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BAYFISH: A MODEL OF ENVIRONMENTAL FACTORS DRIVING FISH PRODUCTION IN THE LOWER MEKONG BASIN

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ABSTRACT

In tropical floodplain systems local populations are generally highly dependent upon the system's natural aquatic resources. In such systems the annual fish production depends on a combination of biological and physical parameters, principally 1) hydrological factors; 2) environmental factors and 3) fish migrations. Developing management plans is complicated as assessing the role of each factor is usually made difficult by their diversity, their interactions or feed-back loops, and by the frequent absence of data on certain factors. We present here a tool developed to overcome these difficulties with the aim of facilitating the management of large tropical rivers.

Despite the absence of adequate regional or national statistics and comprehensive time series data, a review of existing studies has allowed, the identification of ten factors driving the fish production in the Mekong River Basin. They are 1) hydrological factors: water level, flood duration; flood timing, flooding regularity; 2) floodplain factors: bank types, flooded zone land cover, dry season refuges, bank types, turbidity; 3) biological factors: longitudinal or lateral migrations. This assessment provided the framework for the production of a model integrating the driving environmental parameters and their interactions. Fishing, that also influences fish production, is not yet part of this model focussing on hydrological and ecological factors.

The model is based on Bayesian networks. The above variables are interconnected in a logical fashion and related to fish production with the connections being expressed in terms of probabilities. The model calculates conditional probabilities at each level and the overall trend resulting from the sum of interactions within the system. When quantitative information is not available, probabilities are based on local knowledge drawn from experienced biologists and fishers.

This model was developed for three groups of fishes (black fishes, white fishes and opportunists) and three geographic sectors (Upper Mekong, Tonle Sap system and Mekong Delta). The natural production that can be expected for each fish group in each sector is qualitatively expressed by a percentage between "Bad" and "Good". This result could have been converted into tonnes of fish had statistical time series been available.

The model is transparent and user-friendly. Variables having the strongest influence on fish production are identified and each variable can be easily varied to assess the consequences of various management options on fish production.

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INTRODUCTION

The environment

The Mekong River flows through China, Burma (Myanmar), the Lao PDR, Thailand, Cambodia and Vietnam. Among the large rivers of the world, the Mekong ranks tenth in length and third in mean maximum discharge (Welcomme 1985). This results in large monsoon-driven floods, and floodplains are a dominant feature of the Lower Basin, their total surface amounting to 84,000 km^2, the surface of Ireland (Scott 1989, Lacoursiere *et al.* 1998). The extent of these floodplains and wetland favours the abundance and diversity of fish; the total number of species is estimated at 1200 (Rainboth 1996) and the total fish catches basinwide amounts to an estimated 1.5 million tonnes (Sverdrup-Jensen 2002). Another feature of the Mekong River is the importance of fish migrations over long distances, in particular between countries (Lagler 1976, Pantúlu 1986, Roberts & Warren 1994, Poulsen *et al.* 2000). Numerous species migrate between spawning grounds (in Laos or Northern Cambodia) and feeding grounds in the wetlands and floodplains of Southern Laos, Cambodia and Vietnam. The use of these inundated zones by fishes has long been identified as a factor which strongly influences their total production (Petillot 1911, Chevey & Le Poulain 1940, Baird and Phylavanh 1999).

Importance of the fish resource

Rice and fish from capture fisheries are the two major staple food resources of the 60 million people living in the basin. Fish from capture fisheries (75% of the total yield, Sverdrup-Jensen 2002), supplemented by reservoir fisheries, aquaculture and by aquatic animals such as frogs and snails (Shoemaker et al. 2001, Balzer et al 2002), constitute the dominant source of protein in the region. The populations of the countries of the Lower Mekong Basin have one of the highest rates of fish consumption in the world with an average of 33.4 kg/person/year (Baran & Baird 2001), compared to the world average that is around 16 kg/person/year (FAO 2000). For instance, in Cambodia, fish constitute up to 65-75 per cent of total protein in the diet (Guttman 1999).

Access to this common property resource is particularly important for rural poor and landless people. However, at the national and regional levels the importance of water-dependant resources for food security and livelihoods has so far been poorly recognised (Jensen 2001, IIRR *et al.* 2001).

The need for management tools

In relation to its recent economic expansion, the Mekong River Basin has been experiencing a dramatic increase in the demand for water, arising from irrigated agriculture, hydropower production, and domestic and industrial uses. The optimised and sustainable use of the water and related resources of the Basin is dependant upon allocation rules to be defined among the riparian countries. This requires hydrological and water quality monitoring, development of modelling tools, simulation of the effects of basin development scenarios and the definition of rules for water allocation "so that water flow and ecological systems are maintained while Basin resources are developed" (MRC 2000).

The importance of aquatic resources in the diet and livelihood of rural communities, in particular poor people, requires that fish production be taken into consideration in management plans and strategies. Furthermore the dependence of aquatic resources upon flooding and floodplains requires that land management and environmental issues be also factored in to avoid development options that threaten food security in parts of the basin. In such a context the usually distinct objectives of modelling are needed simultaneously: identification of critical questions; building of a conceptual framework; synthesis of existing knowledge and identification of gaps; production of simulation scenarios for managers.

In 2000-2001, ICLARM-The WorldFish Center, in collaboration with the Mekong River Commission and the International Water Management Institute (IWMI), developed a hydro-biological research program on the relationships between hydrology, environmental factors and fish production in the Mekong River Basin. Research activities have continued in 2002 in order to integrate interactions between hydrological, biological and environmental factors into a computer model (Baran & Cain 2001, Baran 2002).

The resulting model, named BayFish, indicates the probability of having a good or bad natural fish production in the Mekong Basin, as a function of hydrological and environmental parameters. Production is undestood here literally as the biomass produced in a given year, and not as the yield resulting from a fishing effort.

The model aims to assess the consequences of various management options regarding flows and floodplain environment on natural fish production basinwide, and to provide scenarios for planning and decision making at the basin level.

MATERIAL AND METHODS

Constraints

As in several developing countries, the absence of data in the region is a major impediment to modelling.

Classical fisheries models require data on harvested biomass but also, depending upon the models, on stock virgin biomass, growth, length frequencies, natural mortality, recruitment, or fishing effort and selectivity. In the case of the Mekong River Basin and given the history of the region, reliable data of this nature are not available even for dominant commercial fish species. Despite some recent efforts to improve representativeness, "the total reported production from inland waters appears to be under-estimated by a factor of between at least 2.5 and 3.6" in national catch statistics (Coates 2002). Furthermore most fisheries models (with the exception of Halls *et al.* 2001) do not address floodplain environmental variability and do not allow for the simulation of different options for land and water use.

