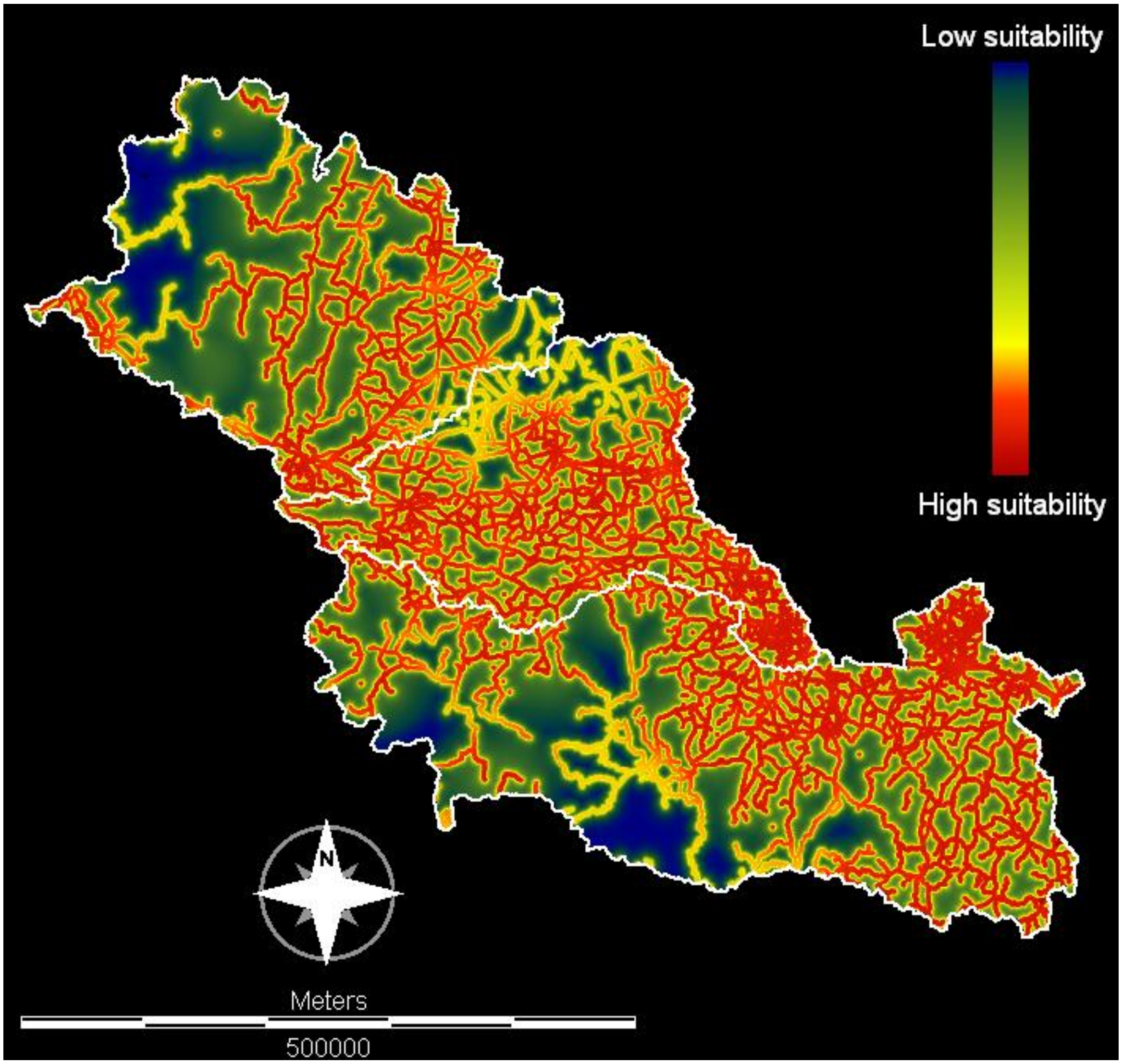


Figure. 5.7: Infrastructure sub model for semi-intensive aquaculture in the basins of Lerma-Santiago and Balsas.

5.4.4 Environmental Risk sub model

The Environmental Risk sub model successfully identified those areas with least human influence. Almost 49% of the Lerma-Santiago hydrologic system and 58.5% of the Balsas catchment showed high suitability value of 0.8 or more. For the Lerma-Santiago basins, the Environmental Risk sub model showed 63,324 km^2 and 47,525 km^2 of high and marginal suitability, respectively. For the Balsas basin the sub model identified 65,667 km^2 of highly suitable areas and 34,286.44 km^2 of marginally suitable areas. Roads and highly populated areas constituted the greatest risk factor, since they consistently presented the lowest suitability values in this model, especially in the vicinities to the principal cities (fig 5.8 A, Guadalajara; B, Toluca; C, Puebla).

From the combined highly suitable area (128,991 km^2), 9,809 km^2 presented the highest suitability of 1 which was equal to 0% of human influence according to the HFP (Lerma-Santiago: 5,533 km^2 and Balsas: 4,275 km^2). Such areas were also included in the constraint layer in order to avoid the development of aquaculture (Fig. 5.8).

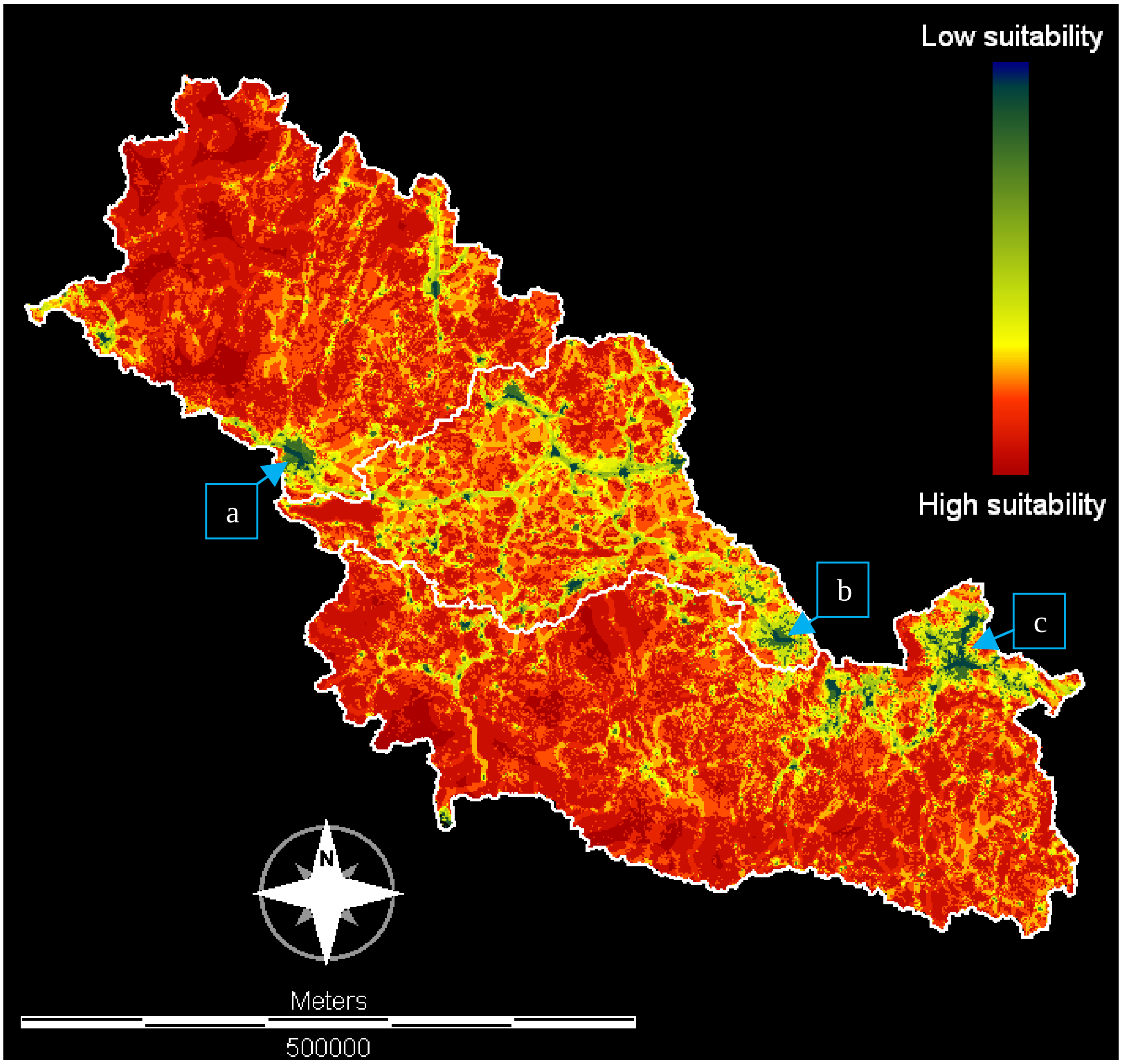


Figure 5.8: Environmental Risk sub model for semi-intensive aquaculture in the basins of Lerma-Santiago and Balsas. The lowest suitability can be seen near the big metropolis, Guadalajara (a), Toluca (b) and Puebla (c).

5.4.5 Site Suitability model for semi intensive aquaculture of native species

The final model encompasses a 12 months' time series for each species within its native catchment on a scale of suitability from 0 to 1.

5.4.6 Site Suitability model for aquaculture of Atherinids in central Mexico

The model of Site Selection for aquaculture of Atherinids in central Mexico identified 6,216 km^2 of highly suitable area (averaged over 12 months >0.8) in the Lerma-Santiago basins. This area can be recommended for the culture of *C. estor, C. promelas*, and *C. jordani.* The model also identified 27,575 km^2 of marginal suitability (average over 12 months >0.7) for aquaculture of these species in the same basins. For the Balsas basin the final model identified 7,799 km^2 of highly suitable areas and 22,927 km^2 of marginally suitable areas for the culture of *A. balsana* (Fig 5.9).

The model also showed that for the culture of *C. estor, C. promelas*, and *C. jordani* in the Lerma-Santiago basins, 3,252 km^2 have high suitability (>0.8) throughout the year (Fig 10a,b). In the Balsas basin, 3,408 km^2 have high suitability (>0.8) for the culture of *A. balsana* throughout the entire year (Fig 10c). The main factors that determined this results was the presences of water sources and access points, however temperature and water balance determined seasonality and therefore suitability year around.

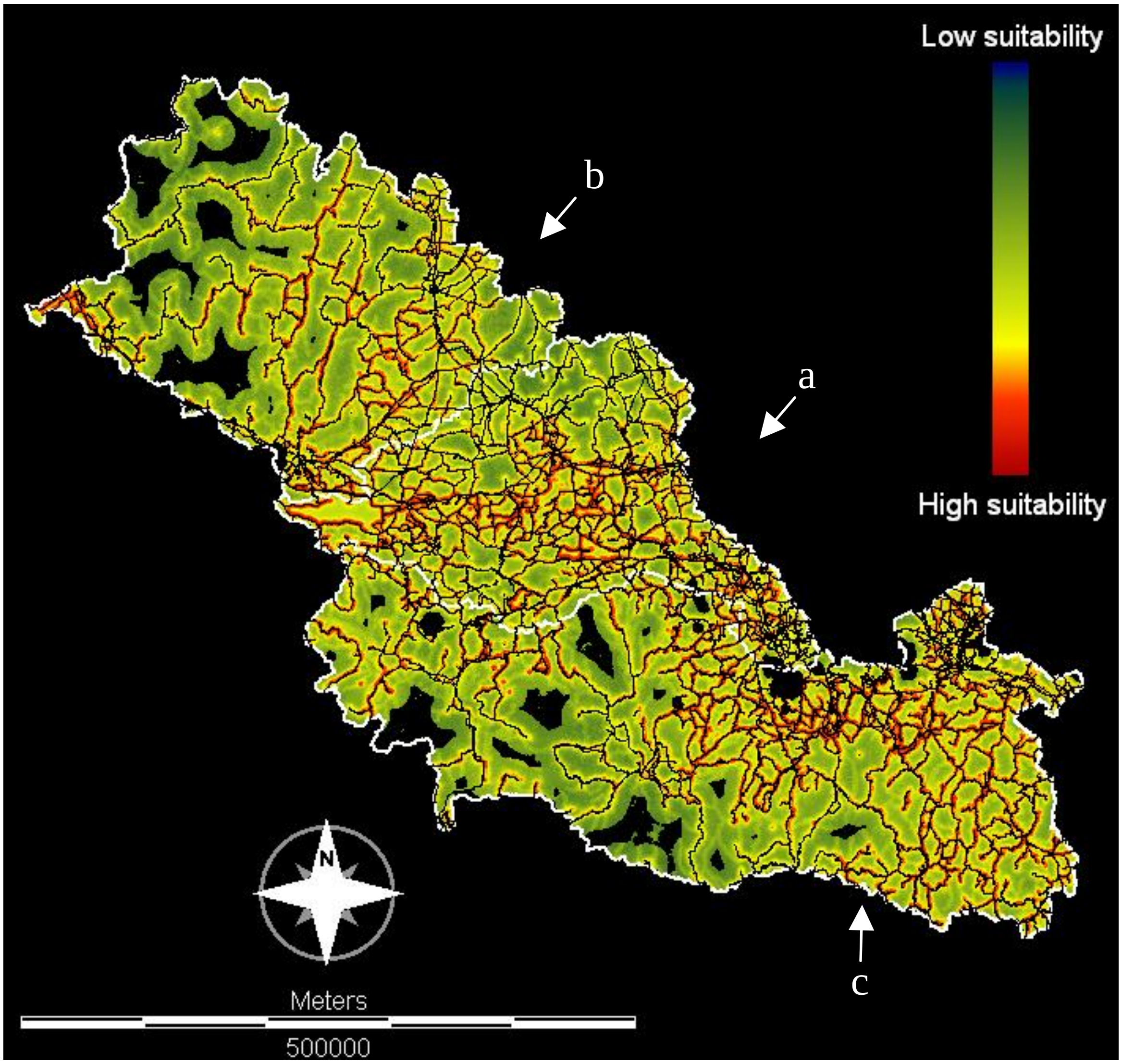


Figure 5.9: Site suitability model for aquaculture of *C. estor, C. promelas,* and *C. jordani* in the Lerma-Santiago basins (a,b), and *A. balsana* in the Balsas basin (c). Areas in dark red show the highest suitability for the development of semi-intensive aquaculture.

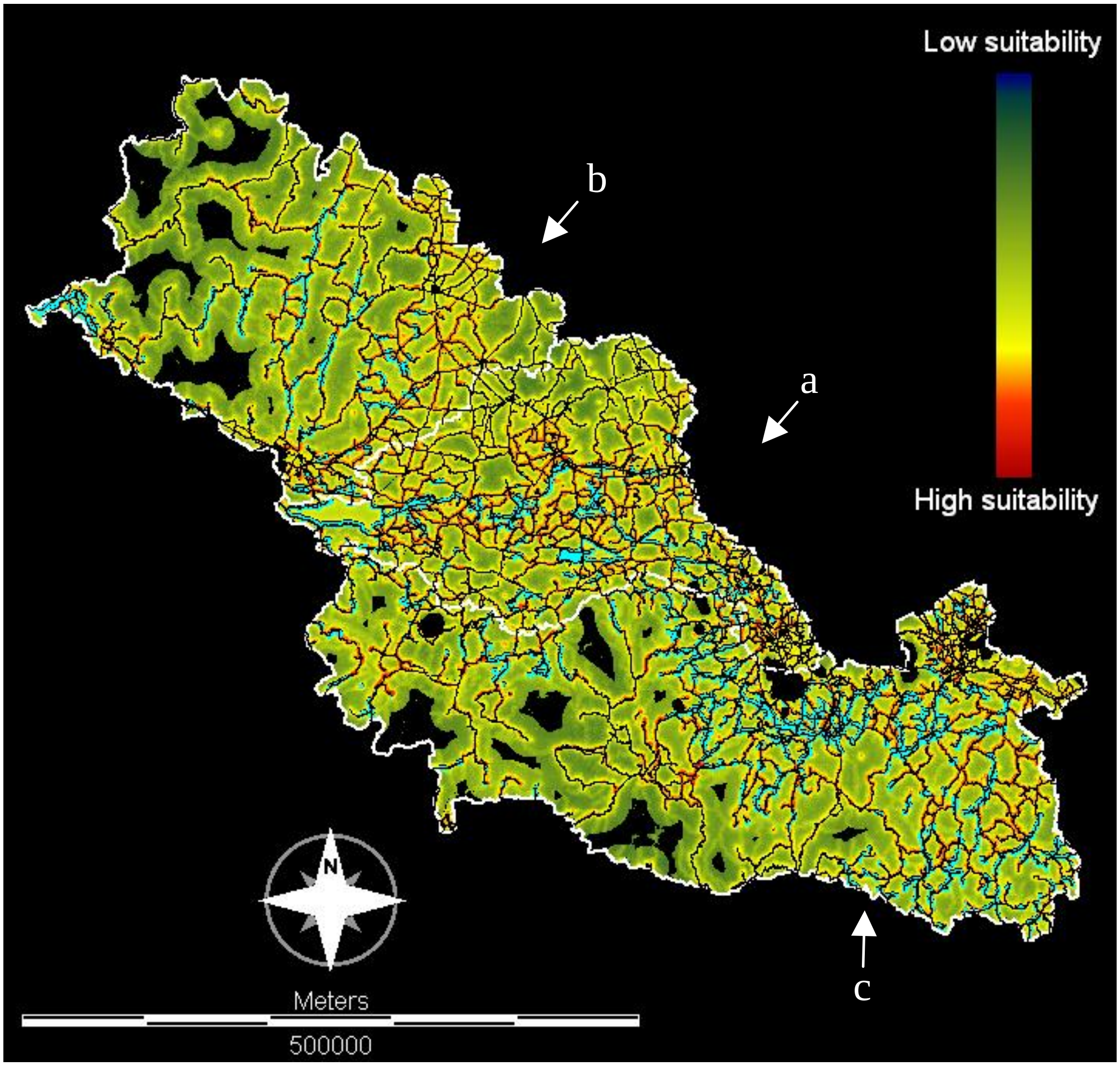


Figure 5.10: Site suitability model for aquaculture of *C. estor, C. promelas,* and *C. jordani* in the Lerma-Santiago basins (a,b), and *A. balsana* in the Balsas basin (c). Areas with suitability values higher than 0.8 over 12 continuous months are highlighted in bright blue.

5.4.7 Site selection model for aquaculture of Ictalurids in central Mexico

The site selection model for the aquaculture of Ictalurids in central Mexico identified 6278 km^2 of high suitability and 27,972km^2 of marginal suitability areas for the culture of *I. dugesii* in the basins of Lerma-Santiago (Fig 5.11 a,b). For the culture of *I. balsanus* in the Balsas basin, the model identified 7,997 km^2 of high suitability and 23,417 km^2 of marginal suitability areas (Fig 5.11 c).

The model also showed that for the culture of *I. dugesii* in the Lerma-Santiago basins, 3,883 km^2 have high suitability (>0.8) throughout the complete year (Fig 5.12 a,b). In the Balsas basin, 4,102 km^2 have high suitability (>0.8) for the culture of *I. balsanus* throughout the entire year (Fig 5.12 c). The main factors that determined this results was the presences of water sources and access points, however temperature and water balance determined seasonality and therefore suitability year around.

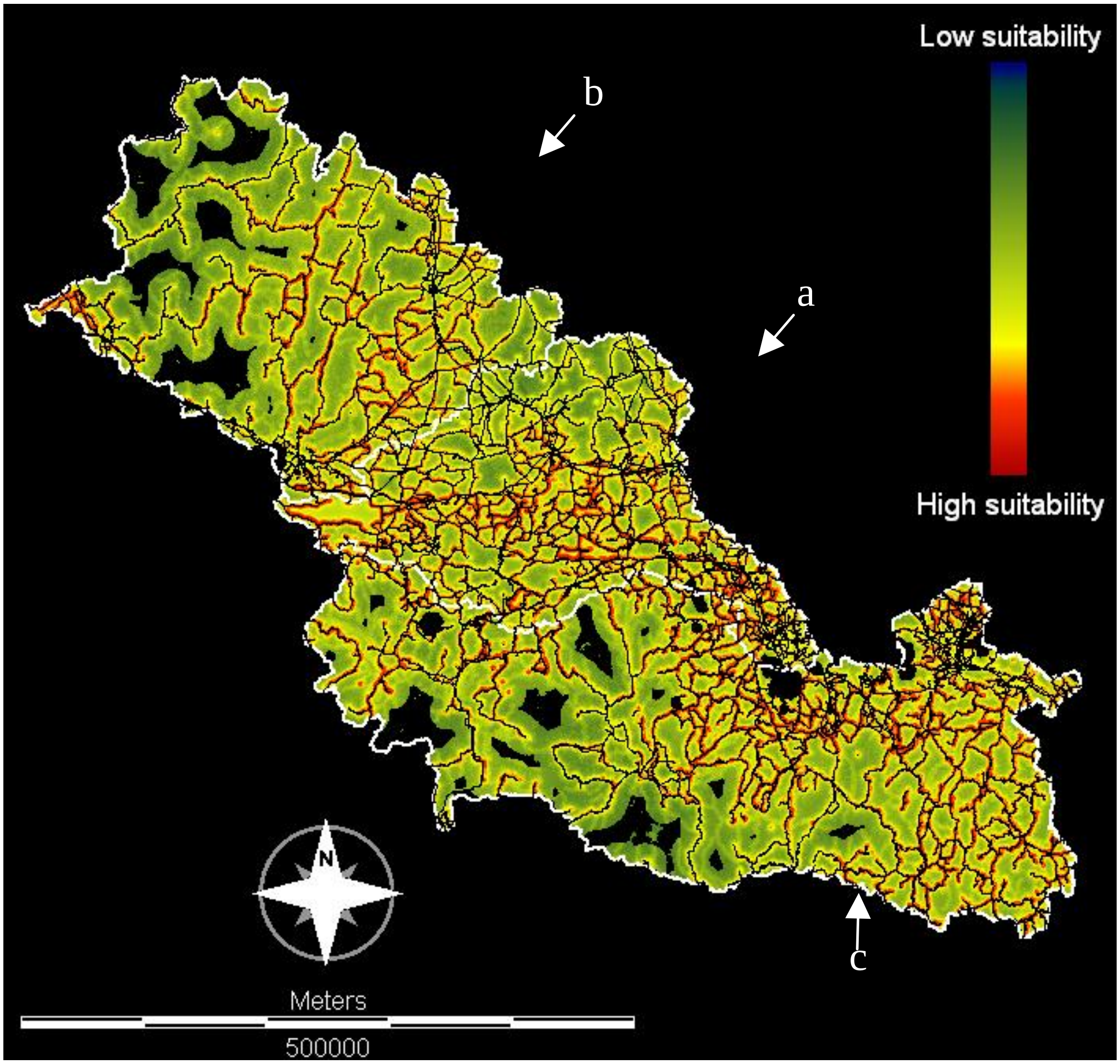


Figure. 5.11: Site suitability model for aquaculture of *I. dugesii* in the Lerma-Santiago basins (a,b), and *I. balsanus* in the Balsas basin (c). Areas in dark red show the highest suitability for the development of semi-intensive aquaculture.

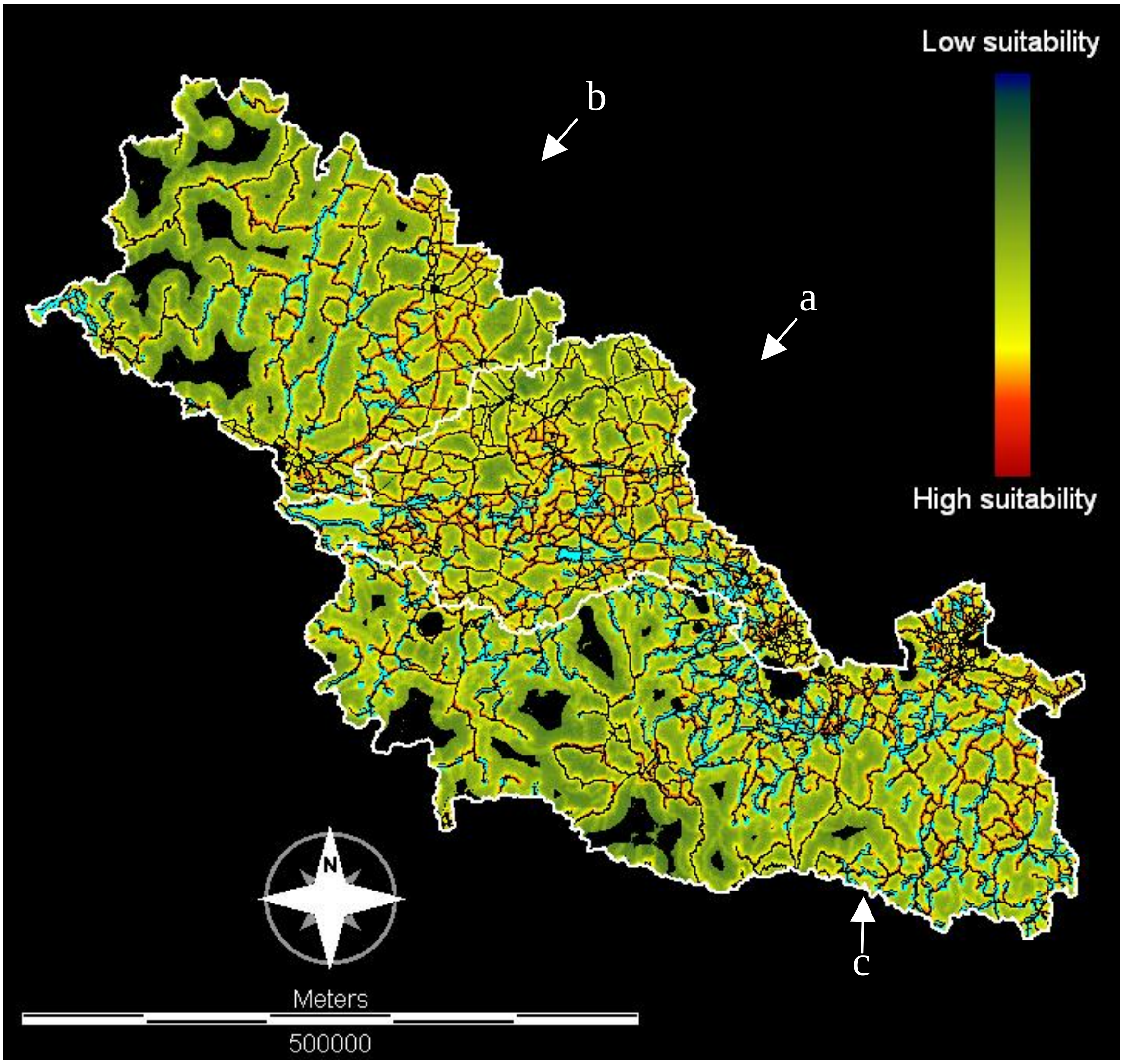


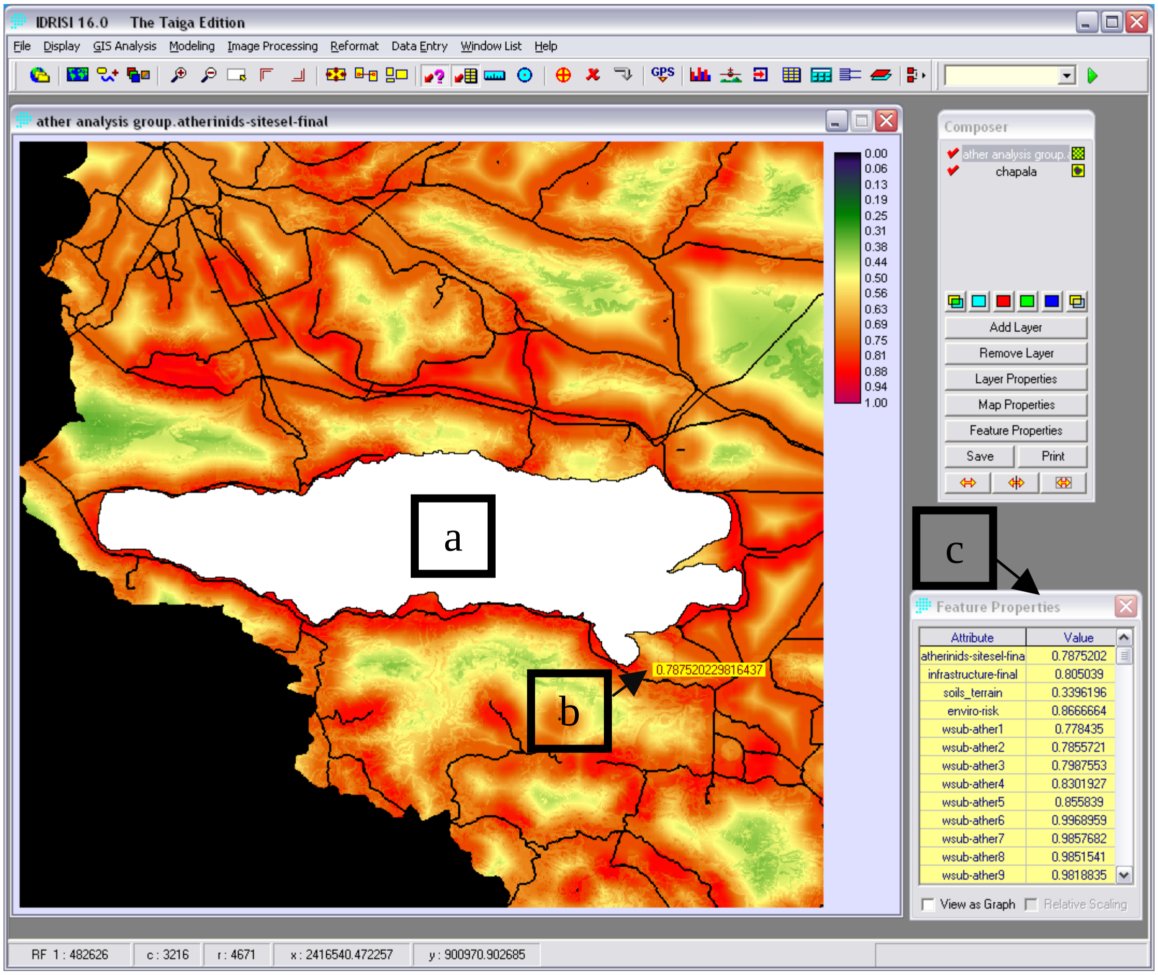
Figure 5.12: Site suitability model for aquaculture of *I. dugesii* in the Lerma-Santiago basins (a,b) and *I. balsanus* in the Balsas basin (c). Areas with a suitability value higher than 0.8 over 12 continuous months are highlighted in bright blue.

5.4.8 Final model outcomes

The final outcome images for these modesl were linked to a Raster Group, which includes the image files for all four sub models and their primary variables. This allows exploration the final image of the site suitability models for the culture of native species and the use of pixel level cursor-based database query for examining the factors involved in the calculation for each location. The extended cursor inquiry produces a listing of the values occurring at each pixel across the set of images that integrate the final model. This product is available in digital format for IDRISI.

Case scenario example 1:
Decision support for the aquaculture of C. promelas in the Lerma-Santiago basin

The query point situated 1 km south of Lake Chapala, shows a marginal suitability value of 0.787 (Fig 5.13b). The raster group analysis allows all components of the final model to be explored in order to identify the reason for this lower suitability value. The feature properties table displayed (Fig 5.13c) shows suitability values for the sub-models of Infrastructure (0.805); Soil and Terrain (0.339); Environmental Risk (0.866); and Water Quality and Availability (>0.778). This tool allows us to identify that the low suitability score is a consequence of the low soil and terrain suitability and gives the decision maker the opportunity to evaluate the risk for the establishment of the activity, for example the cost of a liner or levelling the ground or other engineering or system related solutions.



Attribute	Value
atherinids-sitesel-fina	0.7875202
infrastructure-final	0.805039
soils_terrain	0.3396196
enviro-risk	0.8666664
wsub-ather1	0.778435
wsub-ather2	0.7855721
wsub-ather3	0.7987553
wsub-ather4	0.8301927
wsub-ather5	0.855839
wsub-ather6	0.9968959
wsub-ather7	0.9857682
wsub-ather8	0.9851541
wsub-ather9	0.9818835

RF 1 : 482626
c : 3216
r : 4671
x : 2416540.472257
y : 900970.902685

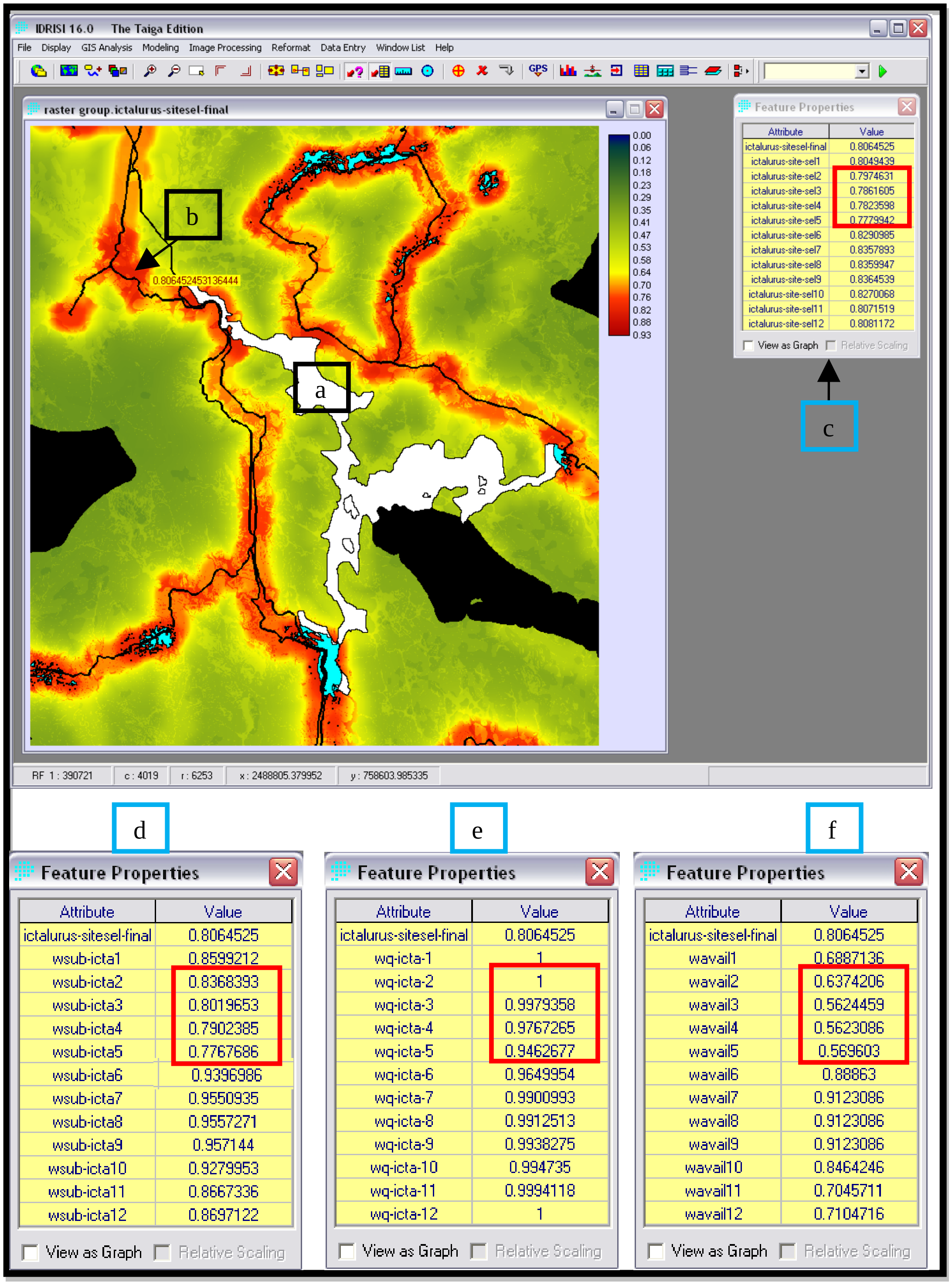
Figure 5.13: Raster group analysis featuring Lake Chapala (a), the enquiry point indicating the value of suitability of the final model for aquaculture of Atherinids in the Lerma-Santaigo basins (b), and the Feature Properties table (c) showing the suitability values for the sub-models of Infrastructure, Soil and Terrain, Environmental Risk and monthly Water uality and Availability.

