Dynamic Bayesian Networks as a Decision Support Tool for assessing Climate Change impacts and adaptation of groundwater systems

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Abstract

Bayesian Networks (BNs) are powerful tools for assessing and predicting consequences of water management scenarios and uncertain drivers like climate change, integrating available scientific knowledge with the interests of the multiple stakeholders. However, among their major limitations, the non-transient treatment of the cause-effect relationship stands out. A Decision Support System (DSS) based on Dynamic Bayesian Networks (DBN) is proposed here aimed to palliate that limitation through time slicing technique. The DSS comprises several classes (Object-Oriented BN networks), especially designed for future five years length time steps (time slices), covering a total control period of 30 years (2070-2100). The DSS has been developed for assessing impacts generated by different Climate Change (CC) scenarios (generated from several Regional Climatic Model (RCM) under two emission scenarios, A1B y A2) in an aquifer system (Serral-Salinas) affected by intensive groundwater use over the last 30 years. A calibrated rainfall-runoff model was used to generate hydrological CC scenarios, and then a simulation groundwater flow model (MODFLOW) was employed in order to analyze the aquifer behaviour under CC conditions. Results obtained from both models were used as input for the DSS, considering rainfall, aquifer recharge, variation of piezometric levels and temporal evolution of aquifer storage as the main hydrological components of the aquifer system. Results show the evolution of the aquifer storage for each future time step under different climate change conditions and under controlled water management interventions. Furthermore, results also reveal the economic cost of the different land use scenarios under such CC conditions. The DBN application is seen to be effective in propagation of probabilities into the future to represent impacts generated by different hydrological scenarios. This type of applications would allow establishing adaptation strategies for aquifer systems as the CC comes into effect.

Key words: Dynamic Bayesian Networks, Climate Change, Decision Support Systems, Aquifers management, Adaptation, Groundwater Intensive Use

1. Introduction

The prediction of hydrological impacts generated by Climate Change is an appealing and emerging research area. However, research studies about climate change impacts on groundwater systems are still relatively scarce (Scibek et al., 2007; Roosmalen et al., 2007, Barron et al., 2010; Pulido-Velázquez et al., 2011; Green et al., 2011). Predicted changes on meteorological variables such as temperature or rainfall can provoke significant changes on aquifer recharge rates (Jyrkama and Sykesa, 2007), which can drive to important piezometric level variations. Consequently, water resource availability can be reduced, modifying stream-aquifer interaction, pumping cost rates and, eventually, leading to aquifers contamination. The aforementioned scarcity of research studies about the influence of Climate change on groundwater resources has been shown by the Intergovernmental Panel on Climate Change (IPCC) (Parry et al., 2007).

A methodology for assessing the potential impacts produced by Climate Change is proposed in this study. These impacts are made up of different nature and produce results on the different aspects involved in the management of aquifer systems. This analysis has been developed from the regional scenarios of Climate Change developed for Europe through the research projects Prudence (2004) and Ensembles (2009). Furthermore, the study is aimed to analyze the sensitivity of the results when a change in intensity in the climatology series (rainfall and temperature) takes place, but also in the frequency of the events. This aspect could be of great interest in arid and semi-arid regions due to the increment in rainfall variability and intensity that should be related with an increment in aquifer recharge rates, while greater variability in humid regions would decrease aquifer recharge rates as more water is lost to runoff (WRF, 2009).

In this study, a 30 year time series (2070-2100) is used as the period for the predictions of long-term Climate Change. The year 2070 is taken as the starting time point, assuming existing hydrological and economic conditions from 2011. The methodology has been applied to the overexploited Serral-Salinas aquifer (Molina et al., 2009). An exhaustive analysis of the potential hydrological impacts of Climate Change has been developed, considering two emission scenarios (A2 y A1B) resulting from the assemble of different models.

The paper is mainly aimed to show the utility of Dynamic Bayesian Networks as a modeling tool for analyzing long-term hydrological impacts on aquifers generated by Climate Change. Secondly, this paper is aimed to show the utility of this type of methodologies and tools for providing strategies of adaptation, especially for vulnerable aquifers systems mainly located in arid and semiarid regions.

The paper is structured as follows. First, the state of the art on Dynamic BNs related to water management and hydrology is is discussed, followed by the description of the case study. Then, the explanation of the methodology and the results drawn from this application are shown. Finally, two sections are dedicated for discussion and for conclusions respectively.

2. Tool and Methods: Dynamic Bayesian networks as a modeling tool for integrated water resources management

All real world systems change over time. Modeling their equilibrium states or ignoring change altogether, when it is sufficiently slow, can be enough for solving a wide spectrum of practical problems. In some cases, however, it is necessary to follow the change that the system is undergoing and introduce time as one of the model variables

This research is focused on models that belong to the class of probabilistic graphical models, with their two prominent members, Bayesian Networks (BNs) (Pearl, 1988) and dynamic Bayesian networks (DBNs) (Dean and Kanazawa, 1989). BNs are widely used practical tools for knowledge representation and reasoning under uncertainty in equilibrium systems.

A BN consists of three main elements; a set of variables that represent the factors relevant to a particular environmental system or problem; the relationships between these variables that quantify the links between variables and the set of conditional probability tables (CPTs) that quantify the links between variables and are used to calculate the state of nodes. The first two elements form a Bayesian Diagram and the addition of the third forms a full network.

BNs are probabilistic graphical models that offer compact representations of the joint probability distribution over sets of random variables. Formally, a BN is a pair (ζ, Θ), where ζ is an acyclic directed graph in which nodes represent random variables X1…..Xn and edges represent direct dependencies between pairs of variables. Θ represents the set of parameters that describes the probability distribution for each node Xi in ζ, conditional on its parents in ζ, i.e., P(Xi | Pa(Xi)). Often, the structure of the graph is given a causal interpretation, convenient from the point of view of knowledge engineering and user interfaces. BNs allow for computing probability distributions over subsets of their variables conditional on other subsets of observed variables.

A BN can be run as a standalone network, but it is possible to link together a number of networks to produce an Object-Oriented Bayesian Network (OOBN) model (Koller and Pfeffer, 1997). OOBNs are based on the Object-Oriented Programming paradigm (OOP) and thus adopt the same attributes used in OOP languages (Koller and Pfeffer, 1997; Molina et al., 2010; Weidl et al., 2005). OOP techniques and languages include features such as encapsulation, modularity, polymorphism, and inheritance (defined below) (Armstrong, 2006). The traditional programming approach tends to separate data from behaviour, whereas in OOP this separation is not necessary; the result is that real-world phenomena can be represented in a much more realistic way (Booch, 1996). As Wirth (2006) states ''this paradigm closely reflects the structure of systems in the real-world, and it is, therefore, well suited to model complex systems with complex behaviour''.

A conventional BN is a single system that is unable to receive or transmit information from outside the network. In contrast an OOBN represents a number of networks that can be linked together such that it is possible to transfer information from one to the other. The transfer of information is accomplished through the creation of output and input nodes in each network. These types of node are able to import and export information outside individual networks; these linking nodes are called interface nodes. Together the interface nodes form what in Object-Oriented programming terminology is known as an 'instance node', which in effect represents an 'instance' of another network (Fig. 1). In object-oriented terms each network becomes equivalent to a class. OOBNs are a hierarchical description (or model) of real-world problems that mirror the way in which humans conceptualize complex systems. To cope with complexity humans think in terms of hierarchies of different classes. When considering this problem the human mind will abstract selectively from this hierarchy of class types. The use of instance nodes provides support for working with these different levels of abstraction in the construction of object-oriented network models.

OOBNs can be utilized in two ways. First, they can be used for ‘‘time slicing’’ for problems in which processes take place over multiple time periods (Kjaerulff, 1995). This is how Dynamic BNs (DBNs) are built. Because BNs are not intended for transient analysis, time slicing provides one way to generate predictive simulations. This is the approach that has been adopted for the current study where networks representing different time domains are linked to outputs nodes to produce a dynamic model for the period 2070-2100. The second way in which OOBNs can be used is to form Sub- and Master-Networks, referred to here as an ‘‘organizational’’ application (Molina et al., 2010).

To summarize, an OOBN is a network that in addition to the usual network nodes, contains instance nodes. Instance nodes represent an instance or representation of another network, and provide the means by which networks are linked. The links are made via interface (input and output) nodes that are embedded within the instance nodes. Note that instance nodes should be viewed as a copy of the network of which it is an instance. Instance nodes only comprise a subset of the nodes (interface nodes) in the master network, while nodes that are not directly connected to other networks are said to be hidden.

DBNs extend them to time-dependent domains by introducing an explicit notion of time and influences that span over time (Nodelman and Horvitz, 2003). Most practical uses of DBNs involve temporal influences of the first order, i.e., influences between neighboring time steps. This choice is a convenient approximation influenced by existence of efficient algorithms for first order models and limitations of available tools.

After all, introducing higher order temporal influences may be costly in terms of the resulting computational complexity of inference, which is NP-hard even for static models. Limiting temporal influences to influences between neighboring states is equivalent to assuming that the only thing that matters in the future trajectory of the system is its current state. Many real world systems, however, have memory that spans beyond their current state

DBNs (Dean and Kanazawa, 1989) are an extension of BNs for modeling dynamic systems. The term dynamic means that the system's development is modeled over time and not that the model structure and its parameters change over time, even though the latter is theoretically possible. In a DBN, the state of a system at time t is represented by a set of random variables $X^t = X_1^t ....X_n^t$. The state at time t generally dependents on the states at previous k time steps. There is nothing in the theory that prevents k from being any number between 1 and t - k. When each state of the model only depends on the immediately preceding state (i.e., k = 1, the system is called first-order Markov (Markov Chains), often assumed in practice), we represent the transition distribution $P(X^t \mid X^{t-1})$. This can be done using a two-slice BN fragment (2TBN) β^t, which contains variables from X^t whose parents are variables from X^{t-1} and/or X^t, and variables from X^{t-1} without their parents. A first order DBN is often defined as a pair of BNs (β^0, $\beta^{\rightarrow}$) where β^0 represents the initial distribution $P(X^0)$, and $\beta^{\rightarrow}$ is a two time slice BN, that defines the transition distribution $P(X^t \mid X^{t-1})$ as follows:

$$P(X^t \mid X^{t-1}) = \prod_{i=1}^{n} P(X_i^t \mid P_a(X_i^t)) \qquad \textbf{(1)}$$

BNs can become a type of DSS based on a probability theory which implements Bayes' rule (Jensen, 1996, 2001; Pearl, 1988). A BN can also be defined as 'nodes' used to represent random variables that interact with others (Cain, 2001). Bayesian Networks have been used as decision support systems 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. It has been in the last 5 years when BNs have been increasingly used to deal with problems framed within the Integrated Water Resources Management (IWRM) paradigm. In this sense, BNs have been used for many purposes and from different perspectives that are explained as follows: BNs have been used as a modeling tool for water planning and management of catchments in an overall way (Varis and Fraboulet-Jussila, 2002; Castelletti and Soncini-Sessa, 2007), they have been also used for integrated aquifers management from the groundwater perspective from a hydraulic view (Henriksen and Barlebo, 2007; Molina et al., 2010 and 2011), or from an agroeconomic perspective (Carmona et al., 2011). Furthermore, BNs have been applied for Coastal Lake Assessment and Management (Ticehurst et al., 2008) or for the study and management of groundwater contamination (Farmani et al., 2009). BNs have been also useful for studies on water domestic supply (Bromley, 2005) or for the management and assessment of the hydrology on forest fires (Wisdom, 2011). Additionally, BNs are also applied in reservoirs management with operating rules for flooding control (Malekmohammadi, 2009), in Limnology with application in eutrophication models (Borsuk et al., 2004) or in management of fishing vessels (Little et al., 2004).

3. Case Study

The present study is focused on the Serral-Salinas aquifer, between Murcia and Alicante provinces (SE Spain; Fig. 1). This area is bounded to the east by the Alto and Medio Vinalopó (which belong to the province of Alicante), to the south by the Oriental and

Vega Alta de Segura (in Murcia), and to the north by the province of Albacete. The region experiences a mild Mediterranean climate. Water demand is at its highest in the summer months, when availability is lowest. In general, current demand greatly exceeds available supplies, and water is an issue of paramount importance. The main economic activity in the area is agriculture, which is characterized by its high profitability, partly due to the effective marketing of its products (Molina et al. 2009). From a hydrologic standpoint, the area has no permanent surface water bodies, and the only available water is that obtained from exploitation of the Serral-Salinas aquifer. The impacts of pumping from this aquifer extend to the regional scale, well beyond the boundaries of the aquifer area (Molina and García-Aróstegui 2006, 2007). Responsibilities for the monitoring of the aquifer are shared by the Júcar and Segura River Basin authorities. Finally, note that to date this region has been historically excluded of the large hydraulic projects that have been carried out in SE Spain like Tajo-Segura water transfer. The historical overexploitation of the Serral-Salinas aquifer has severely affected its hydraulic behavior. Mean renewable water resources in the aquifer are estimated to be about 5 Mm^3 per year, these being derived exclusively from the infiltration of precipitation onto permeable outcrops (Molina et al. 2009). Pumped abstraction can only be estimated indirectly, as very few boreholes are fitted with volumetric control meters. In this study, the volume and rate of water abstraction is estimated by studying bibliographic records and from field surveys of the main water users. Consequently, the average rate of exploitation over the last 10 years amounts to some 18 Mm^3 per year.

The water budget calculated from the above data is clearly negative, which is evidenced as a notable consumption of water reserves (−13 Mm^3 per year and an accumulated drawdown exceeding 350 Mm^3). In some parts, groundwater heads have fallen by up to

200 m over a period of 30 years with a depletion rate over 10 m/year in some sectors of the aquifers (Fig. 1).

All of this has raised the cost of water extraction, and has induced negative effects on the related environment such the drying up of springs that represented the eastern aquifer sector natural discharge. On the other hand, it must also be recognized that this intensive exploitation has produced positive effects too, by increasing agricultural income, which in turn has enabled demographic stability or even an increase in some regions, as well as other socio-economic benefits. Recently measures have been proposed aimed to alleviate the water problems of the region and specifically, aimed to alleviate the imbalance of aquifer water budgets MIMAM (2001 and 2004). Among others, stands out the import of domestic water through a pipe from the Segura Basin headwaters reservoirs to supply the main cities (Jumilla and Yecla) that have an urban demand of about 6 Mm^3 per year. This intervention has been stopped or slowed down and only Jumilla has asked for the inclusion on the Mancomunidad de los Canales del Taibilla (MCT). Another important proposed intervention is the consideration of replacing groundwater extraction rights by water rights from desalination. However, the possibility of returning the aquifers to their original condition have yet to be assessed, as well as the required time scales or the costs and benefits involved.

Figure 1. Location of Case Study.

4. Methodology

The methodology comprises two main branches (Fig. 2). On one hand the Climate Change procedure made up of several phases described in the next section. On the other hand, the land use change procedure described in section 4.2. The outputs from both methodologies become inputs to the Non-transient Bayesian network model. Then, once this model is calibrated and tested, is fragmented in different time steps. Thus, the previous model becomes a Dynamic Bayesian Network which is able to analyze the temporal evolution of the model for that period.

Figure 2. General Methodology

4.1 Climate Change procedure

Future groundwater recharge scenarios for the period 2071-2100 under 2 emission scenarios [A2, A1B] were generated with the information available about several CRM simulations previously developed in the European PRUDENCE [2004] and ENSEMBLES [2009] projects. The approach involves generating future rainfall and temperature series by modifying mean and standard deviation of the historical series in accordance with the estimation of the increment or decrement produced by climate change (obtained from the differences between the control and future series provided by Climate Regional Models (CRM). The corresponding future groundwater recharge series is generated by simulating the new daily rainfall and temperature series through a calibrated soil water balance model (Samper et al., 1999). We have also developed a multi-objective analysis to propose an ensemble predictions by giving more value to the information obtained from the best calibrated models (those that provide better approximations to the historical period). The scheme of the methodology is summarized in Figure 3.

Figure 3. Climate change methodology

This paper is not aimed to describe in detail the different steps of the methodology to generate the future climate change scenarios (the reader is referred to Pulido-Velazquez et al., 2011) (the objective of this paper is to show the applicability and utility of Dynamic Bayesian Networks to analyze future climate change impact scenarios).

Therefore, in this section we will just show the scenarios finally obtained that will be used as input in the Bayesian Network.

Figure 4 shows the future recharge obtained for the period 2071-2100 with an ensemble of 5 RCM for the scenario A2 and for the scenario A1B. This ensemble of predictions estimates a reduction in mean annual recharge of 14% for the A2 scenario and 57.7% in the A1B scenario derived from the infiltration of precipitation onto permeable outcrops.

Figure 4. Expected and Historical annual Series for Rainfall and Recharge. Figure 4a: Scenario A1B; Figure 4b: Scenario A2

Natural recharge from rainfall infiltration was the only source of recharge considered and it was estimated by using the Visual Balan model (Samper et al., 1999) (Molina et al., 2010) which is a soil water balance model that consider the main parameters of the root zone: a root zone thickness of 0.5 m; total porosity (8%), wilting point (3%), field capacity (7%), permeability (0.08 m/day) and a Useful Water Reserve (UWR) rate of 20 mm. Recharge was evaluated from daily hydrometeorologic (Rainfall and Temperature) records from Ensemble data series under both CC scenarios (A1b and A2) from 30 years period of Climate Change (2070-2100). The model calibration was done by comparing observed and simulated groundwater heads of a neighbor aquifer (El Cantal) that remains unexploited and consequently, it is behaving in natural regime, so the piezometric level variations uniquely are due to natural recharge impulses. Hydraulic parameters were obtained from the literature and pumping tests, in the absence of sufficient data, hydraulic conductivity values were assumed to be isotropic (Table 4; Kx = Ky = Kz). The assumption of equal K in all directions is not realistic, however, due to the calibration method and shifting layers of aquitards/aquifers this may not have importance in the present case. The considered aquifer area is 65.5 km^2 with a storage coefficient of 0.02 an initial aquifer level of 475 m. This recharge data were introduced in a calibrated Groundwater Flow Model (Modflow) (Molina et al., 2010), based on an existing hydrogeological conceptual model. Regarding the aquifer geometry, the aquifer was represented by up to 17 layers in the model; these layers represent the various lithological units of the Serral-Salinas aquifer. The geometry and nature of the aquifer was obtained through the interpretation of over 100 borehole logs and geological sections, as well as the results of geophysical studies. Topography details were taken from digital maps at a scale 1:25,000. Spatially, the model defined the aquifer within a finite difference grid covering an area of approximately 690 km^2. The grid contained 2,760 cells (60 horizontal, 46 vertical) with a cell size of 500 × 500 m. For the transient version of the model calibration was made using data from October 1956 to September 2006 (50 years) at monthly time steps. Boundary conditions were defined by two types (no flow and drain). No flow conditions (Cheng and Cheng 2005) have been applied to the base substrate, as well as to the main boundaries of the model. On the other hand, drain or flow conditions were used to simulate discharge through the Salinas' spring in a non-influenced (natural) regime. Further explanation of this GFH may found at Molina et al. 2010.

The output from this GFM can be seen in figure 5 in the form of the evolution of piezometric levels. Accordingly with the recharge rates for CC scenarios A1B and A2 the water table depletion is larger under scenario A1B where a lower rainfall and recharge rates take place. Historical evolution of piezometric levels follows an intermediate tendency between CC A1B and A2 scenarios.