Alternatively models based on an ecosystem approach such as *Ecopath* or *Ecosim* (Christensen & Pauly 1992, 1993, Walters *et al.* 1997) require data on biomass of certain animal and vegetal taxa (e.g. macrophytes, zooplankton, meiobenthos, etc…) and data on trophic flows; both of which are non-existent for the Mekong system.

Use of existing knowledge as an alternative approach

Despite the paucity of quantitative data and the absence of time-series basinwide, the ecological knowledge of Mekong fishing communities is rich (Sokheng *et al.* 1999, Poulsen *et al.* 2000, MRC 2001, Baird 2002) and constitutes a source of integrative and low-cost information appropriate for exploratory studies (Poizat & Baran 1997). A number of ecological descriptions of the Mekong system and fisheries (e.g.: Chevey & Le Poulain 1940, Lagler 1976) provide useful sources of information to be considered. The BayFish model has been developed with the aim of overcoming the paucity of quantitative data and of integrating this qualitative bio-ecological information. Bayesian networks have been demonstrated to be a convenient tool for the modelling of knowledge (Cowell *et al.* 1999), and BayFish was developed following this approach.

Model conceptual framework

The conceptual framework presented here is based on a thorough analysis of hydrological, environmental and ecological factors influencing the natural fish production basinwide. The steps followed are detailed below.

- In order to assess the variability of the water level and the extent of each type of vegetation flooded, a hydrological model was developed by IWMI (Kite 2000, 2001). This model provides, on a daily basis, the discharge and river water levels basinwide. The availability of a digital terrain model and vegetation maps for the Tonle Sap sub-basin allowed the calculation of the area of each type of vegetation flooded, on the same temporal basis.
- The analysis of the monitoring of the Cambodian bag net fishery, done in collaboration with the project "Management of the Cambodian freshwater Capture Fisheries" (MRC/DoF/DANIDA), showed the strong correlation between water level and opportunistic fish species catches in Cambodia (Deap Loeung 1999, Baran *et al.* 2001).
- Analysis of fish monitoring data from Southern Lao PDR allowed migration-driven abundance patterns to be identified for 110 Mekong species (Baran & Baird 2002). It also showed the role and importance of dry season deep-water refuges for fish in the mainstream Mekong River.
- Other parameters important to fish have been identified from literature review and from interviews, and have been compiled (Baran and Coates 2000, Baran *et al.* 2001).

Ten factors have been identified as driving natural fish production in the Mekong River Basin. They are 1) hydrological factors (water level, flood duration; flood timing, flooding regularity); 2) floodplain factors (bank type, type of vegetation flooded, zone land cover, presence of dry season refuges, turbidity); 3) biological factors (possibility for fish to undertake longitudinal or lateral migrations). These variables have been linked in the following conceptual framework (Figure 1).

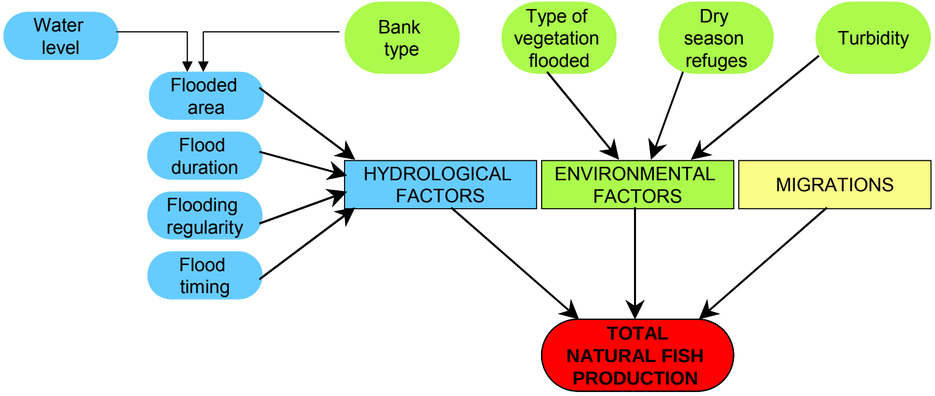


Figure 1: Parameters driving the fish production basinwide

In addition to these natural factors, it should be noted that fishing is a factor also having a strong influence on fish production or productivity, on fish sizes and on species assemblages. (Laë 1995, van Zalinge *et al.* 2000, Baran *et al.* 2003). Due to the complexity of fisheries in the Mekong Basin, to the absence of reliable catch and effort statistics basinwide and to our initial focus on environmental management, fishing has not been included in the model at this stage.

Bayesian modelling

Bayesian networks are based on three basic components (Jensen 1996):

- *nodes* representing system variables (e.g. flood duration; type of vegetation flooded,).
  Each variable can be continuous or discrete with a finite set of mutually exclusive states (e.h. long/short; forest/shrubs/grass). Driving or independent variables are called parent nodes and driven or dependant variables are called child nodes.
- *links* representing causal relationships between these nodes (from parent to child nodes, i.e. from cause to effect);
- *probabilities* attached to combination of states, and quantifying the believed relationships between connected nodes.

