# Fuzzy logic-based expert system for native fish habitat assessment in a scarcity information context

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**Abstract** Expert systems are typically developed to solve unclear application fields or problems. Such is the case for Chilean river ecosystems, and their fish fauna. In Chile, fish fauna studies are led almost exclusively by biologists, but no or little information is available about reproductive season, fertility, reproductive strategies, age, locomotive capacity, migration, trophic dynamic or niche, to name a few. Quantitative studies are required to analyse the impact of exotic over native species and the antropic effect over a population's decrease. This information is essential to take appropriate conservation measures for each species and aquatic system. On the other hand, the lack of an adequate hydrometric network forces the use of complementary tools that introduce uncertainties, which are expensive and of difficult quantification. Due to the absence of gauged data for the study area, an expert system application methodology was coupled to the hydrological and hydraulic models, GR4J and HEC-RAS, respectively. Fish species information was taken from biological studies performed for the basin of the Bio Bio River where 17 fish species (13 native and 4 exotic, were found); furthermore, 7 species are classified as vulnerable and 7 are endangered. Conclusions are focused on the methodology as well as on information quality and source. The research indicated that habitat modelling efforts would be strongly limited by Chile's unclear environmental policy, including lack of data in all areas for an environmental study. Chile's capacity to adopt holistic tools for water resources management is commented. The study concludes with recommendations for improving the integration of environmental policy issues into Chile's water resource management.

**Key words** CASIMIR; Chile; Huequecura; fish habitat assessment; fuzzy logic; hydraulic modelling; hydrological modelling; water resources management; water law; free-market approach

## INTRODUCTION

Managing the inherent variability and uncertainty of ecosystems is essential for sustainable natural resource management and restoration programmes (Mackinson, 1999; Wheaton, 2004; Rogers, 2006). Natural systems are complex, non-stationary and nonlinear (Mackinson, 1999) and fuzzy logic is an innovative modelling technique that can be applied to the study of such systems because of their capacity for handling inherent uncertainty of ecological variables (Adriaenssens *et al.*, 2006; Ahmadi-Nedushan *et al.*, 2006). In Chile there are limited data and few studies in key areas of water management, such as hydrology, ecology of aquatic communities, groundwater, snowmelt and meteorology. Moreover, the main and principal sources of information come from expert opinion and published literature reviews (Puppe, 1993). The habitat simulation model CASIMIR (Computer Aided SImulation Model for Instream flow Requirements) is a fuzzy logic-based expert system that allows the incorporation of critical judgement and experience of skilled specialists within a fuzzy application domain (Puppe, 1993). It can be applied in many different settings, especially those with inadequate data, such as that faced in the water industry in Chile.

This paper focuses on the application and assessment of CASIMIR to a reach of the Huequecura River, Chile, for water resources management. Analysis focuses on the model's capacity to respond to fluvial ecosystem protection. It is demonstrated that Chile does not have full capacity to develop integrated and adaptive water resources management (IAWRM), but the use of fuzzy logic can assist in this process.

### Study area

The Huequecura River is located in central Chile. It is a tributary of the Bio Bío River (Fig. 1), which is one of the three major river basins in Chile. The Huequecurra River is an ungauged basin with low human impact (Meza, 2009). The study reach is located at 37.706°S and 71.786°W, and has a drainage area of 340 $km^2$ and a length of 70 m. Maximum streamflow occurs during autumn and winter, while minimum flow occurs in the summer, reflecting the seasonal rainfall pattern.

