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An Applied Assessment Model to Evaluate the Socioeconomic Impact of Water Quality Regulations in Chile

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Abstract In many developing countries, natural resource management is based on traditional, expert-based methods that often exclude a variety of stakeholders. This paper presents a conceptual model and methodology that represent a first step toward a more integrated evaluation and management of large basins. The main objective of this paper is to evaluate the socioeconomic impact of the application of secondary water quality regulations in the Aysén River Basin of Southern Chile. We employ the concept of physical, ecological and social (PHES)-system as a conceptual framework. Three indices based on this framework were created to characterize different aspects of the Aysén Basin: an environmental vulnerability index, an index of the water quality impact of the different economic sectors, and an index that quantifies the economic contribution of these sectors. Finally the three indices were combined as a measure of the socioeconomic impact of the proposed regulations in what we referred to as the 'applied assessment model'. Our results suggest that the applied regulations would have little socioeconomic impact on the Aysén Basin. Finally we discuss challenges to integrated watershed assessment in the context of developing countries.

Keywords PHES-system · Patagonia · Chile · Environmental regulations · Environmental vulnerability index · Integrated environmental assessment · Watershed management

1 Introduction

Natural resource management and the water quality regulatory framework in Chile are based on the paradigm of positivist science in which experts are the principal interpreters of ecological systems (Marin and Delgado 2004). The transition to other modes of defining and managing the relation between socioeconomic and bio-physical realms has begun, although in many places this process appears difficult and non-linear (Garces 2005; Volk

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et al. 2007; Chaves and Alipaz 2007). This paper embraces the movement toward integrated watershed management in Chile, however the methodologies used here are restricted by monitoring programs and regulatory processes that are still part of the aging paradigm.

In the developing world, state-sponsored monitoring and data collection programs are often inconsistent in breadth, temporal coverage and data quality. There is often a notable paucity of information and research on the effect of diffuse contamination sources on freshwater systems (Alfaro and Salazar 2005). In this context, the use of vulnerability indices and the synthesis of information from economic and ecological sub-systems via geographic information systems (GIS) can aid in decision-making and in identifying areas where more information and research is needed (e.g. Pandey et al. 2007). In this paper, we combine an environmental vulnerability index developed for the study system with spatially-explicit economic and contamination risk information. The results were used by regional authorities in the Chilean Patagonia for the development of secondary water quality regulations in the Aysén River Basin.

1.1 Chilean Regulatory Context

As part of the elaboration process of secondary water quality regulations in Chile (defined by the 1995 law DS 93), it is required that a study of the socioeconomic impact of the application of the proposed environmental regulations be carried out (CONAMA 1995). This study should “evaluate the costs and benefits for the population, ecosystems or species directly affected or protected [and] the costs and benefits to the emitters who are required to meet the regulation…” For other basins in Chile that have developed secondary water quality regulations, a cost–benefit analysis (CBA) has been applied. Previous studies have pointed to conceptual and methodological problems in the application of CBA in a regulatory context. (Munda 1996; Spash and Hanley 1995). Due to the lack of funds for additional data collection, the relevant guidelines indicate that the socioeconomic impact study is to be completed using existing information. For the Aysén Basin, the draft water quality regulations identified 15 sub-watersheds of interest and 18 water quality parameters (CONAMA 2005).

1.2 Conceptual Model: The Physical, Ecological and Social System

Due to the inadequacy of CBA for the evaluation of the potential socioeconomic impact of the secondary water quality regulations, a different methodology was needed. Because the socioeconomic impact of the regulations depends on ecological and physical characteristics intrinsic to the basin in consideration, we decided to use the concept of the physical, ecological and social (PHES)-system as a conceptual framework. The PHES-system is a spatially explicit conceptual model that includes the physical (geographic, edaphic), ecological (ecosystem processes, biodiversity) and socioeconomic components of a local system (Marin and Delgado 2004). The physical and temporal system limits, the internal components, and the interactions between components that are considered depend on the study questions and the observers involved in defining the PHES-system. This concept integrates two key concepts into the classic ecosystem concept: (1) that human societies are explicitly incorporated as components of the system, and (2) the ecological components considered are only those that are necessary to respond to the guiding questions (Pavlikakis and Tsihrintzis 2000; Delgado and Marín 2005).

