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Stochastic hydro-economic model for groundwater quality management using Bayesian networks: El Salobral-Los Llanos aquifer system

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Abstract:

A strong normative development in Europe, including the Nitrate Directive (1991) and the Water Framework Directive (WFD) (2000), has been promulgated. The WFD states that all water bodies have to reach a good quantitative and chemical status by 2015. It is necessary to consider different objectives, often in conflict, for tackling a suitable assessment of the impacts generated by water policies aimed to reduce nitrate pollution in groundwater,. For that, an annual lumped probabilistic model based on Bayesian Networks (BNs) has been designed for hydro-economic modelling of groundwater quality control under uncertain conditions. The information introduced in the BN model comes from different sources such as previous groundwater flow and mass transport simulations, hydro-economic models, stakeholders´ and expert opinion, etc. The methodology was applied to the El Salobral-Los Llanos aquifer unit within the "Easter Mancha" groundwater body, which is one of the largest aquifers in Spain (7400 km^2), included in the Jucar River Basin. Over the past 30 years, socioeconomic development within the region has been mainly depending on intensive use of groundwater resources for irrigating crops. This has provoked a continuous groundwater level fall in the last 2 decades and significant streamflow depletion in the connected Jucar River. This BN model has proved to be a robust Decision Support System for helping water managers at the decision making process.

Keywords: Aquifers Management; Bayesian Networks; EU Water Framework Directive; Fertilizer standards; Nitrate pollution

Introduction

In the last 25 years, an important transformation from dry to irrigated lands has taken place in La Mancha, a vast region located in central Spain. This transformation has promoted the development of an intensive agriculture that represents one of the main factors in the current economic development of the region. In La Mancha Oriental System (MOS), more than 80,000 ha of lands equipped with modern technologies are currently irrigated, regarded as one of the most important in Spain, with most of these lands depending on groundwater (López-Fúster 2000; Ferrer and Gullón, 2004). Water extraction, which has steadily increased since the 1980s, together with an intense period of drought experienced in recent years, has resulted in a continued fall of water table levels with environmental consequences, such as the drying of an important section of the Júcar River in the summers of 1994 and 1995 (López-Fúster 2000; Estrela et al., 2004). An intense social, economic, political and environmental debate among farmers, the administration, and other stakeholders are currently trying to establish a sustainable management for the MOS. The Mancha Oriental System (MOS) is part of the Jucar River Basin (JRB) which was declared as EU Pilot Basin in 2002 for the implementation of the Water Framework Directive. Another significant issue in the area is the increase in groundwater nitrate pollution due to intensive farming and fertilizer use; nitrate concentrations have reached values of 125 mg/l (Moratalla et al., 2009). Nowadays modern tools combining remotely sensed data with geographic information systems are applied to help farmers in the region to irrigate according to the actual crop requirements (Martin de Santa Olalla et al., 2003), increasing water application efficiency. Although the Irrigation Advisory Services issue recommendations on the application of fertilizers and there are legal limits to the maximum fertilizer rate depending on the type of crops (as ‘‘nitrate vulnerable zone” according to the EU Nitrate Directive), this has not been enough to enforce EU standards regarding groundwater nitrate concentrations. In Europe a legal framework has been developed for groundwater protection. The 2000 EU Water Framework Directive (WFD) (Directive 2000/60/EC) requires that Member States take the necessary measures to ‘‘protect, enhance and restore all bodies of groundwater”. For groundwater bodies, the WFD objective is to reach a good groundwater status by 2015, which implies a good quantitative and chemical status. The Groundwater Directive (GWD), 2006/118/EC, specifies criteria for assessing the ‘‘good groundwater chemical status”. To meet the WFD–GWD environmental objectives, the most cost-effective programme of measures should be selected. This requirement leads to the assessment of the effectiveness of the proposed measures, but also to the analysis of the costs of water protection, and finally the benefits if potential exemptions based on cost-disproportionality are to be considered. The Drinking Water Directive (80/778/EEC) first, and the GWD later, have limited nitrate concentration in groundwater bodies to 50 mg/l. To control groundwater diffuse pollution is necessary to analyze and implement management decisions. Economic theory characterizes numerous mechanisms to control negative externalities, but these instruments cannot be easily implemented nor can their efficacy be clearly assessed (Shortle and Horan, 2001). Policy mechanisms for agricultural non-point pollution control include direct regulations (i.e., standards on the amount and use of potential pollutants and production practices) and pricing policy like taxes or subsidies. Taxes and subsidies can be applied directly to the polluting emissions through ‘‘effluent” taxes or based on emission proxies like polluting inputs ‘‘influent taxes” or subsidies). This paper describes the design and application of a stochastic hydroeconomic model embedded within a broader Decision Support System (DSS) based on Bayesian Networks aimed to analyze optimal groundwater pollution control from agriculture in the El Salobral-Los Llanos Domain (SLD) aquifer, a subdomain of the Mancha Oriental Aquifer.

