Institut für Hydrologie
der Albert-Ludwigs-Universität Freiburg i.Br.

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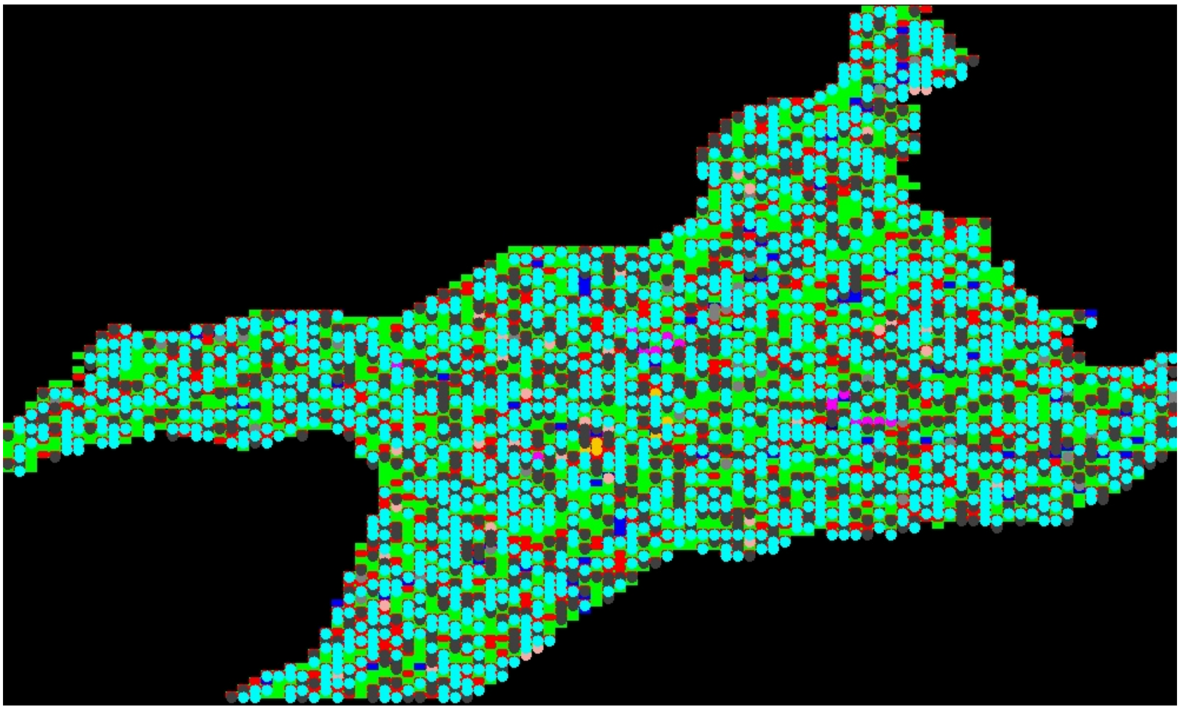
The Application of Multi-Agent Systems for Water Resources Research – Possibilities and Limits



Diplomarbeit unter Leitung von Prof. Dr. Ch. Leibundgut
Freiburg i.Br., November 2005

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Hiermit erkläre ich, dass die Arbeit selbständig und nur unter Verwendung der angegebenen Hilfsmittel angefertigt wurde.

Freiburg, 11. November 2005 Anne Gunkel

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Summary

Hydrology and water resources research should feel obliged to look for new methodologies that help to address current and future water conflicts over freshwater. The aim of this thesis is to evaluate whether multi-agent approaches are a valuable tool within this context. Multi-agent systems that are frequently applied in various academic disciplines represent the system based on more or less autonomous and cognitive agents. Complexity emerges thereby through actions and interactions of these entities.

In the theoretical part of this thesis, the method is critically reviewed. Applications conducted in hydrology, water sciences and related areas are considered for this purpose. Possibilities and limitations of multi-agent systems are evaluated that either apply generally to the methodology or are specific for applications in hydrology and water resources research. In addition, existing software systems for multi-agent modelling are discussed. Four of these systems are rated with a special focus on qualities that are interesting from a hydrological point of view, namely Cormas, NetLogo, Repast and SeSam. Since the representation of the environment has proved itself one of the most important points for applications in hydrology and water resources research, recent developments in this field of research are taken into account, such as coupling of multi-agent systems with Cellular Automata, Geographical Information Systems (GIS) or dynamic models.

In the second part of this thesis, a prototype of a multi-agent model of the water supply in the area of Tauá is developped. This poor rural area in the Northeast of Brazil is characterized by the absence of a public water supply infrastructure on the one hand and a semi-arid climate on the other hand. The model aims at exploring the way the local population handles this situation and manages to satisfy its daily demand of drinking water. Thereby, the representation of the natural water resources is based on empirical data and hydrological assumptions. The water consumers are equipped with the goal to satisfy their basic demand of drinking water and their additional demand for domestic use. The model captures some of the seasonal variation in the preferences of the water consumers for certain water sources. Furthermore, the model is used for simulating two scenarios, a climatic scenario and an economic scenario. The climatic scenario results in lower water consumption as reaction of the system to the reduced precipitation in dry years, whereas the reduction of the mean income does not show any effects on the system. Although it is a relatively simple representation of the system, the model seems promising if improved and developed further. Even though the area has been addressed in many studies, a modelling including the behaviour of the water consumers in this way is new and may serve as another step towards finding the best option for the water supply crucial to the poor population.

Keywords
multi-agent systems; agent-based simulation; multi-agent programming environments; integrated modelling; drought polygon Northeast Brazil; decisions on water consumption

Zusammenfassung

Um aktuelle und zukünftige Wasserressourcenkonflikte bewältigen zu können, ist es notwendig, alle geeigneten Methoden heranzuziehen. Oftmals weisen Entwicklungen in den Nachbardisziplinen auf viel versprechende, neue Ansätze hin. Multi-Agenten-Systeme, die ihren Ursprung in der Forschung zur Verteilten Künstlichen Intelligenz haben, werden inzwischen in sehr unterschiedlichen Disziplinen eingesetzt, darunter Wirtschaftslehre, Soziologie und Biologie. Die grundsätzliche Idee ist es, Agenten zu modellieren, die mehr oder minder autonom und kognitiv sind. Deren Verhalten und deren Interaktionen führen zu komplexem Verhalten des gesamten Systems, obwohl die Agenten selbst eher einfachen Regeln folgen. Dieser Effekt wird als Emergenz bezeichnet und ist charakteristisch für Multi-Agenten-Systeme.

Zu den Zielen dieser Diplomarbeit gehört es zu untersuchen, inwieweit Multi-Agenten- Systeme bereits Einzug in Hydrologie und Wasserressourcen-Forschung gehalten haben. Möglichkeiten und Grenzen der Methodologie werden diskutiert, sowohl im Allgemeinen, als auch speziell bei Anwendungen im Zusammenhang mit Wasserressourcen. Zusätzlich beschäftigt sich die Arbeit mit existierenden Software-Lösungen für die Realisierung von Multi-Agenten-Systemen. Vier dieser Programmierumgebungen, die als besonders geeignet für Modellierungen in der Hydrologie erscheinen, werden in Form eines Ratings miteinander verglichen (Cormas, NetLogo, Repast und SeSam). Repast erweist sich von den diskutierten Systemen als generell besonders geeignet für Anwendungen im Kontext von Hydrologie und Wasserressourcen. Jedoch hängt es vom Modellierungsziel und von den Kenntnissen des Modellierers ab, welches Programm im Einzelfall am Sinnvollsten ist. Die Darstellung der Umweltkomponente des Multi-Agenten-Systems hat sich in der Diskussion als besonders kritisch für Anwendungen mit hydrologischem Bezug erwiesen. Neuere Entwicklungen in diesem Kontext werden daher gesondert untersucht. Betrachtet wird die Kopplung von Multi-Agentenansätzen mit Zellulären Automaten, Geographischen Informationssystemen (GIS) oder hydrologischen Modellen.

Im zweiten Teil dieser Diplomarbeit wurde ein Prototyp eines Multi-Agenten-Modells der Wasserversorgung in Tauá in Nordost-Brasilien entwickelt. Diese arme Region ist geprägt durch ein semi-arides Klima sowie durch das Fehlen einer öffentlichen Wasserversorgung. Das Modell versucht nachzuempfinden, wie die örtliche Bevölkerung mit der Situation umgeht und unter den ungünstigen klimatischen Bedingungen ihre Versorgung mit Trinkwasser sicherstellt. Die natürlichen Ressourcen werden im Multi-Agenten-System nicht zufällig, sondern auf realen Daten basierend und unter Berücksichtigung hydrologischer Prozesse dargestellt. Als Agenten sind alle Haushalte der Region repräsentiert, die sich zwischen den verschiedenen Wasserressourcen entscheiden müssen. Ihr Ziel ist dabei, ihren Bedarf an Trinkwasser und Wasser für den Haushaltsverbrauch zu befriedigen. Das Modell repräsentiert eine jährliche Dynamik in den Präferenzen der Agenten für die jeweiligen Ressourcen. Von den zahlreichen Szenarien, die mit dem Modell realisiert werden könnten, wurden zwei beispielhaft ausgeführt, ein klimatisches und ein ökonomisches Szenario. Im klimatischen Szenario zeigt sich eine geringere Versorgung der Bevölkerung mit Wasser als Reaktion des Systems durch den verringerten Niederschlag in trockenen Jahren. Die Reduktion des durchschnittlichen Einkommens dagegen hatte keine Auswirkung auf das Verhalten des Systems.

Obwohl das Modell in der jetzigen Version nur eine sehr einfache Repräsentation des Systems darstellt und noch einige Mängel aufweist, scheint es viel versprechend für zukünftige Weiterentwicklungen und Verbesserungen. Trotz der zahlreichen früheren Untersuchungen im Modellgebiet ist die vorgestellte Art und Weise, die Wassernutzer im Modell abzubilden, ein Novum.

Keywords

multi-agent systems; agent-based simulation; multi-agent programming environments; integrated modelling; drought polygon Northeast Brazil; decisions on water consumption

1 Introduction

The Northeast of Brazil is equipped with only scarce natural resources. The rural population is badly affected by an extreme uncertainty in the precipitation regime with long-lasting and recurrent drought periods (Bach et al., 2003, p.361). Moreover, water quality problems deteriorate the conditions partly. Although parts of the semiarid area have been subject to international research for decades, the situation has practically not improved (Hydroisotop, 2002). Among the last research projects are the numerous studies in the WAVES project (Water Availability and Vulnerability of Ecosystems and Society in the Semiarid Northeast of Brazil) (Gaiser et al., 2003b). Nevertheless, the controversy on possible solutions continues.

However, this is only one of many areas in the world where individuals are affected by today's water crises and conflicts over freshwater. Barely anyone would doubt that hydrological sciences should feel duty-bound to help to solve such conflicts and support the people concerned. Answering the question which methodologies hydrology should apply to face the challenges of the future is more complicated. Nowadays, hydrological modelling is possibly the most powerful tool in water sciences for both, research and practical work. However, there is an increasing uneasiness among researchers about some of the limitations and problems of classical deterministic models. In respect to these aspects, hydrologists should feel obliged to look for new ways of modelling and new research tools. Particularly the exclusion of human decisions and of socio-economics topics is a problematic limitation in classical models when the research question includes issues of water resources management. Due to an increasing demand for clean water by the growing world population, the world is likely to face a higher number of resource conflicts within the next decades and centuries. Hydrologists are forced to integrate social and socio-economic issues into their attempts to model reality.

Multi-agent approaches may provide a valuable framework for such new kinds of hydrological models. Originally developed in the context of Distributed Artificial Intelligence, multi-agent Systems are widely adopted across academic disciplines as different as biology, economics and sociology. They are meant to be especially capable of modelling complex systems which is a valuable characteristic in the context of Integrated Water Management. Additionally, their ability to represent individuals explicitly in the models is promising for applications related to water resources management.

However, promising methods should be reviewed critically before they are adopted in a scientific community. The objective of this thesis is therefore to discuss the possibilities of the use of multi-agent systems in hydrology on the one hand and limitations and drawbacks on the other hand. Additionally, a multi-agent simulation of the water supply system in the state Tauá in the Northeast of Brazil is developed. Based on empirical data, an explicit representation of some of the local water users and their available water sources is implemented. Hopefully, this is one step towards finding the best option for the water supply crucial for the poor rural population in this drought prone region.

2 Research Question and Objectives

The thesis is divided into two major parts, the theoretical part (chapter 3 and 4) and a practical application. The objective of the theoretical part is to provide an elaboration of the possibilities and the limitations of multi-agent systems in hydrology and water resources management. To achieve this goal, it is necessary to discuss and classify applications conducted in hydrology, water sciences and related areas. The characteristics of multi-agent modelling have to be considered based on a review of the literature as well as on personal reflections. Of interest are the requirements of hydrology from such an approach, the potential for applications in this scientific field as well as inherent problems. In this context, possible future applications and aspects of adapting the methodology to hydrological applications are considered as well. Additionally, the theoretical discussion aims at providing an overview of some of the existing software systems for multi-agent modelling with a special focus on systems that are interesting from a hydrological point of view. Features of the systems that are discussed include their availability, their adequateness for hydrology and water resources and their flexibility. Additionally, recent developments in this field of research are taken into account, such as coupling of multi-agent systems with Geographical Information Systems (GIS) or with dynamic models.

The objective of the second part of this thesis is to develop a practical application of a multi-agent model addressing the water supply in the area of Tauá. This poor rural area in the Northeast of Brazil is characterized by the absence of a public water supply infrastructure on the one hand and a semi-arid climate on the other hand. The scientific question is to explore the way the local population handles this situation and manages to satisfy its daily demand of drinking water. The aim is to consider explicitly the representation of the natural water resources as well as the behaviour of the water consumers. The most suitable of the discussed software systems is chosen for this purpose. Using this practical example, the application of a multi-agent system is demonstrated and practical problems in using such a methodology are discussed, e.g. include advances and drawbacks in working on such questions.

3 Multi-agent systems and hydrology

3.1 Multi-agent systems

3.1.1 Definition of agents

Although multi-agent systems (MAS) are a comparably recent concept with its origin in computer sciences, such systems are now widely applied in other disciplines and for various purposes (Berger, 2004, p.3). Despite their growing 54popularity, it is not possible to find a generally used definition for multi-agent systems.

First of all, it is necessary to define agents. Apparently, there is no commonly accepted definition of what an agent is. Instead, different authors try to give some sort of 'minimal common definition' (Ferber, 1999). The definition of Woolridge (2002) is short and often cited. He states that an agent is "a computer system that is *situated* in some *environment*, and that is capable of *autonomous action* in the environment in order to meet its design objectives". Regarding the content the definition of Ferber (1999) is similar but more complex and is given in Table 3.1.

However, the use of multi-agent methodology in different contexts and with varying intentions leads to a great variety of slightly different definitions. Consequently, a long list of agent attributes exists that includes intentionality, autonomy, reactivity, flexibility, communication, learning and self-actuation (Davis, 2000, p.176). Especially the aspect of flexibility is interesting, since it is related to two different abilities, namely goal-directed behaviour, i.e. the drive of the agent to satisfy or maximise its utility function, and reactive behaviour. The latter means that the agent reacts to its environment and interacts with other agents. Reactive and goal-directed behaviour are somehow contradictory, although both of them determine human behaviour (Janssen, 2005, p.3). It is one of the challenges in modelling individuals to balance these two tendencies.

"An agent is a physical or virtual entity
(a) which is capable of acting in an environment,
(b) which can communicate directly with other agents,
(c) which is driven by a set of tendencies (in form of individual objectives or of a satisfaction/survival function which it tries to optimise,
(d) which possesses resources of its own,
(e) which is capable of perceiving its environment (but to a limited extent),
(f) which has only a partial representation of this environment (and perhaps none at all),
(g) which possesses skills and can offer services,
(h) which may be able to reproduce itself,
(i) whose behaviour tends towards satisfying its objectives, taking account of the resources and skills available to it and depending on its perception, its representations and the communications it receives. "

Figure 3.1: The definition of agents of Ferber (1999, p.9)

As the term 'virtual or physical entities' in the first line of Ferber's definition indicates, the agents under study are either beings in the physical world, which is the case for robots, or entities in the cyberspace, which refers to software agents (Janssen, 2005). However, for a discussion of agent technologies in hydrology, only the latter case is interesting, since there is no apparent application for robots in hydrology at the moment.

3.1.2 Definition of multi-agent systems

An appropriate definition of multi-agent systems may be even harder to achieve than defining agents. Again, (Ferber, 1999) delivers an useful, but complex definition that is cited in Figure 3.2. Additionally, Figure 3.3 provides a graphical illustration of such a multi-agent system.

"The term 'multi-agent system' (MAS) is applied to a system comprising the following elements:
(1) An environment, E, that is, a space which generally has a volume.
(2) A set of objectives, O. These objects are situated, that is to say, it is possible at a given moment to associate any object with a position in E. These objects are passive, that is, they can be perceived, created, destroyed and modified by the agents.
(3) An assembly of agents, A, which are specific objects ($A \subseteq O$), representing the active entities of the system.
(4) An assembly of relations, R, which link objects (and thus agents) to each other.
(5) An assembly of operations, Op, making it possible for the agents of A to perceive, produce, consume, transform and manipulate objects from O.
(6) Operators with the task of representing the application of these operations and the reaction of the world to this attempt at modification, which we shall call the laws of the universe."

Figure 3.2: Definition of a multi-agent system (Ferber, 1999, p. 11)

Generally looking for a definition of multi-agent systems leads to a similar problem as defining agents. Because of its application in different academic disciplines, the term 'multi-agent system' is not strictly defined, but used as an umbrella term for different types of systems. One of these systems consists of interacting hardware agents, a phenomenon that is also known as collective robotics. Another type of system is built by interactive software agents, also known as softbots, and is mainly used in distributed planning tasks, for example for scheduling applications of telephone companies. Simulations with multi-agents, also called multi-agents simulations, are another possibility (Ferber 1999, pp.30 ff). Mainly this third option is relevant for applications in hydrology and water resources research. Chapter 3.3 provides a more detailed discussion on the different uses of multi-agent systems.

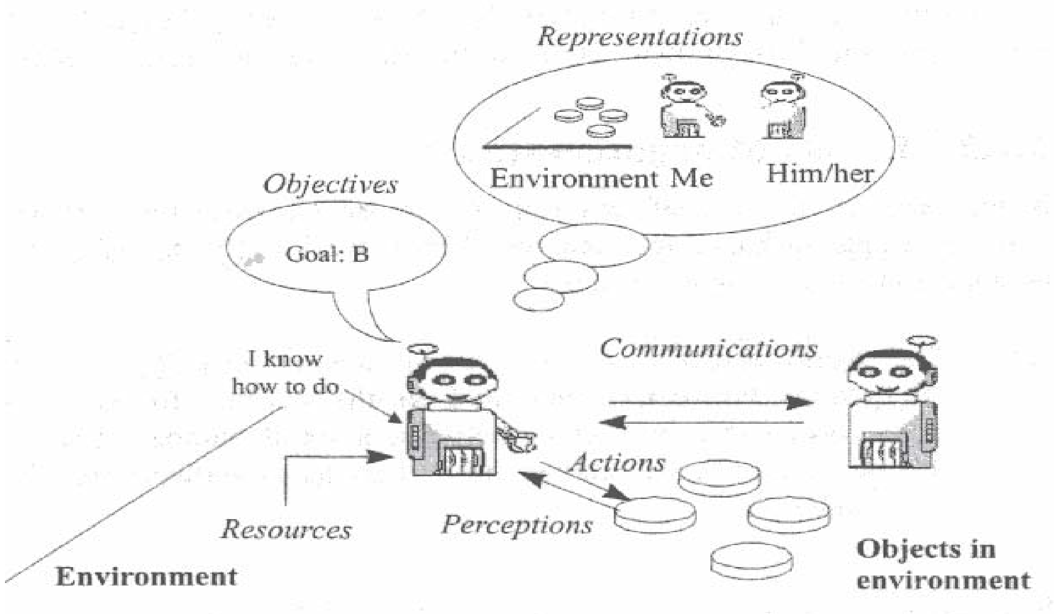

Figure 3.3: Illustration of a multi-agent system (Ferber, 1999)

3.1.3 Disentangling terminology

A literature review reveals not only a plethora of definitions for agents and multi-agent systems, but also different terms and dictions for the same methodology. Whereas most authors refer to the described kinds of models as multi agent models or multi-agent models, others talk about agent-based modelling. Similarly, the terms multi-agent simulation (MAS) and agent-based simulation (ABS) are used interchangeably. Some authors refer to 'multiple-agents' as well [see for example (Berger, 2004)]. Moreover, some authors talk explicitly about software agents, when they refer to virtual agents and not to robots. For the sake of simplicity, the term 'agents' is used in the following text instead of 'software agents', since only this kind of agent is discussed. Furthermore, the terms 'multi-agent' and 'agent-based' are applied interchangeably.

3.1.4 Architecture

Multi-agent systems are as various as their definitions, their purposes and the areas they are applied in. Mainly, they can differ in the attributes of agents, interactions and environment. Table 3.1 provides an impression of the high number of attributes that characterize multi-agent systems and their range of variation. Due to this diversity, it is not possible to provide more than a coarse overview of the architecture of multi-agent system in this thesis.

Table 3.1: Some attributes of multi-agent systems together with their potential range (Weiss, 1999, p.4)

	Attribute	**range**
agents	Number	from two upward
	Uniformity	homogeneous…heterogeneous
	Goals	contradicting…complementary
	architecture	reactive…deliberative
	abilities (sensor, effectors, cognition)	simple…advanced
interactions	Frequency	low…high
	persistence	short-term…long-term
	Level	signal-passing…knowledge-intensive
	pattern (flow of data and control)	decentralized…hierarchical
	Variability	fixed…changeable
	Purpose	competitive…cooperative
environment	predictability	foreseeable…unforeseeable
	accessibility and knowability	unlimited…limited
	Dynamics	fixed…variable
	Diversity	poor…rich
	availability of resources	restricted…ample

A simple description of agents in the field of environmental modelling is given in Figure 3.4. One of the most important aspects in the architecture is the duality between the agents and their environment. Agents perceive the state of the environment and influence it in turn through their actions. Thereby, their actions depend on their internal goals and attributes. The interaction between agents takes place either directly by communication or indirectly, for example when different agents affect a common environment. The communication can have different goals, e.g. negotiation of possible solutions or exchange of information about resources or strategies (Janssen, 2005).

The individual agents in agent-based models have particular states and rules of behaviour. The typical steps in running such models are instantiating an agent population, letting it interact and monitoring what happens. In other words, solving such models means simply running them, i.e. spinning them forward in time (Axtell, 2000). Related to this kind of design are some key issues in creating multi-agent systems, which all belong to the problem of specifying the coordination among agents, namely decision-making, control and communication (Bousquet and Le Page, 2004). It is beyond the scope of this thesis to discuss these and similar aspects related to the architecture of multi-agents model in detail. However, in order to understand the following case studies and the discussion thereof, it seems necessary to have an insight into some of the aspects involved in designing a multi-agent system. For further general information on the methodology and concepts of multi-agent systems, the reader is referred for example to (1999), (Weiss, 1999) and (Wooldridge, 2002).

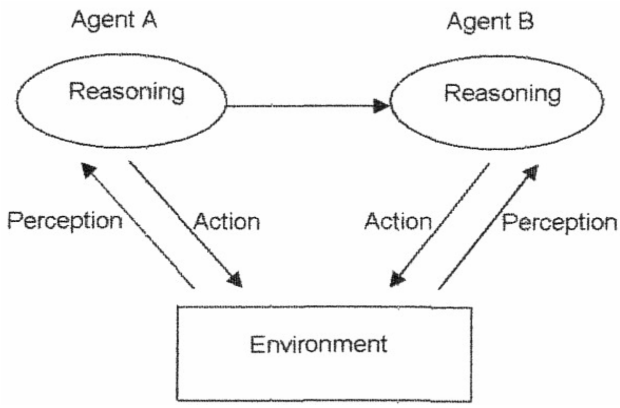

Figure 3.4: A Scheme of two agents, their environment and the included interactions (Janssen, 2005, p.4)

Different types of agents

To avoid confusion, it is important to differentiate between very different types of agents. The field of Artificial Intelligence, where agents originate from, is very diverse. Moreover, the term 'agent' is used nowadays for work in many different areas (Davis, 2000, p.176).

As mentioned before, one fundamental distinction has to be made between scientific studies on the behaviour of agents in the physical world, working on robots, and studies with agents in cyberspace, i.e. software agents (Janssen, 2005). Only the latter is dealt with in this thesis. However, not all software agents have the same purpose. In multi-agent modelling, most agents normally represent actors of the real system. It is important to note at this point that one should not confuse the terms 'agent' and 'individual'. An agent does not have to represent an individual. It can as well represent any other level of organization, e.g. a swarm or an institution. Consequently, the actors are either represented personally or summarized in groups or institutions. As an example, if the task is to model a water supply system, one option is to represent all the water users in the system. Another possibility is to include the water supply company as one agent and the water users as another one.

A second group of software agents is not part of the model in terms of content. Such agents that are called 'service agents' in the following text do not represent real beings, but are utilized to support and organize the running of the model. The software system DAWN (Athnansiadis et al., 2004) for example contains a Simulator Agent for moderating and synchronizing the system. The 'directory facilitator' in the model of Espinasse and Franchesquin (2005) manages a list of the various agents in the system together with their competences. The decision support system for water mains rehabilitation strategies by Davis (2000) includes several of these service agents, e.g. an Interface agent with the ability to learn the language of the users for communication between user and model. Other service agents are for example a data-warehouse agent that manages data out of different data-bases, a data-mining agent, a strategy agent and a communication agent (Davis, 2000). Figure 3.5 illustrates this structure, for a further discussion of these examples see also chapter 3.5.2.

As a consequence of these different types of agents, the modeller has to decide which parts of the natural system shall be included as agents into the model, which service agents shall be implemented and which functions are to be handled without agents. For example, the delivery of information to agents in the system can be realized conventionally via a data file. Alternatively, it is possible and more realistic to implement an agent that represents an organisation delivering the information to the agents, possibly the same institution as in reality. An example is the representation of a meteorological institute as an agent providing knowledge about meteorological conditions (Athnansiadis et al., 2004). However, another type of service agents is not limited to providing services within a simulation environment. Maybe the best known example for such service agents in every day life are software demons, e.g. programs managing background processes in operating systems or looking for information in the internet. They monitor the state of a software environment for example and act in order to modify it (Wooldridge, 2002). Service agents within multi-agent simulation should not be confused with this type of agents.

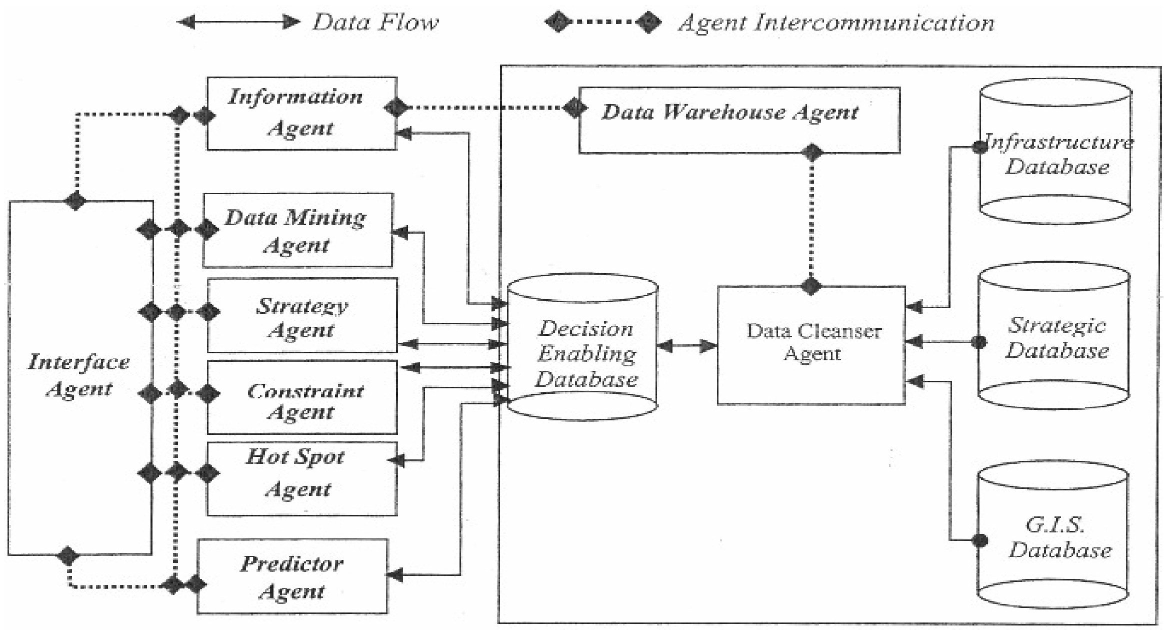

Figure 3.5: Schematic perspective on the agent-based framework for water mains rehabilitation decision support (Davis, 2000, p.180)

Multi-agent systems differ furthermore in the degree of complexity and intelligence that is implemented in every single agent. Ferber (1999) differentiates between cognitive and reactive agents. Multi-agent systems with cognitive agents consist normally of few, but ‘intelligent’ agents with individual knowledge bases and intentional behaviour. This is a typical approach in social sciences and closely related to expert systems and distributed artificial intelligence. In the reactive school, the idea prevails that individual intelligence is not a prerequisite for intelligent behaviour of the whole system. This approach is chosen more often in biological applications, e.g. for simulating the behaviour of ants (Ferber, 1999). A similar distinction is that between weak and strong agents (Davis, 2000). Whereas weak agents are simple, more or less intelligent information-processing systems, strong agents are computational cognitive models that are able to some degree to explain or simulate reported findings and theories in studies on minds or life (Davis, 2000). Obviously, this notion is closer related to Artificial Intelligence. Whether agents are used as a paradigm for software engineering or as a tool for understanding human societies

(Wooldridge, 2002), depends mainly on the field of application. In hydrology and water sciences, the purpose of the research is not to create agents being as intelligent as possible. Although in some cases water users are represented with some cognitive abilities, say the ability to make decisions, these cognitive aspects are rather simple. Consequently, the agents in these contexts are likely to be weak agents only, whereas it may depend on the actual model whether they are rather cognitive or more reactive.

Defining agent behaviour

Generally speaking, agents possess states, i.e. data, as well as rules of behaviour (Axtell, 2000). For the definition and implementation of the behaviour of agents, a great variety of possibilities exists. From a theoretical point of view, the actions of an agent can be approached with a variety of more or less mathematical formalisms. For example, action can be modelled either as transformation of a global state, as a physical displacement or as a local modification (Ferber, 1999). However, such detailed reflections are not in the focus of interest of this thesis.

Less theoretically, the problem is to specify what the agent is supposed to do without determining how the agent is supposed to do it (Wooldridge, 2002), since otherwise emergence is not likely to occur. A simple method to achieve this is to specify the behaviour indirectly, by applying some sort of performance measure (Wooldridge, 2002). One possibility to do this is to create a utility function for associating utilities with states of the environment. The numeric utility values specify how desirable a state of the environment is and the agents try to maximise their utility. However, it is often difficult to find an appropriate utility function and the approach is not very suitable for specifying long-term goals, since the utilities are assigned to local, individual states (Wooldridge, 2002).

