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An iterative construction of multi-agent models to represent water supply and demand dynamics at the catchment level☆

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A R T I C L E I N F O

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A B S T R A C T

Companion Modelling (ComMod) is an iterative approach of modelling in interaction with local stakeholders. KatAWARE is a multi-agent model constructed through a ComMod process with the Water User Association of the Kat River Valley, Eastern Cape, South Africa. By describing the construction of the KatAWARE model, the aim of this paper is to propose a detailed methodology to formalize and to systematize the modelling phases of Companion Modelling. The Kat River catchment will serve as case study for the application of the proposed methodology. This methodology is composed of four steps: (1) the specification of the structure of the system, its dynamics and the indicators one wants to monitor, (2) the description of the initial state of the simulation, (3) the implementation of the model which can take the form of a computer program or of a role-playing game, (4) the reflection step to criticize the model and to propose further improvements. For the first two steps, we propose to use a representation based on the Unified Modelling Language.

1. Introduction

Within the project: “a stakeholder driven process to develop a Catchment Management Plan for the Kat River Valley”, funded by the Water Research Commission (WRC) of South Africa, a process of participatory water resource management was initiated by the Institute for Water Research (IWR) and the Geography Department at Rhodes University. An integral part of the participatory process was the development of a negotiation-support tool to enable the local water management institution, i.e., the Kat River Water User Association (KRWUA), to discuss future scenarios related to possible water allocations among the different sectors in the catchment, and the consequences of these scenarios in terms of economic, social and environmental outcomes (Farolfi et al., 2008). This tool, a Multi-Agent System (MAS) called KatAWARE, was developed and used following a participatory action research approach called Companion Modelling (ComMod) (ComMod, 2003).

Participation in the decision-making process by all involved stakeholders is a crucial principle of Integrated Water Resource Management (IWRM) (Conca, 2006, p. 141). Furthermore, two European Union (EU) directives give new importance to public participation in water management (EU, 2001, 2003). Computer models can provide a general and flexible framework to study how water and river basin systems behave and how these systems may react to different policy choices. They can also contribute to the involvement of citizens and other stakeholders, by allowing a range of “what-if” scenarios to be tested simply and rapidly (Brugnach et al., 2007).

Water management has a long history of using models as bases for decision making (Horlitz, 2007). However, policy makers were mostly not familiar with the modelling process. Many policy makers used models as if they were a black box, i.e., a device that, operating in a way that is completely ignored, provides the desired output result (Brugnach et al., 2007).

In order to move from the “top-down” traditional way of implementing decision making in water management into a participated process involving all stakeholders, participatory modelling (PM) was introduced. PM can take many forms (conceptual, practical, and formal) and can serve many needs (Magnuszewski et al., 2004). However, the common purpose of this type of approach is to increase understanding of the complex socio-ecological systems across all levels and sectors of society. PM is characterized by the fact that stakeholders are directly involved into the design of the models in order to ensure that the models are

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aiming at the problems and stakeholders are able to use them (Horlitz, 2007). This form of participation is not only used to collect local or regional knowledge about environmental problems (Yearley et al., 2003), but also creates a forum in which "experts may learn about different aspects of the usefulness of their tools in a policy process" (Jonsson and Alkan-Olsson, 2005, p. 13). In such a process, potential users are actually asked to help develop and test the models (Horlitz, 2007).

A particular PM posture is represented by the ComMod approach. ComMod is a process where "modelling deals with the dialectic among the researcher, the model and the field. Simulation accompanies an iterative research process, which is specific to each situation. The endless following cycle 'field work—modelling—simulation—field work again, etc.' corresponds to this concept. This leads to the acceptance of a diversity of models and methods, each contributing to a new kind of relationship between the simulation, the research itinerary, and the decision-making process" (ComMod, 2003). Consequently ComMod is a participatory research methodology where the researchers' research process and the stakeholders' negotiation process are conducted in close interaction. In this methodology, building a model, implemented as a role-playing game and/or a computer program, is considered as a mean and not as an end. The model is, in general, not considered as a delivery to be used outside of the process. Consequently, the intelligibility of the model (rather than its usability) by both the researchers and the stakeholders is of outmost importance. ComMod scientists make wide use of MAS, a powerful way to represent and to simulate multi-stakeholders activities in interactions with their environment (Ferber, 1999). A MAS is a kind of model composed of an environment with its dynamics, and a set of interacting agents, i.e., autonomous, goal-oriented, acting and perceiving entities. The interactions among the agents and with the environment are able to produce emerging organizations. The environment in MAS is particularly suited to model the biophysical dynamics (here the hydrology) and the agents are able to model the stakeholders' behaviours as well as their interactions (here the farmers' individual and collective practices). Such models are considered easier to understand by the stakeholders than a bundle of variables and equations or even than dynamical models (e.g., Purnomo et al. (2009)).

MAS is more and more used for modelling socio-ecosystems. Extensive reviews can be found in Bousquet and Le Page (2003) for ecosystem management and in Parker et al. (2003) and Matthews et al. (2007) for modelling land-use change. Bithell and Brasington (2009) and Monticino et al. (2007) are using MAS coupled with a forestry and a hydrology model but do not address water management *per se*. Smajgl et al. (2009) proposes a multi-agent model for water trading but, even if data are elaborated with the stakeholders, the outcomes of the model was not discussed with them. A number of natural resource management cases implying the stakeholders in south-east Asia is described in Bousquet et al. (2005) among which are some cases on watershed management.

Several examples of MAS can be found in the recent literature more specifically about decision support tools and processes for water management. SHADOC (Barreteau and Bousquet, 2000) is a MAS reproducing a kind of "virtual irrigated system" in order to study the influence of existing social networks on the viability of irrigated systems in Senegal. Ducrot et al. (2004) developed a prototype multi-agent model to represent the relationships between urbanization dynamics and land and water management in a peri-urban catchment area in Brazil. The CATCHSCAPE model (Becu et al., 2003) is a MAS that enables to simulate the impacts of upstream irrigation management on downstream agricultural viability in a small catchment in Thailand. SINUSE (Feuillette et al., 2003) explores the interactions between the physical and the socio-economic components of a water table system based in Tunisia. It allowed pointing out the importance of non-economic and local behaviour on the global dynamics of the system. Berger and Ringler (2002) developed a MAS to generate valuable information about interrelated water and land issues at multiple scales in the Mekong basin. Some of the multi-agent models illustrated above were constructed in a sort of participatory process involving local stakeholders and decision makers at various degrees.

The previous examples either were not used within a ComMod approach, or, when Companion Modelling was adopted, it followed a different methodology with respect to the one presented in this study.

The ComMod iterative process proposed to develop the KatAWARE model, conducted the research team to produce several versions of the model by following a method based on four main phases: (1) the specification of the structure of the system, its dynamics and the indicators one wants to monitor, (2) the description of the initial state of the simulation, (3) the implementation of the model which can take the form of a computer program or of a role-playing game, and (4) the reflection step to criticize the model and to propose further improvements. This sequence of four phases constitutes an attempt to formalize and to systematize the modelling phases of Companion Modelling.

The objectives of this paper are twofold: (1) to present and to discuss the proposed methodology to formalize a ComMod process and its iterative production of models on the Kat River catchment, and (2) to propose a detailed representation of the models using the Unified Modelling Language (UML). The UML representation plays an important role in facilitating a shared understanding of the model structure and dynamics among the experts and between the experts and the modelers.

The paper is organized as follows: the Section 2 illustrates and discusses the four methodological phases through which each version of the model was developed; the Section 3 provides a short overview of the case study area; the Sections 4–6 present the model versions, while the Sections 7 and 8 discuss the results, conclude and indicate some research perspectives.

2. Methods

ComMod is an iterative process as illustrated by the Fig. 1 in which, at each cycle, a new version of a model is presented to the stakeholders either in their computer form or as a role-playing game (RPG) for validation and discussion. In order to enable the interactions and discussions among the experts and the stakeholders, each cycle operates in four stages:

1. in a first stage a conceptual model (composed of the structure and the dynamics) is built using a representation largely independent from any implementation within a concrete software,

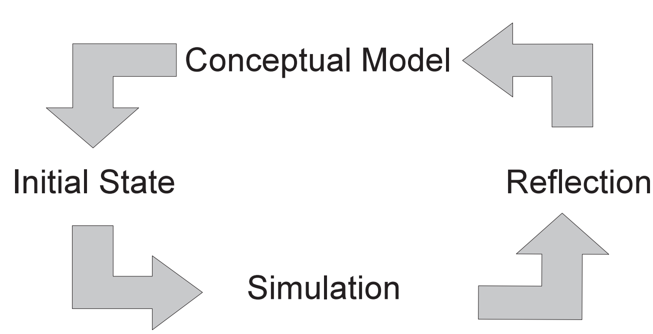

Fig. 1. A cycle of iterative modelling in four stages.

2. in a second stage, the initial state of the concrete system is defined, collecting all the necessary data,
3. in a third stage, the whole system is implemented and simulated, either as a computer program or as a RPG,
4. finally the resulting model and its simulation results either as a computer program or as an RPG are discussed through debriefing sessions for validation and improvement.

Each cycle is aimed to contribute to a better understanding of the situation, a clearer formulation of the research and development questions as well as a better adequacy of the model. These stages are described in details in the following text.

2.1. *Building the conceptual model*

Modelers have recognized the need to build conceptual models either for designing their models and simulations, or for communicating what is inside their models, or both. Unified Modelling Language (UML) (Booch et al., 1999) is more and more used for such a purpose (see Müller and Bommel (2007) for a detailed introduction to UML for modelling). UML provides a number of diagrams especially for describing a software system. However, we as well as other authors (e.g., Muzy et al., 2005) recognize that UML can be used not only for representing the implementation, but also for the domain knowledge of the scientists. This domain knowledge is composed of a structural part describing the concepts translated into the model's variables and their relations and a dynamic part describing the processes. Additionally, we will describe which information the stakeholders as well as the scientists want to monitor during the simulation in accordance with the identified research and development questions.

2.1.1. *Model structure*

In UML, the model structure can be illustrated through a class diagram. A class diagram (Booch et al., 1999) is made of classes linked by associations and taxonomic relations. A class is represented by a three parts box with the name of the class or category (e.g., the categories River, Farmer, etc.), a list of attributes characterizing this concept (e.g., the size, the cash flow, etc.) and a list of operations on the concept (e.g., growing, earning money, etc.). In Becu et al. (2003), the class diagram describes the actual implementation using the CORMAS simulation framework (Bousquet et al., 1998) as a set of predefined classes. This class diagram is very close to the conceptual model we will present, but it is mix of implementation classes and domain concepts which may produce confusion.

However, from the experience reported in this paper, UML appears to be at the same time too specific and too general:

- too specific because the operations in the object-oriented languages have a well defined operational semantics (i.e., procedure calls) which does not correspond to our intended meaning. For us, the operations are the specification of events associated to activities or processes.
- too general because the attributes can be anything: parameters, state variables, details of implementation, caches, etc. From a conceptual point of view we need the former two distinctions but not the others.

In order to better specify the meaning of our constructs, we systematically use the stereotypes as provided in UML.

In this paper, we propose for the attributes the following distinctions:

2.1.1.1. Parameters. The attributes which have a fixed value for each simulation (but possibly varying from one simulation to another). For specifying how to initialize the model, we must be even more specific by distinguishing:

1. parameters which are fixed for all the individual of a given category. For example, all the crops have the same given growing rate.
2. parameters which are fixed but different for each instance, called the individual parameters. For example, each crop might have its own specific growing rate, introducing heterogeneity in the system.
3. parameters whose variation is determined for each simulation, called the dynamic parameters. For instance, the rainfall could be defined over periods of time, introducing weather scenarios.
4. parameters whose variation is defined for each instance, called the individual dynamic parameters. For example, one could predefine (rather than compute) a sequence of crop choices for each farmer.