Methods

The concept used for the treatment of uncertainty in Bayesian Networks (BNs) is that of conditional probability. A conditional probability statement is of the following type: if the variable B is in state b1, then from either evidence or experience, we know that as a result, the probability of the variable A being in state a1, is x. The notation for this statement is:

$$P\left(a1 \middle| b1\right) = x$$

The expression P(A|B) denotes a Conditional Probability Table (CPT) containing numbers P(ai|bj). This probability distribution of B, written as P(B), together with the values given in the CPT can be used to calculate the resulting (a posteriori) probability distribution for P(A). To obtain this distribution BNs use the fundamental rule, which can be written as:

$$P(B|A) = \frac{P(A|B)P(B)}{P(A)}$$

Here the term P(A,B) is an expression of the joint probability for the variables A and B. It consists of a table (CPT) of all possible configurations. Using the probability values for B and the values in the CPT the fundamental equation to calculate (it follows):

Bayes' rule can be used to obtain the Table P(B|A), which is the CPT showing the likely state of the variable B given the variable B, which is the reverse of the previous situation also called back propagation of probability. Under the Bayesian interpretation of probability, uncertainty measures the chance that something is false or wrong (measure of error). On this view, Bayes' theorem links the uncertainty of a probability model before and after observing the modelled system, describing mathematically how existing beliefs can be modified by the input of new evidence. A BN can become a DSS based on a probability theory that implements Bayes' rule (Jensen 1996, 2001; Pearl 1988). BNs have been used as DSS for many years in fields such as road safety, medicine, and artificial intelligence. During the last decade Bayesian networks (BNs) have become a worldwide modeling tool for dealing with environmental problems. Some reasons for that is that the tool is very flexible for linking the different factors that need to be considered in environmental decision making, allows for an explicit treatment of the uncertainties, and permits an active stakeholder participation, influencing in the design and content of the network and the data. During the last 5 years the BNs have been increasingly used to deal with problems framed within the Integrated Water Resources Management (IWRM) paradigm. . BNs have been used as a modeling tool for water planning and management of catchments in an overall way (Varis and Fraboulet-Jussila 2002; Said 2006; Castelletti and Soncini-Sessa, 2007), for integrated aquifers management (Henriksen and Barlebo 2007; Molina et al., 2010 and 2011), or from an agro-economic perspective (Carmona et al., 2011). Furthermore, BNs have been applied for the study and management of groundwater contamination (Farmani et al. 2009).

Case study

The methodology was applied to ‘‘El Salobral-Los Llanos Domain” (SLD), a hydrostructural domain in the southeast part of the Mancha Oriental System (Sanz, 2005; Sanz et al., 2009), extends over about 420 km^2 (Figure 1). The SLD supplies water to a population of about 5000. According to 2004 data (CHJ 2004), 80% of the land is agriculture (337 km^2), from which 100 km^2 are irrigated crops. The Castilla-La Mancha region has a Mediterranean climate, with continental degradation, noticeable fluctuations in daily and seasonal temperatures, a skewed distribution of scant rains, dry summers, with most rain occurring in spring and autumn. The mean summer temperature is about 22^{o}C and the mean winter temperature is about 6^{o}C. The mean annual precipitation is about 360 mm. The average groundwater recharge is estimated in 165 mm/year (CHJ 2008). From 1970 to 2002, the increase of irrigated crops has induced negative environmental impacts in the area; the groundwater table has decreased from 60 to 80 m and nitrate concentrations have increased, exceeding 54 mg/l in 2005 (Moratalla et al., 2009) exceeding the allowed concentration for human consumption of 50 mg/l (Drinking Water Directive, 80/778/EEC). Poor groundwater quality forced closure of some drinking water wells in 2003, later substituted by surface water from the Alarcon reservoir in the Jucar River (UCLM 2006). The policy of groundwater substitution by surface water of the Jucar River through the Tajo-Segura transfer channel has had a positive impact in reducing the quantitative pressure on the aquifer. All these events led to the declaration of the aquifer as a ‘‘nitrate vulnerable area” by the Castilla-La Mancha regional government (DOCM 1998). El Salobral-Los Llanos aquifer is formed mainly by two hydrogeological units. The deepest one is constituted by mid Jurassic dolostones and limestones that can reach 250 m in thickness. This unit has a mean transmissivity of 10000 m^2/day (Sanz 2005; Sanz et al., 2009). A detrital aquitard overlies it and reaches a maximum thickness of about 75 m. El Salobral-Los Llanos Domain is limited by low permeability boundaries which do not allow the lateral inflow of groundwater from/to the neighbouring domains.

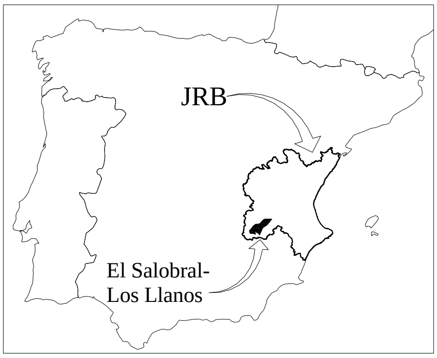

Figure 1. El Salobral-Los Llanos aquifer location

Methodology

A BN has been designed as a lumped probabilistic aquifer management DSS that takes into account the historical evolution of several variables. This DSS has been made following a methodology described in Figure 2. The data introduced in the BN model comes from different sources, depending on the subject (Figure 3). Consequently, this model combines very varied hydrogeological, economic, legal and ecological information (CHJ 2008; Peña-Haro et al., 2011; ITAP (2000-2010); JCRMO (2000-2010), CHJ 2008, 2011).

The BN model can be broadly divided into four main general parts: the hydrological, the economic, the intervention and water policies and the water quality (Figure 3). This paper is focused on the water quality part of the DSS. The model comprises qualitative and quantitative variables. The first ones are called labelled and the quantitative ones can be discretized in intervals, can be Boolean, when just two values are permitted (binary), or can adopt discrete values. The DSS model is driven by six water management policies that condition its functioning. This paper mainly addresses Fertilizer quotas and Fertilizer prices.

Fertilizer quotas

Irrigated crop development has led to significant consequences for regional groundwater flow and high nitrate concentrations in groundwater. The maximum groundwater nitrate concentrations in 1971 were about 29 mg/l and in 2005 it exceeded 54 mg/l. The highest nitrate concentration is located in the middle part of the aquifer where the irrigated agriculture area is located; 54.1 mg/l were recorded in the El Salobral well (Moratalla et al., 2009), exceeding the allowed concentration for human consumption of 50 mg/l (Drinking Water Directive, 80/778/EEC). All these events led to the declaration of the aquifer as a ‘‘nitrate vulnerable area by the Castilla-La Mancha regional government (DOCM 1998).