Figure 5. Piezometric levels Evolution under Climate Change scenarios in representative boreholes. Historical, A1B and A2

4.2 Land uses changes procedure

The previous Serral-Salinas aquifer OOBN model (Molina et al., 2010) did not deal with Climate or Land Use changes. In order to deal with expected changes in land uses (section 4.3), specifically in the irrigated area, the original network has been expanded with new variables such as “Irrigated Area Scenarios”, “New Agricultural Net Profit”, “New Water Abstraction for Irrigation”, “New Water Abstraction”, “New Aquifer Water Budget” and, “New Natural discharge recovery (years)”.

The new variable “Irrigated Area Scenarios” allows considering four scenarios in the analysis, depending on the increasing or reduction of the current irrigated area. These scenarios are defined as 10% increase, 20% increase, 10% decreasing and 20% decreasing of the current (baseline) Irrigated area. Obviously, the profits coming from the agriculture will change depending on the land use scenarios.

4.3 Stationary or time aggregated CC-BN modeling

Two DBNs DSS have been developed, one for each climate change scenario (A1B y A2) previously described in the previous part of the methodology. These models have identical structure but differ in the information provided by the soil water balance model, introduced in the DBN model as the relationship between rainfall and the corresponding aquifer recharge.

The BN or class used to modelyze the aquifer system is divided into two main sections; one deals with the hydrology, the other with social and economic variables (Fig. 6). Figure 6 and Table 1 reveal all the 38 variables introduced in the aquifer network (Class 1). The variables of the second class, the module that implement the dynamic process, are shown in Figure 7 and Table 2. The BN model of Molina et al. (2011) has been modified for incorporating the Climate and Land use changes conditions. The reader is referred to the cited previous studies to find a deeper explanation of those invariant parts of the BN model.

The probability distributions for the hydrological variables, under each CC scenario, were derived from the calibrated soil water balance model and from the previous hydrological flow model developed for this research. The CPTs for hydrological variables were entered automatically via the Learning Wizard module of the Hugin software (HUGIN 2011). This module automatically discretizes data by transforming continuous distributions into discrete counterparts (i.e. get into groups or intervals with its resultant probability). Automatically entered hydrological variables were “Rainfall”, and “Recharge”. Then, the variable “Water abstraction” is coming from the historical pumping data for agricultural and domestic uses and finally, “Annual Water Budget” is calculated as the difference between Recharge to the aquifer and Water abstraction.

The socioeconomic variables were defined in agreement with the stakeholders based on two general meetings. An agro-economic simulation model was used to define these main variables: “Crop distribution”, “Market Trend”, “Variable Costs” “Agricultural Net Profit”, and “Total number of Agricultural Direct Employment”. Then, from an economic study of non-agricultural activities in which the land market price is the key factor (“Sale of land” variable) we derive the following variables: “Total Income from alternative activities” ,“Sale of land for Tourist activities”,” Income from sale land”, “Sale Land Offer Price (Rustic)”and finally ” Total Income” that is the sum of both ways. For socioeconomic variables, the CPTs were also derived in two ways; firstly, by using an agro economic simulation model of the irrigated area; secondly, non-agricultural variables were defined by the economic study of land and properties.

Variables are divided into five groups according to their function in the network (Table 1). (1) Parent nodes: these are not subject to changes in the states of other nodes; in this study most parents represent proposed strategies that may or may not be implemented; (2) Intervention actions: these are actions that follow from the strategies selected through the parent nodes; (3) Intermediate variables: represent simulation of the intermediate processes that take place between action and objective; (4) Partial objectives: intermediate objectives that contribute toward final objectives; (5) Final objectives: represent the variables that are of key importance to the system; it is the states of these variables that are of most concern to stakeholders. Here, two variables have been added, representing the number of year that the aquifer would take to be restored its natural regime. One variable "Natural discharge recovery (years)", dealing just with Climate Change Conditions and second one "New Natural discharge recovery (years)" including also the effects of Land Uses change.

Finally, 'interface' variables in the system include "Agricultural Net Profit", "New Agricultural Net Profit", "Aquifer Water Budget" and "New Aquifer Water Budget", connect to the second class or network which represents the dynamic module (Section 4.4, Table 2).

Figure 6. Stationary BN DSS Structure

GROUP	NAME	EXPLANATION	STATES CC SCENARIO A1B	STATES CC SCENARIO A2
1. Parents	Rainfall	Annual Average Rainfall under CC scenario (mm/year)	45 – 156; 156 - 267; 267 - 378; 378 - 489; 489 - 600	80-176; 176-272; 272-368; 368-464; 464-560
	*HDRC (Coercive Tools)	% Reduction of Agriculture Water Demand Applying Coercive Tools	No Reduction; 0-25; 25-50; >50	No Reduction; 0-25; 25-50; >50
	*HDRV (Incentive Tools)	% Reduction of Agriculture Water Demand Applying Incentive Tools	No Reduction; 0-25; 25-50; >50	No Reduction; 0-25; 25-50; >50
	*External irrigation water resource income TJV	Mm3 y-1	0; 0-5; 5-10	0; 0-5; 5-10
	*External irrigation water resource income Desalinitation	Mm3 y-1	0; 0-5; 5-10	0; 0-5; 5-10
	*Purchase of WR Offer price	€/ha	3000-6000; 6000-9000; 9000-12000	3000-6000; 6000-9000; 9000-12000
	*External domestic water resource income JV Transfer	Boolean (False/True)	False; True	False; True
	*External domestic water resource income TS Transfer	Boolean (Y/N)	False; True	False; True
	*Reduction in water concession or quotas	% Reduction in total water quotas assigned	0; 0-25; 25-50; 50-100	0; 0-25; 25-50; 50-100
	Sale Land OfferPrice (Rustic)	€/ha	10000-20000; 20000-50000; >50000	10000-20000; 20000-50000; >50000
2. Intervention Action	Price of External Irrigation Water Resource	€/m^3	0.2-0.4; 0.4-0.6; 0.6-0.8	0.2-0.4; 0.4-0.6; 0.6-0.8
	External Irrigation water resource Income or Availability	Mm3 y-1	0; 0-5: 5-10	0; 0-5: 5-10
	Purchase of water rights	% Water Rights sold by the farmers	0; 0-25; 25-50; 50-100	0; 0-25; 25-50; 50-100
	Sale of land for Tourist activities	% Irrigated Crop Area sold	0-33; 33-66; 66-100	0-33; 33-66; 66-100
	Income from sale land	€/ha	0-1000; 1000-5000; 5000-10000; 10000-20000	0-1000; 1000-5000; 5000-10000; 10000-20000
3. Intermediate Nodes	Recharge (mm/year) ENSAMBLE	Annual Average Recharge from rainfall under CC scenario (mm/year)	0 – 32; 32 - 64; 64 – 96 ;96 - 128; 128 - 160	0-30; 30-60; 60-90; 90-120; 120-150
	Recharge (Mm3/year) ENSAMBLE	Annual Average Recharge from rainfall under CC scenario (Mm3/year)	0-2; 2-4; 4-6; 6-8; 8-10; 10-12	0-2; 2-4; 4-6; 6-8; 8-10; 10-12
	Irrigation Water Need After Rainfall	Mm3 y-1	<7.5; 7.5-10; >10	<7.5; 7.5-10; >10
	Water irrigated abstraction 1	Mm3 y-1	0-5; 5-10; 10-15; 15-20	0-5; 5-10; 10-15; 15-20
	Water irrigated abstraction 2	Mm3 y-1	0-5; 5-10; 10-15; 15-20	0-5; 5-10; 10-15; 15-20
	Water irrigated abstraction 3	Mm3 y-1	0-5; 5-10; 10-15; 15-20	0-5; 5-10; 10-15; 15-20
	Water domestic abstraction	Binary (Current Abstraction/None)	None; Current Abstraction	None; Current Abstraction
	New Water Abstraction for Irrigation 1	Mm3 y-1	0-5; 5-10; 10-15; 15-20; 20-25; 25-30	0-5; 5-10; 10-15; 15-20; 20-25; 25-30
	Water abstraction	Mm3 y-1	0-5; 5-10; 10-15; 15-20	0-5; 5-10; 10-15; 15-20
	New Water abstraction	Mm3 y-1	0-5; 5-10; 10-15; 15-20; 2-25; 25-30; 30-35: 35-40	0-5; 5-10; 10-15; 15-20; 2-25; 25-30; 30-35: 35-40
	Annual Water Budget	Mm3 y-1	-30--25; -25--20; -20--15; -15--10; -1--5; -5-0; 0-5; 5-10; 10-15	-30--25; -25--20; -20--15; -15--10; -1--5; -5-0; 0-5; 5-10; 10-15
	New Aquifer Water Budget	Mm3 y-1	-40--35; -35--30;-30--25; -25--20; -20--15; -15--10; -1--5; -5-0; 0-5; 5-10; 10-15	-40--35; -35--30;-30--25; -25--20; -20--15; -15--10; -1--5; -5-0; 0-5; 5-10; 10-15
	Crop distribution	% Crop surface	D1;D2;D3;D4	D1;D2;D3;D4
	Current Dotation for Irrigation	m^{3}ha^{-1}	0; 1073; 2243.51; 4850.5	0; 1073; 2243.51; 4850.5
	IRRIGATED AREA SCENARIOS	% Changes in the irrigated area based on Baseline Irrigated Area=5000 ha	-0.2; -0.1; 0; 0.1; 0.2	-0.2; -0.1; 0; 0.1; 0.2
	Market Trend	Trend of crops prices in the last 5 years	Strong decrease prices; Light decrease prices; Steady; Light Increase price; Strong increase prices	Strong decrease prices; Light decrease prices; Steady; Light Increase price; Strong increase prices
	Variable Costs	% Increasing above Retail Price Index (RPI) RPI: 4,5 %	No increasing; 5; 10	No increasing; 5; 10
4. Partial Objectives	Total Income from alternative activities	€ ha-1	0-1000; 1000-5000; 5000-10000; 10000-20000	0-1000; 1000-5000; 5000-10000; 10000-20000
	Agricultural Net Profit	€ ha-1	0-1000; 1000-5000; 5000-10000	0-1000; 1000-5000; 5000-10000
	Agricultural Net Profit	M €	0-10; 10-20; 20-30; 30-40; 40-50	0-10; 10-20; 20-30; 30-40; 40-50
	Agricultural Net Profit	M €	0-10; 10-20; 20-30; 30-40; 40-50; 50-55; 55-60	0-10; 10-20; 20-30; 30-40; 40-50; 50-55; 55-60
5. Final Objectives	Total Income	€ ha-1	0-1000; 1000-5000; 5000-10000; 10000-20000	0-1000; 1000-5000; 5000-10000; 10000-20000
	Natural discharge recovery	Years	Never; 100-200; 70-100	Never; 100-200; 70-100
	New Natural discharge recovery	Years	Never; 100-200; 70-100	Never; 100-200; 70-100
	Total number of Agricultural Direct Employment	Number of employments/ha	0-0.1; 0.1-0.3; 0.3-0.4	0-0.1; 0.1-0.3; 0.3-0.4

Table 1. Variables at Stationary BN-DSS

4.4 Dynamic CC-BN modeling

The DSS has been designed considering 6 identical time steps (time slice technique) of 5 years length for the 30 years period (2070-2100). This was done aimed to develop a dynamic analysis and to prove how OOBN can deal with a dynamic or transient behavior. 6 identical networks or classes have been developed, populated with the corresponding data of each time step. Those 6 networks are linked to a final seventh network or class that link each time step and allows developing the dynamic analysis. This final network comprises 6 instance nodes belonging to each time step aquifer class and other variables for each time step: "Agric Net Profit Variation", "Agric Net Profit Variation IAC", "Annual Average Storage Variation", "Total Accumulated Storage Variation", "Annual Average Storage Variation IAC" and "Total Accumulated Storage Variation IAC".

The variable "Agric Net Profit Variation" describes the temporal variation of the economic variable Agricultural Net profit. The variable "Agric Net Profit Variation IAC" describes the same but including the effects of Land Uses Changes. The variable "Annual Average Storage Variation" represents the temporal variation of the annual aquifer storage and the variable "Total Accumulated Storage Variation" represents the aggregated previous value for the entire time step. Finally, "Annual Average Storage Variation IAC" and "Total Accumulated Storage Variation IAC" represent the same but taking into account the effects of Land Uses Changes.

VARIABLE NAME	EXPLANATION	STATES CC SCENARIO A1B	STATES CC SCENARIO A2
Agric Net Profit Variation (TIME STEPS 1,2,3,45,6)	Variation of Agricultural Net profit per Time Step (M €/year)	-80—40; -40-0; 0-40; 40-80	-80—40; -40-0; 0-40; 40-80
Agric Net Profit Variation IAC (TIME STEPS 1,2,3,45,6)	Variation of Agricultural Net profit per Time Step Incluiding Irrigated Area changes (M€/year)	-80—40; -40-0; 0-40; 40-80	-80—40; -40-0; 0-40; 40-80
Annual Average Storage Variation (TIME STEPS 1,2,3,45,6)	Variation of Annual Average Storage Variation (Mm^3/year)	-30--20; -20--10; -10-0; 0-5; 5-10	-30--20; -20--10; -10-0; 0-5; 5-10
Total Accumulated Storage Variation (TIME STEPS 1,2,3,45,6)	Variation of Accumulated Average Storage Variation per Time Step (Mm^3)	-1100--900; -900--700; -700--500; -500--300; -300--100; -100-0; 0-50; 50-100; 100-150; 150-200; 200-250; 250-350	-1100--900; -900--700; -700--500; -500--300; -300--100; -100-0; 0-50; 50-100; 100-150; 150-200; 200-250; 250-300
Annual Average Storage Variation IAC (TIME STEPS 1,2,3,45,6)	Variation of Annual Average Storage Variation including Irrigated Area Change (Mm^3/year)	-40--30; -30--20; -20--10; -10-0; 0-5; 5-10	-40--30; -30--20; -20--10; -10-0; 0-5; 5-10
Total Accumulated Storage Variation IAC (TIME STEPS 1,2,3,45,6)	Variation of Accumulated Average Storage Variation including Irrigated Area Change (Mm^3)	-1200--1000; -1000--800; -800--600; -600--400; -400--300; -300--100; -100-0; 0-50; 50-100; 100-150; 150-200; 200-250; 250-300; 300-350	-1200--1000; -1000--800; -800--600; -600--400; -400--300; -300--100; -100-0; 0-50; 50-100; 100-150; 150-200; 200-250; 250-300

Table 2. Extended list of variables and their states for the second class (Dynamic module)

Figure 7. Dynamic BN DSS Structure

5. Results

5.1 Stationary or time aggregated analysis

The climate change scenarios, which provoke a reduction in the rainfall and consequently, in the groundwater recharge rates, affect the results of the hydrological and economic variables. In this sense, in order to keep the current crop distribution, the aquifer abstraction rater will be higher to compensate by irrigation the lower rainfall rates. This will produce hydrological and economic impacts quantified and analyzed in this study.

All these impacts are quantified and shown through the use of this specific DSS based on OOBNs. Several scenarios are defined. The first scenario (“Scenario A1B_No Land Use Changes) considers climate change conditions under emission Scenario A1B without land use change; then, the second scenario (“Scenario A1B_Land Use Changes”) considers climate and land use changes together. The third scenario (“Scenario A2_ No Land Use Changes”) deals with climate change conditions under emission Scenario A2 without considering land use change; finally, the fourth scenario

("Scenario A2_Land Use Changes") considers climate and land use changes simultaneously.

1.- Scenario A1B_No Land Use Changes

Under this CC scenario, the annual average rainfall for the whole control period is 160 mm·year^{-1}, producing an annual average recharge of 33 mm· year^{-1} (2.2 Mm^{3}· year^{-1}) according to the soil water balance model. In contrast, the historical average values for rainfall is 281 mm· year^{-1}, producing an average recharge rate of about 74 mm· year^{-1} (4.9 Mm^{3}· year^{-1}). Consequently, under this scenario, the recharge rate is reduced in more than half of the situation without CC conditions. This makes the water budget (-12.1 Mm^{3}· year^{-1}) even more unbalanced, reducing the chances of the long-term sustainable groundwater exploitation (aquifer budget equilibrium) in about 4%, what means a practical absence of chances for reaching the long-term sustainable groundwater exploitation (0.4%).

With regards to the economic variables, there are not significant changes under this scenario due to the non-annual (woody crops) nature of the crops in this area. Thus, reducing the rainfall and recharge rates due to A1B CC scenario, just would involve a slight increase of groundwater pumping and the abstraction costs does not increase significantly (Fig. 8a).

2.- Scenario A1B_Land Use Changes

Sub-scenario Increase 10% Irrigated Area

This sub-scenario establishes an increase of 10% in the irrigated area for the whole control period. This will produce a slight increase of the groundwater abstraction of about 0.3 Mm^{3}· year^{-1}. In contrast, this would produce an increase in the total agricultural profits of about 1.54 M€ (Fig. 8b).

Sub-scenario Increase 20% Irrigated Area

This scenario establishes an increase of 20% in the irrigated area for the whole control period. According to the agronomic model and the BN model this increase will not produce a relevant increase of groundwater abstraction. Additionally, this would produce an increase in the total agricultural profits of about 0.83 M€ over the previous scenario (Fig. 8c).

Sub-scenario Decrease 10% Irrigated Area

Decreasing the irrigated area in 10% would produce a reduction of 1.50 M€ in total agricultural net profits in comparison with the scenario without land uses change. On the other hand, the hydrological variables will not change significantly (Fig. 8d).

Sub-scenario Decrease 20% Irrigated Area

Decreasing the irrigated area in 20% would produce a reduction of 3.33 M€ in total agricultural net profits. On the other hand, the hydrological variables will change significantly. Thus, groundwater abstraction will be reduced in 5 $Mm^3 \cdot year^{-1}$ which makes the chance for the aquifer restoration increase in 3.3% (Fig. 8e).

3.- Scenario A2_ No Land Use Changes

Under this Climate Change scenario, the annual average rainfall for the whole control period is 256 $mm \cdot year^{-1}$, producing an annual average recharge of 62 $mm \cdot year^{-1}$ (4.1 $Mm^3 \cdot year^{-1}$), according to the previous calibrated rainfall-runoff model. In contrast, the historical average values for rainfall is 281 $mm \cdot year^{-1}$, producing an average recharge rate of about 74 $mm \cdot year^{-1}$ (4.9 $Mm^3 \cdot year^{-1}$). Consequently, under this scenario, the recharge rate to aquifer is reduced in about 12 mm the situation without climate change conditions. This makes the water budget more balanced (-10 $Mm^3 \cdot year^{-1}$) than the previous scenario but more negative than the historical behavior (-8.9 $Mm^3 \cdot year^{-1}$). Despite this more balanced aquifer budget, the chances for an aquifer restoration remains similar than for the previous scenario.

In regards to the economic variables, there are not significant changes under this scenario due to the same reason than for the previous scenario (Figure 9a).

4.- Scenario A2_Land Use Changes

Sub-scenario Increase 10% Irrigated Area

This scenario establishes an increase of 10% in the irrigated area for the whole control period. This will produce a slight increase of the groundwater abstraction of about 0.2 $Mm^3 \cdot year^{-1}$. In contrast, this would produce an increase in the total agricultural profits of about 1.54 M€ (Figure 9b).