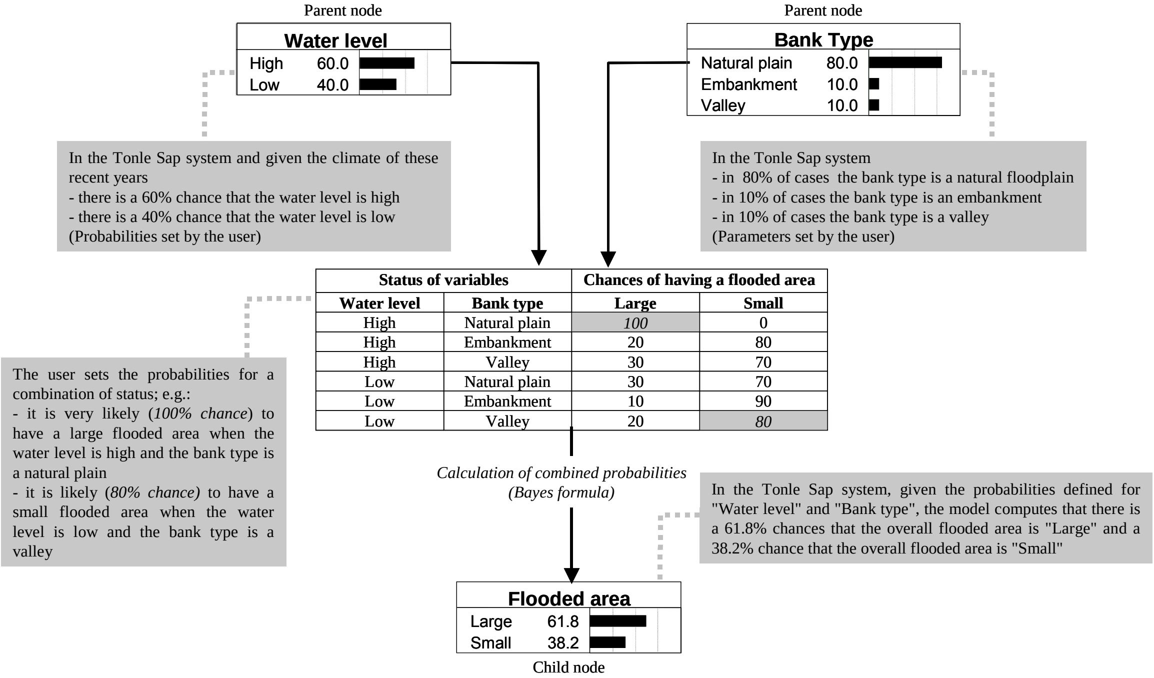
• For each driving variable ("parent nodes") the states are defined after the consultation of experts, and a probability is set for each state; this is the first step of the parametrization process ("elicitation of probabilities"). For example in the Tonle Sap system,

- there is a 80% chance that the bank type is a natural floodplain
  (i.e.it is estimated that in 80% of cases the banks are in relation with a non-altered floodplain);
- there is a 10% chance that the bank type is a man-made embankment
  (i.e. it is considered that 10% of the Great Lake perimeter is restrained by National roads 5 and 6);
- there is a 10% chance that the bank type is a valley
  (i.e. it is estimated that 10% of the banks are bordered by hills -"phnoms"- and thus constrained from flooding by a natural feature, as in a valley).

• For each variable driven by independent variables, experts attribute a probability of occurrence to every combination of states in the parent nodes; this is the second and last step of the parametrization process. For instance in the Tonle Sap system

- there is a 100% chance that "flooded area" is "large" when "water level" is "high" and "bank type" is "natural plain", but
- there is only a 30% chance that "flooded area" is "large" when "water level" is "low" and "bank type" is "natural plain".

• For all child nodes subject to the combined influence of two or more parent nodes, the software calculates the probability of each state that results from the combination of states of parent nodes. In other words "child probabilities" resulting from several "parent probabilities" are calculated after the Bayes formula for combined probabilities (hence the name of Bayesian network), down to the last child node (the probability of a good natural fish production basinwide). This represents the overall trend resulting from the sum of interactions within the system. Figure 2 gives an example of this process for two parent variables and one child variable in the case of the Tonle Sap system.



In the Tonle Sap system and given the climate of these recent years
- there is a 60% chance that the water level is high
- there is a 40% chance that the water level is low
(Probabilities set by the user)

In the Tonle Sap system
- in 80% of cases the bank type is a natural floodplain
- in 10% of cases the bank type is an embankment
- in 10% of cases the bank type is a valley
(Parameters set by the user)

Status of variables		**Chances of having a flooded area**	
Water level	**Bank type**	**Large**	**Small**
High	Natural plain	*100*	0
High	Embankment	20	80
High	Valley	30	70
Low	Natural plain	30	70
Low	Embankment	10	90
Low	Valley	20	*80*

The user sets the probabilities for a combination of status; e.g.:
- it is very likely (*100% chance*) to have a large flooded area when the water level is high and the bank type is a natural plain
- it is likely (*80% chance)* to have a small flooded area when the water level is low and the bank type is a valley

Calculation of combined probabilities (Bayes formula)

In the Tonle Sap system, given the probabilities defined for "Water level" and "Bank type", the model computes that there is a 61.8% chances that the overall flooded area is "Large" and a 38.2% chance that the overall flooded area is "Small"

Figure 2: Example of interactions between 3 nodes of a Bayesian network ***(example taken from BayFish / Tonle Sap system, Cambodia)***

By modifying the probabilities in parent nodes one at a time, the user can identify the variables of the system and observe the result of changed parameters on the intermediate and final child nodes. Different scenarios can thus be considered, and sensitivity analysis can point out variables that are critically important in the general behaviour of the system.

BayFish specificities

• BayFish was developed using Netica software (Norsys Corporation); this software is simple, user-friendly and a user-version of the operating software can be downloaded freely on Internet at www.norsys.com.

• BayFish was developed for three distinct groups of fishes (Welcomme 1985, Hoggarth *et al.* 1999):
- "white fish"(they undertake mostly long longitudinal migrations and move back to the mainstream of perennial rivers when water recedes)
- "black fishes (they undertake mostly short lateral migrations and move back to ponds when the water recedes)
- opportunists (small cyprinids of short life span able to reproduce within one year; a dominant and apparently growing part of catches in the Mekong Basin (Van Zalinge & Thuok 1999, Van Zalinge *et al.* 2000). The importance of these fishes in catches in Cambodia justified the creation of a special group for them.

• BayFish was also developed for three distinct zones in the Mekong Basin:
- upland zone (Northern highlands and Khorat plateau, Lao PDR; valley-dominated bank type; migrations of fishes to central zone)
- central zone (Lower Mekong plain, including the Tonle Sap river and lake; large non-modified floodplain)
- delta (from below Phnom Penh to the sea; floodplain controlled by embankments).

• The initial parametrization of the model was done by the authors, then modified by four Mekong River Commission fisheries and environment specialists (see acknowledgements) until a consensus was reached on the final set of parameters. Each geographical zone was parameterized independently according to the local environment and hydrology. The detail of the parameterization (i.e. probabilities used) is given in annex I.

RESULTS

Three sub-models and an integrative one.

For each geographical zone (upper catchment, Tonle Sap, Delta), the interaction between hydro-environmental variables and their resulting impact on the natural production of three fish groups (white fish, black fish, opportunists) has been be modeled. In each zone the fish production of each group is expressed by a probability between 0 and 1 (i.e. between "Bad" and "Good"). Figure 3 details this model for the Tonle Sap sub-system.