Case scenario example 2:

Decision support for the aquaculture of I.balsanus in the Balsas basin

In Fig 5.14b, a query point is situated 6 km north of the Infiernillo reservoir. The explored pixel shows a value of 0.806 in the scale of suitability, however it has not been identified as suitable over 12 continuous months. The raster group analysis allows exploration of the site suitability results for each month in order to identify those months with low suitability. In this case, marginal suitability values are observed from February to May in a range from 0.777 to 0.797 (Fig 5.14c).

The raster group analysis also shows temporal changes in the water sub-model from the range between 0.776 and 0.863 (Fig 5.14d). Analyzing the two components for the Water sub-model, the Water Quality sub-model showed suitability values higher than 0.946. However, low suitability values (between 0.562 and 0.569) were observed in the Water Availability sub model (Fig 5.14e). Low water availability in the region is commonly related to high temperatures and scant amount of rainfall (Fig 5.14f).



Feature Properties (c)

Attribute	Value
ictalurus-sitesel-final	0.8064525
ictalurus-site-sel1	0.8049439
ictalurus-site-sel2	0.7974631
ictalurus-site-sel3	0.7861605
ictalurus-site-sel4	0.7823598
ictalurus-site-sel5	0.7779942
ictalurus-site-sel6	0.8290985
ictalurus-site-sel7	0.8357893
ictalurus-site-sel8	0.8359947
ictalurus-site-sel9	0.8364539
ictalurus-site-sel10	0.8270068
ictalurus-site-sel11	0.8071519
ictalurus-site-sel12	0.8081172

☐ View as Graph ☐ Relative Scaling

Feature Properties (d)

Attribute	Value
ictalurus-sitesel-final	0.8064525
wsub-icta1	0.8599212
wsub-icta2	0.8368393
wsub-icta3	0.8019653
wsub-icta4	0.7902385
wsub-icta5	0.7767686
wsub-icta6	0.9396986
wsub-icta7	0.9550935
wsub-icta8	0.9557271
wsub-icta9	0.957144
wsub-icta10	0.9279953
wsub-icta11	0.8667336
wsub-icta12	0.8697122

☐ View as Graph ☐ Relative Scaling

Feature Properties (e)

Attribute	Value
ictalurus-sitesel-final	0.8064525
wq-icta-1	1
wq-icta-2	1
wq-icta-3	0.9979358
wq-icta-4	0.9767265
wq-icta-5	0.9462677
wq-icta-6	0.9649954
wq-icta-7	0.9900993
wq-icta-8	0.9912513
wq-icta-9	0.9938275
wq-icta-10	0.994735
wq-icta-11	0.9994118
wq-icta-12	1

☐ View as Graph ☐ Relative Scaling

Feature Properties (f)

Attribute	Value
ictalurus-sitesel-final	0.8064525
wavail1	0.6887136
wavail2	0.6374206
wavail3	0.5624459
wavail4	0.5623086
wavail5	0.569603
wavail6	0.88863
wavail7	0.9123086
wavail8	0.9123086
wavail9	0.9123086
wavail10	0.8464246
wavail11	0.7045711
wavail12	0.7104716

☐ View as Graph ☐ Relative Scaling

Figure. 5.14: Raster group analysis showing areas with high suitability over 12 continuous months in bright blue. Also featuring: the Infiernillo reservoir (a), enquiring point (b), Feature Properties tables for Monthly final model (c), Water sub-model (d), Water Quality (e), and Water Availability (f). The enquiring point indicates the suitability value of the final model for aquaculture of *Ictalurus balsanus*.

5.5 Discussion

This study focused on the site suitability selection for the aquaculture of native species relatively new to aquaculture. A number of factors were grouped into four sub models of Infrastructure, Water, Soil and Terrain, and Environmental Risk. These sub models were then combined to identify site suitability for the development of native fish semi-intensive aquaculture in three of the principal catchments in Mexico, the Lerma-Santiago, and Balsas basins. Four fish species native to the Lerma-Santiago basins (*C. estor, Ch promelas Ch jordani*, and *I dugesii*), and two fish species native to the Balsas basin (*A. balsana and I. balsanus*) are suggested for use in aquaculture. Following a number of simple assumptions and guidelines from successfully developed technologies in the aquaculture of related species, a Geographic Information System (GIS) model capable to identify site suitability for semi-intensive aquaculture at catchment level has been developed to assist decision support. GIS has been described as a powerful tool for decision-makers who evaluate biophysical and socioeconomic characteristics for the development of aquaculture (Nath *et al*., 2002, Radiarta *et al*., 2008).

One of the main concerns is to promote the use of native species for aquaculture, a view that is shared by different authors (Perez 2002; Magurran 2009). In his response to Gozlan (2008), Vitule *et al*., (2009) provide persuasive information regarding the negative impact that the introduction of exotic fish species has on biodiversity. Vitule *et al*., (2009) go on to suggest that extended risk assessments should be performed before introducing new species for aquaculture and conclude that a safer approach would be to foster research on culturing local native species instead of the introduction of a few robust non-native species.

The selection of native fish species for this work was based not only on morphological parameters and the availability of related culturing technologies but also on these species’ profound relevance in local traditions, and very well established markets. Ross and Beveridge (1995) recommend that it would be unsuccessful to attempt developing an industry around a species with a limited market. Furthermore, Asche *et al*., (2009) suggest that price in many cases is one of the most important arguments regarding which species to stock. Therefore one important consideration on the selection of these species was their market potential. According to Martinez-Palacios *et al*., (2008), the price of *C. estor* in markets was between 40 and 80 USD kg^{-1}, and although the great majority of catfish production in Mexico occurs in the north of the country, its demand is particularly high within the studied catchments (CONAPESCA 2008). The aquaculture of catfish is well established in Mexico. Perales-Flores *et al*., (2007) explained that apart from shrimp, the culture of *I. punctatus* is the most important aquaculture activity in the northern state of Tamaulipas in Mexico, producing more than 50% of the national catfish crop in 2007.

The planning of native fish aquaculture at catchment level is also a strategy aimed to reduce further species' translocations and it is proposed here that GIS is an appropriate tool for the selection of the most suitable areas for aquaculture within the native catchment area. Due to the similarities of the species of each family group, the results show the suitability for the establishment of aquaculture for each species in the contiguous catchment (outside of their range of natural distribution). In order to promote aquaculture of native species at catchment level, alternatives for the culture of similar organisms in both hydrologic systems was recommended, for example, the catfish *I. dugesii is* native to the Lerma-Santiago and *I. balsanus* native to the Balsas basin, or the "charal" *C. jordani* from Lerma-Santiago and *A. balsana* for Balsas.

The adequate site selection for the development of native species in aquaculture is extremely important. Not considering the natural range of distribution for the culture of species new to aquaculture could result in the introduction of new exotic species with catastrophic results to the environment; it can also have negative economic repercussions to the stakeholder. Incorrect site selection could have a significantly negative impact on the economic viability by affecting the running cost of the aquaculture site (Perez *et al*., 2005; Londgill 2008). According to Buitrago *et al*., (2005), the lack of adequate planning and inappropriate site selection increases the probability of environmental problems. Sanderson *et al*., (2002) also point out that transformation of land in order to satisfy the necessities for an increasing human population represents the greatest near-term threat for most ecosystems. Addressing these points by using GIS has greatly improved the decision making process for site evaluations. The GIS model of site suitability for the aquaculture of native fish, presented in this document, successfully identified the most suitable areas for the development of the activity. The model and sub models gathered information of different infrastructural, geographic, demographic, chemical and biological factors into a Multi-Criteria Evaluation. The final results also provide the opportunity to update the databases as required when new or better information becomes available. According to Kapetsky *et al*., (1988) this is one of the important advantages of a GIS, which can adaptively update or expand the database information in order to generate new ratings.

Asche *et al*., (2009) suggest that the most efficient site will depend on which area offers most advantages in key factors, such as access to suitable land localities, good market access, favourable regulations, etc. In agreement with this statement, we considered that the availability of existing infrastructure was one of the most important factors for site selection and the infrastructure sub model considered roads and rail roads, points of access, and rural and urban market availability. This selection agrees with Radiarta *et al*., (2008) who included distance to town, piers and land based facilities as social-infrastructural factors. For the final model's MCE the Infrastructure sub model was used as the most important factor just above Water Quality and Availability. This decision reflects the fact that areas with existing infrastructure such as road accesses require a smaller investment of capital for the development of the site. This is an important aspect when investing in the site, since infrastructure's salvage value tends to be zero (Bunting and Shpigel 2009). Furthermore, as Dey *et al*., (2010) explain, places with available infrastructure have a more efficient marketing chain, which reflects in the improvement of the value chain for the fish industry.

The Water Quality and Availability sub model was considered the second most important factor for the final model. The identification of areas with a sustainable amount of water was paramount to this model and it is one of the major limiting factors in aquaculture. The model was clearly affected by seasonality, showing a higher suitability during the rainy season from June to October, in the case of Atherinids, and July to October in the case of Ictalurids.

For the Environmental Risk sub model, the methodology proposed by Sanderson *et al*., (2002) ws used for the Human Footprint and the "last of the wild". In their work Sanders and collaborators calculated the total sum of the ecological footprints of the human population, producing a continuum of human influence across the land surface. Finally they also identified those areas with no human influence as "the last of the wild". For Sanderson *et al*., those few places in all the biomes around the globe that are relatively little influenced by human beings should be protected before they disappear. In their work, Sanderson *et al*., (2002) did not consider areas in central Mexico as the last of the wild due to the relatively small surface area of such patches found in the region. However, we considered that the development of aquaculture sites in these undisturbed areas would be irresponsible (despite their relatively small size) and that it would be better to maintain those areas as pristine as possible. This is why all 13,591 km^2 of undisturbed areas were included in the constraint layer for the final model.

The final model successfully identified the most suitable areas for aquaculture in the Lerma-Santiago and Balsas basins. More than 80% of the highly suitable areas overlap for both family groups; this gives the opportunity to develop aquaculture of different species within close distances, avoiding competition between stakeholders, increasing agglomerative effects and increasing the availability of a variety of products. The species sensitivity of the model was provided by the Water Quality sub model, which included specific requirements for Dissolved Oxygen and Temperature for the culture of each family. The results clearly show a relatively bigger area for the aquaculture of Ictarulids both for the Lerma-Santiago and for the Balsas hydrologic systems. This response was clearly affected by the bigger tolerance for temperature that the catfishes have compared to the atherinids.

The results also indicate that in areas where water quality and availability coexist with infrastructure, site suitability criteria are more likely to be satisfied. However there are further factors that could be included in order to refine the areas to allow much more sensitive site selection, for example the inclusion of electricity supply for aeration systems as a relevant factor for the Infrastructure sub model.

Efficient use of electricity is an important criteria for aquaculture production (Mungkung *et al*., 2006), and therefore should be taken into account.

The models also showed high suitability in areas where the use of these species has extremely high social value. That is the case in the vicinity of the Lake Chapala, where *C. promelas* is of great importance to the local communities and in Lake Patzcuaro, which attracts a great number of tourists for the taste of its endemic silverside *C. estor*.

The use of raster group analysis is of great help in the decision making process. It is clear that this analytical approach allows exploration of the different components involved in the decision in a well structured methodology. This methodology allows decision makers to base their decisions on a range of accessible criteria using a package which can identify the limiting factors in an area of relatively low suitability. This enables restrictions to be overcome, for example by using engineering techniques.

There is still a necessity for the development of complete culture technologies for each of these native species. Hatchery management, rearing technologies, physicochemical parameters and feeding methodologies can be adopted from existing technologies. However, more research is required. One aspect of particular interest could be the difference in pond sizes between the culture of *C. estor* or *C. promelas* and the culture of charales. It seems clear that the culture of small fish would require particularly large land areas for the construction of ponds. For a sustainable production of “charales” the amount of biomass produced must be in great numbers due to the small size of the organism. However it is strongly believed that such enterprise could have a strong positive impact on the market.

Currently, the species recommended in this study are under great pressure from local fisheries, and the high demand for their meat. Species such as *C. estor* and *I. balsanus* are considered endangered species due to overfishing, environmental pollution and the introduction of exotic species (Martinez-Palacios *et al*., 2002; Arce and Luna-Figueroa, 2003). The combination of market demand and scarcity of these native species make them ideal candidates, both economically and environmentally. The development of aquaculture of these species represents a great opportunity for the protection of biodiversity in the region and the use of GIS tools to guide such development has great potential

References

Aguilar-Manjarrez, J. & Nath, S.S., 1998. *A strategic reassessment of fish farming potential in Africa*, Food & Agriculture Org.

Aguilar-Manjarrez, J. & Ross, L.G., 1995. Geographical information system (GIS) environmental models for aquaculture development in Sinaloa State, Mexico. *Aquaculture International*, **3**:103-115.

Alcocer, J. & Bernal-Brooks, F.W., 2010. Limnology in Mexico. *Hydrobiologia*, **644**:15-68.

Análisis de la pesquería de la tilapia (Oreochromis aureus) en la presa Melchor Ocampo, municipio de Angamacutiro, Michoacán. Available at:

ehttp://journals.unam.mx/index.php/rxm/article/view/6978/0 [Accessed January 31, 2011].

Arce U.E. and Luna-Figueroa J. 2003. Efecto de dietas con diferente contenido proteico en las tasas de crecimiento de crias del Bagre del Balsas *Ictalurus balsanus* (Pisces: Ictaluridae) en condiciones de cautiverio. *Revista AquaTIC.* **18**: 39-47.

Arismendi, I. *et al*., 2009. Aquaculture, non-native salmonid invasions and associated declines of native fishes in Northern Patagonian lakes. *Freshwater Biology*, **54**:1135-1147.

Arnold, W.S. *et al*., 2000. Hard clam (Mercenaria spp.) aquaculture in Florida, USA: geographic information system applications to lease site selection. *Aquacultural Engineering*, **23**:203-231.

Arthur, R.I. *et al*., 2010. Assessing impacts of introduced aquaculture species on native fish communities: Nile tilapia and major carps in SE Asian freshwaters. *Aquaculture*, **299**:81-88.

Asche, F., Roll, K.H. & Tveteras, R., 2009. Economic inefficiency and environmental impact: An application to aquaculture production. *Journal of Environmental Economics and Management*, **58**:93-105.

Badillo, J.M.L. & Garcia G., A., Evaluación de la pesquería multiespecífica de charales (Chirostoma spp., Pisces, Atherinidae) del Lago de Pátzcuaro, Michoacán, México. Available at: http://www.revistas.unam.mx/ojs/index.php/zoo/article/view/7136 [Accessed March 18, 2011].

Benetti, D.D. *et al*., 2010. Site Selection Criteria for Open Ocean Aquaculture. *Marine Technology Society Journal*, **44**:22-35.

Beveridge.M.C.M, Ross. L.G and Phillips M.J. 1985. Chemical and biological methods of water analysis for aquaculturists. Stirling. H.P. Institute of Aquaculture, University of Stirling.

Buentello, J.A., Gatlin, D.M. & Neill, W.H., 2000. Effects of water temperature and dissolved oxygen on daily feed consumption, feed utilization and growth of channel catfish (Ictalurus punctatus). *Aquaculture*, **182**:339-352.

Buitrago et al., 2005. J. Buitrago, M. Rada, H. Hernandez and E. Buitrago, A single-use site selection technique, using GIS, for aquaculture planning: choosing locations for mangrove oyster raft culture in Margarita Island, Venezuela, *Environ. Manage.* **35** :544–556.

Bunting, S.W. & Shpigel, M., 2009. Evaluating the economic potential of horizontally integrated land-based marine aquaculture. *Aquaculture*, **294**:43-51.

Ceballos-Silva, A. & López-Blanco, J., 2003. Delineation of suitable areas for crops using a Multi-Criteria Evaluation approach and land use/cover mapping: a case study in Central Mexico. *Agricultural Systems*, **77**:117-136.

Chen, Y., Yu, J. & Khan, S., 2010. Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation. *Environmental Modelling & Software*, **25**:1582-1591.

Collier, K.J., Haigh, A. & Kelly, J., 2006. Coupling GIS and mulitvariate approaches to reference site selection for wadeable stream monitoring. *Environmental Monitoring and Assessment*, **127**:29-45.

CONAPESCA, 2010. July 20. Anuario 2010, Retrieved July 20 from http://www.conapesca.sagarpa.gob.mx/wb/cona/anuario_2010

Cooke, S.J. *et al*., 2010. Is there a need for a '100 questions exercise' to enhance fisheries and aquatic conservation, policy, management and research? Lessons from a global 100 questions exercise on conservation of biodiversity. *Journal of Fish Biology*, **76**:2261-2286.

Copp, G.H., Vilizzi, L. & Gozlan, R.E., 2010. Fish movements: the introduction pathway for topmouth gudgeon Pseudorasbora parva and other non-native fishes in the UK. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **20**:269-273.

Corner, R. *et al*., 2006. A fully integrated GIS-based model of particulate waste distribution from marine fish-cage sites. *Aquaculture*, **258**:299-311.

Cotler, H., 2004. El manejo integral de cuencas en México: estudios y reflexiones para orientar la política ambiental, Instituto Nacional de Ecología.

David, P., Somodevilla, M. & Pineda, I., 2007. Fuzzy Spatial Data Warehouse: A Multidimensional Model. In *Current Trends in Computer Science, 2007. ENC 2007. Eighth Mexican International Conference on*. Current Trends in Computer Science, 2007. ENC 2007. Eighth Mexican International Conference on. pp. 3-9.

Dey, M.M. *et al*., 2005. Fish consumption and food security: a disaggregated analysis by types of fish and classes of consumers in selected Asian countries. *Aquaculture Economics & Management*, **9**:89-111.

Doehring, K., Young, R.G. & McIntosh, A.R., 2011. Factors affecting juvenile galaxiid fish passage at culverts. *Mar. Freshwater Res.*, **62**:38-45.

Duarte M.C. Marba N., Holmer M. 2007. Rapid Domestication of Marine Species.*Science.* **316**: 382-382.

Eastman, J.R. 2009. IDRISI ANDES. Manual. Clark Laboratories for Cartographic Technology and Geographic Analysis. Clark University, Worcester, MA, USA

Ekmekçioglu, M., Kaya, T. & Kahraman, C., Fuzzy multicriteria disposal method and site selection for municipal solid waste. *Waste Management*, **30**:1729-1736.

El-Sayed, A.M., 2006. *Tilapia culture*, CABI.

Erisman, B.E. *et al*., Spatial structure of commercial marine fisheries in Northwest Mexico. *ICES Journal of Marine Science: Journal du Conseil*. Available at: http://icesjms.oxfordjournals.org/content/early/2011/01/06/icesjms.fsq179.abstract [Accessed January 24, 2011].

FAO. 2001. http://www.fao.org/fishery/statistics/global-aquaculture-production/en

FAO, 2010. July 26. FAO Fisheries & Aquaculture - Aquaculture. Retrieved July 26, 2010, from http://www.fao.org/fishery/aquaculture/en.

Fei, X., Gao, X. & Zhang, Z., 2009. Park site selection based on RS and GIS -a case study of Zaozhuang in Shandong province. *2009 Joint Urban Remote Sensing Event, VOLS* **1-3:** 473-477.

Fishbase, 2011. Feb 18, Accessed February 18 2011 from http://fishbase.org/

Giap, D.H., Yi, Y. & Yakupitiyage, A., 2005. GIS for land evaluation for shrimp farming in Haiphong of Vietnam. *Ocean & Coastal Management*, **48**:51-63.

Goodrich, J., 2000. Branchial arches of suspension-feeding Oreochromis esculentus: sieve or sticky filter? *Journal of Fish Biology*, **56**:858-875.

Gozlan, R.E., 2008. Introduction of non-native freshwater fish: is it all bad? *Fish and Fisheries*, **9**:106-115.

Gozlan, R. *et al*., 2010. Current knowledge on non-native freshwater fish introductions. *Journal Of Fish Biology*, **76**:751-786.

Habbane, M., El-Sabh, M.I. & Dubois, J.-., 1997. Potentiel aquacole regional par teledetection passive et SIG: Application aux eaux cotieres de la baie des Chaleurs (est du Canada). *International Journal of Remote Sensing*, **18**:3439.

Habit, E. *et al*., 2010. Changes in the distribution of native fishes in response to introduced species and other anthropogenic effects. *Global Ecology and Biogeography*, pp.no-no.

Holmer, M. *et al*.,. eds., 2008. *Aquaculture in the Ecosystem*, Dordrecht: Springer Netherlands. Available at: http://www.springerlink.com/content/978-1-4020-6809-6#section=196764&page=3&locus=5 [Accessed January 20, 2011].

Hossain, M.S. *et al*., 2007. Multi-criteria evaluation approach to GIS-based land-suitability classification for tilapia farming in Bangladesh. *Aquaculture International*, **15**:425-443.

Hossain, M.S. *et al*., 2009. Integration of GIS and multicriteria decision analysis for urban aquaculture development in Bangladesh. *Landscape and Urban Planning*, **90**:119-133.

Hossain, M.S. & Das, N.G., 2010. GIS-based multi-criteria evaluation to land suitability modelling for giant prawn (Macrobrachium rosenbergii) farming in Companigonj Upazila of Noakhali, Bangladesh. *Computers and Electronics in Agriculture*, **70**:172-186.

Irons, K.S. *et al*., 2007. Reduced condition factor of two native fish species coincident with invasion of non-native Asian carps in the Illinois River, U.S.A. Is this evidence for competition and reduced fitness? *Journal of Fish Biology*, **71**:258-273.

Jelks, H. L. and others. 2008. American Fisheries Society Imperiled Freshwater and Diadromous Fishes of North America. Available at: http://fl.biology.usgs.gov/afs/ [Accessed January 30,2011.

Jeffrey E. Hill, 2010. FA-121/FA121: Regulations Pertaining to Non-native Fish in Florida Aquaculture. Available at: http://edis.ifas.ufl.edu/fa121 [Accessed January 24, 2011].

Karthik, M. *et al*., 2005. Brackish water aquaculture site selection in Palghar Taluk, Thane district of Maharashtra, India, using the techniques of remote sensing and geographical information system. *Aquacultural Engineering*, **32**:285-302.

Kapetsky, J. M. y J. Aguilar-Manjarrez. 2007. Geographic Information Systems, remote sensing and mapping for the development and management of marine aquaculture FAO Fish Tech Paper, No 458, Roma. 125 p.

Kapetsky, J.M., Hill, J.M. & Worthy, L., 1988. A geographical information system for catfish farming development. *Aquaculture*, **68**:311-320.

King, A., Tonkin, Z. & Mahoney, J., 2009. Environmental flow enhances native fish spawning and recruitment in the Murray River, Australia. *River Research and Applications*, **25**:1205-1218.

Kwak M.,Kami J.A. and Gepts P. 2009. The Putative Mesoamerican Domestication Center of *Phaseolus vulgaris* Is Located in the Lerma-Santiago Basin of Mexico. *Corp Science Society of America*. **49**: 554-563.

Lazard, J. *et al*., 2010. Aquaculture system diversity and sustainable development: fish farms and their representation. *Aquatic Living Resources*, **23**:187-198.

Longdill, P.C., Healy, T.R. & Black, K.P., 2008. An integrated GIS approach for sustainable aquaculture management area site selection. *Ocean & Coastal Management*, **51**:612-624.

López-Medellín, X., Castillo, A. & Ezcurra, E., Contrasting perspectives on mangroves in arid Northwestern Mexico: Implications for integrated coastal management. *Ocean & Coastal Management*, In Press, Corrected Proof. Available at: http://www.sciencedirect.com/science/article/B6VG5-51X1VR2-4/2/0b105536defa71cedb329a63f80f2838 [Accessed January 24, 2011].

Lyons, J. *et al*., 1998. Decline of Freshwater Fishes and Fisheries in Selected Drainages of West-central Mexico. *Fisheries*, **23**:10-18.

Lyons, J., Gutierrez-Hernandez A., Diaz-Pardo E., Soto-Galera E., Medina-Nava M., and Pineda-Lopez R., 2000. Development of a preliminary index of biotic integrity (IBI) based on fish assemblages to assess ecosystem condition in the lakes of central Mexico. *Hidlobiologia* **418**: 57-72

Magurran, A., 2009. Threats to Freshwater Fish. *Science*, **325**:1215-1216.

Martinez-Palacios *et al.,* 2002. Effect of temperature on growth and survival of *Chirostoma estor estor,* Jordan 1879, monitored using a simple video technique for remote measurement of length and mass of larval and juvenile fishes. *Aquaculture* **209**:369-377.

Martinez-Palacios *et al.,* 2004. The effects of saline environments on survival and growth of eggs and larvae of *Chirostoma estor estor* Jordan 1880 (Pisces: Atherinidae). *Aquaculture* **238:** 509-522.

Martinez-Palacios, C. *et al*., 2007a. The effect of photoperiod on the reproduction of Chirostoma estor estor Jordan 1879 from Lago de Patzcuaro, Mexico. J*ournal of Applied Ichthyology*, **23**:621-623.

Martínez-Palacios, C. *et al*., 2007b. Dietary protein requirement of juvenile Mexican Silverside (Menidia estor Jordan 1879), a stomachless zooplanktophagous fish. *Aquaculture Nutrition*, **13**:304-310.

Martínez-Palacios, C.A. *et al*., 2008. Developments in the nutrition of Menidia estor Jordan 1880. *Aquaculture Research*, **39**:738-747.

McLeod, I., Pantus, F. & Preston, N., 2002. The use of a geographical information system for land-based aquaculture planning. *Aquaculture Research*, **33**:241-250.

Miller, R.R., Minckley, W.L. & Norris, S.M., 2005. Freshwater Fishes of Mexico. University of Chicago Press.

Miller, T.J. *et al*., 2010. FishSmart: An Innovative Role for Science in Stakeholder-Centered Approaches to Fisheries Management. *Fisheries*, **35**:424-433.

Mungkung, R., Udo de Haes, H. & Clift, R., 2006. Potentials and Limitations of Life Cycle Assessment in Setting Ecolabelling Criteria: A Case Study of Thai Shrimp Aquaculture Product (5 pp). *The International Journal of Life Cycle Assessment*, **11**:55-59.

Nath, S.S. *et al*., 2000. Applications of geographical information systems (GIS) for spatial decision support in aquaculture. *Aquacultural Engineering*, **23**:233-278.

Pearson, P. & Green, B., 2006. A device to continuously monitor dissolved oxygen and temperature at user-selected depths and locations in culture ponds. N*orth American Journal of Aquaculture*, **68**:253-255.

Pelicice, F.M. & Agostinho, A.A., 2008. Fish fauna destruction after the introduction of a non-native predator (Cichla kelberi) in a Neotropical reservoir. *Biological Invasions*, **11**:1789-1801.

Perales-Flores L.E., Sifuentes-Rincon A.M. & Garcia de Leon F.J. 2007. Microsatellite variability analysis in farmed catfish (*Ictalurus punctatus*) from Tamaulipas, Mexico. *Genetics and Molecular Biology,* **30** : 570-574.

Pérez, O.M. *et al*., 2003. Water quality requirements for marine fish cage site selection in Tenerife (Canary Islands): predictive modelling and analysis using GIS. *Aquaculture*, **224**:51-68.

Perez, O., Telfer, T. & Ross, L., 2003. On the calculation of wave climate for offshore cage culture site selection: a case study in Tenerife (Canary Islands). *Aquacultural Engineering*, **29**:1-21.

Pérez, O.M., Telfer, T.C. & Ross, L.G., 2005. Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. *Aquaculture Research*, **36**:946-961.

Pérez-Sánchez, E. & Páramo-Delgadillo, S., 2008. The culture of cichlids of southeastern Mexico. *Aquaculture Research*, **39**:777-783.

Pérez, O.M., Telfer, T.C. & Ross, L.G., 2003. Use of GIS-Based Models for Integrating and Developing Marine Fish Cages within the Tourism Industry in Tenerife (Canary Islands). *Coastal Management*, **31**:355.

Radiarta, I.N., Saitoh, S. & Miyazono, A., 2008. GIS-based multi-criteria evaluation models for identifying suitable sites for Japanese scallop (Mizuhopecten yessoensis) aquaculture in Funka Bay, southwestern Hokkaido, Japan. *Aquaculture*, **284**:127-135.

Ribeiro, F., Collares-Pereira, M.J. & Moyle, P.B., 2009. Non-native fish in the fresh waters of Portugal, Azores and Madeira Islands: a growing threat to aquatic biodiversity. *Fisheries Management and Ecology*, **16**:255-264.

Robinson, V.B., 2003. A Perspective on the Fundamentals of Fuzzy Sets and their Use in Geographic Information Systems. *Transactions in GIS*, **7**:3-30.

Ross, L.G. & Beveridge, M.C.M., 1995. Is a better strategy necessary for development of native species for aquaculture? A Mexican case study. *Aquaculture Research*, **26**:539-547.

Ross, L.G. *et al*., 2006. Determination of feeding mode in fishes: the importance of using structural and functional feeding studies in conjunction with gut analysis in a selective zooplanktivore Chirostoma estor estor Jordan 1880. *Journal of Fish Biology*, **68**:1782-1794.

Ross, L., J. Blanco, C. Martinez-Palacios, I. Racotta, and M. Cuevas. 2007. Anaesthesia, sedation and transportation of juvenile Menidia estor (Jordan) using benzocaine and hypothermia. *Aquaculture Research* **38**:909-917.

Saaty, T.L. 1977. A scaling method for priorities in hierarchical structure. *Journal of Mathematics and Physiology*, **15**: 234-281.

Salam, M.A., Ross, L.G. & Beveridge, C.M.M., 2003. A comparison of development opportunities for crab and shrimp aquaculture in southwestern Bangladesh, using GIS modelling. *Aquaculture*, **220**:477-494.

Salam, M., Khatun, N. & Ali, M., 2005. Carp farming potential in Barhatta Upazilla, Bangladesh: a GIS methodological perspective. *Aquaculture*, **245**:75-87.

Sanderson, E. W., Jaiteh M. Levy, M.A. Redford, K.H. Wannebo, A.V. Woolmer, G. 2002. The human footprint and the last of the wild. *BioScience,* **52**:891-904.

Sánchez-Martínez, J.G. *et al*., 2007. First detection of channel catfish virus associated with mortality of cultured catfish (Ictalurus punctatus, Rafinesque) in Mexico. *Aquaculture Research*, **38**:1428-1431.

Schröder, V. & Garcia de Leaniz, C., 2010. Discrimination between farmed and free-living invasive salmonids in Chilean Patagonia using stable isotope analysis. *Biological Invasions*, **13**:203-213.

Silva, S.S.D. *et al*., 2009. Alien Species in Aquaculture and Biodiversity: A Paradox in Food Production. *AMBIO: A Journal of the Human Environment*, **38**:24-28.

Simms, A., 2002. GIS and aquaculture: Assessment of soft-shell clam sites. *Journal of Coastal Conservation*, **8**:35.

Simsek, C., Kincal, C. & Gunduz, O., 2005. A solid waste disposal site selection procedure based on groundwater vulnerability mapping. *Environmental Geology*, **49**:620-633.

Staay, T.L., 1997. A Scaling Method for Priorities in Herarchical Structures, *J. Math. Psychology,* **15**: 234-281.

Store, R., 2009. Sustainable locating of different forest uses. *Land Use Policy*, **26**:.610-618.

Tapia, M. & Zambrano, L., 2003. From Aquaculture Goals to Real Social and Ecological Impacts: Carp Introduction in Rural Central Mexico. *AMBIO: A Journal of the Human Environment*, **32**:252-257.

Toledo, A., 2003. Ríos, costas, mares: hacia un análisis integrado de las regiones hidrológicas de México, Instituto Nacional de Ecología.

Toledo-Cuevas E. M., *et al.* 2006. Initial characterization of the digestive enzymatic activity during the early ontogeny of *Chirostoma estor estor*, a zooplanktophagous stomachless fish. AQUA 2006. Florence, Itally, 9'13 May 2006.

Tseng,, C. *et al*., 2001. GIS-assisted site selection for artificial reefs. *Fisheries Science*, **67**:1015-1022.

Vitule, J.R.S., Freire, C.A. & Simberloff, D., 2009. Introduction of non-native freshwater fish can certainly be bad. *Fish and Fisheries*, **10**:98-108.

Voogd, H., 1983. *Multicriteria Evaluation for Urban and Regional Planning,* Pion, LTD London.

Wester P., Burton M. and Mestre E. 2001. Managing the Water Transition in the Lerma-Chapala Basin, Mexico. Intersectoral Management of River Basins. Ed Abernethy C.L. 161-168.

Winfield, I.J., Fletcher, J.M. & James, J.B., 2010. Invasive fish species in the largest lakes of Scotland, Northern Ireland, Wales and England: the collective UK experience. *Hydrobiologia*, **660**:.93-103.

Wilson, J. P. & Fotheringham, A. S. (2007). The Handbook of Geographic Information Science, Malden, MA: Blackwell Publishing, pp. 3–12

Xiaodan, W., Xianghao, Z. & Pan, G., 2010. A GIS-based decision support system for regional eco-security assessment and its application on the Tibetan Plateau. *Journal of Environmental Management*, **91**:1981-1990.

Yang, B., Chen, X. & Yang, J., 2010. Non-native carp of the genus Cyprinus in Lake Xingyun, China, as revealed by morphology and mitochondrial DNA analysis. *Biological Invasions*, **13**:105-114.

Yates, A.G. & Bailey, R.C., 2009. Selecting objectively defined reference sites for stream bioassessment programs. *Environmental Monitoring and Assessment*, **170**:129-140.

Yoshida, T. *et al*., 2007. Biological invasion as a natural experiment of the evolutionary processes: introduction of the special feature. *Ecological Research*, **22**:849-854.

Yonekura R., Kawamura K., Uchii K. 2007. A peculiar relationship between genetic diversity and adaptability in invasive exotic species: blufill sunfish as a model species. *Ecology Research.* **22**. 6

Zepeda, R.V., 2005. Las regiones climáticas de México 1.2.2, UNAM.

Chapter 6

Predictive Habitat Distribution Model for Native Species with Aquaculture Potential in Central Mexico; a Catchment Level Assessment

VM Peredo-Alvarez, Trevor C Telfer and Lindsay G Ross.

This chapter describes the use of ecological-niche based Predictive Distribution models for native species and Potential for Invasion models by non native species for their use in the development of sustainable aquaculture in three basins in central Mexico.

The body of the text is presented as a publication-ready manuscript.

The main author, **VM Peredo-Alvarez**, developed all sub models and final model. Trevor C. Telfer and Lindsay G. Ross provided supervisory and editorial support throughout the whole study.

This manuscript will be submitted to **Biodiversity and Conservation**, an international journal devoted to the publication of articles on all aspects of biological diversity.

Chapter 6

Predictive Habitat Distribution Model for Native Species with Aquaculture Potential in Central Mexico; a Catchment Level Assessment

VM Peredo-Alvarez, Trevor C Telfer and Lindsay G Ross.

Abstract

Native fish abundance and distribution is declining worldwide, and aquaculture of exotic species is seen as a significant pressure on native populations. There are, however, clear examples where aquaculture of endangered native species has proved successful in conservation. In order for aquaculture development to enhance aquatic biodiversity, it has to respect the natural distribution of aquatic species as a safety measure to avoid introductions of new exotic. To support the design of a development programme for the aquaculture of native species and the protection of biodiversity, a Predictive Species Distribution Model was developed in order to identify the geographic potential of 6 native species selected as candidates for aquaculture in the basins of Lerma, Santiago and Balsas in central Mexico. The model relates ecological characteristics of the known species distributions to those of the corresponding catchment and for this a Geographic Information System was created with a 90 m resolution, which included data on the known distribution for each species, relevant environmental and topographic parameters. The model gives robust predictions of the potential natural distribution of this species and their potential for invasion in neighbouring basins. The model also provides a solid decision support for planning and project design.

6.1. Introduction

Aquaculture of native species is a recent approach to the protection of biodiversity and the production of a reliable source of protein. With the fast growth of the aquaculture industry over the last 20 years (Subasinghe *et al*., 2009, Diana, 2009), it is possible to expect that over the next decade the interest of culturing native species will increase substantially. Aquaculture of native species provides considerable advantages for the protection of biodiversity (Vitule *et al*., 2009). However, there are also associated risks such as the interactions between genetically or selectively improved organisms for aquaculture broodstocks with wild populations (McGinnity, 2003). The establishment of aquaculture sites outside of each species' natural range of distribution would represent another form of exotic species introduction or translocation. Subsequently, there is the potential that this could lead to the same negative impacts on biodiversity than those seen before with other non-native species introductions (Canonico *et al*., 2005; Alves *et al*., 2007; Arismendi *et al*., 2009).