Sub-scenario Increase 20% Irrigated Area

This scenario establishes an increase of 20% in the irrigated area for the whole control period. According to the agronomic model and the BN model this increase will not produce a relevant increase of the groundwater abstraction. Additionally, this would produce an increase in the total agricultural profits of about 0.81 M€ over the previous scenario (Figure 9c).

Sub-scenario Decrease 10% Irrigated Area

Decreasing the irrigated area in 10% would produce a reduction of 1.8 M€ in total agricultural net profits in comparison with the scenario without land uses change. On the other hand, the hydrological variables will not change significantly (Figure 9d).

Sub-scenario Decrease 20% Irrigated Area

Decreasing the irrigated area in 20% would produce a reduction of 3.31 M€ in total agricultural net profits. On the other hand, the hydrological variables will change significantly. Thus, groundwater abstraction will be reduced in 4.9 $Mm^3 \cdot year^{-1}$, producing a more balanced aquifer budget (-5.19 $Mm^3 \cdot year^{-1}$) which makes the chance for the aquifer restoration increase in almost 9 % (Figure 9e).

Figure 8. Compiled BN as DSS as a Stationary or Time Aggregated analysis (Scenario A1B)

8a,b,c,d,e

Figure 9. Compiled BN as DSS as a Stationary or Time Aggregated analysis (Scenario A2)

9a,b,c,d,e

5.2 Dynamic analysis

As mentioned before, in order to analyze the behavior of these variables dynamically, the time horizon has been discretized in 6 time steps (slices) of 5 year length each one. This was done mainly for a methodological purpose, in order to probe the suitability of OOBN for dealing with this type of analysis. Furthermore, interesting information from this dynamic analysis has been drawn, mainly regarding the hydrological variables, such the dynamic evolution of the aquifer storage under these scenarios.

Scenario A1B_No Land Use Changes

Under this scenario, the total aquifer storage drawdown is around 405 Mm^3 with an average drawdown rate for each time step of around 13 $Mm^3 \cdot$ $year^{-1.}$ However, not all the time slices have the same loss of storage. In this sense, the beginning of the period is where the maximum drawdown takes place (13.4 $Mm^3 \cdot$ $year^{-1}$). On the other hand the last years if the time series (sixth time slice) is where the minimum drawdown rate occurs (12.3 $Mm^3 \cdot$ $year^{-1}$).

Regarding the economic variables, there is a continuous slight increase of agricultural profits over the time period at a variant rate. However, it is not possible to define a clear tendency or any pattern over the time. Furthermore, the inherent uncertainty of the economic variables can be so high that any prediction on this, become too risky and erroneous.

Scenario A1B_Land Use Changes

Sub-scenario Increase 10% Irrigated Area

Under this scenario, the total aquifer storage drawdown (around 412 Mm^{3}) is bit larger than in the previous scenario, with an average drawdown rate for each time step over 13 Mm^{3}·year$^{-1.}$ The beginning of the period is where the maximum drawdown takes place (13.7 Mm^{3}· year^{-1}). On the other hand the last years if the time series (sixth time slice) is where the minimum drawdown rate occurs (12.5 Mm^{3}· year^{-1}).

Sub-scenario Increase 20% Irrigated Area

Under this scenario, the total aquifer storage drawdown remains the same than in the previous simulation (around 412 Mm^{3}).

Sub-scenario Decrease 10% Irrigated Area

Under this scenario, the total aquifer storage drawdown remains the same than in the Scenario A1B_No Land Use Changes (around 405 Mm^{3}).

Sub-scenario Decrease 20% Irrigated Area

Under this scenario, there is an important reduction of the total aquifer storage drawdown with a value of (around 223 Mm^{3}). This makes perfect sense and can be an intervention to address in order to balance the aquifer water budget or even restore the aquifer natural regime.

Sub-scenario Scenario A2_ No Land Use Changes

Under this scenario, the total aquifer storage drawdown is around 376 Mm^{3} with an average drawdown rate for each time step of around 11 Mm^{3}· year^{-1}. However, there are some differences between time slices. In this sense, the beginning of the period is where the maximum drawdown takes place (11.8 Mm^{3}·year^{-1}). On the other hand the last years if the time series (sixth time slice) is where the minimum drawdown rate occurs (10.4 Mm^{3}· year^{-1}).

Regarding the economics variables, there is a continuous increase of agricultural profits through the time period at a variant rate. However, as for A1B_No Land Use Changes scenario, it is not possible either to define a clear tendency or any pattern over the time.

Scenario A2_Land Use Changes

Sub-scenario Increase 10% Irrigated Area

Under this scenario, the total aquifer storage drawdown (around 383 Mm^3) is bit larger than in the previous scenario, with an average drawdown rate for each time step over 11 $Mm^3 \cdot year^{-1.}$ The beginning of the period is where the maximum drawdown takes place (12.1 $Mm^3 \cdot$ $year^{-1}$). On the other hand the last years if the time series (sixth time slice) is where the minimum drawdown rate occurs (10.6 $Mm^3 \cdot$ $year^{-1}$).

Sub-scenario Increase 20% Irrigated Area

Under this scenario, the total aquifer storage drawdown remains the same than in the previous simulation (around 383 Mm^3).

Sub-scenario Decrease 10% Irrigated Area

Under this scenario, the total aquifer storage drawdown remains almost the same than in the Scenario A2_No Land Use Changes (around 375 Mm^3).

Sub-scenario Decrease 20% Irrigated Area

Under this scenario, there is an important reduction of the total aquifer storage drawdown with a value of (around 200 Mm^3). This makes perfectly sense and can become an intervention to address in order to balance the aquifer water budget or even restore the aquifer natural regime if a larger reduction of irrigated area is established.

Figure 10. Compiled DSS for the Dynamic or transient Analysis (Scenario A1B)

10a,b,c,d,e

Figure 11. Compiled DSS for the Dynamic or transient Analysis (Scenario A2)

11a.b.c.d.e

6. Discussion

OOBNs have been recently considered and applied in a non-transient manner due to their flexible and modular nature. This has caused that OOBNs have been used only for structuring those complex problems in terms of organization (Molina et al., 2010), especially in environmental problems. Thus, the use of OOBNs for the study of dynamic processes is an innovative application of this tool. This research has proven the utility of Dynamic BNs (DBNs) for those studies that involve a transient analysis of the probability distributions or functions. The evolution of those probability distributions over time can become very important, especially regarding the coupling between OOBNs and physical models (groundwater flow models, hydraulic models, agronomic models, etc).

Dynamic BNs should be seen as a structure for the propagation of probabilities over the time. Each instance node represents a time step that likewise can represent a whole set of classes or domains (BNs). Thus, Dynamic BNs play a double role; on one hand, the way the problem is structured and then, the dynamic implementation of the problem. In this sense, DBNs extend them to time-dependent domains by introducing an explicit notion of time and influences that span over time. Most practical uses of DBNs involve temporal influences of the first order, i.e., influences between consecutive time steps. After all, introducing higher order temporal influences may be costly in terms of the resulting computational complexity, which is NP-hard even for static models. Limiting temporal influences to influences between neighboring states is equivalent to assuming that the only thing that matters in the future of the system is its current state. Many real world systems, however, have memory that spans beyond their current state

According to many authors, DBNs are an extension of BNs for modeling dynamic systems. The term dynamic means that the system's development is modeled over time and not that the model structure and its parameters change over time, even though the latter is theoretically possible. In a DBN, the state of a system at time t is represented by a set of random variables which are probability distributions or functions $X^t = X_1^t ....X_n^t$ The state at time t generally dependents on the states at previous k time steps. When each state of the model only depends on the immediately preceding state (i.e., k = 1, the system is called first-order Markov (Markov Chains), often assumed in practice), we represent the transition distribution $P(X^t \mid X^{t-1})$. This can be done using the technique called Time Slicing (Kjaerulff, 1995).

This application has been developed for analyzing the impacts produced by Climate and Land-Use Changes in a historically overexploited aquifer system (Serra-Salinas aquifer), located in SE Spain. This aquifer has been supplying groundwater for all the uses since 1960´s. High profitable agriculture is the main consumer, but also domestic as well as recreational uses have been supplied by this aquifer during the last 5 decades (Molina et al. 2009).

This research is focused on the analysis of hydrological and economic impacts produced by two emission scenarios of Climate Change (A1B, and A2). Despite both scenarios forecast an important reduction in average annual rainfall and consequently in the recharge rate to the aquifers, there are important differences between them. Thus, Scenario A1B estimates a reduction in the rainfall in more than the half comparing with the historical situation. This makes the water budget (-12.1 $Mm^3 \cdot year^{-1}$) even more unbalanced, reducing the chances of the aquifer restoration in about 4%, what means a practical absence of restoration chances (0.36%). On the other hand, Scenario A2 estimates a lower decrease of rainfall and consequently, the impacts on the hydrological functioning of the system are less important.

Furthermore, an analysis of different scenarios of land use changes has been done with a double goal; first, in order to analyze the important of these changes in the water management of the aquifer and secondly, to compare the importance of land use changes regarding with CC impacts. Attending to this second goal, it is clear that a reduction of only 20% of the irrigated would produce a larger impact to the aquifer hydrological functioning than the climate change effects. This result would allow palliating and adapting the situation as the climate change effects revealed. Finally, it is remarkable to mention that the fact that this aquifer system is so far away from the hydrological equilibrium makes the results obtained less attractive. In this sense, those aquifer systems with a water budget close to the equilibrium allow obtaining more attractive results for reaching a long-term sustainability.

7. Conclusions

DBNs have been used for the assessment of impacts produced by climate and land use changes in an extremely overexploited aquifer system in SE Spain. Results from different Climate Change models and scenarios (A1B and A2) probe the high variability in the forecast of the main meteorological variables such as rainfall and temperature. This high uncertainty in the predictions condition the right water planning and management, especially for those water systems located in arid and semiarid regions where the impacts associated with CC are expected to be the largest. Furthermore, the satisfactory results obtained from this research prove the usefulness of this technique when a propagation of information (conditional probability) is required. Also, this research can become a starting point for further studies that comprise coupling between physical transient models and DBNs. Results obtained can be also useful for establishing strategies for the adaptation of water systems to climate change effects. In this sense, the development and use of this kind of tools can help to assess and implement in advance adaptive management strategies aimed to palliate future potential negative effects to be produced by climate and land use changes.

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Figure 1
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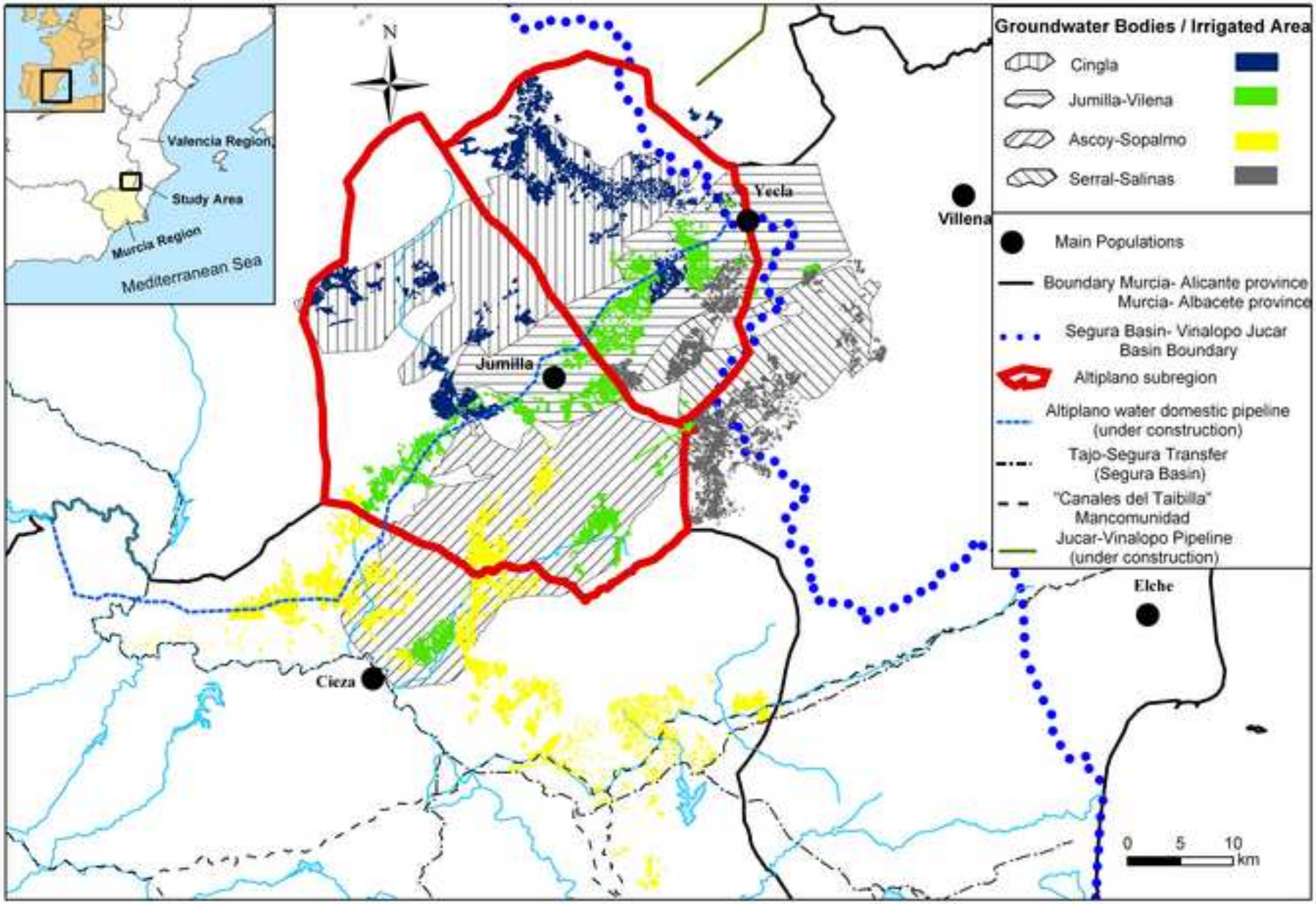

Figure 2

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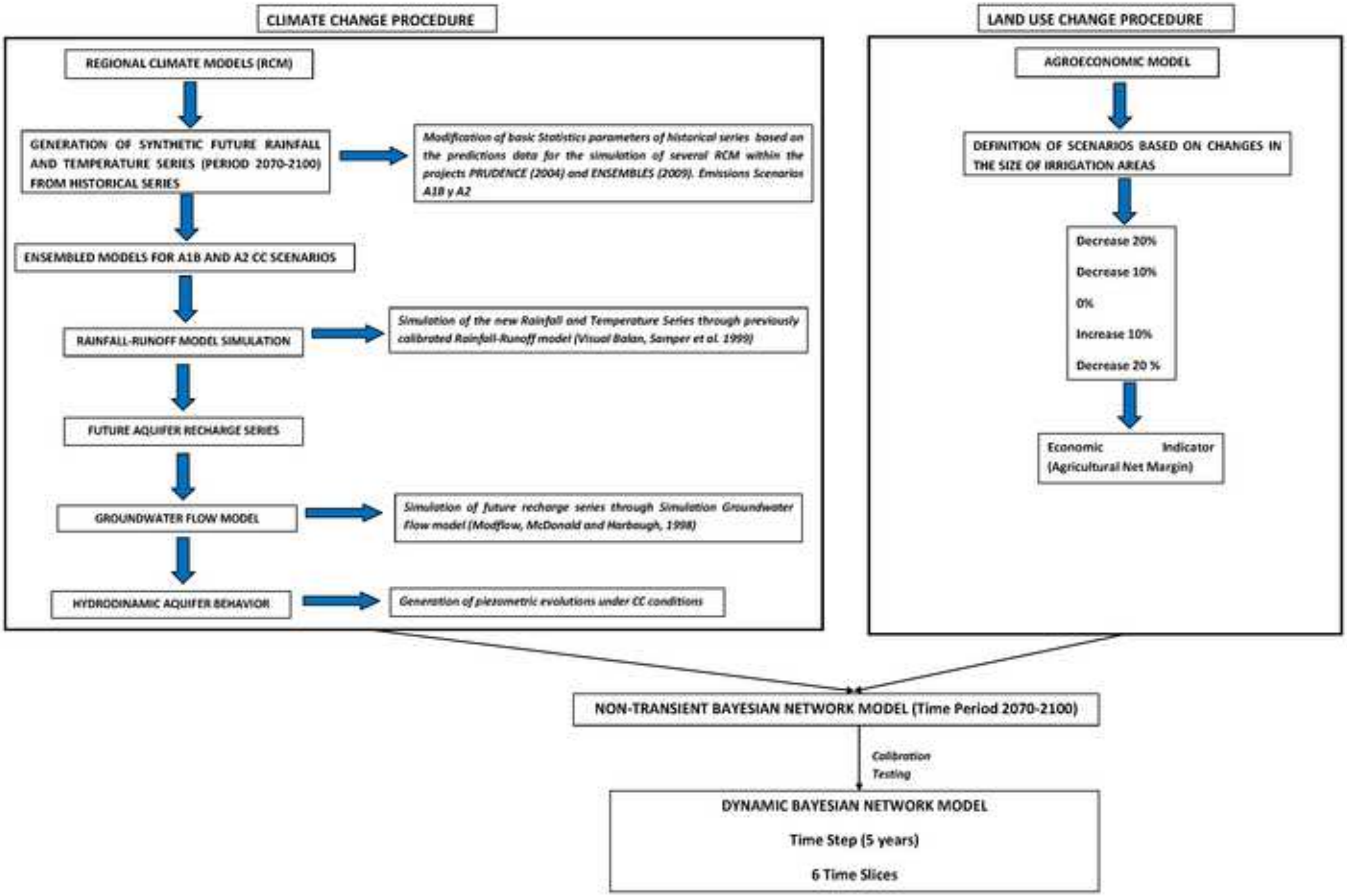