With this conceptual framework in mind, the analysis was divided into three components: (1) *economic contribution*, where six economic sectors were ranked according to their economic contribution to the regional economy; (2) *water quality impact*, where the number of parameters likely affected by each economic activity was established in each sub-watershed; (3) *environmental vulnerability*, where a vulnerability index was created that took into account several geological, edaphic, and land use variables. Finally, the three indices developed for each of these components were combined spatially in a method we have termed: the applied socioeconomic assessment model.

1.3 Description of the Aysén Basin

The Aysén River Basin is located between 45°S and 46°S in the XI administrative region of Chile and covers an area of 11.456 Km^2 (Fig. 1). Due to tectonic subsidence, the Aysén basin crosses the main range of the Southern Andes and includes areas along the Argentine

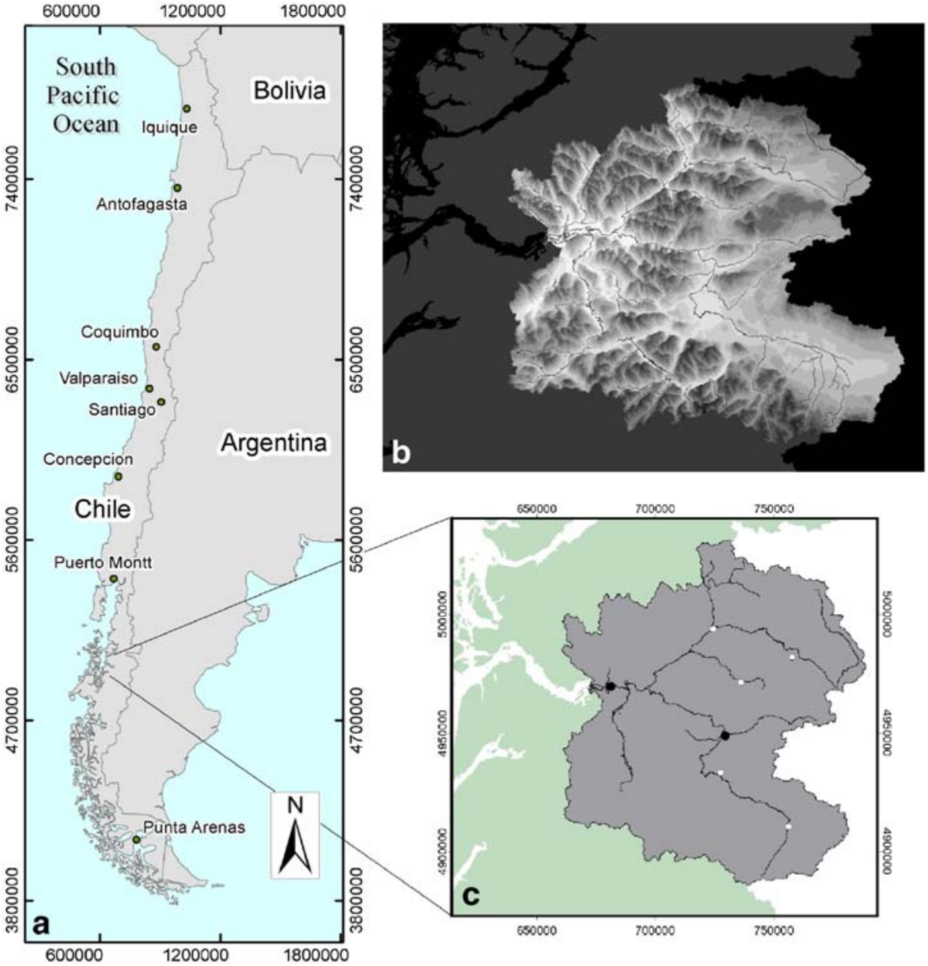

Fig. 1 **a** Location of the Aysén River Basin in Southern Chile. **b** 3D representation of the basin showing the principal landform patterns. **c** Map of the basin showing principal towns (*solid dots*) and villages (*open dots*). Coordinates correspond to UTM 18S

border that have relatively gentle relief (although overall the basin has an average slope of 17%). The main Andes range, with a high point of 2,227 m, produces a pronounced orographic precipitation pattern. Along the western edge, near the mouth of the Aysén River, the annual precipitation ranges between 3,000 and 4,000 mm. Near the regional capital of Coyhaique in the center of the basin, the annual precipitation is close to 1,300 mm. Finally, along the Argentine border, precipitation rates of 400–600 mm year^{-1} are common (IREN-CORFO 1979).