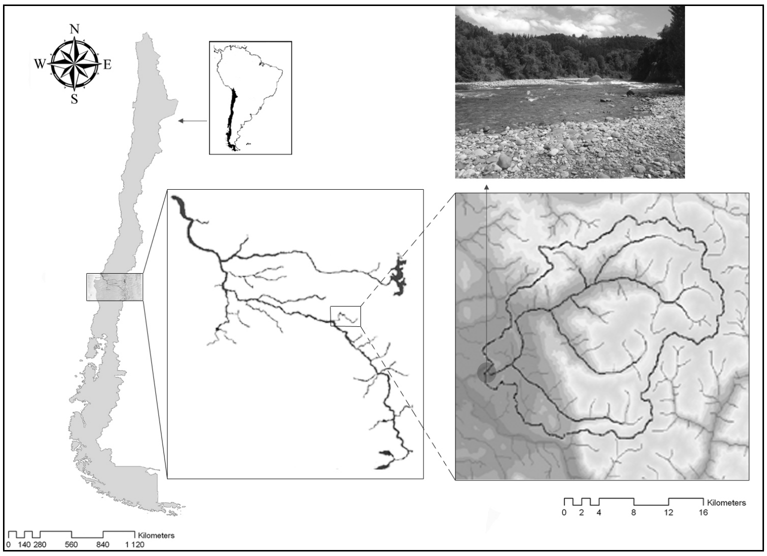


**Fig. 1** Location of the study area. Left to right is Chile, Bio Bío River, Huequecura basin.

## METHODOLOGY

As the study reach is a non-controlled basin, streamflow was simulated using the GR4J model (Génie Rural à 4 paramètres Journalier). This is a daily lumped four-parameter rainfall–runoff model (Perrin *et al.*, 2003) and because of the lack of flow data, the method designed by Salvatierra (2008) was used in order to establish the model parameters. Here a set of physical indexes (GI), based on a set of geomorphological parameters (Table 1) are used. The model developed for this study was adjusted for the 2006–2007 period (two years of daily mean data) and calibrated against discharge measurements made during 2007. As a result, some of the models flow parameters were adjusted.

To assess habitat suitability in the study reach, data from a series of fish surveys undertaken between 2002 and 2004 were used (see Table 2). These data represent an important source of field information to calibrate the habitat suitability model and were provided by *Centro de Ecología Aplicada* (Center for Applied Ecology – CEA). In addition, topographic, substrate, water level and flow gauge data were obtained during a field campaign in March 2007. This information was processed and used to calibrate a HEC-RAS 3.1.3 hydraulic model for the study reach. The uncertainties from both the hydrological and hydraulic models were transferred to the CASIMIR model. While field data is important for model calibration, the modeller's experience is in this case important to deal with data absence and uncertainty by choosing adequate variables. In addition, a series of measurements of flow velocity, depth and river bed representative grain size and its associated linguistic expressions, were collected in September 2007. In total, 36 measurement points and a fuzzy c-means algorithm were used to generate a fuzzy clustering, based on the numeric structure of the database (Babuska, 1998). The expert linguistic assessment allows the adjustment and the making of piecewise linear multivariate fuzzy sets, where membership functions can take triangular and trapezoidal forms, or any combination of linear functions (Schneider, 2008). Fuzzy rules were defined by the expert biologist after fuzzy set campaign, in order to generate fuzzy sets based on the relationship between species and river characteristics (García, 2007).

Results were analysed and discussed with fish experts to obtain reflections about the model. Four species: *Diplomystes nahuelbutaensis* (Dn), *Trichomycterus areolatus* (Ta), *Bullockia maldonadoi* (Bm) and of *Percilia irwini* (Pi), separated into juvenile and adult individuals, were studied (Meza, 2009). Due to a larger capture of *P. irwini* (Pi), the Petersen methodology was applied to separate juvenile and adult individuals (UBA, 2004). This methodology, although less precise, makes such distinction possible. This is a good technique to estimate fish age, especially where there are no samples of fish scales or otoliths (UBA, 2004). For comparison, García (2006) finds that Pi reaches adulthood at a size of 5 cm, while the Petersen methodology indicates 4–4.5 cm.