Although many freshwater fish species have a wide natural distribution, for the majority distribution is limited by geographic features such as catchments, rivers or lakes (Avise *et al*., 1987). For example, freshwater fish species that live in closed systems are incapable of natural movement from one water body to another. However many species have been moved for aquaculture or fisheries purposes as it is the case of *Chirostoma estor* originally endemic to Lake Patzcuaro, in the state of Michoacan in Mexico, which is now distributed in all major lakes in state (Barriga-Sosa *et al*., 2002).

For the development of native species aquaculture it is essential to know the natural range of distribution as it is their potential to establish themselves as invasive species that is of great importance. Ecological niche-modelling is a powerful tool for the assessment of potential geographic distribution of many species (Peterson, 2003; Elith *et al*., 2006). Maps of potential species distributions combine statistical models of species-occurrence with environmental variables maps in a Geographic Information Systems (GIS) (Guisan and Zimmermann, 2000, Sundbald *et al*., 2009). GIS conjugated with multivariate statistical tools form a useful link between studied species and their habitat, in particular quantifying parameters for habitat-suitability models (Hirzel *et al.,* 2002, Rotenberry *et al.,* 2002). Several concepts of ecological niche modelling have been developed, such as the Generalized Linear Models (GLM), Generalized Additive Models (GAM), (GAP) and Genetic Algorithm for Rule-set Prediction (GARP) (Guisan and Zimmermann, 2000; Zheng and Agresti, 2000; Guisan and Thuiller, 2005; McNyset 2005; Austin , 2007).

Predictive models should be understood as partial niche models, because of the difficulty to include all the relevant parameters for every analysis (Wiley *et al*., 2003). These models contribute significantly to management and conservation of species populations and communities (Oberdorff *et al*., 2001, Lehmann *et al*., 2002, Brotons *et al*., 2004), climate change (Thomas *et al*., 2004), potential areas for species reintroductions (Martinez-Meyer *et al*., 2006), can predict the probability of invasion of exotic species (Peterson 2003; Thuiller *et al*., 2005; Ficetola *et al*., 2007) and can predict areas for the conservation of biodiversity (Scott, 1993; Pearce predict areas and Ferrier, 2001; Olden *et al*., 2002; Graham *et al*., 2004; Dietz and Czech, 2005; Peterson, 2006).

As one of the main concerns for the development of native species aquaculture is to avoid the introduction of non-native organisms, the inclusion of natural ranges of distribution into the decision making process for aquaculture is a fundamental factor. Predictive Species Distribution models allow the aquaculture planner to assess the risks associated to the potential of invasion by aquaculture species. This is a factor worth considering since the continued decline of fish biodiversity is a major concern for scientist and fish and wildlife management agencies (Richter *et al*., 1997, Argent *et al*., 2003).

In this document we present a Predictive Species Distribution Model of six fish species native to three neighbouring catchments in central Mexico, the Balsas and the Lerma-Santiago basins. Members of the Atherinid family *Atherinella balsana* endemic to the Balsas basin and five species of the genera Chirostoma native to the Lerma-Santiago basins C. aculeatum Barbour, 1973, *C. arge* , *C. humboldtianum*, *C. jordani*, and *C. promelas*, along with two species of catfish *Ictalurus balsanus* and *I. dugesii* native to the Balsas and Lerma-Santiago basins respectively, were studied to explore their predictive distribution within their native catchment, and the Predictive Potential of Invasion (PI) as a result for their introduction into the neighbouring basins.

Silversides are worldwide marine shoreline fishes (Miller *et al*., 2005). However a number of freshwater representatives inhabit water bodies in the Mexican Central Plateau (Ross *et al*., 2006). *Atherinella balsana* is a small atherinid (Maximum SL 65 mm) native to the Balsas basin that inhabits the Pacific slope, Río Balsas and tributaries (Miller *et al*., 2005). Its status is considered as rare (Trujillo-Jimenez *et al*., 2010). This species is recommended for aquaculture of native "charales" in the Balsas basin. "Charales" is the common name for the small atherinids members of the "arge" group (Martinez-Palacios *et al*., 2008). They have high economic, social, cultural and ecological importance in the region (Olvera-Blanco *et al*., 2009) and are a popular dish in central Mexico. Members of the arge group are more commonly used as a source of food in the Lerma-Santiago basins. C. aculeatum (SL 109 mm), is a species of "charal" endemic to the Lerma basin, that distributes along the lower and middle Rio Lerma and tributaries (Bloom *et al*., 2007). The conservation status for his species is endangered Lyons *et al*., (1998). *C. arge*, also member of the arge group, has a natural distribution in the Lowe Rio Lerma and tributaries, as well as the Rio Verde in the Santiago basin (Miller *et al*., 2005; Mercado-Silva *et al*., 2006).

The black nose silverside (Ch. promelas) is a species with low population density that inhabits the Chapala Lake and Rio Grande de Santiago above El Salto de

Juanacatlan in the Lerma-Santiago basins (Miller *et al*., 2005; Barriga-Sosa *et al*., 2002). Existing aquaculture of the species is directed to re-stocking and for human consumption (Montero-Rocha, 2007). Ch. humboldtianum, fisheries are one of the most important in the Lerma-Santiago basins (Sanchez-Merino *et al*., 2009). Within the Lerma-Santaigo basins, *C. humboldtianum* is distributed in lentic environments of the region, the Rio Grande de Santiago and Rio Lerma (Barbour, 1973; Cardenas *et al*., 2008). *C. jordani* is widely spread across the Lerma-Santiago basin and is the Chirostoma species with the greatest range of natural distribution (Ibañez *et al*., 2008). These species have being recognized as a species with potential for aquaculture (Hernandez-Rubio, 2006).

The Balsas catfish *I. balsanus*, is endemic to the Balsas River and tributaries (Salgado-Maldonado *et al*., 2004; Rosas-Valdez *et al*., 2007). Currently it is considered an endangered species due to overfishing, pollution and the introduction of exotic species (Arce and Luna Figueroa, 2003). The lerma catfish *I. dugesii* lives in clear to turbid quiet pools near vegetation along the rivers Lerma and Ameca (Miller *et al*., 2005). It is considered a vulnerable species by the AFS Endangered Species Committee list of imperilled freshwater and diadromous fish of North America (Jelks *et al*., 2008). Production of *Ictalurus* sp is one of the strongest industries in Mexico (CEDRSSA, 2006).

6.2. Area of study

The basins of the rivers Lerma and Grande de Santiago in central Mexico are connected by the Chapala Lake forming together the hydrologic system 23

(Alcocer and Bernal-Brooks, 2010). This hydrologic system is located between the coordinates 19°03’ N and 21°32’ N latitude, and 99° 18’ W and 03° 46’ W longitude (Fig 6.1, a, b). The Lerma-Santiago hydrologic system has a catchment area of 132,724 km2, with an average annual temperature of 18 to 22 ° C (Kwak, *et al*., 2009). The Lerma basin is one of the most endangered in the world due to its water depletion (Wester *et al*., 2001).

The Rio Balsas’ basin (Fig 6.1, d) is situated in south- central Mexico in between the mountain chains of the “Eje Neovolcanico Transversal” and the “Sierra Madre del Sur” (17°00' N and 20°00' N latitude, and 97°30' W and 103°15' W longitude). The Balsas basin has a catchment area of 117, 406 km2 (Toledo, 2003). Due to its location, the catchment fits into the tropical zone, with yearly mean temperature varying according to the altitude from 26° C to 18° C (Zepeda, 2005). Regardless of the Rio Balsas basin’s size (nearly as big as the Lerma and Santiago basins together), it is scarcely populated due to its rough terrain (Toledo, 2003); it also produces considerably less water (~1.2x1010 m3) and it lodges only 30 native species (Miller *et al*., 2005).

6.3. Methodology

The GIS database was created with a 90 m resolution grid and projected in a Lambert Conformal Conic projection (LCC) which is often use to project charts for Mexico, United States and Canada. It includes the basins of Lerma, Santiago and Balsas in central Mexico.

6.3.1. Environmental and Topographic training data

Habitat-suitability models use information on species records and environmental factors to generate statistical functions that allow the prediction of potentially suitable habitat distribution for species (Guisan and Zimmermann, 2000). A set of 11 variables was grouped into environmental and topographic factors. Mean annual precipitation, mean annual temperature, mean annual minimum temperature, mean annual maximum maximum temperature, vapour pressure and dissolved oxygen were included as environmental factors, whereas land cover, elevation, aspect, slope and run off were included as topographic factors. This selection of factors is similar to previous studies (Peterson, 2003, Zambrano *et al*., 2006, Chen *et al*., 2007).

5.1.1. Known distribution data

Distribution data for each species was extracted from literature, the Institute of Biology of the National Autonomous University of Mexico (UNAM); the fish collections of the University of Michoacan (UMSNH), the University of Michigan Museum of Zoology, division of Fishes (UMMZ) and the internet fish databases (FishBase). Each occurrence point was then digitized and georeferenced. In many cases, occurrence points were imprecise and refer to a river and not to a given

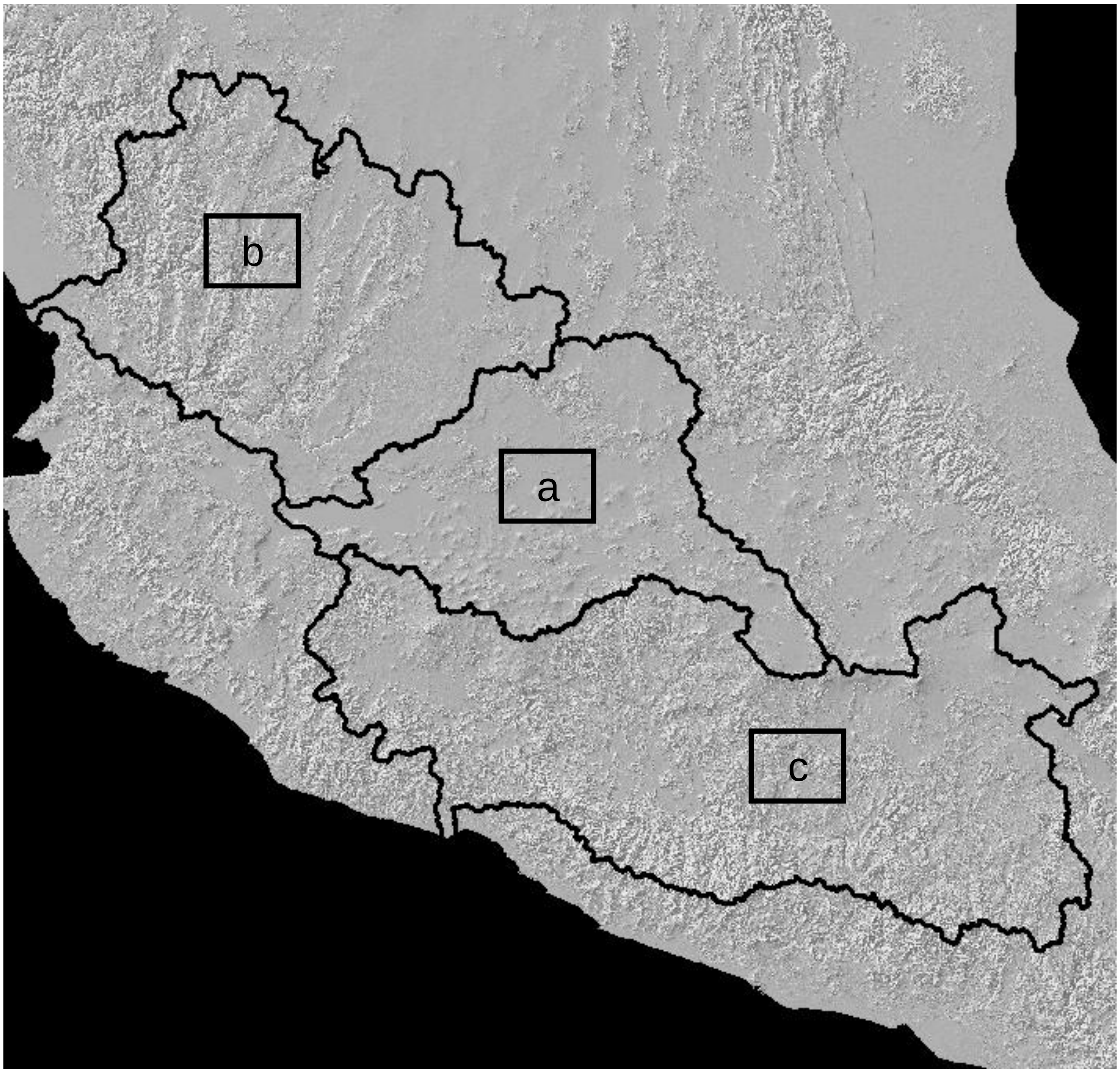


Figure. 6.1: Three of the major basins in central Mexico have been selected for this study; the hydrological region No. 23 formed by the Lerma (a) and Santiago (b) basins and the Balsas basin (c).

coordinate. To address this issue, known distribution points for each species were input in the form of river sections rather than points, under the assumption that fish do not stay static in specific points. Rivers from the studied area were obtained as a vector file digitized by the National Institute of Geography and Populations (INEGI) in Mexico. The vector file was then transformed to a raster image for its use in the model.

5.1.2. Predictive Species Distribution Models (PSD)

The PSD models were produced through the Habitat Suitability and Species Distribution module (HSSD) of IDRISI Andes (Clark Labs, Clark University, Worcester, MA). The HSSD module analyzes the known presence data with environmental factors through Mahalanobis typicality. The Mahalanobis typicality process identifies the likelihood of any pixel being the same as or similar to those of the distribution points or training pixels (Sangermano and *Eastman*, 2007).

The Mahalanobis distance is defined as:

$$D^2 = (x - m)^T C^{-1} (x - m)$$

Where m is the mean vector and C is the covariance matrix of S (Clark *et al*., 1993). The output is in form of typicality probabilities on a scale from 0.0 to 1.0. Low typicalities express that the area may be unusual but still part of the probable range for the species (Eastman, 2009). Values of 0.001 or less were considered small enough to be considered outside the distribution range for each species.

5.1.3. Validation

Validation is an important step in the modelling process because it quantifies out confidence in the predictions produced from future applications of the model (Olden *et al*., 2002). For the purpose of validation, a number of random known distribution points were kept from the training data in order to use them as control points. These control points where then compared to the final prediction maps. Due to *C. promelas*' small range of distribution, this approach for validation was not possible for this species.

5.2. Results

The results show the predicted occurrence for each targeted species within its native catchment on a probability scale. Those rivers shown in blue have a predicted probability of P= < 0.001, signifying that it is highly improbable that a given species will be found in those locations.

5.2.1. Predictive Species distribution model (PSD) for native atherinids

The PSD model for native species showed that *Atherinella balsana* has a high probability for distribution in the Balsas basin. The model's result successfully covered the verification control river sections. Out of the studied native species for the Balsas basin, *A. balsana* had the broadest range of potential distribution (Fig 6.2.).

Between the two Chirostoma species of the “arge” group C. aculeate showed a smaller potential range of distribution with areas of high probability in Lake Chapala, it’s inlet of the Rio Lerma, and it’s outlet to the Rio Grande de Santiago (Fig 6.3). Whereas *C. arge* presented a larger potential range of distribution, that spread throughout the Lerma basin, covering all major Lakes. In the Santiago basin *C. arge*’s higher probability of distribution was present in the Rio Verde and tributaries (Fig, 6.4.).
The predictive distribution model of *C. humboldtianum* showed high probability of distribution in the Rio Lerma section of the Chapala Lake’s inlet, also Lake Chapala and the outlet to the Rio Grande de Santiago (Fig. 6.5.).

C. jordani’s potential range of distribution covers all major lakes in the Lerma basin. It also shows continued potential distribution along the Rio Lerma in the Lerma basin, and the Rio Verde in the Santiago basin (Fig. 6.6.).

The smallest range of distribution for all studied species was presented by *C. promelas*, limiting to the inlet to the Chapala Lake, the Lake itself and its outlet (Fig. 6.7.).

6.4.2. Potential distribution model (PSD) of native catfish

The PSD model for predictive distribution of *Ictalurus balsanus* showed a potential range of distribution along the Rio Balsas and tributaries, the reservoir “Presa del Infiernillo” and the Rio. The potential distribution range of *I. balsanus* covers all

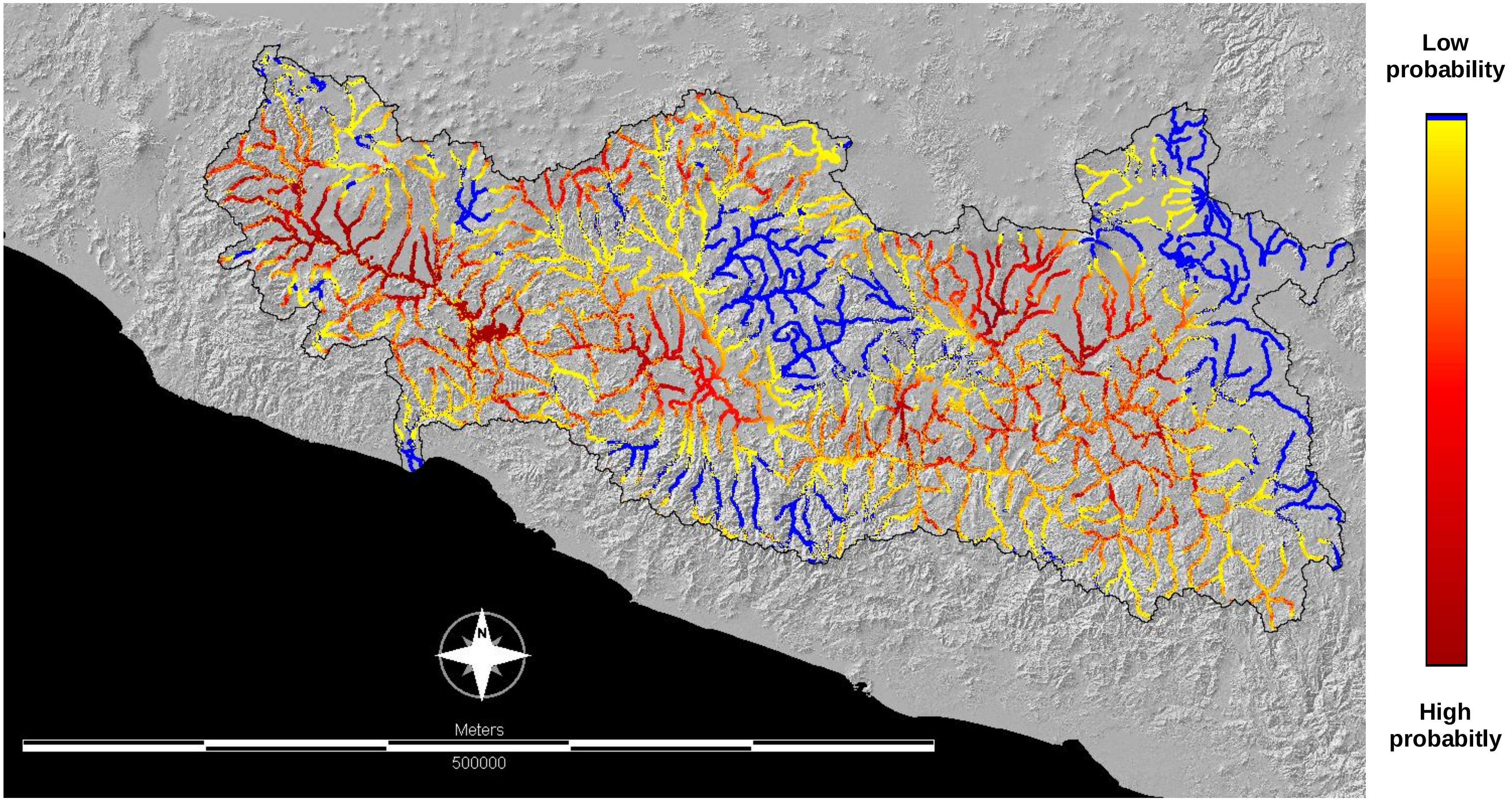


Figure 6.2. Predictive Species Distribution Model (PSD) result showing the potential distribution for *Atherinella balsana* in the Balsas basin, Mexico. The legend represents the probability of distribution for the species, based on abiotic factors.

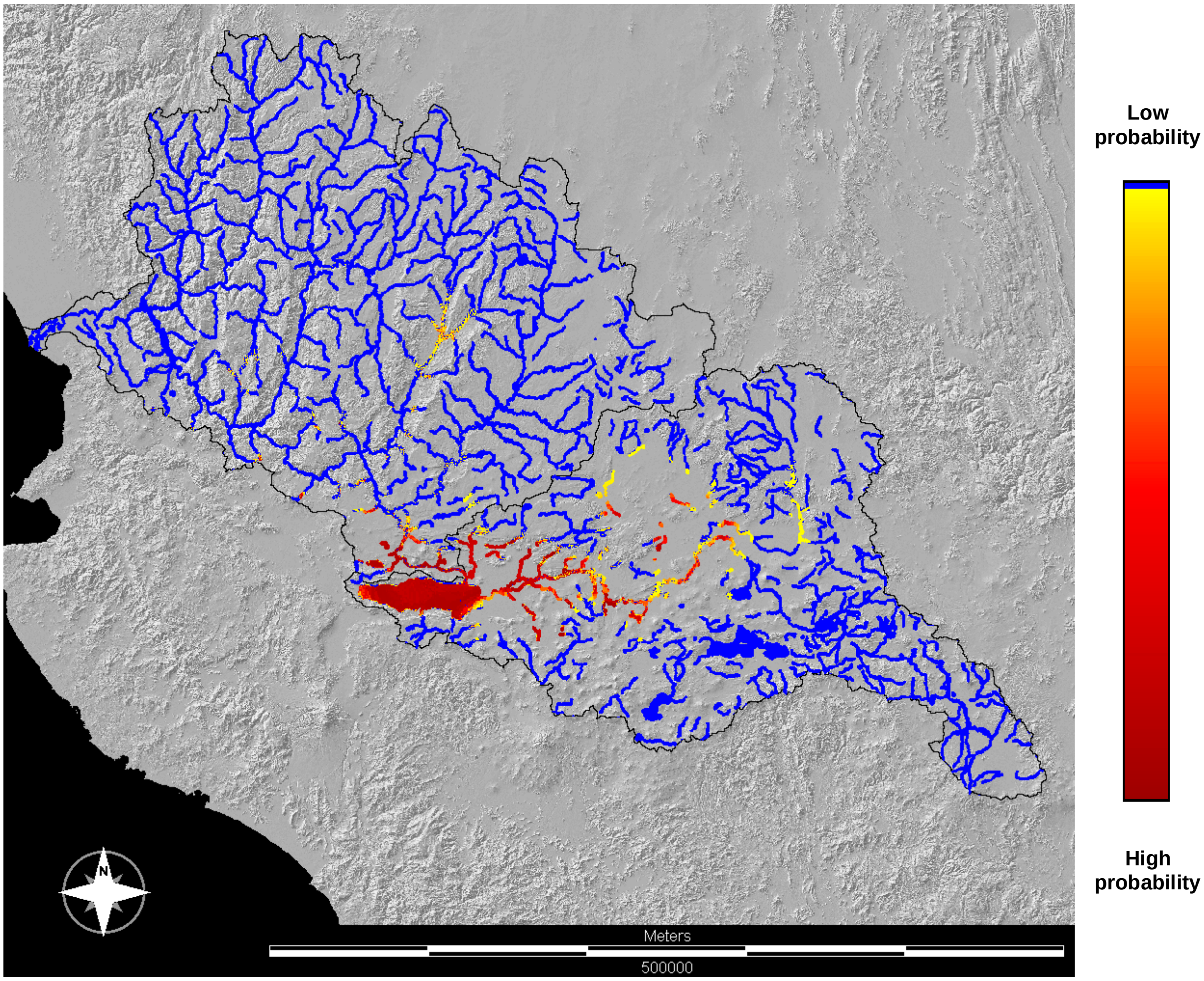


Figure. 6.3. Predictive Species Distribution Model result showing the potential distribution for *Chirostoma aculeatum* in the Lerma-Santaigo basins, Mexico. The legend represents the probability of distribution for the species, based on abiotic factors.

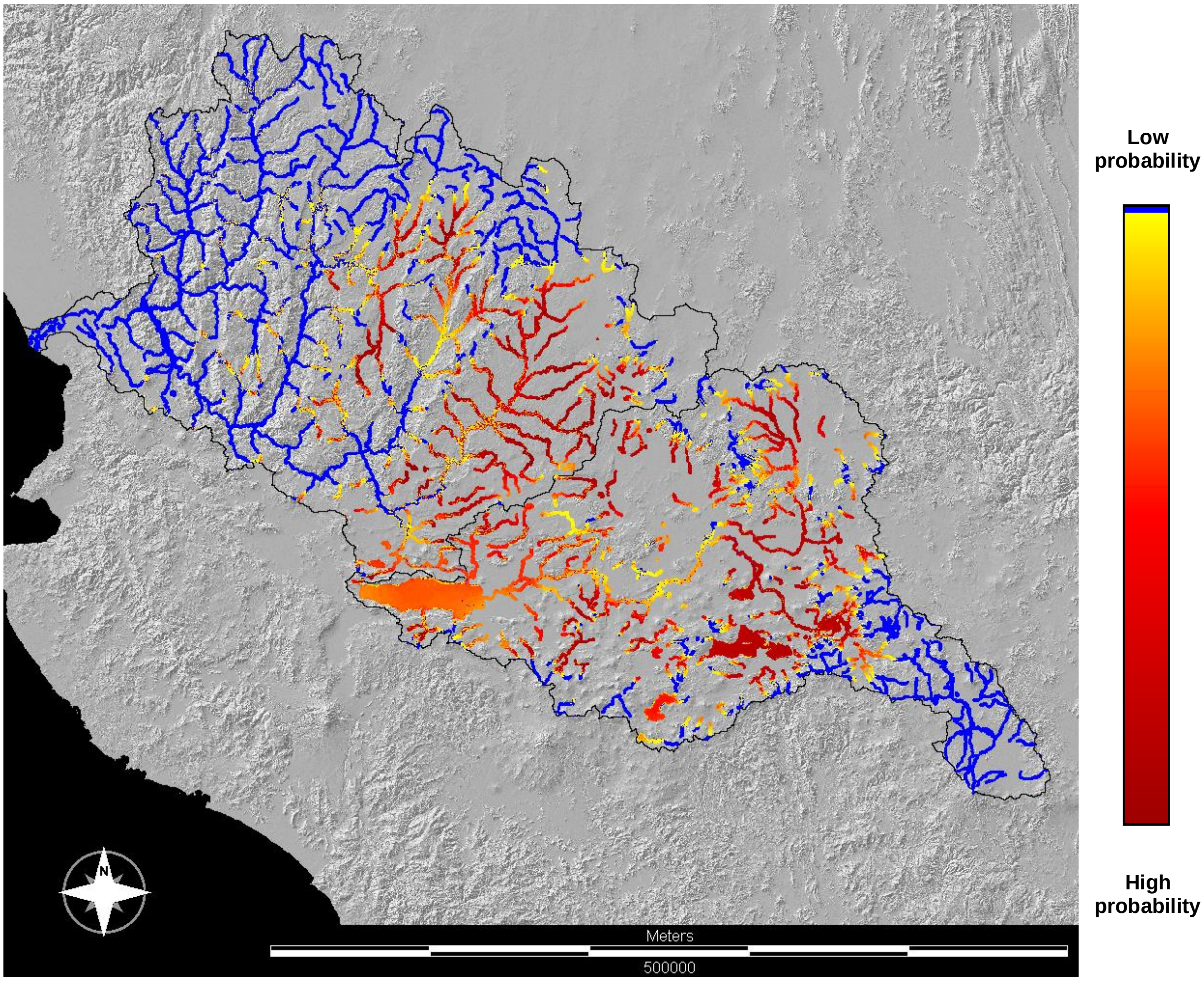


Figure. 6.4. Predictive Species Distribution Model result showing the potential distribution for *Chirostoma arge* in the Lerma-Santaigo basins, Mexico. The legend represents the probability of distribution for the species, based on abiotic factors.

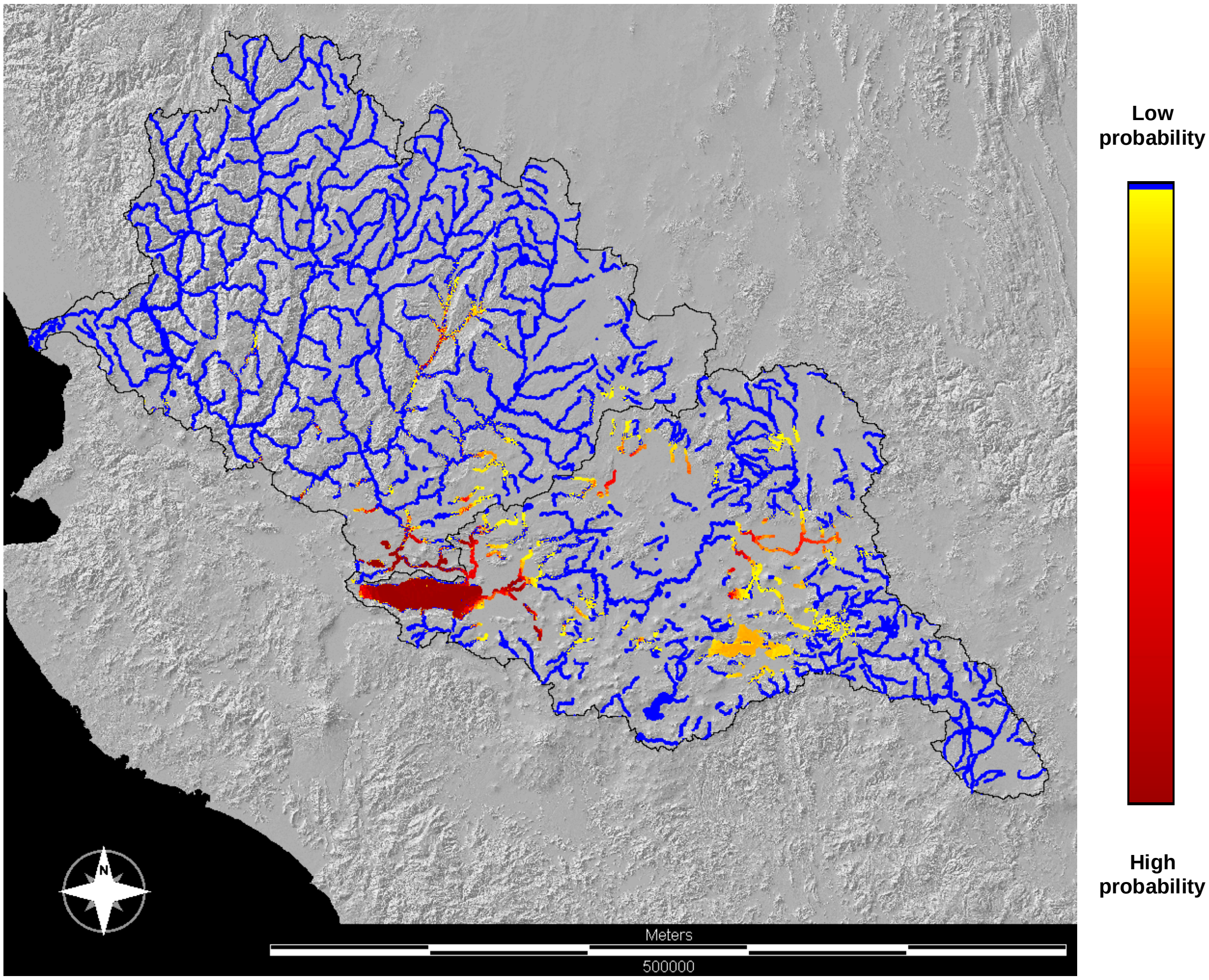


Figure. 6.5. Predictive Species Distribution Model result showing the potential distribution for *Chirostoma humboldtianum* in the Lerma-Santaigo basins, Mexico. The legend represents the probability of distribution for the species, based on abiotic factors.

verification control points (Fig 6.8.). Highest probability occurred in the Balsas River and tributaries.

The potential distribution range of *I. dugesii* is the broadest of all studied species. It covers the major lakes in both basins with the exception of Lake Patzcuaro. Probability values are low across the studied area; however they still represent part of the potential distribution range. Highest probability is shown in the Basins outlet to the Pacific Ocean (Fig. 6.9.).

6.4.3. Potential of Invasion model (PI) for atherinids

The species *Atherinella balsana*, native to the Balsas basin, shows a low probability for invasion in the Lerma Santiago basins. Invasive probability is higher across the area known as “Medio Lerma” (Middle Lerma). Probability for invasion is greater in the Lerma basin than the Santiago basin (Fig. 6.10). Chirostoma species, natives to the Lerma-Santiago basin, did not show a great potential for invasion in the Balsas basin. However, high probability of invasion can be seen in the north of the basin in higher altitude areas of the mountain chain “Eje Neovolcanico Transversal”. C. aculeate shows high probability of invasion in small areas at the north-west border of the basin, and the East border of the Basin (Fig 6.11.). *C. arge*’s potential for invasion is restricted the high altitude areas of the mountain chain “Eje Neovolcanico Transversal”, and the East border of the basin (Fig 6.12.). *C. humboldtianum* showed high probability of invading small

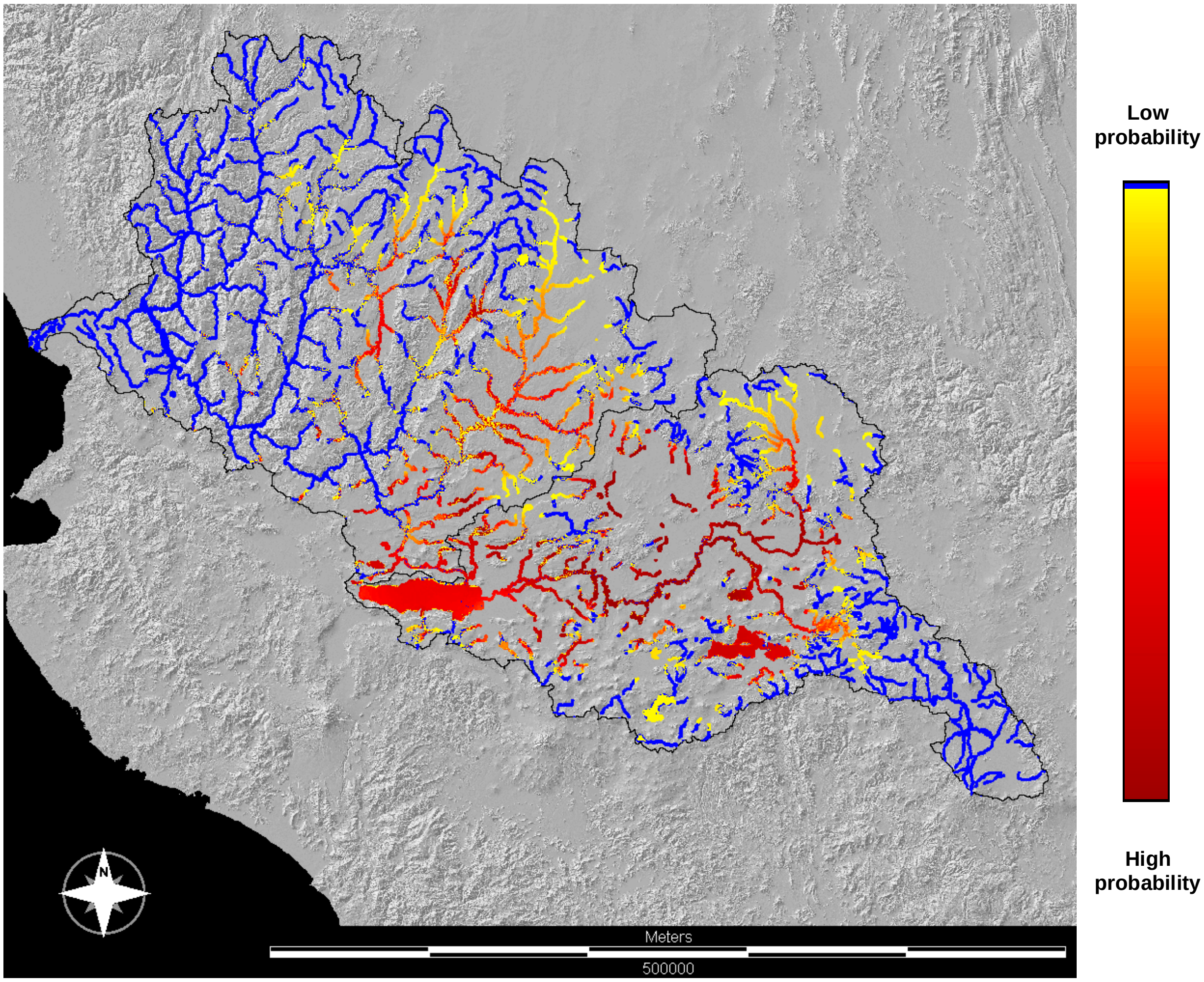


Figure. 6.6. Predictive species Distribution Model (PSD) result showing the potential distribution for *Chirostoma jordani* in the Lerma-Santaigo basins, Mexico. The legend represents the probability of distribution for the species, based on abiotic factors.