2.1.1.2. State variables. The attributes of which the value changes during the simulation and for which an initial value must be provided.

These distinctions are introduced in our conceptual model by using stereotypes (see Booch et al., 1999), i.e., markers of the form <<parameter>> (fixed value for all individuals), <<iParameter>> (fixed value by individual), <<dParameter>> (time series for all individuals), <<idParameter>> (time series by individual) or <<state>> (varying through simulation) in front of each attribute.

2.1.2. *Model dynamics*

To fully describe the dynamics one should specify:

- the state variables changed by the dynamics;
- the interactions among the entities using event specifications;
- how and when these events are issued in case of endogenous behaviour and at a finer detail, how each entity reacts to events and behaves.

2.1.2.1. State specification. The state specification is made by defining the state variables using the <<state>> stereotype as described in the previous section.

2.1.2.2. Event specification. For the first aspect, we use UML operations to document the dynamics. However, these operations should not be taken as methods in the sense of the object-oriented languages but rather as specifying events possibly received by the associated classes (i.e., input events). We distinguish three types of events:

- the endogenous or *internal* events: for example, the class Quaternary catchment must compute its water yield every month or the farmer must choose its crops every year. We chose to use either the verb "compute" (for biophysical dynamics) or "choose" (for human behaviour) for these events (and, therefore, these events trigger a computation or a choice);
- the *external* events which can affect the state of an entity: for example, the cropping system of the farm is changed by setting the crop allocation. We chose to use the verb "set" for these events;
- the events to get information from the entities (in principle, without changing their state) called the *logical* events: for

example, the class Quaternary must ask to the situated entities their water demands in order to compute its water balance. We chose to use the word “get” for these events.

We also use the UML stereotypes to tag the various events.

2.1.2.3. Process specification. For the second aspect, the UML activity diagram (Booch et al., 1999) illustrates how the endogenous activities (triggered by the <<internal>> events) are sequenced over time. An activity diagram is made of boxes for each activity, linked by arrows to indicate the sequence. Additional bold lines are used to mark the moments where several activities are starting or finishing a parallel execution (for example, simultaneously doing something and monitoring the environment). In Becu et al. (2003), for instance, an activity diagram illustrates the crop choice algorithm.

More diagrams are provided to describe not only the sequencing of the activities but also the activities themselves. However, at the conceptual level, methods to express the dynamics, including differential equations, are numerous and exceed what exists in UML, as UML is only devoted to describing computational processes. A general model should be able to combine arbitrarily discrete and continuous time as well as processes, respectively, described by ordered actions or differential equations. We, therefore, chose to combine UML and other methods more appropriate to the dynamics to describe.

2.1.3. Simulation observables

Describing the dynamics of the system is not sufficient. We must also specify which parts of the system state to monitor in order to follow what is going on throughout the simulation. In order to do that, we also introduce the *probes* as a kind of events to monitor the simulation state and, therefore, to define the observables or indicators the stakeholders and domain experts are interested into. Again, the stereotype <<probe>> is used to tag this particular kind of events.

2.2. Initial state

Building the initial state consists of describing the concrete model, providing the full list of instances (e.g., the list of rivers, farmers, etc.) as well as the values for all the parameters and state attributes. It results into the actual structure of the system as an instance of the conceptual structure. The UML object diagram (Booch et al., 1999) can be used for this purpose. The object diagram is made of boxes representing the concrete instances of the classes (or concepts) described in the class diagram, structured with links as instances of the corresponding associations among the classes. However, the object diagram is not very sophisticated because using it for describing a complete system can be tedious. In the following, we will only use this diagram to illustrate parts of the system. Most of the initial state will be described by simple tables presenting the parameters.

2.3. Implementation and simulation

We shortly present how the model has been implemented and used with the stakeholders. Deriving the implementation from the conceptual model refers more to the field of software engineering, which is not the purpose of this paper, and is very dependent of the targeted platform (in our case CORMAS or MIMOSA) and programming language (here Smalltalk or Java) and environment. However, an original way of implementing our models in the ComMod approach is through the design of a RPG where the biophysical dynamics are implemented with computer simulations or with very simplified physical mockups and where the social dynamics are played by the stakeholders themselves. Therefore, the simulation can be carried out either by the stakeholders or by the computer in front of the stakeholders, providing two different and complementary ways to allow interactions among the various involved actors. The advantages and disadvantages of either approaches (use of model Vs. use of RPG) will be discussed.

2.4. Reflection

Building a model within ComMod is an iterative process to improve the understanding of the model and the suitability of the model to the stakeholders' needs. One cannot expect from the start to have thought (both the scientists and the stakeholders) about all the necessary details, and even about the actual question to be answered. Therefore, it is part of the modelling process to report on the outcome of the debriefing sessions in terms of validation and proposed improvements to be taken into account in the next modelling cycle.

3. The Kat catchment

The Kat River Valley (see Fig. 2) is situated in the Eastern Cape province of South Africa. The river is a tributary of the Great Fish River and falls within the Fish to Tsitsikamma Water Management Area. Although the watershed has a relatively high rainfall, much of the climate of the 1700 km^2 catchment is sub-humid to semi-arid. The area is either marginal for or unsuitable for rainfed agriculture; only through irrigation using water from the Kat River can the agricultural potential of fertile land on the valley floor be realised.

The present land use in the catchment is the result of a complex history of politically driven changes to land access since the time of settlement by white colonialists in the early 19th century.

In 1969 the Kat Dam was completed at the behest of farmers to irrigate tobacco and citrus crops, as well as to supply water to the town of Fort Beaufort, located in the middle of the catchment. The total area of land scheduled for irrigation below the dam was 1500 ha. Farmers with scheduling paid an annual license fee in return for which they were able to irrigate freely the amount of land granted to them, but could not expand beyond this area. The scheduled land was almost exclusively located between the dam and Fort Beaufort. Farmers below Fort Beaufort opted out of scheduling on the grounds that sufficient water would always be available for their needs. These unscheduled farmers did not pay a license fee, but could request a release from the dam at their own cost.

Today there are four groups of irrigators in the Kat Valley: small scale black farmers, often forming cooperatives, large-scale ‘emerging’ black farmers, white commercial farmers with scheduled water rights, white commercial farmers without scheduled water rights.

Domestic water users and the municipality of Nkonkobe can be added to these irrigators to complete the picture of the main water related stakeholders in the Kat Valley: the four groups of irrigators, domestic water users and the municipality.

The complex and contentious political history of the valley has given rise to a power dynamic that historically has favoured the white commercial farmers at the expense of the black population. These white farmers controlled water use through the Kat River Irrigation Board. As part of the redress process, all irrigation boards have been required under the National Water Act to transform themselves into Water User Associations (WUA) that are representative of all water users in the area.

The Kat River WUA came into being in December 2001 when its constitution was gazetted by the Minister of Water Affairs and Forestry. The process had begun in October 1999 when the

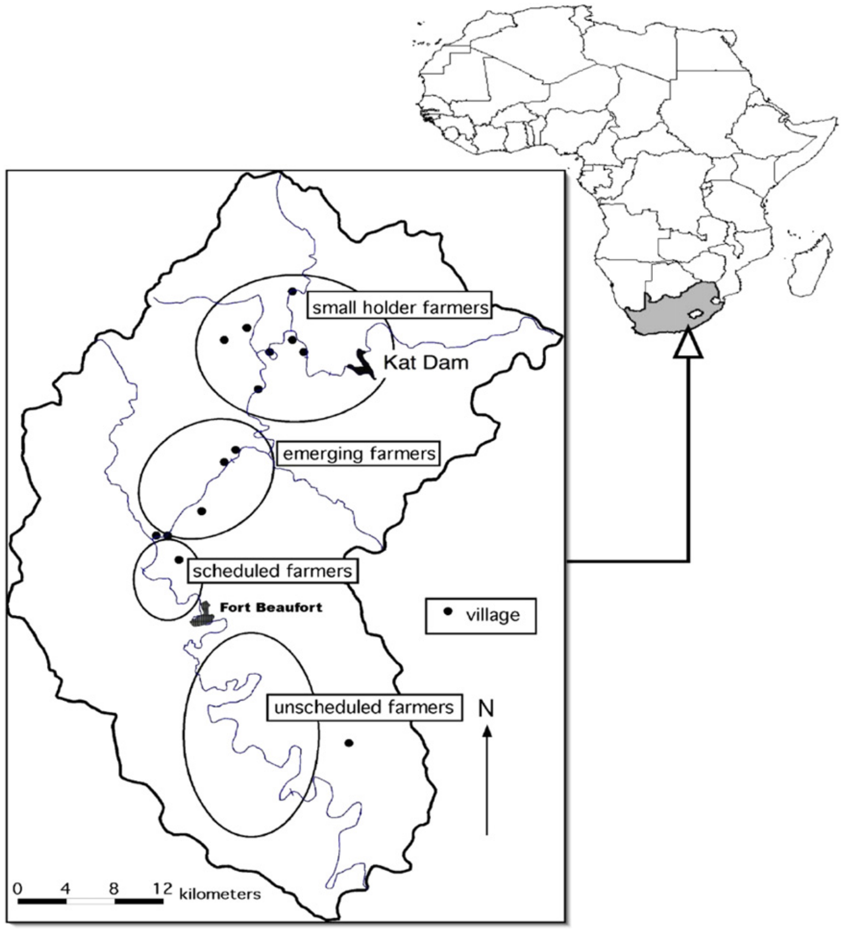

Fig. 2. The Kat River Catchment (Farolfi and Rowntree, 2007).

commercial citrus farmers from the Kat River Irrigation Board approached researchers from Rhodes University for assistance in facilitating the transformation to a broader WUA that represented all water users in the Kat Valley. Water users represented on the WUA are at present as follows: large-scale irrigators (over 5 ha), small scale irrigators (under 5 ha), domestic users and the municipality. The steering committee of the Kat WUA has spatial representivity, with members coming from the area falling within the former Bantustan called Ciskei (the upper Kat), the scheduled areas for irrigation water use from the dam that remained within the RSA (the Middle Kat) and the unscheduled irrigated areas (the Lower Kat). The upper Kat is mainly populated by small scale black irrigators producing annual crops and emerging farmers that have inherited former communal irrigated plots previously managed by the Bantustan authority. In the middle Kat live large-scale white farmers producing citrus in scheduled lands. In the lower Kat operate unscheduled large-scale white farmers. In addition there are representatives from the Kat River Catchment Forum, a group representing mostly domestic users who are concerned about catchment management and water use issues in the 'upper' Kat. The constitution of the WUA includes the following objectives: to provide water for the beneficial use of members; to actively care for and manage the health of the Kat River and Kat Dam through educational programmes. Under ancillary functions the WUA is mandated to "provide catchment management services to or on behalf of responsible authorities".

In 2000 researchers from Rhodes University became actively involved in the process of transforming the irrigation board to a water user association, and more recently (2004–2007) have led a Water Research Commission funded project through which the WUA has been developing its own catchment management plan for allocating water to the various water user groups. It is this project that provides the context within which ComMod was situated, giving rise to several versions of the KatAWARE model.