Two scenarios (Boolean node) have been considered with regards to the compliance of fertilizer quotas; the first scenario involves the compliance of the fertilizer quotas. In this scenario, we have also analyzed the behavior of the farmers against fertilizer prices. In this sense, the more expensive the fertilizer price, the lower the fertilizer application with a limit representing the official quotas. The second scenario is the situation when no quotas are considered; in this case, the application of fertilizer will be maximized, which has been found at 217 kg/ha. This value should be seen as the maximum value for the most demanding crop where higher fertilizer application rates do not produce an improvement in the crop yield.

Fertilizer Prices

The use of fertilizer prices or taxes has been proposed by some authors as a policy for controlling nitrate pollution. Peña-Haro et al. (2009) presented a hydro-economic modelling framework for determining the effect of fertilizer prices on groundwater nitrate concentration, and compared this policy with the use of fertilizer quotas. In this case, we have used the date from the historical control period 2001-2011 for the evolution of fertilizer prices. For that period, the average price has been estimated in 0.26 €/kg. Although this price has a direct impact on the amount of fertilizer applied and it is part of the agricultural production direct costs, the influence is found to be very small. This policy has been introduced in the BN model through the variable Fertilizer Prices as an interval node with a range from 0.18 to 0.38 €/kg discretized in 5 intervals. This relationship between Fertilizer application and Fertilizer Prices has been found to follow this expression by adjusting values obtained from the hydro-economic model (Peña-Haro et al. 2009):

$\wp$(Fertilizer application $\vert$ Fertilizer Prices)= -27.158•$\wp$(Fertilizer Price) + 219.09)