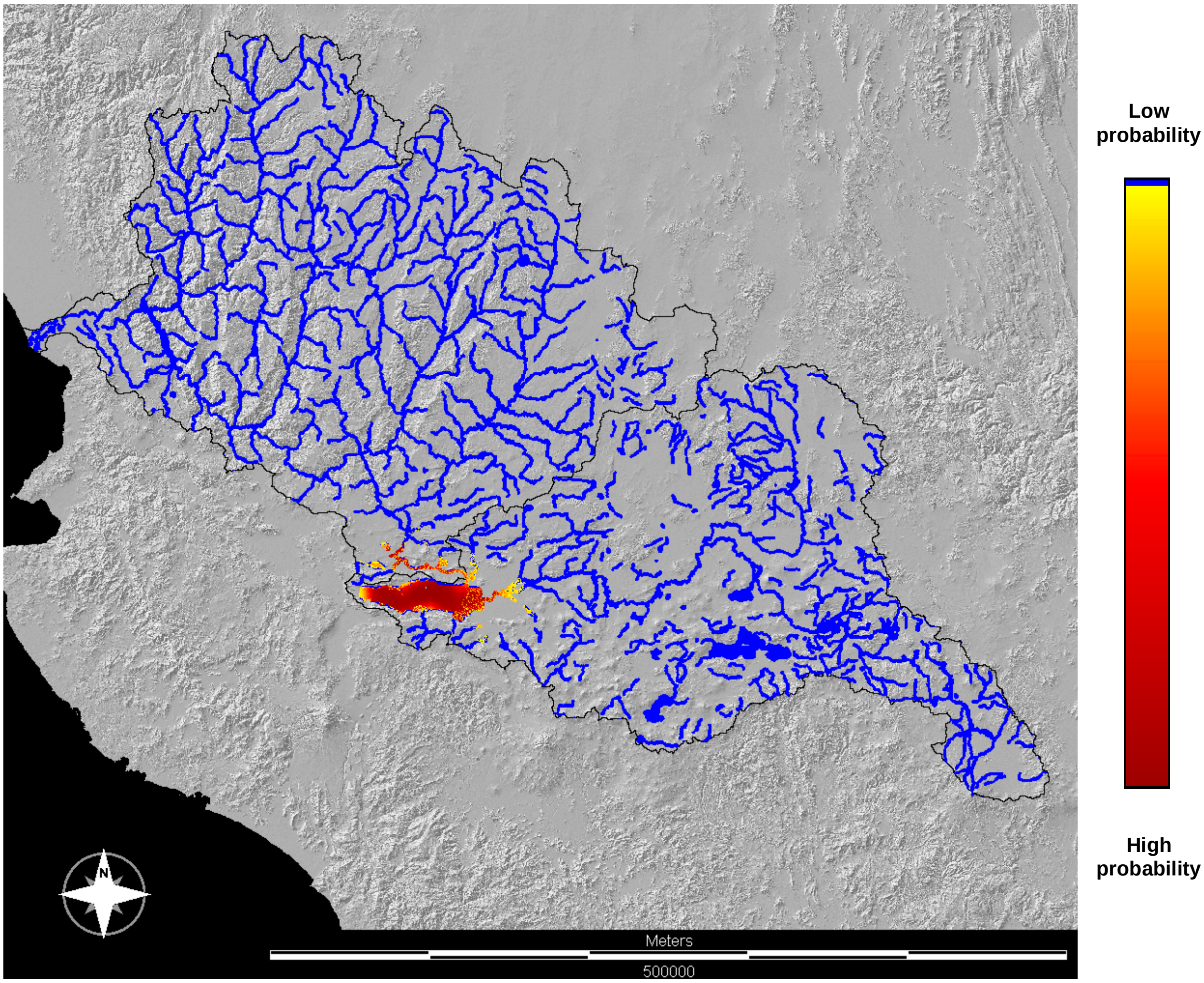


Figure. 6.7. Predictive Species Distribution Model (PSD) result showing the potential distribution for *Chirostoma promelas* in the Lerma-Santaigo basins, Mexico. The legend represents the probability of distribution for the species, based on abiotic factors.

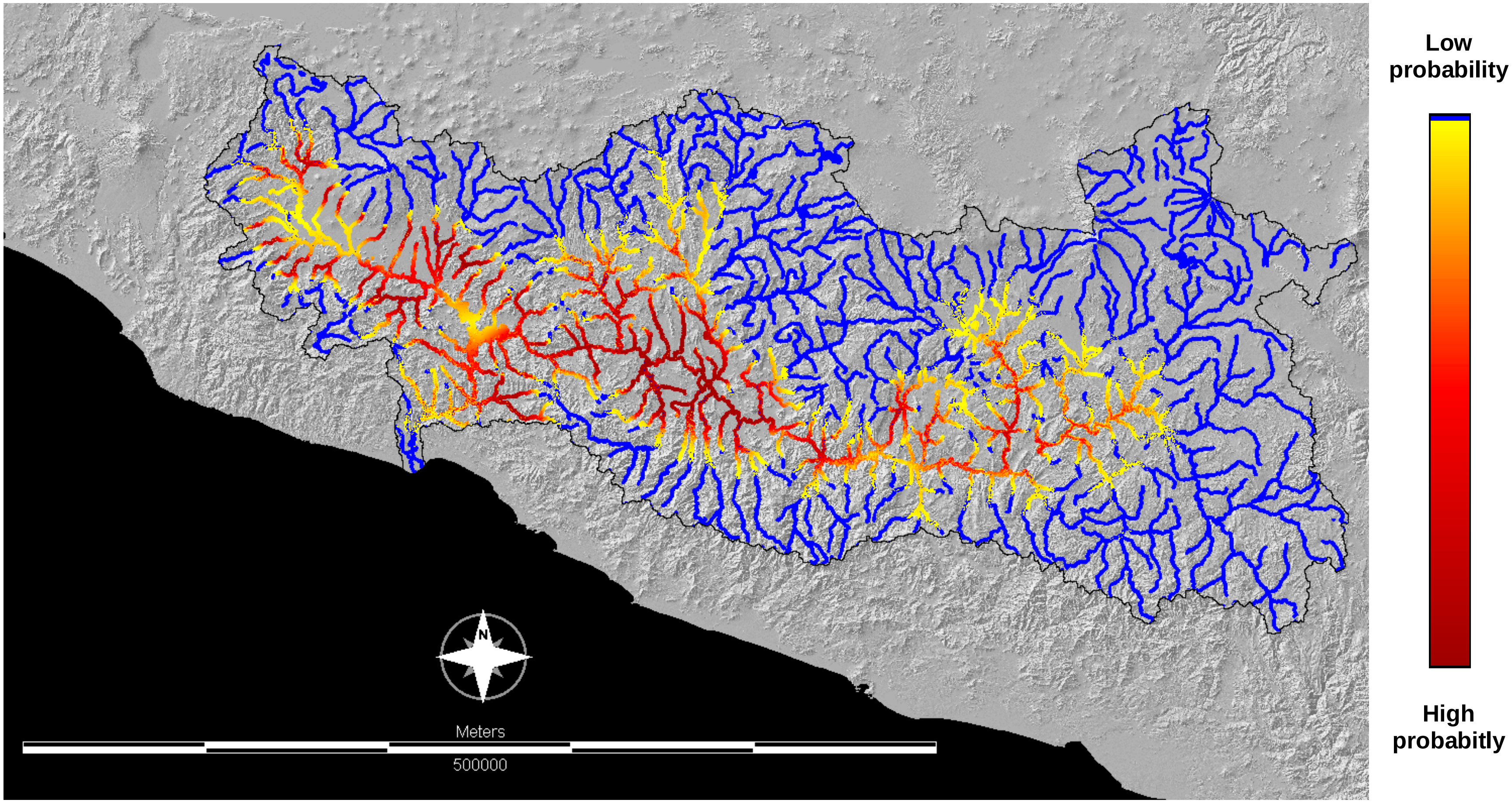


Figure 6.8. Predictive Species Distribution Model (PSD) result showing the potential distribution for *Ictalurus balsanus* in the Balsas baisin, Mexico. The legend represents the probability of distribution for the species, based on abiotic factors.

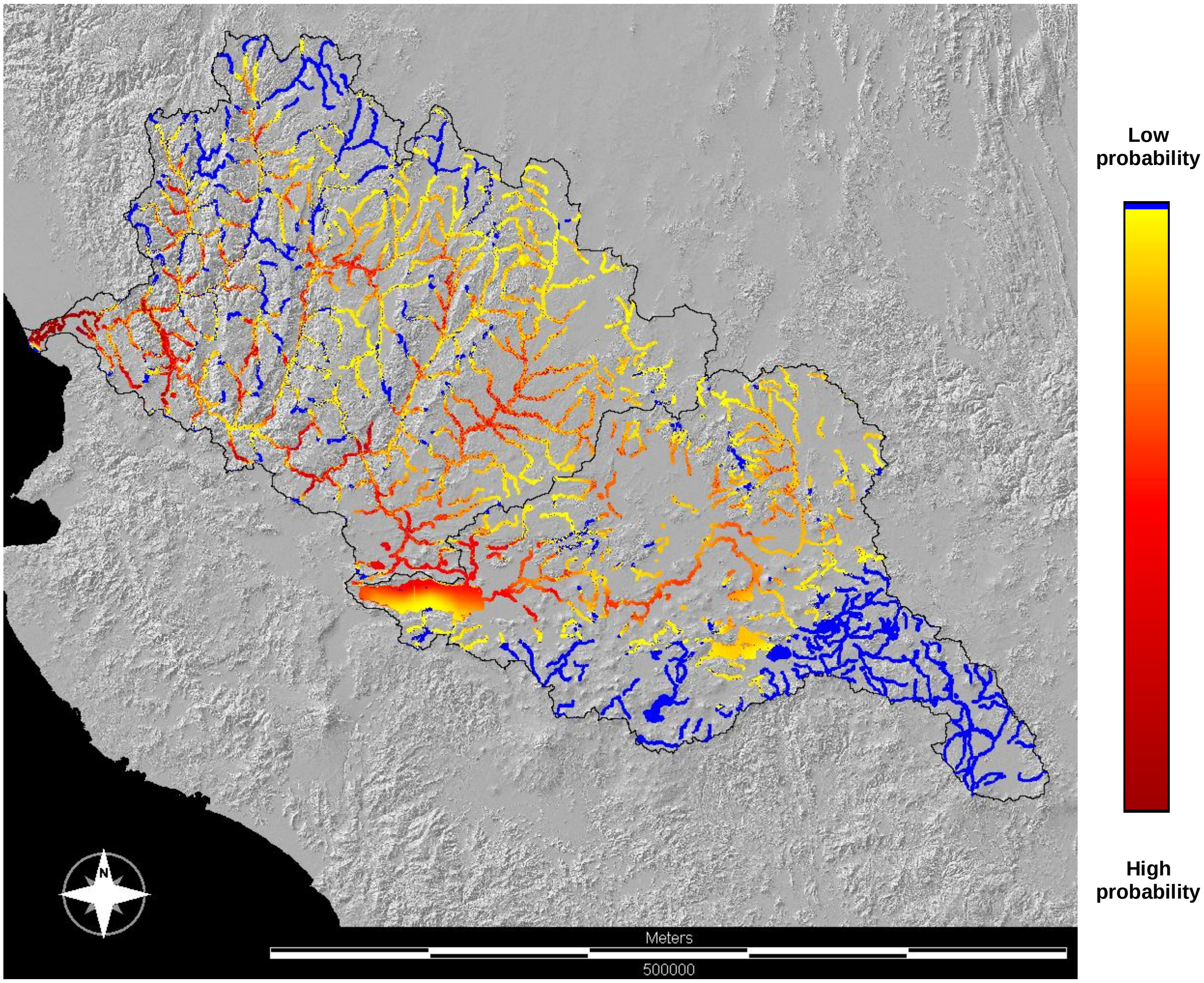


Figure. 6.9. Predictive Species distribution Model (PSD) result showing the potential distribution for *Ictalurus dugesii* in the Lerma-Santaigo baisins, Mexico. The legend represents the probability of distribution for the species, based on abiotic factors.

areas in the North-West and East borders of the basin (Fig 6.13.). The potential for invasion by *C. jordani* in the Balsas basin is similar to that one of *C. arge* (Fig 6.14). Whereas *C. promelas* showed no probability of invasion in the Balsas basin.

6.4.4. Potential of Invasion model by ictalurids

Although *Ictalurus balsanus* showed no potential for invasion in the Lerma-Santiago basins, I. dugessi presented a broader range of potential for invasion than other species natives to the Lerma-Santiago basins. The PSD model also showed invasive probabilities in higher altitudes near the mountain chains of the “Eje neovolcanico Transversal” and the “Sierra Madre del Sur” (Fig.6.15).

6.5. Discussion

The Predictive Species Distribution Model developed in this work represents an important part in the decision making process for the development of aquaculture. The impact of PSD models in aquaculture of native species is twofold. They provide the decision maker the opportunity to examine natural ranges of distribution for the establishment of aquaculture sites in areas where escapes will have a milder impact on biodiversity. PSD models are also powerful tools for potential invasive assessments, a key aspect on native species aquaculture. from different methods. For the PSD model presented here 11 variables were included which are similar to those used by Zambrano *et al*., (2006) and Peterson (2003).

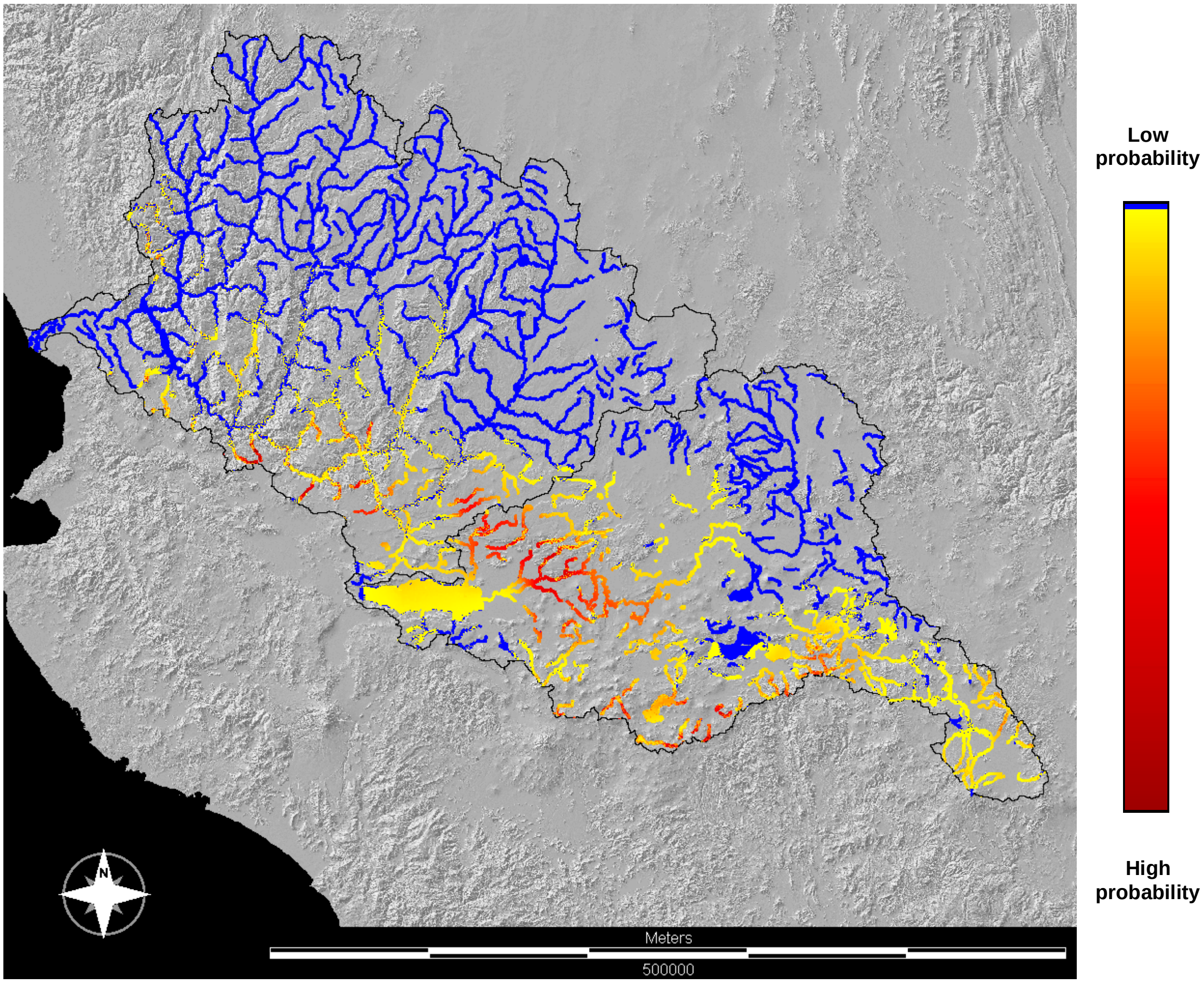


Figure. 6.10. Potential for Invasion Model result showing PI by *Atherinella balsana* in the Lerma-Santaigo baisins, Mexico. The legend represents the probability of invasion for the species, based on abiotic factors.

Such variables represent climatic and topographic factors, essential for the prediction of potentially suitable habitat distributions (Guisan and Zimmerman, 2000).

The outcome from predictive models have to be interpreted carefully, since these tools only provide result regions that resemble the training data, in terms of the factors provided (Soberon and Peterson, 2005). Species with a broad range of known distribution such as *Atherinella balsana* and *Ictalurus dugesii* are prone to show a larger range of predictive distribution, with probable imprecise results. This was discussed by Stockwell and Peterson (2002), and Gusian and Hofer (2003) who found that results for highly common species are often overestimated. The lack of physical barriers in the modelling process can also limit the accuracy of the results, showing areas that are of limit for natural migrations (Soberon and Peterson, 2005). This statement has direct repercussions on the predictive natural range of distribution for any aquatic species. For example, false negatives can be obtained if training data was not based on the species' native range (Curnutt, 2000). However most of the studied fish species in this work have been the subject of regional translocations for aquaculture purposes over the years and the presented results can help to show the impact on their native basins of such introductions.

It also provides a solid prediction of the potential for invasion, since training data is already considering areas where the studied species has been introduced before and thrived.

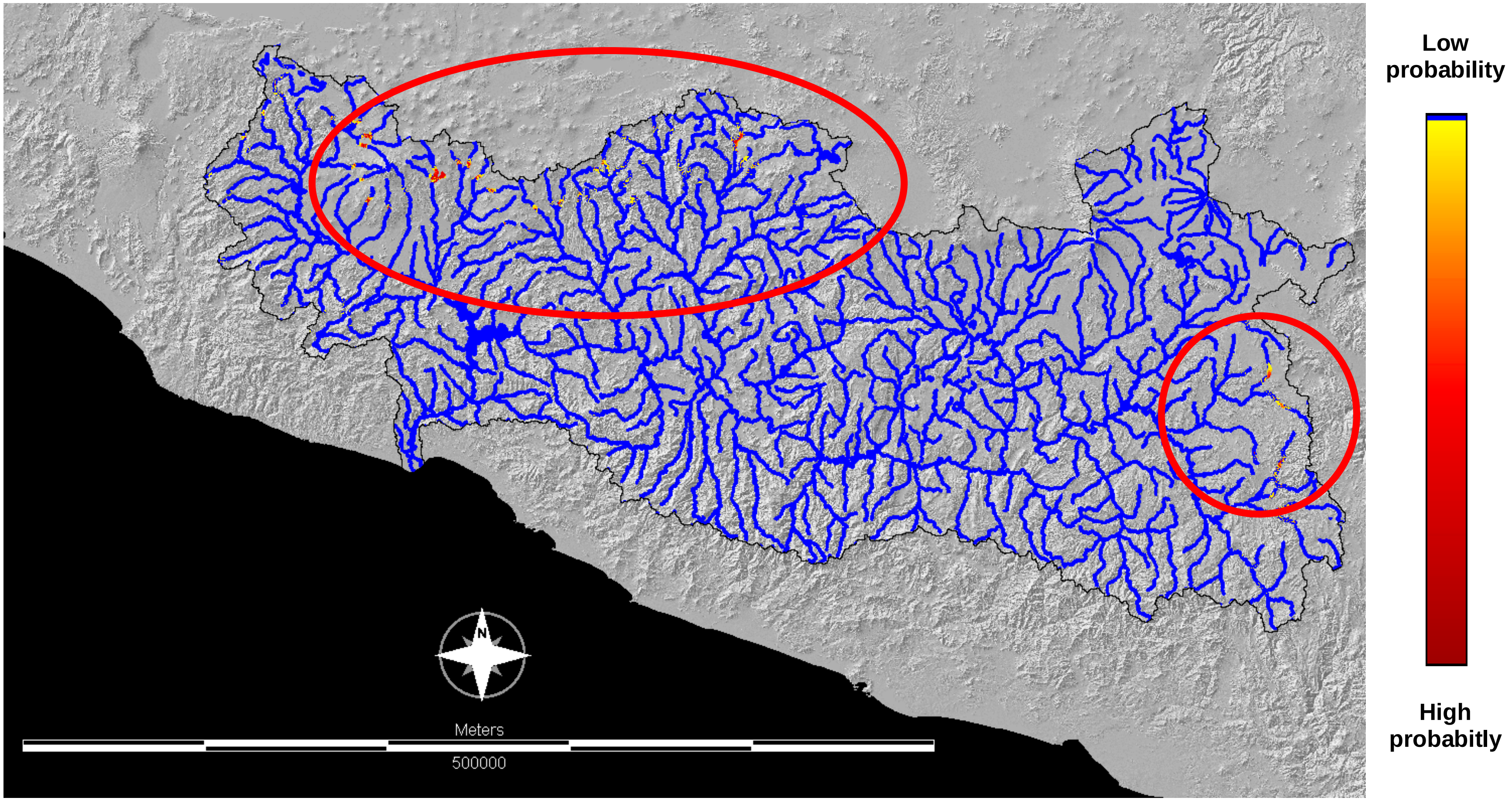


Figure. 6.11. Potential for Invasion Model result showing the PI by *Chirostoma aculeatum* in the Balsas baisin, Mexico.

The legend represents the probability of invasion for the species, based on abiotic factors.

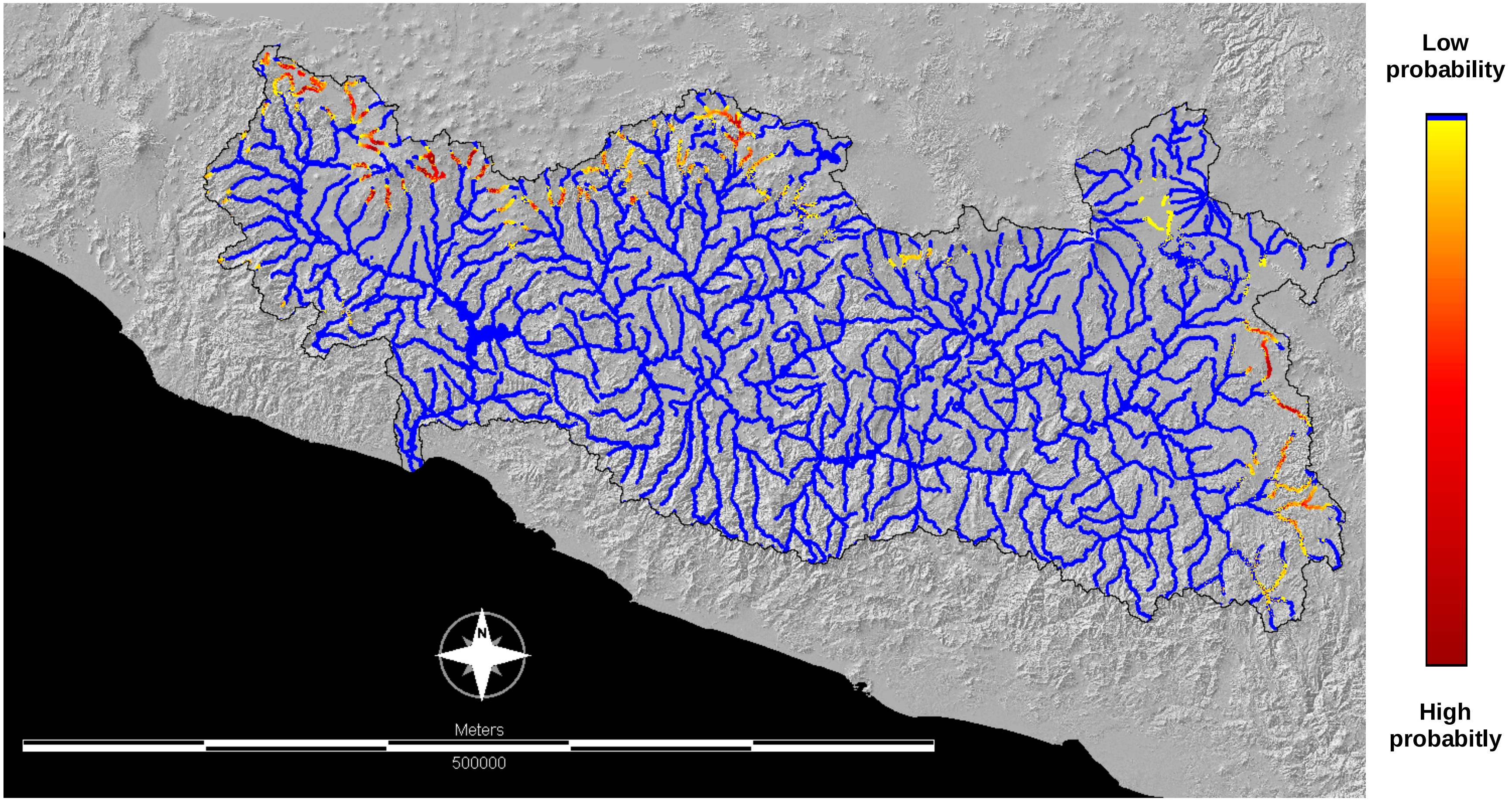


Figure. 6.12. Potential for Invasion Model result showing PI by *Chirostoma arge* in the Balsas baisin, Mexico. The legend represents the probability of invasion for the species, based on abiotic factors.

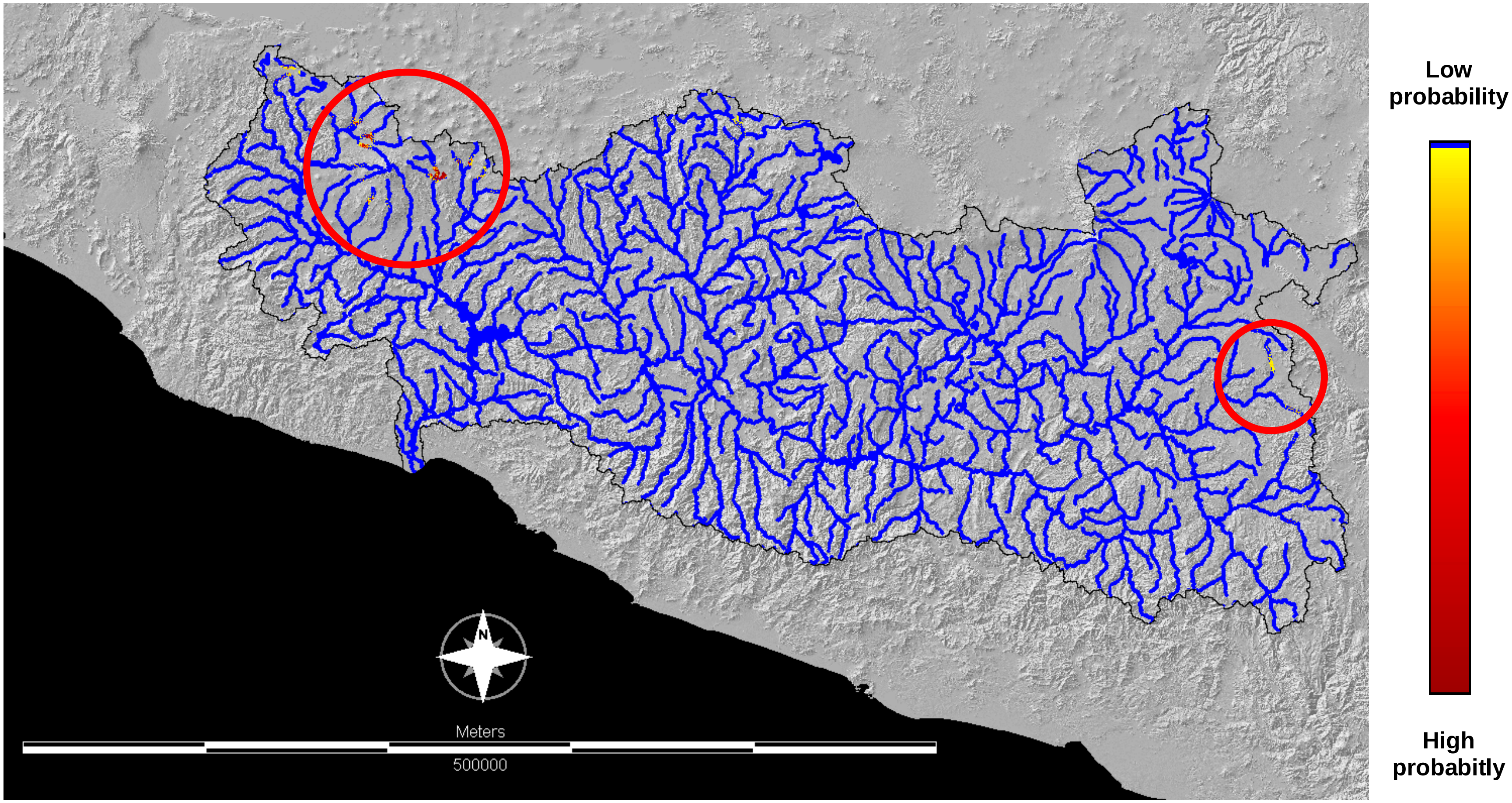


Figure. 6.13. Potential for Invasion Model result showing PI by *Chirostoma humboldtianum* in the Balsas baisin, Mexico.

The legend represents the probability of invasion for the species, based on abiotic factors.

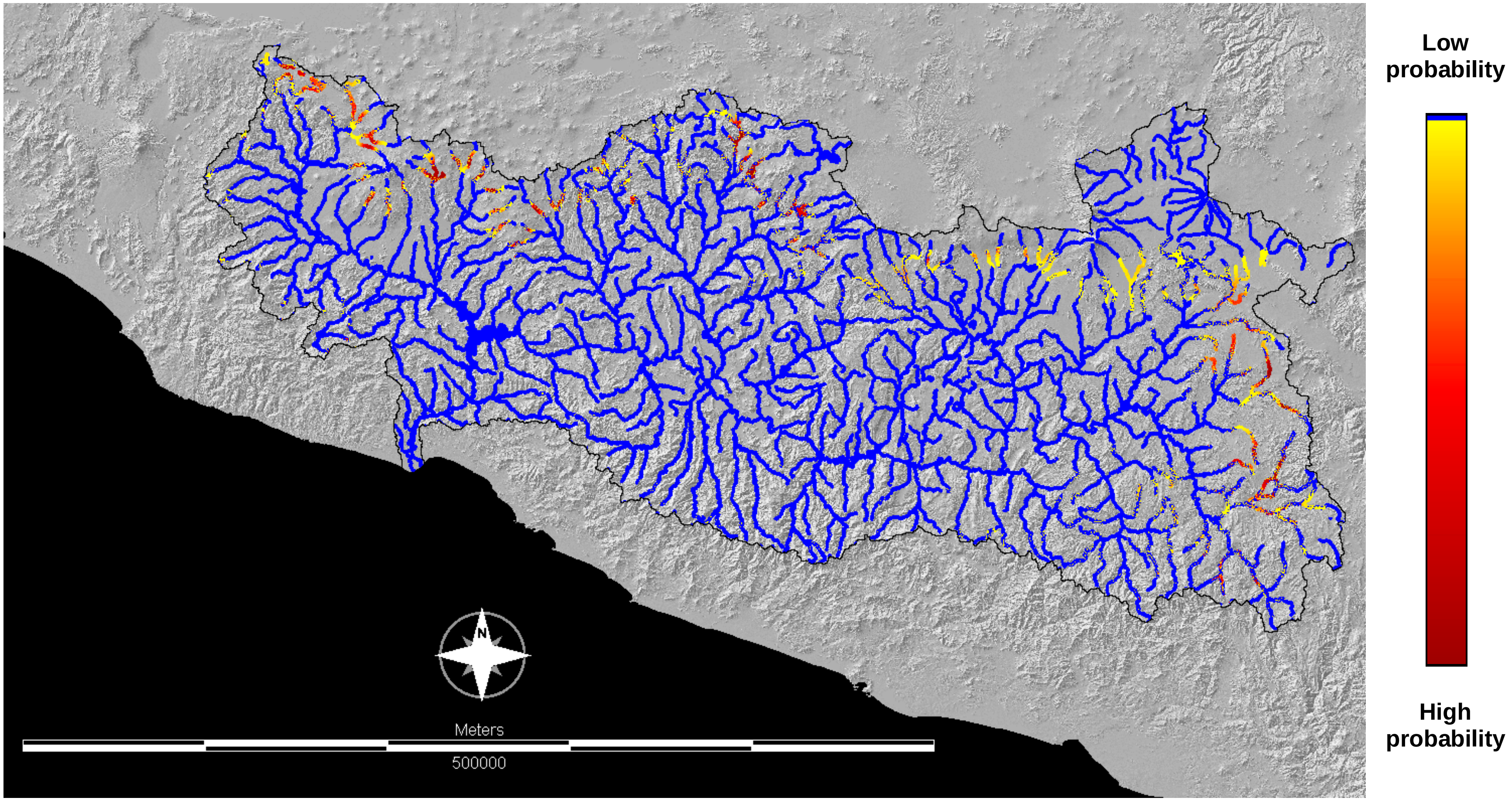


Figure. 6.14. Potential for Invasion Model result showing PI by *Chirostoma jordani* in the Balsas basin, Mexico.

The legend represents the probability of invasion for the species, based on abiotic factors.