The local stakeholders participating in the KatAWARE process were the members of the Kat River Water User Association (WUA) board as suggested by the Rhodes University team. During a presentation workshop that took place in Fort Beaufort in October 2004, the 9 WUA board members (3 per subcatchment) were asked whether they wanted to be involved in the whole process of Companion Modelling in the Kat. Their positive reaction was followed by their participation to all ComMod phases described in this paper. It is worthwhile noticing that although the Kat WUA represents all main groups of stakeholders in the catchment (large-scale farmers, small scale farmers, domestic users urban and rural, municipality) clearly some stakeholders (large-scale farmers, urban settlers) enjoy better socio-economic conditions and higher educational levels, which provide them a great advantage in terms of skills required for participation and contribution to the collective learning process. This had important implications on the way the ComMod approach could be followed by the different participants as well as on the input they could provide to the whole process. A detailed discussion on these issues is provided in Farolfi et al. (2008).

4. KatAWARE version 0

KatAWARE V0 is a new generation of the AWARE (Action Research and Watershed Analyses for Resource and Economic

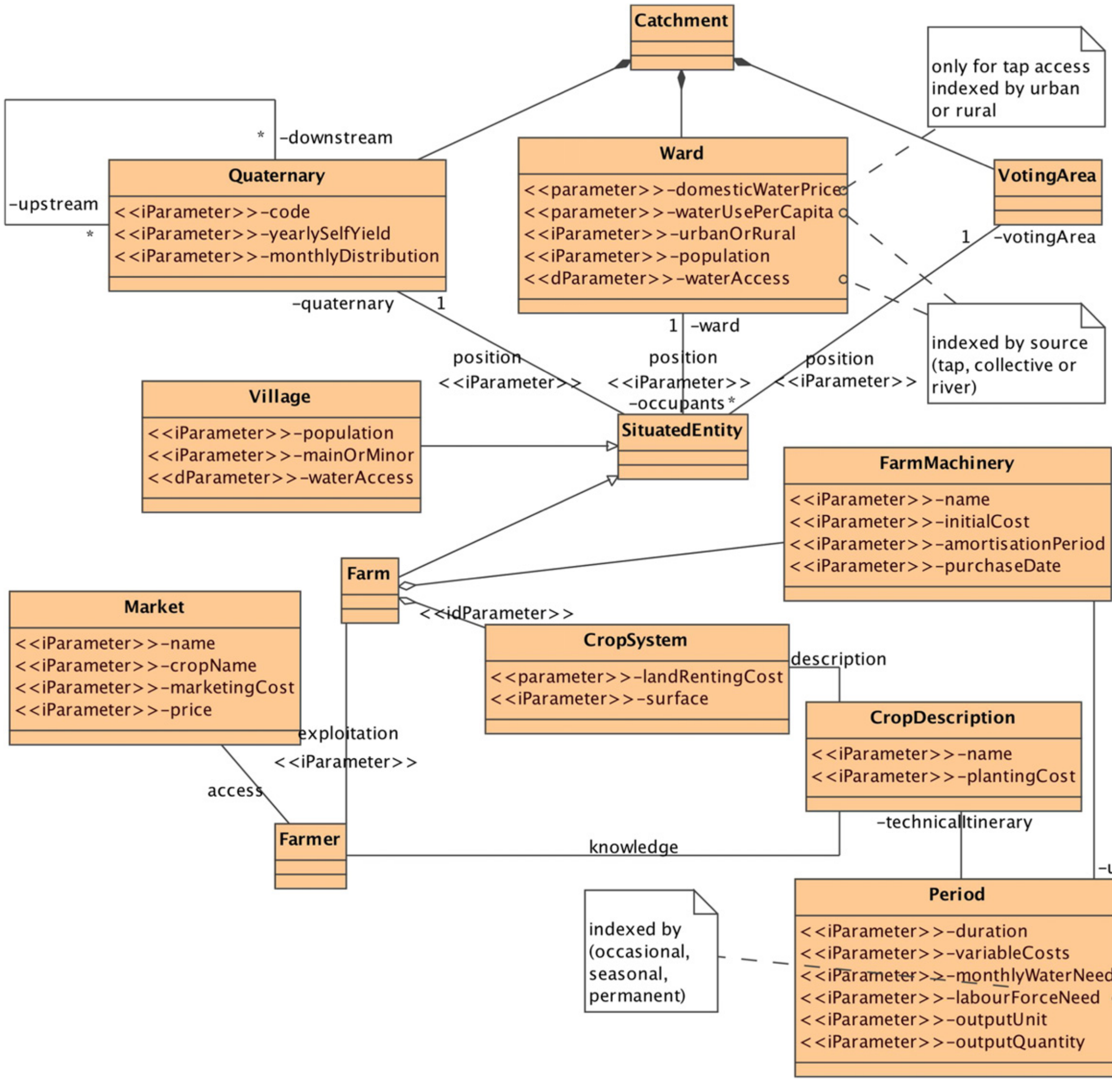

Fig. 3. The KatAWARE V0 structural model.

sustainability) model, described in Farolfi and Hassan (2003) and Hassan and Farolfi (2005). Although the two models are radically different in their structure and functioning, KatAWARE shares the same philosophy and calculates the same kind of outputs as AWARE. Hence, KatAWARE allows representing water demand and water supply in a watershed at different spatial and temporal scales. The demand is the water required by the agents and the supply is the water provided by the environment. The model focuses on social (here the employment), economic (here the farmers' income) and environmental (here the minimum water level in the river) consequences of alternative strategies of water allocation, addressing the three dimensions of sustainable development.

Demand may exceed the available water, determining a situation of stress. In this model, it is possible to observe the balance between water supply and water demand at the tertiary catchment scale or at the quaternary subcatchment scale. We did not describe the access to water by the stakeholders inside a given quaternary, hence in case of water stress inside a subcatchment it is not possible to evaluate the amount of water received by a given farm or village. However, working at these scales enables the analysis of spatially focused water stresses in the catchment, according to socio-economic choices and evolution of the different activities.

4.1. Building the conceptual model

4.1.1. Model structure

Fig. 3 describes the conceptual model. The environment is the Kat river catchment itself. The Kat River *catchment* can be decomposed into following three criteria:

- *quaternaries* for the hydrological dynamics. Each quaternary provides a given yield (the yield is defined by the South African Department of Water Affairs (DWAF) as "water that can reliably be withdrawn from a water source at a relatively constant rate") which is calculated by month. The yield and its monthly distribution is the same for all the quaternaries but the quaternary where the dam is located. The latter has a higher yield, and a uniform monthly distribution. The available water flows downstream;
- *wards* which are the smallest administrative units for which socio-economic data are available;
- the three *voting areas* corresponding to the catchment zones (upper, middle and lower Kat) having representatives in the Kat River Water User Association (WUA) for the different water use sectors.

It is worthwhile noticing that no geo-referenced data is necessary in this conceptual model. GIS data are exclusively necessary for preparing the initial state for the parameters of the model and for visualizing these units. They are not required to construct the conceptual model.

The *situated entities* are the *villages* and the *farms*. They constitute the agents of the MAS. The villages can be towns or rural settlements and represent the domestic use of water in the various wards. The farms represent the agricultural water consumption, which depends on *crop allocation*. The farms have a capital of *farm machineries*, with the amortization costs included in the budget. The *farmers* are the decision-making components, as they choose the crops to be cultivated in the farms. This choice is based on *crop descriptions* together with their technical itinerary, which is decomposed into *periods* with specific input needs and production. The farmers have access to various *markets* to sell their products. Each market has an associated price and marketing cost.

In Fig. 3 we introduced as UML attributes all the *parameters* that remain fixed throughout the simulation.

4.1.2. Model dynamics

4.1.2.1. State specification. When defining the dynamics of an object, one must define its possible states and the processes modifying the state as a function of time (internal behaviour) or in response to exogenous events (external behaviour). In terms of water dynamics:

- the state of the environment entities (*ward*, *quaternary*, *voting area*) of the *catchment* corresponds mainly to the remaining available water month after month. In our case only the quaternary monthly yield is defined (cf. Section 4.1.1);
- the state of the *situated entities* (*farms* and *villages*) is the water they actually receive depending on their demand and the available water in the quaternary.

Other dynamics concern the current *crop allocation* of the farms as a result of the farmers' decisions, the repartition of the kind of domestic *water access* (either river, collective taps or indwelling taps) as a result of the village managers' decisions and the available *cash flow* (or debt) as a result of the crop production and the subsequent commercialization on the markets. The age and the period number of the crop system (see Fig. 4) are incremented through time.

4.1.2.2. Event specification. The dynamics as explained here are specified in the Fig. 4 where only the relevant entities are described with the corresponding states and events.

4.1.2.3. Process specification. Two dynamics are intertwined:

- the water dynamics, including the supply and demands, which are computed on a monthly basis;
- the farmers' decisions on a yearly basis.

We will describe these two dynamics in the following paragraphs and finally how these dynamics are sequenced over time.

4.1.2.4. Water dynamics. Water supply is parameterized through the yearly self-yield and the monthly distribution. For each quaternary $q \in Q$ (the set of all subcatchments), given:

- $U(q)$ the set of upstream quaternary,
- $D(q)$ the demand of water in that quaternary,
- $Y(q)$ the monthly self-yield:

$$\mathrm{yearlySelfYield} \times \mathrm{monthlyDistribution}(\mathrm{month}),$$

the water runoff $R(q)$ from the quaternary q is computed as the difference between water supply and water demand: $R(q) = A(q) - D(q)$. Water supply is computed as follows:

$$A(q) = Y(q) + \sum_{q' \in U(q)} R(q').$$

Water demand $D(q)$ is the sum of the water consumed by each occupant of the subcatchment (villages and farms). For a village the water demand is independent of the month, it corresponds to:

$$\mathrm{waterDemand}\big(\mathrm{village}\big) = \mathrm{population} \times \Big(\sum_x \mathrm{waterAccess}(x) \times \mathrm{waterUsedPerCapita}(x)\Big)$$

where $x \in \{\mathrm{tap}, \mathrm{collective}, \mathrm{river}\}$ corresponds to a kind of water access.

For a farm, for a month m, the water demand is the following:

$$\mathrm{waterDemand}(\mathrm{farm}, m) = \sum_{c \in C} (c.\mathrm{surface} \times c.\mathrm{crop.technicalItinenary.period.monthlyWaterNeed}(m))$$

where C is the set of crop allocations of the farm, and the water demand for one crop system c is given as the path to reach the attributes in the Class diagram Fig. 3. The results depend on two decisions: the equipment for domestic water access and the choice of irrigated surface and cultivated crops.

In the occurrence of water demand exceeding available water, the latter is distributed to domestic users first and then as a proportion of the demand of each situated entity in the given quaternary. Then for the villages:

$$\mathrm{waterConsumed}_{\mathrm{villages}} = \min\left(\sum_{v \in V_q} \mathrm{waterDemand}(v), A(q)\right)$$

where V_q is the set of villages situated in quaternary q, and for the farms, for month m:

$$\mathrm{waterConsumed}_{\mathrm{farms}}(m) = \min\Big(A(q) - \mathrm{waterConsumed}_{\mathrm{villages}}, \times \sum_{f \in F_q} \mathrm{waterDemand}(f, m)\Big)$$

where F_q is the set of farms situated in quaternary q.