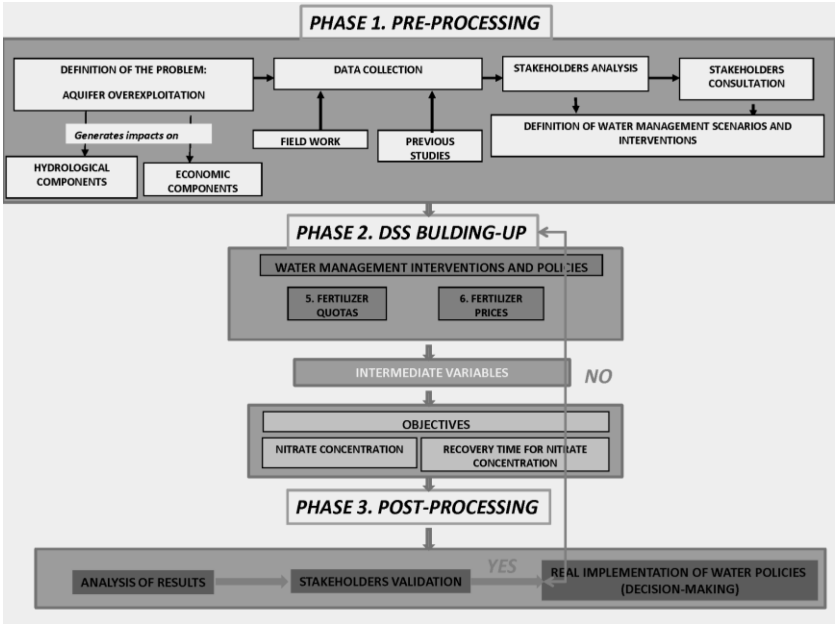

Figure 2. General Framework of the BN DSS for Mancha Oriental Aquifer

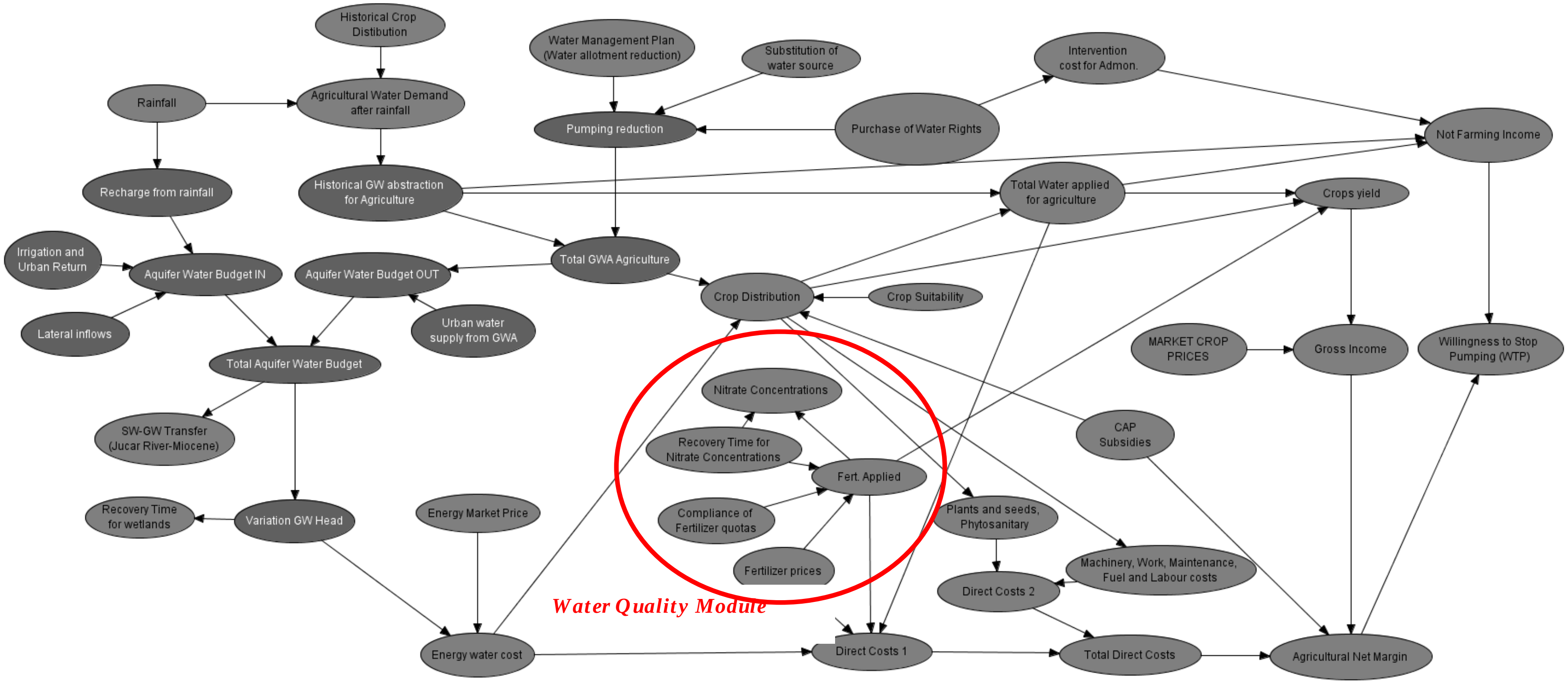

Figure 3. BN Network as a Decision Support System for Mancha Oriental Aquifer

5. RESULTS AND CONCLUSIONS

Scenario 1. Business As Usual BAU

This scenario represents the average historical situation with regards to the management of the Mancha Oriental Aquifer system. This scenario represents the baseline and reference for further scenarios. The comparative analysis between these scenarios represents the analysis of impacts for the study.

The fertilizer application, with an average value of 215 Kg/ha is directly affected by fertilizer prices, at an average price of 0.26 €/kg, as well as time horizon for the compliance of the chemical Status of the aquifer (50 mg of Nitrate/l). The average value for Nitrate concentration under this scenario is 61.4 mg Nitrate/l (Figure 4).

Furthermore, the most expected time horizon to be recovered is the year 2030 for all scenarios, unless the DSS is forced to reach that quality limit (50 mg of Nitrate/l) for a particular time horizon (Figure 5). In that case, the value of fertilizer applied is affected.

Scenario 2. Maximum Agricultural Net Margin.

This scenario is established by maximizing the probability distribution of the objective variable Agricultural Net Margin. This maximization has been made by assigning 100% chance to the upper state of the variable (20000-30000 €/ year•ha). The aforementioned back probability of BNs allows updating the whole BN model to the new situation of maximum Net Margin.

There are not significant impacts on the quality objectives of the BN model; in this sense, the average Nitrate concentration would be reduced in 6 mg/l respecting the BAU scenario but still outside the WFD limits of 50 mg/l (Figure 4); furthermore, the most expected time horizon to be recovered is also the year 2030 (Figure 5)

Scenario 3. Compliance of WFD Nitrate Concentrations

This scenario is established by applying the right level of fertilizer, prices and quotas, to let farmers using a certain amount of fertilizer so that nitrate concentration standards are met. This has been assessed for different recovery times (2015, 2021, 2027, 2033, 2039 and 2045) as defined by the WFD. Results probe that even with a full compliance of fertilizer quotas, it is not possible to reach the limit of 50 mg/l for the time horizon 2015 (Figure 4). Results also probe that, logically, the further the time horizon is established the less Nitrate Concentration can be obtained in groundwater and, consequently, the more chance to fulfil the EU requirement (Figure 4).

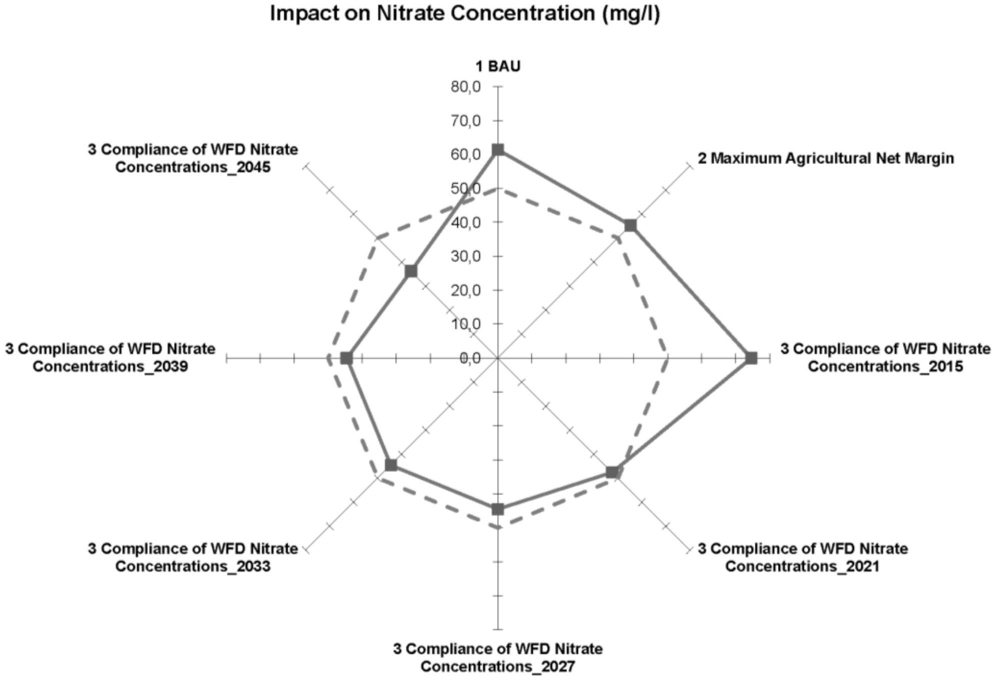

Figure 4. Impact on Nitrate concentration (mg/l) under different water management scenarios. Broken line : limit of 50 mg/l