Figure 3
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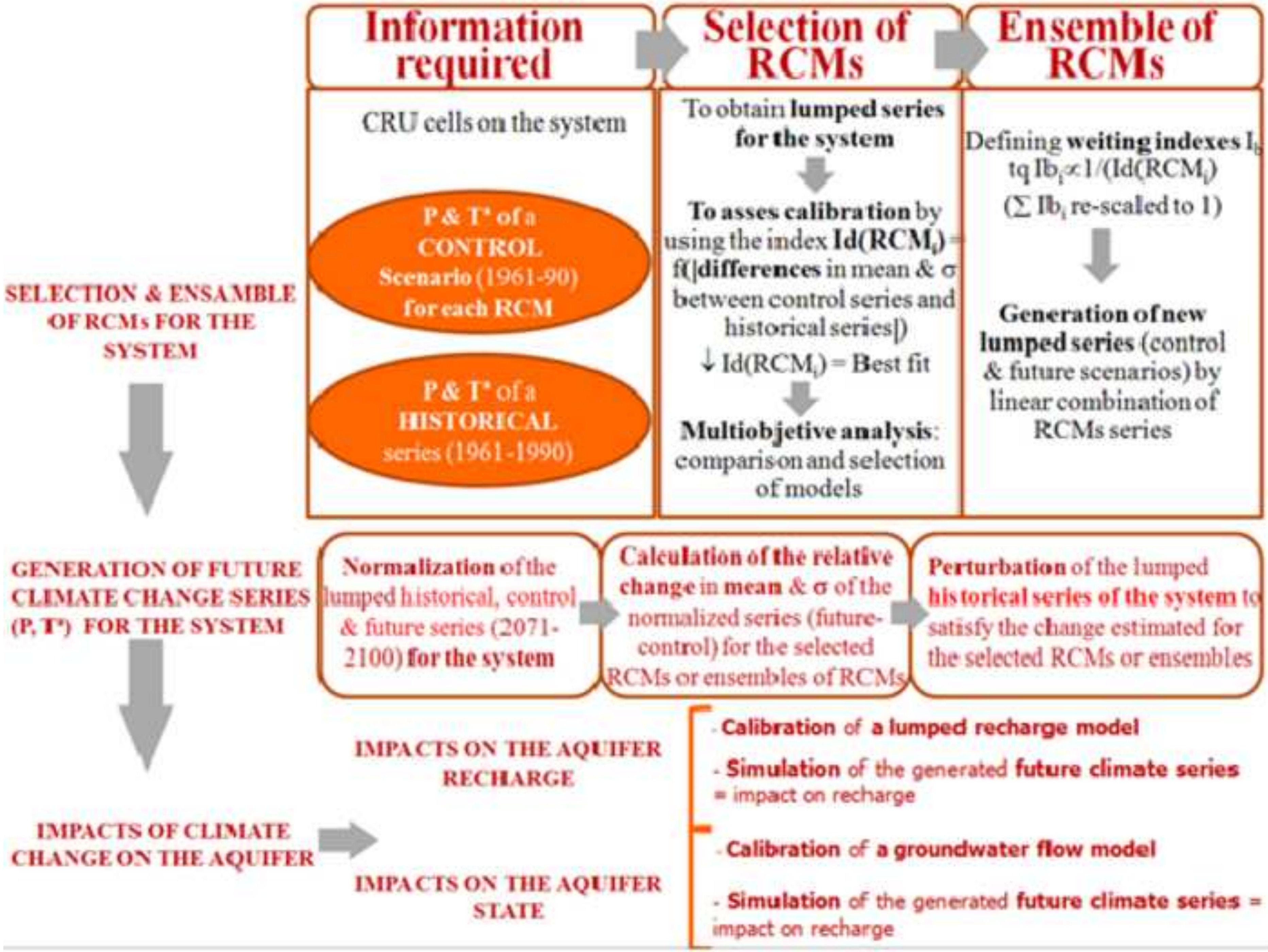

Figure 4a

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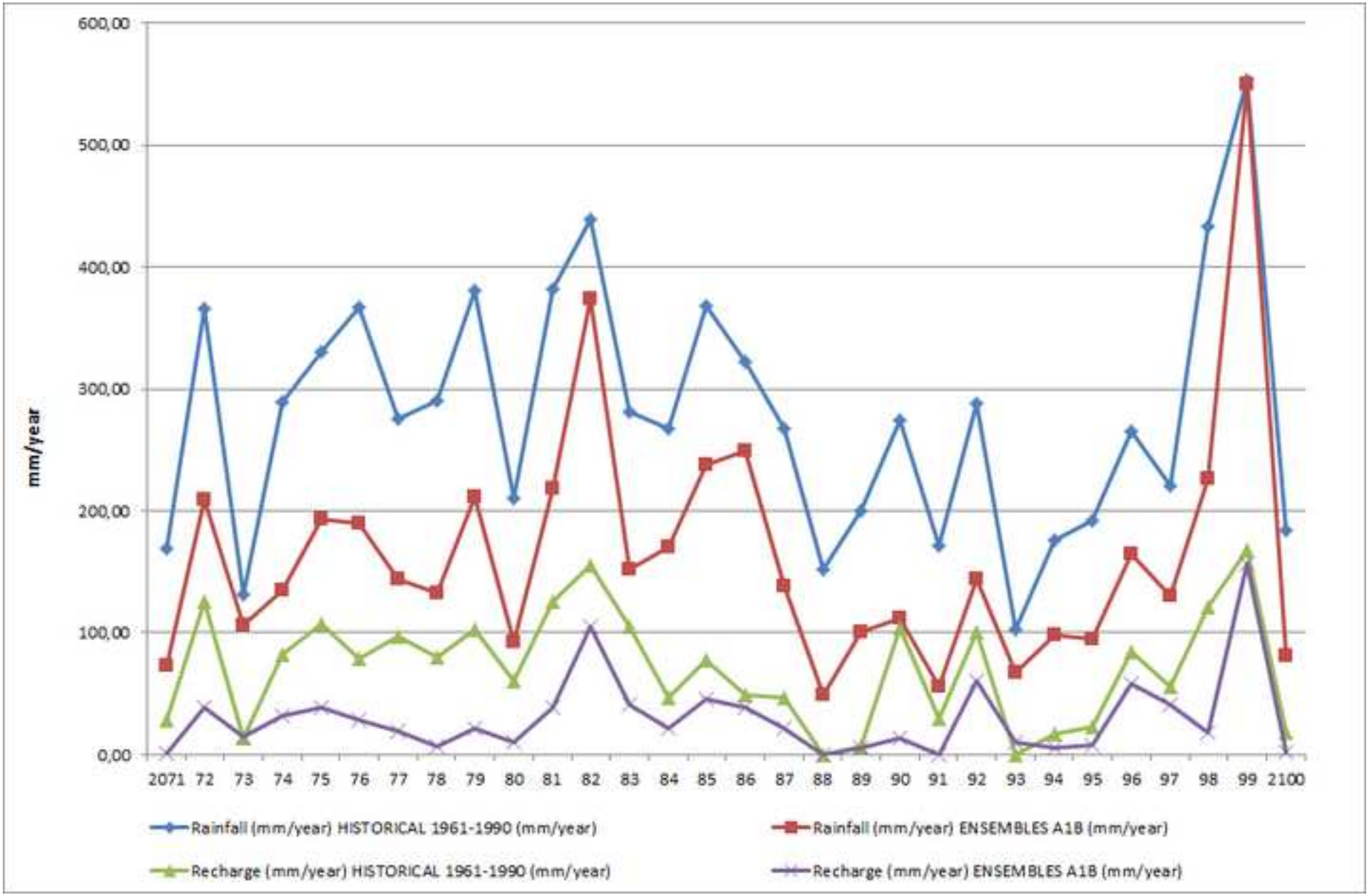

Figure 4b
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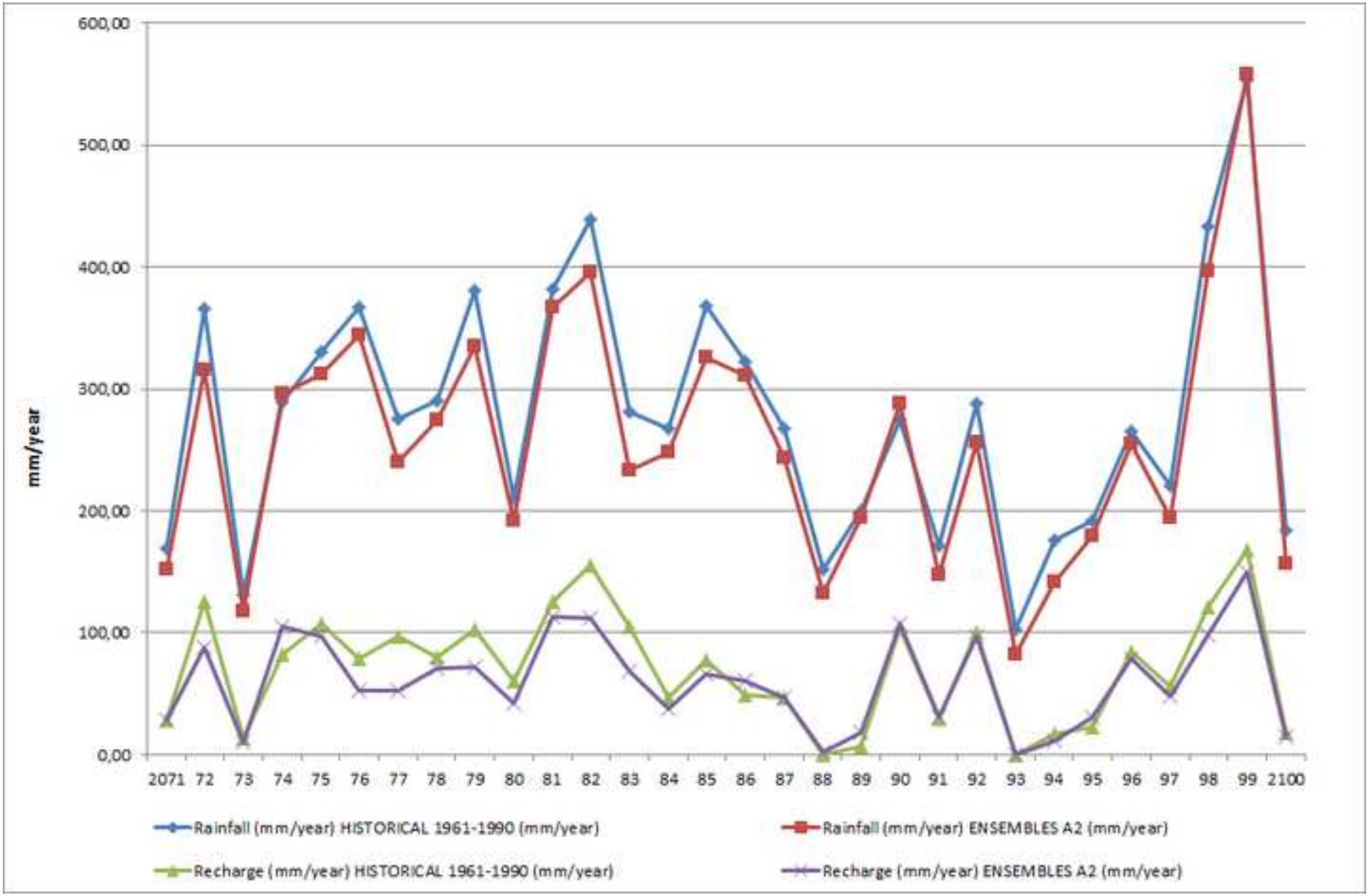

Figure 5

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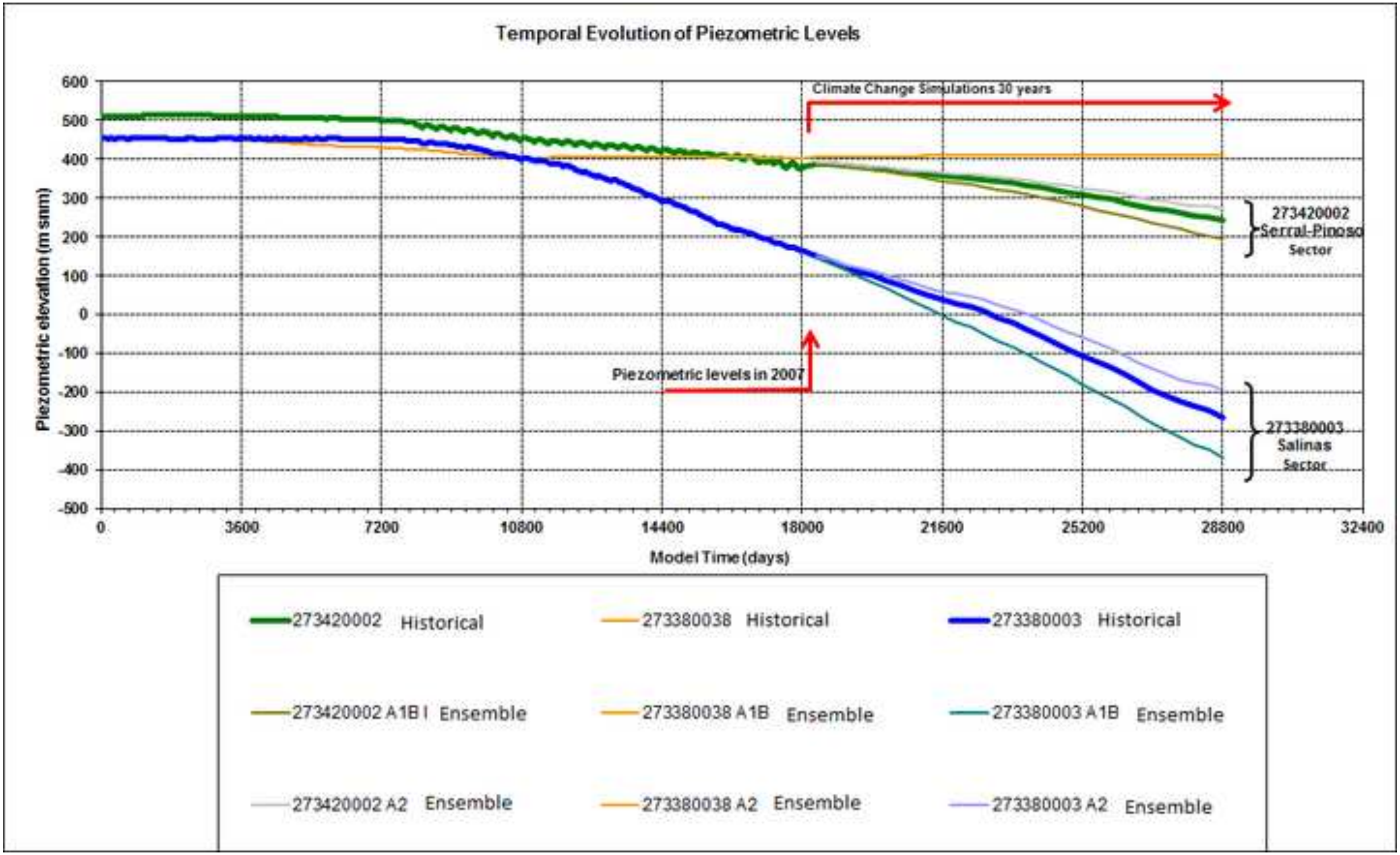

Figure 6

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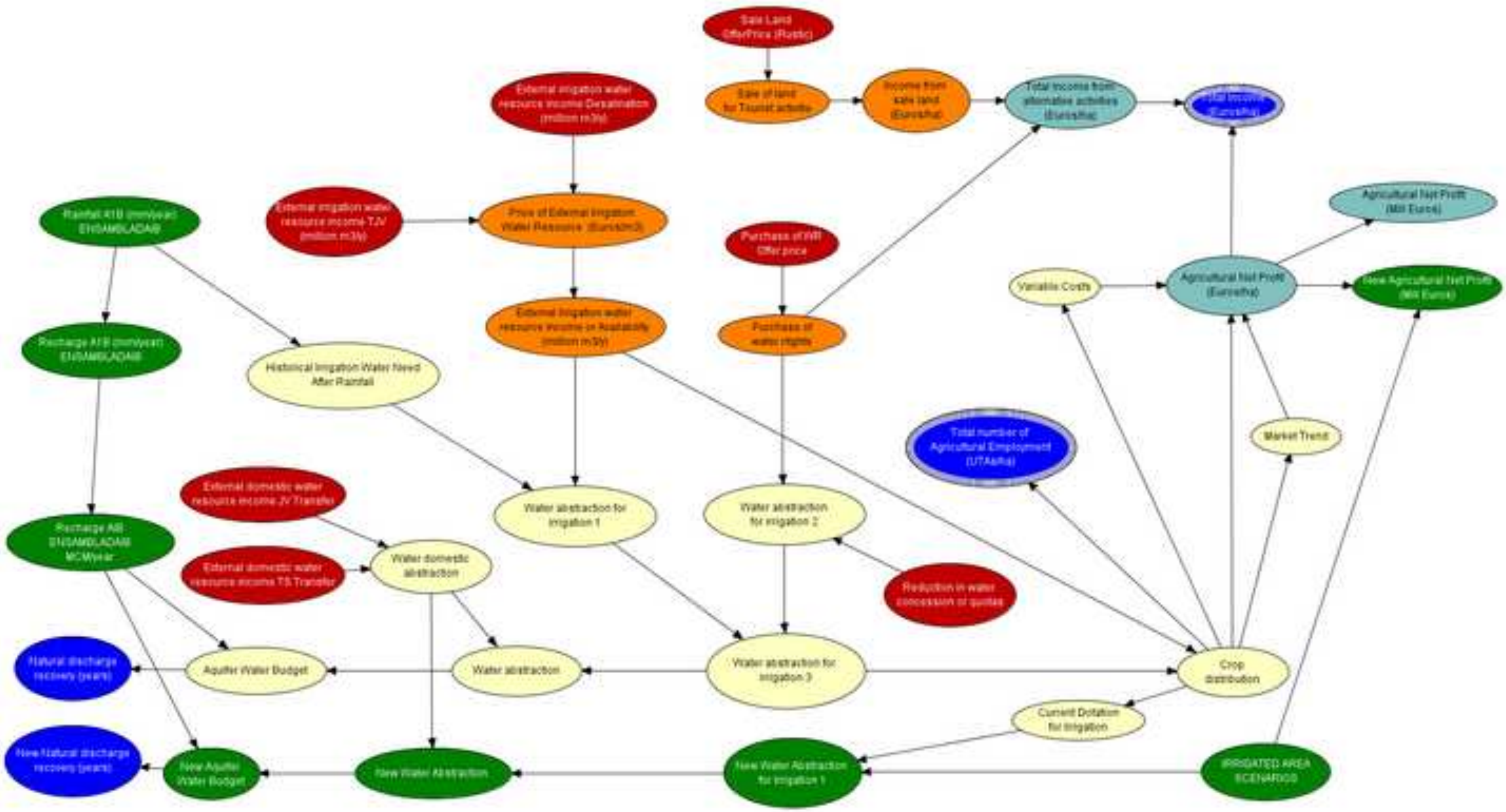

Figure 7

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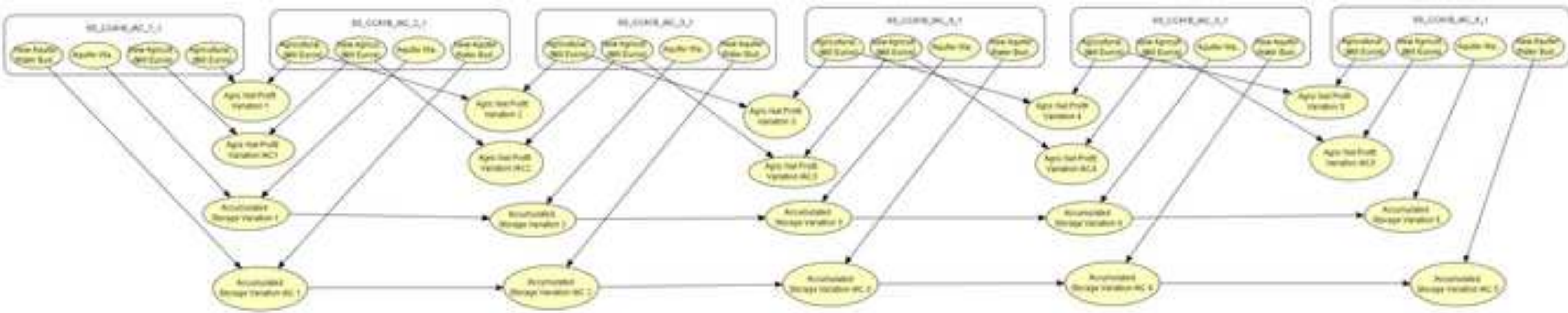