From a geological point of view, the soils of Aysén are quite young, having formed after the last glaciation (<10,000 years bp). Furthermore, the reoccurring landslides and pluviosity of the Andean range and the eolian erosion in the Eastern plateau have historically limited pedogenesis in a large part of the basin. During the first four decades of the XX century, the settlers of the basin (supported by the Chilean government) used fire as tool to clear forests for sheep and cattle. About 31% of the surface area of the basin was burned with the greatest impact concentrated in the valley bottoms (ECOManage 2005). In fact, the riparian zones throughout the basin have been among the most altered areas.

2 Materials and Methods

The analytic framework used here is simple: the socioeconomic impact of the secondary water quality regulations increases with increasing contribution of a given economic sector to the local economy and with increasing ecological impact of this sector. If an economic sector currently has a large impact on the ecology of the freshwater systems (before the application of the secondary norms), then the costs associated with meeting the new regulations will be high (possibly involving liquid waste treatment, new production technologies, or personnel training). The higher these costs, the more the application of new regulations will affect – either positively or negatively – numerous social variables within the basin that depend on the productivity of a given economic sector (eg. employment, regional productivity) (Telle and Larsson 2007). Furthermore, we consider that this framework is constrained by the bio-physical system of the basin, which is condensed into the environmental vulnerability index. Figure 2 presents a schematic of how the analytic framework is based on different components of the PHES-system.

Taking into consideration that: (1) the analysis performed integrates ecological and socioeconomic information; (2) this information is available at different spatial scales and in different formats; and (3) the results should be easily interpretable by a group of professionals from different backgrounds, we deemed that the use of GIS was necessary for data analysis and the presentation of results (Sugumaran 2002). Below we describe how each index was produced.

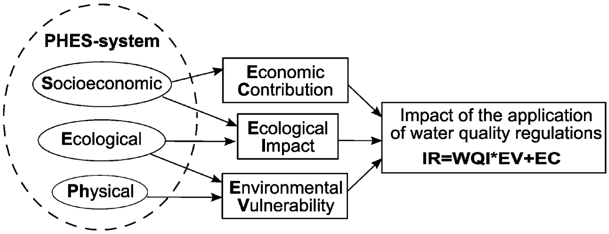

Fig. 2 Schematic of the analytic framework, based on the PHES-system

2.1 Economic Contribution

The economy of the Aysén Basin was divided into 7 sectors: mining, aquaculture, forestry, industry, agriculture, tourism and livestock. Each of these sectors was ranked using five economic variables giving each one the same weight:

1. Average of the annual percent variation in the GDP (gross domestic product) between 1996–2002.
2. Average participation (by sector) in the aggregated value generated by the regional economy in the period 1996–2002. (These first two indicators reflect the trajectory of each sector during this 6-year period).
3. Distribution (in percent) of the regional GDP for the year 2002 by sector.
4. Average participation of each sector in regional exports (The second two indicators reflect the current relative weight of each sector in the regional economy).
5. Percent of the working population within the Aysén Basin employed by each sector. (This indicator reflects the social importance of the economic sectors analyzed).

The results of this ranking are shown in Table 1.

2.2 Water Quality Impact

The current legal process for the creation of secondary water quality regulations in Chile is based on the monitoring of a series of parameters chosen to reflect the ecological status of the water bodies in question. In this study, we used the list of 18 parameters provided by CONAMA and created a binary matrix that considers whether each economic sector will or will not have an impact on these parameters. In order to create this matrix, we did a literature search and organized a Delphi panel of regional experts. The final ecological impact index for each economic sector was calculated as the sum of each column of the binary impact matrix, then the values where standarized between 1 and 10. The parameters affected by each economic sector are listed in Table 2.

2.3 Environmental Vulnerability Index

Vulnerability refers to the intrinsic characteristics of a physical–ecological system without taking into account the actual presence of contaminants. On the other hand, risk indexes combine the vulnerability of a system and a specific contamination scenario (Lobo-Ferreira and Cabal 1991). Taking into account the data available, relevant publications, and input from regional authorities, four factors were chosen to define the environmental vulnerability of the Aysén Basin (see Table 3):

1. *Erosion Potential*: Our research indicated that hydraulic erosion was an important factor to consider, especially in relation to the transport of nutrients, sediments, and fecal coliform bacteria to the rivers (IREN-CORFO 1979; Sharpley 2005). However, the data was not available to implement the full USLE (Universal Soil Loss Equation).