Another common and simple way to determine the activities of agents is to specify a number of condition-action rules (Doran, 2001). Thereby, the modeller creates some ‘if – then’ statements, e.g. in the form of “If I am in front of the door and I have a key, then open it” (Ferber, 1999, p.19). Figure 3.6 gives an example how such procedures specifying agent behaviour may be realized. Unfortunately, these rules are normally fixed and the architecture is thereby inflexible, since the agents themselves are not able to change or vary the rules (Doran, 2001). The approach is therefore more suitable for reactive agents, since it may limit the autonomy of the agent and it is difficult to specify long-term goals or plans in such a way. Consequently, such an approach is often combined with other forms of specifying agent behaviour, e.g. defining a satisfaction matrix (Espinasse and Franchesquin, 2005). The satisfaction matrix defines the satisfaction values for all possible combinations of the two relevant factors, i.e. salinity and water level, and for the all three types of agents (Table 3.2). The matrix is applied in a negotiation process for specifying the preferences and the subsequent behaviour of the agents (Espinasse and Franchesquin, 2005). State transition graphs provide a method for illustrating the behaviour of agents and describing it formally. Afterwards, the specified behaviour converts almost automatically into applicable condition rules (Espinasse and Franchesquin, 2005). An example of this approach is the Agent Behavior Representation (ABR) method. Symbols for different state types (e.g. initial states, communication states or unlimited wait states) and two kinds of transition types (internal vs. external transitions) allow it to describe how the agents react when interacting with other agents or to changes in its environment (Espinasse and Franchesquin, 2005).

Besides these comparably simple approaches, other approaches and formalisms for specifying the behaviour of agents exist that are too numerous and complex to be described here [see for example (Ferber, 1999) and (Wooldridge, 2002) for detailed information]. The architecture has to be more complex, if beliefs, goals, internal representations of social contexts and speech-acts are to be included to some degree. A possible implementation is a Belief, Desires and Intentions (BDI) architecture (Weiss, 1999). The advantage of this approach is that it is more sophisticated and realistic to implement agents with self-interested goals. The activities of agents then depend on their goals, the plans they create and execute to achieve the goals and their beliefs about the environment (Doran, 2001). However, such architectures have seldom been realized for agent-based social simulation, although for example Doran (2001) attempted such an implementation.

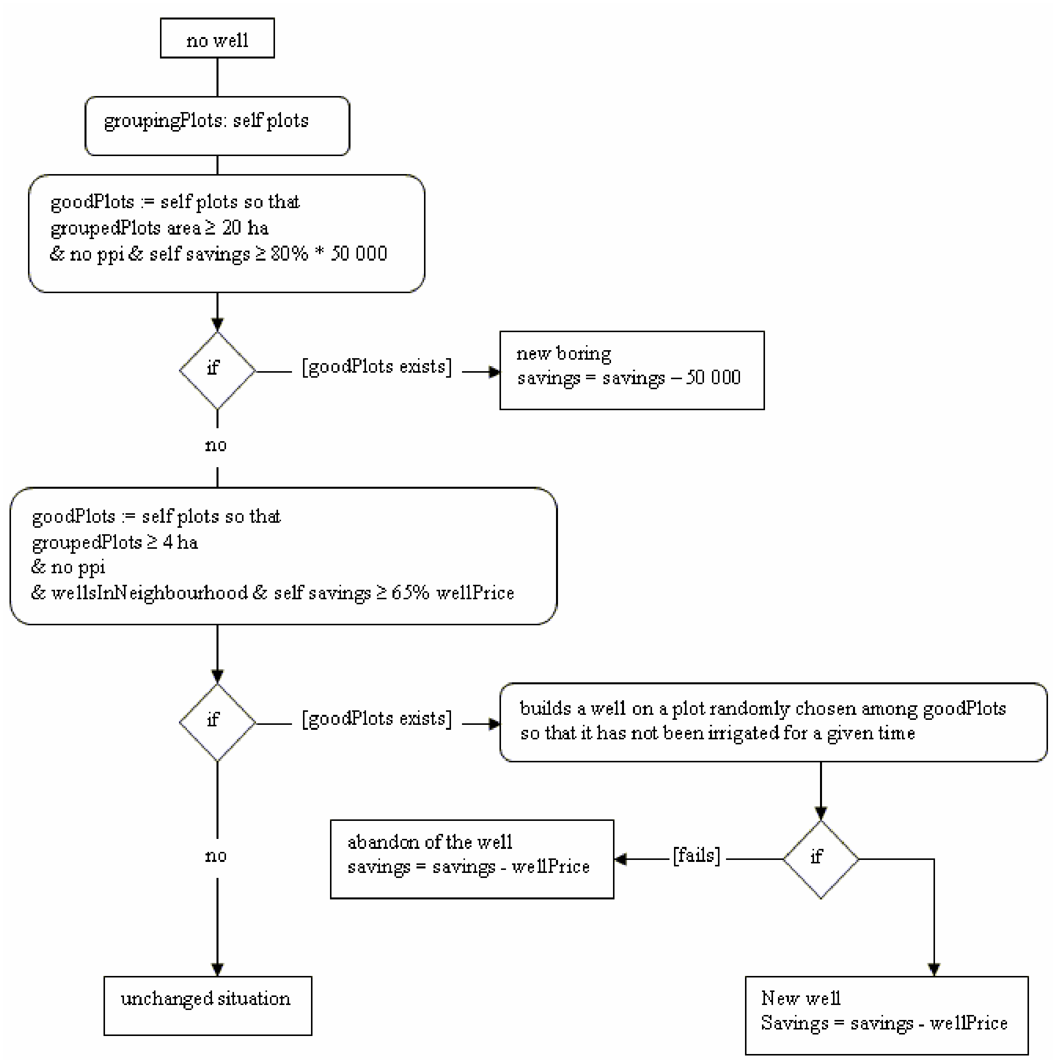

Figure 3.6: Illustration of an implementation specifying agent behaviour for allowing the agent to build a well under given conditions (in Unified Modelling Language (UML))(Feuillette et al., 2003, p.42)

Table 3.2: Satisfaction values for the different agent types (Espinasse and Franchesquin, 2005, p.209)

	Salinity (g/l)						
Water Level (cm)	5	10	15	20	35	>35	
<−30	5	4	4	3	2	1	AgricultureAg
−10	5	4	4	3	2	1	
0	5	4	4	3	2	1	
20	5	4	3	2	1	1	
40	3	3	2	1	1	1	
>40	1	1	1	1	1	1	
<−30	2	2	2	3	2	1	FishingAg
−10	2	2	2	4	2	1	
0	3	3	3	5	2	1	
20	3	3	4	4	2	1	
40	2	2	3	3	2	1	
>40	2	2	2	1	1	1	
<−30	1	1	3	5	5	3	NaturConsAg
−10	1	1	4	5	5	2	
0	1	1	3	4	3	1	
20	1	2	3	4	2	1	
40	1	1	1	1	1	1	
>40	1	1	1	1	1	1	

Decision making

Modelling water resources issues includes most likely the representation of some sort of human decision making. Therefore, different possibilities exist, depending on the focus of interest in the study and the level of aggregation that is chosen for the representation of the behaviour of the agents. Most likely, sociological, socioeconomic or psychological knowledge has to be included into the model for this purpose. This section may provide only a first insight into this complex issue.

Mathematical programming is one possibility for modelling the decision rules of human agents, based on a socio-economic background. Berger (2004) for example represents the decision making of land managers with this methodology. Mathematical programming is a constrained optimization technique. A function of independent variables, e.g. the size of the area assigned to a certain land use type, is optimized depending on a priori limitations for the values of the independent variables. For example, the total size of farmed areas is limited by the total area of arable land. The ‘objective function’ is characteristic for different decision rules, e.g. if profit-maximization is aimed at, it is the sum of profits of all land use activities. Berger (2004) argues that formalization in mathematical programming is possible for all sorts of decision rules.

Another possibility is to include some psychological factors, e.g. attitudes, in the model in addition to objective parameters, e.g. family size or water price. Modelling of water consumption decisions of families may be based for example on the available water supply in the area, economic factors such as water price, size and income as well as psychological factors, e.g. social attitudes towards behaviour in drought times and imitation in the closest neighbourhood (López-Paredes et al., 2005) (Figure 3.7).

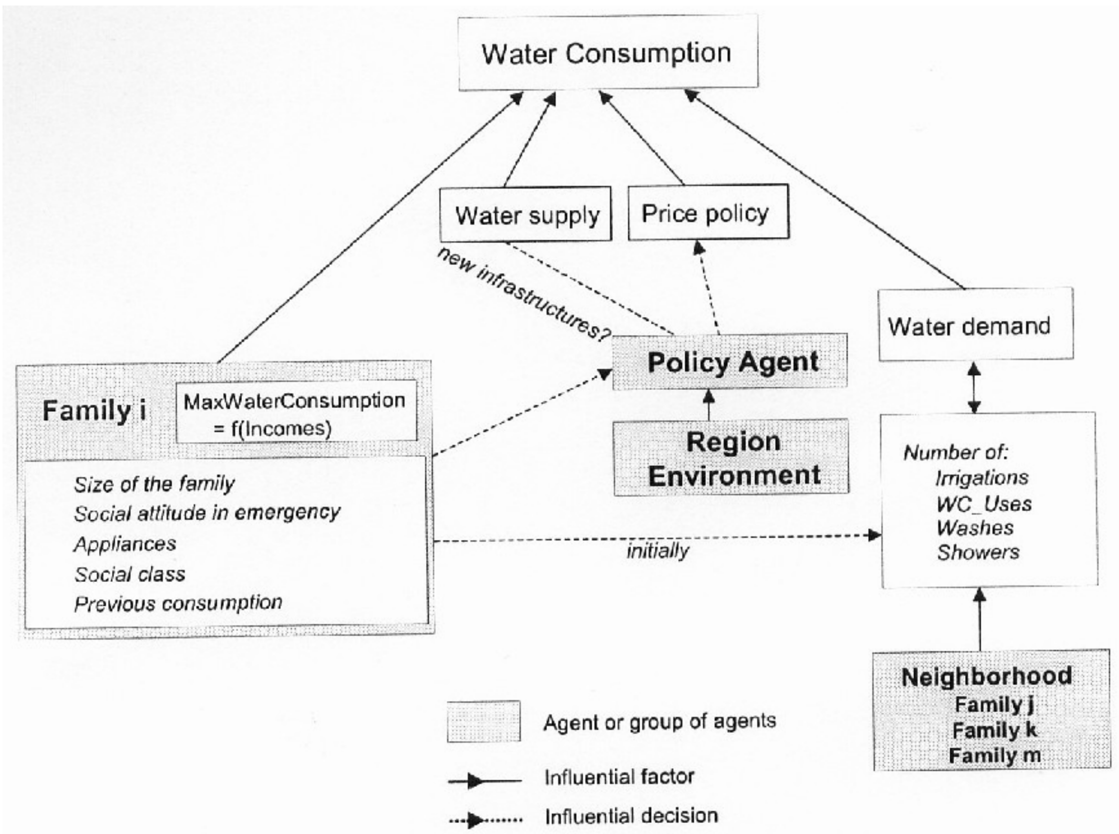

Figure 3.7: Water consumption decision algorithm for a family in one time step (López-Paredes et al., 2005, p.192)

Negotiation

Many multi agent models contain elements of negotiation. For this purpose, special interaction or negotiation protocols exist, e.g. the Contract Net Protocol (Davis and Smith, 1988, cited in Espinasse and Franchesquin, 2005). Two of the most important issues in this context are the organization of the exchange of proposals between the participants and the way an agreement is reached. Figure 3.8 illustrates the example of a negotiation management protocol based on the Contract Net Protocol (Espinasse and Franchesquin, 2005). Modelling a negotiation process leads to the problem of defining the goals or aims of the agents for the negotiation. One possibility is the aforementioned satisfaction matrix. In some modelling tasks, a solution with or without negotiation process may be possible. Negotiation might be costly, but it preserves the autonomy of the agents, for example because they are able to apply individual strategies (Espinasse and Franchesquin, 2005).

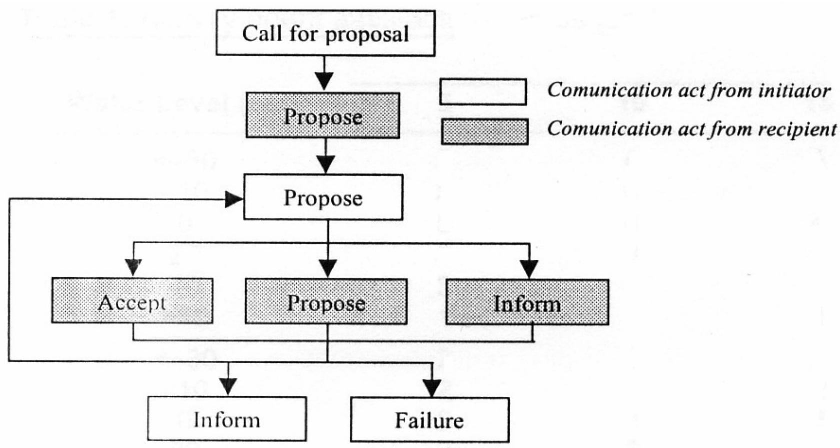

Figure 3.8: Water council negotiation protocol (Espinasse and Franchesquin, 2005, p.208)

Time

Multi-agent simulations are executed in time steps. Usually, the length of the most important processes in reality determines the length of the time steps in the model, i.e. the amount of real time that is represented by one time step. A time step of one day for example is chosen if the necessary data is available on a daily base and if the relevant processes can be modelled meaningfully based on days. Even though the length of the time step is consequently part of the concept in most models, it is also possible to allow the users to specify the time intervals (Athnansiadis et al., 2004). When the users specify the number of time steps executed, as it is often the case in multi-agent simulations, they thereby define the total length of the simulation as well, e.g. whether the model simulates a period of 10 or of 20 years.

Environment

As mentioned before, it is characteristic for agent-based modelling that the agents are placed in some sort of environment. Possible implementations for this environment range from simple grids to coupling with Geographical Information Systems (GIS) or other models. The way this environment is realized in the model depends naturally on the research question addressed. In hydrology and water management, the relevance of the environment is obviously high. Chapter 4 discusses some possible realizations of environments in this context.

Software and output of data

Two general possibilities exist for implementing a multi-agent model as a computer model. One option for the modeller is to choose the most suitable of the software platforms available for multi-agent modelling. Alternatively, the whole system can be implemented in a standard programming language in combination with different suitable software systems or packages for specific tasks, e.g. for inter-agent communication. Among the programming languages, an object-oriented language as Java is chosen often nowadays.

There are two ways of observing the dynamics of the model: either through changes in the visualization in the spatial grid in different time steps or through a representative selection of indicators, e.g. the global piezometric level of the water table that can be written to a data file (Feuillette et al., 2003).

3.1.5 Characteristics of multi-agent systems

Of course, the question arises why multi-agent modelling approaches are of increasing interest in different academic disciplines. To answer this question, it is necessary to evaluate characteristic aspects of multi-agent modelling.

One of the most striking features of agent-based systems is the phenomenon of emergence. The idea is to explain even complex behaviour with simple rules. The interest of the researcher is to explore the emergence of macro phenomena based on behaviour among interacting heterogeneous agents on micro level (Janssen, 2005). Consequently, a system shows features that are not specified in the behaviour of the single agents. For the context of social sciences, this phenomenon can be expressed as micromotives leading to macrobehaviours. For other than human agents it is more appropriate to talk about microrules leading to macrophenomena (Bankes, 2002).

A closely related characteristic is the distributed nature of problem-solving with multi-agent models. One possibility is to divide the necessary knowledge into sub-units that are associated with independent intelligent agents. The problem is consequently solved by coordinating the activities of the agents (Bousquet and Le Page, 2004). This can considered as an aspect of decentralization, in the case that the agents are distributed in space or represent different levels in a hierarchy. Because most real life situations include decentralization to some degree, it is reasonable to choose methods that follow decentralized approaches.

Another feature of multi-agent modelling is that agents are a comparably natural analogy for simulating human behaviour. Multi-agent modelling allows to represent observed behaviour almost directly and intuitively in a computational model (López-Paredes et al., 2005). When compared with other styles of modelling, this will hopefully result in refined and detailed representations of the individuals and consequently greater realism of the model.

Multi-agent modelling is not a top-down process in most cases, but a kind of bottom-up approach. Starting from the attempt to understand the processes on the small scale, it is tried to understand the processes at the higher scales as well. Contrarily, in traditional equation-based modelling the problem is addressed as a whole. It is tried to find an equation that approximate the dynamic of the system under study. For the context of ecological modelling, Bousquet and LePage (2004) differentiate between modelling with differential equations and computer simulation. They distinguish between two different perspectives on complexity, dynamic vs. organizational. Table 3.3 summarizes the differences. Multi-agent systems belong to the organizational point of view, whereas traditional kinds of hydrologic modelling represent the dynamic view.

These traditional models are generally equation-based models. The fundamental difference between agent-based and equation-based modelling is the different representation of individuals, i.e. entities showing behaviours as time passes, and observables, i.e. measurable characteristics of interest whose values change over time (Parunak et al., 1998). Equation-based modelling starts with expressing relationship among observables through a set of equations that are either algebraic or capture variability over time or over time and space. In contrast, agent-based models represent behaviours through which individuals interact with each other directly or indirectly. Relationships between observables are an output, not an input of such models (Parunak et al., 1998). In addition, agent-based models have the natural tendency to focus on observables available to the individual agent, not on a system-level information. Equation-based models consider observables on system-level as well as on individual level, but tend to make extensive use of system-level observables (Parunak et al., 1998).

Table 3.3: Two systems of interpretation representing two concepts of complexity (Villa, 1992, as cited in Bousquet and LePage, 2004)

	dynamic view	**organizational view**
system conceptualisation	state variables	lower level processes/entities
suitable metaphors	cybernetic systems	parallel computers
specifications of mechanism	Centralized	distributed
means of analysis	differential equations	computer simulations
key behaviours	equilibrium, dynamic complexity	self-organization, structural complexity
system organization	fixed, single level	variable, multilevel

3.2 Short history of multi-agent systems

Writing an objective, unchallengeable history of multi-agent systems may not be possible, mainly since the roots of the approach are spread into different academic disciplines. However, it is thought that providing at least a sketch of the history and mentioning some of its milestones is necessary to improve the understanding of multi-agents systems and their development. If not indicated otherwise, the following section is based on Wooldridge (2002). In their compact and useful review of multi-agent simulation and ecosystem management, Bousquet and LePage (2004) provide a short overview on the history of multi-agent system as well.

Doubtlessly, the most obvious root of multi-agent systems lies in the field of Artificial intelligence (AI). Agents appear already in the earliest AI literature in the middle of the 20th century. Nevertheless, agents as holistic entities did not play an important role until the mid-1980s. In the classic period of AI planning between 1969 and 1985, they were instead mainly used as systems capable of independent actions in the context of reasoning and planning. Besides, a great deal of scepticism existed, whether computers would ever be able to show intelligent behaviour such as problem solving, learning or communicating in natural languages. Some scientists tried hard to prove the critics wrong and subsequently topics as planning, learning or communication emerged as sub-disciplines of AI.

However, although these disciplines were rather highly developed by the mid-1980s, attempts to integrate these single skills into whole entities were actually missing. As a result, a complete new approach of building agents emerged, which was called Behavioural AI, Reactive AI or simply New AI. In this context, the idea developed that intelligent behaviour may emerge through interactions between simpler behaviours. Additionally, more attention was given to the agent's environment and its influence on the actions of agents. Of course, these new ideas challenged scientists working in the field of classical AI and led to the splitting of the AI community into classical and behavioural scientists. The latter took inspiration from biology, emphasized reactive behaviour and worked mostly in an area that is called Artificial Life today (Wooldridge, 2002). Mainstream AI started to consider the integration of components of intelligent behaviour into agents and accepted the value of testing and deploying agents in realistic scenarios. Nowadays, most kinds of agent architectures are based on reasoning and reactive behaviour likewise, since such a hybrid structure seems necessary for creating intelligent autonomous agents (Wooldridge, 2002).

Another distinction in the terminology is made between AI and Distributed Artificial Intelligence (DAI), whereby the latter is considered the root of multi-agent systems by some authors, e.g. by Bousquet and LePage (2004). They state that AI mainly aims at representing the knowledge and reasoning of one intelligent agent. In contrast, the aim of DAI is to reproduce the knowledge and reasoning of several heterogeneous agents that solve planning problems by coordinating their actions. Whereas researchers in AI are more interested in the agent and its autonomy, the DAI research focuses on interactions of multiple agents and how to organize them. The latter kind of research became influenced by social and life sciences, especially by the aforementioned Artificial Life approach. Artificial Life is based more on physics and the sciences of complexity and tries to examine scientific questions while focusing on the interactions between elementary entities and their mode of organization (Bousquet and Le Page, 2004).

Research of multi-agent systems developed independently and simultaneously until about the early 1990s. Its roots are production systems that consist of rules and a working memory for facts and match patterns to actions. The main drawback of this approach is the unstructured knowledge of the system. A first solution to this problem has been provided by blackboard systems [see for example (Englemore and Morgan, 1988)] which are most likely the first approach that deserves being called multi-agent systems. The main components of blackboard systems are a knowledge source, i.e. a collection of independent entities with rules expressing a specialized knowledge, and a blackboard as a shared data structure. Knowledge sources that happen to know a solution to a partial problem write it on the blackboard, until the problem is solved. Within the 1970s, other prototypical multi-agent systems developed that realized issues such as actors receiving and sending messages, delegating sub-problems to other agents or negotiation. The common feature of these systems is that a common interest of the agents is implicitly assumed. This means that until the mid 1980s, parallelism in problem solving or distributed problem solving were the main focus of interest. However, agents are not necessarily benevolent as these agents, but can be self-interested instead (Wooldridge, 2002).

An interesting decade for multi-agent modelling began in the 1990s. Interest in agents grew steadily, corresponding to their increasing application in industry. Especially the growing importance of the internet supported this trend, because it indicated that distributed, networked systems might be the future of computing and require appropriate methodologies. Later in the 1990s, agents became important in the booming area of electronic commerce for automating many tasks. Parallel to this trend, the idea of the mobile agent developed, i.e. an agent able to transmit itself across electronic networks and to recommence execution at a remote site. From the mid-1990s onwards, interest in standardization increased as well, since a lack of international standards hinders the spreading of a methodology. At the same time, the first researchers started to apply multi-agent systems to the modelling of natural societies and initiated the first workshops on this topic. Recently, researchers tend towards applying multi-agent system to increasing realistic domains, as soccer contests for robots indicate (Wooldridge, 2002).

Today, the remarkable number of conferences indicates the importance of multi-agent systems in different academic fields conferences, e.g. MABS (workshop on multi-agent systems and agent-based simulation), AAMAS (Conference on Autonomous Agents and Multi-Agent Systems) or ABS (agent-based simulation), among others. Furthermore, special forums for multi-agent researchers exist, e.g. AgentLink (European co-ordination action for agent-based computing).

All in all, it cannot be denied that the history of multi-agent systems is influenced by their multidisciplinary nature. The development of the methodology lived and lives out of the mutual influence of scientists from different academic communities. On the one hand, the approach that originally developed in computer sciences induces scientists in social and natural sciences to reformulate some of their research questions. On the other hand, computer scientists are getting influenced by some concepts of cognitive psychology, sociology, linguistics and other social sciences (Bousquet and Le Page, 2004).

3.3 Different kinds of use

The numerous applications of multi-agent systems can be categorised. Ferber (1999) for example differentiates between five main categories: problem solving in the broadest sense, multi-agent simulation, building artificial worlds, collective robotics and program design (Figure 3.9). Of these categories, the last three are not relevant to applications in hydrology and water resources research.

Problem solving is defined in Ferber (1999) as “concerning all situations in which software agents accomplish tasks which are of use to human beings” (p.31). This definition includes the concepts ‘distributed solving of problems’, ‘solving distributed problems’ and ‘distributed techniques for problem solving’. The first concept takes the fact into account that in some cases the expertise of different persons – or agents –has to be combined in order to maintain satisfying results (Ferber, 1999). Such a kind of automated expert system may be relevant for hydrological purposes as well, although no case study or model is known applying multi-agent modelling in this sense in a hydrological context. ‘Solving distributed problems’ applies if the area in question is itself distributed. A typical example is the monitoring of a telecommunication network (Ferber, 1999). Accordingly, such an approach may be applied to hydrological distributed systems as well, e.g. river networks or runoff generation processes. Again, no example is known following this idea. The last technique that belongs to the category ‘problem solving’ has been discussed before: ‘Distributed techniques for problem solving’ refers to the general idea to assign agents to smaller units of the problem (Ferber, 1999). Surely, this would be an interesting approach for addressing the complexity involved in hydrology and water resources research.

However, multi-agent simulation is the most common technique in applications related to natural systems, whereby multi-agent systems are used as representations of real ecosystems, i.e. as kinds of virtual ecosystems. It is possible that the users define different scenarios and experiment with them. Similar to small-scale physical models, the evolution of the ecosystems under given hypotheses can be tested (Barreteau et al., 2001). Such simulation models may serve different purposes, e.g. as research tools, as training tools and decision support tools (Barreteau et al., 2001). Particularly common is the use of simulation tools for water management. Since policy making is principally difficult in this sector, it is useful to support this process with tools that simulate the water management cycle. The goal thereby is not to predict the exact state of the modelled system, but to explore the system’s evolution caused by these policies (Athnansiadis et al., 2004). This corresponds to the application of multi-agent simulations as training tools. In the context of managing natural resources, different schools of thoughts exist with the purpose to ensure the viability of the systems. Naturally, each of the schools has its own specific weakness (Barreteau et al., 2001). In the past, the testing of different approaches to managing water resources has been done mostly by learning by doing. As a result, errors in the management had severe consequences for the persons in the system. In this sense, learning by simulation instead of trial and error methods would be very helpful for the affected people. Multi-agent simulation models may well be used in this way. However, they must be legitimated and partly validated, if they are supposed to be useful and relevant (Barreteau et al., 2001).

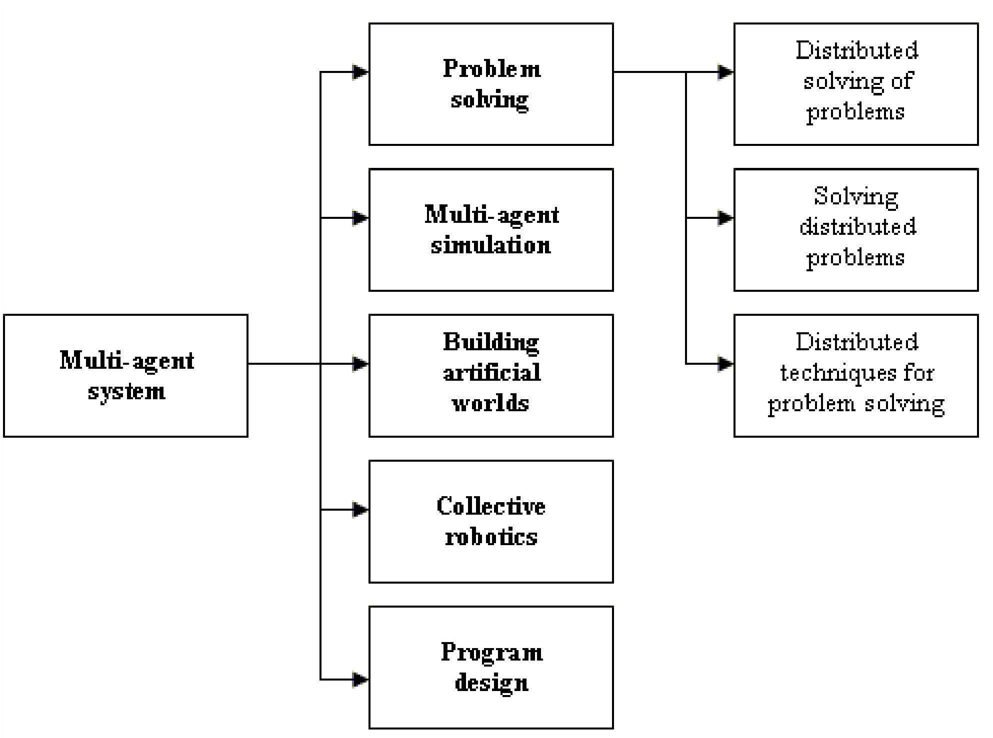

Figure 3.9: Various types of application for multi-agent systems (Ferber, 1999)

3.4 Applications in different disciplines

Probably, there is no such thing as one singular view on multi-agent systems. A key characteristic of the work in this field is its interdisciplinary nature. It is influenced by such different fields as economics, philosophy, logic, ecology and social sciences (Wooldridge, 2002). Correspondingly, a wide variety of academic disciplines has used multi-agent systems in its research. Some of these applications are described here briefly, in order to give a first impression of the method. Moreover, most of them are related somehow to possible applications in the context of water management or hydrology e.g. have related topics or exemplary features. Multi-agent modelling in hydrology may not develop independently of the development in other academic disciplines.

Economics

Economics is one of the disciplines that use multi-agent systems, and many examples in this field are concerned with the management of renewable resources. The idea of representing individuals is not new to economical modelling; micro-simulations for example have a long tradition in this area (Janssen, 2005). The advantage of multi-agent approaches is not only the increased flexibility and complexity, but also the step beyond rational and homogeneous agents that represent an ideal behaviour and are therefore not very realistic (Axtell, 2000). For example a multi-agent simulator can be used as a framework for illustrating and discussing economic theory related to resource management, e.g. to compare two different economic theories for resources management, a market-oriented approach versus specific trade rules (Antona et al., 1998).

Agriculture

Closely related to economics, but nevertheless an independent discipline is agriculture. Especially in agricultural economics, modelling real farm agents has a long history. Technical and structural changes have been explored through the simulation of the farmers' decision-making process as well as through the direct interactions within multiple-agent models (Berger, 2004). Such applications are often related to hydrology and water resource management because irrigation and water allocation problems are included. Furthermore, in agricultural sciences like in hydrology, multi-agent modelling provides the connection with the human behaviour. One application for example explores how the seasonal climate forecast affects the farming decisions of farmers in Lesotho, depending on the accuracy of the forecast (Ziervogel et al., 2005).

Ecology

Very typical applications of multi-agent systems belong to the area of ecology, especially the biology of swarms and flocks, including ants, termites, birds [see for example Mach and Schweitzer (2003)]. One of the most famous examples for the representation of reactive agents and emergence is the metaphor of the ant-hill (Bousquet and Le Page, 2004). It is especially suitable for demonstrating the basic principle of multi-agent modelling: complex structures like ant hills emerge out of the simple rules that determine the behaviour of not sophisticated animals like ants. The simulation of vortex swarming of Mach and Schweitzer (2003) is interesting from a hydrological point of view because the authors use the concept of potentials for realizing the attraction through the environment. As discussed later, the concept of potentials leading to motion is essential for many hydrological models. The main idea of the model of Mach and Schweitzer (2003) was to represent the behaviour of Daphnia swarms with minimal, but biologically relevant assumptions. The motion of the agents are made up by a deterministic and a stochastic term (random noise), whereby the first accounts for direct interactions with other agents, e.g. avoidance, as well as for external influences, e.g. attractive environmental potentials.

In ecology, multi-agent systems belong to a new approach in modelling, the so-called individual-based models (IBM) with their own tools and methods. Some of the researchers in this field took not only the individual with its unique characteristics and its autonomy into account, but also social and organizational aspects. Thereby, they laid the fundamentals for an interdisciplinary encounter with computer scientists and their multi-agent system methodology (Bousquet and Le Page, 2004). The differences between multi-agent simulation and individual-based models are based on their history. Because multi-agent simulation has been more influenced by social and computer sciences, there has been more emphasis on decision-making process of the agents and the social organizations are emphasized more. Moreover, multi-agent modelling is not necessarily individual-based, since any level of organization can be represented, including herds and villages (Bousquet and Le Page, 2004).