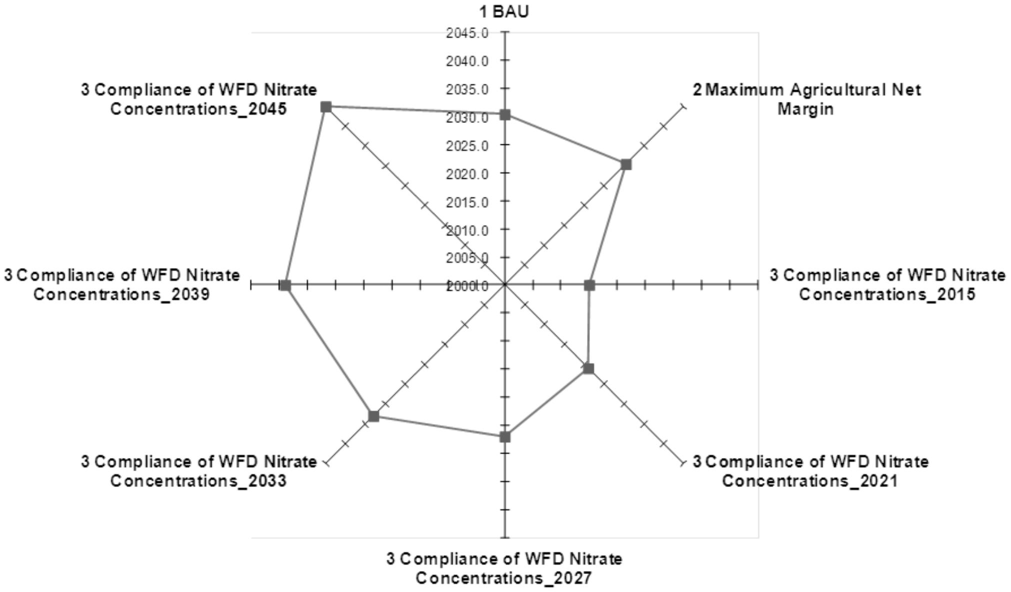

Figure 5. Comparative impacts of the scenarios on the variable Recovery Time for Nitrate Concentration (years)