Table 1 Ranking of the seven economic sectors of the Aysén Basin, results are standardized to a 1–10 scale

Economic sectors	Agriculture	Livestock	Forestry	Tourism	Mining	Aquaculture	Industry
Ranking	1.16	1.17	1.23	1.76	3.22	10.00	1.27

Table 2 Binary ecological impact matrix produced by the Delphi panel

Parameters	Economic sectors					
	Mining	Aquaculture	Industry	Livestock	Forestry	Agriculture
Chemicals & physical						
Specific conductance		•	•	•	•	•
Dissolved oxygen		•	•	•	•	•
pH	•	•		•		
Sodium adsorption rate (SAR)			•			
Inorganic						
Chloride	•					
Sulfate	•	•	•			•
Metals						
Boron		•	•			
Copper	•	•	•			
Chromium	•	•	•			
Iron			•			
Manganese	•		•			
Molybdenum	•					
Nickel	•	•	•			
Selenium						
Zinc			•			
Aluminum						
Arsenic	•		•			
Microbiological						
Fecal coliform bacteria			•	•		
Total coliform bacteria		•	•	•		
Total score	10	9	14	5	2	3
Standardization	7.4	6.8	10.0	4.2	2.3	2.9

The rows show the 18 parameters that are to be monitored under the secondary norms. The columns show the six economic sectors considered in this analysis. (Tourism was not included because it was considered to have minimal potential impact on the parameter set)

Therefore we combined R and K factors from USLE with categorical erosion data from a regional soil survey (IREN-CORFO 1979).

2. *Leaching Potential*: We were confronted with an almost complete lack of information about groundwater dynamics within the Aysén Basin. However, considering that soils in the basin are often thin, sandy and overlay permeable fluvial and glacial material, nutrient transport via subterranean water flow is a distinct possibility (Hepp 1996). Therefore, the qualitative information about the drainage capacity of the regions' soils was represented numerically by using three values between one and ten (IREN-CORFO 1979).
3. *Dilution Factor*: We reasoned that the vulnerability would be higher in watersheds with little precipitation—where the capacity of river systems to dilute contaminants is diminished. We calculated the annual volume of water that would flow through each sub-watershed via the river system weighted by the area of the sub-watershed. The resultant values we termed 'dilution factor' and expressed in units of meters per year, although ultimately the inverse of these values was taken and standardized to a maximum of ten. For sub-watersheds that received discharge from adjacent watersheds, the dilution factor was modified to reflect the increase in contributing area.

Table 3 GIS layers included in the environmental vulnerability index

Coverage	Layers used	Source	Description
Erosion potential	Runoff (from soil survey)	IREN-CORFO (1979)	The potential of each soil type to contribute to runoff. Qualitative database
	R Factor—erosivity	ECOManage (2005)	R Factor—erosive force of rain
	K Factor—erodability	ECOManage (2005)	K Factor—susceptibility of the soil to hydraulic erosion
	Slope	ECOManage (2005)	Percent slope generated from DEM
Leaching potential	Drainage (from soil survey)	IREN-CORFO (1979)	The potential of each soil type to contribute to leaching. Qualitative database
Dilution factor	Precipitation/ watershed area	ECOManage (2005)	Represents the capacity of a river to dilute contamination

4. *Riparian Zone*: Riparian zones are well known for their erosion prevention and sediment trapping functions and are often referred to as buffer strips (Naiman et al. 2005). The retention of nutrients, bacteria and organic matter, and heavy metals by riparian zones could lower the vulnerability of rivers to serious environmental impact by industry or agricultural land-use. Using ArcView 3.3, we calculated the area of each land use within a 100 m buffer of the main rivers. The proportion of each land use was weighted by the buffer coefficients taken from the literature and then summed (Table 4).