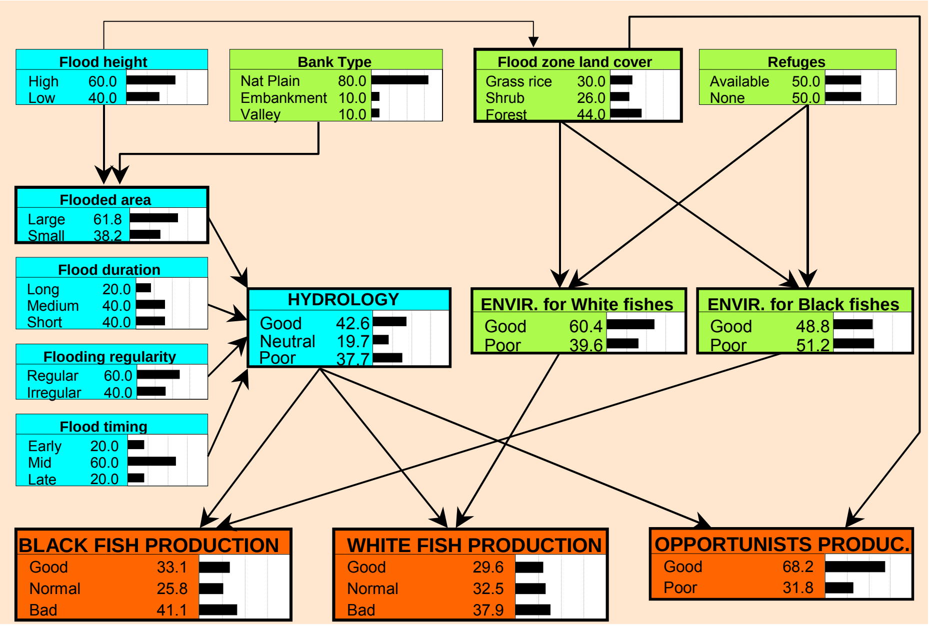


Figure 3: BayFish model of fish production for the Tonle Sap sub-system

The three zones have been connected by links representing migrations and spatial interactions; their respective natural fish productions are combined to give the total natural fish production basinwide. Outputs of the model for the natural fish production of the three geographical zones are given in Figure 4.

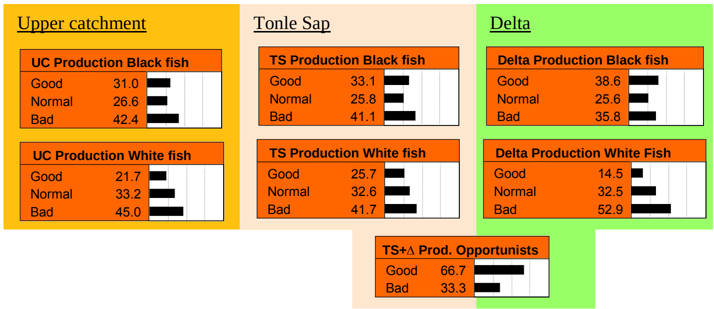


Figure 4: Outputs of the model for the three fish groups of the three geographical zones

The output of the overall model is therefore a probability of having a good fish production basinwide, depending upon the production in each zone. The overall model is represented (without attached probabilities, for readibility) in Figure 5.

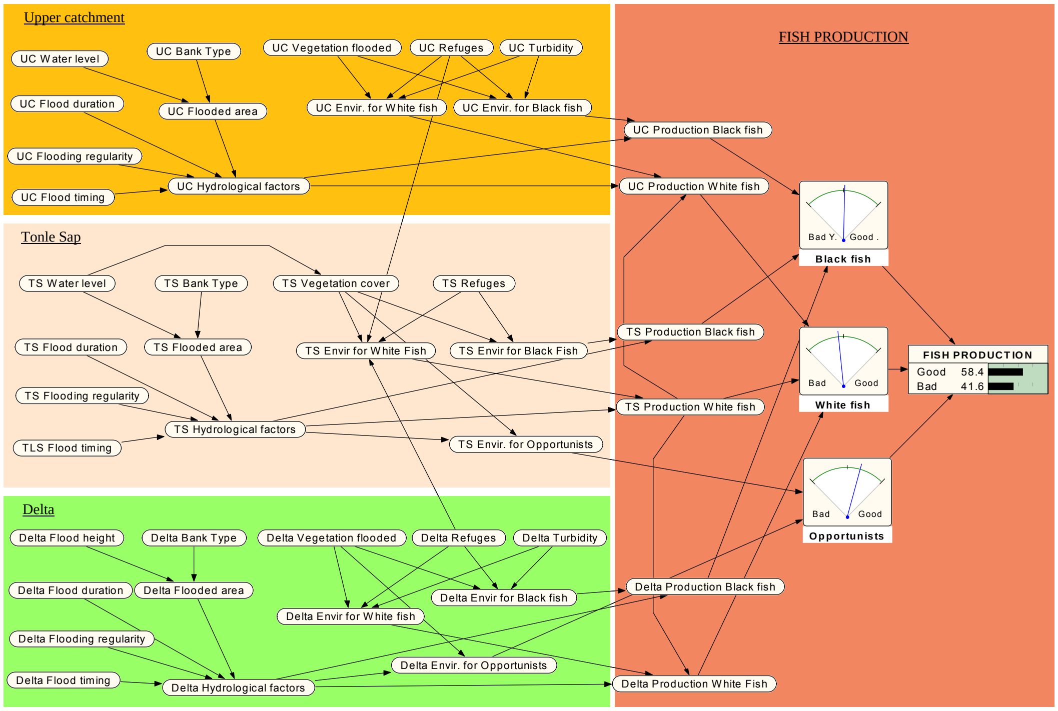


Figure 5: Summary of the Mekong BayFish model

Sensitivity analysis

With a classical statistical approach, testing the interactions among 23 variables would require more than a century-long time-series. In the Bayesian approach, a sensitivity analysis allows for the identification of the variables that contribute most to the variability of a given node. This consists in a systematic variation of each probability of each network node; the output probabilities are investigated, some variables having a considerable effect on the final node, while others hardly reveal any influence (Coupé *et al.* 2000). In practice the percentage which each parent node (i.e. driving variable) contributes to the total entropy reduction in the system (i.e. the reduction of uncertainty) was calculated and plotted. This approach can be used in the knowledge acquisition process to focus attention on the most influential parameters, thus improving the efficiency of monitoring (Coupé *et al.* 1999).