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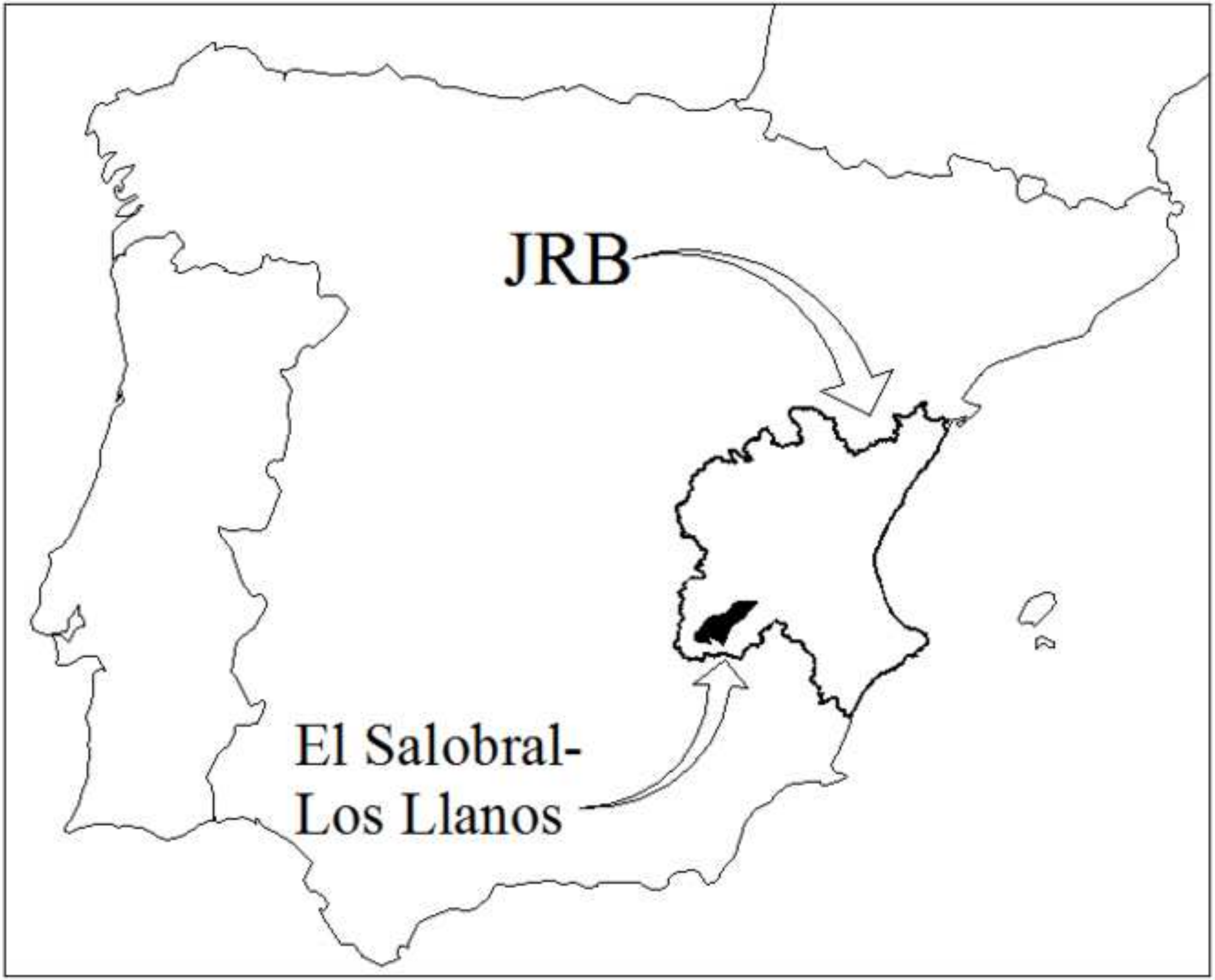
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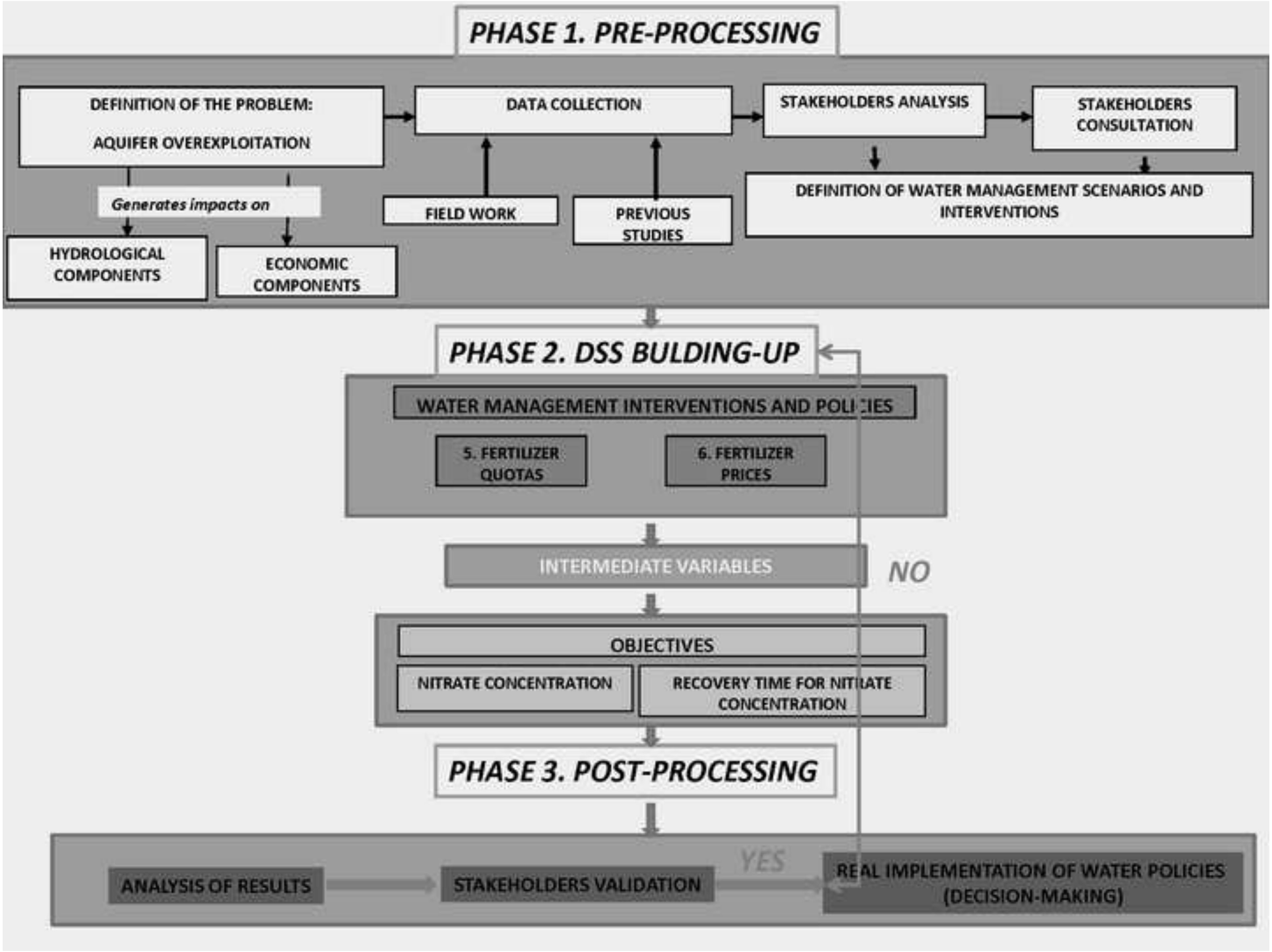
PHASE 1. PRE-PROCESSING
DEFINITION OF THE PROBLEM:
AQUIFER OVEREXPLOITATION
DATA COLLECTION
STAKEHOLDERS ANALYSIS
STAKEHOLDERS CONSULTATION
Generates impacts on
FIELD WORK
PREVIOUS STUDIES
DEFINITION OF WATER MANAGEMENT SCENARIOS AND INTERVENTIONS
HYDROLOGICAL COMPONENTS
ECONOMIC COMPONENTS
PHASE 2. DSS BULDING-UP
WATER MANAGEMENT INTERVENTIONS AND POLICIES
5. FERTILIZER QUOTAS
6. FERTILIZER PRICES
INTERMEDIATE VARIABLES
NO
OBJECTIVES
NITRATE CONCENTRATION
RECOVERY TIME FOR NITRATE CONCENTRATION
PHASE 3. POST-PROCESSING
ANALYSIS OF RESULTS
STAKEHOLDERS VALIDATION
YES
REAL IMPLEMENTATION OF WATER POLICIES (DECISION-MAKING)