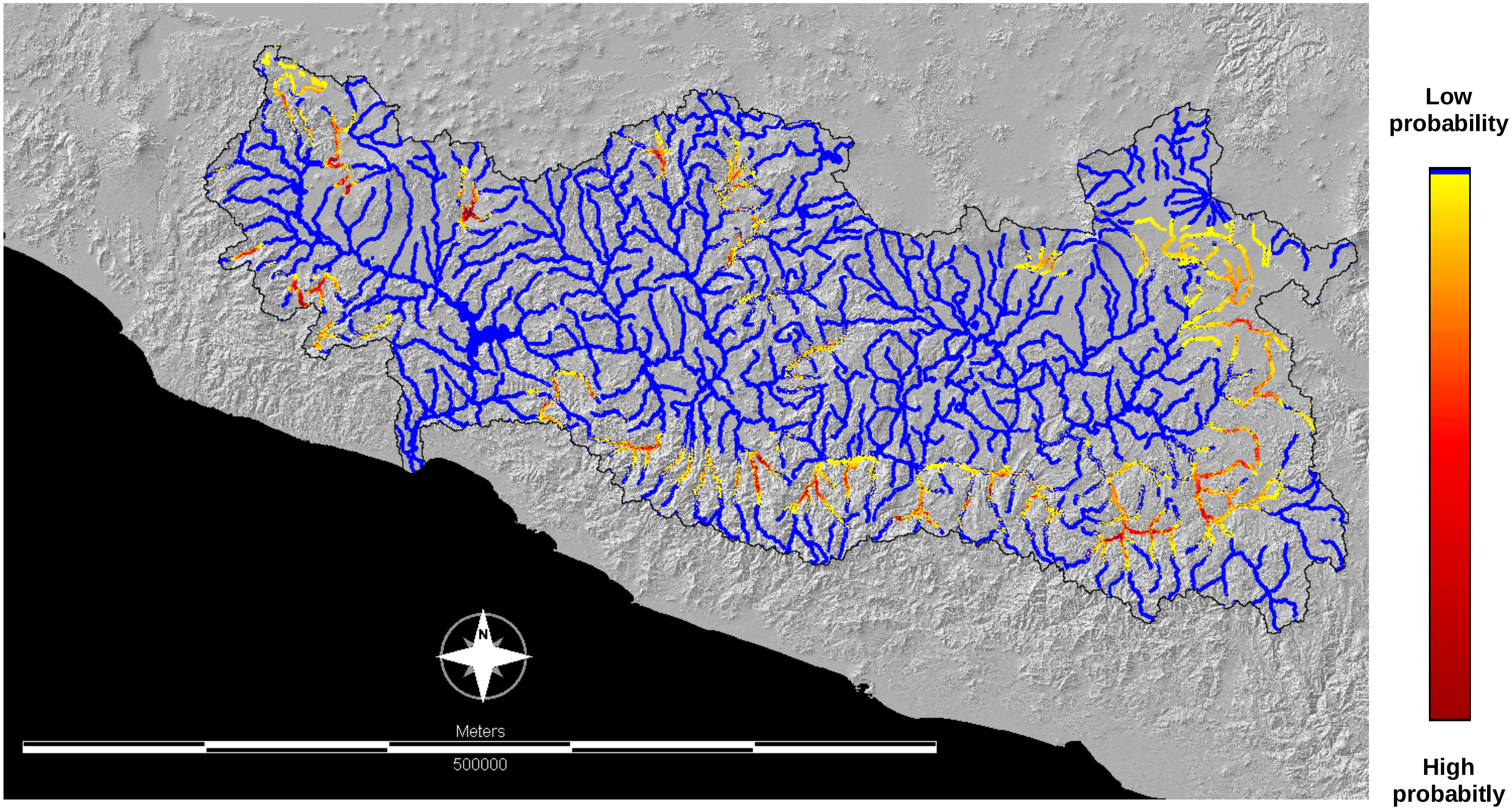


Figure. 6.15. Potential for Invasion Model result showing PI by the catfish *Ictalurus dugesii* in the Balsas basin, Mexico.

The legend represents the probability of invasion for the species, based on abiotic factors.

The use of Predictive Species Distribution maps in aquaculture, can give the decision maker a major advantage for the selection of sustainable recruitment areas. Species that are new for aquaculture require the development of hatcheries in the region or the recruitment of wild seed. Extraction of wild organisms for aquaculture may transform the activity so that it becomes unsustainable for the ecosystem; however recruitment of a reproductive stock is essential in the process of domestication for the development of the culturing technology and later on the production of hatcheries that will make the process sustainable (Hair *et al*., 2002). In the Lerma-Santiago basins, Chirostoma arge, *C. jordani* and *I. dugesii* showed the broadest range of distribution, whereas *C. humboldtianum* and *C. promelas* showed the smallest range. This is congruent with the low population densities reported for this species (Barriga-Sosa *et al*., 2002; Elias-fernandez *et al*., 2008).

The PSD maps for *C. promelas* and *Ictalurus balsanus*is showed that the potential distribution matches their natural distribution (Miller *et al*., 2005). This reflects on the results obtained for their Potential of Invasion, since both species showed that they are unlikely to establish far from their natural range of distribution.

The PSD maps for Potential Invasion are extremely important for the development of aquaculture. The introduction of exotic species for aquaculture has been considered one of the biggest problems associated with biodiversity loss. When the targeted new species for aquaculture are also threatened and endangered, conservation of their natural habitats also becomes a priority. Knowing the potential natural range of distribution for each species also provides the decision making planner the opportunity to address the risks of establishing aquaculture of a certain species. Recognizing the natural range of distribution for freshwater fish species that are considered for their use in aquaculture is a key factor for the success of aquaculture of native species, if this should help protecting biodiversity. Of the species studied *Atherinella balsana* and *Ictalurus dugesii* showed the highest potential for invasion which is a matter of concern since there are limited possibilities for eradication of established exotic species (Kolar and Lodge, 2002).

Peterson and Vieglais (2001) suggested that niche based modelling cannot provide perfect predictions of future invasions. The lack of biotic factors that are on the modelling process such as competition or predation, can affect the results even when the abiotic conditions are optimum (Brown *et al*., 1996; Fielding and Haworth, 1995). However, the inclusion of PSD models for the prediction of Invasive Potential in the process of native species aquaculture development is, as Chen *et al*., (2006) suggested a proactively method for the assessment of risk before introduction.

6.6. Conclusion

The Predictive Species Distribution Model represents a powerful tool for conservation, for it provides objective basis for the identification of gaps in knowledge of species distribution. For aquaculture, it provides reliable information on the natural range of distribution for each species; an important factor for aquaculture of native species that gives strong guidelines for site selection and translocation limitation. The Potential for Invasion model proposed is a powerful tool for the decision maker in order to avoid introduction of highly invasive species. This model also provides a robust tool for the development of conservation programs for species with reduced distribution, such as *C. promelas.* The studied species have a massive socio-economic impact and significance in central Mexico. Their high market demand has been reflected in the reduction of the fisheries; therefore the establishment of aquaculture of such species is relevant to the economics of the region and as a measure for the protection of biodiversity.

References

Alcocer, J. & Bernal-Brooks, F.W., 2010. Limnology in Mexico. *Hydrobiologia*, **644:**15-68.

Alves, C. *et al.,* 2007. mpacts of Non-Native Fish Species in Minas Gerais, Brazil: Present Situation and Prospects. *Ecological and Genetic Implications of Aquaculture Activities* T. M. Bert, ed., Dordrecht: Springer Netherlands. Available at: http://www.springerlink.com/content/g776734330641hxp/ [Accessed March 17, 2011].

Arce U.E. and Luna-Figueroa J. 2003. Efecto de dietas con diferente contenido proteico en las tasas de crecimiento de crias del Bagre del Balsas *Ictalurus balsanus* (Pisces: Ictaluridae) en condiciones de cautiverio. *Revista AquaTIC.* **18:** 39-47.

Argent, D. *et al*., 2003. Predicting freshwater fish distributions using landscape-level variables. *Fisheries Research*, **60**:17-32.

Arismendi, I., Soto, D., Penaluna, B., Jara, C., Leal, C. and León-Muñoz, J. 2009. Aquaculture, non-native salmonid invasions and associated declines of native fishes in Northern Patagonia lakes. *Freshwater Biology.* **54:** 1135-1147.

Austin, M., 2007. Species distribution models and ecological theory: A critical assessment and some possible new approaches. *Ecological Modelling*, **200**:1-19.

Avise, J.C., Reeb, C.A. & Saunders, N.C., 1987. Geographic Population Structure and Species Differences in Mitochondrial DNA of Mouthbrooding Marine Catfishes (Ariidae) and Demersal Spawning Toadfishes (Batrachoididae). *Evolution*, **41**:991-1002.

Barbour, C.D., 1973. The systematics and evolution of genus *Chirostoma* Swainson. Tulane Studies in Zoology and Botany **19** : 97–141.

Barriga-Sosa I. Ibañez'Aguirre A.L. and Arredondo'Figueroa J.L. 2002. Morphological and genetic variation in seven species of the endangered *Chirostoma "humboldtianum* species group" (Atheriniformes: Atherinopsidae). *Rev. Biologia Tropical* **50**: 199-216.

Bloom, D.D. *et al.,* 2007. Threatened fishes of the world: *Chirostoma aculeatum* Barbour, 1973 (Atherinopsidae). *Environmental Biology of Fishes*, **82**:221-222.

Brown, J.H., Stevens, G.C. & Kaufman, D.M., 1996. THE GEOGRAPHIC RANGE: Size, Shape, Boundaries, and Internal Structure. *Annual Review of Ecology and Systematics*, **27**:597-623.

Brotons, L. *et al.,* 2004. Presence-absence versus presence-only modelling methods for predicting bird habitat suitability. *Ecography*, **27**:437-448.

Canonico, G.C. *et al.,* 2005. The effects of introduced tilapias on native biodiversity. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **15**:463-483.

Cardenas, R Chavez M., Gonzalez J.L., Aley P., Espinosa J. and Jimenez-Garcia L.F. 2008. Oocyte structure and ultrastructure in the Mexican silverside fish *Chirostoma humboldtianum* (Atheriniforme: Atherinopsidae). *Rev. biol. trop*.**56**: 1371-1380.

CEDRSSA,. 2006. Pesca, Acuicultura e Investigación en México. *Centro de Estudios para el Desarrollo Rural Sustentable y la Soberanía Alimentaria*. Available at: http://groups.ucanr.org/Ballast_Outreach/files/46382.pdf#page=67 [Accessed March 13, 2011]

Chen, P., Wiley, E.O. & Mcnyset, K.M., 2006. Ecological niche modeling as a predictive tool: silver and bighead carps in North America. *Biological Invasions*, **9**:43-51.

Clark, J.D., Dunn, J.E. & Smith, K.G., 1993. A Multivariate Model of Female Black Bear Habitat Use for a Geographic Information System. *The Journal of Wildlife Management*, **57**:519-526.

Curnutt, J.L., 2000. Host-area specific climatic-matching: similarity breeds exotics. *Biological Conservation*, **94**:341-351.

Diana, J.S., 2009. Aquaculture Production and Biodiversity Conservation. *BioScience*, **59**:27-38.

Dietz, R.W. & Czech, B., 2005. Conservation Deficits for the Continental United States: an Ecosystem Gap Analysis. *Conservation Biology*, **19**:1478-1487.

Eastman, J.R. 2009. IDRISI ANDES. Manual. Clark Laboratories for Cartographic Technology and Geographic Analysis. Clark University, Worcester, MA, USA

Elías Fernández, G., Navarrete Salgado, N. A. y Rodríguez Robles, J. L.. 2008. "Alimentación de *Chirostoma* humboldtianum (Valenciennes); (Pisces: atherinopsidae) en el estanque JC en Soyaniquilpan, Estado de México". *Revista Chapingo. Serie ciencias forestales y del ambiente*, num. Julio-Diciembre, pp. 129-134.

Elith, J. *et al.,* 2006. Novel methods improve prediction of species’ distributions from occurrence data. *Ecography*, **29**:129-151.

Ficetola, G.F., Thuiller, W. and Miaud C. 2007. Prediction and validation of the potential flobal distribution of a problematic alien invasive species- the American bullfrog. *Diversity and Distributions.* **13**: 476-485.

Fielding, A.H. & Haworth, P.F. (1995) Testing the generality of bird-habitat models. *Conservation Biology*, **9**: 1466-1481.

Graham, C.H. *et al.* 2004. New developments in museum-based informatics and applications in biodiversity analysis. *Trends in Ecology & Evolution*, **19**:497-503.

Guisan, A. & Hofer, U. 2003. Predicting reptile distributions at mesoscale: relation to climate and topography. *Journal of Biogeography,* **30**: 1233-1243.

Guisan, A. & Thuiller, W., 2005. Predicting species distribution: offering more than simple habitat models. *Ecology Letters*, **8**:993-1009.

Guisan, A. & Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. *Ecological Modelling*, **135**:147-186.

Hair, C., Johann, B. & Peter, D., 2002. *Responsible marine aquaculture* R. R. Stickney & J. P. McVey, eds., CABI.

Hernández-Rubio, M.C. *et al.,* 2006. Early development of the shortfin silverside *Chirostoma* humboldtianum (Valenciennes, 1835) (Atheriniformes: Atherinopsidae). *Aquaculture*, **261**:1440-1446.

Hirzel A.H., Hausser J., Chessel D. and Perrin N. 2002, Ecological-Niche Factor Analysis: How to compute Habitat-Suitability Maps without Absence Data?*Ecological Society of America* **83** : 2027-2036.

Ibanez, A. L., Garcia-Calderon, J. L. and Torres-Orozco B. R. 2008. Aspectos reproductivos de una población del charal *Menidia jordani* (Woolman) del Lago de Metztitlán, Hidalgo. *Hidrobiológica*. **18**: 1-9.

Jelks H.L., *et al.,* Conservation Status of Imperiled North American Freshwater and Diadromous Fishes. Available at: http://cat.inist.fr/?aModele=afficheN&cpsidt=20639296 [Accessed August 8, 2011].

Kolar, C.S. & Lodge, D.M., 2002. Ecological Predictions and Risk Assessment for Alien Fishes in North America. *Science*, **298**:1233 -1236.

Kwak M.,Kami J.A. and Gepts P. 2009. The Putative Mesoamerican Domestication Center of *Phaseolus vulgaris* Is Located in the Lerma-Santiago Basin of Mexico. *Corp Science Society of America*. **49**: 554-563.

Lehmann, A.*,* Overton, J.M. *and* Leathwick, J.R. 2002*.* GRASP: generalized regression analysis and spatial prediction*. Ecological Modelling,* **157:** 189–207*.*

Lyons J, González-Hernández G, Soto-Galera E, Guzmán-Arroyo M (1998). Decline of freshwater fishes and fisheries in selected drainages of West-central México. *Fisheries* **23**:10–18

Martínez-Meyer, E. *et al.*, 2006. Ecological Niche Modelling and Prioritizing Areas for Species Reintroductions. *Oryx*, **40**:.411-418.

Martínez-Palacios, C.A. et al., 2008. Developments in the nutrition of Menidia estor Jordan 1880. Aquaculture Research, 39(7), pp.738-747. Available at: [Accessed March 13, 2011].

McGinnity, P., P. Prodöhl, A. Ferguson, R. Hynes, N. O. Maoiléidigh, N. Baker, D. Cotter, B. O'Hea, D. Cooke, G. Rogan, J. Taggart, and T. Cross. 2003. Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon. Proceedings of the Royal Society B: Biological Sciences **270**:2443-2450.

McNyset, K.M., 2005. Use of ecological niche modelling to predict distributions of freshwater fish species in Kansas. *Ecology of Freshwater Fish*, **14**:243-255.

Mercado-Silva, N. *et al.,* 2006. Long-term changes in the fish assemblage of the Laja River, Guanajuato, central Mexico. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **16**:533-546.

Miller, R.R., Minckley, W.L. & Norris, S.M., 2005. Freshwater Fishes of Mexico. University of Chicago Press.

Montero-Rocha, 2007. *Assessment of freshwater fish seed resources for sustainable aquaculture* M. G. Bondad-Reantaso & F. A. A. O. O. T. U. Nations, eds., Food & Agriculture Org.

Oberdorff, T. *et al.,* 2001. A probabilistic model characterizing fish assemblages of French rivers: a framework for environmental assessment. *Freshwater Biology*, **46**:399-415.

Olden J.D. Jackson D.A. and Peres-Neto P.R. 2002. Predictive Models of Fish Species Distributions: A Note on Proper Validation and Chance Predictions. *The American Fisheries Society*. **131**: 329-336.

Olvera-Blanco Y.M. Gomez-Marquez J.L. Peña-Mendoza B. Gaspar-Dillanes M.T. and Perez C. 2009. Reproductive biology of *Menidia jordani* (Atherniformes:Atherinopsidae) in Xochimilco Lake, Mexico. *Ciencia pesquera,* **17**: 65-75.

Pearce, J. & Ferrier, S., 2001. The practical value of modelling relative abundance of species for regional conservation planning: a case study. *Biological Conservation*, **98**:33-43.

Peterson, A.T. & Vieglais, D.A., 2001. Predicting Species Invasions Using Ecological Niche Modeling: New Approaches from Bioinformatics Attack a Pressing Problem. *BioScience*, **51**:363.

Peterson, A.T., 2003. Predicting the Geography of Species' Invasions via Ecological Niche Modeling. *The Quarterly Review of Biology*, **78**:419-433.

Peterson, A., 2006. Uses and Requirements of Ecological Niche Models and Related Distributional Models. Available at: https://journals.ku.edu/index.php/jbi/article/viewArticle/29 [Accessed March 13, 2011].

Richter, B. D., D. P. Braun, M. A. Mendelson, and L.L. Master. 1997. Threats to imperiled freshwater fauna. Conservation Biology **11**:1081–1093.

Rosas-Valdez, R. *et al.,* 2007. Helminth Parasites of the Balsas Catfish *Ictalurus balsanus* (Siluriformes: Ictaluridae) in Several Localities of the Balsas River Drainage, Mexico: Species Composition and Biogeographical Affinities. *Comparative Parasitology*, **74**:204-210.

Ross, L.G. *et al.,* 2006. Determination of feeding mode in fishes: the importance of using structural and functional feeding studies in conjunction with gut analysis in a selective zooplanktivore *Chirostoma* estor estor Jordan 1880. *Journal of Fish Biology*, **68**:1782-1794.

Rotenberry J.T., Preston K. L., and Knick S. T. 2006. GIS-Based Nich Modeling for Mapping Species' Habitat. *Ecological Society of America* **87** :1458-1464.

Salgado-Maldonado, G. *et al.,* 2004. Helminth Parasites of Freshwater Fishes of the Ayuquila River, Sierra de Manantlán Biosphere Reserve, West Central Mexico. *Comparative Parasitology*, **71**:67-72.

Sanchez- Merino, R., Fermin B.M., and Mendoza E. A. 2009. Selectividad del zooplancton y solapamiento trófico entre tallas del pez *Menidia humboldtiana* (Atheriniformes: Atherinopsidae) en el embalse Danxhó, México. *Rev. biol. Trop* .57, n.1-2, pp. 187-194. ISSN 0034-7744.

Sangermano F., Eastman, J.R. 2007. Linking GIS and ecology-The use of Mahalanobis typicalities to model species distribution. Clark Laboratories for Cartographic Technology and Geographic Analysis. Clark University, Worcester, MA, USA

Scott, J.M. 1993. Gap Analysis: A Geographic Approach to Protection of Biological Diversity. *Wildlife Monographs*, **123:**3-41.

Soberon, J. & Peterson, T., 2005. Interpretation of Models of Fundamental Ecological Niches and Species' Distributional Areas. Available at: https://journals.ku.edu/index.php/jbi/article/viewArticle/4 [Accessed March 17, 2011].

Stockwell, D.R.B. & Peterson, A.T., 2002. Effects of sample size on accuracy of species distribution models. *Ecological Modelling*, **148**:1-13.

Subasinghe R. Soto D., and Jia J. 2009. Global aquaculture and its role in sustainable development. *Reviews in Aquaculture*. **1**, 2-9.

Sundbald, G. *et al.,* 2009. Transferability of predictive fish distribution models in two coastal systems. *Estuarine, Coastal and Shelf Science*, **83**:90-96.

Thomas, C.D. *et al.,* 2004. Extinction risk from climate change. *Nature*, 427(6970), pp.145-148.

Thuiller, W. *et al.,* 2005. Niche-based modelling as a tool for predicting the risk of alien plant invasions at a global scale. *Global Change Biology*, **11**:2234-2250.

Toledo, A., 2003. *Ríos, costas, mares: hacia un análisis integrado de las regiones hidrológicas de México*, Instituto Nacional de Ecología.

Trujillo-Jiménez, P. *et al.,* 2010. Patterns in the distribution of fish assemblages in Río Amacuzac, Mexico: influence of abiotic factors and biotic factors. *Reviews in Fish Biology and Fisheries*, **20**:457-469.

Vitule, J.R.S., Freire, C.A. & Simberloff, D., 2009. Introduction of non-native freshwater fish can certainly be bad. *Fish and Fisheries*, **10**:98-108.

Wiley, E.O., McNyset, K.M., Peterson, A.T., Robins, C.R. & Stewart, A.M. 2003. Niche modeling and geographic range predictions in the marine environment using a machine-learning algorithm. Oceanography **16**: 120–127.

Wester, P., Melville, R. and Ramos-Osorio, S., 2001. Institutional arrangements for water management in the Lerma-Chapala Basin. In: Hansen, A.M. and van Affreden, M., Editors, 2001. *The Lerma-Chapala watershed: evaluation and management*, Kluwer Academic/Plenum Publishers, New York, pp. 343–369.

Zambrano, L. *et al*., 2006. Invasive potential of common carp (*Cyprinus carpio*) and Nile tilapia (*Oreochromis niloticus*) in American freshwater systems. *Canadian Journal of Fisheries and Aquatic Sciences*, **63**:1903-1910.

Zepeda, R.V., 2005. *Las regiones climáticas de México 1.2.2*, UNAM.

Zheng, B. and Agresti, A. 2000. Summarizing the predictive power of a generalized linear model. Stat. Med. **19**: 1771 - 1781.

Chapter 7

Aquaculture Management Strategies for Native Fish Species in central Mexico

VM Peredo-Alvarez, Trevor C Telfer and Lindsay G Ross.

This chapter describes the application of an Aquaculture Management Strategy for Native Species in central Mexico. It integrates Site Suitability and Predictive species Distribution models into a Geographic Information System for development of environmentally friendly aquaculture of native in Central Mexico for sustainable development.

The body of the text is presented as a publication-ready manuscript.

The main author, **VM Peredo-Alvarez**, developed all sub models and final model. Trevor C Telfer and Lindsay G Ross provided supervisory and editorial support throughout the whole study.

This manuscript will be submitted to **Ecological Modelling**, a journal concerned with the use of mathematical models and systems analysis for the description of ecological processes and for the sustainable management of resources

Chapter 7

Aquaculture Management Strategies for Native Fish Species in Central Mexico

VM Peredo-Alvarez, Trevor C Telfer and Lindsay G Ross

Abstract

Modern aquaculture in Mexico needs innovative management strategies in order to satisfy the growing social and political awareness of biodiversity while at the same time satisfying requirements for food security. The increasing demand for “green” products represents a niche for environmentally friendly aquaculture. The creation of Aquaculture Strategies for the Protection of Biodiversity (ASPB) provides the industry with the right tools for the sustainable development of aquaculture. The use of ASPB management tools allows the decision maker to consider the needs of stakeholders and industry, whilst also considering biodiversity requirements. In this work, an ASPB was constructed under a catchment level approach and promotes multilateral ecological management instead of administrative management, for aquaculture at catchment level. This strategy, in combination with Geographic Information Systems, aims towards sustainability of native species aquaculture and biodiversity, integrating site suitability and predictive distribution models. The final product proposed is a flexible, easy to access tool that allows developing authorities and stakeholders to assess available information for an ecosystem approach to site selection. The ASPB model identified 7,651 km2 of suitable areas for the culture of native *Ictalurus balsanus* and 15,633 km2 highly suitable for the culture of the non native *I. dugesii* in the balsas basin; more than

3,600 km2 of high suitability areas for aquaculture of the native *C. jordani* in the Lerma-Santiago basin. Also, the potential for Invasion by *Atherinella balsana* was assessed for its introduction in the Lerma-Santiago basins.

7.1 Introduction

Aquaculture of native fish species in Mexico requires robust and dynamic management instruments for the regulation of the activity and protection of biodiversity. Management strategies are essential for the sustainability of aquaculture and the environment. Dey *et al*., (2010) suggest that aquaculture management strategies are required to meet the needs and priorities of the stakeholders. However the recent increment in social awareness of declining biodiversity (Lindemann-Matthies and Bose, 2008; Novacek, 2008; Joly *et al*, 2010) and the rapid development of green markets (Hamilton and Zilberman, 2006), demand that ecological needs and priorities be recognised in aquaculture management strategies. The introduction of exotic species has been pointed out as one of the major causes for biodiversity loss (Gaertner *et al*., 2009). Conventional freshwater aquaculture in Mexico still relies on a handful of species such as Tilapia and Carp (Dominguez-Dominguez, 2006; Zambrano *et al* 2010). However, in response to the rapid decline of fish biodiversity worldwide and the continued introduction of exotic species, the use of native species in aquaculture has been suggested, in different parts of the world, as an alternative aimed to protect native fish fauna, (Perez *et al*., 2000; Vitule, 2009). Although the development of native species aquaculture in Mexico is still in the pilot stage, many advances have been made in the subject (Martinez-Palacios *et al*., 2008; Alarcon-Silva *et al*., 2009; Arce and Luna-Figueroa, 2010).

One of the main objectives of the Mexican National Commission for the Use and Understanding of Biodiversity (CONABIO) is to support the creation of innovative models for the sustainable use of the natural resources and the protection of biodiversity (CONABIO, 2011). In that context, regulatory instruments for the management of aquaculture are needed aimed at sustainability. The use of Geographic Information Systems in the development of modelling tools provides the opportunity to produce a dynamic and realistic instrument for aquaculture planning (Ross *et al*., 1993). From a management strategy point of view, integration of a large amount of information from a wide range of backgrounds is essential (Dey *et al*., 2010). The use of GIS in management strategies allows the decision maker to relate several temporal and spatial variables such as socio-economic, ecological, and topographical, into a well founded flexible development tool (Kapetsky and Manjarrez, 2007).

This project aimed to develop an Aquaculture Strategy for the Protection of Biodiversity tool (ASPB) based on GIS models for the use of native aquatic resources. National and international data sources were implemented into a GIS and used to produce a spatial database and guidelines for the development of sustainable aquaculture. Two main aspects were prioritised for the development of the ASPB tool: the identification of areas which contribute both as ecosystem services for humans and as hotspots for conservation of biodiversity (Egoh *et al*, 2007), and the identification of cost effective species both in terms of biodiversity and the productive sector (Hanley and Barbier, 2009).

The presented ASPB is based on ecological management, which means that planning strategies are delimited based on ecological factors rather than political boundaries, with basins as the fundamental unit of analysis as these are likely to be the major delimiters of biodiversity (Pikitch *et al*., 2004). Two species of native catfish (*Ictalurus balsanus* and *I. dugesii*) and two species of native silversides (*C. jordani* and *Atherinella balsana*) were the principal subjects for the use in the ASPB management tool for the development of native species aquaculture in the Lerma-Santiago and Balsas basins in central Mexico.

Ecological niche modelling is one component of the ASPB management package. The ecological niche based Predictive Species Distribution model (PSD) intended to predict the potential distribution of the targeted species, with the aim of delimiting the natural range of distribution for its use as a geographical factor in the development of the activity. Potential for Invasion models (PI) can derive from PSD models and represent one of the most powerful and applied tools in ecological niche modelling (Herborg *et al*, 2007; DeVaney *et al*., 2009). These are robust risk assessment tools, recommended for the prevention of hazardous introductions (Peterson *et al*., 2003).

Arguably, Site Suitability Models (SSM) are the most commonly used GIS tool in aquaculture (Perez *et al* 2005; Hossain *et al* 2007); and the primary component of the ASPB management tool.

The ASPB presented in this manuscript, integrates natural ranges of distribution, potential for invasion by non-native species aquaculture and site suitability for the development of aquaculture. In order to analyse the potential for the tool it was tested for aquaculture of native species and non-native species at catchment level in the Lerma-Santiago and Balsas basins in central Mexico.

7.2 Area of study

The Balsas basin is situated at 17°00' N and 20°00' N latitude and 97°30' W and 103°15' W longitude (INEGI, 2011) and it contributes more freshwater to the Pacific Ocean than any other river in Mexico. Its local fish fauna has 30 species with a high degree of endemism (Abell *et al*., 2000). This is not a highly populated area due to its topographic characteristics produced by the mountain chains that surround the basin, the Trans-Mexican Volcanic belt and the “Sierra Madre del Sur”. However it has some of the most polluted waters in Mexico (SEMARNAT, 2010).

The Lerma Santiago basins are connected by Lake Chapala at I,510 meters above sea level, and together form the hydrologic system no 12, at 19°03’ N and 21°32’ N latitude, and 99° 18’ W and 03° 46’ W longitude (INEGI, 2011). This is one of the most populated areas in Mexico as it is also one of the richest in biodiversity (Lyons *et al*., 1995). There are more than 40 endemic fish species in both basins but due to the intense human activity in the region several of those species they are now endangered or extinct (Sedeño-Diaz and Lopez-Lopez, 2007).

An extended description of the study area can be seen in Chapter 2.

7.3 Aquaculture Strategy for the Protection of Biodiversity model

The aim of the Aquaculture Strategy for the Protection of Biodiversity (ASPB) model is the development of aquaculture from a protection of biodiversity perspective. This planning strategy can be applied with two different approaches. A Catchment level approach for aquaculture of native species, recommended throughout this research as the most viable alternative for the protection of biodiversity and a Translocation approach which includes intentional movement of species in part of its planning strategy.

For the development of a catchment level approach, an ASPB model was produced for the use of the native catfish *Ictalurus balsanus* in the Balsas basin and aquaculture of the native *Chirostoma jordani* in the Lerma-Santiago basins. And for the development of a translocation approach, an ASPB model was produced for aquaculture of the non-native *I. dugesii* in the Balsas basin and aquaculture of the non-native *Atherinella balsana* in the Lerma-Santiago basins.

7.4 ASPB main components

The ASPB integrates a Site Suitability Model (see chapter five) with a Predictive Species Distribution and Potential for Invasion model (see chapter 6), in order to produce a reliable planning tool for the development of catfish aquaculture in the Balsas basin and atherinid aquaculture in the Lerma-Santiago.

7.4.1 Development of a Site Suitability Model for aquaculture.

The model included 17 variables used in 4 sub models of Soil and Terrain, Water, Environmental risk, and Infrastructure. The sub models were produced using Multi-Criteria Evaluation (MCE), with the exception of the Environmental risk sub model which followed the methodology proposed by Sanderson *et al*., (2002) for the Human Foot Print and the Last of the wild. The final model was also produced with a weighted MCE which integrated the four sub models. An extended description of the methodology and results can be seen in Chapter 5.

7.4.2 Development of a Predictive Species Distribution Model

The ecological-niche-based Predictive Species Distribution model (PSD) related known distribution points from the studied species with environmental and topographic variables encountered at the specific locations. With the use of a Mahalanobis typicality, the produced PSD model identifies the characteristics existing in each training point. Then the Mahalanobis distance identifies whether other pixels are equal to the training points or, if not, how different they are. The Mahalanobis distance indicates whether a studied pixel is likely to represent the ecological niche for the species. An extended description of the method and results of more species can be seen in Chapter 6.

7.4.3 Development of a Potential for Invasion Risk assessment

The PSD model identified areas within the natural range of distribution of species known to be endemic to a particular river catchment. The extrapolation of the model to areas known to be outside of the natural range for the species produces a Potential for Invasion model (PI) (Peterson *et al*., 2003). This model can be used as a Risk assessment tool prior to movement or introduction of any species with interest for example in aquaculture, fisheries, sport fisheries, or even biological control. Results of this PI for more species can be seen in Chapter 6.

7.4.4 ASPB procedure

Before embarking upon any aquaculture development or activity that requires movement of species, the use of a PI risk assessment is highly recommended. This will ensure that the decision making process will take into consideration the possible effects that the introduction of any given species may have on local biodiversity. It must also be understood that highly adaptable species may have the potential to establish in different environments. Therefore species with high potential for invasion should not be considered for movement outside of their natural range of distribution.

7.4.5 Catchment level approach

For the development of a Catchment level approach ASPB model a PSD model and a SSM for the aquaculture of the native species were developed. A catchment Level constraint was applied to the modelling process in order to restrict the establishment of the selected species to their native distribution. A Boolean layer was created from the PSD results by reclassifying all values of p= >0.001 to 1 and all values of p= <0.001 to 0. Also, a 2 km buffer was created around the predictive species distribution. Finally the SSM and the boolean PSD layer (BPSD) were combined in a weighted overlay to produce ASPB final results at catchment level. The mathematical expression applied was as follows:

ASPD = (SSM x 0.75) + (BPSD x 0.25)

This approach attempts to identify the most suitable areas for aquaculture within the natural range of distribution for the species.

7.4.6 Translocation approach

This approach should be taken into consideration when plans for aquaculture include the intentional introduction of a non-native species. For the construction of a Translocation approach ASPB model, a PI model was created in the planned basin. The results were then used to create a boolean layer by reclassifying all values of $p= >0.001$ to 1 and all values of $p= <0.001$ to 0 for its use as a constraint. A PSD of related native species was included as a constraint to reduce the probability for intra-species interactions. The PSD of the related native species was transformed into a Boolean layer by reclassifying all values where $p= >0.001$. Finally a SSM was created for the development of aquaculture of the non-native species with the non-native species PI and the native species PSD layers as constraints.

7.5 Results

The results showed ASPB for aquaculture of native catfish *I. balsanus* in the Balsas basin and native *C. jordani* in the Lerma-Santiago basins. An ASPB for aquaculture of the non-native to the Balsas basin *I. dugesii* and the non-native to the Lerma-Santiago *A. balsana* were also created.

Values of ≥0.8 were consistently observed in all variables as the lower range of the recommended parameters. Based on this observation values of ≥0.8 were considered as highly suitable in the SSM and the ASPB models.

7.5.1 Aquaculture of *Ictalurus balsanus* at Catchment level approach

The PSD results for the native *I. balsanus* showed that the species is widely distributed throughout the Balsas river system and the reservoirs of La Villita and El Infiernillo (Fig. 7.1). Distance from the resulting predictive distribution was reclassified using a monotonically increased Sigmoidal function (Fig 7.2). The higher suitability is observed in the first 2,000 m from the predictive species distribution and lower suitability from 10,000 m.

The SSM for the aquaculture of I.balsanus showed 4,102 km2 highly suitable (≥0.8) for aquaculture of the species in the Balsas basin (Fig. 7.3). The ASPB model for I.balsanus showed areas suitable for aquaculture. The model showed a higher value in areas near the natural range of distribution for the species (Fig. 7.4). A hard classification of the ASPB result for *I. balsanus* can be seen in figure 7.5. Reclassification parameters and areas are shown in table 7.1.

Table 7.1 ASPB result reclassification and areas for *I. balsanus*

Class	Reclassified		Area (km^2)
	From	To	
Low suitability	0.2	0.4	14,410
Medium low	0.4	0.6	50,139
Medium high	0.6	0.8	27,993
High suitability	0.8	1	7,651

7.5.2 Aquaculture of *Chirostoma jordani* at Catchment level approach

The PSD results for the native *C. jordani* showed that the species is primarily distributed the throughout the Lerma basin, occupying all major water bodies and the Rio Verde in the Santiago basin (Fig. 7.6). Distance from the resulting predictive distribution was calculated and then reclassified using a monotonically increased Sigmoidal function (sigmoidal function parameters: a,b,c=2,000; d=10,000) (Fig 7.7). The higher suitability was observed in the first 2,000 m from the predictive species distribution and lower suitability from 10,000 m.

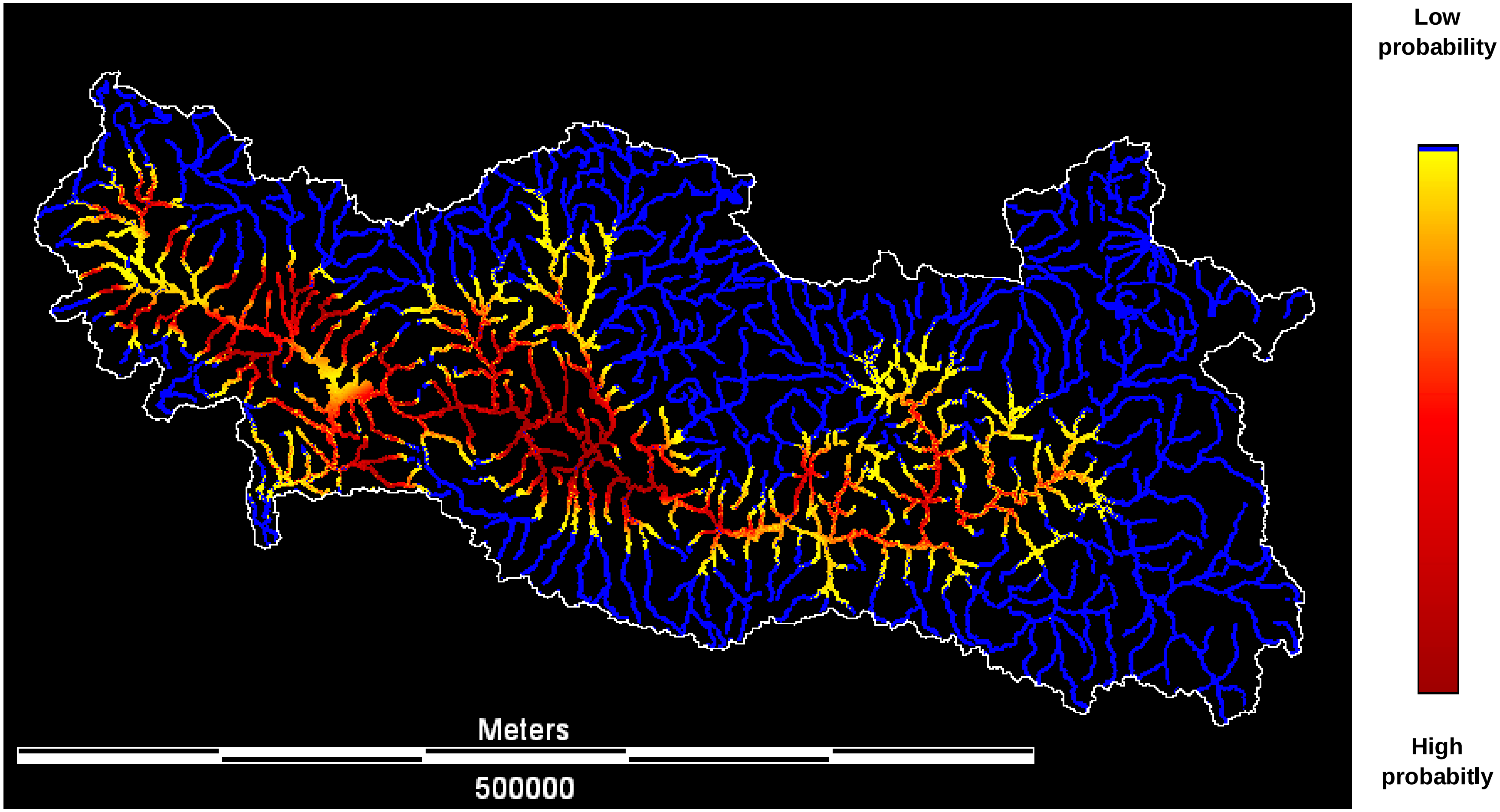


Figure 7.1: Predictive Species Distribution Model (PSD) result showing the potential distribution for *Ictalurus balsanus* in the Balsas basin, Mexico. The legend represents the probability of distribution for the species, based on abiotic factors.