In the case of BayFish the sensitivity analysis outlined the critical variables of the system (Figure 6).

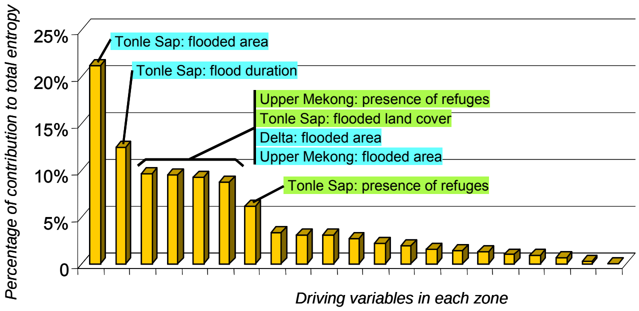


Figure 6: Variables contributing most to the natural fish production.

For readability variables “Water level” and “Bank type” have been merged into variable “Flooded area”. Ordering of variables results from their contribution ot the total entropy of the system, as identified after a sensitivity analysis.

This figure shows that the area of flooding around the Tonle Sap is the most influential parameter driving the fish production; among 7 influential factors, the area flooded is present 3 times, highlighting the importance of natural flooding for natural fish production. Among environmental factors, the nature of the vegetation flooded in the Tonle Sap floodplain and the availability of dry season refuges (in the Tonle Sap and upstream) also rank high in effects on overall production.

DISCUSSION

The strength of BayFish is that it is based on an extensive review of information on fish and fisheries in the Basin. It has been developed to overcome the paucity of reliable statistics in the Mekong Basin by integrating expert and local knowledge. In its current version all quantitative information has been coded as probabilities ("codage"), but the software permits the replacement of qualitative information by data when they become available (Figure 7).

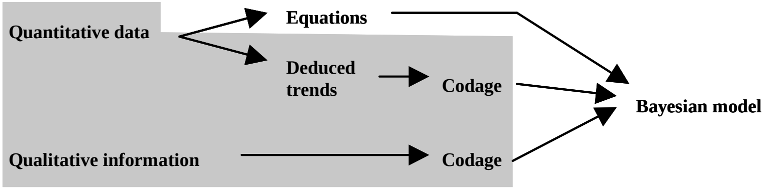


Figure 7: Possible inputs for a Bayesian network. In grey inputs used for the BayFish model.

The model is intuitive and user-friendly. Sources are open, size is small (60 kB). Experience has shown that such a model is easily understood and generates interest and discussions among users.

However BayFish is not a dynamic model, in the sense that it does not integrate a temporal component. This reflects the fact that information backing this model is integrative and does not rely upon regular monitoring of the system modelled. It is possible for Bayesian networks to integrate temporal evolutions by connecting several models, each of them representing a certain time period, and parameters being re-examined from one step to the other according to the outputs of the previous model. This is a possible development of BayFish, as long as it can rely on studies of trends in Mekong Basin land and water use.

BayFish is hampered, as other models would be, by i) the absence of data systematically gathered at the basin level, in particular for fisheries; ii) the limited information on fish productivity by habitat type and habitat distributions in floodplains; and iii) the unknown fishing effort basin wide. Subsequently the production is expressed in terms of probability, but the catch, depending upon the fishing effort, cannot be quantified/forecasted. This would have been done had reliable statistical time series been available.
The issue of fishing effort is important, as the size of fishes and the species composition of catches are known to be largely influenced by the fishing pressure (Welcomme 1995). Integrating fishers and their fishing effort in the next versions of this model are planned developments. Among other perspectives are the integration of i) floodplain inundation patterns and ii) available habitats at different water levels for the rest of the Basin.

Last, it can be argued that BayFish only reflects the knowledge and beliefs of those who took part in its parameterization (Bayesian networks being also called belief networks). In the context of management of tropical environments with little scientific data, this can be considered as a strength. Bayesian networks indeed allow for the integration of experiences drawn by specialised resource persons, and permit the synthesis of the best available information about a complex system. The model itself integrates the information entered at different levels and provides a synthesis that is beyond the reach of individual experts. This is shown for instance in the sensitivity analysis, which provides a simple ranking of the most influential parameters when interactions among them are integrated. However the way the locally available information is integrated into the model is an important issue. In Bayfish the parametrization was made by six experts in Mekong fisheries and environment. However one might recommend a larger consultation of experts, in particular of fishers (Cain 2001). This is of particular importance in future versions of this model integrating the effect of fishing on the fish resource. A greater number of contributors would then require the definition of a formalized consultation process for a proper (consensual, averaged or weighted) parametrization of the model.

CONCLUSIONS

BayFish as it stands is mostly a tool for discussions about development options among and between regional agencies, national management bodies and companies conducting Environmental Impact Assessments.

Bayesian networks have been developed in the mid-90’s to build Decision Support Systems. Being intuitive and easy to compute or modify, they constitute a good tool for building a common representation of a system between stakeholders willing to discuss consequences of various management scenarios. They have been developed in recent years for natural resources management (review in Cain 2001), fisheries management (Varis & Kuikka 1997, Kuikka *et al.* 1999, Marcot *et al.* 2001) and watershed management (Borsuk *et al.* 2001). In the same spirit, multi-agent systems (Weiss 1999, Ferber 1999) have also been used to holistically model floodplain fisheries and integrated river basin management (Bousquet 1994, FIRMA 2000). Tharme (2002) has shown that in the field of river management a new generation of holistic models was mostly being designed and applied in tropical countries. This probably reflects the fact that in the tropics people are in more direct relation to natural environments and their dynamics, and dependant upon rivers and their aquatic resources.

Beyond refinements of the current model, the long term perspective is to develop this approach as part of an integrated modelling package to assist in floodplains management, in particular in the tropics. This would correspond to a decision-support system encompassing three successive levels: fish and their environment; then users of the environmental resources; and then the local, national and regional management bodies having a stake in a river basin. In order to model these three layers of increasing complexity, variables and their interactions have to be identified and qualified or quantified, which requires extensive interdisciplinary interactions and consultations.