The values of the first three layers were standardized to the range 1–10 in order to equalize their impact on the final values of the vulnerability index. For the riparian zone, values correspond to the nutrient and sediment removal function and range between 0 and 1. Lastly, because we considered that the riparian vegetation acts primarily on superficial water and sediment flows, we took the inverse of the riparian zone values and multiplied by the erosion potential factor. The following equation was then used to generate the environmental vulnerability index (EV):

$$EV = ES * ZR + FS + D \tag{1}$$

EV environmental vulnerability
ES runoff potential
FS leaching potential
ZR riparian zone
D dilution factor

Table 4 Buffer coefficients for different land uses

Land use in the riparian zone	Buffer coefficients for riparian zone
Native and old-growth forest	0.9
Plantations and forestry	0.6
Pasture and grassland	0.3
Agricultural land	0
Wetland	0.7
Without vegetation	0

Source: (Naiman et al. 2005; Wetzel 2001; Sharpley 2005)

This index reflects the vulnerability of fluvial systems to contamination via runoff and leaching, the ability of a river segment to dilute contaminants, and the capacity of the riparian vegetation to filter potential contaminants. The higher values represent higher environmental vulnerability and a greater probability that the thresholds for the regulated parameters would be exceeded. The EV values were further standardized between 0 and 1 for use in the regulation impact equation (Fig. 3a).

2.4 Sensitivity Analysis

The effect of the magnitude of the four factors in the environmental vulnerability index on the rank of the 15 subwatersheds was examined using a simple sensitivity analysis. The results are shown in Table 5. The use of equal weights for factors D, ES, y FS appears justified because the results are minimally sensitive to weights between 0.8 and 1.2 and only moderately sensitive to weights within the range 0.5–2.

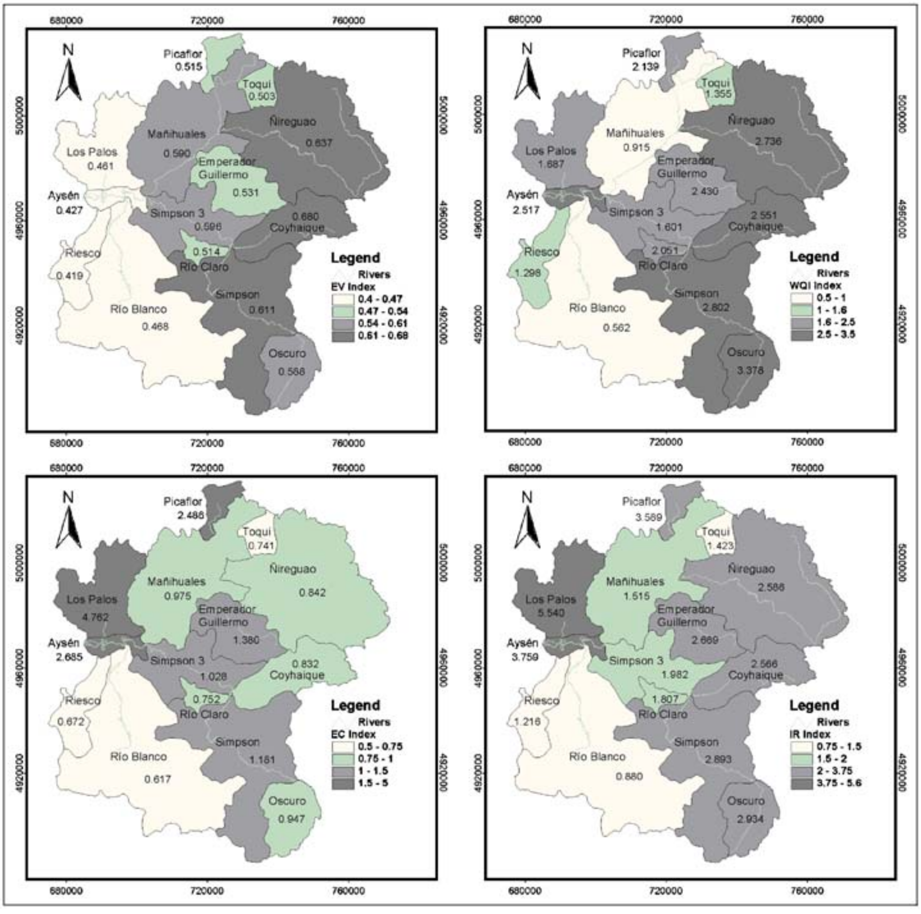

Fig. 3 Spatial representation of the indices developed in this study: environmental vulnerability (*EV*), economic contribution (*EC*), water quality index (*WQI*), and socioeconomic impact of new water quality regulations (*IR*). Coordinates correspond to UTM 18S