4.1.2.5. Farmers' decisions dynamics. Farmers' decisions dynamics are based on global scenarios. No individual decision making is introduced in this model:

- The *baseline* scenario for each of the agents in the system consists of changing nothing. For the farmers this means deciding to replant cabbages every year on the same surface and replacing the existing citrus trees every 32 years (average lifespan for citrus plantations in the area). Citrus and cabbages are the only two crops introduced in the model (cf. Section 4.2).
- The *evolution* scenario for the villages consists in replacing river water access by collective taps during the first five years and then all the collective taps into indwelling taps for the

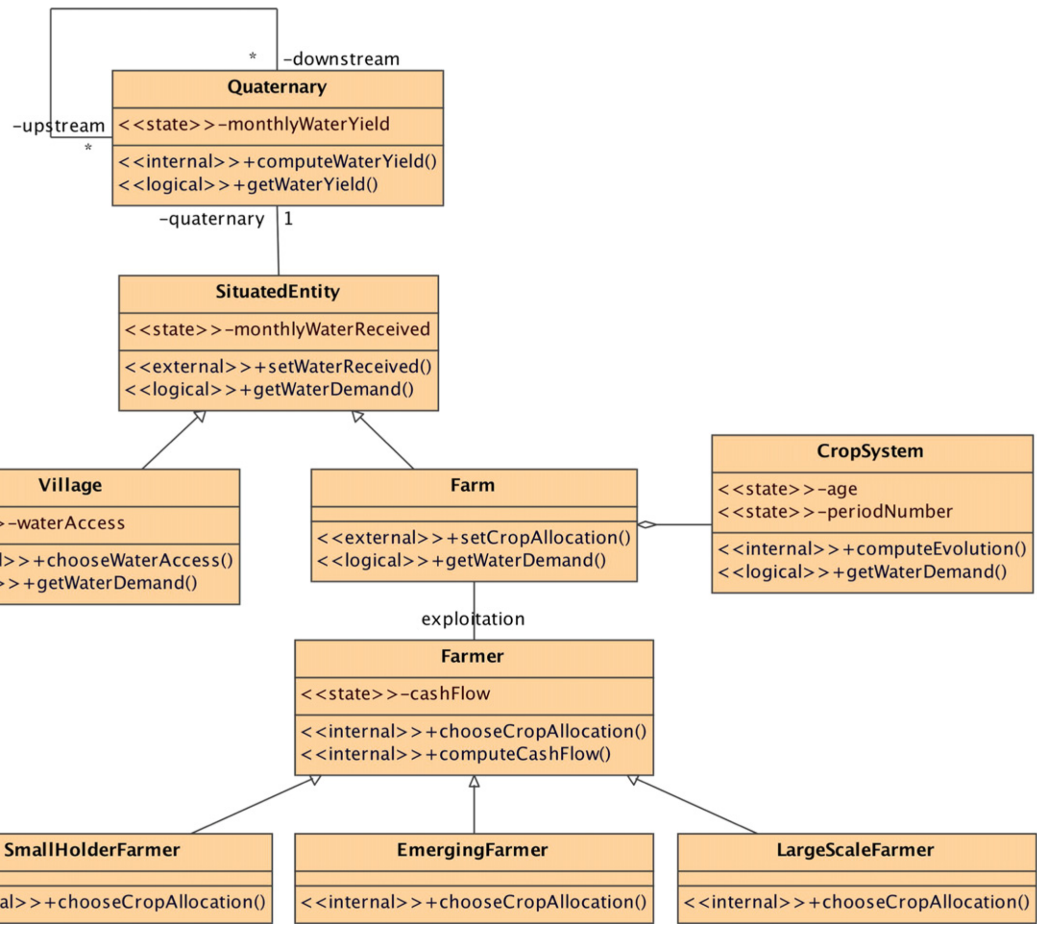

Fig. 4. The dynamics of the KatAWARE V0 model.

following next 5 years. This scenario explores the consequences of increasing domestic consumption in the catchment.

- The *small holder* evolution scenario consists of replacing cabbage with citrus over the cultivated surface that remains unchanged during 10 years.
- The *emerging and large-scale farmers* evolution scenario consists of increasing the cultivated citrus surface every year by 12.23% of the initial farm surface to reach an irrigated surface in the catchment of 2130 ha during a 10-year simulation (the maximum possible according to the DWAF).

These scenarios can also be combined to obtain mixed scenarios.

4.1.2.6. Dynamics sequencing. The description of dynamics is not complete until one specifies when the various events occur and in which order. Villages, farmers and crops operate on a yearly basis: "chooseWaterAccess" and "chooseCropAllocation" are activated at the beginning of each year; "computeCashFlow" is activated at the end of each year. The quaternary will update its water yield on a monthly basis, asking for the water demand to all the other entities (villages, farmers and crops). Water availability must be computed downwards the watershed. This specification is formally specified by an activity diagram as illustrated in the Fig. 5. The round black state is the initial state, i.e., where the process starts at the beginning of the simulation. As represented, the behaviours of the farmers, villages, crops and quaternaries are considered as taking place concurrently.

It is a modelling choice to slice the behaviours into years and months periods. Although decision making appears to be made at discrete time, the water flow could have been described by a single activity with differential equations. A general model should be able to combine discrete and continuous dynamics.

4.1.3. Simulation observables

As our model is related to a development question, it is also important to specify what the modeler and the stakeholders want to get as an output of the simulation, as an answer to their question (s). In our case the question is the impact of various water allocation evolution scenarios as described in Section 4.1.2 on the environmental, social and economic conditions of the catchment. The impact shall be simultaneously evaluated along the following aspects:

- The ecological aspects: the balance of water demand and availability for each quaternary by month and the annual water runoff from the catchment as the latter quantity must remain above a given level (the ecological reserve);
- The economic aspects: the yearly profit, costs and cash flow for each village and farmer to assess the economic sustainability of the various strategies;
- The social aspects in terms of generated employment within the basin.

The specification of these aspects in the form of observables is summarized in Fig. 6 using the <<probe>> stereotype and only showing the relevant categories where these observables can be actually observed. For example, the employment is available for each farm. If we wanted to have the employment at the quaternary level, the employment probe should be put in the quaternary. If in addition

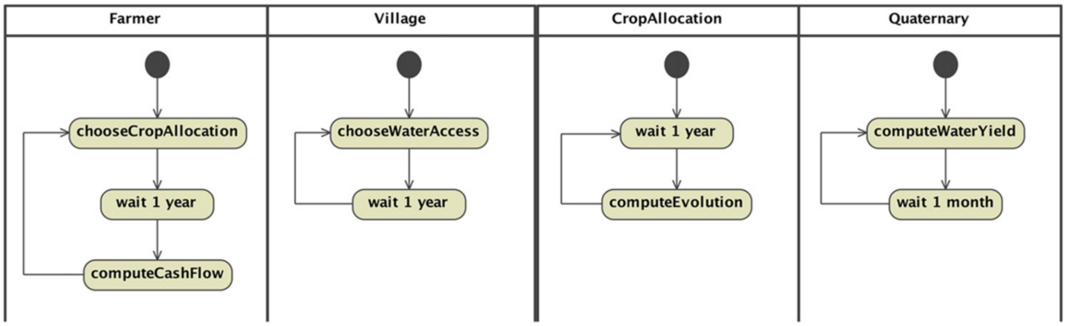

Fig. 5. The sequencing of the internal behaviours.

one wants to visualize the map of the entities, it is possible to add probes for getting the shape and position of each spatial entity.

4.2. Initial state

The list of categories as well as the attributes (parameters and states) also specify how the system must be initialized. It assumes that we have access to:

- The yearly yield and monthly distribution of it for each quaternary as well as the topology, as computed from DWAF data, including the particular case of the quaternary with the dam;
- The socio-economic data for each ward. In particular, the water access defines the percentage of the population for each kind of water access (indwelling tap, collective tap or river). This information is used to initialize the water access description of the villages contained within the quaternary;

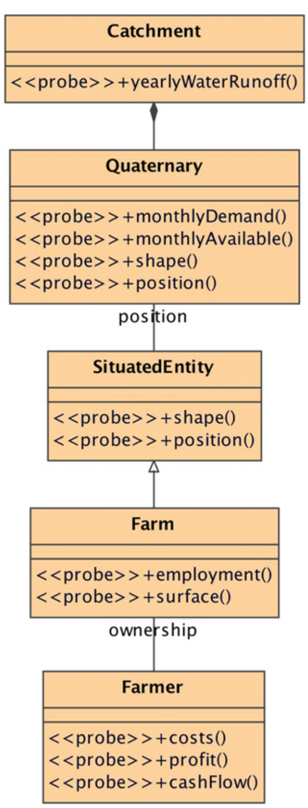

Fig. 6. The output specification of KatAWARE V0.

- The description of each possible crop with its associated cost and its production scheme;
- The description of each farm with its economic data (available fixed capital, initial budget and current perennial crops);
- The typology of farmers.

Notice that some of the attributes are parameters, whilst others define the initial state of the system and should evolve in the simulation.

Finally the various categories and relationships have to be instantiated in a so-called *concrete model*. Regarding the environment of the multi-agent system, we have:

- six quaternaries named Q94A–Q94F according to DWAF and organized as shown in Fig. 7, where Q94A contains a dam;
- twelve wards;
- three voting areas: upper, middle and lower Kat.

For each quaternary, Table 1 defines the yearly water yield and the Table 2 gives the monthly distribution for all the quaternaries but Q94A because of the dam which is assumed to provide a constant yield over the year.

For the multi-agent component of the model:

- a total of 49,530 inhabitants were distributed in 93 settlements;
- a total of 1356 ha of irrigated land were distributed among 36 farms each of them managed by a farmer (with a negligible domestic consumption) according to Table 3 (Fig. 8).

To place the *villages* in the catchment, the Geographic Information System SA Explorer version 2.01 was used (Jhagoroo et al., 2005). In addition, data on domestic water users were made available by previous work on secondary data (Farolfi and Jacobs, 2005), where urban and rural population in the Kat and domestic water sources were estimated by ward. The *villages* were then calibrated using the characteristics of the ward they belong to. The population of a ward was equally distributed among the ward's villages.

Only two crops were considered as representative of the farming activity in the area:

- cabbage, mainly cultivated by small scale farmers;
- citrus, exclusively cultivated today by large-scale and emerging farmers.

Table 4 illustrates the necessary information for the cabbage crop. It shows the value of the CropDescription and the Period attributes as specified in Fig. 3. In particular, the water need is given for each month.

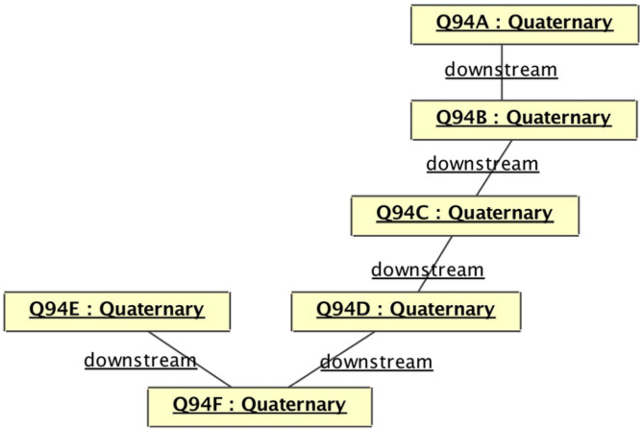

Fig. 7. The subcatchment topology using UML object diagram.

4.3. Implementation and simulation

The CORMAS platform introduces the notions of spatial, social and passive (anything else, in fact) entities:

- a spatial entity is defined by default, also as part of the visualization of the environment, namely the cell, introducing a raster approach to spatiality. In addition CORMAS introduces the notion of aggregates as made of cells with given (combination of) attribute values. Therefore, it was decided to represent the catchment by a grid of 76×61 cells of about 66.5 ha each. The quaternaries, wards and voting areas are aggregates of these cells.
- The social entities are the various types of farmers and the villages (the notion of domestic users was introduced to represent the distribution of water uses within the villages).
- Finally the passive entities are the farms and all the remaining notions from the conceptual model of Fig. 3. A number of additional state variables must be added to the model in order to keep track of the information the user wants to get from the simulation as well as for optimizing the computation.