Last, unlike BayFish that focusses on fish only, and thus has a simple perspective, an integrative decision-support system will be faced with a diversity of perspectives from a variety of stakeholders. This issue of integrating perspectives and achieving a consensus among stakeholders through modelling is an active field of research (e.g. Moss 2000, Borsuk *et al.* 2001, Trebuil *et al.* 2002) and a challenge for water and floodplain management in the Mekong Basin.

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ANNEX I: VARIABLES AND PARAMETERS OF THE BAYFISH MODEL

Each number is a probability entered after consultations with local experts.
The tables below should be read as follows:

Upper catchment: Flood duration

Long	Short
0.5	0.5

⬄ In the Upper catchment, there is a 50% chance that the flood duration is Long, and 50% chances that the flood duration is Short

Tonle Sap: Vegetation flooded

Tonle Sap Water level	Grass or rice	Shrub	Forest
High	0.4	0.2	0.4
Low	0.15	0.35	0.5

⬄ In the Tonle Sap system,
- when the water level is high, there is a 40% chance that the flooded vegetation is rice, 20% chances that it is shrubs and 40% chances that it is a forest
- when the water level is low, there is a 15% chance that the flooded vegetation is rice, 35% chances that it is Shrubs and 50% chances that it is a forest

Parent variables

Upper catchment

Upper catchment: Water level

High	Low
0.6	0.4

Upper catchment: Flood duration

Long	Short
0.5	0.5

Upper catchment: Flood timing

Early	Mid	Late
0.2	0.6	0.2

Upper catchment: Flooding regularity

Regular	Irregular
0.6	0.4

Upper catchment: Vegetation flooded

Grass or rice	Shrub	Forest
0.2	0.4	0.4

Upper catchment: Bank type

Natural plain	Embankment	Valley
0.1	0.1	0.8

Upper catchment: Refuges

Available	None
0.5	0.5

Upper catchment: Turbidity

High	Low
0.5	0.5

Tonle Sap

Tonle Sap: Water level

High	Low
0.6	0.4

Tonle Sap: Flood duration

Long	Medium	Short
0.2	0.4	0.4

Tonle Sap: Flood timing

Early	Mid	Late
0.2	0.6	0.2

Tonle Sap: Flooding regularity

Regular	Irregular
0.6	0.4

Tonle Sap: Vegetation flooded

Tonle Sap Water level	Grass or rice	Shrub	Forest
High	0.4	0.2	0.4
Low	0.15	0.35	0.5

Tonle Sap: Bank type

Natural plain	Embankment	Valley
0.8	0.1	0.1

Tonle Sap: Refuges

Available	None
0.5	0.5

Delta

Delta: Water level

High	Low
0.6	0.4

Delta: Flood duration

Long	Short
0.5	0.5

Delta: Flood timing

Early	Mid	Late
0.2	0.6	0.2

Delta: Flooding regularity

Regular	Irregular
0.6	0.4

Delta: Vegetation flooded

Grass or rice	Shrub	Forest
0.7	0.2	0.1

Delta: Bank type

Natural plain	Embankment	Valley
0.7	0.25	0.05

Delta: Refuges

Available	None
0.5	0.5

Delta: Turbidity

High	Low
0.5	0.5

Child variables

Upper Catchment

Upper catchment: Flooded area

UC Water level	UC Bank type	Large	Small
High	Natural plain	1	0
High	Embankment	0.2	0.8
High	Valley	0.3	0.7
Low	Natural plain	0.3	0.7
Low	Embankment	0.1	0.9
Low	Valley	0.2	0.8

Upper catchment: Hydrological factors

UC Flooding regularity	UC Flooded area	UC Flood duration	UC Flood timing	Good	Neutral	Poor
Regular	Large	Long	Early	1	0	0
Regular	Large	Long	Mid	0.95	0.05	0
Regular	Large	Long	Late	0.7	0.2	0.1
Regular	Large	Short	Early	0.7	0.2	0.1
Regular	Large	Short	Mid	0.6	0.2	0.2
Regular	Large	Short	Late	0.5	0.1	0.4
Regular	Small	Long	Early	0.4	0.3	0.3
Regular	Small	Long	Mid	0.3	0.3	0.4
Regular	Small	Long	Late	0.2	0.2	0.6
Regular	Small	Short	Early	0.2	0.2	0.6
Regular	Small	Short	Mid	0.1	0.2	0.7
Regular	Small	Short	Late	0.1	0.2	0.7
Irregular	Large	Long	Early	0.8	0.1	0.1
Irregular	Large	Long	Mid	0.7	0.2	0.1
Irregular	Large	Long	Late	0.6	0.2	0.2
Irregular	Large	Short	Early	0.4	0.2	0.4
Irregular	Large	Short	Mid	0.3	0.3	0.4
Irregular	Large	Short	Late	0.3	0.2	0.5
Irregular	Small	Long	Early	0.3	0.3	0.4
Irregular	Small	Long	Mid	0.2	0.2	0.6
Irregular	Small	Long	Late	0.1	0.2	0.7
Irregular	Small	Short	Early	0.1	0.2	0.7
Irregular	Small	Short	Mid	0	0.1	0.9
Irregular	Small	Short	Late	0	0	1

Upper catchment: Environment for White fish:

UC Refuges	UC Turbidity	UC Vegetation flooded	Good	Poor
Available	High	Grass or rice	0.2	0.8
Available	High	Shrub	0.7	0.3
Available	High	Forest	0.8	0.2
Available	Low	Grass or rice	0.3	0.7
Available	Low	Shrub	0.8	0.2
Available	Low	Forest	0.9	0.1
None	High	Grass or rice	0.1	0.9
None	High	Shrub	0.5	0.5
None	High	Forest	0.6	0.4
None	Low	Grass or rice	0.2	0.8
None	Low	Shrub	0.6	0.4
None	Low	Forest	0.7	0.3

Upper catchment: Environment for Black fish:

UC Refuges	UC Turbidity	UC Vegetation flooded	Good	Poor
Available	High	Grass or rice	0.7	0.3
Available	High	Shrub	0.6	0.4
Available	High	Forest	0.6	0.4
Available	Low	Grass or rice	0.9	0.1
Available	Low	Shrub	0.8	0.2
Available	Low	Forest	0.8	0.2
None	High	Grass or rice	0.3	0.7
None	High	Shrub	0.2	0.8
None	High	Forest	0.2	0.8
None	Low	Grass or rice	0.5	0.5
None	Low	Shrub	0.4	0.6
None	Low	Forest	0.4	0.6