Land use

Another rather typical application of multi-agent models is the modelling of land use, land cover change or spatial planning [see for example Berger (2004) or Ligtenberg et al. (2001)]. Such studies emphasize the spatial aspects and the physical environment very much, which creates a relation to water resources management and to integrating Geographical Information Systems (GIS) (see Chapter 4). Agents representing stakeholders introduce multi-actor decision making into the traditional models of land use change, e.g. in a hypothetical land use planning situation in the Netherlands (Ligtenberg et al., 2004).

Social sciences

In social sciences, multi-agent simulation offered a completely new approach, namely computer simulations, for studying the mechanisms that are meant to determine the behaviour of human societies (Berger, 2004). One of these models, the Sugarscape model, is often used for demonstrating the idea of multi-agent systems. It simulates the production of sugar by an artificial society of agents, including growing, harvesting, consuming and trading sugar as well as reproduction of the agents and conflicts between them (Epstein and Axtell, 1996).

Even in the context of wastewater treatment, multi-agent systems have been applied. The developed model helps to understand the fundamental mechanisms of biofilms. The advantage of such an approach is the inclusion of individual phenomena like cell-cell communication or mutations together with their effects on macroscopic structures (Lardon et al., 2002, p.231).

Hydraulics and Fluvial Geomorphology

An application that takes place in between hydrological and hydraulic processes is the agent-based simulation of water flow for environmental modelling in estuaries (Bertelle et al., 2000). Water flow problems in an agent-based model are addressed by integrating vortex methods, since vortex particles in great numbers can be used to represent a fluid stream with accurate precision. If coherent structures emerge, they are replaced by a meta-vortex particle. Interesting in a hydrological point of view is thereby the idea to reduce the naturally high complexity in modelling water flows by aggregating particles in clusters.

Closely related to hydrological research is the modelling of fluvial geomorphologic features, e.g. alluvial plains. A model of the Rh∗ne plain is constructed since 15000 years BP, without relying on physically based equations or on the representation of water (Teles et al., 2001). Simple sedimentary rules representing geometrical or empirical laws are applied to ‘sediment’ entities or to conceptual ‘erosion’ entities. Thereby, local deposition and erosion of sediments is simulated while the various climate conditions influencing deposition processes are accounted for. Field data constrains the model. The model achieves to reproduce the general geometry of the alluvial deposits comparably well, according to the authors. Although only local rules are used, characteristic large-scale features emerge during the simulation (Teles et al., 2001).

3.5 Applications in hydrology and water resources research

3.5.1 Applications in hydrology

Objective

When modelling hydrological processes such as runoff or infiltration, the researcher has to deal with the numerous factors influencing these processes, such as attributes of the soil, the vegetation or anthropogenic factors like impermeable road networks (Servat et al., 1998). The classical approach is to integrate all this information into a single hydrological model based on a unique lattice. One of the problems thereby is that the diversity of the underlying temporal and spatial scales is often neglected and that these models often focus on global information (Servat et al., 1998), e.g. water flows at outlets only instead of the spatial distribution of water flows and paths.

With multi-agent modelling, an alternative approach is imaginable that represents the processes in more detail and on a less aggregated level. Such a representation would be based on the smallest particles in the process, i.e. most likely water particles in hydrology. Although representing water particles as agents may be less intuitive than modelling water users in this way, the idea seems promising. To evaluate its potential, it is necessary to know whether models exist already following this idea.

Applications

The only examples for such an approach that have been found in the literature are the studies of Perrier and Cambier (1996) and Servat (2000). The aim of their RIVAGE project is the modelling of runoff, erosion and infiltration on heterogeneous soil surfaces. However, the objective of the thesis of Servat (2000) is not only to apply agent-based simulation for this purpose, but to introduce a new technique in the methodology. He criticizes in current multi-agent simulations that local groups of entities evolve based on interacting individuals, but that these groups do not have an existence of their own. The idea of the project is to realize a computer equivalent to the human ability to recognize emergent features. Theoretically, this dynamic creation of agents by agents themselves would be one step forward towards a concept of agents in their full meaning. The subsequent new possibilities for multi-agent modelling include representing physical laws that depend on scaling, e.g. hydrological processes (Servat et al., 1998). Moreover, the computational costs of the model decrease when individuals with similar behaviour are summarized to new entities.

Since hydrological processes involve different temporal and spatial scales, using models that are able to handle multiple viewpoints in one simulation would be beneficial for modelling. The idea of the RIVAGE project is to represent water as numerous multi-scale agents moving according to their environment. The first work implementing such ‘waterball’ agents has been done by Perrier and Cambier (1996) who used a multi-agent approach to investigate the interactions between heterogeneous agents representing infiltration processes on soils. In their model, the motion of an agent is determined by the information in its environment, e.g. soil maps or topographical maps. The work of Servat (2000) is based on this idea, too, but introduces additionally the formation of agents on higher levels. Unfortunately, the model cannot be described in full detail here, only its main features are sketched. The movement of waterball agents on the surface depends on inclination, friction and acceleration. If some agents share a structurally stable interaction for a certain time, they form an agent on a higher level that represents a hydrological feature. Waterballs agglutinating over local depressions for example result in the emergence of a pond. They regroup and create a macroscopical entity that represents the pond as a whole. Waterballs following the same path regroup in a water path (Servat, 2002) (Figure 3.10). Agents on a higher level have a different hydrological behaviour, e.g. ponds are characterized by a volume, whereas the waterball agents are not. However, the waterball agents are not deleted, but coexist with the macroscopical entities. Rules exist that allow for the breaking up of these agents into the original waterball agents (Servat et al., 1998).

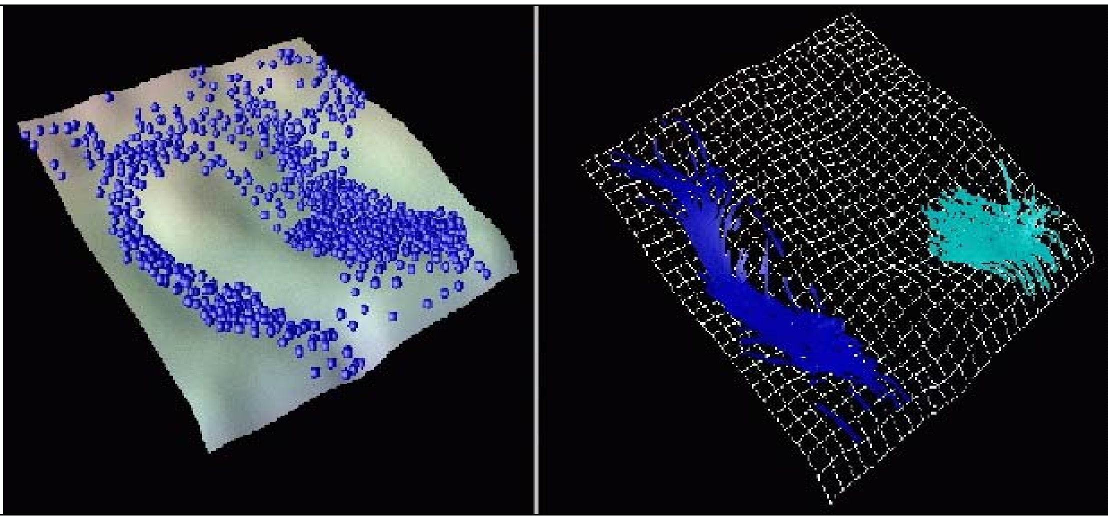

Figure 3.10: Distribution of waterballs on the surface (left) and corresponding trajectories (right) creating a macroscopial water path agent (on the left) or a pond agent (on the right) (Servat, 2000)

These ideas may sound promising, but include nevertheless numerous unsolved theoretical and practical issues. Although the first implementation delivered not only interesting concepts, but some useful results as well (see Servat, 2002), the approach is apparently given up by the research group. Possibly combining a new methodology with a new area of application was too ambitious. Implementing hydrological processes based on water particles is a completely new idea. Consequently, it challenges existing knowledge, assumptions and concepts. Substantial research is needed in this field before it is known which processes and rules have to be included into the models. Moreover, it seems that not only in the context of hydrology, but also in general multi-agent models are seldom applied to pure physical processes (Servat et al., 1998). It is not surprising, though, that methodological problems still exist.

3.5.2 Applications in water resources research

Objective

A high number of studies exist that apply multi-agent modelling to water resources research. The general idea thereby is to simulate the responses of the households to changes in their environmental with quantitative models and to support policy formulation. To achieve this, ideally models integrate biophysical as well as socio-economic processes (Berger, 2004). The problem at the moment is that most models do not address interrelations between evolution of water resource and human development in a balanced way. For managing processes at the river-basin level for example, the emphasis is commonly placed on one side, either on accurate modelling of the water dynamics or of the human activities (Edwards et al., 2002).

The current trend towards application of multi-agent methodology in water management corresponds to current trends in water management, e.g. towards decentralization. For example, many of the examples modelled in the French research community are related to the 1992 French water law that emphasizes decentralized approaches to water management. The initiated process of negotiating local water management rules contributes to the growing interest in analytical tools for supporting the processes of negotiation and decision making (Thoyer et al., 2001). In this context, simulations can be a helpful tool for illustrating the probable consequences of different actions to the stakeholders, especially concerning interactions and second-order effects. Thereby, it is not the aim to predict the future outcomes exactly, which would be over-ambitious anyway, but to foster the stakeholder’s understanding of possible scenarios (Gilbert et al., 2002). Consequently, models in water resources management aim not only at helping the authorities to evaluate possible effects of different kinds of water management actions, but are also used sometimes to foster communication with stakeholders as well (Feuillette et al., 2003). In both cases, the socials aspects have to be represented realistically in the dynamics of the hydrological system (Feuillette et al., 2003).

All in all, water resource problems not only demand the integration of hydrological and social models, but also the communication of the models to stakeholders or even their involvement in creating and interpreting it. All these requirements go beyond the scope of classical hydrological models. Multi-agents models in contrast may be suitable for building models with these characteristics. Support for this assumption is sought in the literature and described below.

Urban water management

Peri-urban areas serve as catchment areas and space for drinking water reservoirs to the cities, but face specific challenges such as urbanization dynamics, illegal settlements and the absence of basic infrastructure and public facilities. A multi-agent model of the metropolitan watershed of aims at representing the hydro-social functioning of the catchment Sao Paulo, Brazil (Ducrot et al., 2004). The prototype of the agent-based model includes legal and illegal market processes as well as the competition for water by rural and urban land owners and pollution (Ducrot et al., 2004). The main activity of the producer and speculator agents is to decide on the use of their plots. Hydrological processes are represented in a spatially distributed manner and the pollution is monitored along the rivers. Furthermore, the availability of water and its pollution influence the decisions of the agents. First results indicate for example the time at which the water reservoirs reach a critical level (Ducrot et al., 2004).

Integrated Natural Resources Management

Integrated Natural Resources Management (INRM) challenges traditional approaches because it considers scale issues, i.e. interrelations between temporal, spatial and social scales, as well as various organizational levels (Abrami et al., 2002). The research in natural resources management shows a growing interest in modelling artificial societies due to the ability of this approach to conceptualise entities (Ducrot et al., 2004). A great part of the literature on multi-agent modelling dealing with natural resources takes place in the context of Integrated Natural Resources Management. The French research community that developed the modelling platform Cormas (Bousquet et al., 1998) realized many applications of multi-agent modelling in this context [see for example Bousquet and Le Page (2004), Barreteau (2001) or Abrami et al. (2002)]. A general problem in integrated management is to match the scales of social and ecological dynamics. In agent-based modelling, it is possible to operate on different levels, which is useful for agent-agent and agent-environment interactions (Janssen, 2005).

Tragedy of the common

A common background assumption in water resources management is that the consumption of water may result in a "tragedy of the common", an overexploitation, which may occur when several users freely access one common resource. 'Tragedies of the commons' are generally a typical application for multi-agent modelling, although not always related to water resources. Applications have often an educational purpose, as for example the multi-agent version of the 'FishBanks game' (Kozlak et al., 1999). Its objective is to explore problems of reaching agreements in negotiations and avoiding the overexploitation of the resource.

SINUSE (Simulator of the water table and user interaction) is a multi-agent model of negotiating water demand management of a water table based on field data of a water table in Central Tunisia (Feuillette et al., 2003).

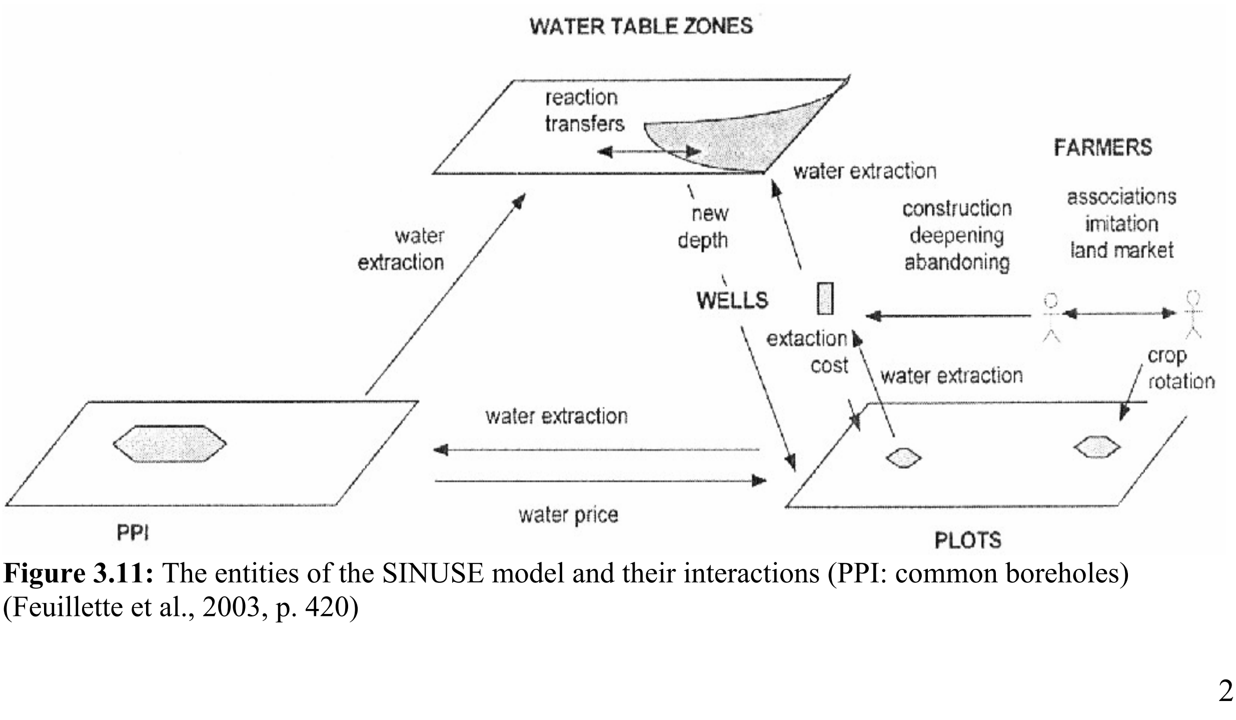

Figure 3.11: The entities of the SINUSE model and their interactions (PPI: common boreholes) (Feuillette et al., 2003, p. 420)

The main topics of the simulation are conditions under which farmers build wells and social influences, e.g. teaming up of two neighbours for building a well (Feuillette et al., 2003). The entities represented are the farmers as social entities, spatial entities such as their plots and finally wells and boreholes as located entities. The interactions between the farmers concern the construction of wells and the exchange of land. Figure 3.11 illustrates the entities of the model together with their possible interactions. First tests of the model reveal that the dynamics in the field are comparably well reproduced for the near future and that logic and realistic tendencies are observed for the long-term (Feuillette et al., 2003).

Participatory modelling

The idea of participatory modelling is that researchers actively involve stakeholders in the process of developing the agent-based model and the resulting solutions (Hare et al., 2002). Different names for this approach exist, including interactive social sciences, participatory methods, integrated assessment or action research (Gilbert et al., 2002) and adaptive management (Janssen, 2005). Researchers and stakeholders both contribute their expertise in order to reach their shared goals. Thereby, the researchers gain new insights, e.g. into the perception, goals and beliefs of the stakeholders and conflicts between them, and identify relevant research questions (Gilbert et al., 2002). Stakeholders are more likely to apply the models to real-life problems due to their higher motivation and positive attitudes towards the models (Hare et al., 2002). Past failures of centralised and bureaucratic management are one reason for the increasing interest in decentralised management with stakeholder participation (Doran, 2001).

Multi-agent models facilitate active participation of stakeholders because of their relative descriptive clarity and the straightforward way of interpreting them (López-Paredes et al., 2005). Stakeholders without profound knowledge in model construction and analysis can have difficulties to interpret the parameters and statistical outputs of conventional models or to find the connection between parameters and practical policies (Gilbert et al., 2002). The specific problems of the method, e.g. the motivation of stakeholders and conflicts between them (Gilbert et al., 2002), are not the focus of this thesis. However, the concept is relevant for this discussion since many applications of multi agent approaches in the context of natural resources research include participatory modelling. To realize the involvement of stakeholders, the models are often, but not necessarily combined with the role playing games approach (see below).

Many case studies combining multi-agent modelling and participatory approaches are part of the EU research programme FIRMA (Freshwater Integrated Resource Management with agents, see http://firma.cfpm.org/). Its five case studies are concerned with applying these two basic principles to water management [e.g. Hare et al. (2002), Edwards et al. (2002), Gilbert et. al. (2002), López-Paredes et al. (2005)]. Water management problems in different water basins across Europe are addressed, and the core objectives are to improve water resource planning by applying new tools based on agent-based modelling (López-Paredes et al., 2005).

The Swiss case study for example addresses the water policy issues in Zurich, the biggest city in Switzerland, where new demand-oriented management strategies are searched for (Hare et al., 2002). The initiated model-building-as-learning process is meant to encourage social learning, perspective sharing, conflict identification and resolution and group solution generation, as it is typical for participatory processes (Hare et al., 2002). The process is divided into different steps, e.g. the actual building of the model in the initial knowledge elicitation phase, the role-playing game and the scenario testing (Hare et al., 2002) (Figure 3.12). Since this specific role-playing game is played rather slowly, an internet version has been developed, that is still in the experimental phase at the time of publication. It enables the stakeholder to play the game at their regular place of work via a user-interface, whereby computational agents driven by production play the role of the human players when these are absent (Gilbert et al., 2002).

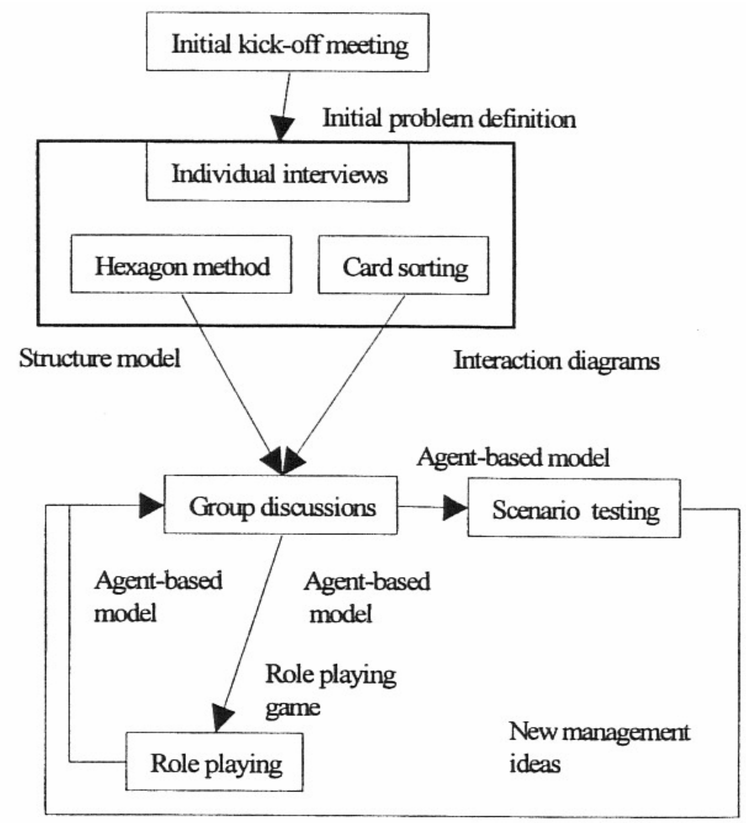

Figure 3.12: Overview of the Model-building-as-learning process (Hare et al., 2002, p. 62)

Another case study of the FIRMA project addresses urban water management and focuses on the water cycle and the role that agents play in it (López-Paredes et al., 2005). The FIRMABAR simulator allows simulating and evaluating different supply-and-demand policies, it is applied to some areas in Spain, e.g. to the metropolitan area of Barcelona. The stakeholder involvement is realised through interviews about attitudes, preferences and objectives of stakeholders related to domestic water management and a questionnaire about the hydrologic cycle of the study area. The interaction with the stakeholders and their knowledge of the system is considered a valuable source of input data for the model that replaces the field data collection. The simulator consists of two coupled models, a territorial model and a social model. The agents are families that are randomly located within a municipality and that are able to move and decide on their maximum water demand. With a monthly time step, the model simulates the urban water consumption based on four different steps: First, climatic data is used for calculating the available freshwater supply. Afterwards, the families decide about their water consumption and possible movement to other areas. Last, the territorial model is updated (López-Paredes et al., 2005). In this respect, the model is similar to the model described in chapter 5.

The research centre Cemagref and other agricultural research institutions in France have been focusing on participative management of renewable resources using agent-based modelling in the past few years (Abrami et al., 2002). To mention just one example, role games are applied in a multi-agent model of the French Drome River basin for acquiring knowledge, building the model, validating it and finally using it in the decision-making process (Abrami et al., 2002). Like other work at Cemagref, this study follows the so called ‘companion modelling approach’ described by (Barreteau et al., 2001). These models are often used as negotiation support tools as well, whereby agent-based models offer the advantage of providing the stakeholders with multiple viewpoints on the dynamics of the systems. Furthermore, interconnected topics may be discovered that have been previously ignored (Barreteau et al., 2003). Summarized, the value of including the humans into the multi-agent system is twofold: The behaviour of the participants can be seen as a form of knowledge acquisition and the stakeholders learn about the policy options and their likely consequences (Gilbert et al., 2002).

Role playing games

Quite frequently multi-agent systems are combined with role playing games, mostly in order to create participative water management support systems or decision support systems [e.g. Abrami et al. (2002), Adamati et al. (2004) and Barreteau (2001)]. Since both multi-agent simulation and role-playing games have been used frequently as tools for natural resources management in the last years, it is a straightforward idea to combine them. Such a combination harvests the dynamic capacity of multi-agent modelling and the ability to generate discussions of role playing games likewise (Adamati et al., 2004). Moreover, the combination is meant to be necessary for opening the black box of multi-agent simulation (Barreteau et al., 2001). Whereas multi-agent simulations are normally restricted to the laboratory, they can be made usable in the field in this way. The role playing game can be considered as a living multi-agent model in which the stakeholders play the agents (Barreteau et al., 2001).

As a prototype, the model JogoMan (Adamati et al., 2004) addresses issues of land and water management in cities with high pressure of urbanization. Based on the multi agent modelling software Cormas and role playing games, the “social laboratory” provides means for learning and analysis by simulating different scenarios without negative consequences in reality (Adamati et al., 2004). The multi-agent model SHADOC has been developed as a research and teaching tool for the case of the Senegal River Valley irrigation system (Barreteau and Bousquet, 2000). The purpose is to investigate the relation between the stakeholder coordination and the lack of viability of this irrigation system. The model is based on field studies and has been coupled with a role playing game to provide a decision support tool (Barreteau et al., 2001). Converting a multi-agent system into a role playing game requires different steps, mainly the development of the multi-agent model, the design of the game and the use of the feedback from the game in the field and as well as the improvement of the multi-agent model. Normally, the multi-agent system has to be simplified before it can be used for the design of a playable game, e.g. by reducing the number of agents or rules (Barreteau et al., 2001). In the case of the SHADOC model, this led to the development of a second multi-agent system called ShadocLight (Barreteau et al., 2001). In the SHADOC role playing game, about 12 players take the roles of farmers who have the task of cultivating a plot in the same irrigated schemes. Each of them receives a random set of three cards defining the behaviour of the players within the session and containing information regarding the social status of the player, the goal for cultivating the plot and the rule for reimbursement of credits (Barreteau et al., 2001).

Role playing games and their combination with multi-agent models cause a number of methodological issues that are not yet clarified, e.g. whether the stakeholders are able to play themselves realistically (Doran, 2001). Nevertheless, it is plausible that combining a technology based on the representation of agents with an involvement of the stakeholders of different backgrounds into the scientific process is a promising way in water management. Water management needs not only reliable scientific results, but also means to communicate them. The question is whether role playing games need the combination with multi-agent systems for their successful application. The problems of pure role playing game approaches are that a lack of control on most parameters causes difficulties in developing the game, in analysing its results and in comparing different experiments. A combination with multi-agent simulations seems therefore reasonable, especially since it is easier to develop a game based on an existing multi-agent simulation (Barreteau et al., 2001).

Decision support systems

Besides role playing games and stakeholder involvement and often combined with them, decision support systems are another way to pass on the results of models to possible stakeholders and to make reasonable use of these results. Decision support systems are academic simulators for exploring different scenarios as well as the included policy options and their possible consequences (Kneer et al., 2003) Thereby, multi-agent models can serve as mediating objects enabling the stakeholders to develop a common representation of the joint natural resource system and to communicate about it. However, all stakeholders have to accept the model and its capacity to represent reality first, because on a legitimized model is a useful tool in the negotiation process (Barreteau et al., 2001). Moreover, the system needs a sophisticated interface for communication between model and user that does not expect the user to be capable of applying a formal computational language (Davis, 2000). This may be achieved either by a graphical user interface limiting the possibilities of the users so that it is easier to translate them into model code or an interface agent that is capable of learning the language of the users.

Most of the often cited examples for participatory modelling and role playing games are used as decision support systems as well. However, creating decision support systems with multi-agent models, but without stakeholder involvement is possible as well. Davis (2000) for example who refers to such approaches as Multiple Agent Decision-Support System (MADSS) developed a decision support system for UK water companies and their decisions on water mains rehabilitation. The model is faced for example with the problem to appropriately distribute the available financial means between different tasks (e.g. unexpected emergency cover vs. regular water supply maintenance), different regions in the area and different consumers (rural vs. urban). The output is a ranking of the relative need of investments in different sectors, resulting from ranking the different uses according to the appropriate attributes.

Integrated watershed management

In the last years, Integrated Watershed Management (IWM) has been of growing importance as a specific form of the more general Integrated Natural Resources Management (INRM) mentioned above. It is of particular interest to hydrologists who are working traditionally in reference to watersheds. IWM is characterized by its complexity and is faced with conflicting interests, e.g. water supply, flood control and recreation, just to mention some (Doran, 2001). The aim is generally to develop and execute a sustainable and equitable strategic program for utilizing and conserving natural resources at all scales in a watershed, thereby integrating different interests (Doran, 2001). Models for this purpose should be integrative as well as spatially distributed and large-scale representations in order to represent the whole system including interactions between natural and other resources and between all relevant processes (Becu et al., 2003).

In the Fraser River basin in British Columbia, Canada, the management problems are mainly based on conflicting stakeholder interests. An agent-based model is supposed to explore possible intervention strategies (Doran, 2001). At the time of publication, the model was not close to complete implementation yet. However, its modelling concept contains some interesting features, such as a highly abstract concept that is not limited to the Fraser watershed. The numerous heterogeneous single agents are summarized in groups of agents with similar goals that are organised as a hierarchy and build the society.

The CATCHSCAPE model (Becu et al., 2003) is an integrative model that simulates a whole catchment, but also the farmer's individual decisions. According to the authors, only a few models exist which are able to deal with both catchment and individual scale representations. Their own model is used to simulate a simplified version of a catchment in northern Thailand focusing on the impact of upstream water management on downstream farming systems (Becu et al., 2003). The model has some interesting features, e.g. the influence of the water expectations of a farmer on his decisions. The aim of such models is to provide a valuable tool for the stakeholders to explore integrated impacts of prospective and alternative management options (Becu et al., 2003), not to deliver accurate predictions.

Lake management

A model of the dynamics of a lake subject to phosphorus pollution includes the cycle between water and sediments (Carpenter et al., 1999). Related to the different states of the system are different economic benefits. The modelled agents decide upon the level of input pollution according to their expectations about the dynamics of the system, the markets and the actions of other agents. Thereby, the agents are heterogeneous in their beliefs and in their access to information and adapt to changes in the ecosystem (Carpenter et al., 1999).

A similar piece of work is done by Möhring and Troitzsch (2001). Based on a conventional computer model of hydrological and limnological processes in Lake Anderson, they created the multi-agent model MIMOSE with the aim to represent potential polluters and local administration directly. For this purpose, they implemented farmer agents and a local government applying different policies against the eutrophication of the lake.

Water resources in agricultural systems

Water resources research and agricultural topics are sometimes closely related, for example, when issues like water allocation for irrigation systems are addressed. An example is the already discussed multi-agent system SHADOC (Barreteau and Bousquet, 2000) for tackling the viability of irrigated systems.

The spread of innovations, e.g. of water saving irrigation methods, is relevant to agriculture and water management likewise. Berger (2004) studies such an innovation diffusion process for agricultural technologies with a focus on decision making in rural households in developing countries. He simulates agents with different adoption behaviours, i.e. early vs. late adopters, with a one-to-one correspondence between real world and modelled agent and several types of interactions, e.g. exchange of land and water resources and return flows of irrigation water. The investigation of the connection between innovation and migration is relevant for water resources research as well, since migration is an important factor in water management especially in water scarce areas. A prototype of the model is applied to an agricultural region in Chile (Berger, 2004).

Water resources research and economy

Issues of water resources research are often closely related to economic topics. A problem of classical economic modelling has been that the assumption of selfish rational agents works well for highly competitive markets, but not for many of the decision situations that are typical for ecological economics. In the latter situation, motivation, fairness and preferences play important roles. Additionally, the situations in environmental management are often complex, so that the second important assumption in conventional economics does not work either: The individuals do most likely not have full information or understanding of the problem and are hardly able to evaluate all different options (Janssen, 2005). Multi-agent modelling is one of the possible alternatives for economical understanding of management of nature resources.

An advantage of multi-agent modelling is the possible inclusion of the parameters influencing the water users' decision-making process, for example environmental awareness and social responsibility. The agent-based social simulation DAWN (distributed agents for water simulation) aims for example at predicting the effects of a public conservation campaign on residential water demands (Athnansiadis and Mitkas, 2005). Focusing on the influence-diffusion mechanisms among water user, it represents a community of interacting, autonomous consumer agents including some so called opinion leaders. The agents decide about actual consumption influenced by their social neighbours, whereby each actor has a different power of persuasion and an individual sensitivity to social influence (Athnansiadis and Mitkas, 2005). A first application of the model in Thessaloniki, Greece delivers some interesting quantitative results, e.g. that the impact of information and education campaigns is less effective than increasing water prices at the beginning, but more intense in the long term (Athnansiadis and Mitkas, 2005).

3.5.3 Combined models

Another possibility in agent-based modelling is the combination with other types of model, e.g. with hydrological models, thereby simulating the environment in which the agents are situated. The society of agents represents human behaviour and all kinds of social and economic aspects.