Figure 8a

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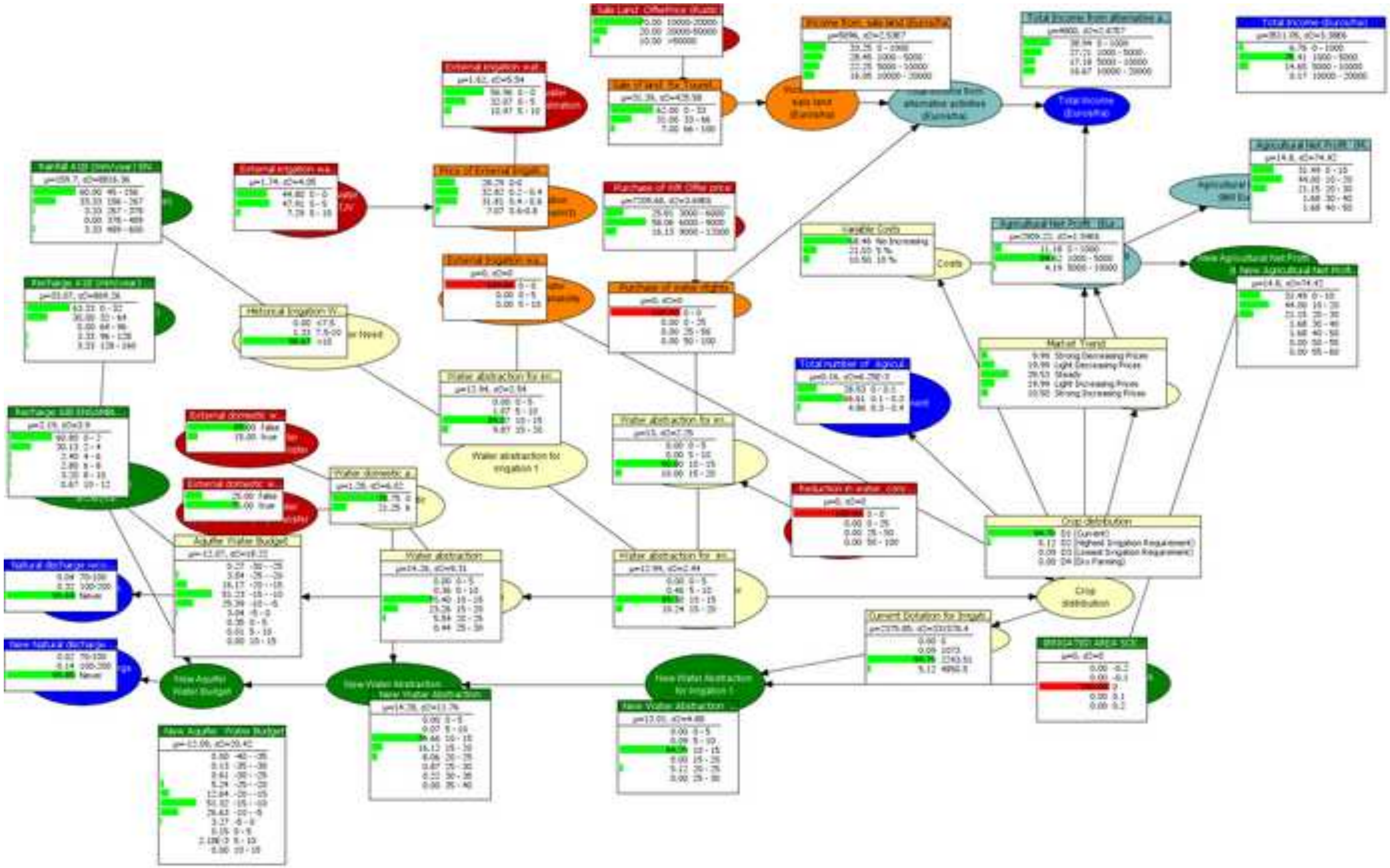

Figure 8b

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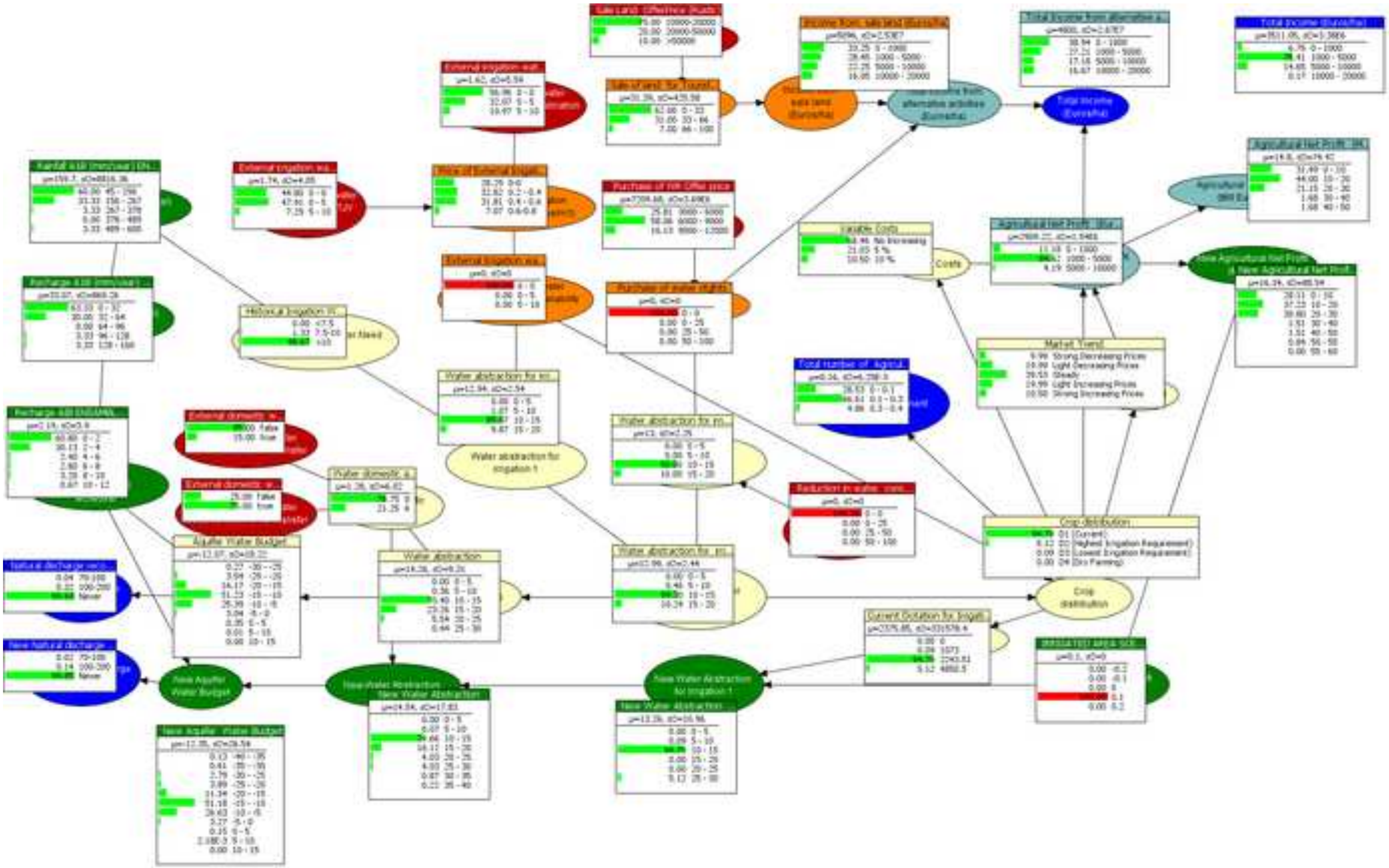

Figure 8c

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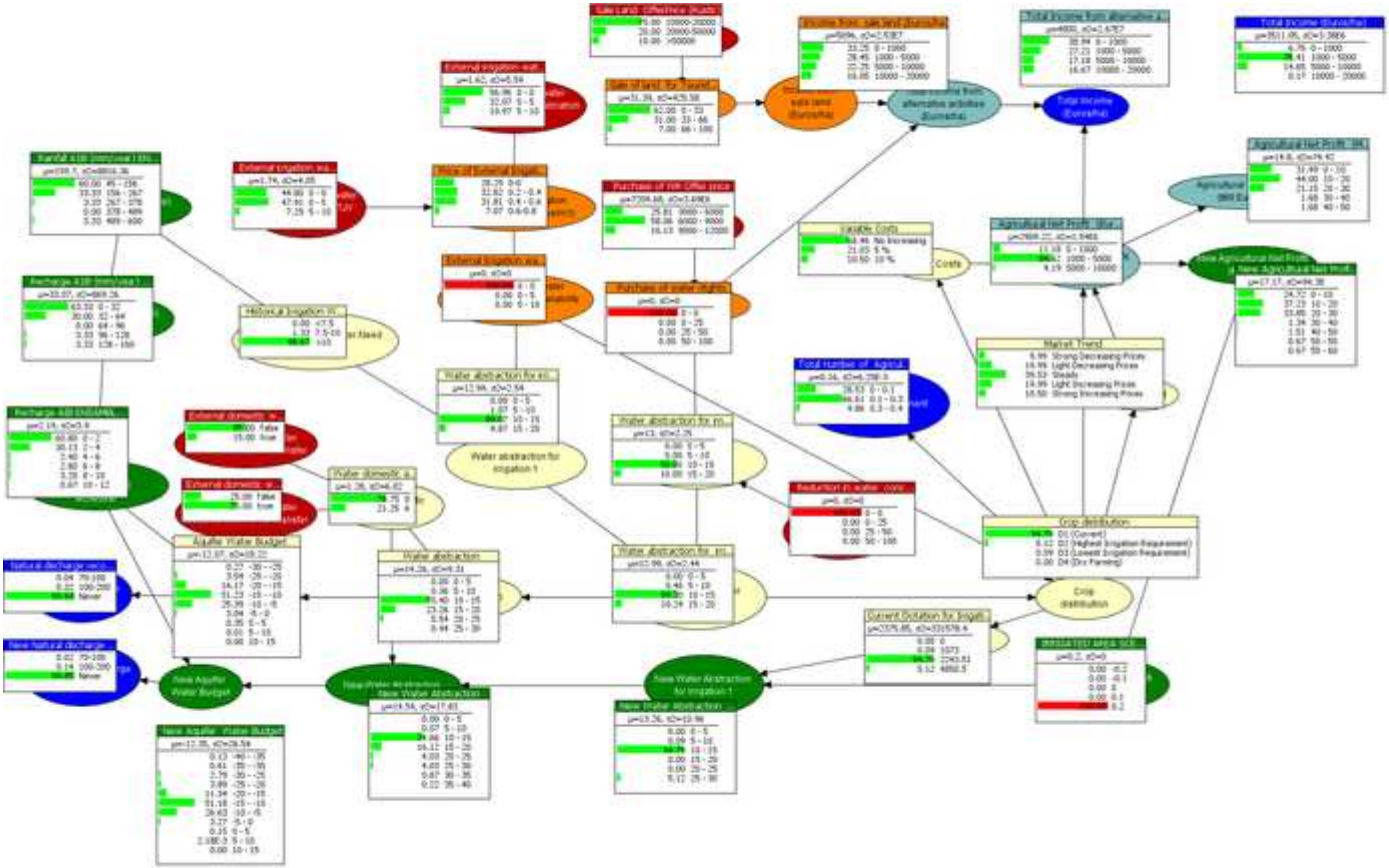

Figure 8d

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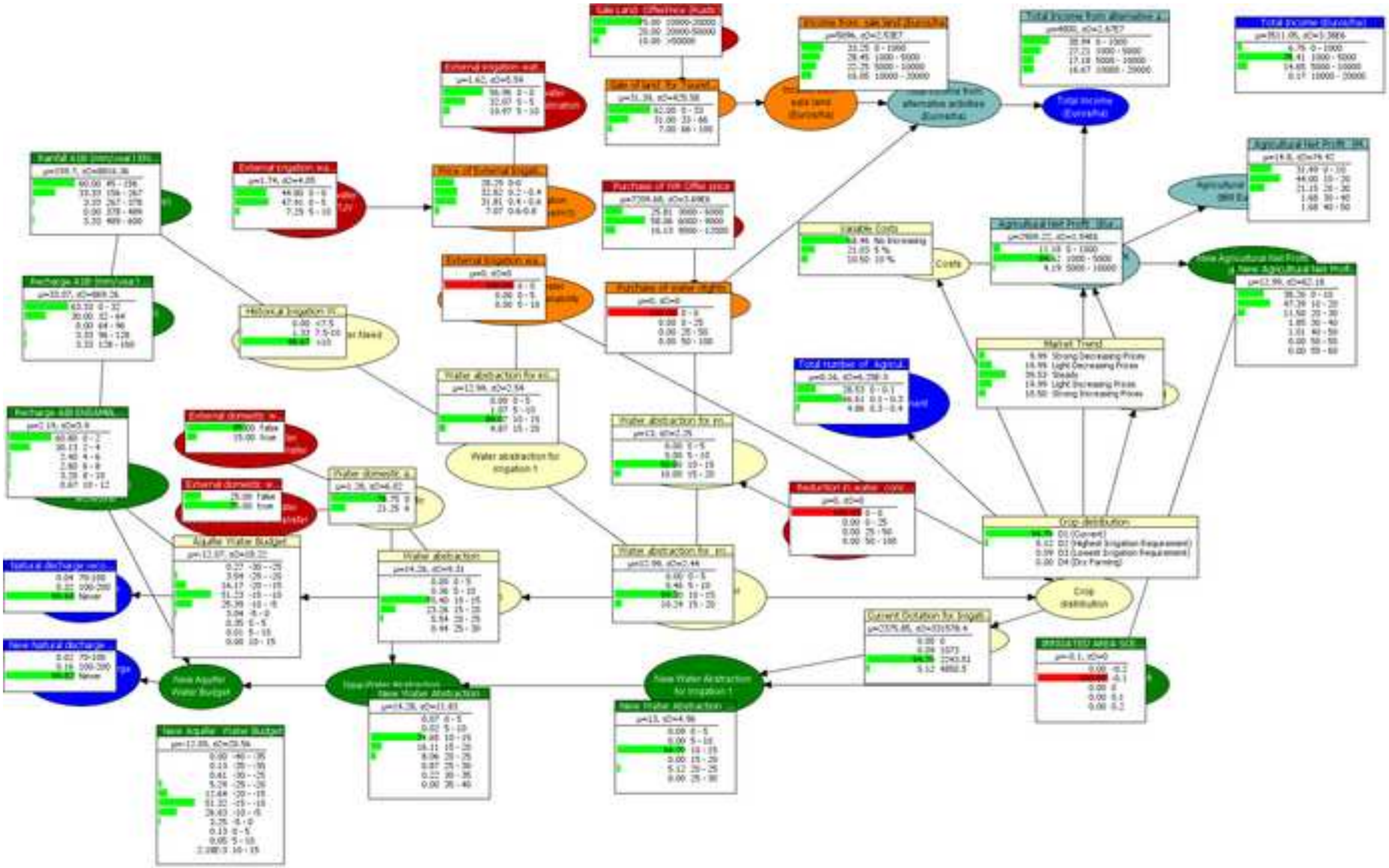

Figure 8e

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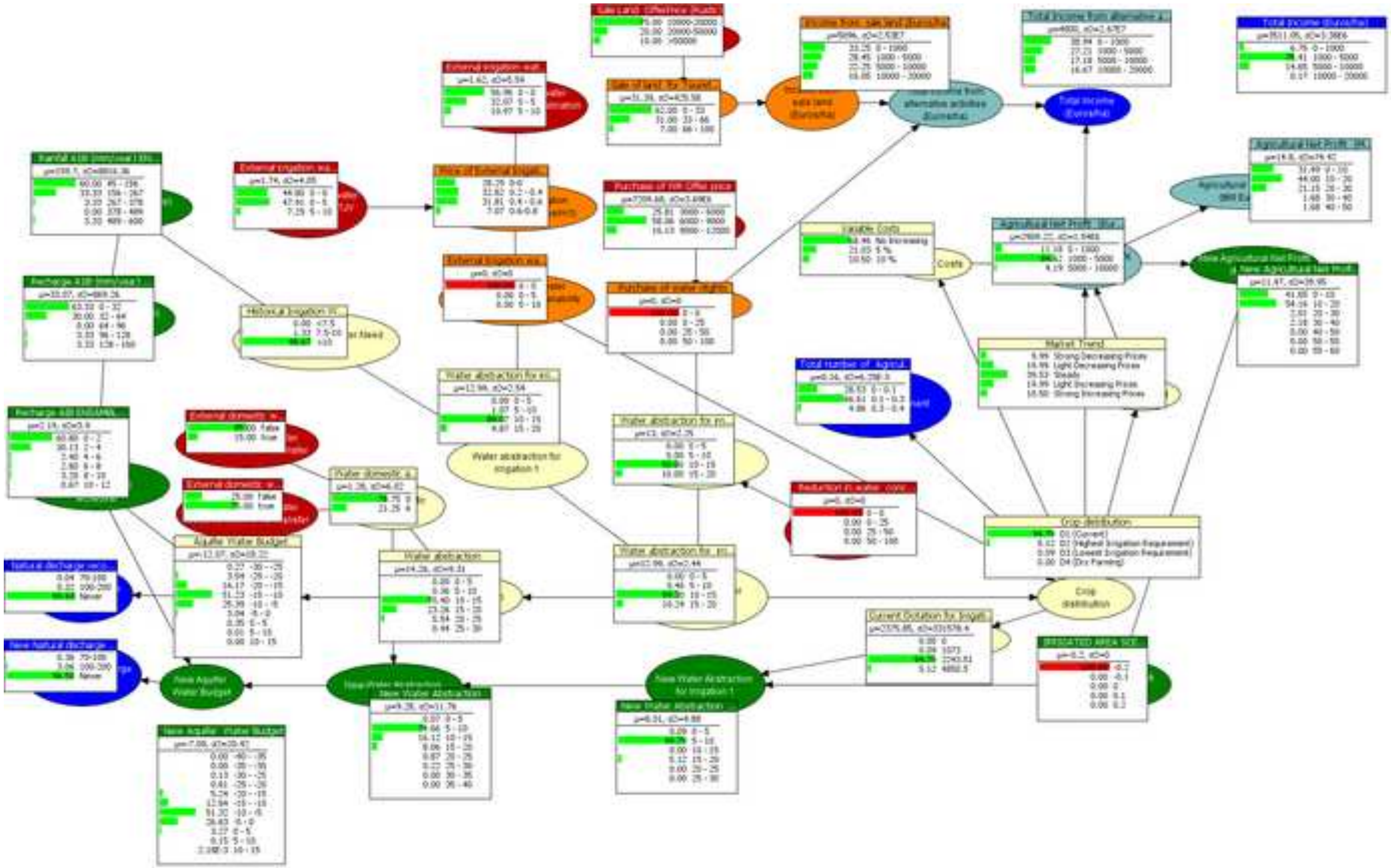