Fig. 9 is a capture of a screen where the availability and demand for each quaternary is shown on the map itself (the color representing the percentage of water yield used in the quaternary). The table on the left (above the color legend) is the yearly mean total water runoff out of the Kat River catchment showing a reduction of water outflow when the demand increases. A detailed description of the results can be found in (Farolfi and Bonté, 2005).

4.4. Reflection on KatAWARE V0

During the workshops with the local stakeholders, a number of limitations of KatAWARE V0 have been pointed out.

The hydrological dynamic is based on the yield, i.e., the water reliably available for use as defined by DWAF. It is the total water flowing in the quaternary minus the ecological reserve plus the water stored within the dam in the quaternary if any. It means that KatAWARE V0 cannot take explicitly into account the management of the dam release nor the possibility to use the ecological reserve in case of drought. Additionally, this version of the model cannot explore scenarios with good and bad years in terms of rainfall because the water yield is an average and it is, therefore, defined as a (fixed) parameter.

Given the decision dynamics by globally defined scenarios, a single agent for each sector (villages, small holders, emerging farmers and commercial farmers) could have been defined. It is in complete accordance with the original AWARE were the dynamics are represented by activity sectors. The improvement of KatAWARE V0 if compared to AWARE is the spatial structure of the consumption allowing the identification of local water shortages due to the combined usage in different quaternaries.

KatAWARE V0 allows localizing spatially and temporally the possible stress on the water resource. This is an environmental issue local stakeholders wanted to discuss. In fact, the Ecological Reserve is defined in the National Water Resource Strategy (DWAF, 2004) as a minimum amount of water that must flow in the system to preserve ecological and biophysical equilibria. And this model points out that it could be interesting to consider a monthly reserve.

However, staying at a subcatchment scale prevented the discussions involving the consequences of water stresses on individuals. It was considered by the stakeholders as a limitation. Although each stakeholder recognized himself in the strategy associated to its category (small holder, emergent or commercial), some of them expressed the need to identify more precisely their individual decision making and in particular the budget on which the decisions are made, as well as their location along the river.

Reflecting on these criticisms and suggestions from the stakeholders allowed the modelers to develop a new version of KatAWARE (V1).

5. KatAWARE version 1

5.1. Building the conceptual model

5.1.1. Model structure

A number of improvements were introduced in KatAWARE V1. The new classes of KatAWARE V1 are the yellow ones in Fig. 10. More environmental data was made available on the hydrology of the catchment (cf. Farolfi and Bonté, 2006) resulting into a further division of the quaternaries into subcatchments.

From the discussion with the WUA members, it appeared that the management of the Kat *dam* and the use of *private water storage* facilities were important. Accordingly, the *water storages* were added to the model as new situated entities. The scheduled farmers

Table 1
Yearly yield for each subcatchment (from Farolfi and Bonté (2005)).

Quaternary	A	B	C	D	E	F	Total
Yearly yield (million of m^3)	12.7	2.26	2.51	1.65	2.06	1.82	23

Table 2
Monthly distribution of rainfall for each subcatchment (from Farolfi and Bonté (2005)).

Month	OCT	NOV	DEC	JAN	FEB	MAR	
Ave. rainfall (mm)	5.93	9.22	8.74	5.79	7.54	13.45	
Supply perc. (%)	8.22	12.78	12.11	8.02	10.45	18.64	
Month	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
Ave. rainfall (mm)	6.9	3.56	2.04	2.16	3.48	3.36	72.17
Supply perc. (%)	9.56	4.93	2.83	2.99	4.82	4.66	100

Table 3
Position of the farms in the subcatchments (from Farolfi and Bonté (2005)).

Farmers	Farms' surfaces	Position	Crops	Water payment
3 Small holder	30 ha	Q94B and Q94C	Cabbage	No
22 Emerging	18 ha	Q94E	Citrus	No
1 Large scale	300 ha	Q94F	Citrus	Yes
5 Large scale	24 ha	Q94F	Citrus	Yes
5 Large scale	90 ha	Q94F	Citrus	Yes

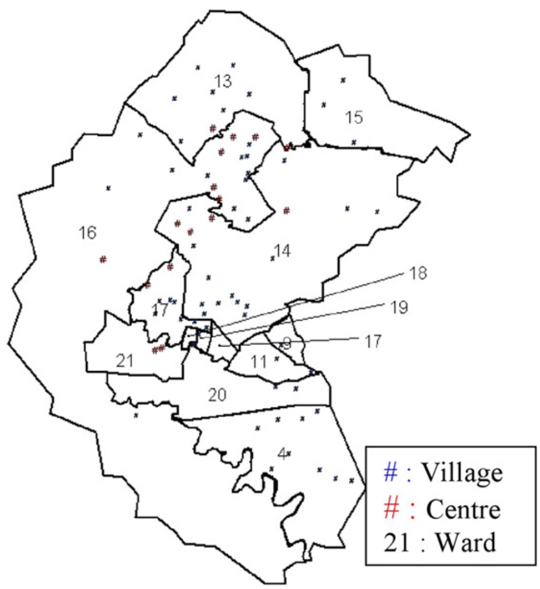

Fig. 8. The ward structure (from Farolfi and Bonté (2005)).

(a new parameter was added) have now the right to ask for releases from the Kat dam when they do not dispose of enough water from the river for irrigation. In addition, in KatAWARE V0 the available water was distributed to a quaternary but not to all the entities situated inside the quaternary. We only summed the consumption of all these entities to calculate the amount of water available for the downstream quaternary. In reality each situated entity receives a certain amount of water depending on its position on the river path. In order to take this effect into account, a row order along the river path in the subcatchment has been added.

Table 4
Cabbage crop description (from Farolfi and Bonté (2005)).

CropDescription	
Name:	Cabbage
PlantingCost:	0
Period	
Duration:	1
VariableCosts:	R 7320
MonthlyWaterNeed:	Jan.: 660, Feb.: 900, Mar.: 1190, Apr.: 370, May: 0, Jun.: 0 Jul.: 0, Aug.: 0, Sep.: 0, Oct.: 0, Nov.: 0, Dec.: 0
labourForceNeed:	0 Permanent, 536 Seasonals, 0 Casual
outputUnit:	Bag
outputQuantity:	1675

As mentioned in the previous section, some stakeholders asked for a clearer visibility of their financial outcomes. Accordingly, a rather complete budget was introduced for each farmer, including a comprehensive description of costs (input, labor, water, investment, machinery, marketing and so on) and income.

Regarding the crops, a more detailed description of the water needs when citrus plants are still not productive was introduced, as well as the possibility to adopt a water-saving technology for irrigation.

One of the aims of the process being to move from the current situation (the scheduled and not scheduled farmers) to a licensing mechanism, the notion of *license* with a duration and quantity specification was added to the model. The *municipality* (as a set of villages) as well as the farmers can acquire these licenses, respectively, for domestic uses and for irrigation.

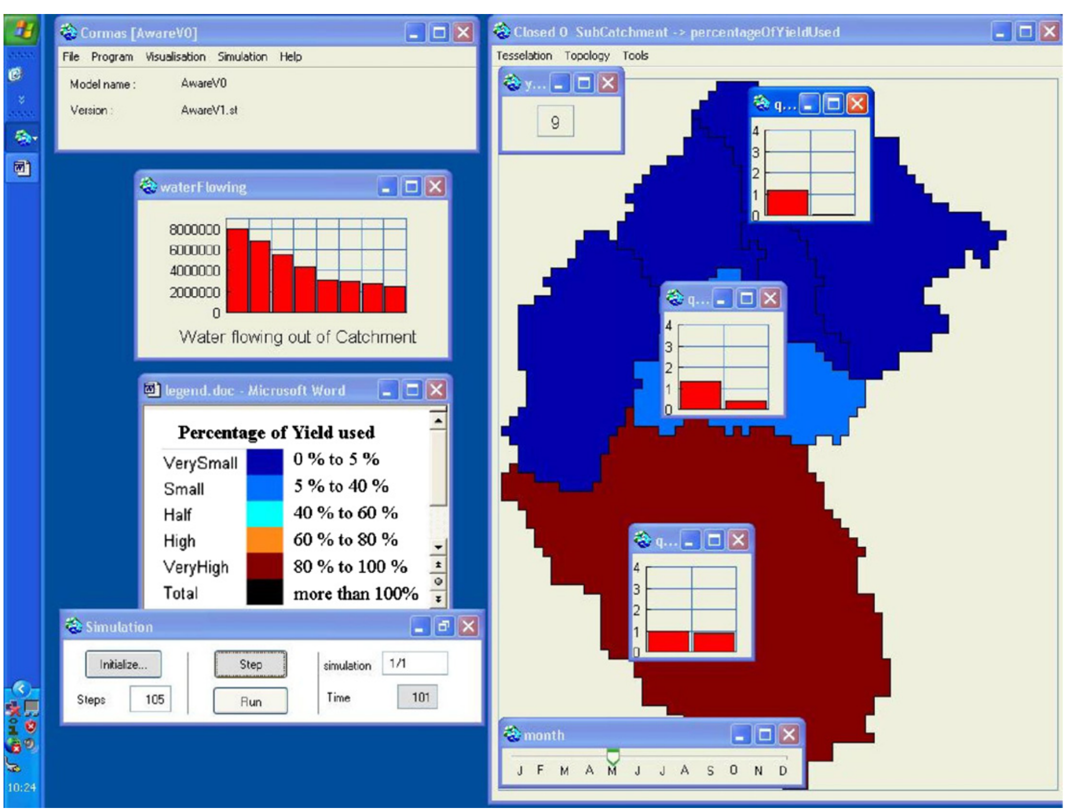

Fig. 9. The state of the Kat River catchment on year 9, month of May in KatAWARE V0 (from Farolfi and Bonté (2005)).