The agent-based simulation of the hydraulic management of the Camargue as a human influenced ecosystem consists of two interacting models (Franchesquin and Espinasse, 2000). The hydrologic model represents subsurface water fluxes and provides the physical environment of the model by computing the hydro-salt state of the system based on input data, e.g. precipitation. The agent-based social model reflects decision processes in water management through agents such as farmers, hydraulic associations and sea dike managers deciding about the resources described in the hydrologic model. The two models interact through objects managed by agents, e.g. the farmers define the land use of the plot (Franchesquin and Espinasse, 2000).

The GLOWA Danube project is a model combining different models. At the same time, it integrates multi-agents methodology and aims at providing a decision support system. It focuses on the water cycle in the upper Danube catchment aiming at the interdisciplinary development of integrative strategies for a sustainable water management on the regional scale (Kneer et al., 2003). The whole model is separated into different modules that are coupled via interfaces and data transfer, whereby agent-based modelling is applied in only one of the modules, the so-called Actor model, for modelling the water use of the households in the area. The modelling of the water consumption starts with an approximation based on objective parameters, e.g. the size of the household, and refines the estimation with economic variables, e.g. the prize of the drinking water, as well as with psychological parameters, such as intentions towards water saving behaviour (Kneer et al., 2003). The combination of different models, combined through the exchange of data, assures that the most suitable model is applied for each of the different tasks, since multi-agent modelling may not be the best solution for all the different disciplines with their specific needs.

3.5.4 Possible applications

The examples described so far illustrate the broad range of possible applications of multi-agent systems in the area of hydrology and water resources research. Nevertheless, some possible applications come to mind that are apparently not realized yet. For hydrological modelling, three generally different approaches are possible. The first concept represents the simplest units of the system, e.g. water particles, as numerous reactive agents, similar to the pioneering work of Servat et al. (1999).

The second possibility applies service agents for hydrological purposes, mainly for gaining information out of data. One idea is to consider the environment in a multi-agent system as some sort of virtual world and the agents as responsible for taking probes in similar way as researchers, e.g. hydrologists, do in reality (Külls, 2005, personal communication). Agents could for example move around on the surface of a groundwater model, probe the place and decide where the most suitable places for drilling wells are. The advantage is that these would not be random samples, since agents could have knowledge and abilities to explore the area in a systematic way.

Beyond this, service agents could conduct a great deal of preparation of data and data mining. Preparation of data for the modelling process takes a lot of time. In the same way as software demons and intelligent software agents perform operational tasks in the internet, e.g. search for information, they may help with the preparation of data. If, for example, databases developed by third parties are not compatible to certain standard for data, the resulting data-cleaning is a time consuming process that could optimally be executed by an automatic data-cleansing agent (Davis, 2000). An agent knowing what it is looking for may be able to select the appropriate data out of a database. Most suitable seems a combination of such agents with GIS technology. Such an approach does not aim at substituting hydrological models with multi-agent systems. In contrast, it could support classical hydrological models by coping with the increasing amount of data available through new technologies such as remote sensing by providing an additional, time-saving access to data.

The third concept is seen somewhere in between these two approaches. The idea is to represent the elements of the water cycles as aggregated agents, e.g. to assign an agent to a layer of the soil or to a river. Modelling of hydrology then consists of determining the appropriate attributes to these agents and specifying their interaction. Thereby, existing knowledge and models can be integrated. Instead of representing infiltration as transfer of water between different storages, it could be implemented as transfer between agents, whereby the soil layer agents behave like storages. At the same time, such a model could be combined with methods of agent-based data mining. If all data is represented as agents, it may be possible to realize agent-based methods that undertake parts of the process of the data preparation autonomously. Thinking ahead in this direction consequently may lead to the assumption that agent-based modelling even may succeed object-oriented programming as standard programming approach one day.

Taking the modular structure of the multi-agent models as well as their bottom-up nature into account gives rise to the idea to consider them as some sort of model laboratory. If the modelling task is divided into smaller tasks, each can be treated as independent modelling experiment. Increasing the complexity gradually may help to understand the system under study and design reliable models by testing the assumptions independently.

As discussed above, a variety of applications exists already concerning water resources research issues. However, even in this context it is possible to think of applications that are not realized yet. Most examples aim at understanding and exploring existing systems. An alternative issue is the development of infrastructure, for example the simulation of settlements in uninhabited areas. Based on data about the natural resources, an agent-based model could aim at providing advice on the optimal spatial distribution of settlements and the best possible setup of the water infrastructure. Clearly, this is one of the cases where a modelling exercise could replace the usual learning-by-doing approach in human settlements, since normally the first settlers have to pay heavily for misjudgements on the best spot to settle down.

3.6 Benefits of multi-agent system in hydrology and water resources research

The discussed models and case studies provide first impressions on possibilities and limitations of multi-agent modelling for hydrology and water resources research. It remains to discuss which conclusions can be drawn based on the literature review. For this purpose, it may not be sufficient to ask what the methodology has to offer. Rather, criteria for judging the suitability of the methodology derive from the question what hydrologists expect from such a methodology. Although multi-agent systems can be considered as a very innovative new modelling approach, their advantages do not necessarily have to fulfil the requirements of hydrological research for new modelling approaches. According to Bankes (2002), not the virtuosity of a technology, but the needs in sciences determine whether an innovation tool is revolutionary or not. Regardless of the greatness of advances in computer sciences that made agent-based modelling possible, what matters are the challenges in the sciences adopting it, that make it necessary (Bankes, 2002).

For the area of social sciences, Bankes (2002) found three often cited reasons why agent-based modelling is potentially important, namely “the unsuitability of competing modelling formalisms to address the problems of social sciences, agents as a natural ontology for many social problems, and emergence” (p.7199). These reasons partly apply to hydrology as well and serve as a guideline for the discussion in the following sections. Additionally, the multi-disciplinary nature of multi-agent modelling is another advantage.

3.6.1 Limitations of traditional approaches

A first reason for applying multi-agent models seems to be simply that other models do not provide the required functionality.

Restrictions in equation-based modelling

The most common modelling approaches are differential equations and statistical modelling (Bankes, 2002). In hydrology, various types of models exist [see for example Dyck and Peschke (1995)], all of them with their specific advantages and disadvantages. However, the general idea is to find a mathematical relationship between variables representing physical values that can be measured in reality (Ferber, 1999). Due to this general principle, most of the criticisms apply to all these hydrological models.

Finding an appropriate mathematical equation requires simplifications of the naturally complex structure. Models contain numerous parameters, whereby it is not possible in all cases to define their values empirically (Beven, 1993). Moreover, such approaches place a high amount of restrictions on the modeller, such as linearity, homogeneity and normality (Bankes, 2002). In many cases, e.g. in the finite differences approaches for modelling groundwater flows, the criteria for the use of the approach are not met in the modelled example. The model is used nevertheless, due to a lack of better options. In other cases, models cannot be applied, since the model cannot account for some of the characteristics of the model, e.g. its non-linearity, or generally for its complexity (Ferber, 1999).

Furthermore, especially conceptual models contain often a high number of parameters. Critical consequences are inter-correlations between the parameters not accounted for and the non-uniqueness of the model solutions, i.e. an infinite number of realizations of equivalent performance (Beven, 1993). Another general disadvantage of equation-based models is the use of averages of system variables over time and space in many cases (Parunak et al., 1998). Often, the systems are highly variable, so that the assumption of homogeneity in the variables is not valid. Especially in non-linear systems, this may cause significant deviations in overall system behaviour.

Agent-based models instead focus on local relations and cope without averaging over time and space (Parunak et al., 1998). Since they are as representational systems not based on mathematical derivation, it is not necessary to bring the problems in forms tractable for mathematical analysis or proof (Bankes, 2002). Thereby, they impose fewer restrictions on the modelling process. They require no a priori assumptions on the structure of the model, such as linearity or homogeneity, and are able to address complex issues, as discussed below. Since the models represent interactions between the agents and not chiefly relations between the observables, they are not likely to rely on too many parameters.

Multiple agents on multiple scales

A limitation of classical hydrological modelling approaches is that they are not dealing very well with the problem of multiple scales, but are specified for either micro-, meso- or macro-scale modelling. However, specifying time and space scale does limit the adequateness of the representation, since the diversity in the natural processes is not accounted for. Contrarily, the concept of multi-agent modelling seems promising for creating frameworks working "multi-level", on multiple scales (Servat et al., 1998). The problem of scaling is particularly relevant in interdisciplinary projects, since different disciplines are used to work on different spatial and temporal scales (Ernst et al., 2001). To avoid technical problems inherent in adapting scales, it may be useful to choose an approach able to handle different scales rather easily.

In multi-agent modelling, it is theoretically possible to handle different scales, although practically not many researchers have met this challenge yet. A simple example is the representation of agents on different levels of aggregation, e.g. individual farmer agents and the government as an agent. Naturally, the actions of these different kinds of agents do not take place on the same spatial scale, possibly not on the same temporal scale as well. The CATCHSCAPE model for example represents the whole catchment area as well as the individual decisions of single farmers (Becu et al., 2003). In this way, it is even possible to represent interactions between entities of different kinds, e.g. between the individual farmer and the population of farmers; thus, a collective opinion formation process can be modelled (Möhring and Troitzsch, 2001).

However, different scales are represented and agents on different scales may interact in such models, but transfer between different scales is not included. This next step in representing multiple scales would include that agents or objects on higher scales are created autonomously within the modelling process. This is the idea in the work of Servat (2000) where a group of water particles behaving in a similar and characteristic way for a certain time group and form an agent on a higher scale representing a hydrological feature.

Another possibility could be combining existing models on different scales to a single model. Whereas the Mekong River Basin Model for example is an aggregate water allocation model operating at a trans-boundary, intra-sectoral level, the Melado River System Model represents a highly disaggregated multi-agent model integrating economics and hydrology (Berger, 2004). The objective of the authors is to combine these models into a "multilevel multi-agent" framework in the future.

Qualitative data

Traditionally, hydrologists are used to deal mainly with quantitative data, which is the kind of data their models are based on. Nevertheless, as soon as one leaves the area of physical hydrological processes and takes water resources research issues into consideration, qualitative data is important as well, e.g. farming strategies and decision characteristics. It would consequently be useful to work with models that are able to handle both kinds of data.

A model exploring the impact of seasonal climate forecasts combines qualitative characteristics of the farmer's decisions with quantitative environmental data. Such a combination is meant to support holistic analyses (Ziervogel et al., 2005) and could be useful for water resources research as well.

Flexibility and capacity for integration

The flexibility and capacity for integration of multi-agent modelling is closely related to its ability to represent complex systems (see chapter 3.7) (Ferber, 1999). For applications in hydrology and water resources research, flexibility and integration are relevant out of different reasons. First, multi-agent models allow the combination of different models. In this way, hydrological processes are addressed with hydrologic models and social processes by representing the stakeholders of the model as agents in a social multi-agent model (see chapter 3.6.2). Second, the representation of the environment is possible in different ways, e.g. as combination with Geographical Information Systems (GIS) (Gilbert et al., 2002). However, the flexibility of multi-agent modelling goes even further. Within one model, quantitative variables, differential equations and rule based behaviour can be integrated (Ferber, 1999). It is therefore possible to choose for each research question individually how the model is set up. Existing models can be integrated, parts out of existing models might be included or the multi-agent model can be built without such elements.

Bousquet and LePage (2004) see the use of multi-agent simulations as a paradigm shift for natural resources research. Before, natural resources were seen either as an ecological system subject to anthropogenic disturbance or as a social system subject to natural constraints. In the former case, social dynamics are represented only as summarized resource exploitation, whereas the dynamics of the resource are represented carefully. In the latter case, the focus of interest is on an economic agent driven by optimizing rationality. Multi-agent methodology can represent the interactions between ecological and social components and account for their heterogeneity.

3.6.2 Agents as a natural ontology

Interpretation and communication of the model

Equation-based modelling has the disadvantage of not being intuitively understandable. Even for scientists with a great knowledge in the area, a differential equation is most likely not a natural metaphor for processes in the real world. If the intended users of a model are not researchers, but stakeholders, this argument weighs even heavier. Because many of the stakeholders may not be trained very well in mathematics or statistics, it may not be trivial for them to understand numerical model output, for example to interpret regression results (Axtell, 2000).

In contrast, pattern recognition and analogical reasoning are quite natural and easy for humans. The mainly visual output of multi-agent models is therefore easier to communicate to the users (Axtell, 2000). Agent-based models are generally easier to understand intuitively, since the representation of entities that may be either individuals or institutions as agents seems naturally, especially if the agents represent humans (Gilbert et al., 2002). Instead of describing the behaviour of humans in abstract equations, the agents and their behaviour are represented more or less directly. Agents can be equipped with simplified versions of the goals, beliefs and capabilities of the stakeholders (Gilbert et al., 2002). Thereby, such models provide a way to handle the enormous amount of data and knowledge about the behaviour and the motivations of the human agents as well as about their relationships with social agents (Bankes, 2002). Such knowledge is normally not represented in other types of models, where behaviour is aggregated (Bankes, 2002).

However, in the case that the entities represented as agents are not humans, the interpretation of the model and its communication to the user may be easier as well. Interactions between real world entities for example can be represented more intuitively as interactions between objects, not between variables (Möhring and Troitzsch, 2001). Furthermore, the methodology supports direct experimentation with the models, for example through ‘what-if’ experiments (Parunak et al., 1998). Since the system is not translated into equations between observables first, the results of the modelling are additionally easier to apply in practice (Parunak et al., 1998).

Because of this quality of the methodology, it is often applied in the context of stakeholder involvement. This combination is meant to exploit the advantages of multi-agent approaches to full extent (Gilbert et al., 2002). Using human agents instead of computational agents, as it is done for example in role-playing games, is an especially engaging way to make the stakeholders familiar with the model and to increase their understanding of the model (Gilbert et al., 2002). Furthermore, the stakeholders see the problem with the same perspective as they do in real life (Gilbert et al., 2002).

Representation and integration of socio-economic aspects

In addition to the restrictions of hydrological models discussed so far, they are not prepared for including socio-economic aspects. Concerning the great challenges in water management in the future, the inability of conventional models to integrate socio-economic aspects is most likely their most serious limitation. Naturally, this is less relevant, if solely hydrological research questions are addressed. However, hydrological systems are interlocked with the surrounding world and anthropogenic influences are not to be ignored in most cases, but should be represented appropriately. It is not sufficient to provide realistic, precise models of the hydrological system, without drawing relevant conclusions or to understand and possibly change the human socio-cultural system associated with the problem (Doran, 2001). If anthropogenic behaviour influencing a hydrological system is not modelled correctly, this goal cannot be reached and the dynamic of the system, especially its reaction to external disturbances, cannot be captured correctly.

In contrast, multi-agent simulations are not only capable of appropriately representing individual agents as well as societies. Additionally, they are highly suitable for empirically studying human-environmental interactions, as are addressed in water resources management, because they manage to simulate interlinked socio-economic and biophysical processes (Berger, 2004). The connection between the physical environment and the social world is handled without problems, whereas different models have to be coupled in other approaches which is not always easy (Gilbert et al., 2002).

Representation of physical hydrological processes

An agent is a less obvious metaphor for representing processes of physical hydrology such as generation or concentration of runoff. However, one should not assume that there is a one-to-one relationship between agents and humans. It is possible, although less common, to represent physical hydrological processes based on their smallest units, most likely water particles, as Servat (2000) does. Many hydrologists are not satisfied with treating the system as a black box and ignoring the processes inside. Instead, they are trying to gain a deeper understanding of the system, including the understanding of the processes behind. The logical continuation of this process may go beyond process-oriented models by going down to the smallest parts of the systems and exploring their behaviour.

If such an approach were successfully applied, it would be revolutionary for hydrology. Based on such a bottom-up approach, processes would not be expressed in complicated equations anymore. Instead, simple, but governing rules were sought and the investigated processes would emerge based on the rules. However, the question whether such a task is achievable is addressed in the next chapter.

3.6.3 Complexity and emergence

In the last years, a trend can be seen in hydrology and hydraulics towards more *complex* models in order to provide more complete and faithful representations of phenomena (Wasson et al., 2003). This kind of development is driven by the wish for general models and by increasing computer capacities likewise. Unfortunately, models of this kind are difficult to implement, to handle and to interpret. Additionally, the complexity of these models makes them difficult to use even for specialists (Wasson et al., 2003).

However, not only hydrological models, but also models in the context of management are characterized by their complexity. The interacting systems, i.e. physical environment and social world, are complex in their own way (Gilbert et al., 2002). Changes to one of these systems will affect the other as well, whereby such side effects are hard to predict. Moreover, it is not reasonable to separate the social processes into the sub-processes evolved, e.g. economic, demographic, spatial or cultural, as it is often tried (López-Paredes et al., 2005). The reality is heterogeneous, i.e. consumers are individuals with their specific goals and motivations (López-Paredes et al., 2005). Various stakeholders are involved, ranging from supra-national authorities, e.g. the European Union, to domestic consumers and including a variety of organisations, e.g. water suppliers, and institutional consumers, e.g. farmers. Their different objectives have to be met while managing water supply and demand on the regional as well as on the local scale (Gilbert et al., 2002).

Due to these sources of complexity in hydrology and water resources research, both areas of research may benefit from a tool able for modelling complex systems. Multi-agent modelling has some of its roots within the broad area of complexity research. Based on the concept of emergence, it allows to model complex situations (Ferber, 1999). Thereby, the complexity is not reduced by dividing the processes into sub-processes that are not inherent in the system, as it is often the case in conventional modelling. Examples for sub-processes are economic, demographic and cultural aspects of social entities. Complex situations are reduced to simple rules and interactions instead, which is arguably a rather natural approach. Possibly, emergence is the only way how complexity can be addressed. It is questionable whether the alternative solution, to make conventional models more and more complex until they account for the complexity of the system, is feasible.

3.6.4 Interdisciplinary approaches

Multi-agent models are frequently applied within interdisciplinary contexts. Due to their flexibility and capacity for integration, they are suitable for research question that are related to more than one academic discipline. Moreover, since their history is comparably interdisciplinary and they are used in many disciplines, they are not strictly belonging to one academic discipline.

Water use and allocation call for interdisciplinary research approaches. Reaching reasonable and feasible solutions to fresh water quality and allocation problems in the future may possible require a tool that can only be derived through integrated modelling of the water availability and the economic, sociological and political aspects of water (Ernst et al., 2001). Developing such a tool or sustainable solutions for the problems caused by the global change cannot be achieved by any academic discipline alone (Kneer et al., 2003).

Hydrologists aiming at integrating their knowledge into interdisciplinary research projects are in need for methodologies to combine their existing models with other tools. It is possible of course simply to couple models out of different disciplines. However, a solution has to be developed for each case individually, because of the specific characteristics of the models. Multi-agent systems may provide a framework for this purpose. As a methodology known to experts of different backgrounds, they may define standards and a way of thinking that guide the development of the individual models. Additionally, due to their flexibility, they may be used for combining these models. Even if such a combination and not the design of multi-agent models of hydrological processes may be the intention of most hydrologists, their modelling could be influenced by this intention. For example, they had to know which output is expected.

3.7 Limitations for hydrology and water resources research

When the limitations of multi-agent systems for hydrology and water resources research are discussed, general limitations of the approach have to be included naturally, e.g. the lack of standards and of techniques for validation and verification. Furthermore, some issues are identified that are specifically problematic for applications in hydrology and water resources management. If they are not addressed in the right way, they have the potential to limit the applicability of the approach.

3.7.1 General problems

As a relative young approach, multi-agent modelling is faced with some generally unsolved issues, e.g. uncertainty analysis and the calibration of models to data (Bankes, 2002) that are not specific to applications in hydrology and water resources research.

Missing standards

At the current state of its development, the methodology seems to miss some standards. The problem starts with the variety of definitions. It can be argued,that the lack of a clear and fixed definition of agent-based simulation or even of agents hinders the efficient and effective use of the methodology (Hare et al., 2002). Especially users who are new to multi-agent modelling may miss a framework that helps them to explore existing applications of the approach (Hare et al., 2002). Not only is there a confusing number of publications in all kinds of academic areas; the understanding and the realization of multi-agents systems vary also highly. Moreover, a wide range of software platforms exists, all providing certain advantages and drawbacks. The modeller has to make the difficult choice whether to use one of these or not and if so, which is the most suitable for his specific purposes (for a further discussion see Chapter 4.2). Some standards for the methodology would possibly promote its development and help to develop the potential of the methodology to full extent.

Emergence

Bankes (2002) states that the topic of emergence is not treated carefully enough in many multi-agent models. It is rarely specified what is meant by emergence and the question remains how to decide reliably that emergence has occurred. According to Bankes (2002), a more scientific profound approach to the phenomenon of emergence is necessary in order to promote the progress of agent-based technologies. He suggests to define that emergence occurs when a measure of macroscopic behaviour reaches a threshold value in a simulation built from microscopic behaviour (Bankes, 2002).

Verification and validation

In terms of scientific accuracy, verification and validation are among the most important steps in model development. Unfortunately, they are hard to achieve for multi-agent models. While in some of the papers about multi-agent systems the authors simply avoid the problem generally, other authors discuss it as one of the main actual problems of the methodology. However, verification and validation are fundamental for avoiding the risk to 'play God' and to create systems without connection to reality (Becu et al., 2003).

For *verification*, researchers often choose simple approaches, e.g. verification of the conceptual model by means of UML schemes and by program debugging (Feuillette et al., 2003). Another possibility is to compare the output of two different versions of the same model, e.g. implemented in two different platforms (López-Paredes et al., 2005).

Validation is a far more complicated issue and may be one of the most difficult tasks involved in the development of processing models (López-Paredes et al., 2005). Techniques for validation of complex models have not been established yet (Feuillette et al., 2003). Among the traditional methods is the comparison of the model outputs with the real system or with other models. However, suitable data has to exist, what is often not the case in ecological systems (Espinasse and Franchesquin, 2005). In the case of a multi-agent simulation used for modelling scenarios, i.e. events occurring in the future, a comparison of the simulated with measured data is not possible as well (Ziervogel et al., 2005).

The remaining question is whether a general technique for validating complex models or multi-agent models has not been found yet or does not exist. A specific problem for validation of multi-agent modelling is the phenomenon of emergence. Since there are no a priori functional requirements of the system, it is hard to distinct for a unexpected result whether it is an implementation error or an emerging behaviour of the system (López-Paredes et al., 2005). The representation of individual agents may cause difficulties for validation, since the goals, visions and desires of individuals are likely to be neither temporal very stable nor well documented (Ligtenberg et al., 2004). The situation may be better for agents representing organizations or groups.

Many interactions in multi-agent systems are beyond validation and prefer to talk about 'authentication' instead (Becu et al., 2003). This term may describe what researchers are supposed to do when they do not have standardized means for validating their models. They are expected to compare the outputs of their models qualitatively to all available data and other kinds of evidence (Ziervogel et al., 2005). Moreover, the accurate documentation of the whole development process including assumptions and simplifications is required, in order to facilitate the critical evaluation of the model by the academic community (Ziervogel et al., 2005). Differences in the available data lead to differences in this 'authentication' process. Remote sensing data can be used for example for comparison with simulated cropping data and feedback of the concerned actors for the implemented social and individual rules (Becu et al., 2003). Participatory methods are thought to be the best-known authentication for the design of the agents and the credibility of the results by some researchers [see for example López-Paredes (Kneer et al., 2003, ; 2005) or Becu et al. (2003)]. Iterative exchange with the stakeholders as experts for the system they live in helps to assure reliable assumptions and structures. Extreme tests, tracing of single agents and partial sensitivity analysis on factors of parameters are an alternative approach for evaluating whether the model outputs are reasonable (Feuillette et al., 2003). Barreteau et al. (2005) propose to compare the results of multi-agent models with simulated results of other models. If these models, e.g. role playing games, are easier to compare with real dynamics, this is an indirect way of validation (Barreteau et al., 2001).

The critical issue in the validation process for all models that are applied in the context of water resources management, e.g. as negotiation support tools, is legitimacy. Empirical evidence illustrates that the negotiation process may fail when the building of the model is not made public to all stakeholders (Barreteau et al., 2001). Although hydrological models exist in some cases that could be used for water management, they are not necessarily accepted by the stakeholders, e.g. because they are not adapted to their specific needs or too difficult for non-specialists (Edwards et al., 2002). Stakeholder involvement is possibly the appropriate way to legitimate a model.

However, some aspects of multi-agent modelling may even offer new possibilities for validation. One possibility is to take advantage of the modular character of most multi-agent models. Sub-models may be tested or even validated separately and finally put together to a general model. Then, not the whole model, but only the combination has to be validated (Möhring and Troitzsch, 2001). Validation at the individual level may be even considered as additional potential for validation (Parunak et al., 1998), when the behaviour of the agent can be compared with observations of the behaviour of the individuals in reality. However, as stated before, the relevant data may not be available for most individuals represented as agents.

All in all, validation and verification are critical aspects of multi-agent modelling. Without proper validation, some uncertainties about the model remain. However, while critically reviewing such models, one has to keep in mind what they are made for. In the context of water resources management, the models are mostly used in an exploratory way and uncertainty is an unavoidable factor, since better data is not available or the interesting events will take place in the future. In such cases, it may be justified to apply models without strict validation, provided that the modelling process is done carefully and enough evidence for the correctness of the model exists. Policies for example refer always to the future and cannot wait until all facts are known, but have to rely on information that is as robust as possible (Ziervogel et al., 2005).

Artefacts

The production of artefacts is another systemic problem in agent-based modelling that is partly related to validation. The order of agent activation for example may influence the results due to inter-agent correlation. Another example is that agents interact more with their neighbours, although equal interactions between all agents are intended (Axtell, 2000). Few lines of source code controlling a long execution code may be one of the reasons for artefacts in object-oriented agent-based computing. Consequently, an idiosyncrasy in this code may produce output that can appear to be a result of the model (Axtell, 2000). The short piece of code yields a wide range of information, in case that no errors or artefacts in it disenable the user to achieve any useful results at all. In short, the models deliver all the information – or nothing at all, depending on the correctness of the programming. Careful programming is possibly the only solution to this problem (Axtell, 2000). Multiple runs with a wide range of parameter values help to identify artefacts.

The representation of time

Generally, the representation of time in computer simulations is a complex topic. Three notions of time can be differentiated (Fianyo et al., 1998), namely the real time, corresponding to the observation of real phenomena, the virtual time representing the real time in the simulation (simulation time) and the computation time, i.e. the execution time.

The problem lies within the fact that processes observed in nature possess an inherent order of causality that expresses itself in a temporal structure as well. The representation of these processes in a model requires that the actions and events in the model follow the same temporal order. The representation of time is especially important when modelling natural physical systems, because representing the true parallelism of nature, the simultaneity and the different rhythms is a special challenge (Fianyo et al., 1998).

As most other models, multi-agent models normally rely on a virtual time that indicates the progress of the simulation through a virtual clock advancing in either regular or irregular time intervals. The main constraint is the causality rule stating that an event causing a second event has to be processed before this second one in the computation time. Of the two ways to implement the virtual time in multi-agent systems, the first is to divide the virtual time into identical interval sizes, the time-steps. The problem of this simple approach is that the length of the time-steps has to be decided upon in advance. Therefore, the processes have to be known well in advance to make sure that the time-steps suit them. As a second possibility, the simulation can be directed by events. Each event is triggered with a precise virtual time which enables sorting of the events. The simulation proceeds to the next event in times of inactivity. The difficulty in this case is to avoid causality errors (Fianyo et al., 1998).

In modelling tasks, not one process alone has to be represented on a suitable time scale, but different dynamic processes with their specific rapidity and rhythm. For this purpose, some sort of scheduling mechanism is needed. If a multi-agent model consists of different parts, it is one possibility to associate each system entity with its own time attribute and to synchronize components with the same virtual periodicity time by scheduler mechanisms. A common time called ‘global virtual time’ results when the different rhythms are set in relation to a central one (Fianyo et al., 1998). However, even if this seems to be an adequate way of tackling the heterogeneity of rhythms in complex modelling tasks, the variability and diversity of these rhythms is not accounted for. An example relevant to hydrology is the different speed of water flow through the soil depending of the height of water charge put on the ground. When the water flows faster, it has to be simulated in shorter time steps in order to represent the relevant processes appropriately. In a model with a layer structure, the water could have flowed otherwise from one layer to the over next layer in one time step. Therefore, it is desirable to create models where the rhythms are adopted when the processes change, optimally automatically (Fianyo et al., 1998).

The representation of time is especially problematic in models that represent biophysical processes and socio-economic contents likewise or combine such models. Two different types of processes can be differentiated explicitly: The first kinds of processes are continuous processes, which can be modelled by continuous mathematical models such as differential equations (Fianyo et al., 1998). Physical processes belong often to this category that is described in models through assigning a period of discretisation or a rhythm. On the other hand, intrinsically discrete processes have to be simulated using their intrinsical rhythm. Human actions often belong to this category, e.g. farmer organisations determining in regular meeting the starting point for some of their actions (Fianyo et al., 1998). Combinations of such processes have to deal with integrating these different types of scheduling mechanisms. A combination of multi-agent models with external structures as GIS components introduces an additional time sensitive issue, the updating of attributes or locations of features, either in a database or in a display (Brown et al., 2005).

Consequently, scheduling of actions is an important part of a multi-agent model. Most software platforms for multi-agent models provide more or less sophisticated scheduling mechanisms. However, it is important that the modellers choose the right scheduling mechanism for the specific purpose, implement the scheduling carefully and keep in mind that each of the scheduling mechanism has its specific weakness.

3.7.2 Problems specific for applications in hydrology and water resources research

Spatial distribution and input data

Research questions related to hydrology and water resources research principally have a spatial, geographic component. Multi-agent systems are characterized in theory by the duality between agent and environment and should consequently be suitable in this context. In practice, however, many multi-agent systems seem to place a strong emphasis on the agent component.

In order to keep the connection between reality and the model, it is important that hydrological features of the systems, e.g. the water resources in the system, are represented realistically. Naturally, modelling of hydrological and water resources issues relies on spatial distributed input data. However, many of the actual models are rather abstract, without proper representation of empirical data. For example, although the SHADOC (Barreteau and Bousquet, 2000) is based on comparably rich empirical data, the agents and environmental objects are located randomly, without taking into account the real distribution. Multi-agent models not based on empirical data are doubtlessly valuable in their own way, i.e. for exploring and understanding basic processes, interactions or dynamics. However, the majority of hydrological models and models of water resources aim at representing reality and have to make use of empirical data consequently.

Multi-agent methods per se do not provide the necessary functionalities in most cases. However, solutions for the problem exist or are possible, e.g. the combination of multi-agent models with hydrological models or the integrating of GIS technology.

Finding the rules that specify the behaviour

In most of the discussions and publications on multi-agent modelling, the idea to model complex phenomena based on simple rules is highly valued. Nevertheless, the question is neglected how these simple rules can be derived.

Humans are doubtlessly complex entities. When they are represented in the context of water resources management, it may not be easy to define their behaviour in the way multi-agent modelling requires it. First, the right level of abstraction has to be defined that contains the basic rules governing the behaviour of the agents. Second, on this level of abstraction the right and important rules have to be identified. Defining the rules for agent-based models of hydrological processes is equally difficult. Since it is a completely new approach for hydrologists, they lack the experience and knowledge about the behaviour of the elementary elements of the hydrological cycle relevant for creating multi-agent models.

Most likely, defining the rules specifying the behaviour is the most difficult, but most important part in agent-based modelling. As mentioned before, the modeller has to define what agents should do without telling them how to do it. Not specifying the task of an agent well enough will not lead to the expected behaviour. Specifying it too precisely hinders the occurrence of emergence and reduces the simulation to a simulation where the agents execute exactly what they were told to do, similar to actors in movies.