Table 5 Sensitivity analysis

Parameter	Value of parameter multiplied by			
	0.5 (%)	0.8 (%)	1.2 (%)	2 (%)
D	27	13	13	13
ES	20	7	0	47
FS	7	7	0	20
ZR	20	7	0	47

Percentage of sub-watersheds that change more than one rank with changes in factor weighting

2.5 Socioeconomic Impact of New Environmental Regulations

The socioeconomic impact of the application of the proposed water quality regulations is based on a sectoral ranking of economic contribution, water quality impact and the environmental impact index. It is calculated using Eq. 2:

$$IR = WQI * EV + EC \tag{2}$$

Where IR corresponds to the impact of the new environmental regulation, WQI is the water quality impact of each sector, EV is the environmental vulnerability index, and EC corresponds to the contribution of each sector to the economy of the basin.

2.6 Spatial Representation of Results

In order to represent the indices developed in this paper in a spatially-explicit manner, the use pressure (density) of each economic sector was calculated for each subbasin. When information was in the form of point locations (e.g. industrial and aquaculture discharges to the river network), the use pressure was calculated using Eq. 3:

$$(N_{is}/L_s[\mathrm{km}]) * WQI = WQI/\mathrm{km} \tag{3}$$

Where N_{is} is the number of plants or activities related to each economic sector i for each subbasin s, L_s is the length of the regulated river segment for each subbasin s in kilometers, and WQI is the water quality impact index.

When the available information was in the form of polygons (e.g. agricultural and livestock activities), the use pressure was calculated by dividing the area of each land-use, by the area of the subbasin using Eq. 4:

$$(A_{is}/A_s) * WQI = WQI/\mathrm{km}^2 \tag{4}$$

Where A_{is} corresponds to the area utilized by a given economic sector i en each subbasin s, and A_s is the total area of the subbasin s.

3 Results

The results of this study were presented as a set of maps produced in ArcView that permitted the easy visualization and comparison of the economic contribution of the different sectors, the environmental vulnerability index, the potential environmental impact of each sector, and finally the socioeconomic impact of the proposed water quality regulations (Fig. 3). It is important to realize that the values shown in the following graphics are meaningful for comparative purposes only.

In Fig. 4, the result of the analysis of the socioeconomic impact of the proposed water quality regulations is shown. This analysis places the different economic sectors in a two-dimensional space defined by EC and WQI. It is expected that those sectors located in the upper-right quadrant of the graph will be the most affected by the application of the water quality regulations. The significant socioeconomic contribution of these sectors to the basin would be threatened because of the large investment in cleaner production systems required to meet the new water quality regulations. Using the same logic, the economic sectors located in the lower-left quadrant of the graph should not be unduly affected by the implementation of new water quality regulations.

The classic view holds that the application of new environmental regulations hampers economic growth and productivity and thus should push the economic sectors in question in the direction of the arrow 1 in Fig. 4 (Christiansen and Haveman 1981; Jaffe et al. 1995). However, recent evidence shows that the inclusion of environmental variables in the determination of productivity and economic growth leads to a different dynamic: a positive relation between productivity and the application of environmental regulations (Telle and Larsson 2007; Porter 1991; Porter and van der Linde 1995). This implies sectoral movement parallel to the x-axis, or even with a negative slope, as indicated by arrows 2 and 3 in Fig. 4.

Taking into consideration the distribution of the different economic sectors in Fig. 4, and the possible paths of development after the application of the regulations (paths 1, 2, and 3), it appears that the socioeconomic impact of the new water quality regulations for the Aysén basin would be low.