Upper catchment: Production of Black fish

Hydrological factors	UC Environment for Black fish	Good	Normal	Bad
Good	Good	1	0	0
Good	Poor	0	0.4	0.6
Neutral	Good	0.6	0.4	0
Neutral	Poor	0.1	0.4	0.5
Poor	Good	0.3	0.5	0.2
Poor	Poor	0	0	1

Upper catchment:Production of White fish

UC Hydrological factors	UC Environment for White fish	TS Production of White fish	Good	Normal	Bad
Good	Good	Good	1	0	0
Good	Good	Normal	0.9	0.1	0
Good	Good	Bad	0.8	0.1	0.1
Good	Poor	Good	0	0.6	0.4
Good	Poor	Normal	0	0.55	0.45
Good	Poor	Bad	0	0.45	0.55
Neutral	Good	Good	0.5	0.5	0
Neutral	Good	Normal	0.4	0.6	0
Neutral	Good	Bad	0.35	0.65	0
Neutral	Poor	Good	0.1	0.6	0.3
Neutral	Poor	Normal	0.05	0.6	0.35
Neutral	Poor	Bad	0	0.55	0.45
Poor	Good	Good	0	0.5	0.5
Poor	Good	Normal	0	0.45	0.55
Poor	Good	Bad	0	0.4	0.6
Poor	Poor	Good	0	0.1	0.9
Poor	Poor	Normal	0	0.05	0.95
Poor	Poor	Bad	0	0	1

Tonle Sap

Tonle Sap: Flooded area

Tonle Sap Water level	Tonle Sap Bank type	Large	Small
High	Natural plain	1	0
High	Embankment	0.2	0.8
High	Valley	0.3	0.7
Low	Natural plain	0.3	0.7
Low	Embankment	0.1	0.9
Low	Valley	0.2	0.8

Tonle Sap: Hydrological factors

Tonle Sap Flooding regularity	Tonle Sap Flooded area	Tonle Sap Flood duration	Tonle Sap Flood timing	Good	Neutral	Poor
Regular	Large	Long	Early	0.4	0.3	0.3
Regular	Large	Long	Mid	0.3	0.3	0.4
Regular	Large	Long	Late	0.2	0.25	0.55
Regular	Large	Medium	Early	1	0	0
Regular	Large	Medium	Mid	0.95	0.05	0
Regular	Large	Medium	Late	0.7	0.2	0.1
Regular	Large	Short	Early	0.7	0.2	0.1
Regular	Large	Short	Mid	0.6	0.2	0.2
Regular	Large	Short	Late	0.5	0.1	0.4
Regular	Small	Long	Early	0.3	0.2	0.5
Regular	Small	Long	Mid	0.2	0.2	0.6
Regular	Small	Long	Late	0.1	0.1	0.8
Regular	Small	Medium	Early	0.4	0.3	0.3
Regular	Small	Medium	Mid	0.3	0.3	0.4
Regular	Small	Medium	Late	0.2	0.2	0.6
Regular	Small	Short	Early	0.2	0.2	0.6
Regular	Small	Short	Mid	0.1	0.2	0.7
Regular	Small	Short	Late	0.1	0.2	0.7
Irregular	Large	Long	Early	0.35	0.4	0.25
Irregular	Large	Long	Mid	0.3	0.4	0.3
Irregular	Large	Long	Late	0.25	0.35	0.4
Irregular	Large	Medium	Early	0.8	0.1	0.1
Irregular	Large	Medium	Mid	0.7	0.2	0.1
Irregular	Large	Medium	Late	0.6	0.2	0.2
Irregular	Large	Short	Early	0.4	0.2	0.4
Irregular	Large	Short	Mid	0.3	0.3	0.4
Irregular	Large	Short	Late	0.3	0.2	0.5
Irregular	Small	Long	Early	0.2	0.2	0.6
Irregular	Small	Long	Mid	0.1	0.1	0.8
Irregular	Small	Long	Late	0.01	0.1	0.89
Irregular	Small	Medium	Early	0.3	0.3	0.4

Irregular	Small	Medium	Mid	0.2	0.2	0.6
Irregular	Small	Medium	Late	0.1	0.2	0.7
Irregular	Small	Short	Early	0.1	0.2	0.7
Irregular	Small	Short	Mid	0	0.1	0.9
Irregular	Small	Short	Late	0	0	1

Tonle Sap: Environment for White fish:

TS Refuges	TS Vegetation flooded	Delta Refuges	Upper catchment Refuges	Good	Poor
Available	Grass or rice	Available	Available	0.15	0.85
Available	Grass or rice	Available	None	0.1	0.9
Available	Grass or rice	None	Available	0.15	0.85
Available	Grass or rice	None	None	0.1	0.9
Available	Shrub	Available	Available	0.85	0.15
Available	Shrub	Available	None	0.65	0.35
Available	Shrub	None	Available	0.9	0.1
Available	Shrub	None	None	0.6	0.4
Available	Forest	Available	Available	0.95	0.05
Available	Forest	Available	None	0.75	0.25
Available	Forest	None	Available	0.85	0.15
Available	Forest	None	None	0.7	0.3
None	Grass or rice	Available	Available	0.2	0.8
None	Grass or rice	Available	None	0.05	0.95
None	Grass or rice	None	Available	0.2	0.8
None	Grass or rice	None	None	0.05	0.95
None	Shrub	Available	Available	0.6	0.4
None	Shrub	Available	None	0.55	0.45
None	Shrub	None	Available	0.5	0.5
None	Shrub	None	None	0.45	0.55
None	Forest	Available	Available	0.7	0.3
None	Forest	Available	None	0.65	0.35
None	Forest	None	Available	0.75	0.25
None	Forest	None	None	0.5	0.5

Tonle Sap: Environment for Black fish

Refuges	Vegetation flooded	Good	Poor
Available	Grass or rice	0.55	0.45
Available	Shrub	0.6	0.4
Available	Forest	0.8	0.2
None	Grass or rice	0.4	0.6
None	Shrub	0.2	0.8
None	Forest	0.3	0.7

Tonle Sap:Environment for Opportunists

TS Vegetation flooded	TS Hydrological factors	Good	Poor
Grass or rice	Good	1	0
Grass or rice	Neutral	0.6	0.4
Grass or rice	Poor	0.1	0.9
Shrub	Good	0.9	0.1
Shrub	Neutral	0.75	0.25
Shrub	Poor	0.6	0.4
Forest	Good	0.8	0.2
Forest	Neutral	0.7	0.3
Forest	Poor	0.55	0.45