Representing physical laws and relevant processes

Physical processes seem to be less frequently modelled with multi-agent systems than human behaviour (Servat et al., 1998). Instead, mostly living beings are represented as agents. According to common definitions of agents, agents are characterized by autonomy and some sort of intention. At first sight, this excludes entities that are not living from being agents. However, one should not assume that autonomy and intentions have to be related to active decision making. The natural metaphor of representing living beings as agents has the disadvantage to create an intuitive image of a certain, cognitive agent type. It is important to keep in mind that agents can be reactive as well and that an emergent behaviour can be based on many simple instead of few complicated agents. Considering for example water particles, their intention could simply be to minimise their potential energy by moving towards the lowest point in the environment that consists of elevations values. Its autonomy could simply be the fact that it is not been told which path to take. The critical question thereby is how to specify such agent behaviour, since empirical results or experience are missing in most cases.

Contrary to most agents representing humans, the behaviour of agents representing physical behaviour may not be based on internal processes, but influenced by the state of its environment. In many cases, these influencing factors are not included regularly in the environment. Water particles for example are mainly reacting to the potentials in its environment. In hydrology, the concepts of potentials and hydraulic gradients are important. Introducing them into the environmental component of the multi-agent model will help to represent physical processes based on agents. Whether or how potentials can be realized depends mainly on the kind of representation of the environment. Generally, displacements in a potential field are considered as one of the possible implementations for movement of agents by Ferber (1999). In this case, movement is simply described as following the line of the steepest slope in the potential field, whereby the agent is attracted by the goal and repelled by obstacles. Multi-agent models implementing potentials already exist, e.g. the aforementioned model of biological swarming of (Mach and Schweitzer, 2003).

3.8 Conclusions

Regarding the applications of multi-agent systems discussed above as well as the consequent discussion of its possibilities and limitations, it is reasonable to conclude that the approach has some qualities promising for hydrology and water resource management, although some issues remain to be clarified or improved.

When discussing multi-agent systems, it has to be emphasized that this term summarizes different types of agents and applications. Clearly, applications in hydrology and water resources research are possible with different types of agents. In water resources research, the typical multi-agent model is based on cognitive agents, although only few agents with higher skills and abilities are represented.

As discussed before, different types of agents may be applied in hydrology. The first of the possible concepts relies on water particles as agents, since they are the smallest entities in the system. In contrast to water resources research, reactive agents are used in the first of these possible concepts, i.e. the numerous agents are comparably simple, but strongly influenced by their environment. Second, service agents can be applied that do not represent entities of the system, but functionality and abilities, e.g. for data mining. The third option represents units of the water cycle as agents that represent hydrologic attributes and behaviour of these units. The aggregated agents in this approach are rather cognitive than reactive agents.

Obviously, more applications of multi-agent modelling are realized for water resources research than for strictly hydrological applications. Multi-agent approaches seem highly suitable for this purpose, because they "facilitate a detailed representation of the individual participants in the systems, capturing their heterogeneity and representing with realism social processes, the explicit representation of the space and the local interactions between agents" (López-Paredes et al., 2005, p.196). Moreover, the approach is favoured because of the relative easiness of interdisciplinary cooperation and participatory modelling. Both issues could be essential for addressing the water management problems of the future.

Judging the suitability of applying agent-based methodologies for modelling hydrological systems is not as simple, since only one practical example has been found in the literature review. Applying multi-agent modelling for this purpose is hindered by a generally low number of applications of multi-agent modelling to any purely physical processes. Additionally, the metaphor of representing parts of the water cycle as agents is less intuitive. However, the discussion of the methodology does not reveal a theoretical reason why multi-agents models should not be considered for modelling physical hydrological processes. Nevertheless, some issues have to be treated carefully for ensuring the best possible outcome of the modelling effort, e.g. the representation of the environment (see chapter 4). Furthermore, specifying the rules governing the behaviour of agents in hydrological multi-agent models is considered difficult, due to the lack of knowledge and experience in the research community. Despite all these unresolved issues and the fact that the approach is challenging and forces hydrologists to open their minds for new, unconventional approaches, multi-agent modelling constitutes a very promising new methodology in research. Of course, applications of the methodology could discover further limitations in this area of research that have not been revealed with the means of literature reviews and theoretical discussions.

Based on heir own experience with agent-based modelling of urban water management, López-Paredes et al. (2005) conclude that multi-agent modelling is suitable ideally for the analysis of domains that are dominated by discrete decisions and are highly localized and distributed. In contrast, equation-based models are useful for central systems dominated by physical laws. Possibly, concluding whether multi-agent models are suitable for hydrological processes is difficult since they are often in between. On the one hand, hydrological processes are dominated by physical laws and not by discrete decisions. On the other hand, they are characterized by a high degree of localization and distribution and should not be modelled centrally.

However, for hydrologists not believing in modelling hydrological processes based on agents, the combination of multi-agent models with classical hydrological models may be an alternative approach that has already been applied comparably often and successfully. The hydrological models deliver the input on the state of the environment to the social model, whereas the agents in the social model represent the human behaviour and act on the environment that is created in the physical process model.

In spite of all the enthusiasm for such a new, integrated approach, one has to consider that modelling complex issues is unlikely to represent a system in its full complexity precisely or deliver scientifically sound predictions now or in the near futures (Ernst et al., 2001). Regarding the future perspective of agent-based systems, some researchers are very optimistic. For example, Axtell (2000) can imagine that agent-based models may be "the first line of attack on new problems in the future." (p.19). It will be interesting to wait and see how widespread and commonly adopted the methodology will be one day. At least, it seems likely that it remains a useful and appreciated method in some areas of research.

4 Realizing multi-agent systems

4.1 Implementation of multi-agent systems

There are two different ways of implementing multi-agents systems in general. The first option is to use one of the numerous existing programming environments for multi-agent systems that make the modelling process easier, especially for researchers new to the approach. It is also possible to use general programming languages, platforms and software systems that are not specialized in multi-agent models but are flexible enough to handle them as well.

4.1.1 Implementations without multi-agent programming environments

Various aspects of multi-agent systems are normally addressed with different software systems and programming languages, if no specific multi-agent programming environment is used. Figure 4.1 illustrates elements in agent architecture and the software used to implement them in the MAJORCA platform (Espinasse and Franchesquin, 2005). The behaviour of the agents is programmed with a software for defining condition rules (JESS), complex computations are performed in JAVA and additionally an agent communication language (ACL) is used (Espinasse and Franchesquin, 2005). Table 4.1 illustrates how many tasks and issues are involved in setting up an agent-based model and it contains for each of them an exemplary realization. However, the only aim thereby is to provide a first impression, because it is beyond the scope of the study to pass on the knowledge necessary for creating multi-agent systems in this way. Apparently, this approach requires apparently more than basic computing skills and it is not suitable for all multi-agent modellers.

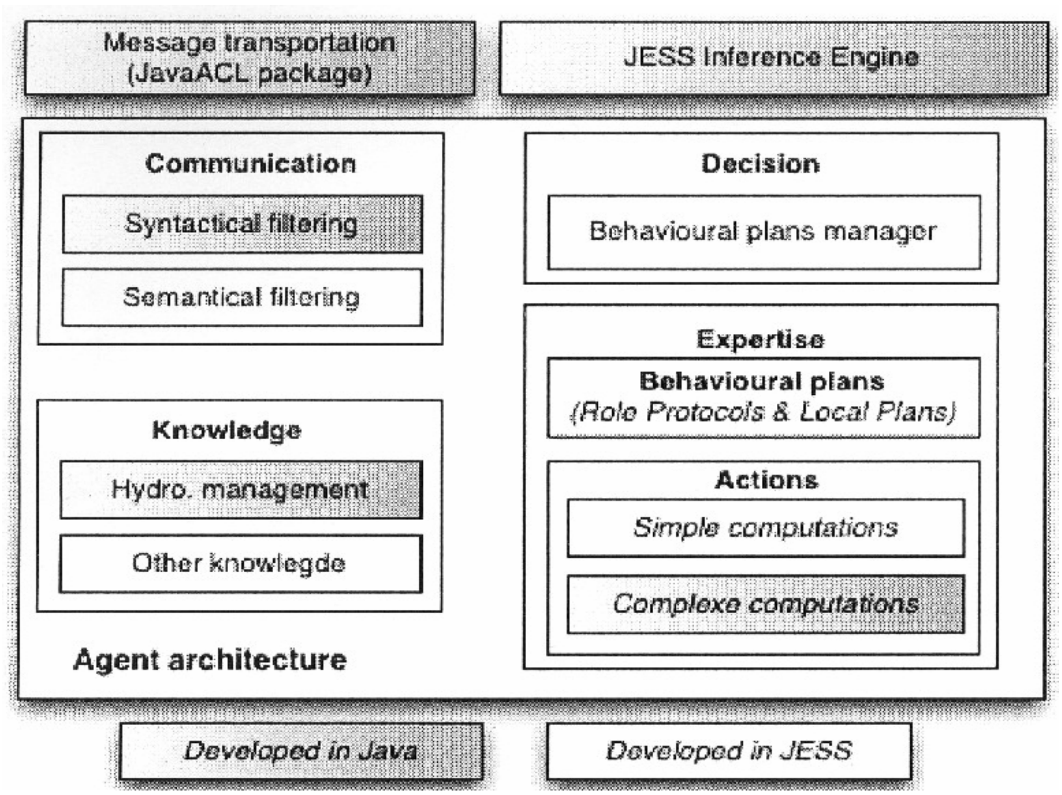

Figure 4.1: Architecture of one agent of the model of Espinasse and Franchesquin (2005, p. 214) using the MAJORCA software system.

Table 4.1: Examples for different tasks involved in setting up a multi-agent model and adequate software

Task /Feature of the architecture	Example for software /system
Design of agents	GAIA methodology (Wooldridge et al., 2000)
Interaction between agents	Agent-Object-Relationship modelling language (AORML) (Wagner, 2003)
Inter-agent communication	KQML [see for example Davis (2000)]
Agent-database communication	SQL commands [see for example Davis (2000)]
Connection of different modules	Java or other objected-oriented programming language
Transfer or illustration of data	Standard software, e.g. spreadsheet or graphic programs [see for example Berger (2004)]

Normally, agent-based models are implemented in object-oriented programming languages. This kind of programming language is especially suitable to manage large amount of data in order to deal with complex model dynamics. Additionally, the flexibility of these languages allows the user to incorporate a wide range of agent decision rules (Berger, 2004). The modular form of the computational models provides these models with more transparency and a clear structure and reduces model development costs and numerical difficulties. In addition, the code is more extendable and portable (Berger, 2004). Nevertheless, the modeller should be aware that the relative short code needed for creating such an object-oriented model may result in a relative large program at runtime, especially when numerous agents with multiple states and behaviours requiring many computations are created (Axtell, 2000).

4.1.2 Implementations based on multi-agent programming environments

Naturally, many research studies applying multi-agent technologies encourage the development of numerous specialized software platforms. Whereas some of them are rather general, others are more specialized. (Bousquet and Le Page, 2004) classify multi-agent platforms into three different categories: General platforms can be used for all kinds of applications, in the sector of professional telecommunications as well as for ecological research. However, they do not offer specialized features useful for special contexts, e.g. social simulations. The possibly most prominent example in this group is the Swarm library. The second group consists of platforms developed for the needs of a single academic discipline, e.g. for social or ecological issues. Examples are the Repast and the Cormas platforms, among others. Their advantages are useful tools, e.g. for Monte Carlo simulations. Very specialized platforms, e.g. the BacSim system for modelling microbiological dynamics, form the third group that is not relevant for hydrological purposes (Bousquet and Le Page, 2004). No platform exists that is specialized in modelling hydrological processes or any kind of processes related to physical geography.

Apparently, methodologies especially created for agent-based modelling, e.g. Repast or Swarm, are more effective when modelling multi-agent systems than general programming languages. Axtell (2000) estimates that a system that can be specified in fewer than 1000 lines of C/C^{++} code can be implemented with Swarm in less than about 100 lines. Besides their effectiveness, the advantage of programming environments for multi-agent modelling is that it is timesaving and comfortable to rely on their built-in features, e.g. user interfaces or input and output procedures. Moreover, the programs are more reliable and efficient, since they are mostly created by professional developers (Tobias and Hofmann, 2004). Disadvantages of the platforms are the additional effort for understanding the code and the specific limitations of the different systems (Tobias and Hofmann, 2004). Therefore, it should be an important part of the modelling exercise to choose the most suitable framework. A standard programming environment for multi-agent modelling, as it is the case for statistical program packages, is not yet in sight (Tobias and Hofmann, 2004).

4.2 Software

Consequently, researchers looking for the optimal software system for developing a multi-agent model do not only have to decide whether they want to use one of the available platforms. If so, they also have to decide which of these platforms is most suitable for a certain purpose. However, choosing the right question requires knowledge of the advantages and disadvantages of each system.

4.2.1 Description of programming environments

One of the aims of this thesis is to provide an overview and a first evaluation of the existing software systems that are useful for multi-agent modelling in a hydrological context. The work of Tobias and Hofmann (2004) is an methodological example for such an evaluation. The authors evaluate free Java-libraries in regard to their suitability for social-scientific simulations. In order to reach this goal, they determine relevant criteria and rate the software according to these criteria. This approach is partly adopted in the following discussion, whereby items are modified or added to meet the requirements of applications in hydrology and water resources research.

Among the numerous multi-agent programming environments, many are very specialized and seldom applied. Since only few frameworks can be included into the evaluation, four are chosen that are considered potentially relevant for multi-agent modelling in hydrology and water management (Table 4.2). This pre-selection based on a research in the Internet and in relevant literature contains only systems available at no charge because free software does not exclude any users, enhances collaboration with other scientists and makes further development and a spread of the program more likely. Besides this criterion, these programming environments are among the more frequently used platforms and their previous applications suggest their suitability in an environmental context. The platforms are Cormas (Bousquet et al., 1998), NetLogo (Wilensky, 1999), Repast (Collier, 2003) and SeSam (www.simsesam.de). The systems are available at the web sites mentioned in Table 4.2. For the sake of simplicity, their developers are not cited every time they are mentioned in the following text, but they are referred to under the names given in Table 4.2. Further reasons for including the four systems into the evaluation are provided in Table 4.3. They are discussed and evaluated in detail in the following sections. However, first of all the programming environments are described briefly in order to facilitate the understanding of the evaluation.

Table 4.2: Selected simulation frameworks

Name	**Developer / developing institution**	**Version**	**Web site**
Cormas	CIRAD, Frankreich	2005	http://cormas.cirad.fr/
NetLogo	Northwestern University, USA	3.0	http://ccl.northwestern.edu/netlogo/
Repast	University of Chicago, USA	3.1	http://repast.sourceforge.net
SeSam	University of Wuerzburg, Germany	1.9	http://www.simsesam.de/

Table 4.3: Basic qualities of the frameworks included in the rating system

Framework	Reason for selection	Programming language[a]	Model development language[b]
Cormas	- specialized for natural resources research	SmallTalk	SmallTalk
NetLogo	- one of the successors of Swarm - interesting tools such as inclusion of real-time data	Java	NetLogo
Repast	- commonly applied and apparently powerful - different approaches to coupling with GIS	Java	RepastJ: Java RepastPy: Python
SeSam	- relatively new tool - user friendly visual programming	Java	-

a Language in which the programming environment itself is programmed, i.e.used by the developper; important for example for coupling with other software, e.g. GIS
b Language in which the models are developed within the programming environment, i.e. used by the modeller

Cormas

In contrast to all other discussed multi-agent programming environments, Cormas (Common-pool Resources and Multi-Agent Systems) is specifically designed for natural renewable resources management (Ducrot et al., 2004). It aims at facilitating the design of agent-based models to focus on interaction between groups of agents using a common resource in specific ways. Thereby, it serves as a tool for exploring the interplay between social and natural dynamics through simulation (Ducrot et al., 2004). Cormas was developed at the CIRAD, the French Agricultural Research Centre for International Development, within a project on renewable resource management that dealt with interactions between resources and societies. Cormas first appeared in the literature in 1998 (Bousquet et al., 1998). The actual release used in this discussion is 'Cormas2005' of February 2005.

The platform is based on the VisualWorks programming environment, which allows the development of applications in the object-oriented programming language SmallTalk. Although the source code can be downloaded by anyone, the modellers have to fill in a form that has to be sent to the authors first. This means that the download can be theoretically prevented.

Cormas allows easy implementation of communicating and situated agents as well as the control of their simulation dynamics (Feuillette et al., 2003). The structure of Cormas is based on three modules. The agents as well as their interactions are defined in the first module. The task of the second module is to control the overall dynamics of the system, mainly the scheduling, i.e. ordering of different events during a time-step of the model. The third module deals with defining the observational features of the simulation. Predefined elements within these three modules make the construction of a model easier, e.g. the Cormas entities in the form of SmallTalk generic classes. HydroSegment exists for example as generic class for designing standard flow processes (Ducrot et al., 2004). Indirect interactions between the situated agents as main entities are mediated through spatial support, direct interactions via messages sent to other agents and delivered in their mailboxes. The cell as the second kind of entities defines the topological support of the situated agents and represents the smallest homogeneous portion of the environment (Ducrot et al., 2004). The standard spatial support is a regular spatial grid resembling a cellular automata (CA) (Ducrot et al., 2004). A special quality of the platform is the aggregation of cells for representing compound spatial entities, e.g. single cells with the state 'on fire' can build an aggregate fire entity. This is a realization of the idea that some natural dynamics are easier to describe at a specific scale (Ducrot et al., 2004).

A definition of the values of the cells is possible in two different ways, by importing a spatial grid or by assigning values to the cells directly by mouse-clicking (Ducrot et al., 2004). Import and export methods exist for raster data of different GIS software systems. Moreover, Cormas provides the possibilities for creating Cormas entities based on vector data that can be used subsequently within the model. Thus, a loose coupling between Cormas and different GIS software is realized.

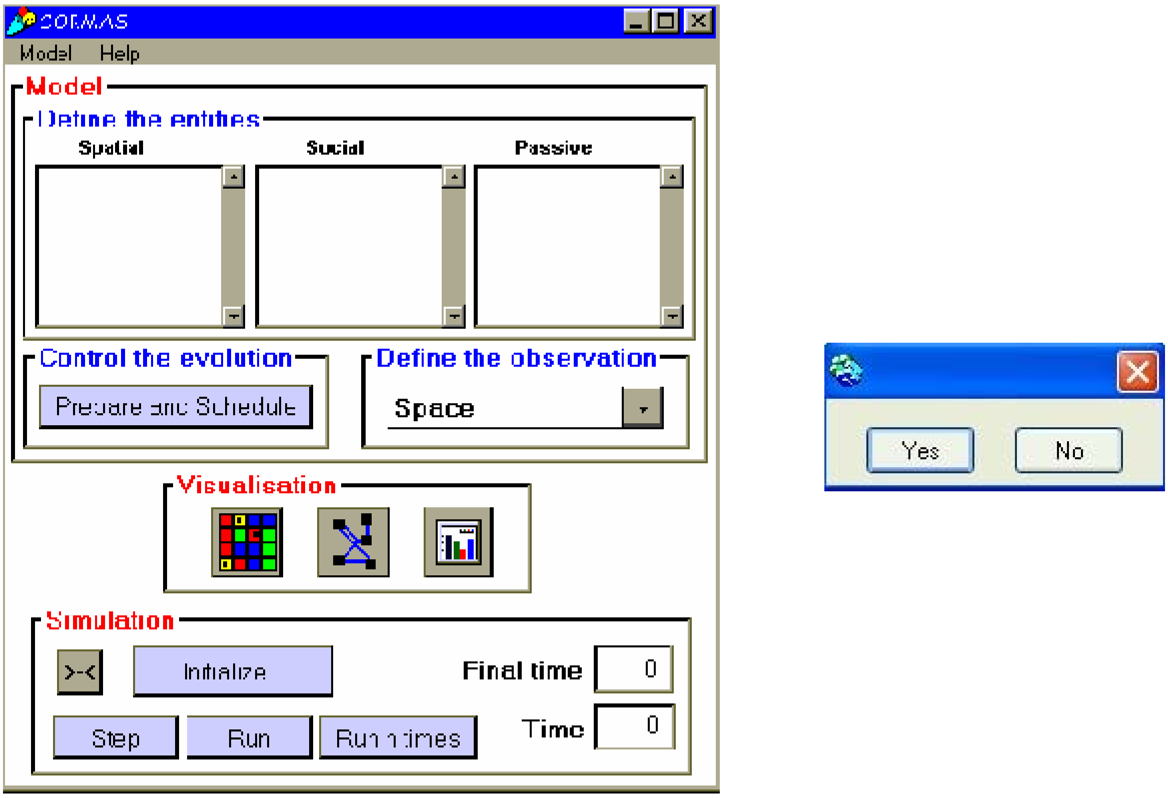

Figure 4.2: Cormas interface (left) and one of the incomplete dialog boxes (right)

Support for the modellers is mainly given in form of two tutorials. Apparently, no user community providing support for modelling problems exists at present, but training courses are offered from time to time. Although the source code is available, it is not documented at all. Apparently, distributions to the model by the user community are not common. One of the main problems of the programming environment is the language. Although an English version exists in addition to the French version, the translation is poor and the English version cannot be recommended for users without any skills in French. Not all the labels of the buttons in the graphical user interface are translated and some labels are even missing (Figure 4.2).

NetLogo

In short, NetLogo is a cross-platform multi-agent programmable modelling environment for simulating natural and social phenomena. Developed at the Center for Connected Learning and Computer-Based Modeling (CCL) (Northwestern University, Evanston/Chicago), it is available free of charge, not including the source code. NetLogo has been first released in April 2002 and is described in the following discussion based on version 3.0. NetLogo and its features are originally developed for educational purposes. Teachers are encouraged to have their students explore existing simulations or write their own models in an authoring environment. However, NetLogo aims at being a powerful tool for researchers as well.

The models are written in NetLogo, the next generation of the series of multi-agent modelling languages that started with StarLogo. NetLogo language is a Logo dialect extended to support agents and concurrency and supports an unlimited number of variables and agents that are called turtles. Figure 4.3 gives an example for the NetLogo code. The platform itself is written in Java and consequently cross-platform. Individual models can be run as Java applets inside a web browser. Since the programming language of the platform and the model developing language are not identical and the source code of the program is not available, the user is principally limited to the built-in functionality available. However, a tool for writing extensions has been introduced recently that allows the users to extend their model to a certain extent with new commands and reporters in Java.

```
ask turtles [
    if not any? turtles-on neighbors [
        die-of-loneliness
    ]
]
```

Figure 4.3: Example for NetLogo code (specifying that a turtle dies when there is no other turtle around)

The graphical user interface in NetLogo is relatively well developed. A graphics display draws the shape and size of the turtles, their exact position and their labels. Running the simulation is supported by an interface for specifying the parameters of the simulation with buttons, sliders, and text boxes as well as for controlling the run, e.g. through a speed slider. Additionally, a high number of predefined graphs and agent monitors for inspecting and controlling agents exists. Furthermore, the programming environment provides export and import functions. The ‘BehaviorSpace’ tool can be used to collect data from multiple runs of a model. Similar to *Monte Carlo Simulations*, the range of possible behaviours in a model can be explored. The combinations of settings that cause the behaviours of interest can be determined in this way.

GIS support is not provided at the moment, not even built-in support for reading common GIS formats. Only the image format .pgm can be imported. Nevertheless, other features interesting for applications in the context of hydrology and water resources research exist. The ‘GoGo Board extension’ allows connecting NetLogo to the physical world by means of sensors, motors, LEDs and other devices. The capacity of integration into other models is provided by an extension that enables the user to invoke NetLogo from another Java program and control it by means of this program. This could provide a means for coupling NetLogo with a GIS system. In addition to the normal 2D version, a version for 3D modelling exists. The extension ‘weather’ allows connecting NetLogo to an external real-time data source. A single reporter delivers the current temperature of any given place in the U.S. to the model, after having received it via a web service.

In comparison to other freeware programs, documentation and tutorials are extensive and carefully produced. The model library provides additional help in building the model, through a large collection of pre-written simulations out of all kinds of academic fields. In the rather active NetLogo User Group the modellers and developers support each other.

NetLogo is closely related to another multi-agent programming environment, StarLogo. Both are based on the original StarLogo, a simple but powerful language for designing self-organized collective systems developed for parallel supercomputers at the MIT Media Lab in 1989. It consists of three different entities: turtles, that represent the agents, patches, i.e. the environment, and the observer, i.e. the global procedures and variables. StarLogoT developed at the Center for Connected Learning and Computer-Based Modelling (CCL) is essentially an extended version for home computers with additional features and capabilities. Subsequently, two Java-based multi-agent Logos have been developed: NetLogo, based on StarLogoT from the CCL, and a Java-based version of StarLogo from MIT. Although the two languages and environment differ in many respects, they are still very similar to each other compared to other kinds of multi-agent programming environments. NetLogo was included into this discussion as an example for both multi-agent platforms and was chosen because of its features which are interesting for hydrology and water resources research.

Repast

Repast (Recursive Porous Agent Simulation Toolkit) is based on the agent-based modelling toolkit Swarm, from which it borrows some concepts. Originally developed at the University of Chicago, it was subsequently maintained by organizations such as the Argonne National Laboratory. Nowadays, it is maintained by the non-profit volunteer 'Repast Organization for Architecture and Development (ROAD)' that is led by a board of directors from a wide range of governmental, academic and industrial organizations. The aim of Repast is to support the development of extremely flexible models of living social agents but it is not limited to modelling living social entities.

As a free open source toolkit, the Repast system is available directly from the web, including the source code. It was first released in January 2000 and the actual, discussed version is 3.1. Repast is available in three implementations that differ in their underlying platform and in their model development language but which contain all the core services typical for Repast. Repast for Java (RepastJ) is a kind of standard version defining these core services. RepastPy uses a version of Python as model development language whereas Repast.Net is specialized on the Microsoft.Net framework. The latter is not relevant in this discussion. RepastJ and RepastPy are written in Java and fully object-oriented. Repast supports all kind of modern computing platforms and both personal computers and large-scale scientific computing clusters. Since the model development language in RepastJ is Java as well, this version offers a very high flexibility to users with the necessary knowledge. On the other hand, guidance for users without sufficient skills for multi-agent programming in Java is poor. In contrast, RepastPy as a rapid application development environment offers a visual interface that helps the user to setup a model as they construct the simulations through component pieces. The behaviour of the simulation is specified in a special subset of the Python computer language called 'NotQuitePython'. It is recommended to write basic models with Repast Py and advanced models with Repast J. Moreover, a tool exists that helps to translate models from Python to Java.

Concerning agent behaviour, Repast offers a variety of agent templates and examples but the user can specify the properties and behaviours of agents completely flexible. For analysis and storage of data, built-in feature for data logging and graphical illustration of results are available. Further features of Repast include a fully concurrent discrete event scheduler supporting both sequential and parallel discrete event operations as well as an automated Monte Carlo simulation framework.

For implementing the environment, Repast offers more than ten different two-dimensional environments and visualizations, including raster spaces and different forms of grids. Spatial distributed data can be loaded into the model as .pgm file, for example for integrating the information into a raster grid. An integration of geographical information systems (GIS) is attempted in different ways. Generally, two different GIS systems are supported, the ESRI ArcGIS and the open source GIS OpenMap. The GIS tool aims at representing vector data as agents, not on importing raster information. Two tasks are handled by Repast for working with a GIS, reading and writing of data and the coordination of the display of the GIS with updates to agent-based simulation data. Moreover, a special type of integration exists for RepastPy and ArcGIS, the Repast Tools Arc Toolbox called AgentAnalyst for using RepastPy from within ArcMap.

The development of Repast relies on integrating different packages. Consequently, it is comparably flexible and extendable. The libraries include genetic algorithms, neural networks, random number generation and specialized mathematics. The documentation is not very extensive and partly outdated. However, the support by the active user community is good and includes a mailing list especially for developers.

SeSam

The multi-agent simulation environment SeSam (Shell for Simulated Agent Systems) has been developed at the Department for Computer Science at the University of Wuerzburg and first released in 2003. Its special focus is to provide a tool for the easy construction of complex models that is domain-independent, i.e. not specialized for a specific kind of models. Examples exist ranging from simulating social insects to modelling of business processes (Figure 4.4). The version discussed is version 1.9 of May 2005.

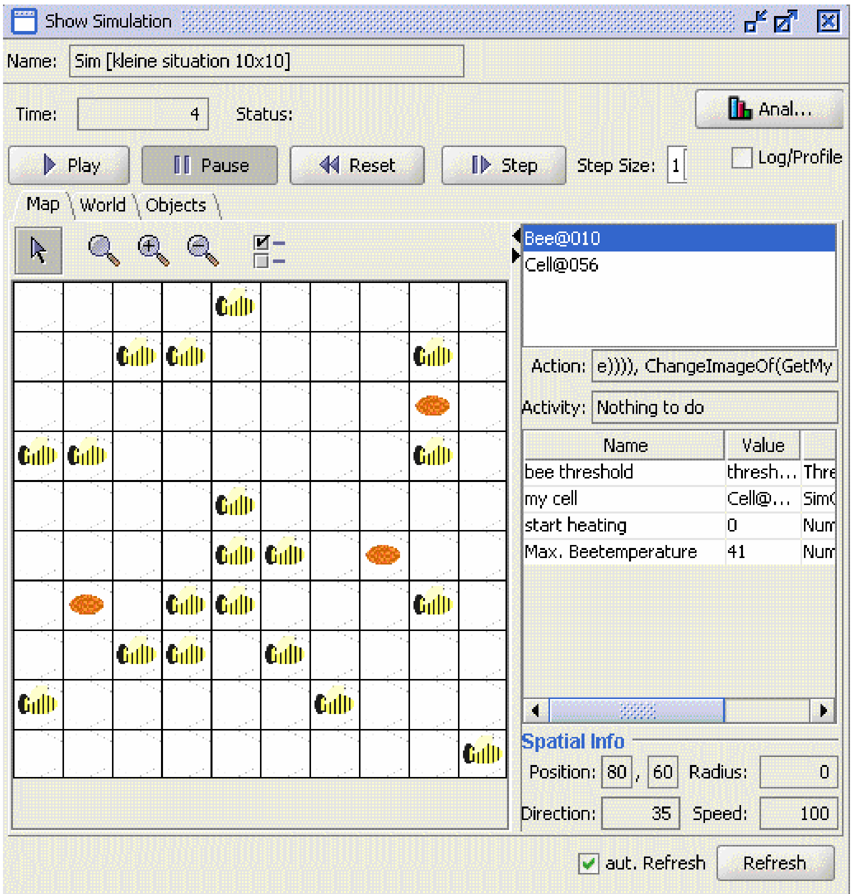

Figure 4.4: Example for the SeSam Simulation Graphical User Interface

The programming environment is set up in Java programming language and is consequently cross-platform. One speciality of SeSam is easy visual agent modelling. An agent in SeSam consists of a body with a set of state variables and a behaviour that is implemented in form of UML-like diagrams. Based on an extensive number of primitive components, the users may specify the design of a simulation graphically without knowledge in a traditional programming language. UML-like activity graphs specify for every agent which action it executes on itself and on its environment in every time step, though the agent is always in one activity. Transitions between activities are determined by rules. In order to realize possibilities in the modelling close to standard programming languages, means such as inheritance, hierarchical activity structures and fine-tuned time dependency of activities are provided for modelling complex data types. The described UML-like activity diagrams are part of the Activity Reasoning Engine, the only reasoning engine implemented in SeSam in the discussed version. Beside the agents, resources exist as entities not actively influencing the world.