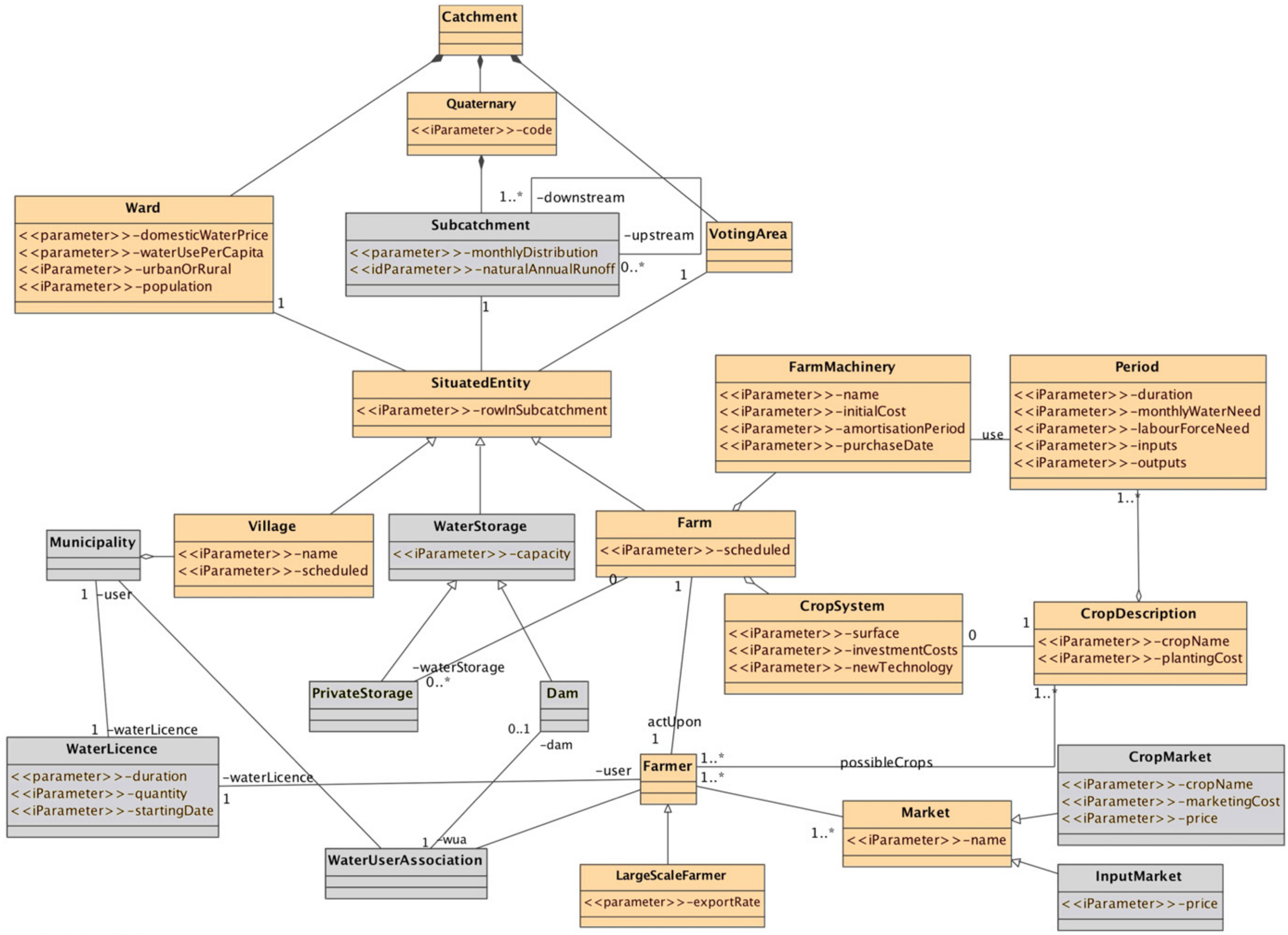

Fig. 10. The structural diagram of KatAWARE V1.

Finally, the *Water User Association* (WUA) was added as the instance which decides on actual water allocation and also on the dam releases.

5.1.2. Model dynamics

As described in the previous section the water dynamics were improved. In particular the satisfaction of the users' water demand depends now on their respective position along the river path. The demand of the first situated entity is fulfilled first and the rest is distributed along the path.

With the introduction of individual water supply for each agent, it becomes possible to represent how a water shortage impacts on a given agent. After discussions and exchanges with agronomists and large-scale farmers, production functions were defined. These functions calculate the monthly crop production for the annual cycle according to the quantity of irrigation water received and the quantity of water the crop needs. The same function, validated for citrus by large-scale farmers, is currently used for citrus and cabbage *Crop Descriptions*. It is foreseen in future versions of the model to calibrate the parameters of the function to cabbage *Crop Description*. Four different periods are defined along the annual cycle; to each period corresponds a coefficient (c_i in the following equations). c_i is the production yield (in percent of the potential production) if no irrigation is provided during the period. At this stage, this coefficient is fixed at 1/3 for every period. Using the following notations, yearly production P_y is calculated as follows:

$$P_y = \sum_{m=1}^{12} P_m$$

where P_m is the production at month m. The production at month m is calculated each month in the following way:

$$P_m = (1 - c_i) \times \frac{P_0}{d} \times \frac{Vr_m}{Vn_m} + c_i \times \frac{P_0}{d}$$

where d is the number of months requiring irrigation, c_i is the coefficient of period i (always 1/3 in the model), P_0 is the yearly production corresponding to full irrigation, Vr_m is the volume of water received this month and Vn_m is the volume of water needed this month.

Two new farmers' decisions have been added in addition to the choice of crops: the possibility to abstract water from a water storage on a monthly basis and the possibility to ask for a water license on a yearly basis:

- if crops' water demand is not satisfied through the catchment runoff, farmers owning private weirs can abstract water from them, while scheduled farmers can request releases from the Kat dam;
- depending on the choice of crops and on the expected weather farmers can request water licenses from the WUA for the following season. The request can be accepted as such by the WUA or a new water quantity is proposed to the farmer until

convergence towards an agreement. In this model, it is assumed that all the requested water licenses are delivered as such.

Given the new internal behaviours introduced in KatAWARE V1, the sequencing of farmers' activities becomes a little bit more complex as illustrated in Fig. 12 where the three activities (chooseCropAllocation, chooseWaterLicence, and chooseWaterRelease) are carried out in parallel. The same complexity is introduced for the village.

5.2. Initial state

Nothing particular was added to the initial state as described for KatAWARE V0 with the exception of the new subcatchment structure as illustrated in Figs. 11–13, the water storages and the scheduled farms. The more realistic computation of water availability by subcatchment derived from the introduction of the storage facilities adds the possibility to simulate various rainfall scenarios.

5.3. Implementation and simulation

Two implementations of the model were made: one on a computer and one with the stakeholders through a Role-Playing Game (RPG). Simulations through the computer model allowed a more refined analysis of individual users' performances as a consequence of different simulation scenarios.

In the Companion Modelling process, the model is not a final product to be used by stakeholders or decision makers as a predictive tool. In fact, most of the time, the model is not directly used by the stakeholders. It is operated during participatory workshops by the scientists involved in the ComMod process. Such a workshop for KatAWARE V1, that occurred in September 2005 in the Kat river valley, is described in Farolfi et al. (2008). However, the user–interface can highly improve the model understanding by the stakeholders Horlitz (2007). Hence, we developed two sets of interfaces. The first one to build the scenarios we want to explore with the stakeholders during the workshops (Fig. 14). And the second one to access the indicators (Fig. 15). In this last one, one can select what to observe on which entity (village, farm or water storage) by clicking on it on the map. This is possible because in katAWARE V1, the description of water supply is done at the individual water user's scale as requested in the previous cycle.

The RPG was based on the same conceptual model backing KatAWARE V1, but in order to make it playable, the reality was "reduced" to three subcatchments, roughly corresponding to the three voting areas of the Kat valley (Upper, Middle and Lower Kat).

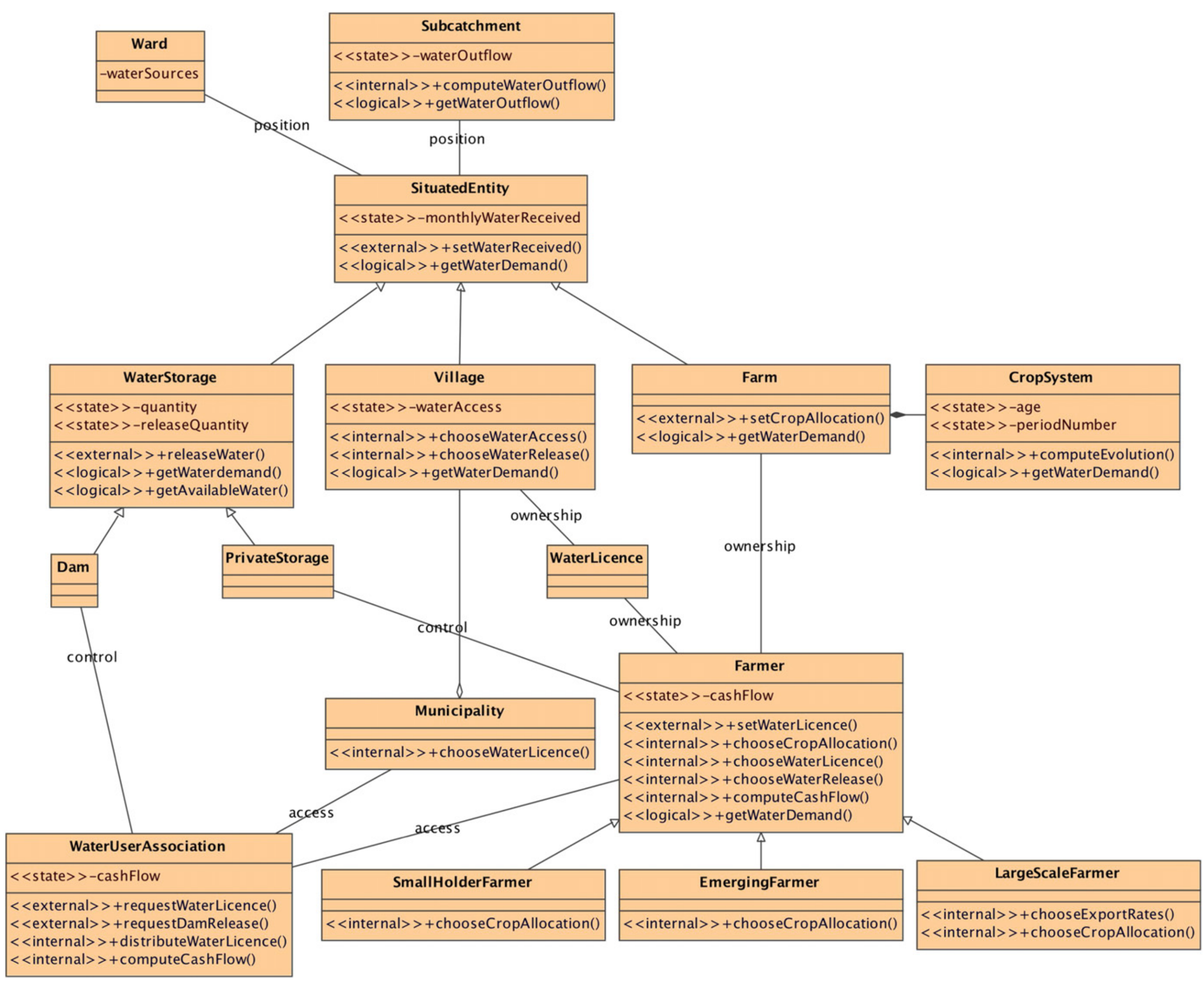

Fig. 11. The dynamics of KatAWARE V1.

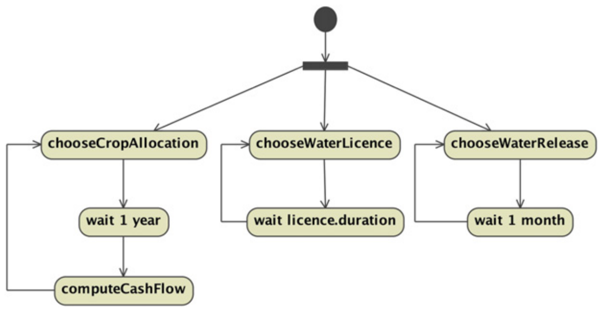

Fig. 12. The internal time model for the farmer.

A number of players corresponding to the members usually participating to WUA meetings (9) was chosen for the game. This resulted in a RPG playfield composed of: three subcatchments each one with different rainfall, two smallholding irrigation schemes (in the Upper Kat), three large-scale citrus farms (two in the Middle Kat and one in the Lower Kat), three villages (one in each subcatchment) and a dam in the Upper Kat. The initial conditions of the RPG correspond to those of the real Kat multiplied by a factor ranging between 1/3.2 and 1/13 (Table 5). The game was played a first time in November 2005, and a second time, with some changes in the parameters and the setup, in March 2006. The main objectives of the game were: (a) to facilitate the understanding of the model KatAWARE V1 from which the RPG was designed; and (b) to provide researchers with further information on stakeholders' individual and collective strategies regarding water use and water management in the basin.