**Table 1** Geomorphological parameters needed to estimate GR4J model parameters; calculated with WMS 7.1 software (http://www.scisoftware.com/products/wms_overview/wms_overview.html ) (Salvatierra, 2008; Meza, 2009) for Huequecura basin (Topography digital data downloaded from: http://seamless.usgs.gov).

| Parameter | Unit | Value | Meaning |
|---|---|---|---|
| A | $km^2$ | 338.85 | Basin area |
| E | m | 1026.2 | Mean basin elevation |
| i | - | 0.395 | Basin slope |
| Per | m | 122040 | Basin perimeter |
| Lp | m | 30304.7 | Main stream flow length |
| Lcg | m | 16605.3 | Main stream flow length to the point closest to the basin gravity centre |
| Dcg | m | 4196.8 | Shortest distance between the main stream flow to the basin gravity centre |
| SL | m | 75836.2 | Sum of all basin channels |
| AOFD | m | 1855 | Average overland flow |
| Shape | – | 1.88 | Shape factor |
| Sin | – | 1.2 | Sinuosity factor |
| Aac | $km^2$ | 86.56 | Superficial projection of basin aquifer |
| e_ac | m | 52 | Aquifer thickness |

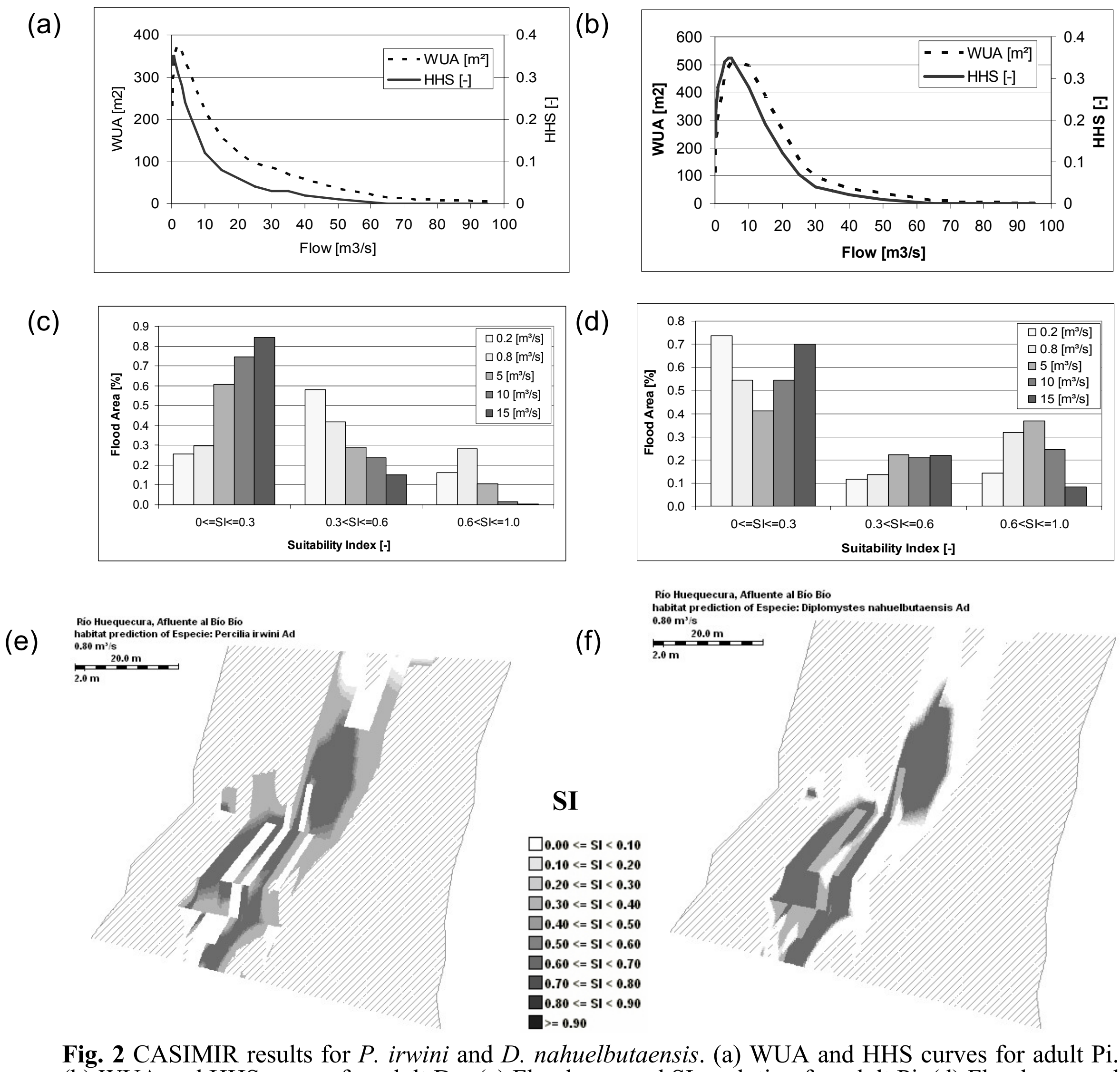


**Fig. 2** CASIMIR results for *P. irwini* and *D. nahuelbutaensis*. (a) WUA and HHS curves for adult Pi. (b) WUA and HHS curves for adult Dn. (c) Flood area and SI evolution for adult Pi. (d) Flood area and SI evolution for adult Dn. (e) Habitat suitability map of Huequecura reach for adult Pi; flow: 0.8 $m^3$/s (f) Habitat suitability map of Huequecura reach for adult Dn; flow: 0.8 $m^3$/s.

## RESULTS

The Bio Bío basin has a high fish species richness with 13 native species being recorded (Campos *et al*., 1993). However, there are few studies of the biology or ecology of these native fish. There is limited information on the reproduction seasons, reproduction strategies, age, migrations, trophic niche, etc. (Habit *et al*., 2006). In this study, model results were analysed in two parts. First, the suitability index (SI) (Jorde, 2006), which