The environment consists either of two-dimensional grid maps or of two-dimensional continuous maps that are inhabited by resources or agents. To enrich the environment, it is possible to define global behaviours in the world. The instruments for gathering data are freely configurable, as are the scripting options for constructing simulation experiments. The current version of the model does not offer any GIS support. However, a plug-in is due to be released soon for implementing access to geographic information systems and creating situations from Shape-file-formats.

The modelling is supported by an incomplete documentation in the form of a wiki, i.e. everybody is free to add contents. Additionally, a developer tutorial exists. Support is realized through a mailing list, but as well through submitting questions to the developer team.

4.2.2 Evaluation of programming environments

A conclusive evaluation of the suitability of the frameworks for hydrologic purposes is only possible with years of experience with the tool (Tobias and Hofmann, 2004). The following evaluation considers more or less superficial features of the systems only that are nevertheless valuable for differentiating between the frameworks. The evaluation is based on documentations and publications about the software as well as on own experiences with the programs.

The rating system that follows roughly the work of Tobias and Hofmann (2004) classifies the criteria according four categories (Table 4.4). Each category contains different items with two or three alternative answers for each item. Each answer is encoded with a rating value, the higher the value, the better.

In the first category, general criteria in programming are summarized that are not specific to agent-based modelling. However, modelling in hydrology and water resources research is disadvantaged if the chosen tools do not perform well in this category. All selected programs are freely available, but the source code is not always included. For scientific research, it is desirable to have at least access to parts of the software, e.g. to detect the source of error (Tobias and Hofmann, 2004). In order to make the system attractive to wider a community, a programming language familiar to many experts is preferable (‘Language’). It is especially important that the systems provide sufficient support for the modeller to understand and use the functionality of the platform (‘Documentation’ and Support’). The actual number of researchers using the programme (‘User base’) is often an indicator not only for the quality of the programme, but also for its further perspectives (‘Future viability’).

The second category is related to criteria for modelling and experimentation. The idea is that frameworks for creating agent-based models should ideally reduce the investments necessary and the required skills for setting up a model, but increase the reliability and efficiency of the simulation (Tobias and Hofmann, 2004). The items are concerned with the way the software supports the different steps in the modelling process, i.e. the setup of the model, application, simulation and experimentation. Moreover, the installation of the software is seen as an indicator for its reliability and efficiency.

The third category is concerned with the flexibility the modellers have for setting up a model, i.e. the modelling options. The category is sub-divided into items concerning agents and items concerning the environment. Although multi-agent modelling of hydrological issues should especially emphasize the environmental component, the agent architecture is nevertheless important. The items are related to inter-agent communication, generating agent-populations and dynamically changing the model structure. The environment items are related to the options for the design of the environment and the coupling with GIS.

The last category summarizes three issues that are especially relevant for modelling in hydrology and water resources research. The software should be flexible enough to be coupled with other software. Special features may be already included that could be relevant in this context, e.g. the integration of real-time data in NetLogo. Moreover, since hydrological models may require functionality, which might be included in the software, it is important that the software offers sufficient flexibility.

The complete rating with is given in Table A 2 in the Annex. Table 4.4 summarizes the results of the different platforms in the four categories and in total. The rating system applied indicates that RepastJ is generally the most suitable programming environment for modelling in hydrology and water resources research. However, the results for the different systems are rather close to each other, only the value for SeSam is remarkably lower.

Table 4.4: Results of the rating (summarized values in the four categories of the rating)

	Cormas	**NetLogo**	**RepastJ**	**RepastPy**	**SeSam**
General criteria	12	12	14	13	12
Modelling and Experimentation Criteria	11	14	11	14	13
Modelling Options Criteria	11	5	11	8	5
Criteria related to hydrology and water resources research	5	7	7	3	3
TOTAL	**39**	**38**	**43**	**38**	**33**

4.2.3 Discussion and conclusions

Apparently, RepastJ is the best of the discussed programming environments. However, the impression that it is the best choice for all purposes and for all modellers should be avoided.

RepastJ is doubtless a powerful tool. Its main advantages are that its programming language is both popular and powerful and it offers a high flexibility in setting up the model. However, it consequently requires that the modellers have some knowledge in modelling and programming, which may not be the case for all potential users with an interest in multi-agent modelling. Compared to other environments, the guidance for the user is low. In the rating system applied above, this results in a low grade in the category ‘Modelling and experimentation criteria’ where support for the user is evaluated. Models as NetLogo or RepastPy, which aim at providing an environment for users with few programming skills have consequently high grades in this category. However, they do not offer a high flexibility to the user and have consequently lower values in the category 'Modeling options criteria'. In most cases, the user has to decide either in favour of an environment that can be applied easily and comfortably, but restricts the flexibility of modelling, or in favour of a more complicated system with more functionality. It depends on the user's situation which approach is more suitable. However, the extra time necessary for applying a more difficult system for the first time are often rewarded in the long term, e.g. because it is less likely that the project reaches a level where functionality is required that the software cannot provide.

However, not all the relevant information about the different systems can be included into the rating. Cormas, for example, has the second best rating value. Although it is definitely a useful tool, not only its specialisation on applications related to natural resources limits its applicability. Apparently, its use is restricted to a French speaking research community that is little interested in spreading its use to a broader community. The software is for example not available without personal registration, the English version is translated only partly, documentation is rather poor and the programming language is not very common. Most of these limitations are not apparent from the good overall result of the programming environment in the rating. However, if not modelling of hydrological processes, but of water resources issues is intended, it is definitely worth to consider this tool.

NetLogo and RepastPy have similar values in the rating. As discussed before, both are comparably user friendly but limited in their functionality. RepastPy inherits some of the qualities of RepastJ but for someone intending to use a powerful programming environment, it may be nevertheless advisable to use RepastJ instead. NetLogo offers some genuine innovative features, e.g. the connection to external devices or real-time data sources. Even though the software and especially the concept of 'turtles' as agents seems childish at first sight, it is definitely worth to considers future developments in this software. Although NetLogo is not very powerful on its own, it has apparently some potential of integration with other softwares.

SeSam is a rather new approach that may not have fully developed its potential yet. It is meant to provide visual setup procedures that allow the setup of the model without knowledge of traditional programming languages. In fact, installation procedure and graphical user interface are user friendly. However, with the actual poor documentation, users without programming skills are expected to be unsuccessful in setting up models. On the other hand, the software offers no innovative features that could increase its value. The actual version is therefore not recommended for multi-agent modelling in hydrology and water resources research.

While discussing these four software systems, it is important to remember that more systems exist that are not discussed and that new systems are developing all the time. Moreover, modellers are not forced at all to use any existing programming environment, but are free to create their own system. A powerful environment as Repast may offer a good balance between flexibility and predefined functionality, such as a graphical user interface. Nevertheless, it is the responsibility of the modeller to decide on the best way of implementing multi-agent systems in the specific case.

4.3 Realization of the environment in multi-agent systems

Although each multi-agent model contains some sort of environment, the possibilities of this element are often not fully exploited. Frequently, the environment does not contain empirical information and it normally encodes only one sort of information. However, real environments influencing the behaviour of entities are far more complex; incorporating real spatial heterogeneity into agent-based models could consequently improve these models. Conclusions about the behaviour of complex systems drawn in realistic environments may differ from these drawn with artificial environments (Brown et al., 2005). Applications in the context of hydrology and water resources research are characterized by a specific need for integrating geographical data such as digital elevation models or the spatial distribution of objects or of input data, e.g. precipitation. The most common method for representing the environment in a multi-agent system, a two-dimensional grid, is often not sufficient for this kind of information, especially not for including different data at the same time. Coupling of the multi-agent system with Geographical Information Systems (GIS), Cellular Automata or other types of models are promising alternatives.

4.3.1 Coupling with Geographical Information Systems

Geographical information are often stored and handled in a Geographical Information System (GIS), thus offering a great range of tools for data processing. Implementing the environment in multi-agent models by means of GIS has different advantages. First, it relies on existing, tested systems and allows hydrologists to make use of previous work, e.g. existing databases. Generally, the numerous persons of different professions that are already familiar with GIS can more easily use multi-agent technologies in connection with the technology that they are already using (Goncalves et al., 2004).

Second, GIS systems are able to handle different types of data by arranging it in layers and offer possibilities to combine and process data. Consequently, multi-agent systems may benefit from functionalities of GIS. Three functionalities are especially useful for modellers: The access to data management systems, GIS operators, e.g. for spatial querying, and visualization (Goncalves et al., 2004).

Third, the combination integrates two generally different approaches to modelling, since a GIS is a data model and a multi-agent system is a process model. Process models are focused on theories of the exchange of energy, mass, ideas, etc. within systems over time. Contrarily, data models aim at understanding the structure of real-world domains, i.e. entities and their attributes organized in interrelated sets (Brown et al., 2005). In GIS data models, the temporal dimensions have been neglected in favour for the spatial dimensions, whereas in process models the representations of time and behaviour are normally more sophisticated than these of space or spatial relationships (Brown et al., 2005). A linkage of GIS and multi-agent systems could possibly create a balance between these disadvantages by overcoming the static consideration of space in the GIS as well as the often poor representation of space in agent-based models. Description of processes could consequently enrich the description of form (Brown et al., 2005).

However, the last advantage is at the same time the greatest problem of combining GIS and agent-based modelling. Since developing concepts of GIS has excluded concepts of time in the last two decades, conventional GIS software is not suitable for studying dynamic phenomena, e.g. the speed of propagation of flooding (Goncalves et al., 2004). In such systems, representing the dynamic change of geographic features or cells, as often intended in agent-based modelling, would require to include the time as the fourth coordinate (4D) and generate an amount of data which would be difficult to deal with (Goncalves et al., 2004). Instead, different concepts for combining a GIS with a multi-agent system exist that have specific advantages and disadvantages (see Table 4.5).

Table 4.5: Classification for the different types of coupling of multi-agent system with GIS (partly based on Mandl (2000))

Type of coupling	**Description**	**Advantage**	**Disadvantages**
Loose coupling	passing interchange files between model and database	- easy to realize	- limited computational efficiency - no use of GIS operators from within the model or of the modelling functions directly with the database
Tight coupling	the functionality of one component, e.g. GIS, is implemented in other software, e.g. multi-agent software	- fast, efficient - functionality of both systems available	- either emphasising GIS or multi-agent model, not balanced - requires changes to software
Direct co-operative coupling	GIS- or Simulation-Software is working as Server or Client, just one interface, server-software in the background	- assumingly few changes to software necessary - functionality of both systems available	- either emphasising GIS or multi-agent model, not balanced
Indirect co-operative coupling / middleware approach	third programming environment couples both types of software	- existing software can be used - both functionalities are optimally combined	- modelling relies on three different software systems

In addition to this classification, an ABM-centric and a GIS-centric approach can be distinguished (Brown et al., 2005). In the ABM-centric approach, software libraries of GIS functions are implemented in the agent-based model system (ABM) in order to foster some of the GIS functionality. The disadvantage of this approach is that its costs are very high when the GIS functionality is used quite often, e.g. due to frequent updates of spatial data. Additionally, GIS operators have to be written again in the code of the multi-agent model, since they cannot be accessed (Brown et al., 2005). In the contrary idea, the GIS-centric approach, the functions of the agent-based model are implemented within a GIS and run through the graphical user interface (GUI) of the GIS (Brown et al., 2005). This approach could increase the number of agent-based modellers, due to the high number of GIS users but a GIS normally does not provide the required tools, namely the connection of agent behaviours to spatial features or the coordination of time. It seems as if there is not even one application of this approach (Brown et al., 2005).

A third option, the so-called 'middleware' approach, offers the possibility to compromise between these contrary approaches, because it is based on the combined functionality. As in the indirect co-operative coupling approach (Table 4.5), a third programming environment is used for coupling both types of software. This middleware software must be developed for handling the relationships between agents and spatial features in the GIS software on the one hand and temporal and topological issues on the other hand (Brown et al., 2005). Besides, the approach avoids unnecessary new software developments by using existing GIS and multi-agent system software. Each of the different systems is used in its most appropriate way, namely the multi-agent system for developing the model and the GIS system for running and visualizing it. A disadvantage is that the modeller has to know two different software packages, which means increased start-up costs and dependencies. Therefore, modellers should take special care not to choose software packages that are more sophisticated then necessary. In future developments, the middleware approaches could optimally be able to work with different GIS and agent-based modelling platforms (Brown et al., 2005). Related to this approach is the work on frameworks for coupling of GIS and multi-agent systems.

However, there is even another way to classify the methods of coupling GIS and MAS (Goncalves et al., 2004). In dynamic coupling, geographic data can be accessed during the execution of the model whereas the operators of the GIS can be used by the agents. In static coupling, the geographic data is imported into the simulator and the simulation is run afterwards, whereby the simulator cannot access any additional data or any GIS operators. The advantage of dynamic coupling is the faster adjustment of the model to the reality being studied. Moreover, the process of simulating different scenarios is simplified (Goncalves et al., 2004). Additionally, implementing operators in the multi-agent system is not necessary, since the operators of the GIS can be used directly from within the model. In this sense, dynamic coupling corresponds to tight coupling and static coupling to loose coupling. Cleary, dynamic coupling has numerous advantages, but is more difficult to realize. Even though they emphasize the advantages of dynamic coupling, the authors of this classification did not achieve more than static coupling for their own multi-agent model up to now (Goncalves et al., 2004).

Coupling a GIS and a multi-agent system means that the relationships between agent-level processes and spatial data have to be specified as well as implemented, whereby four key relationships must be considered (Brown et al., 2005) (Figure 4.5).

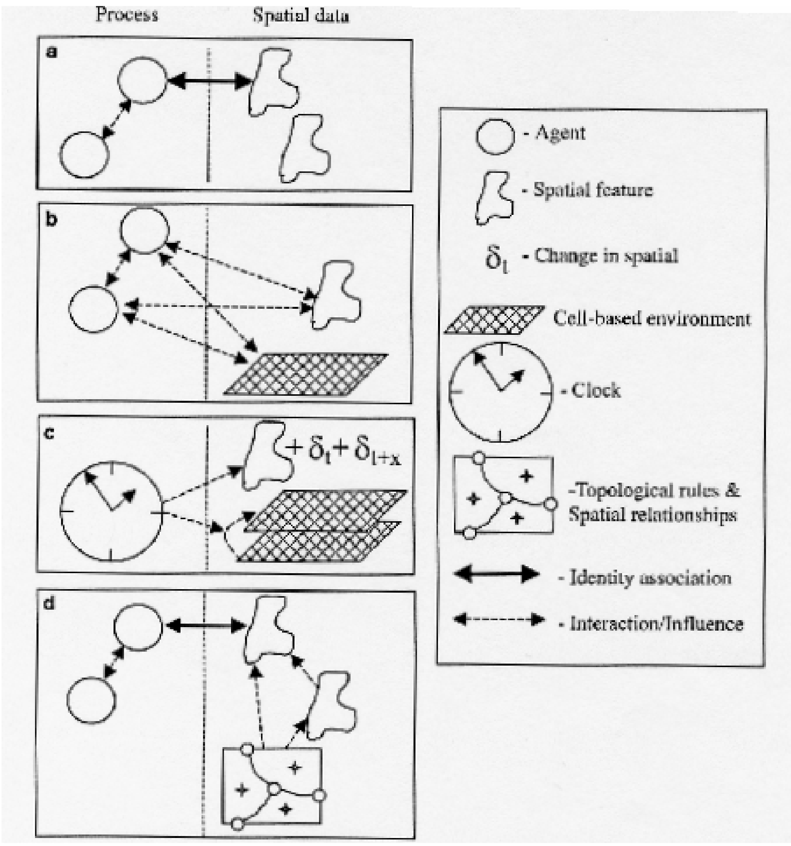

Figure 4.5: Conceptual illustration of the four key relationships between spatial data and agent-based processes, as described in the text. (a) Identity Relationships, (b) Casual Relationships, (c) Temporal Relationships and (d) Topological Relationships (Brown et al., 2005)

Identity relationships are the tightest connection between an agent and spatial features. The geographic extent and attributes of the feature are stored in the GIS part of the model, whereas the agent-based modelling techniques represent the agent's behaviour and the change in associated features. Moves of agents are associated with moves of the corresponding features.

However, not all the agents in a model must have an identity relationship to the spatial features. Instead, agents may affect spatial features including location or attributes even when there is only a *casual relationship* between them. An example is an agent that changes the value of an attribute in a raster. The most important issue in this context is handling the temporal dynamics, since changes in the environment may have a feedback on the behaviour of the agent. Besides these relationships between agents and spatial data, temporal relationships have to be considered. In models coupling multi-agent models and GIS, *temporal relationships* exist at least for the actions of the agents and for the updating of the attributes or locations of features in databases or displays. In both cases, the time component can be handled either through a synchronous or asynchronous approach (see Chapter 3.7.1). Basic information about the physical world or the spatial relationships between features may possibly be necessary, if spatial features have to be moved. Topological rules or spatial associations between features, e.g. determined by calculations of distance, cost of interaction, or visibility, for example belong in this category.

The variety of relationships that have to be taken into account for coupling GIS and multi-agent systems may be one of the reasons why many existing multi-agent software systems do not include GIS coupling. Even though they facilitate in some way access to spatial data, they offer only limited access to GIS operators (Goncalves et al., 2004). If coupling is realized, it is usually limited to loose coupling.

One of the few exceptions is a tight coupling between the Repast platform and the open source GIS Open Map Gis (http://openmap.bbn.com) (Brown et al., 2005). In the ABM-centric approach, the GIS components are accessed through the agent-based model. Avoiding the inefficient process of repeatedly converting data is realized by handling the environment grid within Repast. However, this approach hinders the handling and updating of data. A possible improvement could be the middleware approach for combining Repast with ArcGIS software. In this case, the tight coupling includes updates to the GIS database and the graphic user interface in real time. The middleware is responsible for identity mapping between agent identifiers and spatial feature identifiers. During a model run, an agent for each feature is created by the middleware. Subsequently, the agent properties are created based on the feature attributes. If the attributes of the agents change, the attributes of the corresponding GIS features are updated (Brown et al., 2005). However, the attempts to integrate GIS technology into Repast are not limited to these solutions. A newer development is the aforementioned ‘Agent Analzer’, a GIS-centric approach that integrates the RepastPy functionality into the ArcGIS toolbox. However, descriptions of experiences with this tool have not been found in the literature yet.

Nevertheless, loose coupling may be sufficient in some cases, e.g. if the GIS is only thought to deliver the input data at the beginning of the modelling process. Koch (2000) argues for example that loose coupling is sufficient in his simulation of shopping agents, since the necessary data could easily be implemented into the simulation software in this way.

Considering coupling of GIS and agent-based modelling out of a hydrological point of view, it is not only relevant if the coupling is loose, tight or realized through a middleware solution. In some cases, this is only a question of efficiency but does not affect whether data can be integrated into the multi-agent model or not. However, transferring the relevant data into the model may be the most important point for a hydrologist who may be less interested in the way it is realized. What matters more is the software involved. It is important that the GIS as well as the multi-agent model are easy to understand. Optimally, each researcher could use the systems he or she is familiar with. Especially if databases exist already, transfers between different GIS systems are not desirable. Consequently, a flexible solution capable of coupling different GIS systems with different agent-based software systems would be the best. Of course, it is assumingly the most difficult approach as well and is not expected to be available in the near future.

4.3.2 Cellular automata

Cellular automata (CA) frequently appear in the context of multi-agent modelling. The concept of CA is a rather old approach presented by von Neumann and Ulam at the end of the 1940s. Since the beginning of the 1970s, many disciplines adopted the strategy for studying complex dynamic behaviours (Janssen, 2005). The principle of CA is a simple grid with certain states for each cell and rules for all the cells. Although this is a comparably simple idea, a CA can be used to model complex behaviour. As in multi-agent systems, simple but numerous micro-scale events are used to investigate the outcomes at the macro scales (Gilbert and Troitzsch, 2003).

A regular grid is the basic feature of each CA. It consists of a number of identical cells, often several thousands or even millions and is either one-dimensional, i.e. cells in a row, or rectangular or even occasionally three-dimensional. Thereby, the cells represent individuals or collective actors, e.g. countries (Gilbert and Troitzsch, 2003). Each cell is in one of two or more states that are either binary, i.e. 'on' and 'off' or '0' and '1', or more complex, e.g. encoding attitudes or actions such as cooperating or not cooperating. The advance of time is realized by time steps in the simulation. The states of the cells change at the time steps based on a set of rules that specify how the state of a cell changes depending on the previous state of the cell and the state of the cell's immediate neighbours. Since the same rules are applied to all the cells in the grid, the model is homogeneous. If interactions take place, they are often limited to the intermediate neighbourhood of the agents, for example in order to represent real life limitations of social interactions within communities. The neighbourhood is defined either as Van Neumann neighbourhood or as Moore neighbourhood (Gilbert and Troitzsch, 2003). Whereas the Van Neumann neighbourhood consists of four cells, the Moore neighbourhood contains four more cells, as can be seen in Figure 4.6. Since the influence in a cellular automaton is limited to the immediate neighbourhood, cellular automata are most suitable for modelling local interactions (Gilbert and Troitzsch, 2003).

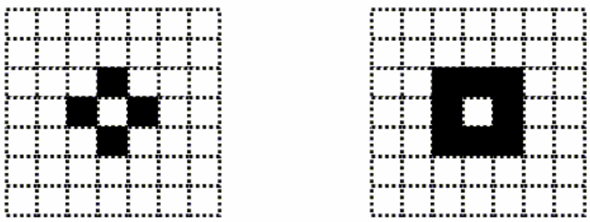

Figure 4.6: Cell neighbourhoods (left: Van Neumann neighbourhood; right: Moore neighbourhood)

Cellular automata have been used in many disciplines, including physical science, biology, mathematics and social sciences (Gilbert and Troitzsch, 2003). Possibly the most famous example is the Game of Life by John Conway [described for example in Gilbert and Troitzsch (2003), pp 123 ff]. The two possible states for the cells are 'dead' or 'alive' and there are only two simple rules: A living cell dies if it has not exactly two or three living neighbours among the eight neighbouring cells. It remains dead if it has not exactly two living neighbours. Although this setup is rather simple, it results in many ever-changing patterns of dead and living cells (Gilbert and Troitzsch, 2003). Figure 4.7 illustrates an example of the evolution of a small pattern of cells within 12 time steps.

In an urban simulation for example, cellular automata are more popular as agent-based models, because the mobility of agents, a characteristic of multi-agent models, is often not considered to be relevant in this context (Ducrot et al., 2004). Cellular automata may be even used for implementing a simple type of GIS. The lattice of the CA can represent for example a map of the area under study, whereby the possible states of the cells equal the possible land uses. Transition rules define the changes of land use, e.g. define the spreading of fire by turning a cell to fire if it consists of forest and one of neighbour cells is on fire. Additionally, rules can prevent changes, e.g. the rule that a secondary forest cannot be turned back into a primary one (Janssen, 2005).

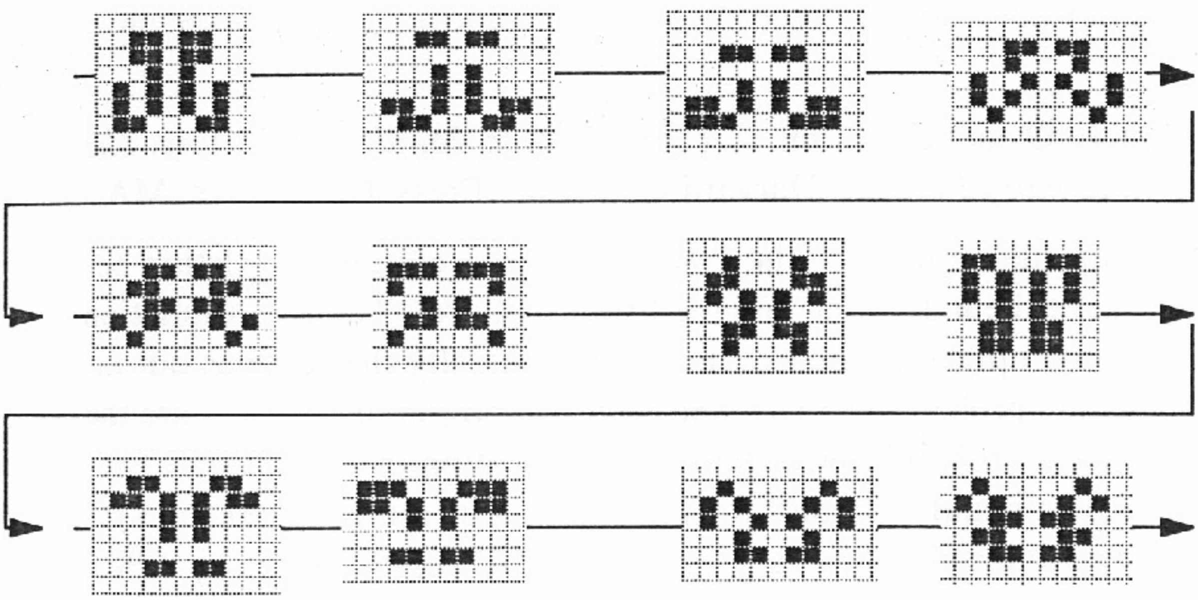

Figure 4.7: A small pattern of cells and its evolution over 12 time steps in the Game of life (Gilbert and Troitzsch, 2003)

A major disadvantage of CA modelling is its simplicity, e.g. the restriction of interaction to the neighbourhood and the limited number of possible states. This limits its value especially for the simulation of social agents (Janssen, 2005), but for hydrological purposes as well. Reducing hydrological systems in a way that it is possible to represent them in a cellular automaton seems difficult to achieve. Although hydrological processes are surely influenced by their neighbourhood, this is probably only one of numerous influencing factors. However, the cells are meant to represent one state only and not made for representing different influencing processes at the same time. Moreover, concepts which are important for hydrological modelling such as potentials could hardly be realized in a cellular automaton.

Cellular automata are often combined with other methods instead, mainly with multi-agent models. A typical example is the Cormas programming environment in which cellular automata are the main methods for implementing the environment. The difference between such an approach and the representation of the environment in a normal grid is the dynamic of the CA. A regular grid may either represent static information that was loaded into the model at the beginning of the modelling process or is updated externally, e.g. through a GIS system. In contrast, the states in cellular automata represent an environment that changes dynamically in the same time steps as the agent behaviour. CA are not used to represent the knowledge needed by the agents for making their decision but to infer the knowledge instead (Ligtenberg et al., 2001).

Such an approach is popular for simulating land use and land-cover change for example, since it allows representing two different components of modelling land use change with appropriate methods: Whereas processes related to land use are represented rather adequately within the Cellular Automaton, agents are more suitable for representing humans and their decisions

(Janssen, 2005). As discussed already, hydrological processes may be less suitable for a representation in CA than land use. The question is whether hydrological applications or topics in water resources research exist where such a combination is nevertheless appropriate. Possibly such a combination is meaningful if the processes modelled in the CA are not hydrological processes but a spatial representation of water users, comparable to models of land use. For example if the cells represent water users, e.g. as in the urban water management simulator FIRMABAR (López-Paredes et al., 2005), CA can represent changes in the area as well, not only the movement of agents as in every multi-agent simulation. A possible example is the definition of rules for the growth of the cities in order to simulate the processes in peri-urban areas.

4.3.3 Coupling with different models

Another possibility to represent the environment in a multi-agent model is the combination of an agent-based social model with another type of model delivering the input for the social model. However, examples for this approach are given in chapter 3.5.3 of combined models. More than the combination of multi-agent systems with GIS and CA, combinations with models of environmental processes tend towards equality in representing agents and environment in multi-agent approaches.

4.4 Conclusions

Each modeller with the intention to create a multi-agent model for the first time is faced with the difficulty to decide on the appropriate software solution. Generally, a modeller can either implement the multi-agent system by combining standard programming languages and tools or rely on one of the numerous existing programming environments. However, in the latter case, he has to decide which the most suitable tool for a given purpose is. Although this question cannot be answered in general, a rating with a focus on systems especially appropriate for models concerning hydrology and water resources provides an overview about important qualities of the different software systems. Repast is apparently recommendable in this context, since it has the highest rating values of the four evaluated systems.

Nevertheless, not only the suitability of the software system but also the appropriate implementation of the environmental component determines whether a multi-agent model in hydrology or water resources research is meaningful. Again, none of the possible applications might be the best for all different kinds of models. However, combinations with GIS or other types of models, in some cases also with Cellular Automata, yield mostly more realistic models than environments implemented as simple grids. As discussed before, the representation of space and spatial attributes is essential for models in this academic field. Consequently, the environmental component of multi-agent models that is sometimes neglected in applications in other scientific fields is of particular importance.

5 Modelling water supply in Tauá, Brazil

5.1 Scientific question and objectives

The discussion of multi-agent methodology in the first part of the thesis gives reason to assume that water resources research benefits from applying such approaches. The aim of this part of the thesis is the practical application of multi-agent modelling to a suitable research question. Concluding from the discussion, multi-agent modelling is possibly more suitable than any conventional approach if a research question involves hydrological and socio-economic aspects likewise. Moreover, a model should correspond to the idea of multi-agent modelling to represent the problem by simple rules on a minor scale. The idea of this study is accordingly to represent a very basic water supply system with the simplest kind of agents, as are the water users in the context of water management. The water supply situation in the municipality Tauá in Brazil seems to be a suitable case study for different reasons. Tauá is among the regions with the highest water scarcity in the drought-prone Northeast of the country. The bad quality of the water prevents the local population from obtaining sufficient water for their daily needs in addition. The water supply infrastructure in the rural areas is comparably simple, lacking a public water supply. The question is how the people in the area deal with these issues. To model such as system, the hydrological situation of the resources as well as the behaviour of the water users have to be represented. Multi-agent modelling may more easily manage such a task than other, more conventional hydrological approaches and models.

The origin of the shortage of water in this area can be seen in the imbalance between the availability of natural resources, the state of development of the water supply structure and the water demand for specific uses (Voerkelius et al., 2003). The current version of the model deals with the first two aspects only, since at the moment, the model focuses solely on the demand for drinking water. The research question is to represent the decision of the water users for one of the available water sources depending on the availability of resources, the quality of the water and the background of the water users, e.g. their economical situation. Representing the decision-making process of the agents in such a simple context is seen as means for exploring the roots of complexity in water supply management.

Additionally, the flexibility of multi-agent modelling is used to include water quality as well as water quantity issues in the model. Besides water allocation, the quality of water is among the most important topics for the future in water resources management. Especially where water or financial means for treating waste water are scarce, as it is often the case in developing countries, not all the available water is of sufficient quality. Nevertheless, many models are not combining both topics, possibly because each of them alone is rather complex. However, in order to create realistic models, it is necessary that researchers accept this challenge.

Tauá has been chosen partly because of the comparably good availability of data because it was one of the focus regions in the WAVES project (Water Availability, Vulnerability of Ecosystems and Society in the Northeast of Brazil). Besides these arguments, choosing Tauá makes sense because the water problems are no trivialities, but badly affect the quality of life of the local population. The controversy regarding the right solution is high. To explore the behaviour of the water users and their interactions with the water resources in detail may be one of the necessary steps towards reducing this controversy. For this purpose, the model can simulate different scenarios, for example the reaction of the system to different climatic situations, e.g. wet vs. dry years, or to different states of the water resources.