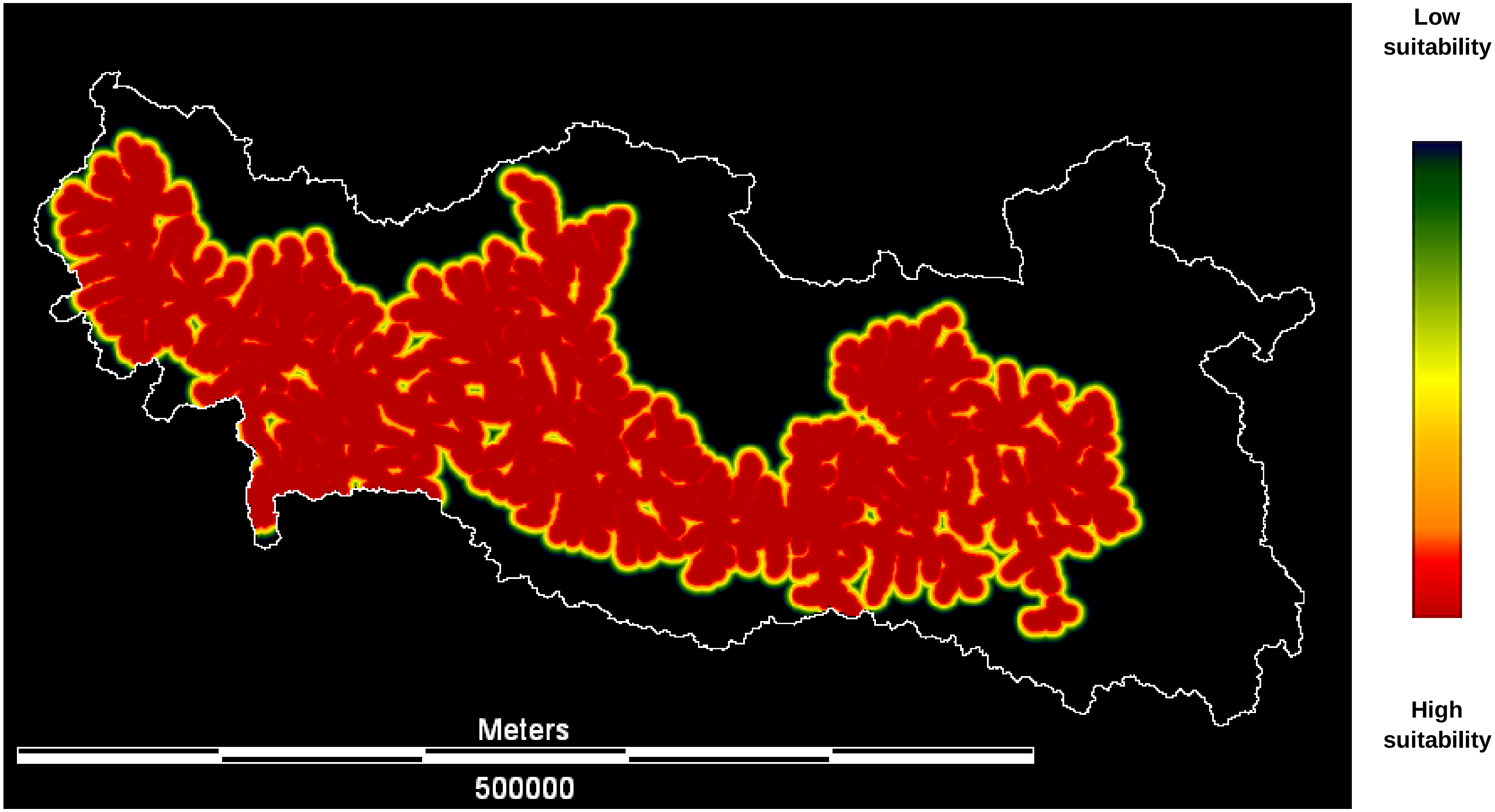


Figure 7.2: The Image shows distance from the potential distribution of *Ictalurus balsanus* in the Balsas basin, Mexico.

The legend represents the suitability for aquaculture.

The SSM for the aquaculture of *C. jordani* showed 6,216 km2 highly suitable (≥0.8) for aquaculture of the species in the Lerma-Santiago basin (Fig. 7.8). The higher suitability values were observed near the principal Lakes of the Lerma basin, the Lower and Middle Lerma and sections of the Rio Verde and Rio Bolaños in the Santiago basin.

Due to the wide distribution showed by *C. jordani* in the PSD model, the ASPB model showed several areas suitable for aquaculture of the species, mostly distributed along the Rio Lerma, and all major lakes (Fig. 7.9). The ASPB results were reclassified into 4 classes for a simple visual analysis (figure 7.10). Reclassification parameters and area calculated are presented in table 7.2.

Table 7.2 ASPB result reclassification and areas for *C. jordani*

Class	Reclassified		Area (km^2)
	From	To	
Low suitability	0.2	0.4	14,992
Medium low	0.4	0.6	41,706
Medium high	0.6	0.8	45,616
High suitability	0.8	1	15,633

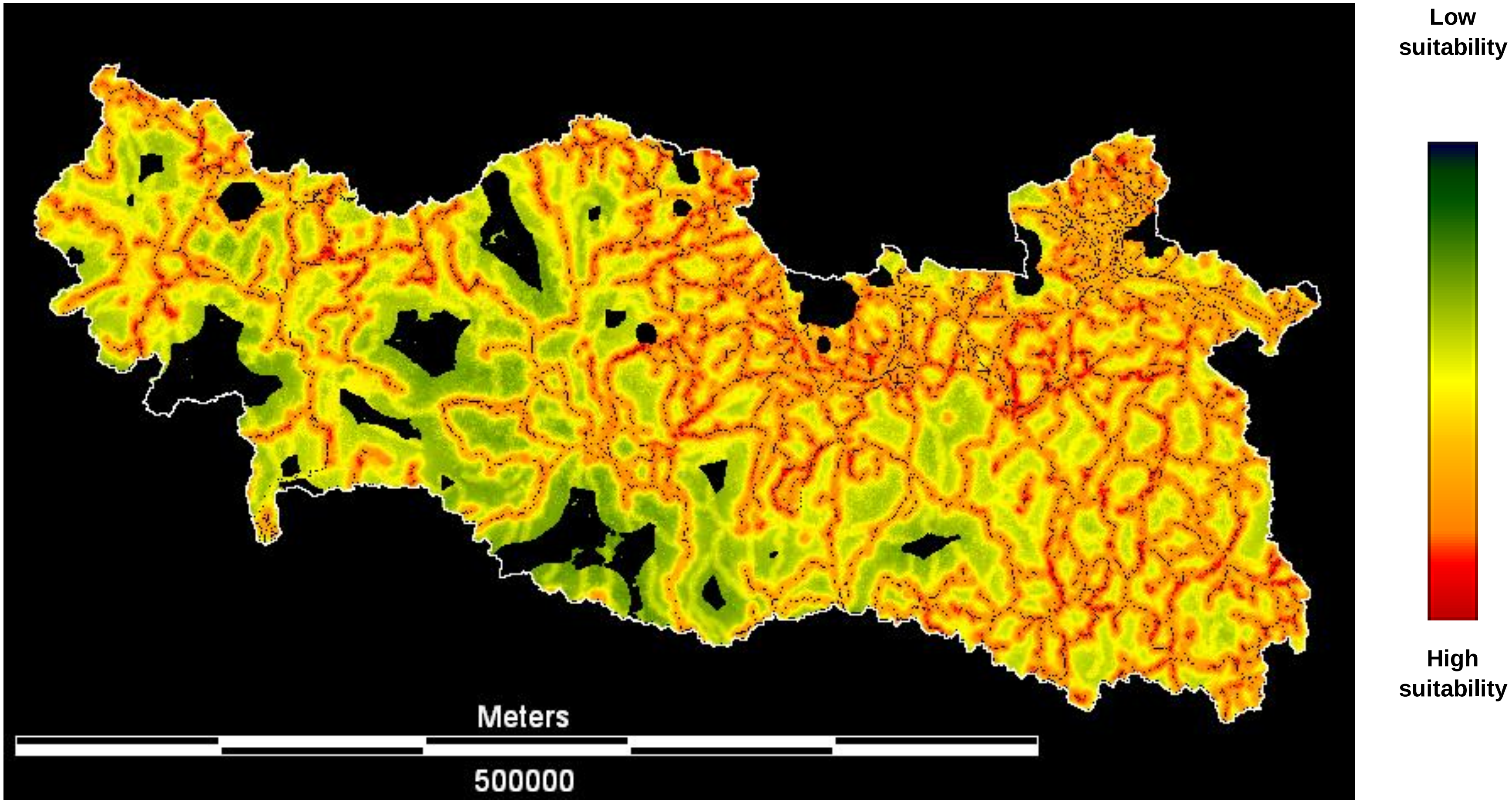


Figure 7.3: Site Suitability Model (SSM) result showing site suitability for aquaculture of *Ictalurus balsanus* in the Balsas basin, Mexico. The legend represents the suitability for aquaculture.

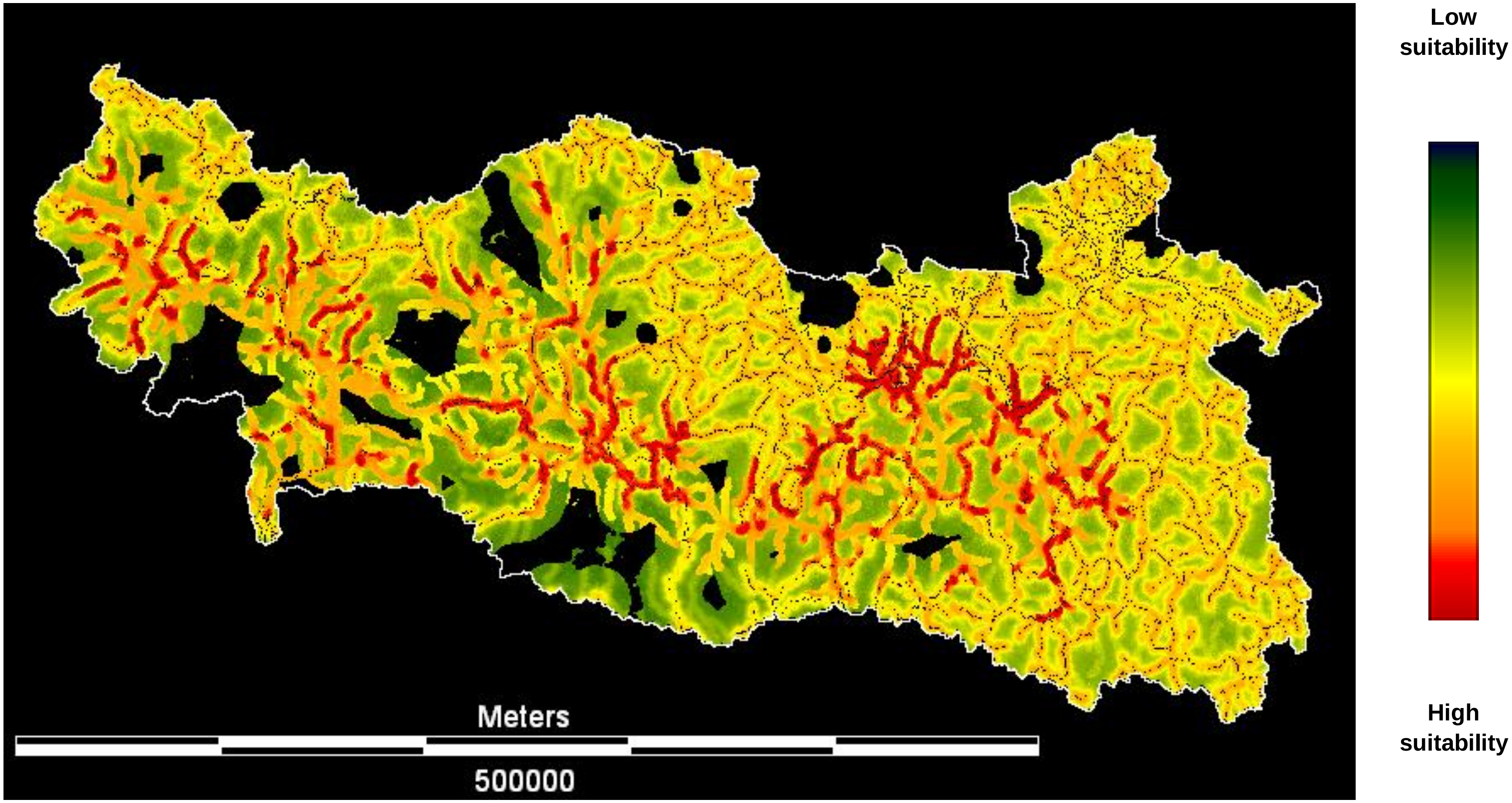


Figure 7.4: Aquaculture Strategy for the Protection of Biodiversity model (ASPB) result showing Environmentally friendly Site Suitability areas for *Ictalurus balsanus* in the Balsas basin, Mexico. The legend represents the suitability for aquaculture.

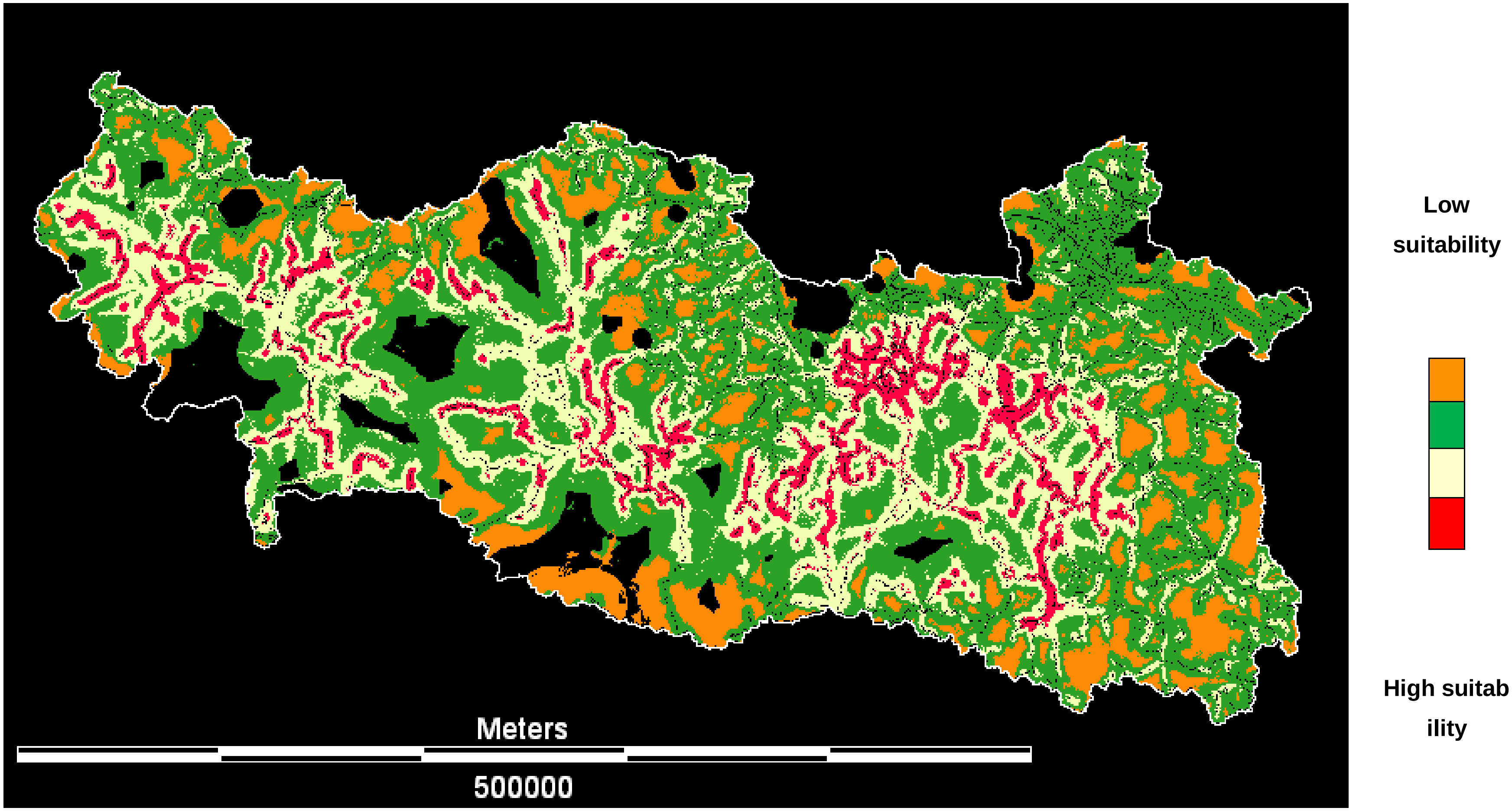


Figure 7.5: Aquaculture Strategy for the Protection of Biodiversity model (ASPB) result showing Environmentally friendly Site Suitability areas for *Ictalurus balsanus* in the Balsas basin, Mexico. The legend shows 4 classes from high suitability to low suitability.

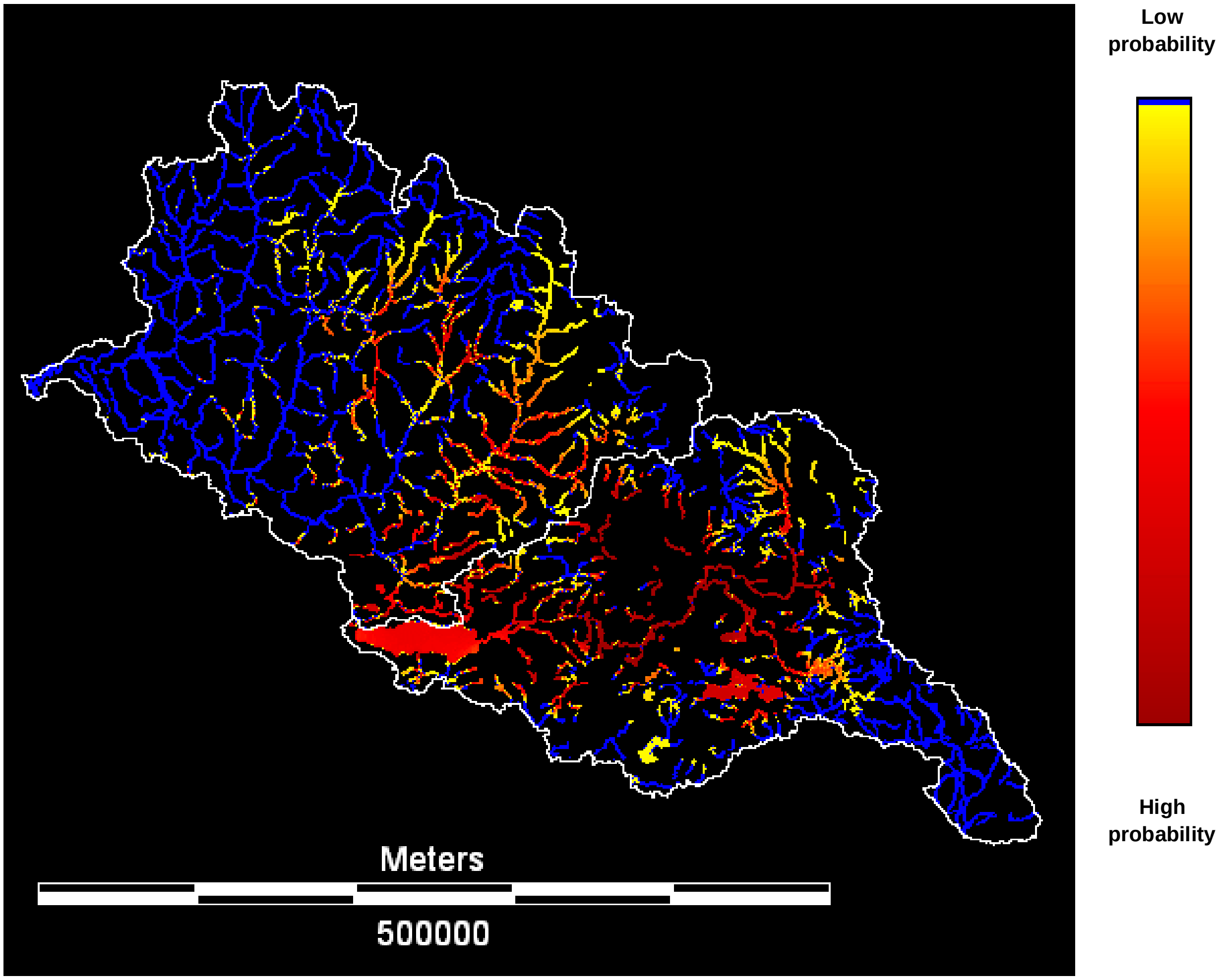


Figure7.6: Predictive Species Distribution Model (PSD) result showing the potential distribution for *Chirostoma jordani* in the Lerma-Santaigo basins, Mexico. The legend represents the probability of distribution for the species, based on abiotic factors.

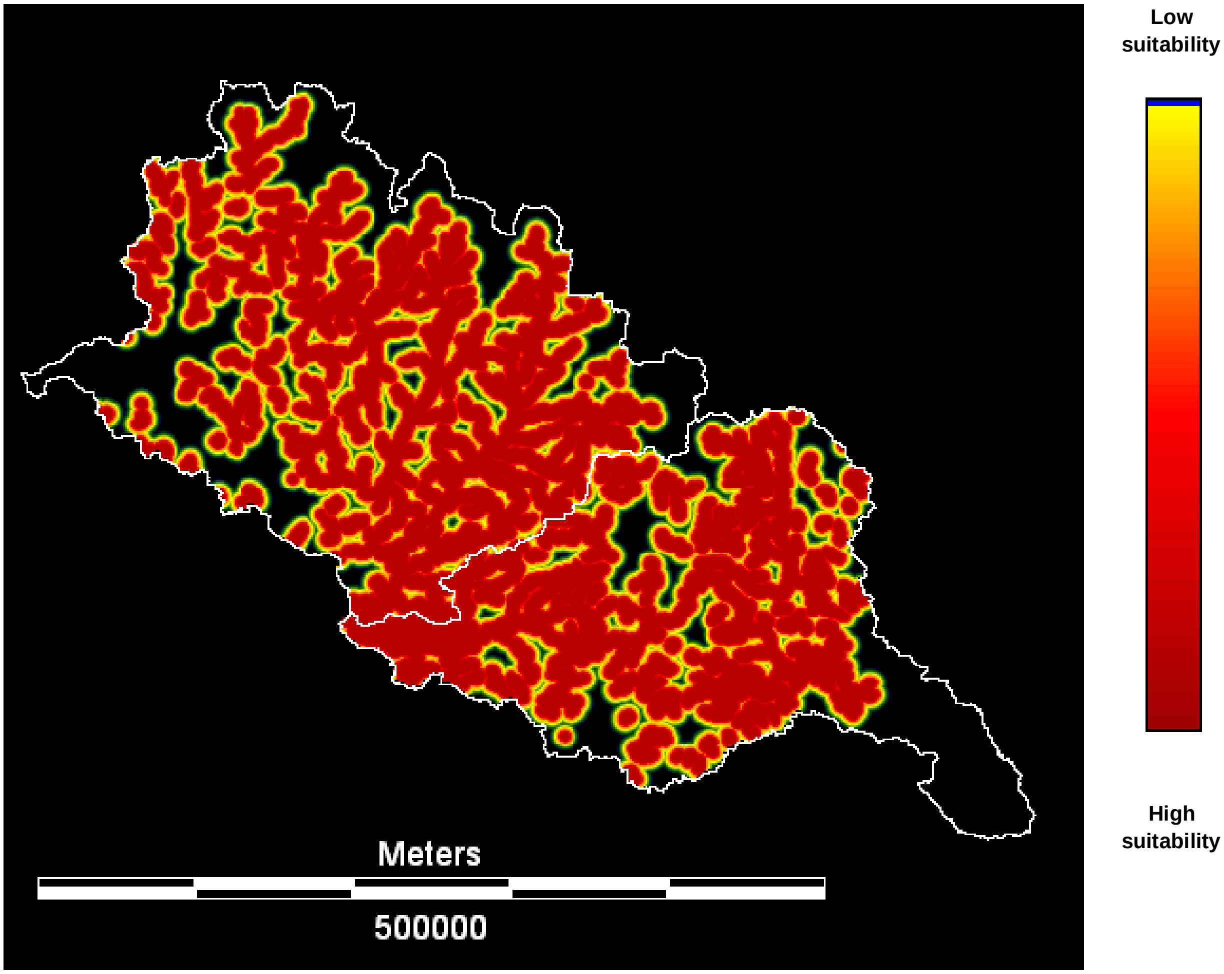


Figure7.7: Thematic layer showing distance from the potential distribution of *Chirostoma jordani* in the Lerma-Santaigo basins, Mexico. The legend represents the suitability for aquaculture.

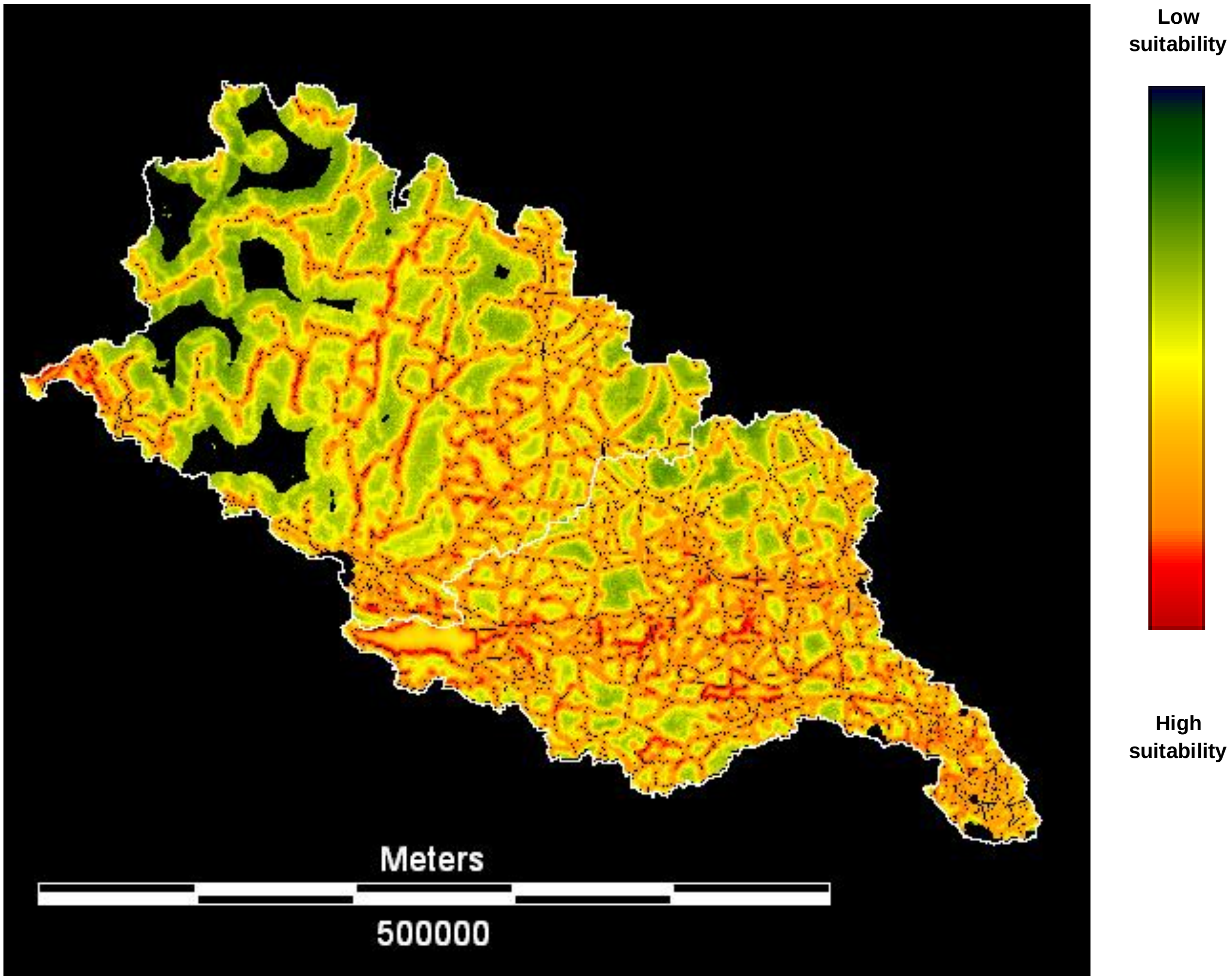


Figure 7.8: Site Suitability Model (SSM) model showing site suitability for aquaculture of *C. jordani* in the Lerma-Santaigo basins, Mexico. The legend represents the suitability for aquaculture.

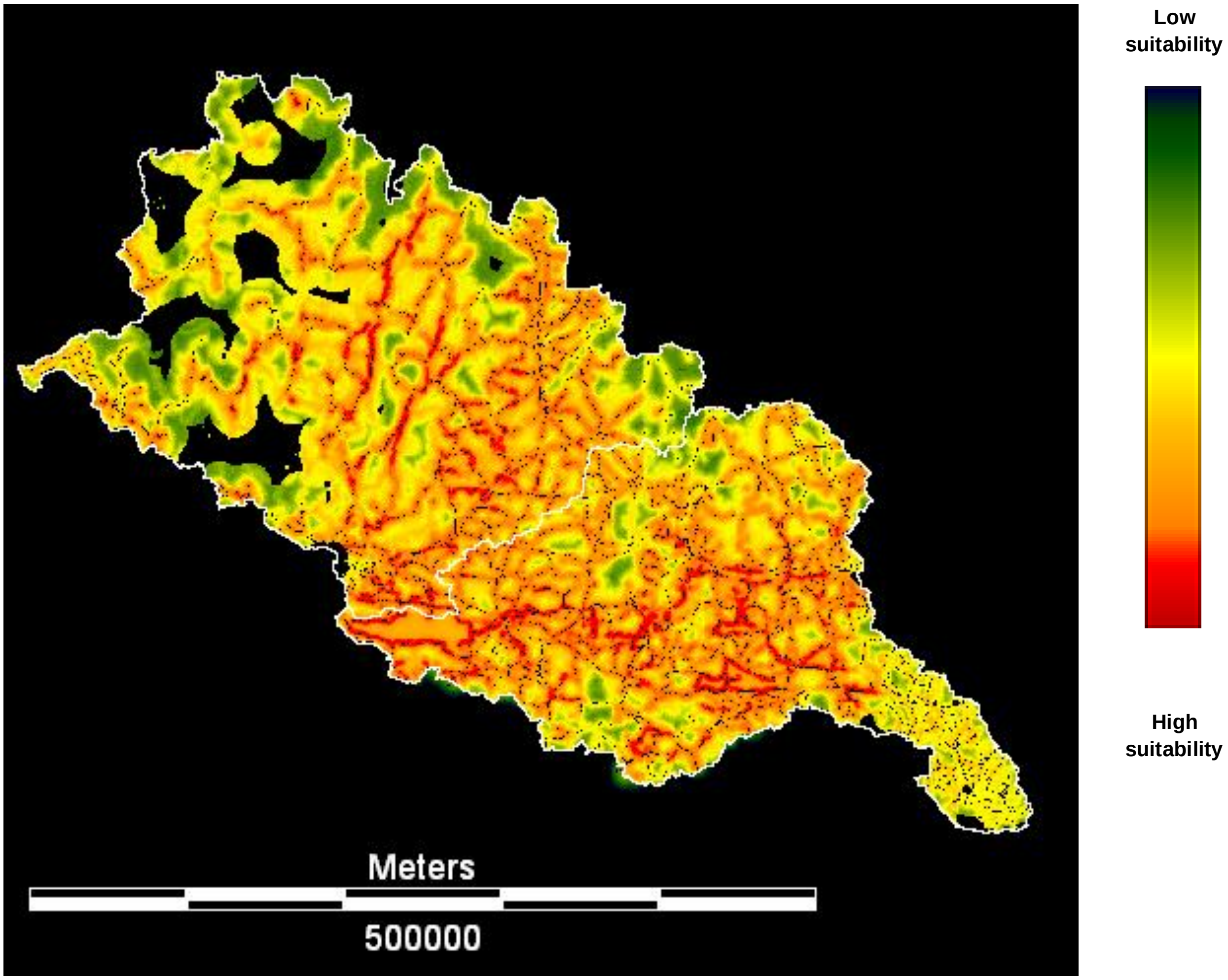


Figure 7.9: Aquaculture Strategy for the Protection of Biodiversity model (ASPB) showing Environmentally friend Site Suitability for aquaculture of *C. jordani* in the Lerma-Santaigo baisins, Mexico.

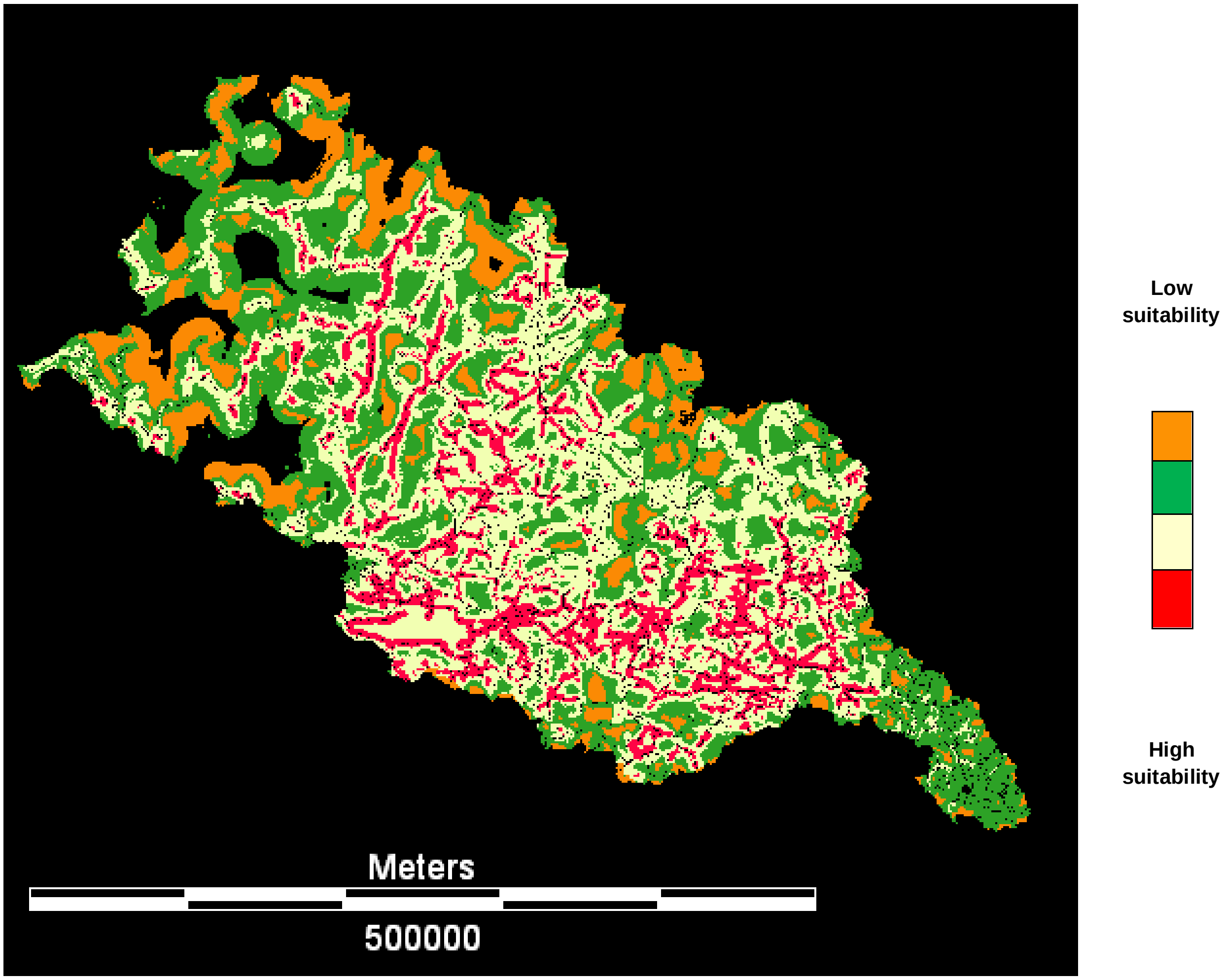


Figure 7.10: Aquaculture Strategy for the Protection of Biodiversity model (ASPB) result showing Environmentally friendly Site Suitability areas for *C. jordani* in the Lerma-Santiago basins, Mexico. The legend shows 4 classes from high suitability to low suitability.