depicts habitat availability in response to flow character, is characterized for each species for both adults and juveniles (Fig. 2). Second, fish data were processed and compared to the Hydraulic Habitat Suitability index (HHS), also called Habitat Suitability Index (HSI), to assess the average habitat quality of the study reach (Jorde, 2006) (Table 2 and Fig. 3). The relationship between flow variability and the response and sensitivity of the studied fish species is given in Fig. 4.

Bm is the most adapted species in the study reach according to the HHS index (Table 2). However, some caution must be taken with these results because of the low number of this species being captured (13 specimens in total). It also appears that the habitat requirements of Bm vary in terms of their habitat quality, resulting in this endemic and endangered species being currently restricted to central and southern Chile. Ta by comparison, is not endemic and although it has a wider distribution and displays trophic plasticity, it is classified as being vulnerable (Dyer, 2000; Habit & Victoriano, 2005; Habit *et al*., 2005, 2006). This may be because, despite the poor habitat quality available for this species, it has a wide adaptation capacity (Table 2).

Flow variability is a feature of the Huequecura River and it has a relatively high low flow dominance (Fig. 4 shows daily variability for 2003). 79% of the time the streamflow is <5 $m^3$/s and only 1% of the time the flow is over 50 $m^3$/s (daily flow between 2002 and 2004). In this context, Bm, Dn and Ta are benthic species (so-called catfishes), which prefer deeper and often faster average velocity conditions than Pi. But it also happens that Pi has good habitat quality at minimal flow, unlike Dn and Ta (Fig. 2(a),(b) and Fig. 4) and less sensitivity to the flow variability (Fig. 4). This is important and may explain the difference between capture amounts (Table 2).