5.2 Study area

The municipality Tauá belongs to the federal state Ceará in Brazil (Figure 5.1). It is located in the drought polygon, an area estimated to cover 950,000 km² in the Northeast of Brazil (Gaiser et al., 2003a). In Ceará, the average monthly income is 215 US $, less than half the Brazilian average (Hydroisotop, 2002). Tauá itself is one of the poorest regions in Brazil. One estimation of the income even assumes that that the income approximates only 25% of the national income (de Oliveira et al., 2003). Total poverty, as indicated by less than 50% of minimum income, applies to 85% of the population, 48% of the inhabitants are illiterate (de Oliveira et al., 2003). These indicators clearly point out the underdevelopment of the region. From a hydrological point of view, neither water availability nor quality are promising. The few water resources in the crystalline underground are of high salinity and therefore of low quality (Hydroisotop, 2002). In the area of about 4000 km² live 51937 citizens, about half of them in rural areas (Figure 5.2). A map of the area including the major infrastructure and dams and wells is provided in Figure A 1 in the annex.

Figure 5.1: Position of the municipality Tauá in the federal state Ceará (de Oliveira et al., 2003)

Table 5.1: Quantitative description of the system (de Oliveira et al., 2003)

Area[a]		3940.3 km²
Location		6° S, 40°18' W
Population[a] (in 2000)	total	51,937
	in urban areas	26,717 (51.44%)
	in rural areas	25,220 (48.56%)
Mean annual precipitation[b]		620 mm

[a] de Oliviera et. al. (2003) [b] Hydroisotop (2002)

Climate, geology and vegetation

Regarding climate, the region in Tauá can be classified as semi-arid, i.e. yearly dry seasons with negative climatic water balances exist. After the dry season from August to October, the rain starts again in November, whereby the movement of the Intertropical Convergence Zone (ITC) causes high variations in the average annual rainfall and the length of the rainy season. Most of the annual average precipitation of 620 mm (Table 5.2 and Figure 5.2) is consumed by a high potential evaporation in the rainy season on the one hand and high temperatures and a wetness deficiency in the dry season on the other hand. The temperature is constantly high throughout the whole year, with 25° to 27° Celsius (Hydroisotop, 2002).

Table 5.2: Mean monthly precipitation [mm] in Tauá, 1962-1971 (Hydroisotop, 2002)

	Month												**Year**
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Tauá	50	100	200	140	60	20	10	0	0	0	10	30	**620**

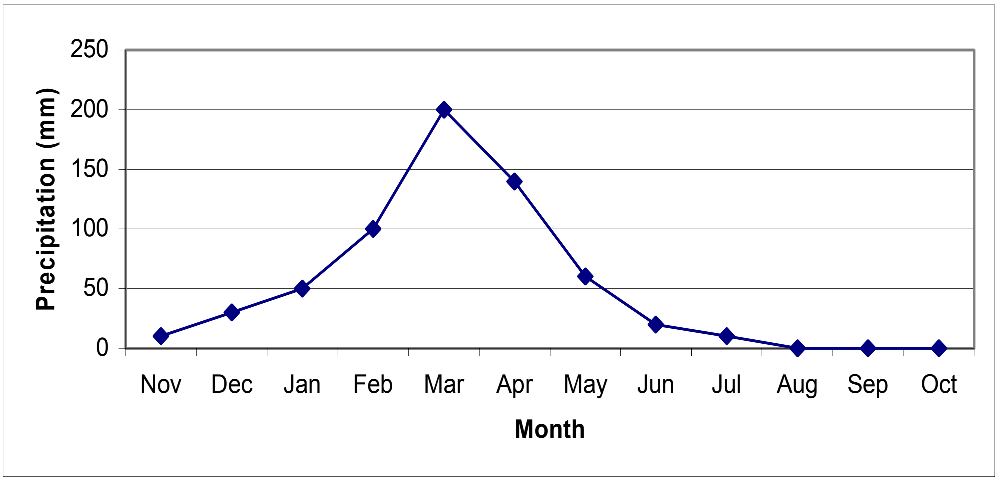

Figure 5.2: Precipitation in Tauá (Hydroisotop, 2002)

The major parts of Ceará are made up by a crystalline geology. Only the major rivers are located within alluvial and littoral sediments. The soils are mostly of low agricultural value due to a limited capacity to store nutrients and water and because of salinisation and acidification (Hydroisotop, 2002). The typical vegetation types in the Northeast of Brazil are *xenomorphic*, whereby the dry forest (Caatinga) is dominant in Tauá. Generally, 92.3% of the area in Ceará is covered by natural vegetation, indicating the small area used for agricultural purposes (Hydroisotop, 2002).

Water availability

Because of the semi-arid climate, the area is characterized by episodic droughts. High temperatures and wetness deficiency in the dry season cause fast drying of the thin topsoils and consequently different kinds of drought. For the Northeast of Brazil in total, the average probability for droughts is 40% to 80%, assuming an *agricultural* or *hydrological drought* with recognisable economical consequences such as deficits in income or water supply (Hydroisotop, 2002).

Concerning water availability, the components of the water cycle have been estimated using a water balance model (Hydroisotop, 2002). A comparison between Tauá and the federal state Ceará reveals for example the small proportion of groundwater recharge in Tauá (1 mm/a) compared to the value in Ceará (48 mm/a), whereas the runoff is about equal (Table 5.3). In Tauá, the crystalline rocks are covered by thin soils only. Fast saturation with water leads therefore to the building of runoff and consequently to a high primary groundwater recharge. However, a major part of this water evaporates again (Hydroisotop, 2002).

Therefore, and because of the crystalline bedrocks, the use of water in Ceará is limited mainly to surface water. Although the rural population is using all possible source, i.e. groundwater and surface water as well as rainwater cisterns (Hydroisotop, 2002), they depend mainly on surface water (Voerkelius et al., 2003). Additionally, the availability of the sources depends partly on the season. As Table 5.3 shows, the largest part of the consumed water is used for irrigation in Ceará, whereas no measurable amount of water is used for this purpose in Tauá. Most water in Tauá is consumed for animals and in the households instead. In the dry and poor region, neither tourism nor industry or agriculture play an important role (Hydroisotop, 2002).

The susceptibility of the region to droughts is based on several factors. First, the natural climate variability in the subtropical semi-arid region can cause natural severe droughts. Secondly, the water supply infrastructure is partly vulnerable to drought conditions, particularly the storage of surface flow in dams. Last, hygienic problems are especially severe during droughts (Hydroisotop, 2002). As in many other municipalities in the Northeast of Brazil, the annual water demand in Ceará cannot be satisfied in dry years, if the water withdrawal is not restricted. The rural population has to be supplied with water by water trucks (‘carro pipa’) on a regular basis (Hydroisotop, 2002).

Table 5.3: Mean annual values (mm/a) of the components of the water circle and of water use for Tauá and Ceará (Hydroisotop, 2002, p. 14, modified)

(mm/a)	Ceará	Tauá
Precipitation[a]	910	741
Potential evaporation[b]	2164	2255
Real Evapotranspiration[b]	708	595
Groundwater recharge[b]	48	1
Runoff[b]	154	145
Withdrawal of water/ consumptive water use[c]	5,21/2,55	0,98/0,70
Irrigation	2,67/1,60	0,00/0,00
Animals	0,56/0,56	0,63/0,63
Household	1,55/0,31	0,35/0,07
Industry	0,32/0,06	0,00/0,00
Tourism	0,11/0,02	0,00/0,00

[a] Historical reconstruction, 1921-1980; [b] Modelling with the large scaled hydrological model HYMO-WA, 1921-1980; [c] calculation with the large scaled Water use model NoWUM, 1996-1998 (irrigation: 1951-1980)

Water supply

In the past, water management in the Northeast of Brazil was mainly supply management oriented, emphasizing the extensions of water supply infrastructures (Hydroisotop, 2002). The Brazilian state founded two governmental organisations for ensuring water supply, which have been initiating the building of dams and the drilling of wells since the 50s. In Ceará, 37 major dams and hundreds of smaller dams (‘açudes’) exist today, the effectiveness of which is diminished by the high potential evaporation in the region (Hydroisotop, 2002). Of the numerous wells in Ceará, only 57% are in use. Shallow wells in the sediments along the river deliver less water, but are more reliable because of the simple techniques, whereas deep wells are productive, but vulnerable, mainly to salinisation. Unfortunately, there is no reliable information on the actual withdrawal of groundwater. The federal state is lacking a systematic area-wide control of water quality and groundwater withdrawal. Table 5.4 summarizes relevant estimations of local experts for Ceará and Tauá (Hydroisotop, 2002).

Table 5.4: Water supply infrastructure in Ceará and Tauá, (Hydroisotop, 2002, p. 17)

	Ceará	Tauá
Total capacity of storage lakes (10^9 m^3)	11.6	-
Number of major storage lakes (capacity > $50 \cdot 10^6$ m^3)	37	-
Mean number of storage lakes per 1000 km²	47.7	-
Number of existing wells	13300	385
Number of active wells	7581	-
Potential withdrawal of groundwater (10^6 m³/a)	-	2
Population connected to public water supply (%)	46	33
Urban population connected to public water supply (%)	66	69
Percentage of population connected to a sewage system (%)	20	0
Irrigated area (ha)	43096	0

Table 5.5: Costs for different water supply systems in Northeast Brazil

Kind of infrastructure	**Approx. Costs in US$**
Connection to public water supply and wastewater treatment system [a]	420 US$/family
Estimated total costs for water supply dams (Investment, Operational and Maintenance costs) [b]	0.068 US$/m³
Estimated total costs for wells (I, O and M)[b]	0.127 US$/m³
Estimated total costs for cisterns (I, O and M) [b]	0.596 US$/m³
Estimated total costs for waterholes (I, O and M) [b]	0.009 US$/m³

a (Hydroisotop, 2002, p.17) (currency conversion: 1 R$ = 0.42 US$ as on 1st September 2005)
b (de Araújo et al., 2003)

Almost exclusively the municipal capitals, i.e. in Tauá the city Tauá, are connected to a public water supply system. Therefore, the total percentage of population connected to public water supply is only 33% in Tauá (Table 5.4). As a result, most people have to transport their water individually from distribution points or from the location of the source to their houses, according to a survey in the area (Voerkelius et al., 2003). Nobody in Tauá is connected to a public sewage system (Hydroisotop, 2002). Apparently, the costs for the water supply infrastructure (see Table 5.5) are a major problem for the poor region. (Hydroisotop, 2002).

Water quality

Concerning water quality, the electric conductivity of the water and the chloride levels are generally high. Many of the groundwater water wells and some of the dams are so highly mineralized that they cannot be used directly. The reasons are high evaporation rates and geochemical interactions with the surrounding substrate in the water of the reservoirs and the slow groundwater (Hydroisotop, 2002). Figure 5.3 illustrates the bulk water quality in Tauá.

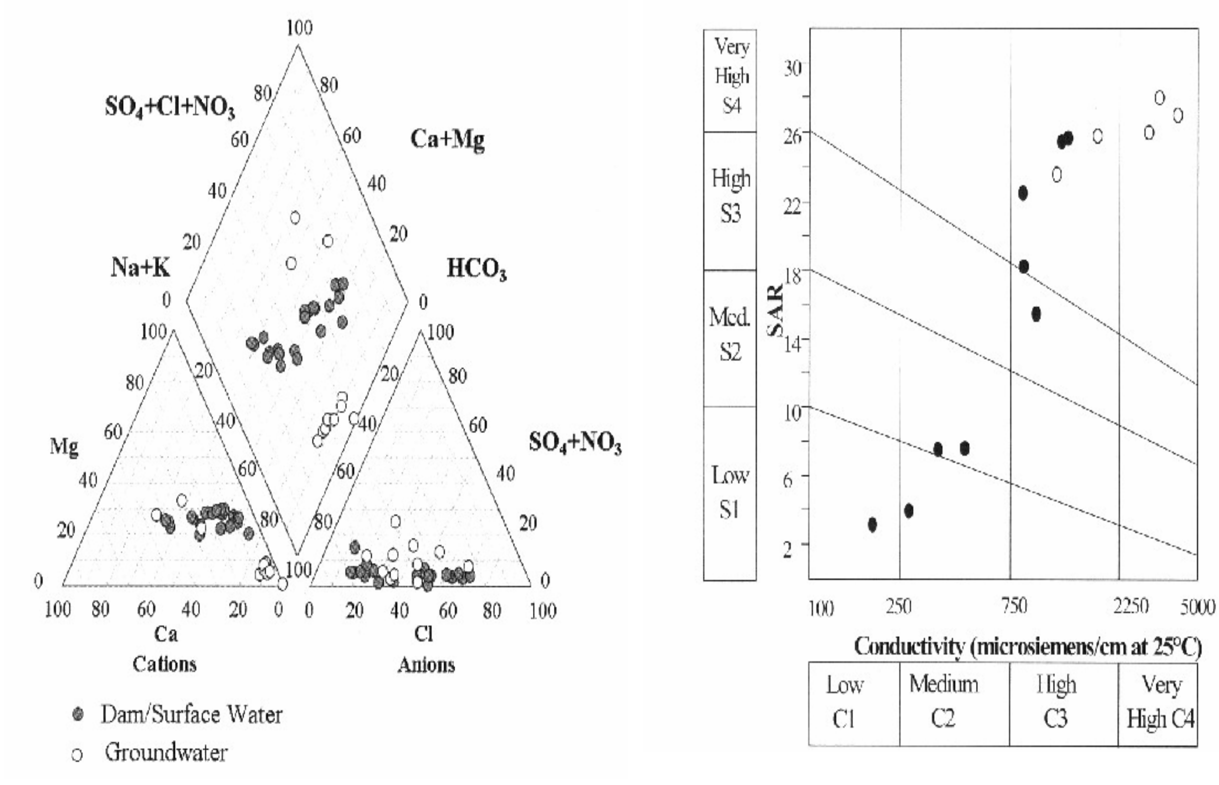

Figure 5.3: Bulk water quality in Tauá (ground and surface water) (Voerkelius et al., 2003, p. 176)

Moreover, intrusion of wastewater influences the water quality negatively. High concentrations of E.coli and other coliform bacteria are found in surface water, including the water of the reservoirs (Hydroisotop, 2002). Among the wells, especially the shallow wells are sensitive to contamination, as indicated by high nitrate values and contamination with bacteria (Hydroisotop, 2002). However, the bad raw water quality in Tauá can be ameliorated through careful treatment and control (Hydroisotop, 2002). Moreover, it depends on different factors whether the water quality affects the water use, e.g. the alternative sources of the water users and their demands on water quality. Water of salty wells, for example, is used in Tauá for animals and for washing, but not as drinking water which is subject to the highest requirements (Hydroisotop, 2002). One of the objectives of the multi-agent modelling of Tauá is to represent such adapted behaviour.

5.3 Concept

Even an apparently simple modelling task as representing the water supply structure and the water users of a rural area with basically no public water supply requires a high number of assumptions. The central idea of the model is to represent a certain number of water users who have the choice between different sources of water for satisfying their water demand. The process of designing an appropriate model starts with identifying possible influencing factors on the decision-making of the agents as well as actions that have to be included to provide a reliable representation of the system. Unfortunately, it is beyond the scope of this study to gain knowledge about the system by interacting with stakeholders and fostering their experience. All information about the system has to be derived from publications about the WAVES project [see for example Gaiser et al. (2003b)] and data collected in this project. Thereby, the available data is rather substantial, whereas the documentation is incomplete and partly in Portuguese. The main source of information about the water users and their interaction with the water resources is a survey undertaken in Tauá in the context of the WAVES project, based on the interrogation of 217 persons. The analysis of this survey is consulted for the design of the model and the interpretation of the results likewise.

5.3.1 Survey

The census based on interviews with local water users aims at providing a structural analysis of existing water supply systems (Voerkelius et al., 2003). The main purpose is to determine the water supply structure of the interviewed families at different times, e.g. in wintertime or during dry years. The survey includes questions on the distance to the different water sources as well as on the hygienic situation and associated diseases and finally on changes to the system the families wish for (Hydroisotop, 2002). Only items related to the water supply infrastructure and the distances to the water sources are used for the modelling. Most of the 217 participants in the study did not answer all the questions, whereby the number of answers varies highly between different items of the questionnaire. Only persons without missing data in the relevant sections of the questionnaire are considered in this thesis, i.e. 72 participants.

Water sources used generally

The first item of interest addresses the possible sources of water of the interviewed persons in general (Table 5.6 and Figure 5.4). Obviously, the number of water users sums up to more than 72, indicating that more than one source of water is mentioned per person. Waterholes and dams are the preferred water sources, but cisterns and wells are frequently used as well. The interesting question is which percentage of the total population, in this case of the 72 water users, uses a certain water source (Table 5.6).

Water sources used in wintertime or drought times

In the next two parts of the questionnaire, basically the same question is asked, i.e. which sources the locals use, but specific times are given, namely winter time and drought times. Moreover, the questions differentiate between different purposes of water use, such as drinking, irrigation or domestic use. The results of these scales for the chosen participants are summarized in Table 5.6. It demonstrates that, as expected, very few water in Tauá is withdrawn for irrigation purpose. Thus, this kind of use is excluded in the further analysis. Dams, waterholes, cisterns and wells are again among the most frequently used water sources for both purposes, i.e. drinking water and domestic use, and in both times, i.e. wintertime and droughts times.

Table 5.6: Number of users for the different water sources at different times and for specific purposes (percentage relative to the total number of users, i.e. 72)

	General	**In wintertime**			**During droughts**	
Water sources		Drinking water	Domestic use	Irrigation	Drinking Water	Domestic Use
dam	54 (75.0%)	32 (44.4%)	37 (51.4%)	0	15 (20.8%)	18 (25.0%)
well	12 (16.7%)	2 (2.8%)	7 (9.7%)	0	2 (2.8%)	4 (5.6%)
public water supply	0 (0 %)	0 (0%)	1 (1.4%)	0	1 (1.4%)	1 (1.4%)
desalinisation	3 (4.2 %)	5 (6.9%)	2 (2.8%)	0	2 (2.8%)	1 (1.4%)
cistern	24 (33.3 %)	27 (37.5%)	8 (11.1%)	0	7 (9.7%)	1 (1.4%)
water hole	55 (76.4 %)	22 (30.6%)	41 (56.9%)	1 (1.4%)	14 (19.4%)	18 (25.0%)
water holes in rivers	10 (13.9 %)	3 (4.2%)	5 (6.9%)	0	5 (6.9%)	7 (9.7%)
river	1 (1.4 %)	1 (1.4%)	2 (2.8%)	0	2 (2.8%)	2 (2.8%)
Water truck	0 (0 %)	13 (18.1%)	7 (9.7%)	1(1.4%)	16 (22.2%)	10 (13.9%)
others	0 (0 %)	5 (6.9%)	3 (4.2%)	0	2 (2.8%)	2 (2.8%)
Sum	**159**	**110**	**113**	**2**	**66**	**64**

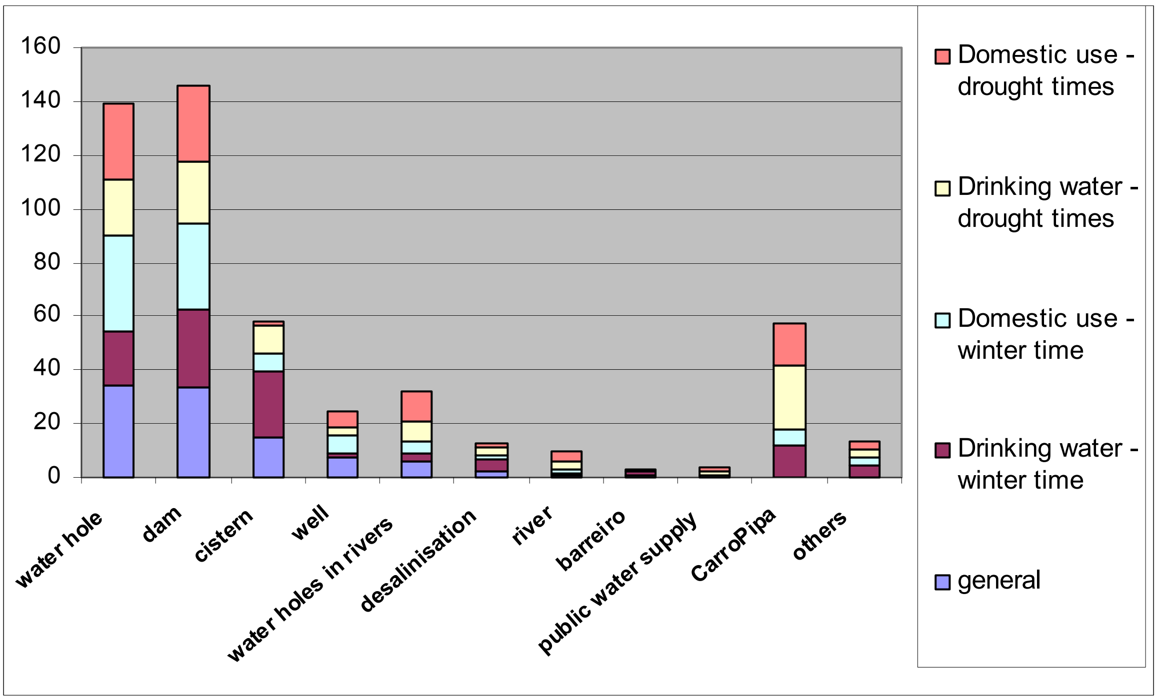

Figure 5.4: Graphical illustration of the number of water users per water source in different conditions

The governmentally paid water truck is not mentioned for general use, but has some users in winter and is the most important source of drinking water during droughts. This data illustrates that the consumers differentiate between different purposes and have to take the quality of the water into account. The cistern water for example is more frequently used as drinking water than for domestic use, especially in wintertime.

Number of sources used

Apparently, the number of different sources used, given in Table 5.7, varies in the different situations. For their general use, the interviewed water users mention for example a total number of 160 used sources. Relative to 72 persons, this means that a person uses 2.2 sources in average, whereas in wintertime, the corresponding average is only 1.6, for drinking water and domestic needs likewise. The quality of the data is challenged by the fact that the 72 users mention less than 72 used sources during drought. The survey contains the option to mention sources of waters that are not explicitly included in the category ‘others’. Moreover, it includes the water trucks as water sources that are supposed to supply the locals with water when other water sources are not available. Consequently, one of the options in the survey should apply to all the users. The data has therefore to be handled and interpreted with great care. The trend in the data may be realistic nevertheless: The families make use of as many sources as possible. If the climatic conditions get worse, the number of available sources is limited and the variety of sources used decreases.

Table 5.7: Number of users with a certain number of sources

Number of used water sources	**Number of users**				
	General use	**Winter time**		**Drought time**	
	-	Drinking water	Domestic use	Drinking water	Domestic use
0	1	1	1	30	33
1	15	40	36	26	21
2	30	24	28	11	12
3	22	5	6	2	5
4	4	1	1	3	1

Table 5.8: Average number of sources per user

	General use	**Winter time**		**Drought time**	
	-	**Drinking water**	**Domestic use**	**Drinking water**	**Domestic use**
Average number of sources	2.2	1.6	1.6	0.9	0.9
Standard deviation	0.88	0.82	0.73	1.03	1.01

In the items asking for the water sources in wintertime and during droughts, the question is included how far the distance between water users and sources is. Unfortunately, the questionnaire does not differentiate between missing values and a mentioned distance of nought. However, a distance of nought meters is not likely, even in the case of cisterns is a small distance more probable. Therefore, all the values of ‘zero’ are interpreted as missing values. Due to high number of ‘zero’ values, the remaining data is scarce. Figure 5.5 gives an overview on the remaining data for the five most frequently used sources and the water trucks. Some trends can be interpreted, even if the conclusions have to be drawn carefully because of the high percentage of missing data. As expected, the cisterns are mainly close to the houses, so are waterholes and many of the dams. However, in these two cases, some agents have to travel great distances in order to reach the sources, i.e. up to 10 km. The few answers related to the water trucks mention distances between 1 and 10 km. Apparently, the governmental service provides water only at some distribution points in the area.

Transportation of water

The last interesting item in the questionnaire is concerned with the way people transport their water into their houses. Although this topic is not included in the model, it is nevertheless worth to have a look at it, since it completes the picture of the basic water supply system. The users mention mainly canisters, private pipes or other sorts of private and simple means of transportation, emphasizing the basic structure of the water supply system (Figure 5.6).

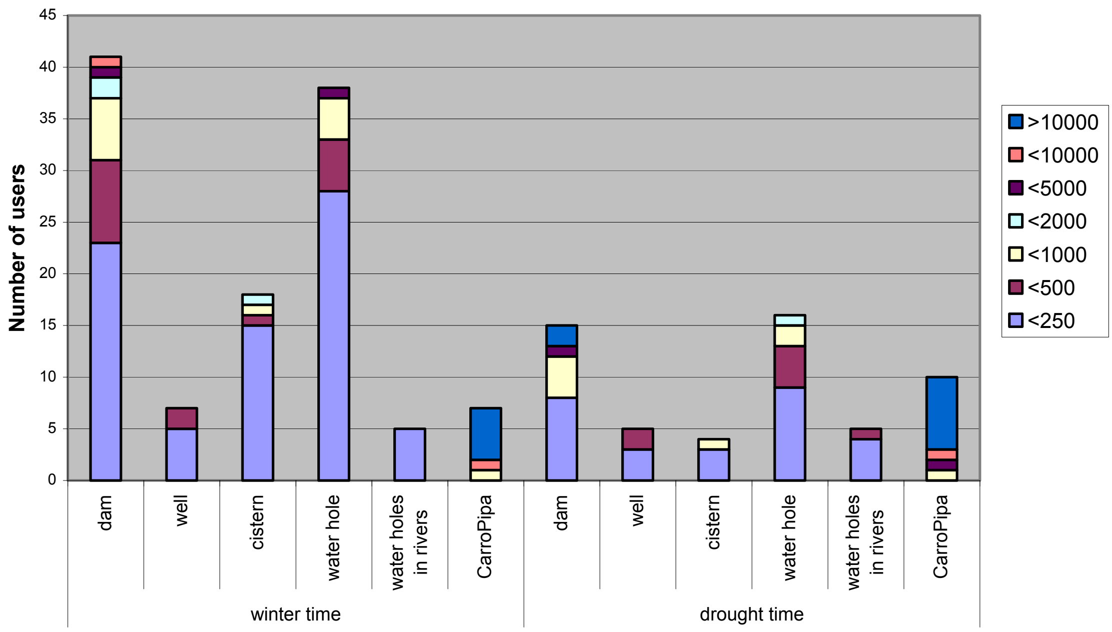

Figure 5.5: Distance between the water consumers and their water sources in winter time and in droughts

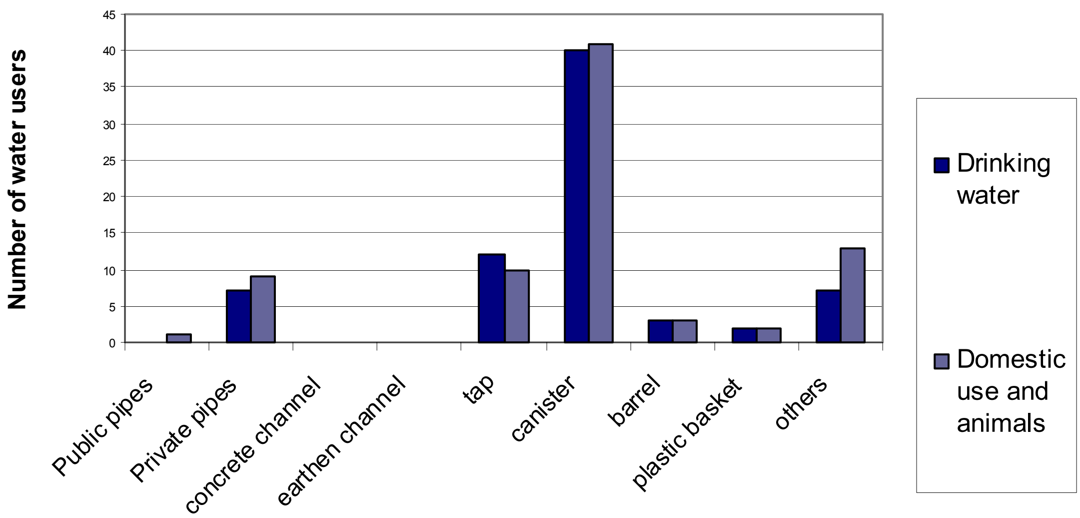

Figure 5.6: Means of transportation for the water from the sources to the houses of the interviewees

5.3.2 Structure

Based on this source of information, the question is which factors generally influence the water supply system in the region of Tauá and which should be represented in the model. At least three categories of such variables can be established. The first category is concerned with the expenditure necessary to get the water. The main factors are expenditure of energy and time, as can be expressed by the distance between the agent and the source on the one hand and the economical expenditures, i.e. the costs for the water on the other side. The second class of influencing factors is concerned with the social interactions between the agents. Possible factors are the influence of the neighbourhood or the mechanisms of competition and imitation. Organizational issues make up the last category, including aspects of mobility, social organisation and nesting of water resources. Table 5.9 summarizes this categorisation in detail. Some of the aspects are realized in the actual, simple version of the model. The others may be realized in future versions of the model. However, while developing the model further, issues may appear that are not included in this overview yet.

Table 5.9: Factors relevant to the water supply system in Tauá, partly implemented in the current version of the model

Category	Subclass	Implemented factors	Factors not implemented
I. Expenditure and risks	*Energy and time*	Distance	-
	Economical aspects	Costs for the water	-
		Credit of the agents	-
	Reliability of the resource	Hydrochemical quality of the water	Hygienic quality
II. Interactions between agents	*Indirect interactions*	Use of shared resources	
	Neighbourhood, density	-	Population density (urban vs. rural) influences consumption
	Competition	Utilization of the resource	Hierarchy
		-	Knowledge and education
	Imitation	-	Preferences for sources are influenced by neighbours
III. Organizational issues	*Organisation of the resources*	-	Nesting (feedback between upstream and downstream users)
	Social organisation	-	Water rights
		-	Collective actions of communities
	Mobility	-	Water transportation
		-	Moving of agents to other areas

5.3.3 Design of the model

Generally, the model consists of two different parts, the physical environment and the agents as the entities living in this environment and interacting with it. Figure 5.7 gives an overview on the principal structure of the model that is described in further detail in the following chapters.

General assumptions

In the current version, the model does not include water for irrigation purposes, but focuses on domestic use including the amount of water used for drinking.

As the time step of the model, a month is chosen. Although water uses are often considered on a daily basis, the dynamics of the system under study are not thought to vary with such a high resolution. The dynamic depends mainly on the seasonal change in water availability and the economical situation of the agent. Both factors are not likely to change considerably from day to day. According to the precipitation regime of the area, the first month in the model is November and not January.