4 Discussion

This study represents an attempt to synthesize information from different disciplinary realms (socioeconomic, geographic, and ecologic) for the evaluation of a PHES-system defined primarily by regional authorities. It might be considered a first step for Chile in moving from traditional CBA methods to methods based on a more holistic and constructivist vision of the study system. The fact that the methods used are inexpensive

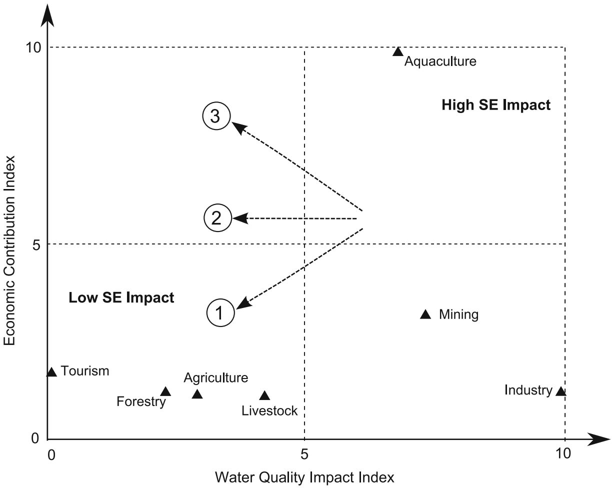

Fig. 4 Distribution of economic sectors according to the Water Quality Index and Economic Contribution Index. *Dashed arrows* represent possible sectoral trajectories after the application of new water quality regulations or norms

is an important consideration for developing countries. We also emphasize that the use of GIS-based indices makes good use of limited information and provide easily comprehensible results for managers and decision-makers.

In many developing countries like Chile, there is often a clash between the vision of rapid economic growth (where environmental concerns are of secondary or tertiary importance) and a more conservation-oriented vision of natural resource management. The utility of Fig. 4 is that it integrates information from socioeconomic and bio-physical realms and can aid government authorities and decision-makers to differentiate between economic sectors according to how they might be impacted by new regulations. Temporary exemptions might be made for sectors that fall in the upper right quadrant if industry-specific analyses indicate that a trajectory similar to Arrow 1 in Fig. 4. Perhaps a more pro-active approach would be to encourage the growth of sectors that could eventually reach the upper left quadrant, which represents a favorable balance between local economic contribution and water quality impact.

It is interesting compare the environmental vulnerability index developed here with similar indices in the literature. Eimers et al. (2000) describe an index that characterizes the likelihood that flows (with or without contaminants) from terrestrial areas will reach drinking water intakes; the following factors were considered: average annual precipitation, land-surface slope, land use, and groundwater flows. The WRASTIC index was created by the EPA and includes the following factors: wastewater discharges (W), recreational land use impacts (R), agricultural land use impacts (A), watershed area (S), transportation avenues (T), industrial land use impacts (I), vegetative ground cover (C) (NMED 2000). The first index is similar to the index used here in terms of factors considered and the use of raster layers to make spatially-explicit calculations. The WRASTIC index includes contamination sources and thus characterizes contamination risk, not just the intrinsic vulnerability of the physical–ecological system. These indices differentially weighted the different factors. In absence of information about the relative contribution of the different factors to the vulnerability of the Aysén PHES-system, we employed an equal weighting. A more integrative approach was taken by Chaves and Alipaz (2007) in deriving their ‘Watershed Sustainability Index’. Similar to the approach taken in this paper, the authors included spatially-explicit information about land cover and economic indicators. However, our focus on several bio-physical aspects of each sub-watershed allows us to indicate the vulnerability of the system to future development and pollution. An index based on measured water quality parameters does not necessarily capture how vulnerable or robust a physical–ecological system might be to human activities.

A further consideration is that the environmental vulnerability index incorporates average annual precipitation values. However, the examination of hydrographs for different sub-watersheds within the Aysén Basin indicates that the drier areas exhibit a marked seasonality in stream flow. This underlines the importance of understanding the behavior of the watershed of interest at different spatial and temporal scales (Sullivan and Meigh 2007). In the case of Aysén, it indicates that indices should be calculated on a seasonal basis or be represented as a range, so that managers will be aware of potential temporal dynamics.

Several obstacles and challenges to further conceptual and methodological change may be mentioned: (1) the lack of comprehensive and long-tem data sets; (2) the exclusion of various stakeholders in the definition of the PHES-system, (3) the rigidity of the regulatory process. On the other hand, regional authorities have expressed interested in different environmental evaluation methods and the concept of ecosystem management as a whole. Future work should provide methods for (1) a more inclusive citizen participation in PHES-system definition and management and (2) the improvement of government-funded data collection so that it complements and supports analysis of the main questions and problems identified by stakeholders.

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