There are large differences in habitat quality for the Dn adult stage (Fig. 2(f)). The best conditions for Dn are faster and deeper waters near the centre of the river, unlike Pi adult, which prefer a medium habitat quality in the riparian zone (Fig. 2(e)). Fish capture records (Table 2) show that Pi has the greatest abundance, and this may reflect differences in sampling effort. Field sampling was made every year in February, May, August, and November, using electric fishing gear with a fishing period of 10–15 minutes at each site. Electric fishing gear can only be used at riparian zones and in many cases, samples were taken on the right bank (also right bank in Fig. 2(e) and (f)). It is therefore easy to understand why there is only one Dn adult captured in three years of campaign, and this also explains the Bm and Ta capture data.

**Table 2** Summary of HHS, frequent flows and fish capture records.

| Species | Q50 HHS reach | Q70 HHS reach | Q90 HHS reach | Samples 2002–2004 |
|---|---|---|---|---|
| *P. irwini* Adult | 0.31 | 0.26 | 0.14 | 53 |
| *P. irwini* Juvenile | 0.32 | 0.26 | 0.156 | 30 |
| *D. nahuelbutaensis* Adult | 0.31 | 0.345 | 0.295 | 1 |
| *D. nahuelbutaensis* Juvenile | 0.33 | 0.305 | 0.24 | 8 |
| *T. areolatus* Adult | 0.19 | 0.22 | 0.21 | 3 |
| *T. areolatus* Juvenile | 0.25 | 0.2 | 0.14 | 12 |
| *B. maldonadoi* Adult | 0.46 | 0.375 | 0.222 | 2 |
| *B. maldonadoi* Juvenile | 0.45 | 0.37 | 0.214 | 10 |

Q50: 50% of time flow (2 $m^3$/s); Q70: 70% of time flow (3.5 $m^3$/s); Q90: 90% of time flow (9 $m^3$/s); HHS reach: average HHS of the reach.