Figure

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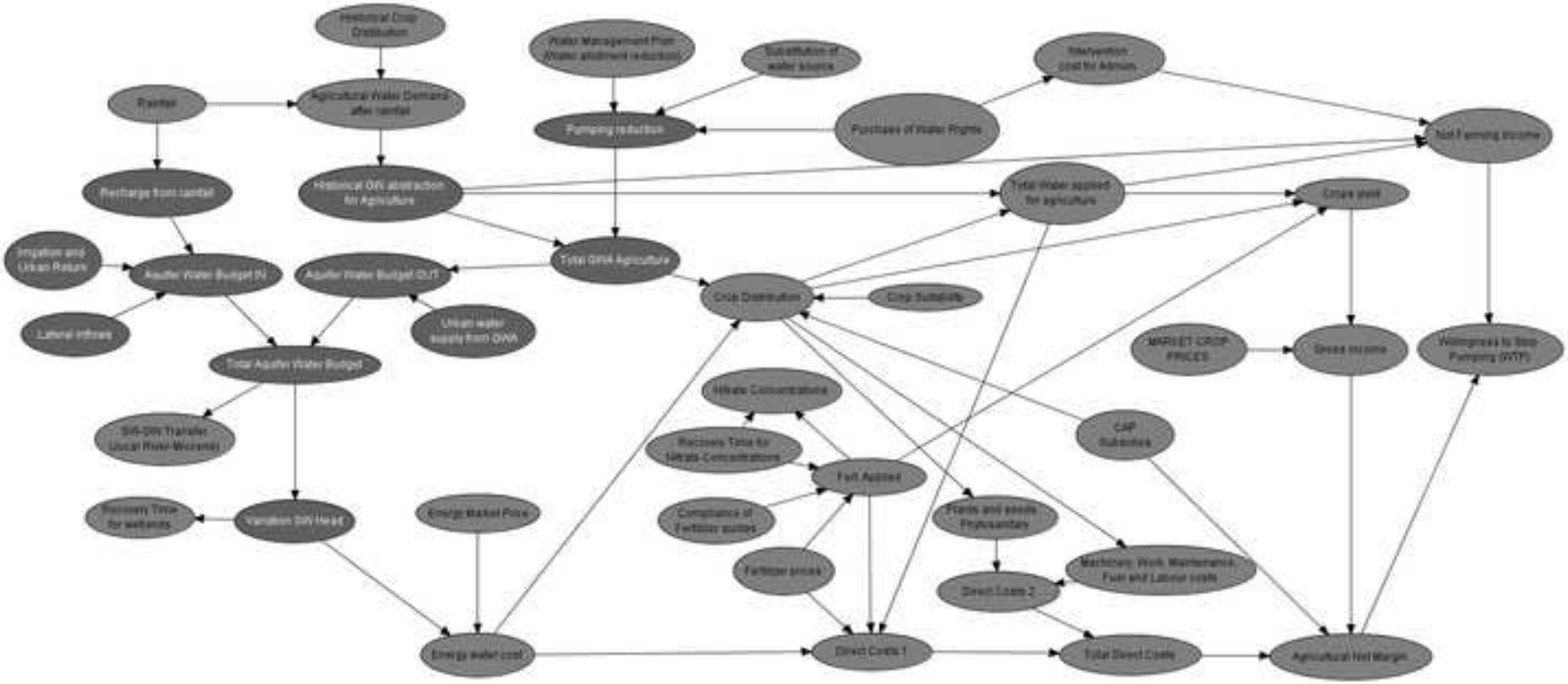