Figure 9a

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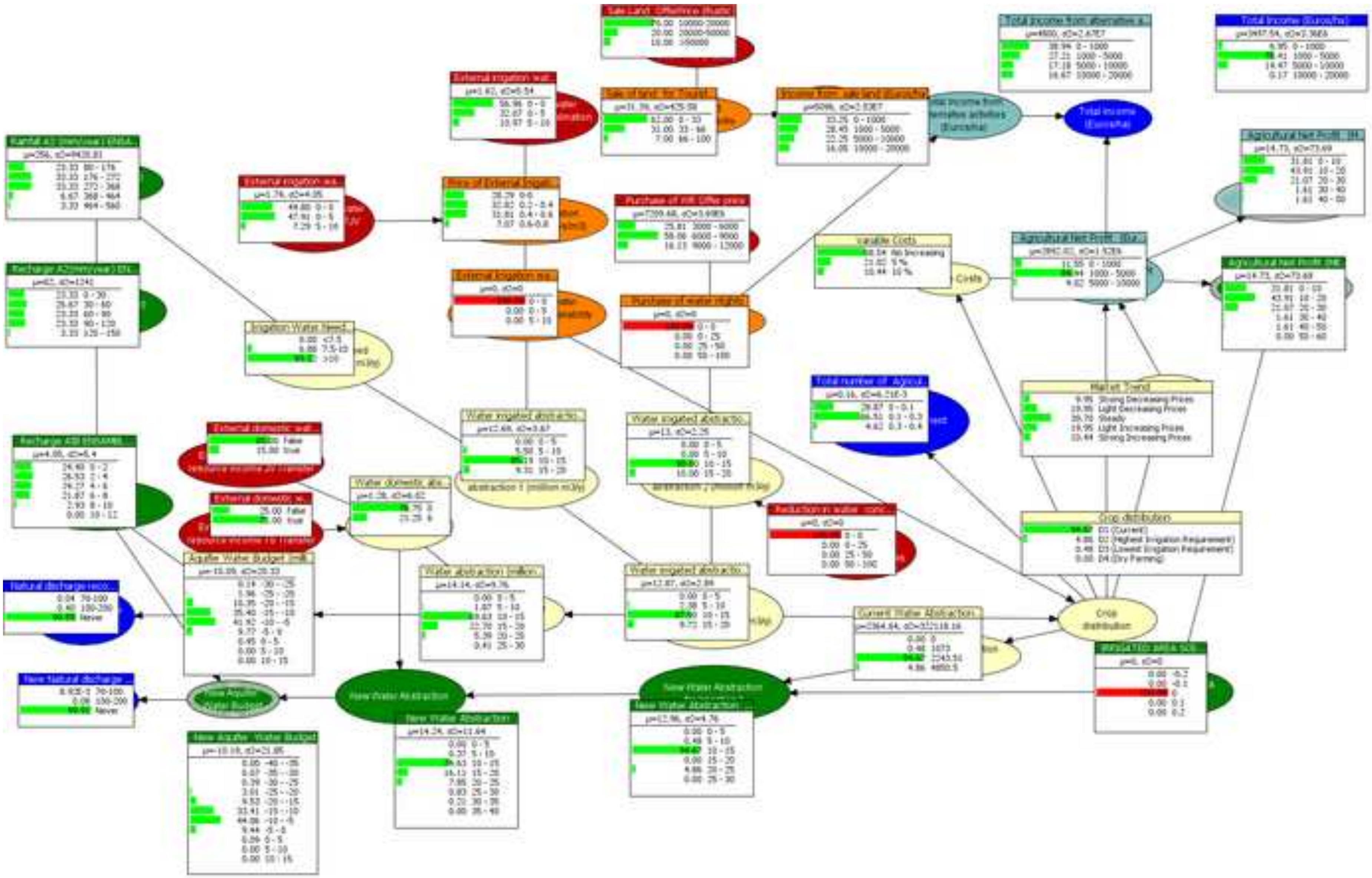

Figure 9b

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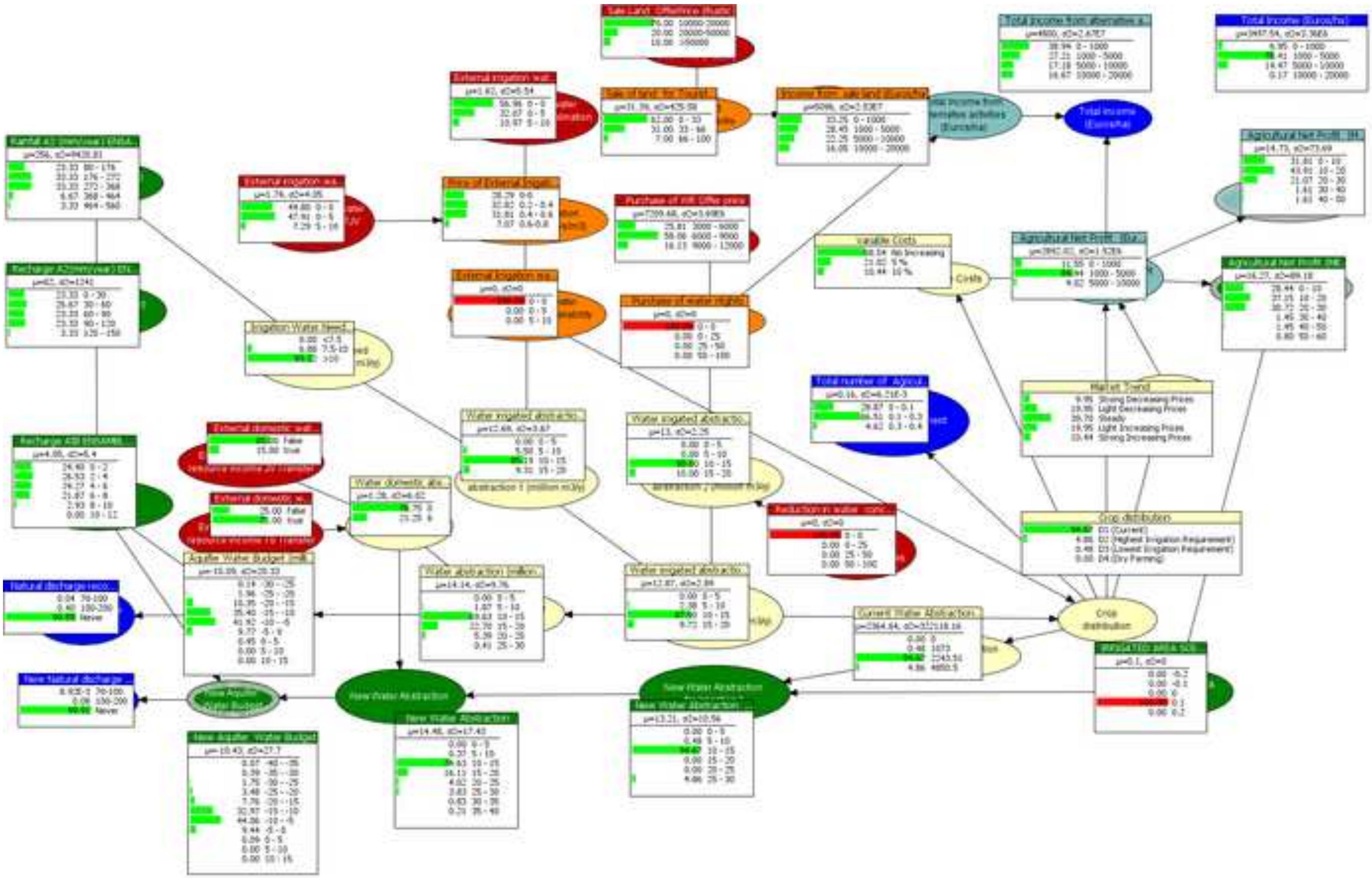

Figure 9c

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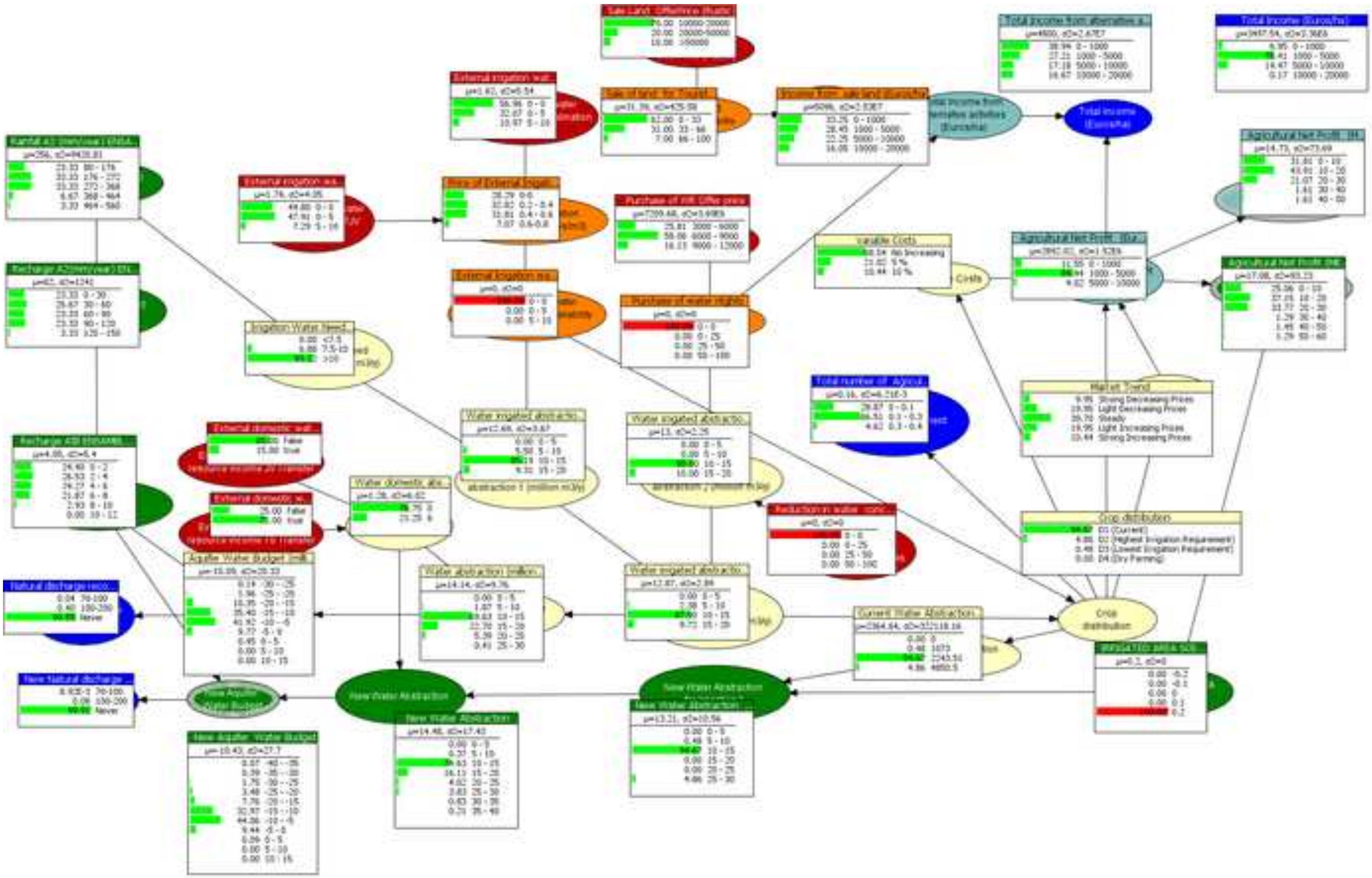

Figure 9d

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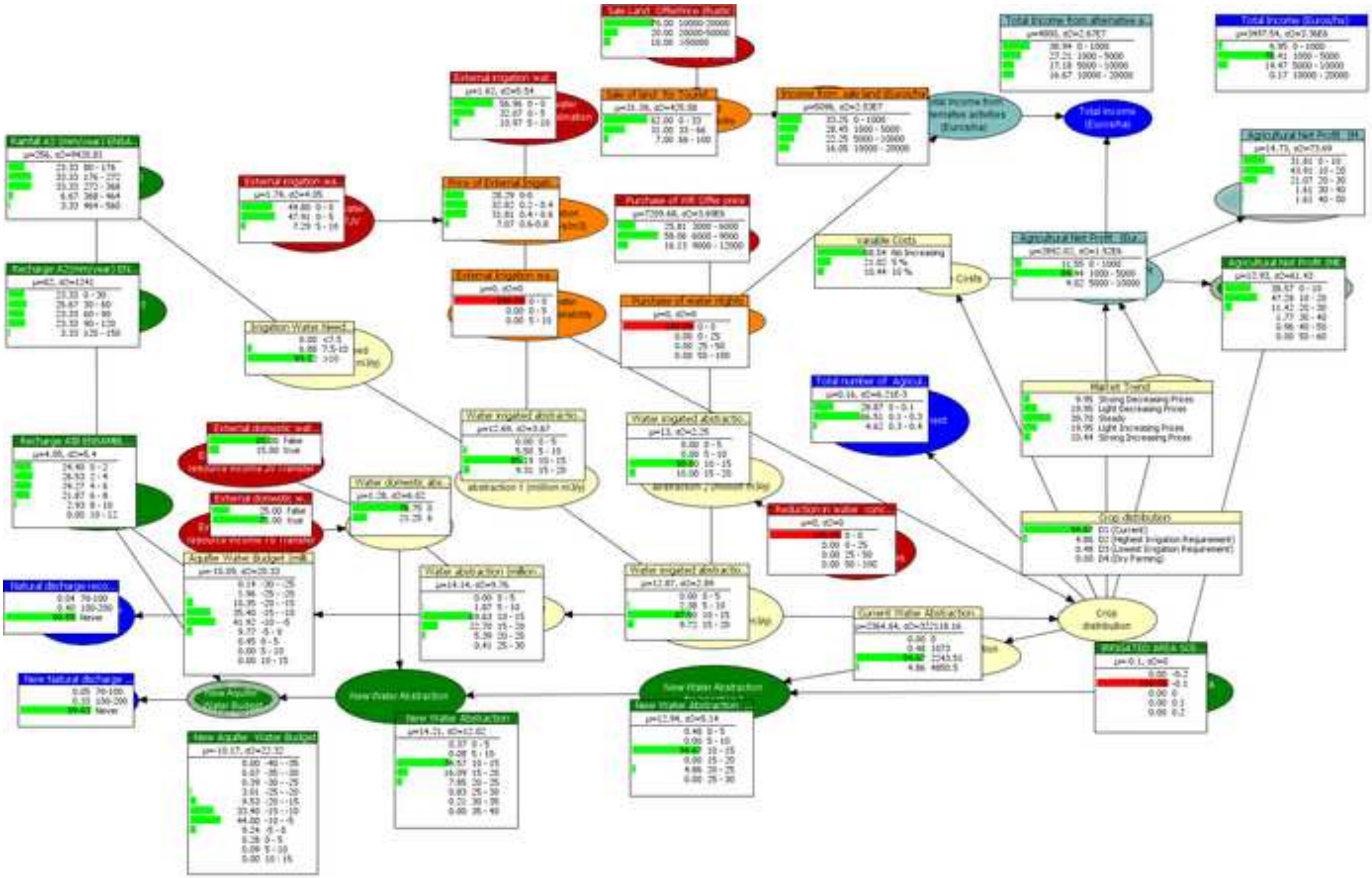

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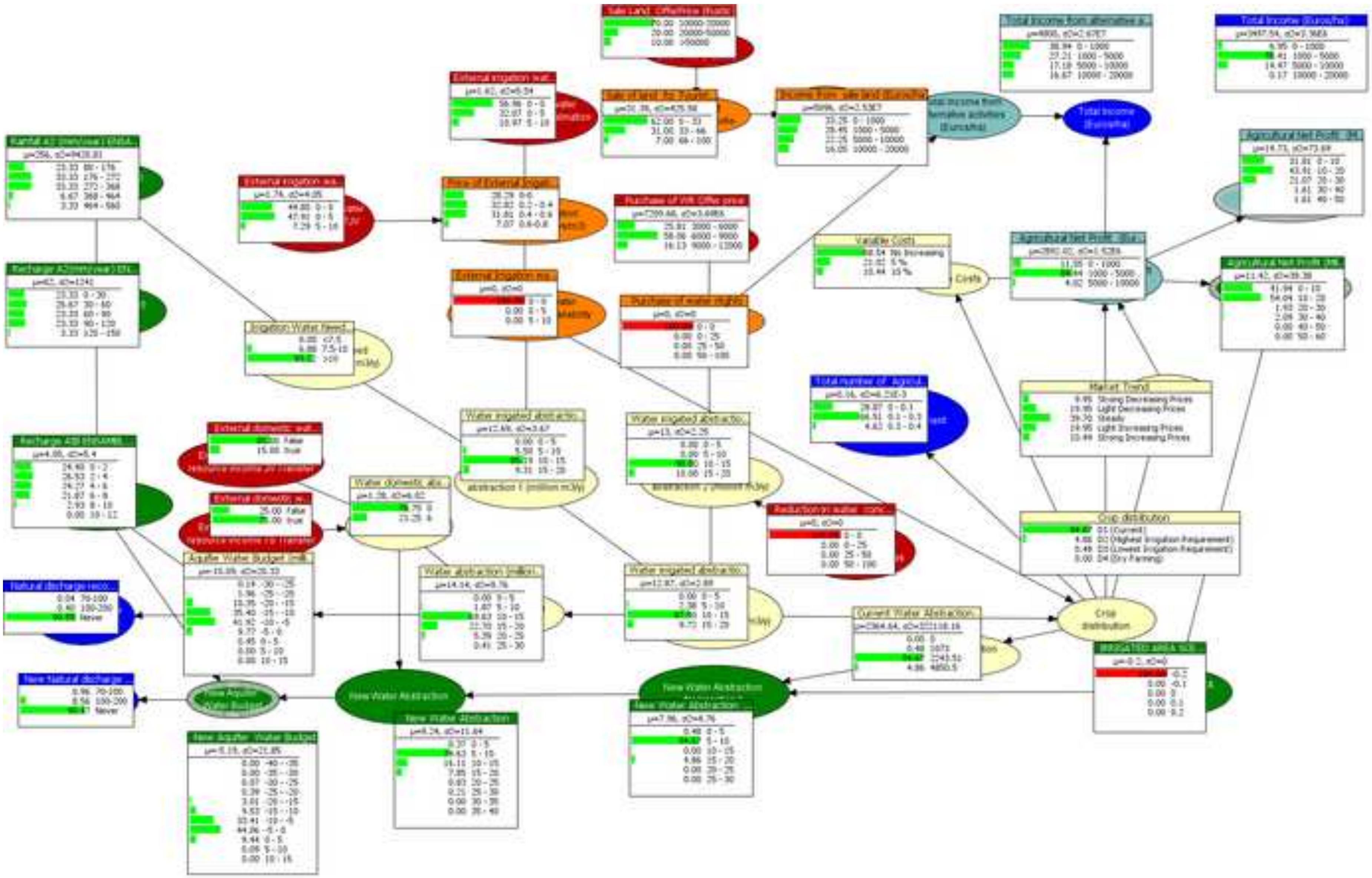