5.4. Reflection on KatAWARE V1

The first development from KatAWARE V0 to KatAWARE V1 is the radical change in the water supply representation. The concept of "subcatchment yield" used in KatAWARE V0 was taken from DWAF definition and used to quantify the "risk" of a given evolution of water consumption. In KatAWARE V1, we use a more realistic representation of water supply which is the natural runoff. It allows to make explicit the water storages which are the main objects of

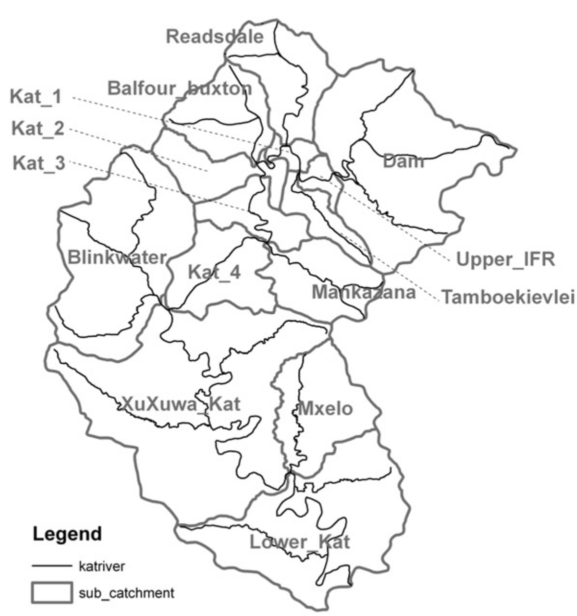

Fig. 13. The subcatchments in KatAWARE V1 (from Farolfi and Bonté (2006)).

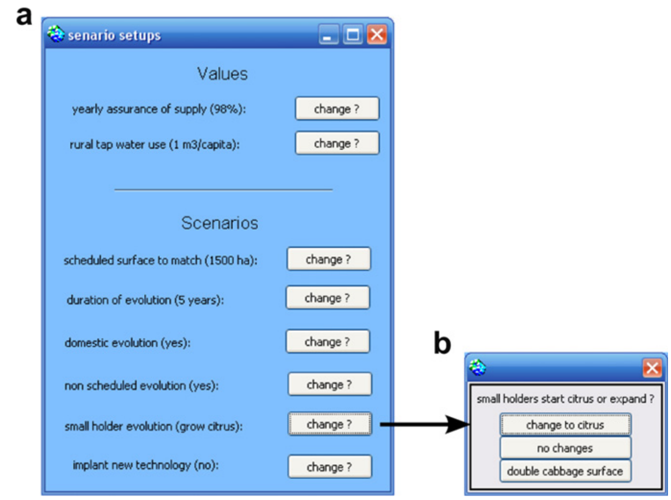

Fig. 14. KatAWARE V1 scenarios definition interfaces: (a) the different parameters to change. (b) The simulated scenarios as a set of parameter values.

decision involved in the water supply. Hence we had to describe the usage of these water storages which lead directly to some of the main issues of water supply management in the Kat. This issue was particularly sensitive among the local farmers as some large-scale citrus producers of the lower Kat are not scheduled and, therefore, rely only on their weirs, whilst small scale irrigators of the upper Kat declare not to be able to take advantage of the water allocated to them due to a lack of storage facilities.

The second main development is to have the model dynamics at the granularity of the individual farm or village for water supply. This allows to directly link individual behaviour (as observed in role-playing games), to the computational model simulation results. The reports on the two RPG sessions (Burt et al., 2005 and 2007) indicated stakeholders' appreciation and high participation to the exercise.

The observation of players' practices and strategies adopted during the two RPG sessions provided the information the researchers were looking for in order to improve KatAWARE V1, particularly in terms of agents' behaviour. A new version of KatAWARE (V2) was, therefore, envisaged.

6. KatAWARE version 2

As mentioned in the previous section, the aim of this version of the KatAWARE model was to take into account:

- the structure of the RPG in order to be able to reproduce the observed behaviour of the stakeholders as well as the same outputs given the scenarios we played. Each RPG took almost a full day to play and another half day for the debriefing. Being able to reproduce it on the computer allows to explore other individual as well as WUA decision strategies and to look at the outcomes much faster, allowing further discussions between the stakeholders on how to manage the WUA and come up with the desired business plan;
- the RPG was an opportunity to observe the individual behaviour of the real stakeholders as observed through the RPG sessions;
- WUA rules of water allocation as assessed through the RPG sessions.

This section describes how the RPG structure was introduced into the KatAWARE V2 model. Then we will present some of the

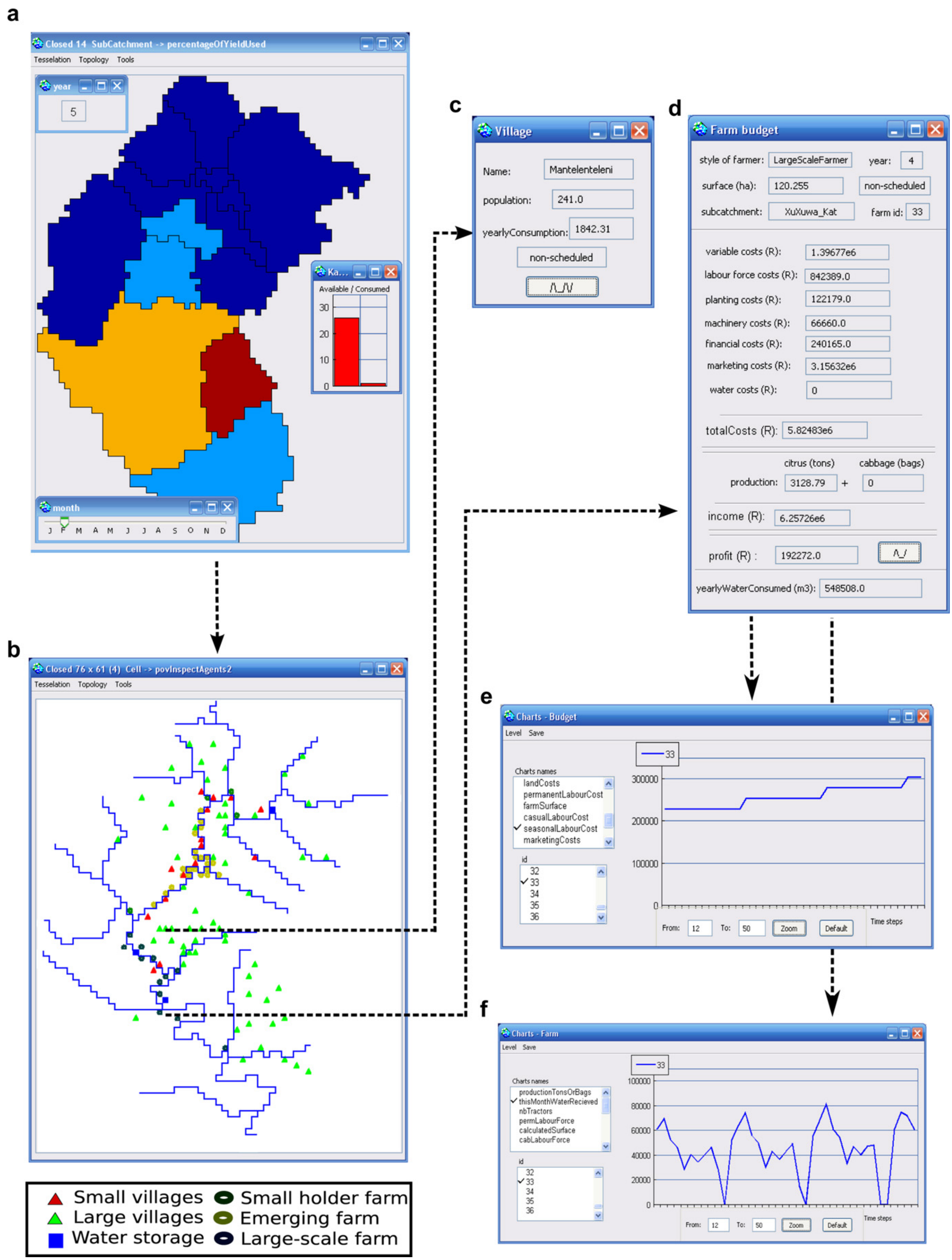

Fig. 15. KatAWARE V1 output interfaces: (a) aggregated view of water situation in the catchment, (b) individual users' point of view, (c) yearly summaries of demography and water consumption for a village, (d) farm yearly budget, (e) farm seasonal employment, and (f) farm monthly evolution of water consumption.

Table 5
Initial parameters in V1 and in the RPG (session 2) (from (Farolfi and Bonté, 2006; Farolfi, 2006)).

	The model	The game	Conv. factor
	98% Insurance supply		
Dam stockage	24,000,000	4,000,000	6.0
Natural runoff	13,500,000	1,800,000	7.5
Domestic consumption	1,500,000	214,200	7.0
Irrigation consumption	11,000,000	1,064,000	10.3
Surface cabbage	180	40	4.5
Surface citrus	1300	100	13.0
Hab. catchment	49,000	10,000	4.9
Annual flow out	1,600,000	500,000	3.2

strategies coming from the RPG observations. Finally, we will summarize the lessons learned from these modelling experiences to identify the requirements of an ideal platform to support such a modelling process.

6.1. Building the conceptual model

6.1.1. Model structure

Fig. 16 is the structural conceptual model of KatAWARE V2. It is composed of two coupled sub-models:

1 a detailed model which is nothing but a part of the KatAWARE V1 model and which is colored in pink;
2 a simplified aggregated model which represents the RPG and which is colored in yellow.

Regarding the RPG (yellow) part of the Fig. 16:

- the subcatchment has an annual water runoff which can be changed during the game to explore climate change scenarios;
- the villages can also have the population changing over time depending on mobility. They can also change their water price as well as the distribution among the water usages;