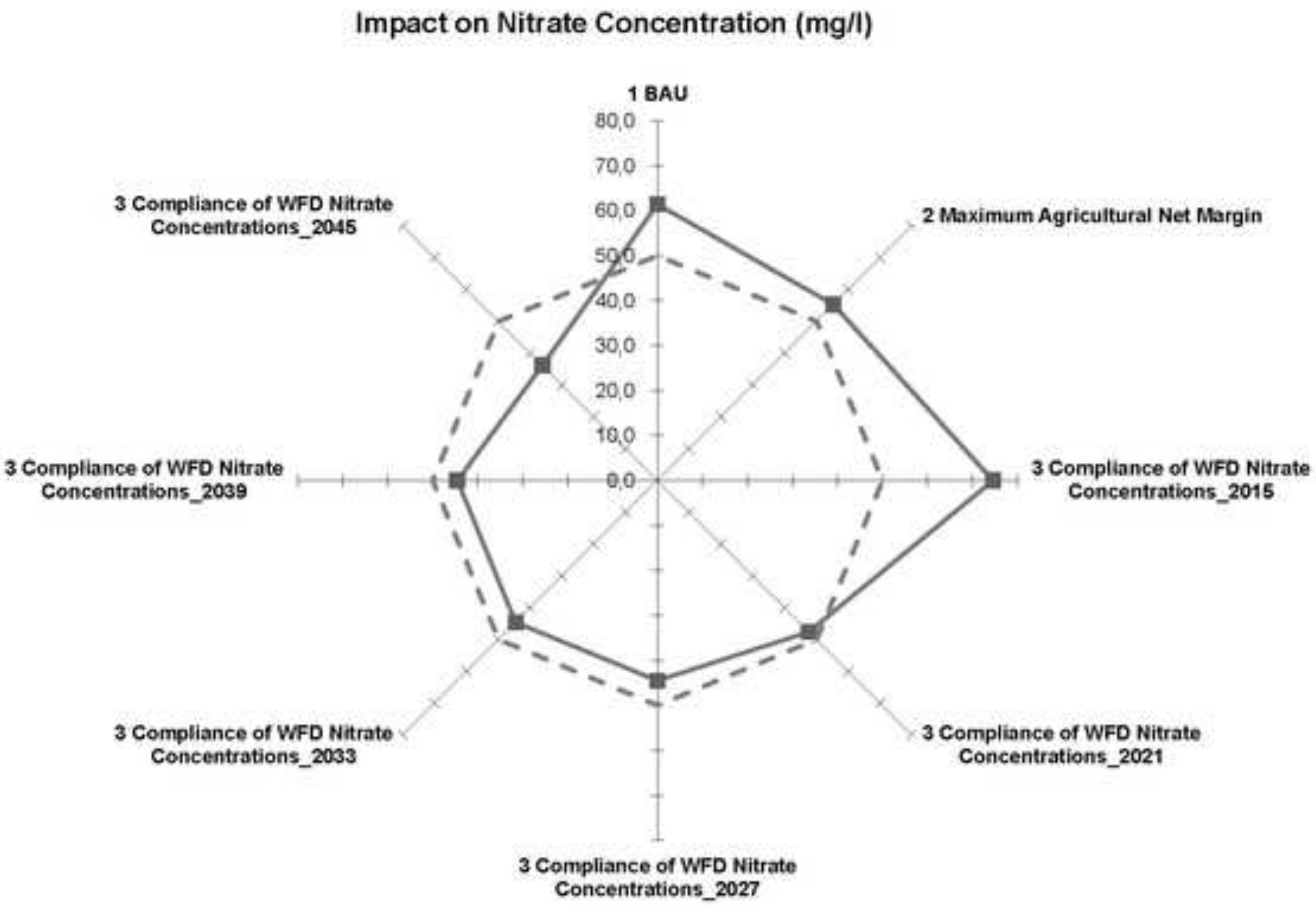
Impact on Nitrate Concentration (mg/l)
1 BAU
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70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
2 Maximum Agricultural Net Margin
3 Compliance of WFD Nitrate Concentrations_2015
3 Compliance of WFD Nitrate Concentrations_2021
3 Compliance of WFD Nitrate Concentrations_2027
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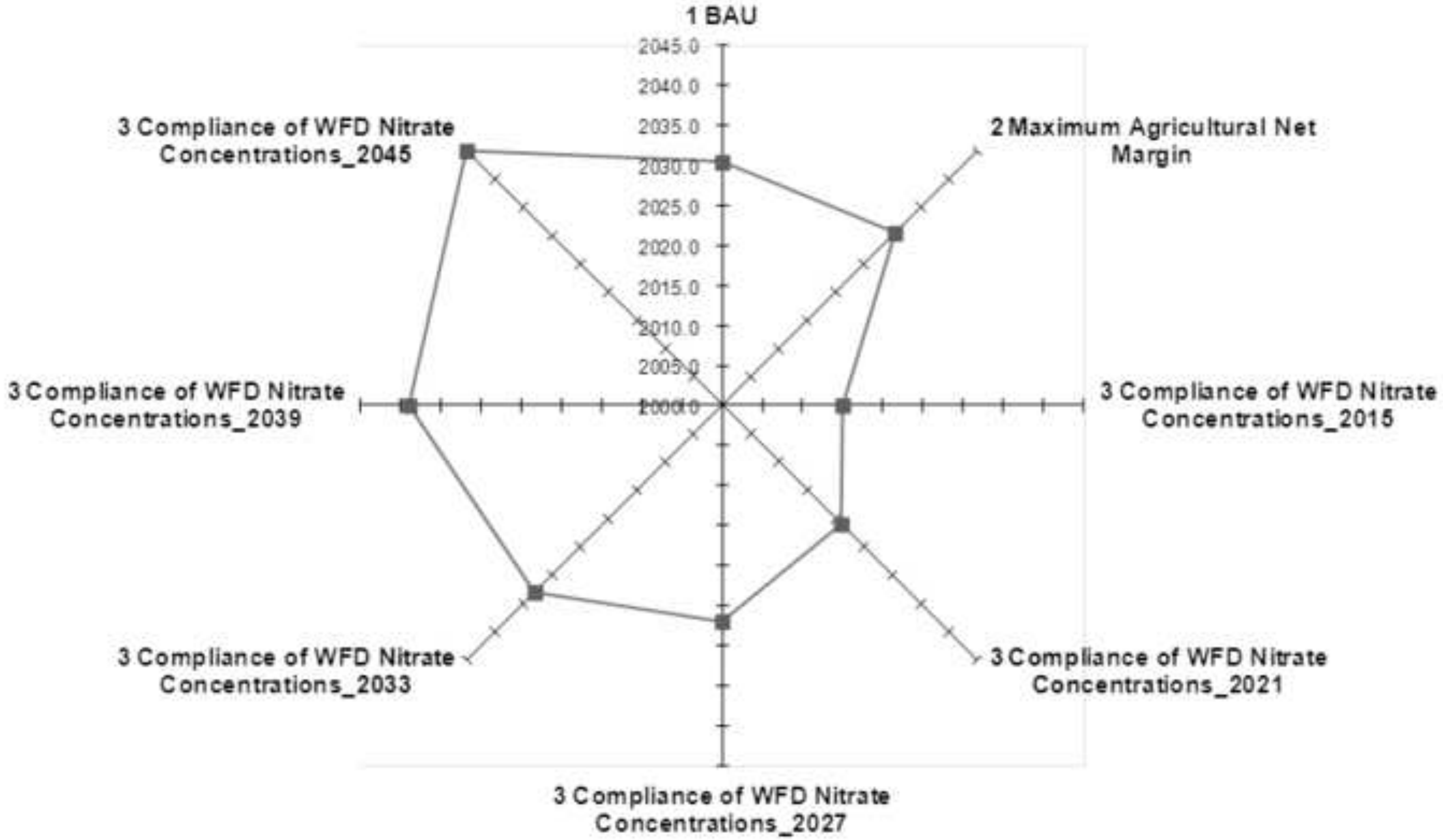
3 Compliance of WFD Nitrate Concentrations_2045


1 BAU
2045.0
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2 Maximum Agricultural Net Margin
3 Compliance of WFD Nitrate Concentrations_2015
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