Figure 10a
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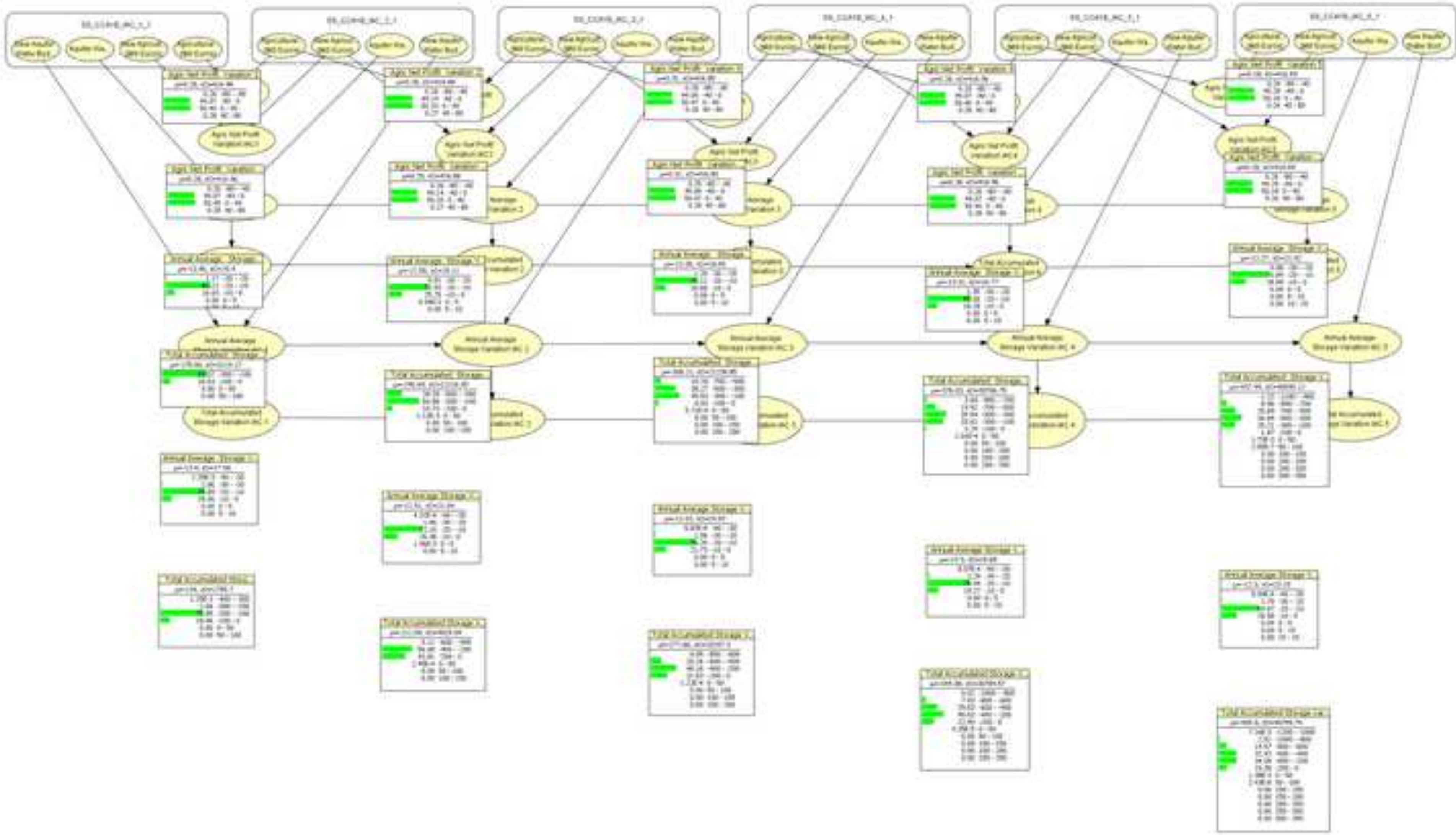

Figure 10b

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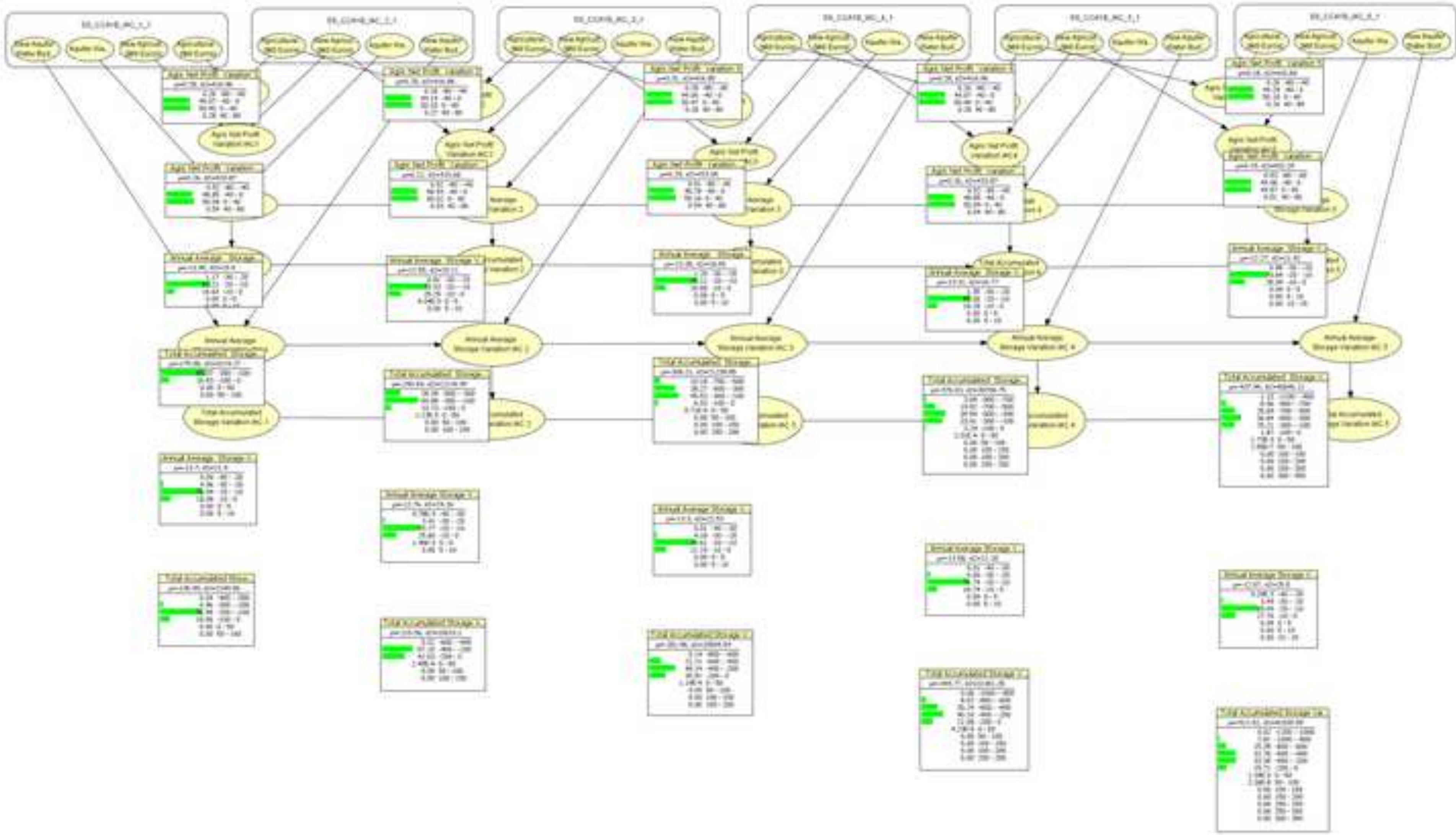

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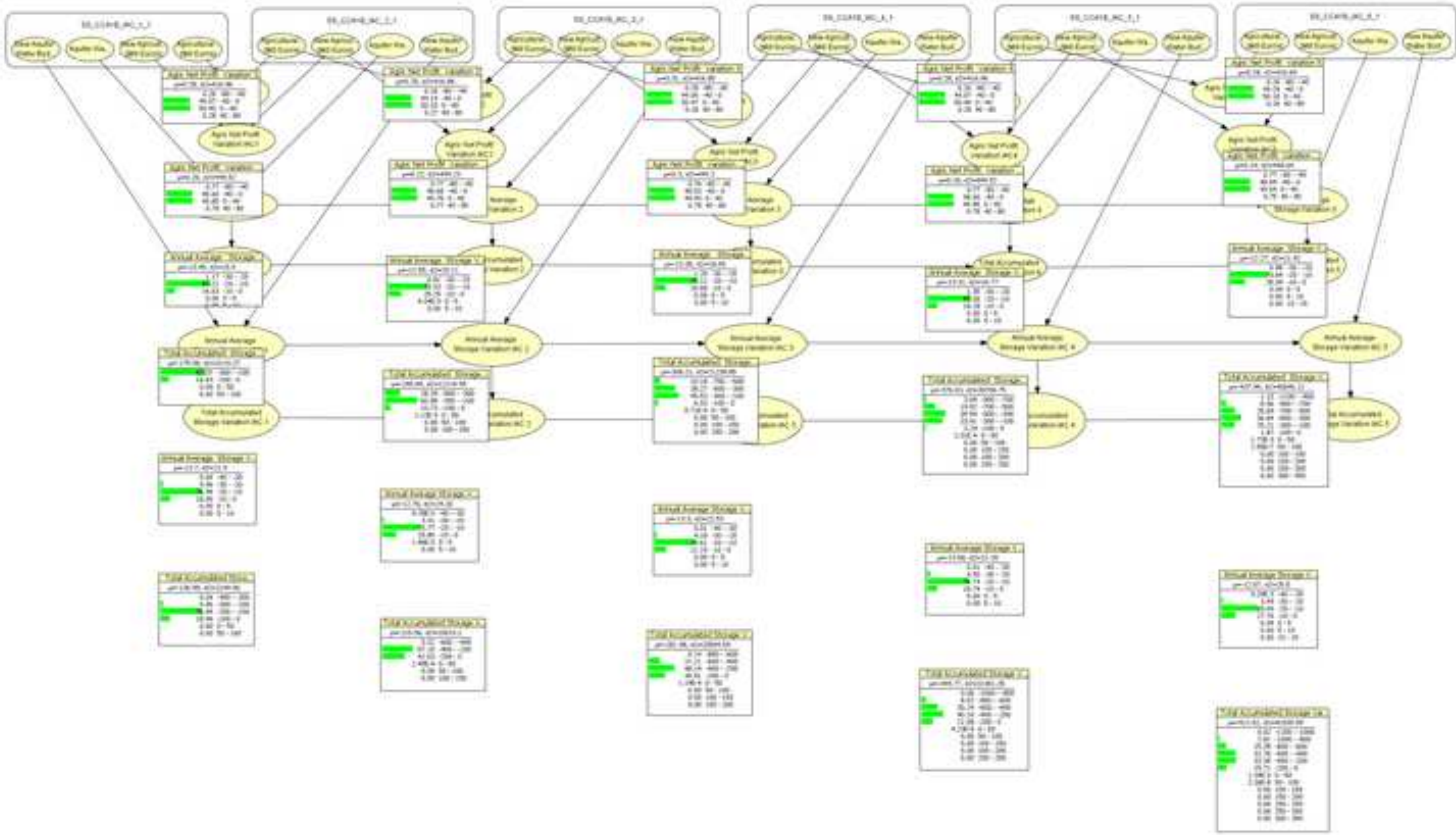

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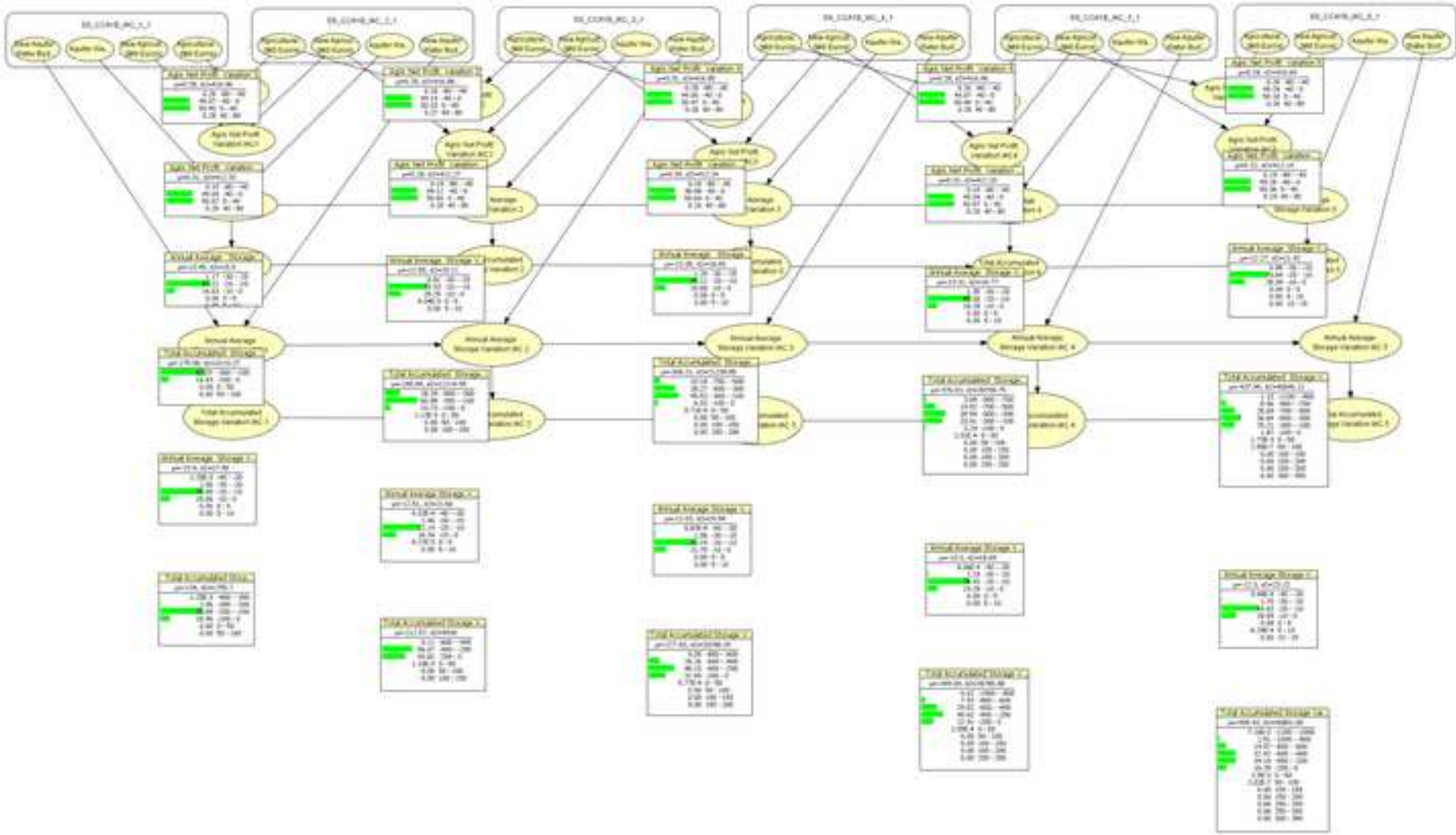

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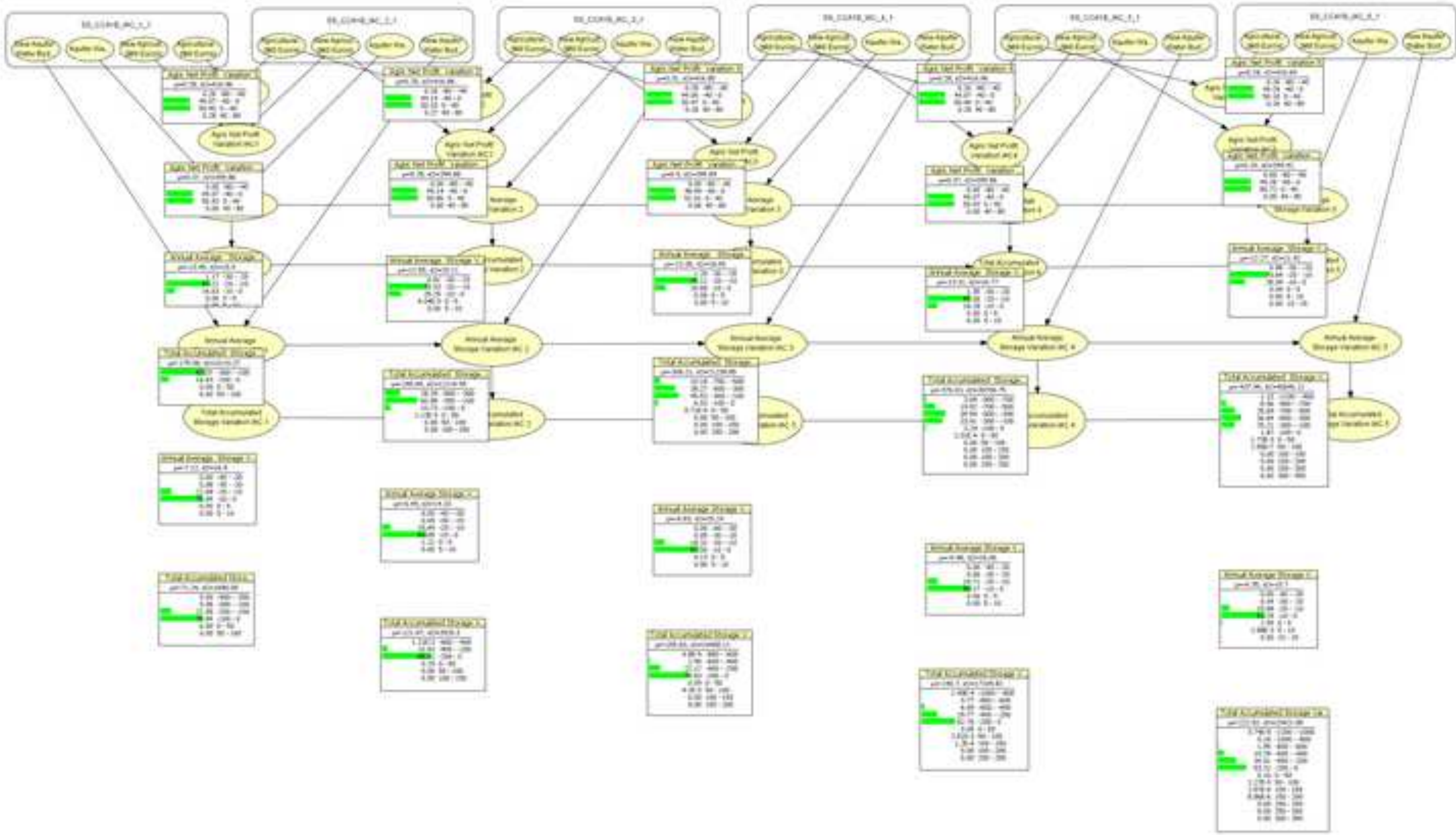