7.5.3 Aquaculture of *I. dugesii* in the Balsas basin. A Translocation approach.

The PI model of *I. dugesii* in the Balsas basin showed a potential invasive distribution in the higher altitudes of the basin, near the mountain chains of the “Eje neovolcanico Transversal” and the “Sierra Madre del Sur” (Fig. 7.11). Distance was calculated from the PI of I. dugessi, in conjunction with distance of the PSD of the native *I. balsanus*, in order to reduce the probability of interaction between the species in the wild. The distance was reclassified into a scale of suitability applying a monotonically increasing Sigmoidal function (sigmoidal function parameters: a=2,000; b,c,d=10,000) (Fig. 7.12). The SSM of *I. dugesii* presented in figure 7.13 shows 4,102 km2 highly suitable (≥0.8) for aquaculture of the species in the Balsas basin. Most of the SSM values of higher suitability can be observed in the North-Norh West of the Rio Balsas.

The figure 7.14 shows the overall results of the ASPB model. Higher suitability can be observed away from the Rio Balsas and tributaries (home to the native *I. balsanus*). The total area of high suitability was 41,433 km2 (Table 7.3). The ASPB was reclassified into 4 classes in order to simplify visual analysis (Fig. 7.15).

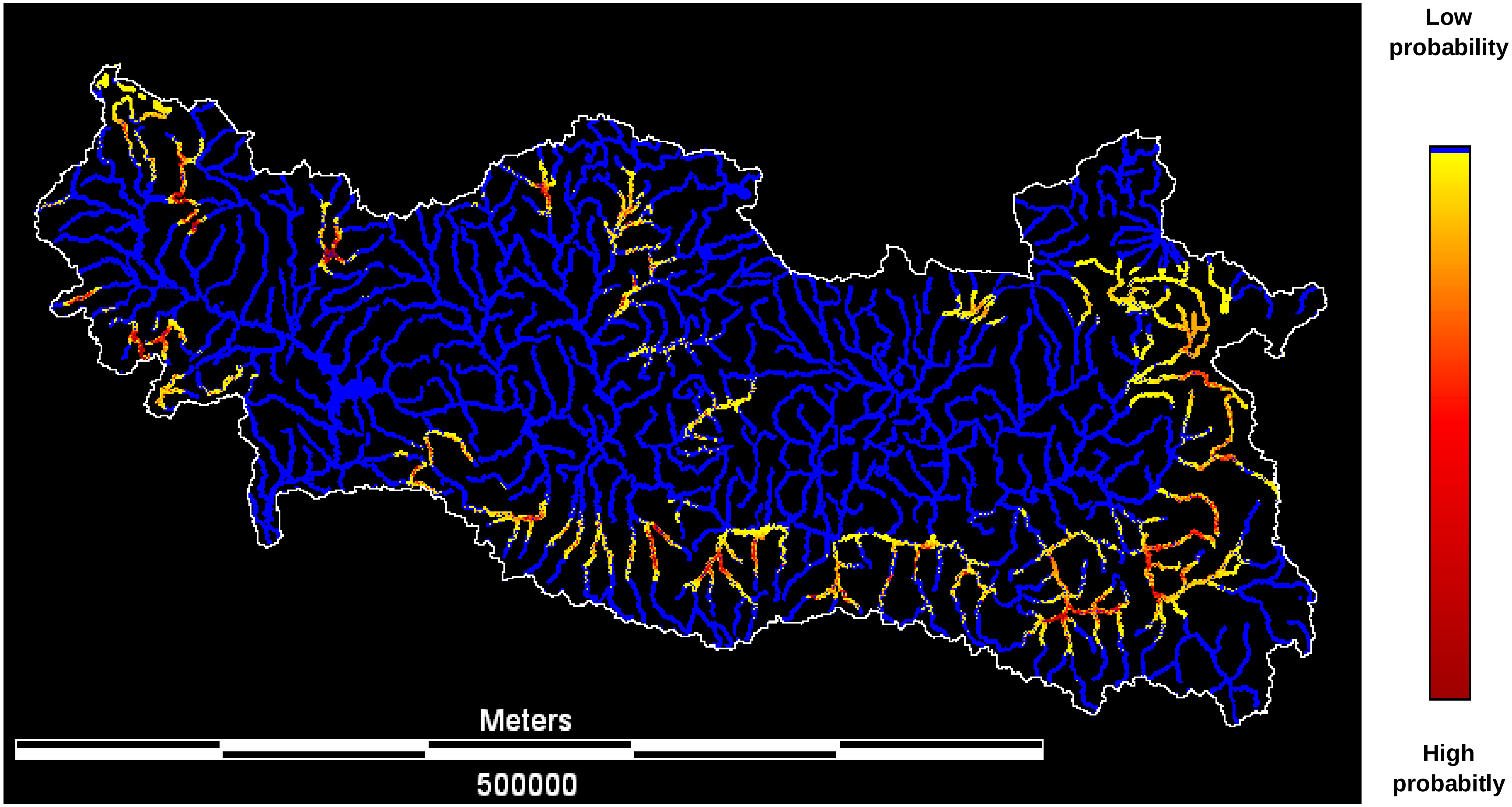


Figure 7.11: Potential Invasion (PI) Model result of *Ictalurus dugesii* in the Balsas basin, Mexico. The legend represents the probability of distribution for the species, based on abiotic factors.

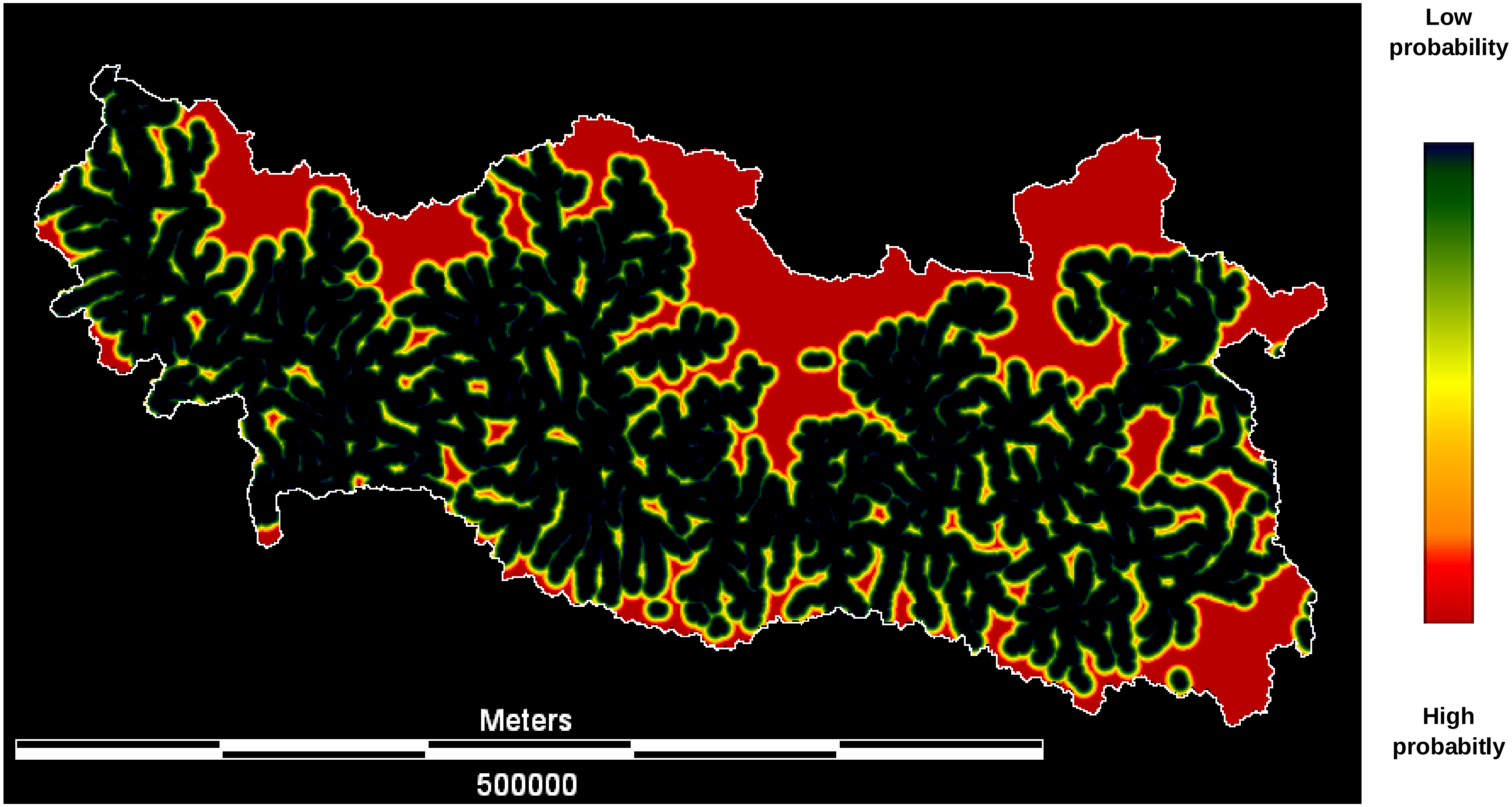


Figure 7.12: Thematic layer showing distance PI by *Ictalurus dugesii* and PSD of *I. balsanus* in the Balsas basin, Mexico.

The legend represents suitability for aquaculture.

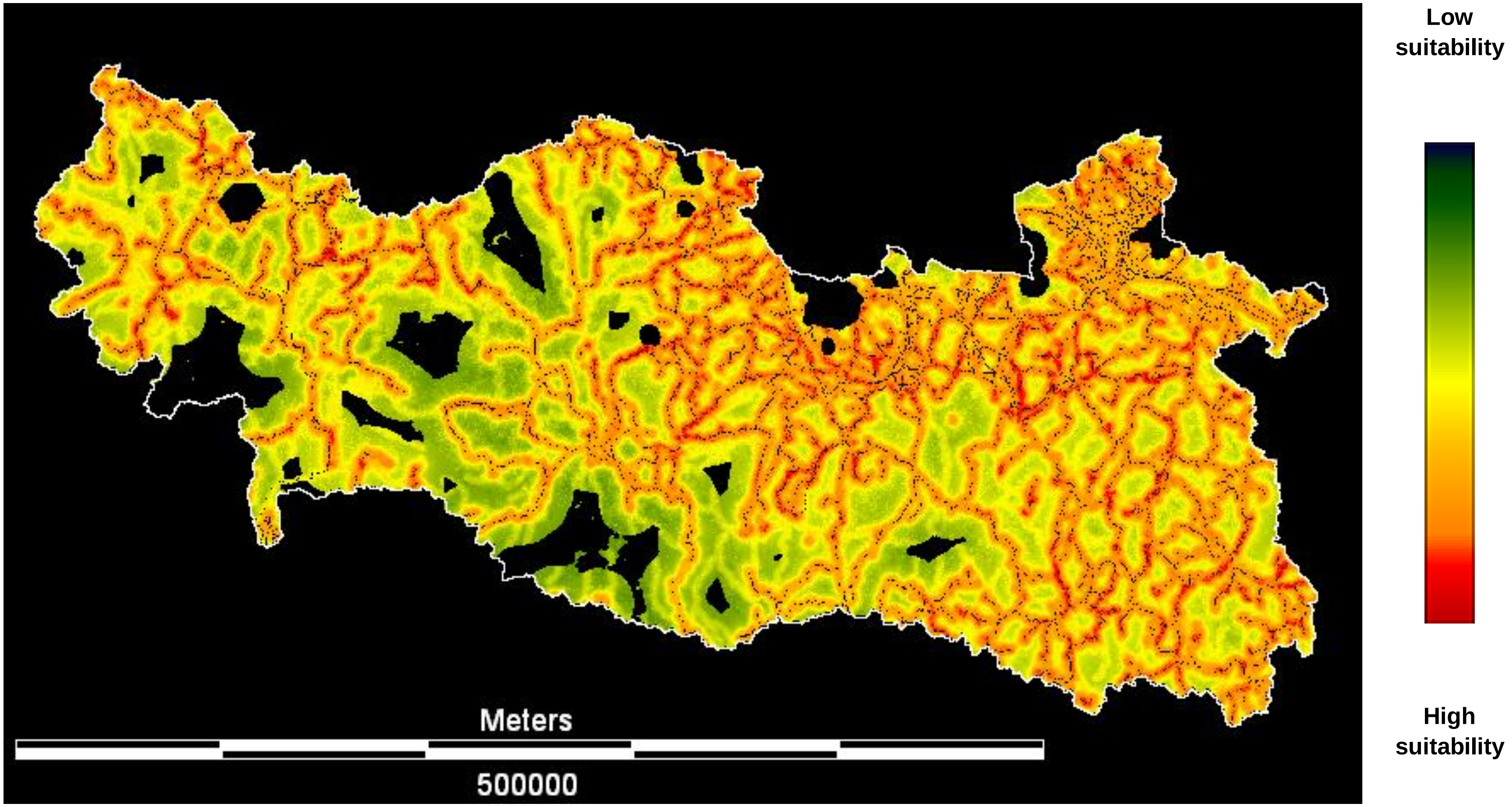


Figure 7.13: Site Suitability Model (SSM) result showing Site Suitability areas for *I. dugesii* in the Balsas basin, Mexico.

The legend represents the suitability for aquaculture

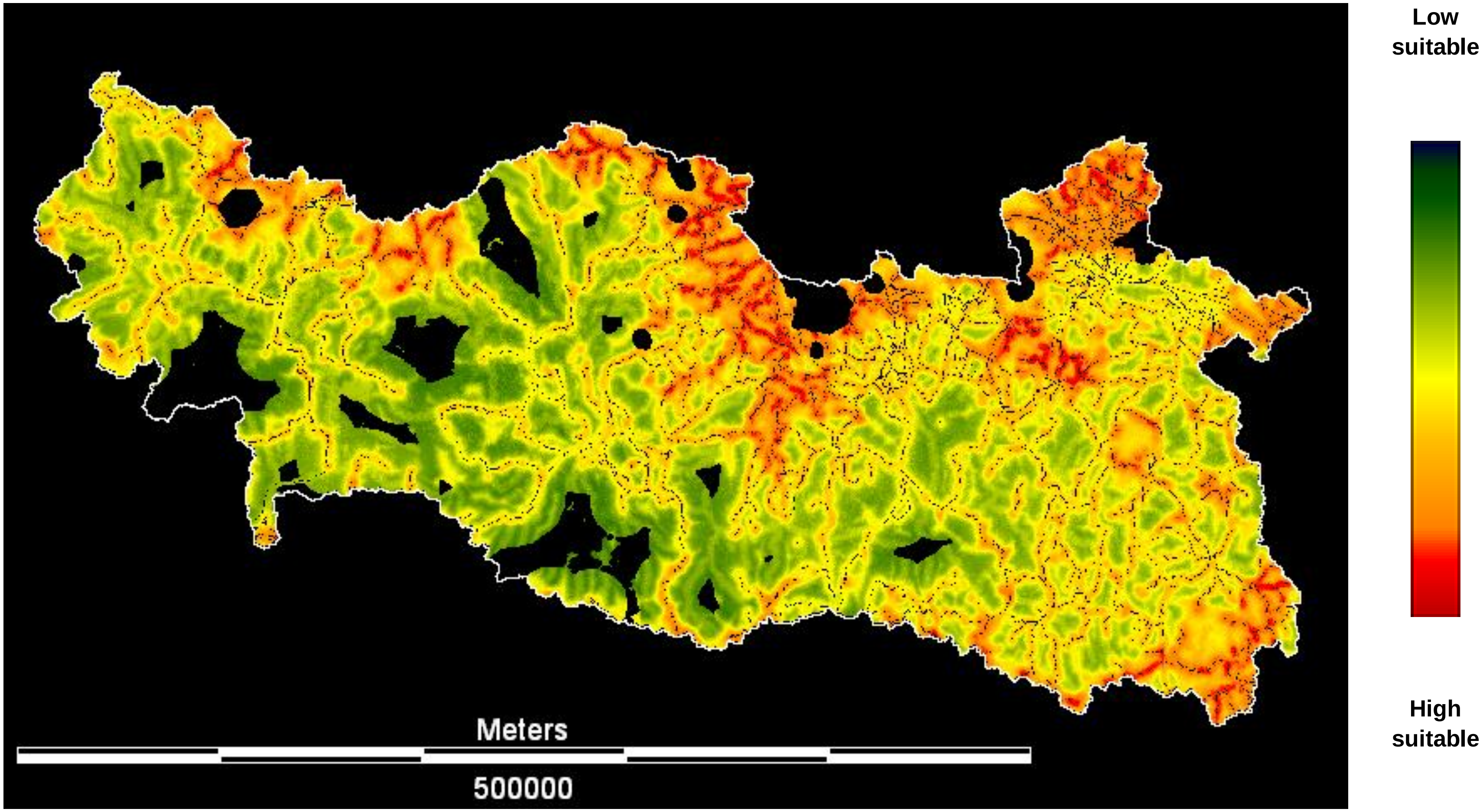


Figure 7.14: Aquaculture Strategy for the Protection of Biodiversity model (ASPB) result showing Environmentally friendly Site Suitability areas for *I. dugesii* in the Balsas basin, Mexico. The legend represents the suitability for aquaculture

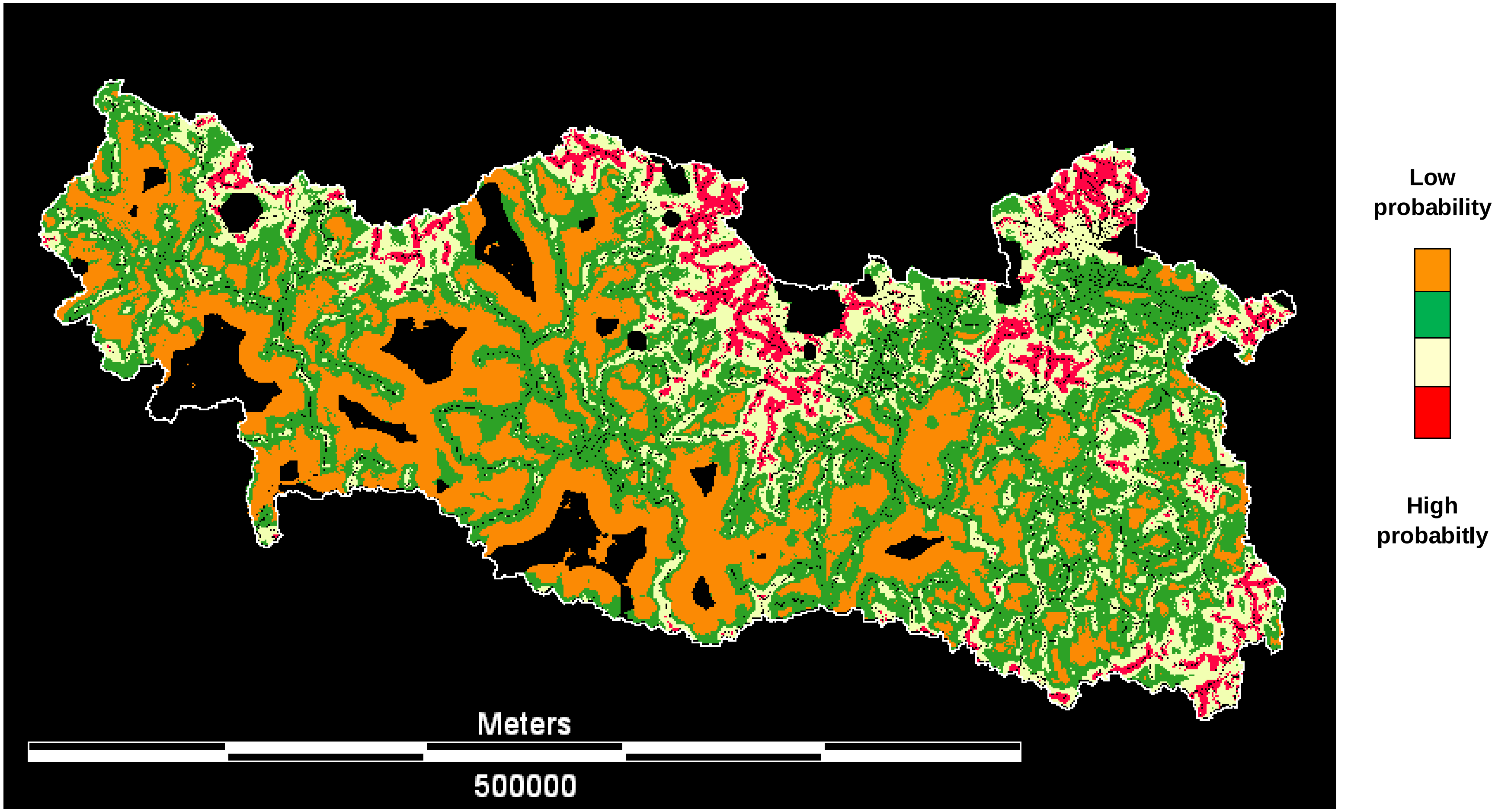


Figure 7.15: Thematic layer showing a 2k constraint around the PSD of *Ictalurus balsanus* in the Balsas basin, Mexico. The legend represents the probability of distribution for the species, based on abiotic factors.

Table 7.3 ASPB result reclassification and areas for *I. dugesii*

Class	Reclassified		Area (km^2)
	From	To	
Low suitability	0.2	0.4	31,125
Medium low	0.4	0.6	41,433
Medium high	0.6	0.8	21,340
High suitability	0.8	1	6,355

7.5.4 Aquaculture of *Atherinella balsana* in the Lerma-Santiago basin. A Translocation approach.

The PI risk assessment showed that *A. balsana* presents high potential for invasion in the Lerma-Santiago basins. In figure 7.10 it is possible to observe that *A. balsana* has potential for invasion in more than 50% of the Lerma river system and most of the major lakes. This area is known to be the home of a considerable number of species related to *A. balsana*. For that reason, the results show that *A. balsana* should not be recommended for aquaculture outside of its natural range of distribution.

7.6 Discussion

The Aquaculture Strategy for the Protection of Biodiversity (ASPB) has the main objective of assisting in the development of environmentally friendly aquaculture

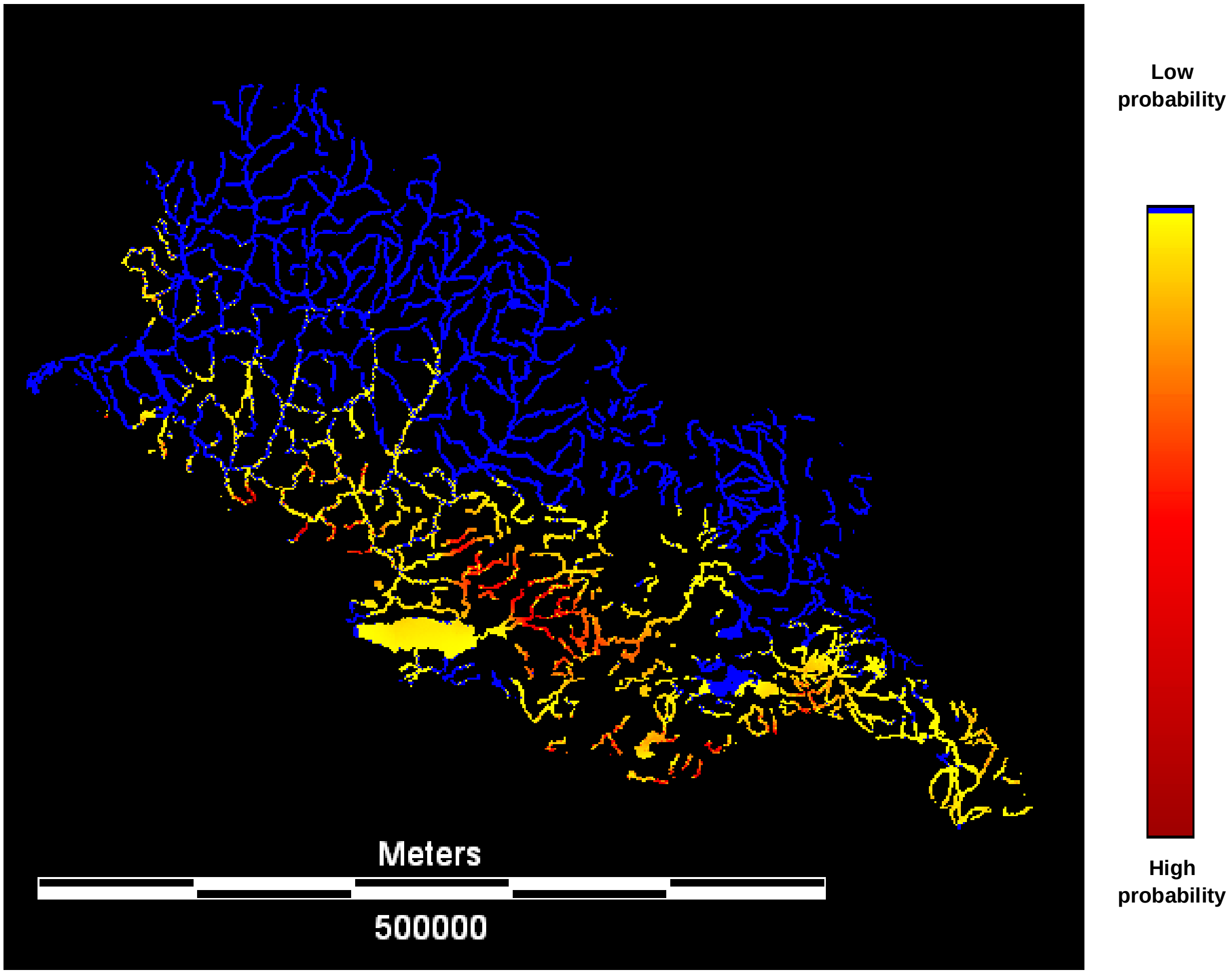


Figure7.16: Potential for Invasion model of *A. balsana* in the Lerma-Santiago basins

sites. The ASPB management tool promotes the use of native species instead of the more frequently used tilapia and carp, for example. Tilapia and carps are so extensively used for aquaculture in central Mexico, that they are now distributed in all major water bodies (Zambrano *et al*., 2006). One of the major problems from this is that extended distribution of a reduced number of species represents a high risk for homogenization of fish biodiversity (Rahel, 2000). This is why aquaculture of a variety of native fish can mitigate this issue whilst simultaneously bringing food and job security to the region.

The ASPB model included Site Suitability models with Predictive Species Distribution and Potential for Invasion models using a weighted overlay, in which the site selection variables had more relevance to the modelling procedure than the natural range of distribution. This conforms with the necessity for identification of optimum conditions in order to obtain the best possible production and sustainability of the site (Ross *et al*, 1993).

One of the main functions of the ASPB management tool is to assess the possible risk of escaped cultured fish and mitigate the associated implications that they have on the wild such as competition predation and hybridization (McDowell, 2006; Ross *et al*., 2008; Pelicice & Agostihnio, 2009, by promoting the use of native species respecting their natural ranges of distribution, a concept supported by several authors (Perez *et al*., 2000; Utter and Epifanio, 2002; Alves 2007; Magurran, 2009, Vitule 2009). However, the development of aquaculture of native species within their natural range of distribution is a debatable argument. For Naylor *et al* (2005) more damage may be produced by salmon escaping into the wild happens when they are farmed in their native range. This is a consequence of the intense genetic modifications that many cultured species have been subject to in order to improve traits of commercial interest (Roberge *et al* 2007). This ASPB management proposal works on the basis that adequate genetic considerations must take place before the development of aquaculture sites (see chapter 4). These considerations focus on biodiversity requirements more than marketing or human benefits. In this context, aquaculture of native species is recommended within the natural range of distribution (see chapter 5).

The inclusion of PSD models into a Catchment level ASPB approach, was designed to favour areas near the natural distribution of the species, whilst site suitability remains the most important factor in the decision making process. On the other hand, the use of PSD-PI for a Translocation ASPB approach, although still considering site selection as the most important factor, strongly favours areas far from the natural range of distribution of related species and from those areas where it is believed, based on the PI model, that escaped organisms could establish.

The ASPB management tool satisfactory satisfactorily identifies the needs of the stakeholder and the suitability of the business site represented by the SSM; both important requirements proposed for aquaculture development (Ross and Beveridge, 1995; Dey *et al*., 2010). At the same time the use of PSD-PI models also satisfies the necessity to recognise biodiversity requirements as an essential factor in the decision making process. This has been recognised as an important step in aquaculture of native species (Ross *et al* 2008) and conforms to the objectives of the CONABIO in Mexico (CONABIO, 2011).

For the adequate use of the ASPB management tool at regional level, responsible authorities must understand the advantages of ecological-based management. The use of catchment areas as geographical constraints for aquaculture development, while providing a more logical approach for the use and conservation of biodiversity (Pikitch *et al*., 2004; Pahl-Wostl *et al*, 2008; Rodriguez-Iturbe *et al* 2009), challenges regional administrative authorities to cooperate in the management process. This type of multilateral ecological management is essential for ecological restoration and conservation. It can involve interstate cooperation or transboundary issues when dealing with the bigger picture even involving different countries as may be the case of ecological corridors (Van Der Windt and Swart 2007).

Social awareness of biodiversity problems has a major impact on how humans use the natural resources (Levy, 2011). Governmental authorities in central Mexico and regional stakeholders can benefit with the use of ASPB management tools, since aquaculture of native species shows great potential as a productive industry, fitting “green” markets and public awareness.

References

Abell, R.A. & (U.S.), W.W.F., 2000. *Freshwater ecoregions of North America: a conservation assessment*, Island Press.

Alarcon-Silva, E.M. Martínez-Palacios C.A. & Martínez-Chavez, C.C. 2009. Recent Discoveries and Advances in the husbandry of a Mexican freshwater silverside *Menidia estor*. 2da Conferencia Latinoamericana sobre Cultivo de Peces Nativos. Buenos Aires, Argentina 3-6 2009.

Alves, C., F. Vieira, A. Magalhães, and M. Brito. 2007. Impacts of Non-Native Fish Species in Minas Gerais, Brazil: Present Situation and Prospects. Pages 291-314 in Ecological and Genetic Implications of Aquaculture Activities

Arce U.E. and Luna-Figueroa J. 2003. Efecto de dietas con diferente contenido proteico en las tasas de crecimiento de crias del Bagre del Balsas *Ictalurus balsanus* (Pisces: Ictaluridae) en condiciones de cautiverio. *Revista AquaTIC.* **18:** 39-47.

CONABIO. 2011. Available at: http://www.conabio.gob.mx/ [Accessed: 18-January 2011]

Dey, M.M., Alam, M.F. & Bose, M.L., 2010. Demand for aquaculture development: perspectives from Bangladesh for improved planning. *Reviews in Aquaculture*, **2**:16-32.

DeVaney, S.C. *et al*., 2009. A Tale of Four "Carp": Invasion Potential and Ecological Niche Modeling. *PLoS ONE*, **4**: 5451.

Domínguez- Domínguez O. *et al*. 2006. Using Ecological-Niche Modeling as a Conservation Tool for Freshwater Species: Live-Bearing Fishes in Central Mexico. *Conservation biology*. **20**: 1730-1739.

Egoh, B. *et al*., 2007. Integrating ecosystem services into conservation assessments: A review. *Ecological Economics*, **63**:714-721.

Gaertner, M. Den Breeyen, A., Cang Hui, & Richardson, D.M., 2009. Impacts of alien plant invasions on species richness in Mediterranean-type ecosystems: a meta-analysis. *Progress in Physical Geography*, **33**:319 - 338.

Hamilton, S.F. & Zilberman, D., 2006. Green markets, eco-certification, and equilibrium fraud. *Journal of Environmental Economics and Management*, **52**:627-644.

Hanley, N. & Barbier, E., 2009. *Pricing nature: cost-benefit analysis and environmental policy*, Edward Elgar Publishing.

Herborg, L.-M. *et al*., 2007. Predicting invasion risk using measures of introduction effort and environmental niche models. *Ecological Applications*, **17**:663-674.

Hossain, M.S. *et al.,* 2007. Multi-criteria evaluation approach to GIS-based land-suitability classification for tilapia farming in Bangladesh. *Aquaculture International*, **15**:425-443.

INEGI. 2011. Atlas Nacional Interactivo de Mexico. Available at: http://www.atlasdemexico.gob.mx/ [Accessed: January 15-2011]

Joly, C.A. *et al*., 2010. Biodiversity Conservation Research, Training, and Policy in São Paulo. *Science*, **328**:1358 -1359.

Kapetsky M.J. & Manjarrez J.A. 2007. Geographic information systems, remote sensing and mapping for the development and management of marine aquaculture. *FAO Fisheries Tehcnical Paper.* 125

Levy, D.L., 1997. Environmental Management as Political Sustainability. *Organization & Environment*, **10**:126 -147.

Lindemann-Matthies, P. & Bose, E., 2008. How Many Species Are There? Public Understanding and Awareness of Biodiversity in Switzerland. *Human Ecology*, **36**:731-742.

Lyons, J. *et al*., 1995. Index of Biotic Integrity Based on Fish Assemblages for the Conservation of Streams and Rivers in West-Central Mexico. *Conservation Biology*, **9**:569-584.

Magurran, A. 2009. Threats to Freshwater Fish. *Science* **325**:1215-1216.

Martínez-Palacios, C.A. *et al*., 2008. Developments in the nutrition of Menidia estor Jordan 1880. *Aquaculture Research*, **39**:738-747.

McDowall, R., 2006. Crying wolf, crying foul, or crying shame: alien salmonids and a biodiversity crisis in the southern cool-temperate galaxioid fishes? *Reviews in Fish Biology and Fisheries*, **16**:233-422.

Naylor, R. *et al*., 2005. Fugitive Salmon: Assessing the Risks of Escaped Fish from Net-Pen Aquaculture. *BioScience*, **55**:427.

Novacek, M.J., 2008. Colloquium Paper: Engaging the public in biodiversity issues. *Proceedings of the National Academy of Sciences*, **105**:11571-11578.

Pahl-Wostl C. Mostert E. & Tabara D. 2008. The Growing Importance of Social Learning in Water Resources Management and Sustainability Science. *Ecology and Society*. 13 [1] 24. Available at: http://www.ibcperu.org/doc/isis/11742.pdf [Accessed: February, 20,2011]

Peterson, A.T., 2003. Predicting the Geography of Species' Invasions via Ecological Niche Modeling. *The Quarterly Review of Biology*, **78**:419-433.

Pelicice, F., and A. Agostinho. 2009. Fish fauna destruction after the introduction of a non-native predator (Cichla kelberi) in a Neotropical reservoir. Biological Invasions 11:1789-1801.PRB. 2008. World Population Data Sheet. Available at: http://www.prb.org/Publications/Datasheets/2008/2008wpds.aspx [Accessed March 3, 2011].