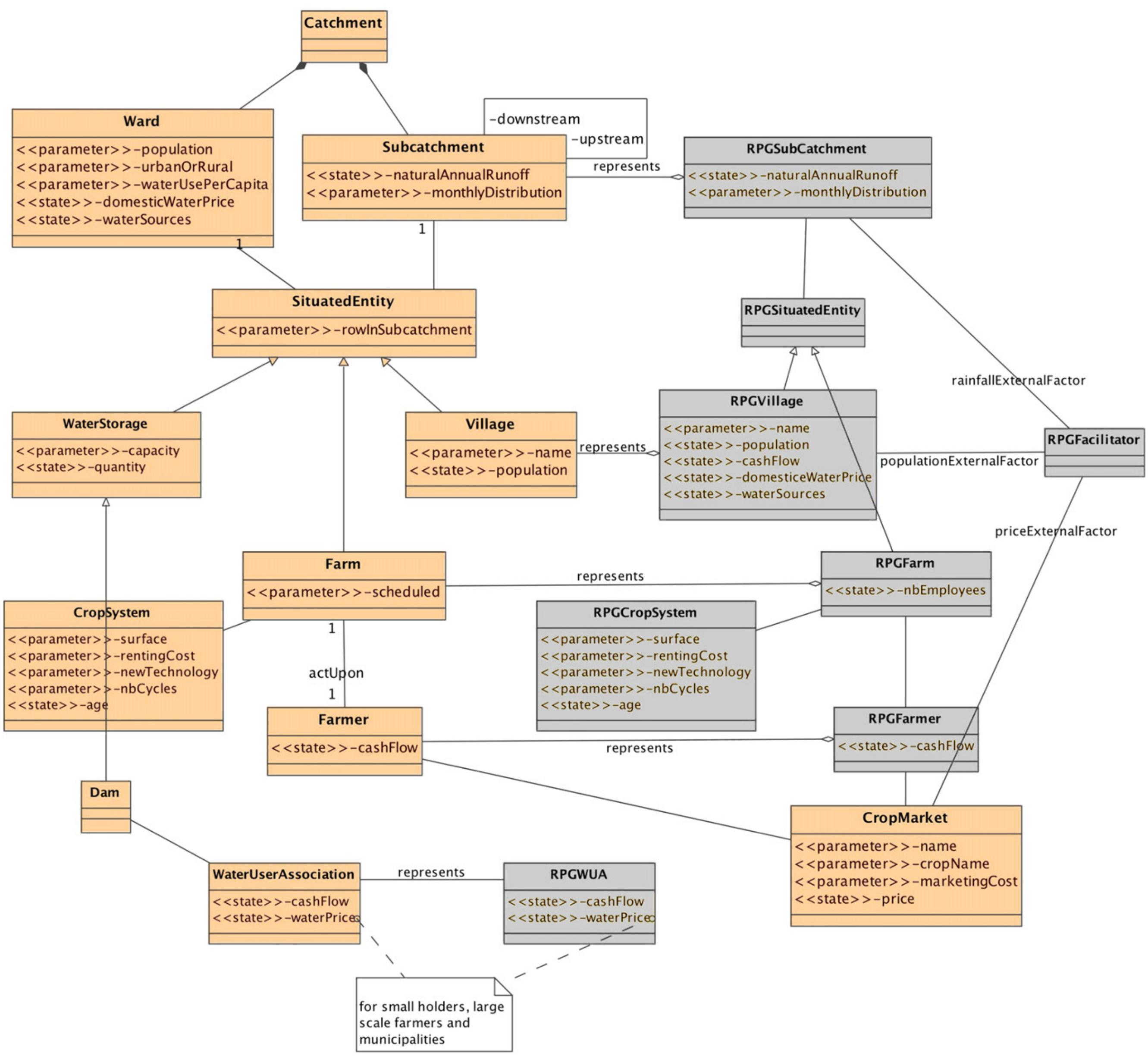

Fig. 16. The structural model of KatAWARE V2. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

- farmers can make decisions on the crops, whether to use water-saving technology or not with citrus, how many cycles of cabbages per year;
- the crop market price can also vary every year;
- finally the WUA decides on the dam releases and the water price for the villages, small scale and large-scale farmers, respectively.

The RPG facilitator was explicitly introduced to define the external factors (s)he can manipulate and the subsequent scenarios.

Between the pink and the yellow parts, there are "representation" relationships explicating the aggregation of the realistic model into the simplified one. It means that any change in the KatAWARE V1 part must be reflected by aggregation in the RPG part and conversely, any decision at the RPG level must be disaggregated or distributed in the KatAWARE V1 part. This configuration of the model is interesting because it represents the Kat River catchment at two levels of abstraction. The dynamical description will take into account how these two levels of abstraction will interact with each other.

6.1.2. Model dynamics

We will dissociate the description of the decision making by farmers, villagers and the WUA from the computation of the consequences of these decisions on the catchment and in particular the water flow dynamics. Moreover, the model simultaneously represents two scales:

- a fine scale corresponding to KatAWARE V1;
- an coarse scale corresponding to the RPG.

The decisions and the computation of their consequences can be simulated at any of these scales. More specifically, we have the following options:

- both the decisions and the consequences are simulated at the RPG (aggregated) level. It is exactly the option which was taken to compute the consequences of the stakeholders decisions in the RPG. The results are further distributed on the finer level.
- the decisions at the RPG level are disaggregated at the lower level (e.g., the crop surface increase is proportionally distributed among the farms at the detailed level), the water dynamics is simulated at the detailed level and the results are aggregated upwards at the RPG level.
- a third option would be to have the decisions themselves taken at the finer level as well as their consequences, the RPG level becoming a mere aggregated view of the underlying dynamics.

The choice depends on the quality of results one wants to obtain as well as the kind of interaction one wants to have with the stakeholders. In our case, let's make the choice of having a detailed water flow dynamics with the decisions at the RPG level. This choice is already reflected in the structural diagram of Fig. 16 by having state attributes at both level. It is expected that changing the decision variables at the RPG level will consequently modify the corresponding state variables at the detailed level. Taking this choice, the hydrological dynamics remain as described for KatAWARE V1 and we can focus our attention on the decision dynamics.

6.2. Initial state

As described in the Section 6.1.1, the KatAWARE V2 model is composed of two coupled sub-models where the pink part is the detailed model and the yellow part is the aggregated model of the same catchment. Therefore, we have the choice to initialize either the aggregated model or the detailed one. The other submodel parameters can always be computed from the chosen one. Here, we decided to initialize the system at the RPG level. The configuration of RPG catchment is illustrated in Fig. 17.]

The initial parameters are the following:

- the annual rainfall is initially of 2 million mc/year in the upper Kat and 1 million mc/year in the two others;
- the villages have, respectively, 3000, 5000 and 15,000 inhabitants with 80% water coming form the river and 20% from collective taps. The price of water for indwelling taps is initially of 1 R/mc.
- the farms have, respectively, 20, 20, 30, 30 and 40 ha. The first two are planted with cabbages, the others with citrus without water-saving technology.
- finally the price of water for small holders, large-scale farmers and villages are, respectively, of 0, 0.05 and 0.05 R/mc.

6.3. Implementation and simulation

The KatAWARE V2 model is not yet implemented. It will be implemented with the modelling and simulation platform MIMOSA (Müller, 2004), instead of CORMAS as the two previous ones. There are several reasons for this choice.

All the diagrams used in this paper were until now for analysis, design and documentation purposes only. In CORMAS, the model must be programmed entirely in the underlying language Smalltalk. There is a number of drawbacks: (1) the diagrams are just documents to help a programmer writing the code and (2) there is no guarantee that the implementation carries the exact operational semantics of the dynamical diagrams. MIMOSA provides the possibility to edit the shown diagram directly and, in particular, the object diagram (like in Fig. 17) is used to generate the simulation model. Currently, the implemented diagrams are the class diagram, the object diagram and the state/chart diagram. Here we used mainly the activity diagram which is not available yet.

By using stereotypes to express our experience in modelling at the conceptual level, we illustrated a specific modelling description language using UML. From thereof, we have two possibilities:

- using the Model Driven Architecture (MDA) as advocated by the Object Management Group (OMG), we can define

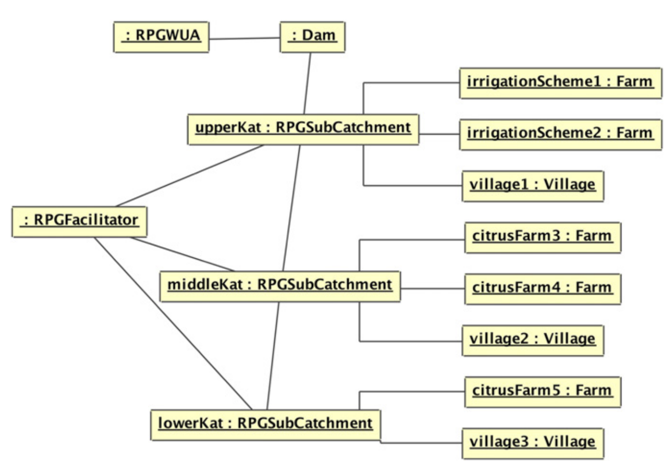

Fig. 17. The RPG catchment setup.

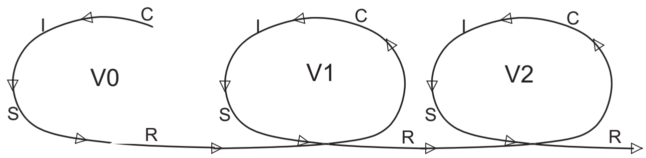

Fig. 18. Iterative design of the three versions of KatAWARE.

a UML profile to specify all the stereotypes we introduced and their semantics in terms of how they relate to each other. This UML profile is a basis to specify automatic code generation from the UML specifications shown in this paper;
- designing a new set of graphical and specification constructs, specific to the proposed language of description, i.e., asking separately for the parameters, the states, the probes, the logical events, etc., which could be directly interpreted by a dedicated platform.

For the time being the second solution is being pursued, the high level specifications being directly interpreted by the MIMOSA platform. However, this solution is seen as an experimental step towards a more standardized approach.

The next operational step is to provide MIMOSA with the missing formalisms used in this paper and to implement the model or even the three models in MIMOSA in order to experiment the applicability of these proposed constructs to completely specify the semantics of our models.

7. Discussion

Collective learning, communication among stakeholders, and joined decision making undoubtedly took place during the ComMod process in the Kat, but it is difficult to separate the effects of ComMod from the effects of the many other projects and initiatives that took place in the Kat since 1994. While some significant insights were gained by the participants, it is important to consider whether or not this would have been possible without the field preparation provided by the previous projects.

Among the numerous lessons provided by this experience, one seems to be particularly relevant for future applications of participatory approaches in similar contexts. In South Africa during the last years, many projects have been implemented with the main goal of helping local stakeholders to express their visions or to elicit mental models about water uses, related problems and perspectives. Most, if not all, of these projects have produced interesting reports and literature that did not actually concretize into a real negotiation support for the involved stakeholders. In other words, the technical phase of negotiation and decision making has always been neglected so far, with the emphasis being on the preparatory phase of visioning.

In the Kat project, which had as its explicit objective the development of a collective management plan (CMP) with the KRWUA, the ambition to go beyond visioning and move towards the real negotiation process leading to the technical decision-making phase was clear. The contribution of ComMod in this direction was instrumental, as the model first allowed quantifying and spatially representing the problems, and the RPG then facilitated the discussions and the debates around these problems. During the Kat project, the preparatory phases leading to visions determined few if no conflicts among local stakeholders. The real conflicts emerged when alternative water allocation strategies expressed as m^3 of water to different groups of stakeholders were proposed and discussed. The quantified scenarios allowed by the model KatAWARE were the bottom line for these discussions.

8. Conclusion

This paper has proposed a methodology to formalize and to systematize the modelling phases of an iterative and participatory process called Companion Modelling. In order to aggregate the numerous sources of knowledge and data, including those coming from the stakeholders, it was necessary to propose a methodology to represent the model of the simulation in all the dimensions of interest (but only these dimensions) to the domain experts and the stakeholders. We have proposed to use a number of UML diagrams to do so, extending the description using UML stereotypes. The method consists in describing:

1. the conceptual model with its structural, dynamical and observational dimensions, in order to agree on what we talk about, what are the processes implied and what we are interested in observing depending on agreed upon questions;
2. the initial state with all the data necessary to describe a given current situation;
3. the implementation and simulation to explore scenarios and discuss about the outcomes.
4. the reflection where the model is criticized by the experts and the stakeholders.

In this paper, we have presented three iterations of such a process (and hence three models) of which only two have been implemented at this stage. The Fig. 18 summarises the cycles of the ComMod process in the Kat River during which the proposed methodological steps produced the three versions of KatAWARE.

Even if the ComMod process and the consequent discussion and provisional choice of scenarios is only preliminary to the technical phase of decision making, which should lead the KRWUA to the definition of the CMP, the crucial step towards local negotiation and decision making around water management was reached in the Kat. Through the co-construction and discussion of quantitative scenarios, the KatAWARE process proved a useful, though improvable, accompaniment to the local WUA as they progressed from the qualitative step of visioning and definition of priorities to the preparation of a negotiated CMP.

Further works include the implementation of V2 in MIMOSA as well as a systematization of the process of presenting the conceptual model to the domain experts and to the stakeholders.

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