Figure 11a

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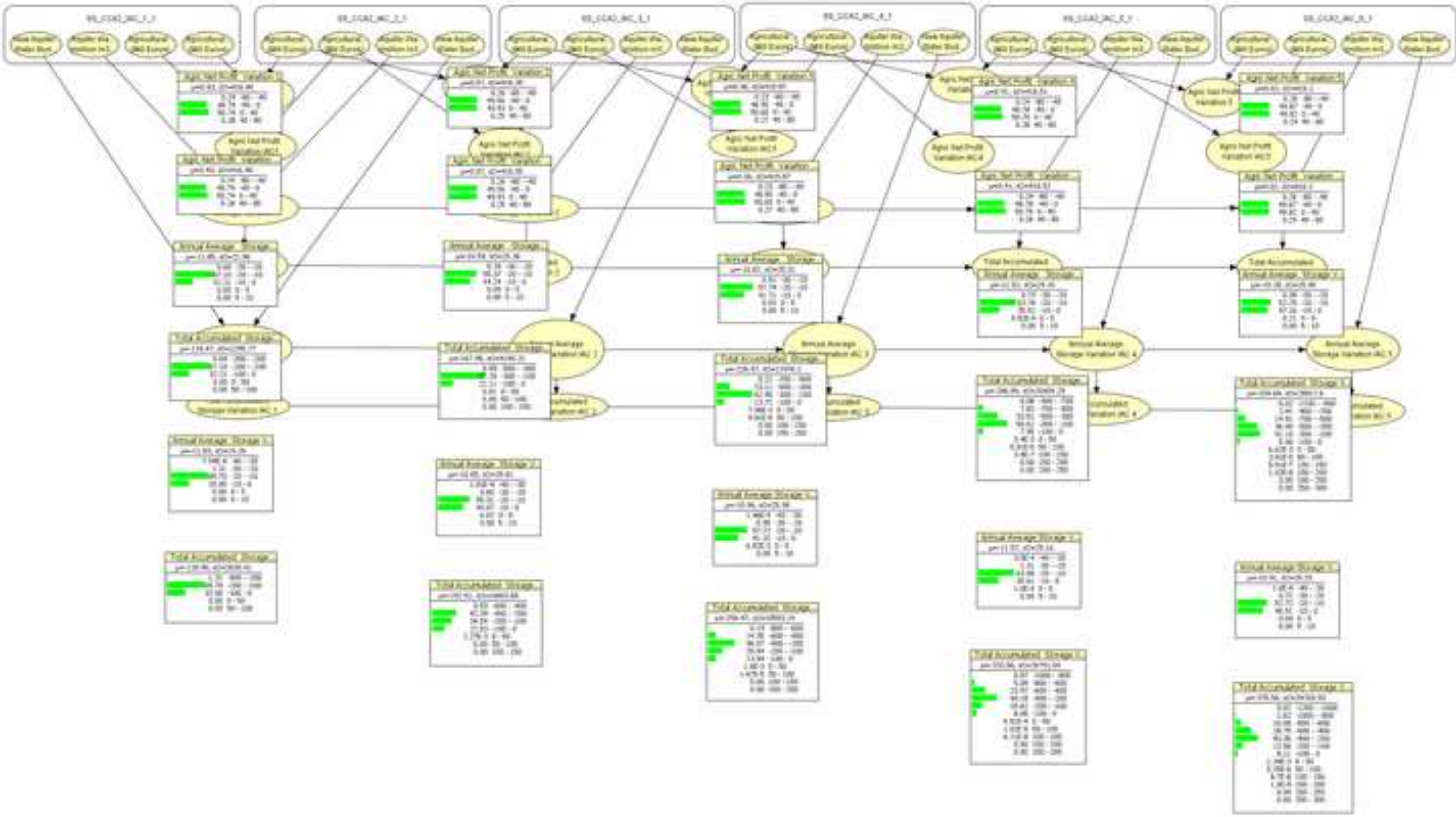

Figure 11b

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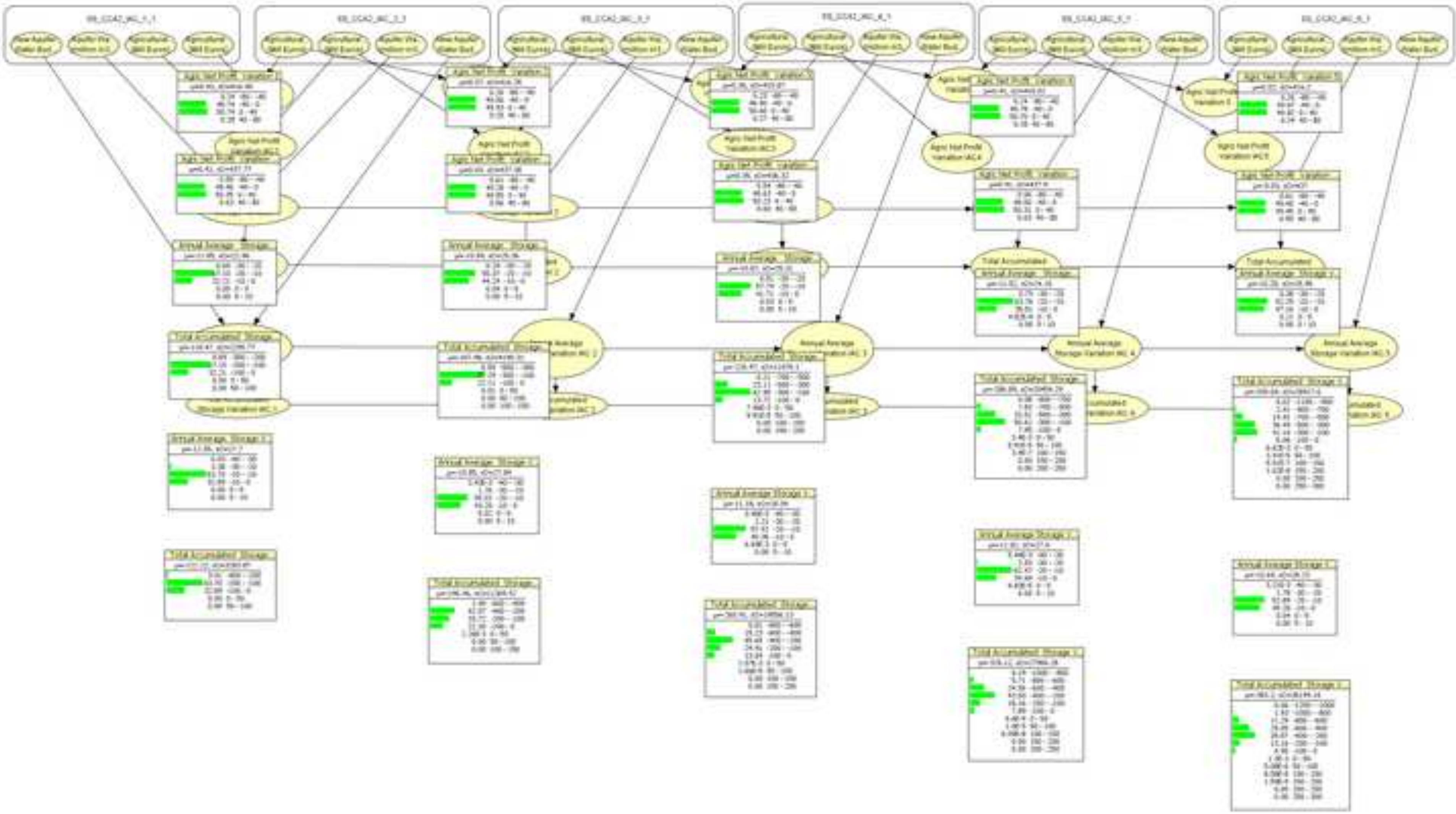

Figure 11c

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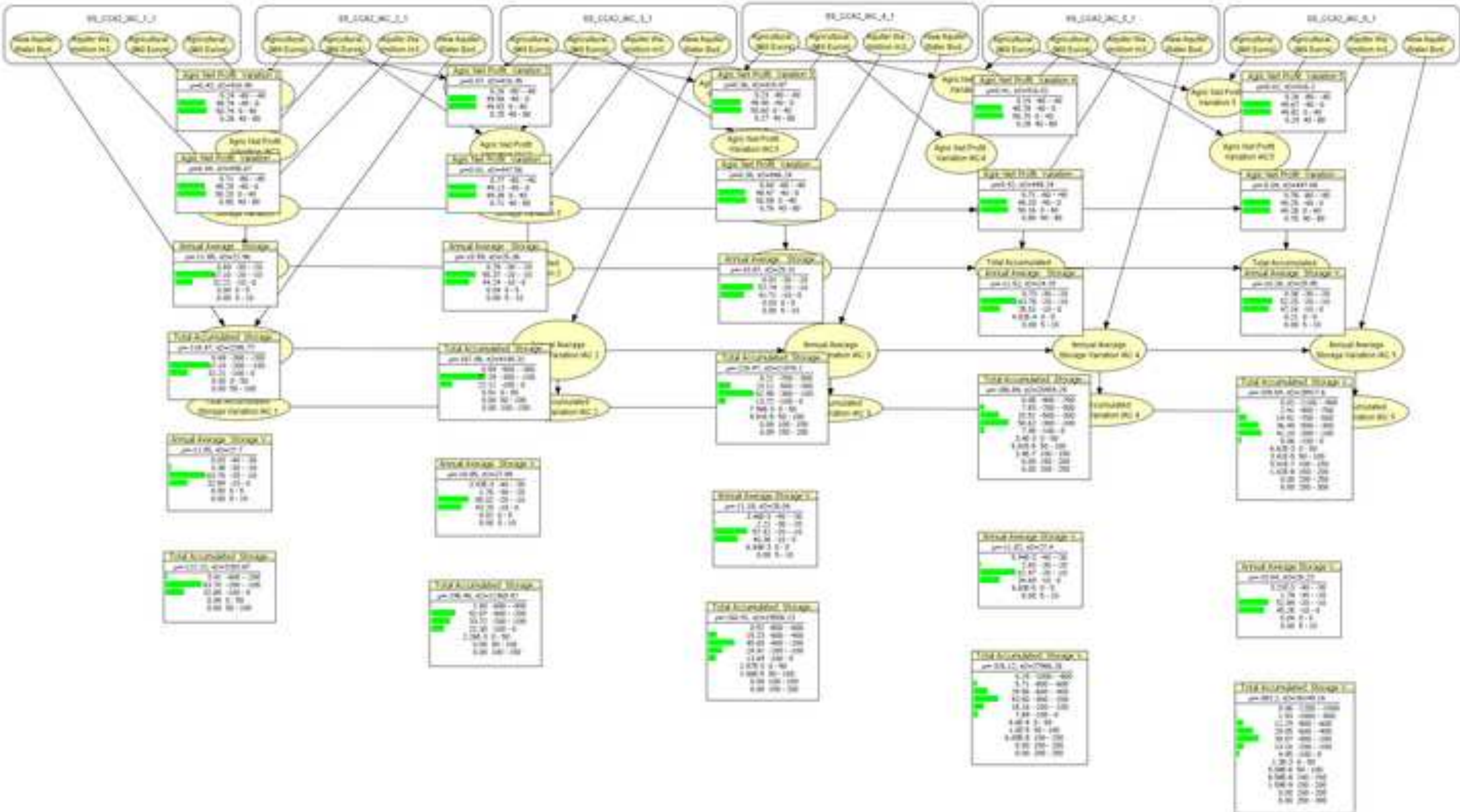

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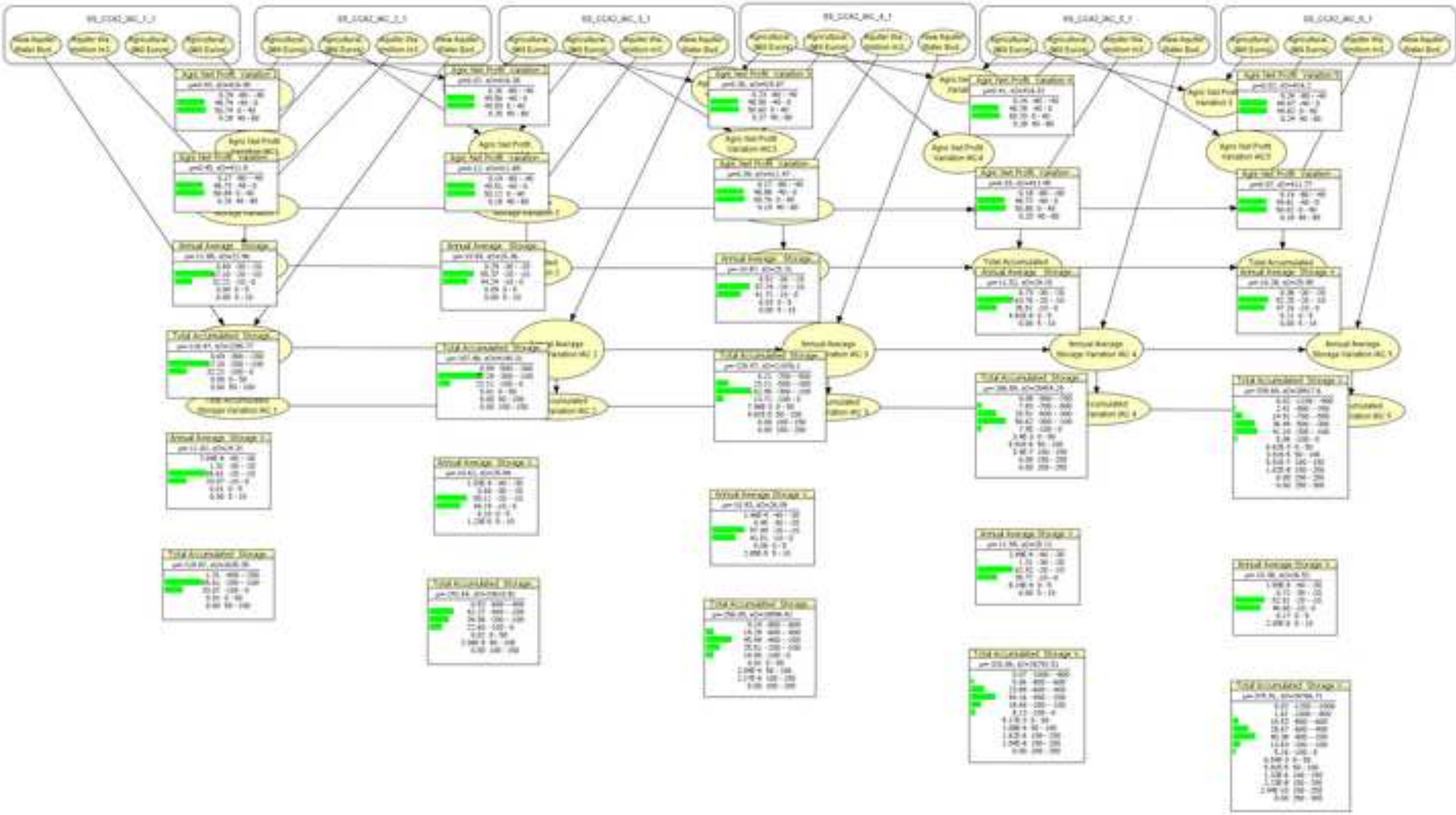

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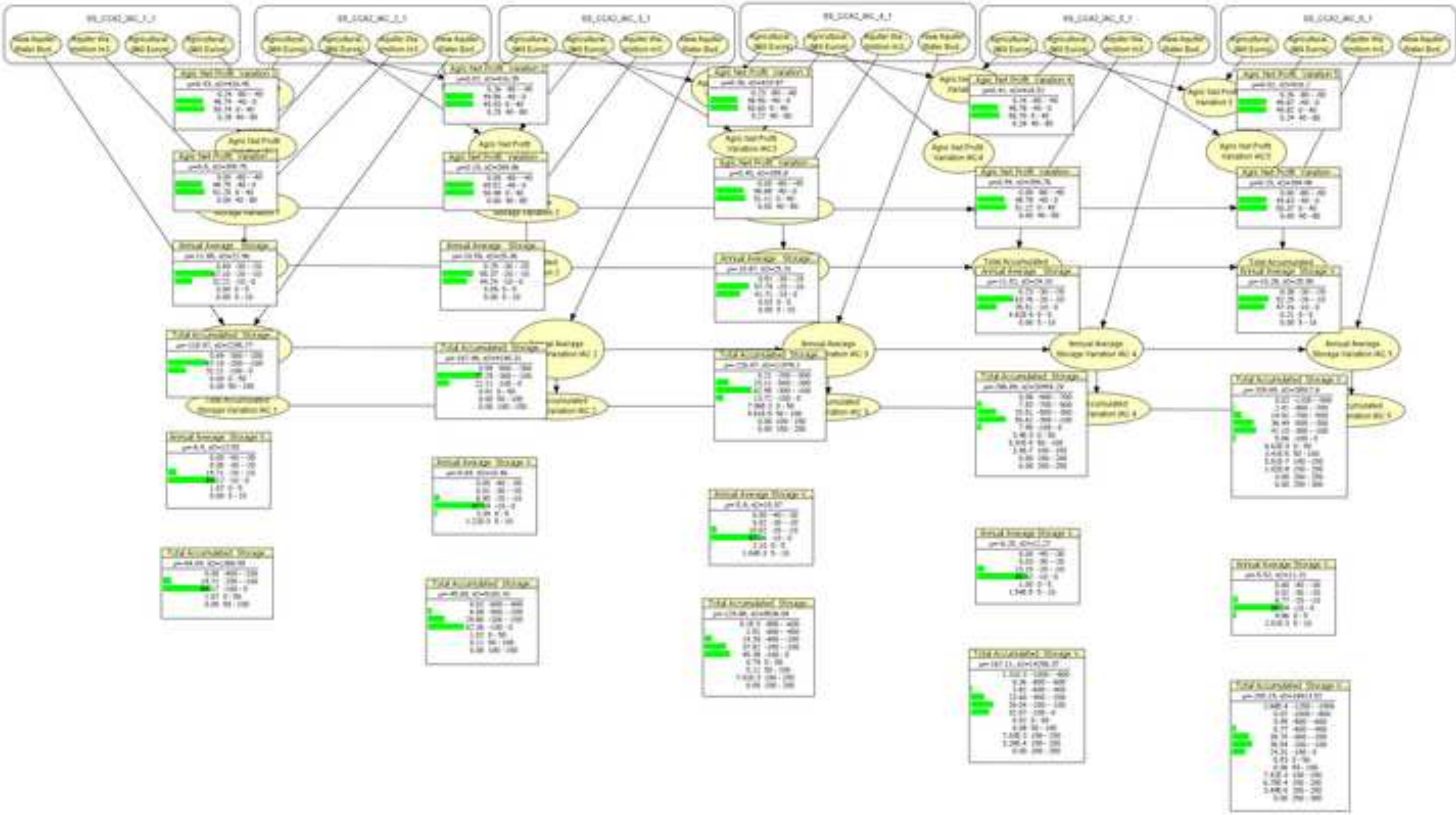

HIGHLIGHTS for the manuscript *"Dynamic Bayesian Networks as a Decision Support Tool for assessing Climate Change impacts and adaptation of groundwater systems"*

- DBNs are used to assess impacts generated by different Climate Change (CC) scenarios.
- We quantify hydrological and socioeconomic impacts generated by Climate and Land Use changes.
- These applications allow establishing adaptation strategies for aquifer systems as the CC comes into effect.
- Uncertainty, by means of probability, is incorporated in the assessment.
- DBNs are an extension of traditional non-transient nature BNs, for modeling dynamic systems.