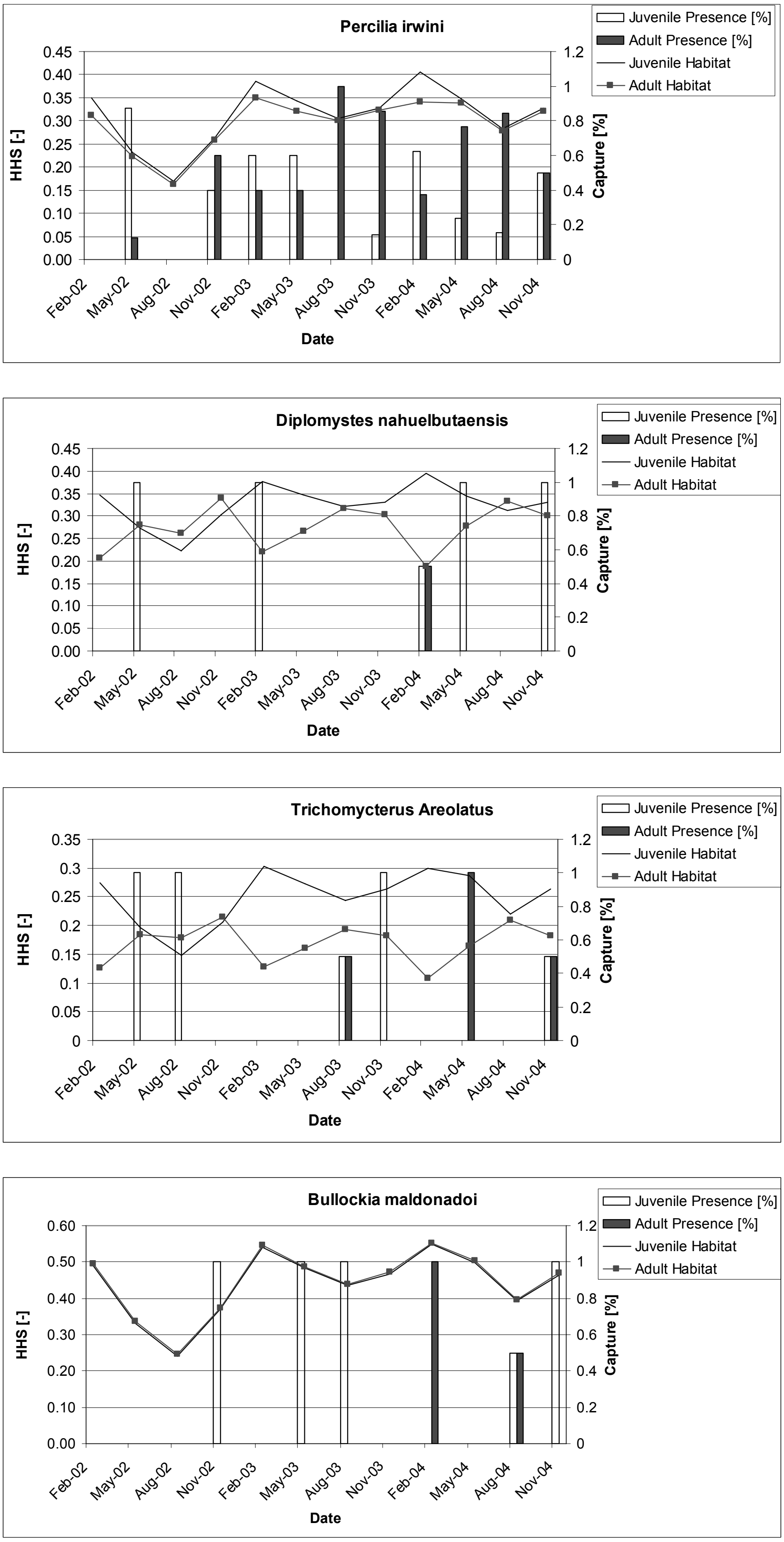


**Fig. 3** Monthly average HHS index and adult and juvenile specimen ratio for: (a) Pi, (b) Dn, (c) Ta, and (d) Bm.

(a)
(b)