Tonle Sap: Production of Black fish

Hydrological factors	TS Environment for Black fish	Good	Normal	Bad
Good	Good	1	0	0
Good	Poor	0	0.4	0.6
Neutral	Good	0.6	0.4	0
Neutral	Poor	0.1	0.4	0.5
Poor	Good	0.3	0.5	0.2
Poor	Poor	0	0	1

Tonle Sap: Production of White fish

TS Hydrological factors	TS Environment for White fish	Good	Normal	Bad
Good	Good	1	0	0
Good	Poor	0	0.5	0.5
Neutral	Good	0.4	0.6	0
Neutral	Poor	0	0.6	0.4
Poor	Good	0	0.5	0.5
Poor	Poor	0	0	1

Delta

Delta: Flooded area

Delta Water level	Delta Bank	Large	Small
High	Natural plain	1	0
High	Embankment	0.2	0.8
High	Valley	0.3	0.7
Low	Natural plain	0.3	0.7
Low	Embankment	0.1	0.9
Low	Valley	0.2	0.8

Delta: Environment for White fish

Delta Refuges	Delta Turbidity	Delta Vegetation flooded	Good	Poor
Available	High	Grass or rice	0.2	0.8
Available	High	Shrub	0.7	0.3
Available	High	Forest	0.8	0.2
Available	Low	Grass or rice	0.2	0.8
Available	Low	Shrub	0.7	0.3
Available	Low	Forest	0.8	0.2
None	High	Grass or rice	0.1	0.9
None	High	Shrub	0.5	0.5
None	High	Forest	0.6	0.4
None	Low	Grass or rice	0.1	0.9
None	Low	Shrub	0.5	0.5
None	Low	Forest	0.6	0.4

Delta: Environment for Black fish

Delta Refuges	Delta Turbidity	Delta Vegetation flooded	Good	Poor
Available	High	Grass or rice	0.8	0.2
Available	High	Shrub	0.7	0.3
Available	High	Forest	0.7	0.3
Available	Low	Grass or rice	0.8	0.2
Available	Low	Shrub	0.7	0.3
Available	Low	Forest	0.7	0.3
None	High	Grass or rice	0.4	0.6
None	High	Shrub	0.3	0.7
None	High	Forest	0.3	0.7
None	Low	Grass or rice	0.4	0.6
None	Low	Shrub	0.3	0.7
None	Low	Forest	0.3	0.7

Delta: Hydrological factors

Delta Flooding regularity	Delta Flooded area	Delta Flooding duration	Delta Flood timing	Good	Neutral	Poor
Regular	Large	Long	Early	1	0	0
Regular	Large	Long	Mid	0.95	0.05	0
Regular	Large	Long	Late	0.7	0.2	0.1
Regular	Large	Short	Early	0.7	0.2	0.1
Regular	Large	Short	Mid	0.6	0.2	0.2
Regular	Large	Short	Late	0.5	0.1	0.4
Regular	Small	Long	Early	0.4	0.3	0.3
Regular	Small	Long	Mid	0.3	0.3	0.4
Regular	Small	Long	Late	0.2	0.2	0.6
Regular	Small	Short	Early	0.2	0.2	0.6
Regular	Small	Short	Mid	0.1	0.2	0.7
Regular	Small	Short	Late	0.1	0.2	0.7
Irregular	Large	Long	Early	0.8	0.1	0.1
Irregular	Large	Long	Mid	0.7	0.2	0.1
Irregular	Large	Long	Late	0.6	0.2	0.2
Irregular	Large	Short	Early	0.4	0.2	0.4
Irregular	Large	Short	Mid	0.3	0.3	0.4
Irregular	Large	Short	Late	0.3	0.2	0.5
Irregular	Small	Long	Early	0.3	0.3	0.4
Irregular	Small	Long	Mid	0.2	0.2	0.6
Irregular	Small	Long	Late	0.1	0.2	0.7
Irregular	Small	Short	Early	0.1	0.2	0.7
Irregular	Small	Short	Mid	0	0.1	0.9
Irregular	Small	Short	Late	0	0	1

Delta: Environment for Opportunists

Delta Vegetation flooded	Delta Hydrological factors for Opportunists	Good	Poor
Grass or rice	Good	1	0
Grass or rice	Neutral	0.6	0.4
Grass or rice	Poor	0.1	0.9
Shrub	Good	0.9	0.1
Shrub	Neutral	0.75	0.25
Shrub	Poor	0.6	0.4
Forest	Good	0.8	0.2
Forest	Neutral	0.7	0.3
Forest	Poor	0.55	0.45

Delta: Production of Black fish

Delta Hydrological factors for Black fish	Delta Environment for Black fish	Good	Normal	Bad
Good	Good	1	0	0
Good	Poor	0	0.4	0.6
Neutral	Good	0.6	0.4	0
Neutral	Poor	0.1	0.4	0.5
Poor	Good	0.3	0.5	0.2
Poor	Poor	0	0	1

Delta: Production of White fish

Delta Hydrological factors for White fish	Delta Environment for White fish	Tonle Sap Production of White fish	Good	Normal	Bad
Good	Good	Good	1	0	0
Good	Good	Normal	0.95	0.05	0
Good	Good	Bad	0.8	0.2	0
Good	Poor	Good	0.05	0.45	0.5
Good	Poor	Normal	0	0.5	0.5
Good	Poor	Bad	0	0.5	0.5
Neutral	Good	Good	0.5	0.5	0
Neutral	Good	Normal	0.4	0.6	0
Neutral	Good	Bad	0.3	0.7	0
Neutral	Poor	Good	0.05	0.55	0.4
Neutral	Poor	Normal	0	0.6	0.4
Neutral	Poor	Bad	0	0.5	0.5
Poor	Good	Good	0.05	0.45	0.5
Poor	Good	Normal	0	0.5	0.5
Poor	Good	Bad	0	0.5	0.5
Poor	Poor	Good	0	0.05	0.95
Poor	Poor	Normal	0	0	1
Poor	Poor	Bad	0	0	1

Production basinwide

Basin: Opportunists

Tonle Sap Environment for Opportunists	Delta Environment for Opportunists	Good	Bad
Good	Good	1	0
Good	Poor	0.7	0.3
Poor	Good	0.3	0.7
Poor	Poor	0	1