Perez, J.E., Nirchio, M. & Gomez, J.A., 2000. Aquaculture: part of the problem, not a solution. *Nature*, **408**:514.

Pérez, O.M., Telfer, T.C. & Ross, L.G., 2005. Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. *Aquaculture Research*, **36**:946-961.

Pikitch, E.K. *et al*., 2004. Ecosystem-Based Fishery Management. *Science*, **305**:346 -347.

Rahel, F.J., 2000. Homogenization of Fish Faunas Across the United States. *Science*, **288**:854 -856.

Roberge, C. *et al*., 2008. Genetic consequences of interbreeding between farmed and wild Atlantic salmon: insights from the transcriptome. *Molecular Ecology*, **17**:314-324.

Rodriguez-Iturbe, I. *et al.,* 2009. River networks as ecological corridors: A complex systems perspective for integrating hydrologic, geomorphologic, and ecologic dynamics. *Water Resources Research*, **45**.

Ross, L.G. & Beveridge, M.C.M., 1995. Is a better strategy necessary for development of native species for aquaculture? A Mexican case study. *Aquaculture Research*, **26**:539-547

Ross, L.G., Martínez Palacios, C.A. & Morales, E.J., 2008. Developing native fish species for aquaculture: the interacting demands of biodiversity, sustainable aquaculture and livelihoods. *Aquaculture Research*, **39**:675-683.

Ross, L., Mendoza Q.M., E. & Beveridge, M., 1993. The application of geographical information systems to site selection for coastal aquaculture: an example based on salmonid cage culture. *Aquaculture*, **112**:165-178.

Ross, L.G. & Beveridge, M.C.M., 1995. Is a better strategy necessary for development of native species for aquaculture? A Mexican case study. *Aquaculture Research*, **26**:539-547.

Sanderson, E. W., Jaiteh M. Levy, M.A. Redford, K.H. Wannebo, A.V. Woolmer, G. 2002. The human footprint and the last of the wild. *BioScience,* **52**: 891-904.

Sedeño-Díaz J.E. & López-López E. 2007. Water Quality in the Río Lerma, MexicoÑ An Overview of the Last Quarter of the Twentieth Century. *Water Resource Management*. **21**: 1797-1812.

SEMARNAT. 2010. Statistic on Water in Mexico.Pp. 249. Available at: http://www.conagua.gob.mx/english07/publications/EAM2010Ingles_Baja.pdf [Accessed: March 10-2011].

Utter, F., and J. Epifanio. 2002. Marine aquaculture: Genetic potentialities and pitfalls. *Reviews in Fish Biology and Fisheries* **12**:59-77.

Van Der Windt, H.J. & Swart, J.A.A., 2007. Ecological corridors, connecting science and politics: the case of the Green River in the Netherlands. *Journal of Applied Ecology*, **45**:124-132.

Vitule, J. R. S., C. A. Freire, and D. Simberloff. 2009. Introduction of non-native freshwater fish can certainly be bad. *Fish and Fisheries* **10**:98-108.

Zambrano, L. *et al*., 2006. Invasive potential of common carp (*Cyprinus carpio*) and Nile tilapia (*Oreochromis niloticus*) in American freshwater systems. *Canadian Journal of Fisheries and Aquatic Sciences*, **63**:1903-1910.

Zambrano, L., Valiente, E. & Vander Zanden, M.J., 2010. Food web overlap among native axolotl (Ambystoma mexicanum) and two exotic fishes: carp (Cyprinus carpio) and tilapia (Oreochromis niloticus) in Xochimilco, Mexico City. *Biological Invasions*, **12**:3061-3069.

Chapter 8

GIS and the development of native fish species aquaculture in central Mexico: final discussion and conclusions.

In this project, the potential for native species aquaculture was widely discussed and recognised as a suitable alternative to conventional aquaculture, which has, to date, been based on a handful of species. The main goal was to produce a Geographic Information System to use as a reliable tool for native species aquaculture planning and for decision support. An extensive spatial and attribute database of freshwater species native to three of the most important river basins in central Mexico was created for use in a GIS (see chapter 3). In chapter 4, the paradox of food production and the protection of biodiversity was thoroughly discussed, recognising the priority of food security and the massive impact that it has had on freshwater biodiversity worldwide. Successful cases of native species aquaculture in Latin America were presented. A Site Suitability Model was created and presented as a reliable tool for the decision making process of native species aquaculture (chapter 5). The strong imperative to recognise natural ranges of distribution, and their importance for the development of responsible aquaculture planning was proposed in chapter 6, with the use of an ecological-niche based Predictive Species Distribution (PSD) model. The potential of PSD models in the early stages of new species aquaculture technology development was also discussed. The results from the PSD model were also expanded outside of the natural ranges of distribution for each species with the intention to identify their Predictive Potential for Invasion (PPI). The resulting modelling tools, developed during this project, were specifically produced for the promotion of native species aquaculture at catchment level; a strategy which aims to ensure food production while mitigating the introduction of exotic species and its negative impacts.

8.1 The problem

According to the Population Reference Bureau (PRB) (2008), from 1950 to 2008 the world human population rose from 2.5 to 6.7 billion people. More than 80% of this population lives in developing countries. During this time, the need for reliable sources of food for an increasing population transformed aquaculture into the fastest growing animal production food industry (Diana, 2009). In 2009, the Food and Agriculture Organization (FAO) reported a staggering 11,296% growth of the world’s freshwater aquaculture production between 1950 and 2008, increasing from just 246,296 tonnes to 28,068,676 t. In 1950 freshwater aquaculture in Asia contributed more than 60% of world production, but by 2008 it had grown to more than 80%. At the same time freshwater aquaculture in Africa and Latin America grew from just a few thousand tonnes to a production of 271,667 t in Africa and 367,437t in Latin America by 2008 (FAO, 2010). This remarkable progress has produced a high demand for the development of more sites for aquaculture. However, only a reduced number of robust fish species have been developed to satisfy such demands worldwide (Tapia and Zambrano, 2003). Tilapia and Carps are the most commonly introduced species worldwide, with cyprinids and cichlids alone generating 81.6% of global freshwater aquaculture production in 2008 (FAO, 2010). In chapter 4 the impact that an increasing number of non-native fish introductions for aquaculture programmes had on fish biodiversity was discussed (Scribner and Avise, 1993; Ryman *et al*., 1995; Moyle & Light, 1996; Masood, 1997; Beardmore *et al*., 1997; Rahel, 2000; Wolf *et al*., 2001; Cambray, 2003; Canonico, 2005; McDowall, 2006; Alves *et al*., 2007; Allendorf, 2008; Crawford and MacLeod, 2009; Kopp *et al*., 2009; Ludwing *et al*., 2009; Pelicice & Agostihnio, 2009; Badiou & Goldsborough, 2010; Nijru *et al*., 2010; Sato *et al*., 2010). In addition the need for extraordinary actions oriented to food security and the protection of biodiversity was discussed.

8.2 Aquaculture of Native Species as a Practical Solution

Aquaculture of native species has been proposed in different parts of the world as a potentially sustainable approach to the protection of biodiversity (Utter and Epifanio, 2002; Pérez *et al*., 2003; Ross & Martínez-Palacios, 2004; Alves *et al.*, 2007; Magurran, 2009, Vitule *et al.,* 2009). However, the impact that aquaculture of native species may have on wild stocks may still be negative without the appropriate genetic approach (Law, 2000; Gjedrem, 2000; McGinnity, *et al.,* 2003; Bekkevold, *et al*., 2006). It is suggested in chapter 4 that properly developed genetic plans for the development of healthy broodstocks, combined with catchment-level aquaculture will help in preventing negative effects on biodiversity. This approach could help to mitigate the arrival of unwanted exotic pathogens and parasites, while inter-species predation, competition, and hybridization can be significantly reduced.

The main objective of the present research was to propose the use of native species for aquaculture at catchment level in the basins of Lerma-Santiago and Balsas in central Mexico. The research focused on aquaculture of seven native silversides and two native catfish. Endemic silversides are abundant in the Lerma-Santiago basins but are under severe environmental and fishing pressure (Martínez-Palacios *et al.,* 2004). They have often been recommended for aquaculture due to their high economic, social, cultural and ecological value, but practical aquaculture remains in the pilot stages (Martínez-Palacios *et al*., 2002; Alarcon-Silva *et al*., 2009; Olvera-Blanco *et al*., 2009). Only two species of atherinids are naturally distributed in the Balsas basin: *Atherinella balsana* and A. guatemalensis (Miller *et al*., 2005). In order to provide a suitable option for the production of native silverside in the Rio Balsas basin, aquaculture of *A. balsana* has been suggested (see chapter 5).

The culture of catfish is a strong well-established industry in Mexico, mainly based on the production of *Ictalurus punctatus* (FAO, 2003; Sanchez-Martínez *et al*., 2007). *I. punctatus* is naturally distributed from southern Canada through central United States between the Rocky and Appalachian mountains, to the east of Mexico (Chihuahua, Chahuila, Nuevo Leon, Tamaulipas and Veracruz) (Miller *et al*., 2005). Suitable substitutes for aquaculture of *I. punctatus* in central Mexico are *I. dugesii* in the Lerma-Santiago and *I. balsanus* in the Balsas basins, based on their similarity and importance in local markets (see chapter 5). Both species of native catfish have been considered as endangered (Arce and Luna-Figueroa, 2003; CEDRSSA, 2006). Endangered species like these, with considerable market value represent excellent candidates to meet the requirements of the high market demand and of conservation programmes for the protection of biodiversity, one of the key factors for this project.

The development of aquaculture of native species would, however, fail without sensitive planning. Adequate planning can help to secure sustainability, both from the production perspective and in terms of biodiversity (Longdill *et al*., 2008; Ross *et al*., 2008; Hossain & Das, 2010).

8.2.1 Native species aquaculture and the decision making process

Geographic Information Systems (GIS) have proved to be a powerful tool for the decision making process in a variety of subjects (Jankowski, 1995; Chang *et al*., 2008; Store 2009; Boroushaki and Malczewski, 2010; Anagnostopoulus, 2010; Ehrogtt, 2010). GIS allows spatial and attribute data to be combined, enabling aquaculture planners to make informed decisions (Nath *et al*., 2000; Kapetsky and Aguilar-Manjarrez, 2007; Radiarta *et al*., 2008). Amongst the potential tools that GIS offers for aquaculture planning, Site Suitability Models (SSM) are the most commonly developed and one of the most important aspects of such models is to ensure sustainable production. Site suitability models have been used for a wide variety of aquaculture industries, for example: marine aquaculture (Ross *et al*., 1993; Pérez *et al*., 2005; Benetti *et al*., 2010), shrimp aquaculture (Salam *et al*., 2003, Hossain and Das, 2010) and freshwater aquaculture (Salam *et al*., 2005; Hossain *et al*., 2007; Ross *et al*., 2010).

In chapter 5 a SSM for the development of native species aquaculture at catchment level in central Mexico, was presented. The model included 17 variables, summarized into Water Suitability, Soil and Terrain Suitability, Infrastructure Suitability and Environmental Risk sub-models. These Suitability Sub-models were combined through a Multi-criteria Evaluation to produce the final Model of Site Suitability. The results showed a wide range of suitable geographic areas for the development of aquaculture for native silversides and catfish in the Lerma-Santiago and Balsas basins. The SSM identified 6,216 km^2 of highly suitable area for aquaculture of atherinids natives to the Lerma-Santiago basin and 3,409 km^2 for the culture of *A. balsana* in the Balsas basin. The SSM also showed suitable areas for aquaculture of native *Ictalurus dugesii* to the Lerma-Santaigo Basins (6,278 km^2) and *Ictalurus balsanus* to the Balsas basin (4,102 km^2).

Because of the scarcity of specific information related to aquaculture of the studied species, the aquaculture parameters applied in the models were derived from related species. For aquaculture of atherinids, the technology developed for *Chirostoma estor* was used in the modelling process, as was the technology of *Ictalurus punctatus* for the two catfish studied species. For this reason, the resulting output images showed areas suitable for the aquaculture of all studied species in both catchments, regardless of their natural distribution. This should not be misinterpreted; it is certainly not suggested that the studied species should be introduced outside of their natural range of distribution for aquaculture. Instead, the use of similar species native to each catchment area is proposed. Since the primary objective of this research was the promotion of native species aquaculture, in order to avoid further introductions of non-native species, recognising the natural range of distribution for each species, and its implementation in the decision making process, is essential.

8.2.2 Predicting Natural Ranges of Distribution

For the development of native species aquaculture and in order to avoid further introductions, it seems only logical to implement geographical constraints in the decision making process. However, aquaculture programmes should not be considered under political boundaries. Instead, ecosystem-based management approach should be recommended. This strategy focuses on the entire ecosystem with river basins as the management unit, rather than political divisions, which are often crossed when looking at natural boundaries (Ketter, 1994; Pikitch *et al*., 2004). River basins are also effective geographic constraints for aquatic biodiversity analyses (Imhof *et al*., 1996; Graney *et al*., 2008) that naturally restrict the distribution of many freshwater species (Gyllensten, 1984; Leprieur *et al*., 2009; McDowall, 2010).

Throughout chapters 1, 4, 5, 6 and 7 it is repeatedly suggested that aquaculture development of native species should respect the natural range of distribution of the targeted species. Natural ranges of distribution can be described in the field by monitoring the appearances of species, which is most usually achieved by sampling for scientific purposes or by enquiring with local fishermen. However, field sampling frequently cannot cover entire geographies. For this reason an ecological niche-based Predictive Species Distribution (PSD) model was explored and presented in chapter 6 for its use in aquaculture planning. Ecological niche modelling is an emerging field that integrates the spatial distribution of environmental variables and the available knowledge of species distribution in order to predict the potential distribution of species, using GIS (Peterson, 2003; Zambrano *et al*., 2006). This tool has been applied for the impact of climate change on species (Thomas *et al*., 2004), potential areas for species reintroductions (Martínez-Meyer *et al*., 2006), dispersion of exotic species (Chen *et al*., 2006) and conservation planning (Oberdorff *et al*., 2001, Lehmann *et al*., 2002, Brotons *et al*., 2004). According to Guisan and Zimmerman (2000), there are several alternative species distribution models. The model explored in this research used a Mahalanobis Typicality (Clark *et al*., 1993) to identify areas where environmental and topographic conditions are similar to those observed in the realised niche. The PSD model identified the potential natural range of distribution for six native species native to the Lerma-Santiago basin and two species native to the Balsas basin (see studied species in chapter 6). The understanding of natural ranges of distribution and the implementation of aquaculture under such spatial constraints should be considered an important tool for the prevention of new non-native species introductions.

8.2.3 Risk assessment and Prevention for further introductions

Arguably one of the most useful applications emerging from Predictive Species Distribution modelling is the prediction of the potential for invasion by exotic species (Peterson *et al*., 2003; Thuiller *et al*., 2005; Ficetola *et al*., 2007). PSD models may overestimate the potential natural range of distribution for native species (Stockwell and Peterson, 2002; Guisan and Hofer, 2003), due to the lack of biotic information such as competition of predation and geographical barriers that would make it impossible for a fish species to migrate to new environments (Fielding and Haworth 1995; Brown *et al*., 1996). However, intentional introductions allow the possibility of non-native species arriving in such new environments with unknown consequences. The PSD model presented in chapter 6 revealed areas where the studied species have the potential to establish; although the success of invasion from a given studied species will ultimately depend on biotic factors (Soberon and Peterson, 2005). Therefore, although the PSD model cannot foresee the response of the non-native species to competition and/or predation outside of its natural range of distribution, it can successfully be a powerful tool for risk assessment in the form of a map of Potential for Invasion.

The PSD model shown predicted the potential of native species from the Lerma-Santiago basins to invade environments of the Balsas basin, and vice versa (see chapter 6). The model showed that *Chirostoma promelas* (endemic to the Lerma-Santigo basins) and *Ictalurus balsanus* (endemic to the Balsas basin) have limited potential for invasion of new environments, whereas *Atherinella balsana* and *I. dugessi* showed a great potential for invasion, a factor that is worth considered during the decision making process for the development of native species aquaculture

8.3 Aquaculture Strategy for the Protection of Biodiversity (ASPB)

The main objectives of this research was to develop a systematic methodology based on spatial modelling in order to provide an efficient instrument for planning development of native species sustainable aquaculture. To develop an aquaculture management strategy for native species from an integral approach based on catchment systems. And to construct an information system that can be consulted analysed, updated and modelled in order to ensure adequate decision-making, and investments on aquaculture. The Aquaculture Strategy for the Protection of Biodiversity (ASPB) integrated Site Suitability models (see Chapter 5), with Predictive Species Distribution and Potential for Invasion models (see Chapter 6). This final model (ASPB) aimed to satisfy the needs of the stakeholder and the aquaculture site at the same time that it recognised essential environmental requirements. This addresses the conflict that Naylor *et al*., (2000) described, between exploitation and conservation. The model prioritises site selection, since the sustainability of the aquaculture farm depends on that (Perez *et al*., 2005). However species distributions and risk assessments of invasion provided the final structure to the presented results.

The ASPB promotes a cooperative management of aquaculture at catchment level, rather than political or administrative management. This idea is supported behind the concept of ecological management which considers that political divisions have little to do with biological processes (Pikitch *et al*., 2004; Pahl-Wostl *et al.*, 2008; Rodriguez-Iturbe *et al*., 2009)

8.4 Implications

The proposal for the use of native species in aquaculture is not a new concept (Pérez *et al*., 2003). The objective of this research work was to step forward from that concept and attempt to generate spatial models providing scientifically-base decision support.

- The Site Suitability Model generated during this research, has strong potential for implementation in Mexico, as a tool for management and regulation, of native species aquaculture.
- The Predictive Species Distribution (PSD) model produced during this research can be implemented in the early stages of the domestication process; this would allow the aquaculture developer to find the best areas for the recruitment of wild seed or reproductive stocks for the development of hatcheries.
- The PSD model also provides a strong risk assessment tool, in the form of a Predictive Potential for Invasion (PPI) model, the use of which should be encouraged prior to any movement of species with potential for aquaculture. The adequate implementation of PPI models can help to mitigate the risks

associated with the introduction of exotic species by preventing future introductions.

- ASPB is a management tool that aims to develop aquaculture in a sustainable way for biodiversity, by introducing ecological requirements (PSD-PI) in the decision making process
- The need for a reliable source of high quality protein has been recognised in this research as a priority for the growing human population. However it is essential to consider the need for the protection of biodiversity in order to ensure sustainability of the environment. The Geographic Information System models produced and presented in this work are flexible and robust tools for aquaculture planning and the protection of biodiversity that should be recommended for implementation as planning instruments for the future growth and regulation of the sustainable aquaculture in Mexico.

8.5 Recommendations

- A catchment level approach (Ecological-based management), is the most suitable alternative for the development of native species aquaculture programmes; a factor that has to be recognised by authorities responsible for the industry development and the protection of biodiversity.
- The use of Geographic Information Systems in the development of Native Species aquaculture provides a powerful and reliable planning tool for the decision making process, thanks to its capability for integrate a wide range of variables. However developers must be encouraged to produce and use

compatible database. Lack of compatibility is one of the major obstacles for the use of GIS in the decision making process.

- The capability to update Geographic Information Systems, as new data becomes available, is one it major assets. The Site Suitability Model presented in this research can be improved as specific technologies for aquaculture of each one of the suggested species is developed.
- Whereas species with low population densities, restricted range of distribution and strong markets are strong candidates for conservation programmes.

8.6 Conclusions

Aquaculture has proved to be an excellent option to meet the requirement for a sustainable source of protein, which is a major concern of our times. However careful planning of aquaculture developments is crucial for the sustainability of fish biodiversity. Aquaculture of non-native species, although has proved as a very productive sector, represents a risk for local fish fauna. Aquaculture of native species is a suitable approach for conservation planning. It can be aimed to satisfy market demands in the same way as reintroduction programmes. In summary responsible development for aquaculture of native species would promote:

- Adequate genetic programs for aquaculture broodstock are essential to minimize risks to wild organisms.

- The correct site selection for aquaculture may help ensuring sustainability, both for the site as for local biodiversity.
- Evaluation of natural ranges of distribution and potential for invasion would help mitigating introduction of exotic species, and its negative effects.
- The use of native resources at catchment level, replacing the need for exotic species in aquaculture.
- Preservation of “wilderness” areas.

The use of Geographical Information Systems as planning instruments for aquaculture in central Mexico, represent a powerful tool. The flexible spatial models developed in this project can be implemented consistently throughout the country and easily modified on basin by basin basis. The data and models can be easily accessed by a range of end-users and stakeholders at a range of appropriate levels.

References

Alarcon-Silva, E.M. Martinez-Palacios C.A. & Martinez-Chavez, C.C. 2009. Recent Discoveries and Advances in the husbandry of a Mexican freshwater silverside *Menidia estor*. 2da Conferencia Latinoamericana sobre Cultivo de Peces Nativos. Buenos Aires, Argentina 3-6 2009.

Allendorf, F. W., P. R. England, G. Luikart, P. A. Ritchie, and N. Ryman. 2008. Genetic effects of harvest on wild animal populations. *Trends in Ecology & Evolution* **23**:327-337.

Alves, C., F. Vieira, A. Magalhães, and M. Brito. 2007. Impacts of Non-Native Fish Species in Minas Gerais, Brazil: Present Situation and Prospects. Pages 291-314 in Ecological and Genetic Implications of Aquaculture Activities

Anagnostopoulos, K.P. *et al.,* 2009. Land suitability analysis for natural wastewater treatment systems using a new GIS add-in for supporting criterion weight elicitation methods. *Operational Research*, **10**:91-108.

Arce U.E. and Luna-Figueroa J. 2003. Efecto de dietas con diferente contenido proteico en las tasas de crecimiento de crias del Bagre del Balsas *Ictalurus balsanus* (Pisces: Ictaluridae) en condiciones de cautiverio. *Revista AquaTIC. 18*: 39-47.

Badiou, P. H. J., and L. G. Goldsborough. 2010. Ecological Impacts of an Exotic Benthivorous Fish in Large Experimental Wetlands, Delta Marsh, Canada. Wetlands **30**:657-667.

Beardmore, J. A., G. C. Mair, and R. I. Lewis. 1997. Biodiversity in aquatic systems in relation to aquaculture. *Aquaculture Research* **28**:829-839.

Bekkevold, D., M. Hansen, and E. Nielsen. 2006. Genetic impact of gadoid culture on wild fish populations: predictions, lessons from salmonids, and possibilities for minimizing adverse effects. J*ournal of Marine Science* **63**:198-208.

Benetti, D.D. *et al*., 2010. Site Selection Criteria for Open Ocean Aquaculture. *Marine Technology Society Journal*, **44**:22-35.

Brown, J.H., Stevens, G.C. & Kaufman, D.M., 1996. THE GEOGRAPHIC RANGE: Size, Shape, Boundaries, and Internal Structure. *Annual Review of Ecology and Systematics*, **27**:597-623.

Brotons, L. *et al*., 2004. Presence-absence versus presence-only modelling methods for predicting bird habitat suitability. *Ecography*, **27**:437-448.

Boroushaki, S. & Malczewski, J., 2010. Using the fuzzy majority approach for GIS-based multicriteria group decision-making. *Computers & Geosciences*, **36**:302-312.

Cambray, J. 2003. Impact on indigenous species biodiversity caused by the globalisation of alien recreational freshwater fisheries. *Hydrobiologia* **500**:217-230.

Canonico, G. C., A. Arthington, J. K. McCrary, and M. L. Thieme. 2005. The effects of introduced tilapias on native biodiversity. Aquatic Conservation: *Marine and Freshwater Ecosystems* **15**:463-483.

CEDRSSA. 2006. Pesca, Acuicultura e Investigación en México. *Centro de Estudios para el Desarrollo Rural Sustentable y la Soberanía Alimentaria*. Available at: http://groups.ucanr.org/Ballast_Outreach/files/46382.pdf#page=67 [Accessed March 13, 2011]

Chang, N., 2008. Combining GIS with fuzzy multicriteria decision-making for landfill siting in a fast-growing urban region. *Journal of Environmental Management*, **87**:139-153.

Chen, P., Wiley, E.O. & Mcnyset, K.M., 2006. Ecological niche modeling as a predictive tool: silver and bighead carps in North America. *Biological Invasions*, **9**:43-51.

Clark, J.D., Dunn, J.E. & Smith, K.G., 1993. A Multivariate Model of Female Black Bear Habitat Use for a Geographic Information System. *The Journal of Wildlife Management*, **57**:519-526.

Crawford, C. & MacLeod C. 2009. Predicting and assessing the environmental impact of aquaculture. In *New technologies in Aquaculture.* Brunell G. &Geoff A. ed. **21**:679-706.

Diana, J.S., 2009. Aquaculture Production and Biodiversity Conservation. *BioScience*, **59**:27-38.

Ehrgott, M., 2010. *Trends in Multiple Criteria Decision Analysis*, Springer.

FAO. 2003. Fishery Country Profile, Mexico. Available at: http://www.fao.org/fi/oldsite/FCP/es/MEX/profile.htm [Accessed: February 20-2011].

FAO. 2010. FishStat Plus- Universal software for fishery statistical time series. Available at: http://www.fao.org/fishery/statistics/software/fishstat/en [Accessed: March 01-2011].

Ficetola, G.F., Thuiller, W. and Miaud C. 2007. Prediction and validation of the potential flobal distribution of a problematic alien invasive species- the American bullfrog. *Diversity and Distributions.* **13**: 476-485.

Fielding, A.H. & Haworth, P.F. (1995) Testing the generality of bird-habitat models. *Conservation Biology*, **9**: 1466-1481.

Gjedrem, T. 2000. Genetic improvement of cold-water fish species. Aquaculture Research **31**:25-33.

Graney, J., Salvage, K. & Zhu, W., 2008. A Watershed-Based Approach to Environmental Education Integrating Ecology, Hydrology, and Geochemistry. *Journal of Contemporary Water Research & Education*, **138**:22-28.

Guisan, A. & Hofer, U. 2003. Predicting reptile distributions at mesoscale: relation to climate and topography. *Journal of Biogeography,* **30**: 1233-1243.

Guisan, A. & Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. *Ecological Modelling*, **135**:147-186.

Gyllensten, U., 1985. The genetic structure of fish: differences in the intraspecific distribution of biochemical genetic variation between marine, anadromous, and freshwater species. *Journal of Fish Biology*, **26**:691-699.

Hossain, M.S. *et al.,* 2007. Multi-criteria evaluation approach to GIS-based land-suitability classification for tilapia farming in Bangladesh. *Aquaculture International*, **15**:425-443.

Hossain, M.S. & Das, N.G., 2010. GIS-based multi-criteria evaluation to land suitability modelling for giant prawn (*Macrobrachium rosenbergii*) farming in Companigonj Upazila of Noakhali, Bangladesh. *Computers and Electronics in Agriculture*, **70**:172-186.

Imhol, J., Fitzgibbon, J. & Annable, W., 1996. A hierarchical evaluation system for characterizing watershed ecosystems for fish habitat. *Canadian Journal of Fisheries and Aquatic Sciences*, **53**:312-326.

Jankowski, P., 1995. Integrating geographical information systems and multiple criteria decision-making methods. *International Journal of Geographical Information Systems*, **9**:251.

Kapetsky, J. M. y J. Aguilar-Manjarrez. 2007. Geographic Information Systems, remote sensing and mapping for the development and management of marine aquaculture FAO Fish Tech Paper, No 458, Roma. 125 p.

Ketter, R.B., 1993. Beyond the Boundary Line: Constructing a Law of Ecosystem Management. *University of Colorado Law Review*, **65**: 293.

Kopp, D., J. Syväranta, J. Figuerola, A. Compin, F. Santoul, and R. Céréghino. 2009. Environmental effects related to the local absence of exotic fish. Biological Conservation **142**:3207-3212.

Law, R. 2000. Fishing, selection, and phenotypic evolution. ICES Journal of Marine Science: *Journal du Conseil* **57**:659 -668.

Lehmann, A., Overton, J.M. and Leathwick, J.R. 2002. GRASP: generalized regression analysis and spatial prediction. *Ecological Modelling,* **157***:*189–207*.*

Leprieur, F. *et al.,* 2009. Contrasting patterns and mechanisms of spatial turnover for native and exotic freshwater fish in Europe. *Journal of Biogeography*, **36**:1899-1912.

Longdill, P.C., Healy, T.R. & Black, K.P., 2008. An integrated GIS approach for sustainable aquaculture management area site selection. *Ocean & Coastal Management*, **51**:612-624.

Ludwig, A. *et al.,* 2009. First evidence of hybridization between endangered sterlets (*Acipenser ruthenus*) and exotic Siberian sturgeons (*Acipenser baerii*) in the Danube River. *Biological Invasions*, **11**:753-760.

Magurran, A. 2009. Threats to Freshwater Fish. *Science* **325**:1215-1216.

Martínez-Meyer, E. *et al*., 2006. Ecological Niche Modelling and Prioritizing Areas for Species Reintroductions. *Oryx*, **40**:411-418.

Martinez-Palacios *et al.,* 2002. Effect of temperature on growth and survival of *Chirostoma estor estor,* Jordan 1879, monitored using a simple video technique for remote measurement of length and mass of larval and juvenile fishes. *Aquaculture* **209**: 369-377.

Martínez-Palacios *et al*., 2004. The effects of saline environments on survival and growth of eggs and larvae of *Chirostoma estor estor* Jordan 1880 (Pisces: Atherinidae). *Aquaculture* **238**:509-522.

Masood, E. 1997. Aquaculture: a solution, or source of new problems? *Nature* **386**:109.

McDowall, R., 2006. Crying wolf, crying foul, or crying shame: alien salmonids and a biodiversity crisis in the southern cool-temperate galaxioid fishes? *Reviews in Fish Biology and Fisheries*, **16**:233-422.

McDowall, R., 2010. *New Zealand Freshwater Fishes*, Dordrecht: Springer Netherlands. Available at: http://www.springerlink.com/content/v247631317124588/ [Accessed March 20, 2011].

McGinnity, *et al.,* 2003. Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon. Proceedings of the Royal Society B: *Biological Sciences* **270**:2443-2450.

Miller, R.R., Minckley, W.L. & Norris, S.M., 2005. Freshwater Fishes of Mexico. University of Chicago Press.

Moyle, P.B. & Light, T., 1996. Biological invasions of fresh water: Empirical rules and assembly theory. *Biological Conservation*, **78**:149-161.

Nath, S.S. *et al*., 2000. Applications of geographical information systems (GIS) for spatial decision support in aquaculture. *Aquacultural Engineering*, **23**:233-278.

Naylor, R.L. *et al.,* 2000. Effect of aquaculture on world fish supplies. *Nature,* **405** : 1017-1024.

Njiru, M., Mkumbo, O. & van der Knaap, M., 2010. Some possible factors leading to decline in fish species in Lake Victoria. *Aquatic Ecosystem Health & Management*, **13**:3-10.

Oberdorff, T. *et al.,* 2001. A probabilistic model characterizing fish assemblages of French rivers: a framework for environmental assessment. *Freshwater Biology*, **46**:399-415.

Olvera-Blanco Y.M. Gomez-Marquez J.L. Peña-Mendoza B. Gaspar-Dillanes M.T. and Perez C. 2009. Reproductive biology of *Menidia jordani* (Atherniformes:Atherinopsidae) in Xochimilco Lake, Mexico. *Ciencia pesquera,* **17**: 65-75.

Pelicice, F., and A. Agostinho. 2009. Fish fauna destruction after the introduction of a non-native predator (Cichla kelberi) in a Neotropical reservoir. Biological Invasions 11:1789-1801.PRB. 2008. World Population Data Sheet. Available at: http://www.prb.org/Publications/Datasheets/2008/2008wpds.aspx [Accessed March 3, 2011].

Perez, J E., C. Alfonsi, M. Nirchio, C. Muñoz, J. A. Gómez. 2003. The introduction of exotic species in aquaculture: a solution or part of the problem?. Interciencia, **28**:234-238. ISSN 0378-1844.

Pérez, O.M., Telfer, T.C. & Ross, L.G., 2005. Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. *Aquaculture Research*, **36**:946-961.

Peterson, A.T., 2003. Predicting the Geography of Species' Invasions via Ecological Niche Modeling. *The Quarterly Review of Biology*, **78**:419-433.

Pikitch, E.K. *et al.,* 2004. Ecosystem-Based Fishery Management. *Science*, **305**:346 -347.

Radiarta, I.N., Saitoh, S. & Miyazono, A., 2008. GIS-based multi-criteria evaluation models for identifying suitable sites for Japanese scallop (*Mizuhopecten* *yessoensis*) aquaculture in Funka Bay, southwestern Hokkaido, Japan. *Aquaculture*, **284**:127-135.

Rahel, F.J., 2000. Homogenization of Fish Faunas Across the United States. *Science*, **288**:854 -856.

Rodriguez-Iturbe, I. *et al.,* 2009. River networks as ecological corridors: A complex systems perspective for integrating hydrologic, geomorphologic, and ecologic dynamics. *Water Resources Research*, **45**.

Ross, L., Mendoza Q.M., E. & Beveridge, M., 1993. The application of geographical information systems to site selection for coastal aquaculture: an example based on salmonid cage culture. *Aquaculture*, **112**:165-178.

Ross, L.G., Martinez Palacios, C.A. & Morales, E.J., 2008. Developing native fish species for aquaculture: the interacting demands of biodiversity, sustainable aquaculture and livelihoods. *Aquaculture Research*, **39**:675-683.

Ross, L.G. *et al.,* 2010. Spatial modelling for freshwater cage location in the Presa Adolfo Mateos Lopez (El Infiernillo), Michoacán, México. *Aquaculture Researc*.

Ryman, N., F. Utter, and L. Laikre. 1995. Protection of intraspecific biodiversity of exploited fishes. Reviews in fish biology and fisheries 5:417-446.Salam, M., Khatun, N. & Ali, M., 2005. Carp farming potential in Barhatta Upazilla, Bangladesh: a GIS methodological perspective. *Aquaculture*, **245**:75-87.

Salam, M., Khatun, N. & Ali, M., 2005. Carp farming potential in Barhatta Upazilla, Bangladesh: a GIS methodological perspective. *Aquaculture*, **245**:75-87.

Sánchez-Martínez, J.G. *et al*., 2007. First detection of channel catfish virus associated with mortality of cultured catfish (*Ictalurus punctatus*, Rafinesque) in Mexico. *Aquaculture Research*, **38**:1428-1431.

Sato, M. *et al.,* 2010. A review of the research on introduced freshwater fishes: new perspectives, the need for research, and management implications. *Landscape and Ecological Engineering*, **6**:99-108.

Scribner, K. T. and Avise, J. C. (1993). Cytonuclear genetic architecture in mosquito fish populations and the possible roles of introgressive hybridization. *Mol Ecol*, **2**: 139–149.

Soberon, J. & Peterson, T., 2005. Interpretation of Models of Fundamental Ecological Niches and Species' Distributional Areas. Available at: https://journals.ku.edu/index.php/jbi/article/viewArticle/4 [Accessed March 17, 2011].

Store, R., 2009. Sustainable locating of different forest uses. *Land Use Policy*, **26**:.610-618.

Stockwell, D.R.B. & Peterson, A.T., 2002. Effects of sample size on accuracy of species distribution models. *Ecological Modelling*, **148**:1-13.

Tapia, M., and L. Zambrano. 2003. From aquaculture goals to real social and ecological impacts: Carp introduction in rural Central Mexico. *AMBIO* **32**:252-257.

Thomas, C.D. *et al*., 2004. Extinction risk from climate change. *Nature*, **427**:145-148.

Thuiller, W. *et al.,* 2005. Niche-based modelling as a tool for predicting the risk of alien plant invasions at a global scale. *Global Change Biology*, **11**:2234-2250.

Utter, F., and J. Epifanio. 2002. Marine aquaculture: Genetic potentialities and pitfalls. *Reviews in Fish Biology and Fisheries* **12**:59-77.

Vitule, J. R. S., C. A. Freire, and D. Simberloff. 2009. Introduction of non-native freshwater fish can certainly be bad. *Fish and Fisheries* **10**:98-108.

Wolf, D. E., N. Takebayashi, and L. H. Rieseberg. 2001. Predicting the Risk of Extinction through Hybridization. *Conservation Biology* 15:1039-1053.

Zambrano, L. *et al.,* 2006. Invasive potential of common carp (*Cyprinus carpio*) and Nile tilapia (*Oreochromis niloticus*) in American freshwater systems. *Canadian Journal of Fisheries and Aquatic Sciences*, **63**:1903-1910.