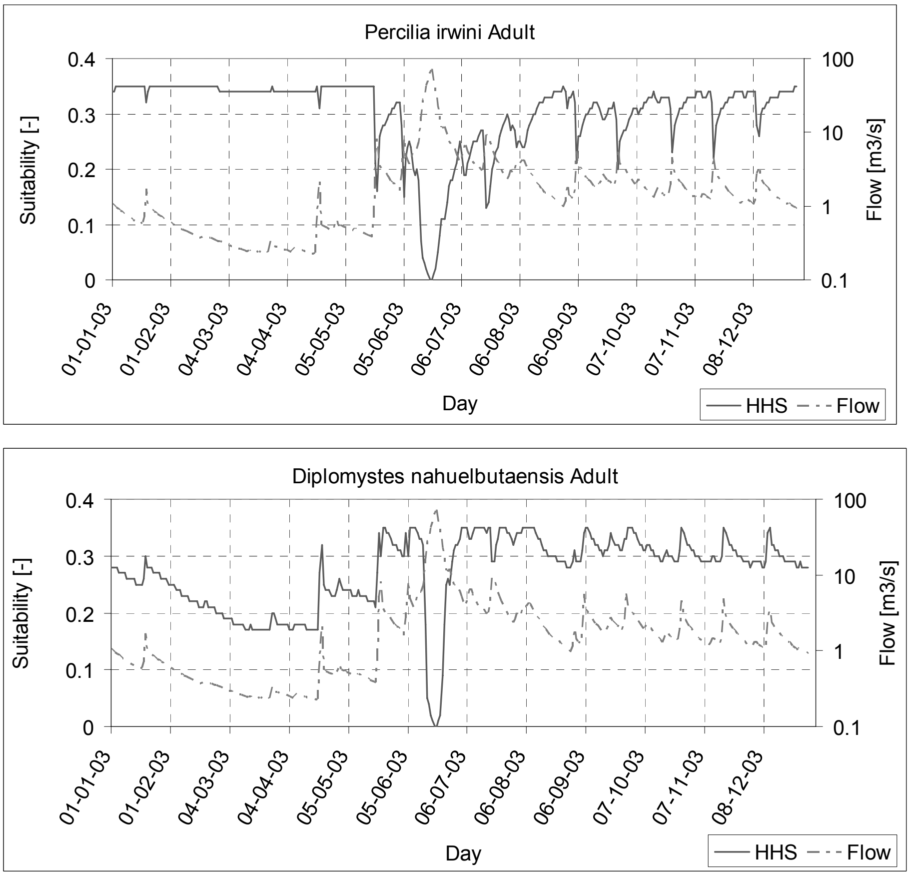


**Fig. 4** Daily variability of flow and reach average HHS in the study zone for: (a) Pi, and (b) Dn.

The monthly average HHS index and the adult and juvenile specimen ratio for every sampling trip is given in Fig. 3. This further reduces model assessment possibility. However, Fig. 3 shows a complementary habitat for Dn and Ta and a similar average habitat availability for Bm and for Pi. This can explain a relative equity of adult and juvenile Pi samples, as opposed to catfish samples. However, such symmetry does not exist if the criterion of García (2006) is used to make a distinction between adult and juvenile specimens of Pi. Although Poff & Ward (1989) indicate the importance of environmental variability as a factor for the structuring of biological communities, the wide flow variability and the high species richness of Huequecura River (Meza, 2009) do not allow a strict conclusion about the real presence of Pi, and it is not possible to ensure that the Petersen methodology will tells us what is happening in Huequecura River. Undoubtedly further investigation is required.

A time lag presence of adult and juvenile Pi, against habitat availability, was observed, which corresponds to the spawning season for each species. No information exists on the Pi spawning season, but information is available for another species of the same genus, *Percilia gillissi* (Pg). The spawning season of Pg occurs between November and January, while their fish larvae appear during January and March (EULA, 2007b). Figure 3 shows more juvenile presence of Pi during February and May, which matches the information of Pg.

## DISCUSSION

### Practicability of the approach

Based on this study a number of limitations for obtaining adequate results were identified. Biological studies of freshwater communities are poor in Chile and those that have been undertaken are concentrated in a few places where large projects have been designed. However, the results of this modelling study using CASIMIR clearly demonstrate different habitat qualities for the adult and juvenile stages of Dn (Fig. 3 (b)), and this makes it impossible to impose a single minimal flow for this important fish species. Thus, models like CASIMIR can provide useful information based on few resources and data scarcity, which may be used as a guideline for further research.

In general, the comparison between the modelled HHS of the study reach and the observed fish presence is reasonable considering the small quantity and low quality of the data, but it is necessary to improve these results through more research about native fish species. One problem was the low fish presence detected for some species. Our results (Fig. 3) reflect insufficient data collection, except for Pi. There is also uncertainty about the separation size used for defining adults and juveniles. In future studies it will be necessary to study a wider range of reach types (Hering *et al.*, 2004) and mesohabitat units (Schwartz & Herricks, 2008). In large river systems, connections are unavoidable and the presence or absence of specimens is not necessarily represented by one reach habitat. Consequently, studies assessing large river systems require large resources in order to understand how spatial variability affects the aquatic ecosystem (Fuentes, 2008).

This is clearly demonstrated in this study that habitat varies significantly with flow (Meza, 2009). These results can be used to formulate recommendations about dam operation rules. Hydropower often compares favourably with nuclear power plants because decommissioning is simpler and no hazardous waste is generated; however, these advantages are counterbalanced by important social conflicts and degradation of aquatic ecosystems (Bratrich *et al.*, 2004). There are alternatives, but often only because companies have no consumptive water rights. For instance, San Pedro River (Chile) has a dam where a single waterfall is being operated as a "pass power station" (EULA, 2007a). This is ecologically reasonable, but is restrictive to one of two options: total storage or non storage. CASIMIR offers an alternative option to consider: more power than "non storage" and less impact than "total storage" through an adaptive management of dam operation rules (Meza, 2009).

### Study case: Ralco hydropower dam project in the Bio Bío River

When ENDESA presented the Environmental Impact Assessment (EIA) required by the authority, the minimum environmental proposed flow was 6.1 $m^3/s$ (Ormazábal, 2004). However, their study was based on wrong fish preference information; for instance, the study indicated that *Diplomystes nahuelbutaensis* and *Trichomycterus areolatus* are "small species, with morphological characteristics of longitudinal development, which makes them particularly adaptable to shallow waters". This information is partial and incomplete because adult individuals need faster and deeper waters than juveniles (Habit, 2005). CASIMIR results show how habitat qualities for adult species of Dn are different from those required by juveniles (Fig. 3(b)), which makes it impossible to impose a minimal flow considering a unique preference. Authority resolution refused proposal of ENDESA and set as environmental flow the lowest flow ever recorded at the place (hydrological methodology is the one widely applied in Chile): 39 $m^3/s$ (Ormazábal, 2004). As justification, they noted "there is not enough biological information to support a different methodology from that used by the Dirección General de Aguas (General Direction of Water), although, on the basis of further information the flow can be modified in the future" (Ormazábal, 2004).

### Chilean model limitations

Liberalization of electricity and water markets is an attractive option in Chile for resource management, with a view that competitive markets create concerned consumers (Bratrich *et al.*, 2004). This seems not to be the case for Chile. A free-market Water Code was created in 1981 and Chile has become an example of the free-market approach to water law and economics (Bauer, 2005). Here water rights are not treated as private property, but as a fully marketable commodity (Bauer, 2005). Indeed, according to many economists and water experts in the World Bank, the Inter-American Development Bank and related institutions, the Chilean model of water markets and water resources management has been a success (Bauer, 2005). The free and unconditional grant of rights, without an *a priori* good purpose reason, has resulted in a monopoly of water ownership – many rivers owned by single power companies. In addition, the lack of an adequate measurement network of surface and underground water resources throughout the country has not allowed for appropriate studies and management of water resources. Since the implementation of the Water Code 27 years ago, there has been no competitive market, no concerned consumers, or improved water management. According to Bauer (2005), the Chilean State, because of its Constitution, does not have legal or institutional instruments to mediate. The task of managing water resources is, by the law, the concern of the water owners.

## Perspectives

Today there is a clear diagnostic of the problem. A few years ago, the Organization for Economic Co-operation and Development (OECD), although recognizing significant environmental improvements in Chile's environmental performance over the past decade, still urged for further efforts to protect the country's environment and natural resources in the face of rapid economic growth (OECD, 2005).

In general, there is an international consensus on the need to reach an integrative and adaptive water management and for holistic approaches to obtain it (Rogers, 2006; Pahl-Wostl, 2008). The so-called multiscale (Redman *et al*., 2004) or global scenarios (Cumming *et al*., 2005; Raskin, 2005) methods for environmental assessment can be regarded as holistic or multidisciplinary approaches. CASIMIR, as well PHABSIM and their variations, are inserted within these approaches, as especially appropriate for developing world regions (Tharme, 2003), such as Chile. However, the focus must be set on the context of each application. We spend a lot of our resources developing field techniques, technological tools and methodologies to assess our water resources, but it is essential to also assign resources to modify our policies, laws and institutions. It is not an easy matter because it is all interconnected.

Development and implementation of adaptive management approaches requires structural changes in water management regimes, but such changes are slow due to the inertia inherent in prevailing regimes (Pahl-Wostl, 2008). In the Chilean case, water resources management takes place in an institutional context that has been shaped by water markets, with strong private property rights, broad private economic freedoms, and weak government regulation (Bauer, 2005). It is not only the inertia, but also the political structure, which is the first and main issue to address in the national discussion.

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