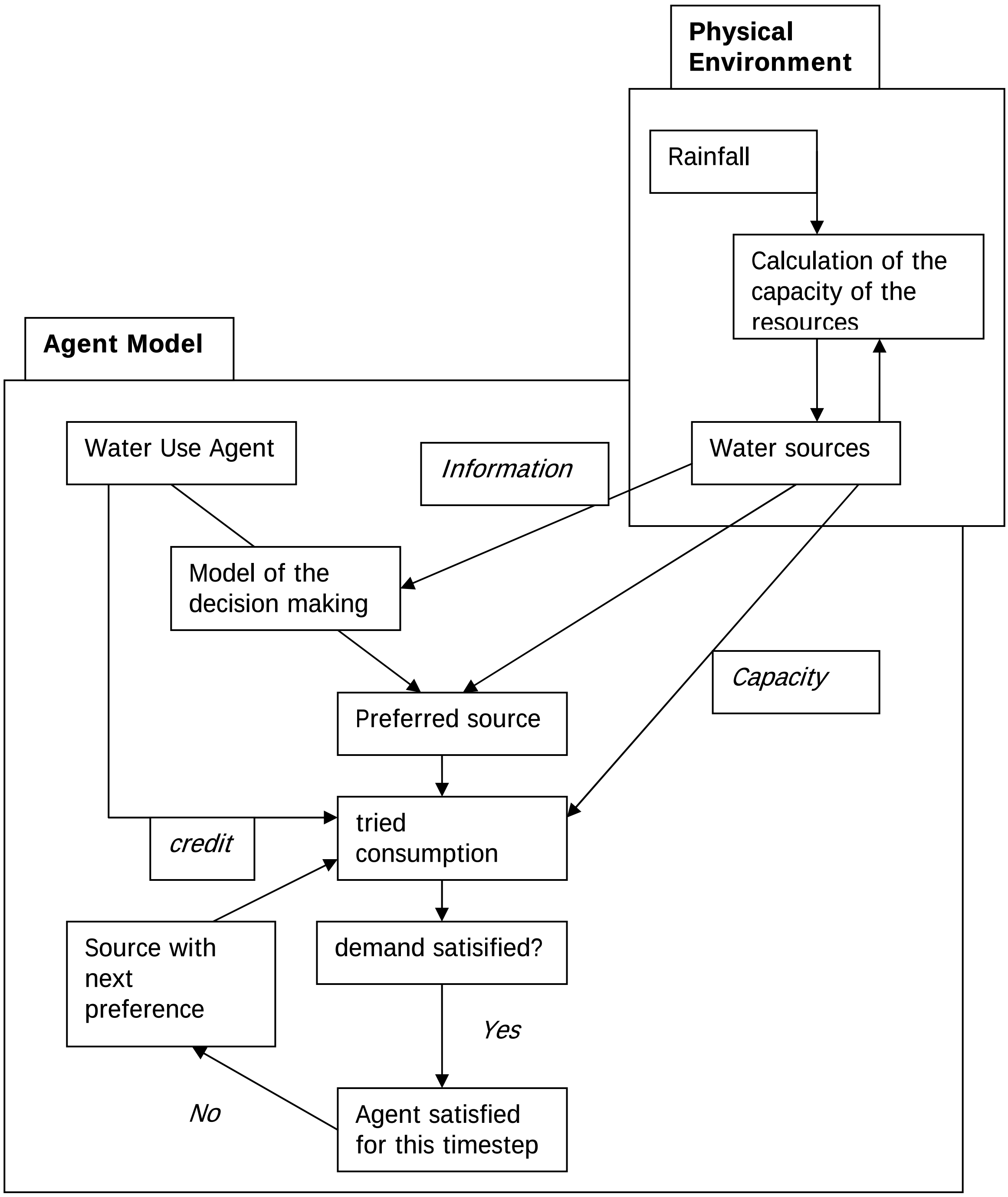

Figure 5.7: Principal structure of the model

Physical environment

The physical environment consists of the spatial distributed water sources. For the sake of simplicity, the inclusion of all the water sources into the model is not thought to be useful. Consequently, only the four most frequently used water sources are modelled, namely cistern, dam, waterhole and well. This selection is meant to provide a good representation of all the water sources, representing groundwater vs. surface water use (e.g. wells vs. cisterns), private vs. public sources (e.g. cisterns vs. major dams) as well as different dimensions of capacity. Water holes and water holes in the river are not differentiated in the model, although they are in the survey. It is assumed that both gain their water resources from the shallow groundwater. For the purpose of the model, it is not necessary to distinct between the two forms that are subsumed in one category consequently.

The main task for the physical environment is to provide the water resources that the agents can use. For this purpose, the capacity of the water resources is calculated based on precipitation data and hydrological assumptions about the involved processes.

Agents

In the current version, the model contains three kinds of agents, the water users, the government and the city. About 50 % of the local population in Tauá lives in urban areas. Since the model attempts to represent the water resources in the whole municipality in Tauá as accurate as possible, it is important that a realistic number of agents is created in order to model the usage of the resources and the water balance correctly. Therefore, the urban areas have to be represented as well, since they get their water out of the water sources in the hinterland. However, because the model focuses on rural areas only being characterized by the absence of a public water supply, the citizens in the urban areas are not represented as individual agents, but as a lumped agent. This agent is located where Tauá, the capital of the homonymous municipality, is located. It gets its water demand from the major dams and from 20 wells close to the city, the so called urban wells.

The 72 citizens that answered the questionnaire are used as a kind of model for the water user agents in the rural areas. For them, important data exists, e.g. how many agents are associated with cisterns and waterholes. Besides creating these so called ‘empirical agents’, the appropriate number of so called ‘randomised agents’ is created in order to represent the whole population in the rural areas of Tauá. The three main attributes of the water use agents are their monthly income, their household size and their location within the system, representing the place where they live. The behaviour of the water users consists of looking for appropriate water sources, choosing which one they prefer and finally trying to get a specific share of water out of this source. This task is divided into different steps that are described in further detail in chapter 5.4.3. For the sake of simplicity, an agent is referred to in the following description as a masculine being, although it represents a household and does not have a specific gender.

One of the critical features of the model is the development of preferences for specific water sources on the side of the agents. To model the way humans decide between different available resources, the most important factors influencing their decision have to be identified. In this model, four factors are assumingly essential: The distance to the source, the costs for using it, the water quality and the remaining capacity of the source.

The empirical data suggests that the water quality may not be neglected when considering the water consumption. Under these conditions, it will surely influence the decision of the water users, especially when water for drinking and domestic purposes is considered. However, in this model only the hydrochemical, not the hygienic quality of water is addressed. For the latter, relevant data is missing and furthermore, compared to chloride and chemicals in the water, hygienic conditions are more easily to change, e.g. by instructing the locals how to treat their water with chlorine. The distance to the source is considered as a measure for the time and energy that the users have to spend for gaining water from a specific source. Consequently, the distance will influence which sources the agents prefer. Of course, it can be assumed that the cost for the water influences the attitude of the agents towards different kinds of water sources, especially in such a poor region like Tauá. Furthermore, it is not likely that the agents use the sources independent of the amount of water that is left to use. Especially since the remaining capacity influences the amount of water they take out of the source, as described later, sources whose capacity is far from being exhausted should be preferred.

However, determining the preferences is far more complex an issue than determining these factors. The question is how they interact and in which way they influence the decision. The general idea is to connect the factors in a way that an index results indicating how strong the preference of the agent for this specific source of water is. To achieve this, the factors have to be categorised first, because they are not directly comparable, e.g. have different units. For this purpose, a rating system is applied that assigns values from one to four to all three factors (for the realization of the rating for the different factors see 5.4.3). The higher the rating value is, the better is the water source for the agent. Different possibilities for calculating an index based on these rating values exist, such as multiplying them, adding them up or multiplying them with weights before adding them. From a psychological point of view, it seems likely that such factors are not all equally influential on the decision of the water users, which is in favour of the idea to weigh the factors, i.e. to multiply them with a factor indicating if the influence of this factor on the decision is especially emphasized or not. Moreover, it is likely that inter-individual differences exist between the weight different water users put on these factors. Based on this assumption, the idea is favoured to represent different kind of water users, e.g. agents with high vs. low mobility or agents emphasizing more or less the importance of clean water.

Another possibility to realize psychological aspects in the model is to assume that humans do not rate the factors objectively, but biased by personal factors, such as their own background (e.g. economical, educational), their intentions (e.g. purpose of water demand) and beliefs (e.g. religious or cultural beliefs). It is a general problem in water management that the agents lack perfect knowledge of the system. Therefore, they base their decision on their personal perception instead, which varies between individuals and does not have to be correct (Janssen, 2005), S.6. A possible realization of this idea would be to base the decisions of the agents in the model not on real values, but on perceived values of the four factors influencing the decision. For example, not the real price, but the perceived price of a good influences the decision of humans.

Nevertheless, no data exists in the questionnaire on the attitudes of the water users and their perceptions and preferences concerning water costs, distances and water quality. Consequently, no empirical data exists at the moment that could serve as base for implementing one of the mentioned approaches. To avoid the danger of making assumptions lacking evidence, a simple approach is implemented for the time being. The values of the four factors are multiplied and the highest value indicates the water source that the agent prefers. However, the model can be easily improved, either if there will be further relevant information or within a scenario for exploring the effects of such changes.

Concerning the water use per person, it is not thought to be likely that all the water users are using the same amount of water, independent of their economical situation or the available resources for example. Thus, the water use per person should not be set as a fixed value, but flexible. This flexibility is relative to the assumed remaining capacity of the water sources. That is, if the agents expect the water resources to be more abundant, they use more water than in times with scarce resources.

Whereas the water users are rather sophisticated agents, the functionality of the government agent is limited to one action at the moment. The government agent monitors how many water users suffer from shortage of water and is responsible for sending the water trucks out to the citizens, if needed. Consequently, the government agent is active in case of severe drought only when there is a critical lack of water. Contrarily to the other agents, it is not located anywhere, because it does not have spatial references in the system.

5.4 Realisation

5.4.1 Software

The model is implemented using the Repast platform (see 4.2.1). The programming language is the object-oriented language Java, but predefined classes and structures exist that are not available within the regular Java class libraries. This offers the flexibility to the modeller either to write his or her own code in standard Java language or to rely on functionality available in Repast.

Beside the class WaterUseModel that provides the functions for setting up the structure and the functionality of the model (described in chapter 5.4.4), the model contains nine classes. Three classes are implementations of agents, namely the relative detailed class for the water users (WaterUseAgent) and far more basic realization of the government (Government) and the city.

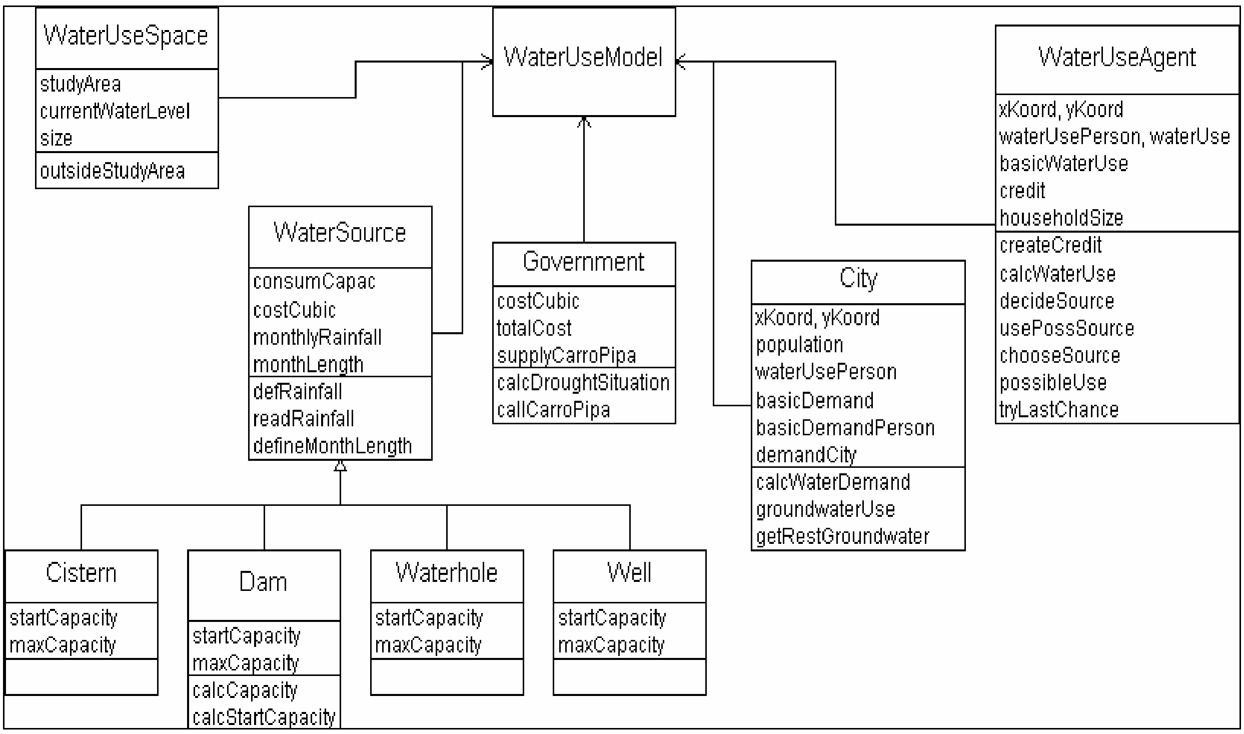

Figure 5.8: UML-like overview of the model structure (closed arrow: inheritance; normal arrow: association)

Five of the classes contain the code for realizing the four represented water sources and the WaterSource class, a super class for all the water sources containing some of the characteristics common to all the sources. The class WaterUseSpace is part of the implementation of the spatial structures of the model. Only one of these classes (ReadIn) does not implement an entity of the system, but realizes the transfer of the data into the model. See also Figure 5.8 for a graphical overview on the classes and their main parameters and methods.

5.4.2 Physical environment

The physical environment in the model consists of the water sources together with their spatial distribution on the one hand and the location of the agents on the other hand. As mentioned before, four of the water sources are included into the model, namely cisterns, dams, waterholes and wells. The water trucks are part of the model as well, but not as regular water sources, but as governmental means in case normal water supply is not assured anymore. To set up the physical environment mainly consists of importing the water sources together with their spatial distribution and their relevant qualities, namely capacity, costs and water quality.

This information is represented in a grid of 100 x 100 cells. However, not all of the 10,000 cells with a size of 950 x 950 m² (0.9025 km²) belong to the modelled area. Only 4155 cells are located within the study area, covering an area of 3750 km² in reality. This is slightly less than the real area of Tauá (3940 km²), since a small part of the area on the borders has been excluded during creation of the grid.

The first idea for realizing the physical environment was using a GIS system. As discussed before, methodological problems still exist for such an approach. The idea had to be abandoned, since it seemed not possible to be successful within the rather short time. Furthermore, the environment that is considered is comparably simple. Since it is not reasonable to apply approaches with a far higher functionality than needed, it may be the better option not to base the system on a GIS. Moreover, Repast offers sufficient alternatives.

Input of data

Reading in data as *.pgm-files* (see glossary) is one of the alternatives to GIS technology that Repast offers for loading spatially distributed data into a model. Although this is an image format, it can be used for transferring information as well. A .pgm-file consists simply of a grid of values indicating the grey value of each pixel in the image. If information is encoded in theses values, it can be read into Repast in a spatial distributed way. Thus, the location of all water sources and empirical agents likewise is read into the system. Differences in the available and necessary data change the general procedure slightly.

The location of the objects has to be defined, either by coordinates in a database or by digitalizing the sources from a map. With these coordinates, the sources are loaded into an ArcView shapefile. Using the Geoprocessing function in ArcView, these files are transferred into a raster format with a 100 x 100 grid size. Objects outside of the shape of the study area are excluded within this step. The raster is exported as ASCII code, and saved as a .pgm file. This file is loaded into the Repast model and transferred into an internal grid structure of Repast, i.e. the Object2DGrid. The values in the .pgm file encode empirical data that is necessary for the modelling, e.g. the size category of the dams. The details of importing the necessary data are described now individually for the different objects.

For the water user agents, the survey data contains the coordinates of the homes of the interviewed persons necessary for creating and locating the empirical agents. However, while creating the grid, it was realized that five of these persons are not living in the modelled area. Excluding them results in a total agent number of 67 empirical agents. The household size, as given in the survey, is transferred as information in the .pgm file into the model.

Taking into account the average household size of 5.4 persons per household in the survey, these 67 agents represent 362 citizens. From the 51937 inhabitants in Tauá, about 26715 live in urban areas (Table 5.1). They are represented by the city agent, not by individual agents. The 25220 citizens in the rural areas minus these 362 persons have to be modelled as ‘randomised agents’. Assuming the average household size, this means that 4603 agents have to be introduced. Since no data is available about their location, they are distributed randomly, whereby more than one agent can be placed into one cell of the grid. Thus, cells with a higher population density exist, analogous to villages in real life.

Governmental and non-governmental organisations support building of cisterns, because these water tanks storing rainwater collected on the house roofs are especially useful for the rural population in drought times (de Araújo et al., 2003). Unfortunately, very few data is available about cisterns for the current study. Therefore, data of the questionnaire is used in the way that a cistern is located where an agent mentioning to use one is located. According to this data, this applies to 33% of the water users. For the empirical agents, 20 cisterns are created plus additional 1521 cisterns for the ‘randomised agents’. The percentage of water users with a cistern is a parameter in the model that can easily be changed. No additional data is encoded in the .pgm file, since none is needed in the case of cisterns.

For the dams, the available data is not very good. An ArcView shape file exists containing all the major dams in the region. Four of these are located in the study area Tauá. With the help of a table with data about major dams their names and attributes are ascertained. Nevertheless, a map of the area shows that there are far more dams in the areas than the major ones. Lacking information about their size or position leads to digitising their locations from the map. Because it is unlikely that all the dams have the same size, they are grouped into two classes according to their apparent size on the map and the estimated catchment area, class 1 for the smaller dams and class 2 for the bigger ones. Via the .pgm file, the locations of the dams are transferred into the model, whereby code numbers indicate the class of the dam: The classes 1 and 2 are encoded by the numbers 1 or 2, whereas numbers 3 to 6 encode the four major dams (Table 5.11). All in all, 93 dams are assumed to be available to the water users (Table 5.10).

For the waterholes, no explicit source of information exists. As the cisterns, they are located where the agents that state to use them are. Although it would be more realistic to locate them within a certain radius of the houses of the agents, say 500 m, this is not possible because of the coarse resolution of the grid (950 x 950 m²). 57 waterholes are implemented for the empirical agents. Since 90 % of the water users have access to a waterhole, according to the survey data, additional 4146 waterholes are introduced into the systems.

Contrarily, comparably detailed data exists for the wells, including location, water quality and depth of the wells. Therefore, this data only has to be transformed into a grid, whereby the numbers in the .pgm file encode the water quality and the depth of the wells. Although the depth of the wells is not important in the actual version of the model, it may be for scenarios, since it is information about the usability of the well if the water level falls. The empirical data is supposed to contain all the active wells in the area, but some of the wells are not implemented due to the coarse resolution of the model. Thus, the model contains 160 wells.

Table 5.10 summarizes the number of specimen created for each category of water sources. In Repast, different grids are used for implementing different water sources and the agents.

Table 5.10: Number of specimen created for the five different kinds of objects

Object		Number of specimen
Agent	**Total number**	**4670**
	Empirical	67
	Randomised	4603
Cistern	**Total number**	**1541**
	Empirical	20
	Randomised	1521
Dam	**Total number**	**93**
	Class 1	77
	Class 2	12
	Class 3	4
Waterhole	**Total number**	**4203**
	Empirical	57
	Randomised	4146
Well	**Total number**	**160**
	Rural wells	140
	Urban wells	20

Table 5.11: Number of cells in the different categories of dams

		Number of cells
Class 1		77
Class 2		12
Class 3	Dam 4	3
	Dam 5	4
	Dam 6	9
	Dam 7	12
	Total	**28**
Total		**117**

Estimation of water quality

An estimation of the water quality of the different water sources is necessary in order to predict the decisions of the water users for or against specific water sources. Empirical data is available only for the wells and for some of the major dams. In this case, the water quality is categorised according to three categories: A good water quality is assumed if the amount of total dissolved solids (TDS) in the water is less than 500 mg/l and is encoded with the number 4. An acceptable water quality means TDS loads of less than 1500 mg/l (rating number 2). Water with more than 1500 mg/l TDS is meant to be unacceptable (rating 0). For the other sources, it is estimated qualitatively whether the quality of the water is good (rating value 4), acceptable (rating value 2) or not acceptable (rating value 0). Table 5.12 summarizes the assumed water quality for all the water sources.

The water in the cisterns is rainwater and therefore basically of good quality (de Araújo et al., 2003). There will be a loss of quality caused by the passage over the roofs, however this is meant to be negligible. The rating value is consequently 2.

The water quality in the smaller dams is less promising, since the cattle coming to the dams diminishes it (de Araújo et al., 2003). Therefore, the water quality is rated with 2 for the dams of the smallest class, the class 1. Generally, the quality of the surface water in the dams that is delivered by rainfall and flooding is assumed to be of good quality. Empirical studies demonstrate that most water samples from dams have lower salinity levels than those from the groundwater wells and that their balanced cation composition resembles that of floodwater. (Voerkelius et al., 2003) (see also Figure 5.3). For three of the four major dams, empirical data exists. The chlorine value in Figure 5.9 indicates that the water quality is good for the dams Forquilhas and Vareza de Boi, but obviously worse for the dam Favelas (Voerkelius et al., 2003). Therefore, the value assumed for this dam is 2, whereas the dams of class 2 and the other three dams of category 3 are rated with a 4.

The waterholes are fed by shallow groundwater with a quality similar to that of surface water and better than the water in the deeper wells, according to Voerkelius et al. (2003). Therefore, the quality of the water in the waterholes could be assumed good. However, a similar argumentation applies as for the smallest dams. After a while in the unprotected waterholes being accessed for example by cattle the water is meant to be of acceptable quality only, resulting in a rating value of 2. The water quality of the wells has been addressed in the WAVES project, so that empirical data exists in this case. Wells with more than 1500 mg/l TDS have not been included into the model.

Table 5.12: Assumed water quality of the different water sources (4: good quality, < 500 mg/l TDS; 2: acceptable water quality, < 1500 mg/l TDS)

Water quality			
Water source	**Classification**	**Ranking**	**Source of information**
Cistern	Good	4	Estimation
Dam	Good: Class 2, Forquilhas, Trici, Vareza do Boi	4	Estimation
	Acceptable: Class 1, Favelas	2	
Waterhole	Acceptable	4	Estimation
Well	Good or acceptable, depending on individual well	2 or 4	Empirical data

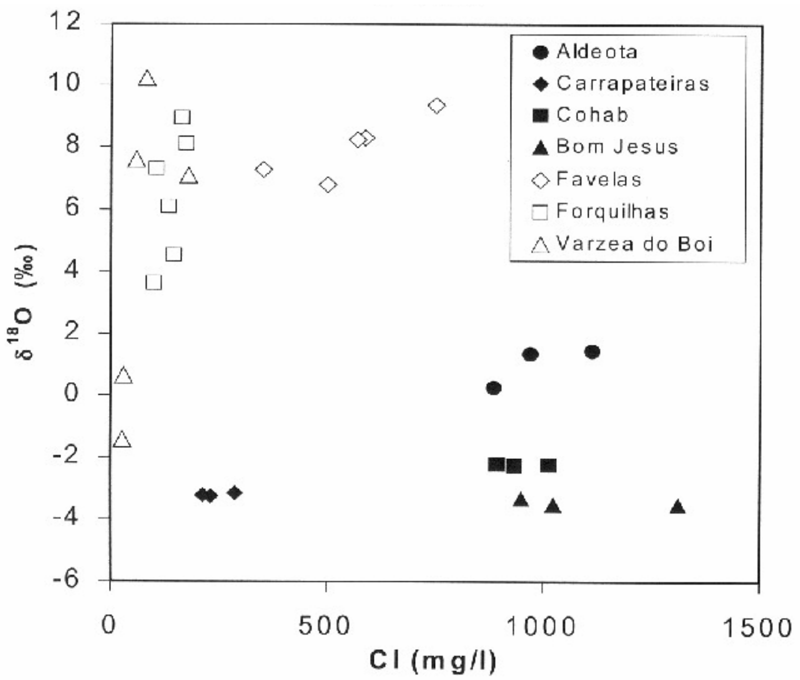

Figure 5.9: Stable isotopes from selected locations (Voerkelius et al., 2003, p. 182)

Estimating capacities

Of course, none of the water sources is of inexhaustible capacity. Since the time step for the simulation is a month, the monthly capacities are the relevant ones. Unfortunately, no data exist concerning the capacities of the different water sources. Therefore, the capacities are estimated by considering the most relevant hydrological processes involved in creating the water resources in the sources. For this estimation, the relevant areas, e.g. the area of the storage lakes of the dams, and the catchment area of the sources, where required, have to be estimated. Additionally, some general assumptions are necessary, for example about the percentage of groundwater recharge.

Regarding precipitation, not the mean monthly precipitation in Tauá (Table 5.2) is taken for the modelling. The intended representation of the behaviour of the system in years with different climatic condition requires precipitation data out of years with different amounts of yearly rainfall. This data is not available for Tauá, so rainfall data of Bocaina is used instead. In Bocaina, estimated to be less than 300 km South-West of Tauá in the municipality Picos, there is a meteorological station of the WAVES project. For the basic version of the model, the rainfall data of 1928-1929, a reference year with normal rainfall pattern in the WAVES project, is chosen. For the scenarios with dry climatic conditions, 1941-42 can be used as reference year (see Table 5.13)

Table 5.13: Monthly rainfall for the two reference years

	Normal year	**Dry year**
Month	1928-1929	1941-1942
November	0	0
December	60	25
January	83	109
February	281	55
arch	130	68
April	170	120
May	41	7
June	0	0
July	0	0
August	0	0
September	0	0
Oktober	0	45
TOTAL	**764**	**428**

Due to the various hydrological processes involved in building the different kinds of water resources, special equations have to be used for estimating the capacities in the water sources. Therefore, the estimation of the capacity is described for each water source individually in the following section. Table 5.14 provides an overview on the necessary assumptions.

To all water sources applies that the capacity of the water sources that can be exploited is limited. Whereas this maximum capacity C_{max} is limited by the size of the water tank in the case of the cistern, it is in the other cases related to the input of water created in one year of normal rainfall and without consumption out of the water source. For example, the maximum capacity of the dam is assumed to be 2.5 times this yearly input.

The total capacity C_{month} (l) in a current month is calculated generally as sum of the capacity at the beginning of this month C_{prev} (l) and the input generated in this month, $Input_{month}$ (l) minus the consumption within this month, U_{month} (l).

The resulting equation is:

$$C_{month}\ (l) = (C_{prev} + Input_{month}) - U_{month} \tag{5.1}$$

However, this equation is only applied if the remaining capacity in the source is high enough to take all this water, i.e. it ($C_{max} - C_{prev}$ (l)) exceeds the monthly inflow $Input_{month}$ (l).

$$C_{max} - C_{prev}\ (l) > Input_{month}\ (l) \tag{5.2}$$

Otherwise, not the whole amount of water can be stored and the capacity in the month equals the maximum capacity C_{max}:

$$C_{month}\ (l) = C_{max} \tag{5.3}$$

Consequently, the only term that has to be calculated for each kind of water source individually is the monthly input. However, it is not likely to assume that the water sources are empty when the simulation starts. Therefore, a start capacity has to be determined as well, again based on the yearly input, whereby the start capacity depends on the climatic conditions as well as on the consumption in the previous years. Since a comparably high exploitation is assumed in the water scarce area, the start capacity is estimated to be one quarter of the capacity created in a year with average rainfall pattern and without water consumption (Table 5.18 and Table 5.19). An exception is the cistern, where the start capacity is assumed to be a quarter of the maximum capacity. The effect of possible errors in these assumptions decreases with a higher number of time steps. Therefore, it is advisable to simulate at least one year of normal rainfall before a simulation is executed.

Table 5.14: General assumptions for estimating monthly capacities

	Cistern	Dam	Waterhole	Well
Area of the source A_{source} (m²)	-	see Table 5.15	-	-
Catchment area $A_{catchment}$ (m²)	50 m²	see Table 5.15	2500	25000
Maximum capacity	15 m³	$2.5 \cdot Input_{year}$	$Input_{year}$	$Input_{year}$
Efficiency Eff (-)	0.85	0.65	1	1
Inflow efficiency Eff_{inflow} (-)	-	0.2 (normal) 0.15 (dry)	-	-
Infiltration Inf (l/(m²·d))	-	$2 \cdot 10^{-8}$	-	-
Coefficient of groundwater recharge r_{gw} (-)	-	-	0.0327 (normal) 0.0013 (dry)	0.0327 (normal) 0.0013 (dry)

Cisterns

The water tanks that define the maximum capacity of the cisterns allow to store 15 m³ of water from the house tailings (de Araújo et al., 2003). The monthly input of a cistern is easily to calculate (equation 5.4). The area of the roof, representing the catchment area for the cisterns, A_{catch} (m²), is rather conservatively estimated to be 50 m², since the people are poor and their houses small. However, the total rainfall on the roof will assumingly not result in storable water. The efficiency term Eff expresses the percentage of the inflowing water that can be stored. Losses are for example a result of leakage in the system or rest water in the cistern that is not usable. The efficiency of the cisterns in Tauá is estimated to be 0.85. The resulting equation is:

$$Input_{month}\ (l) = A_{source} \cdot P_{month} \cdot Eff \tag{5.4}$$

where P_{month} is the monthly precipitation (l/m²) and Eff is the efficiency (-).

Dams

In the case of the dams, the estimation of the capacity is especially complicated. It has to take into account the most important hydrological processes contributing to the amount of storage in the dams, including precipitation in the catchment and on the storage lakes and losses out of the reservoirs.

Therefore, the areas of the storage lake and of the catchments have to be estimated first. The areas of the dams of class 1 and 2 are estimated to be 600 m² resp. 10,000 m². The estimation of area and catchment area for the classes 1 and 2 is based on estimations of likely dimensions for such dams and of their mean depth and capacities. For the major dams, the dam area is taken out of the ArcView shape (see Table 5.15). Concerning the catchment area, empirical values exist only for the biggest dam, Váreza de Boi (Campos et al., 2003) (see Table 5.16). They are used as one source of information, but slightly changed in order to be congruent with the other assumptions. For the three other major dams, the catchment area is estimated based on a map of the area and in relation to the other dams.

Table 5.15: Estimated areas of the different dams

Class	ID	Name	Estimated area A_{source} (km²)	Estimated catchment area A_{catch} (km²)
1	1	-	0.0006	0.02
2	2	-	0.01	0.3
3	3	Forquilhas	2.5	50
	4	Trici	3.7	80
	5	Favelas	9.4	200
	6	Vareza do Boi	10.9	610

Table 5.16: Characteristic of the dam Váreza de Boi (Campos et al., 2003)

Category	Value
Mean annual precipitation	520 mm
Mean annual inflow	$42.6 \cdot 10^6$ m³
Standard deviation of annual inflows	$66.8 \cdot 10^6$ m³
Mean annual evaporation during dry season	1.438 mm
Drainage area	1220 km²
Reservoirs capacity	$51.8 \cdot 10^6$ m³

In order to check the possibility of the estimations of the areas, the values are summed up for the municipality of Tauá. The estimated areas of the dams result in a total area of 26.6 km². Compared to the area of Tauá of 3940 km², this means that less than 1% of the area is covered by storage lakes. The estimated catchment area of all dams together covers with 945 km² only 24 % of the municipality, which seems low considering the high number of dams in the area. However, without further information it is not possible to achieve a better estimation. It has to be kept in mind that estimating the areas related to the dams is one of the weakest points in the setup of the model.

The first step towards the estimation of the capacity in the actual month is determining the input in this month ($Input_{month}$). However, for the dams the matter is more complicated as for the cisterns, since this input does not depend only on the inflow (I_{month}) and the efficiency of the dam (Eff), but on losses in this month due to evaporation (L_{evap}) and infiltration (L_{inf}) out of the storage as well:

$$Input_{month}\,(l) = (I_{month} - L_{evap} - L_{inf}) \cdot Eff \tag{5.5}$$

In this case, the efficiency is less than one mainly because not all of the water in the dam can be used, but that some of the water left in the dam is of poor quality. Since this rest water is estimated to be 35% of the total storage, the efficiency is 0.65. The inflow each month is based on two components, the inflow produced by rainfall on the storage lake on the one hand and in the catchment on the other hand. However, in the latter case only a certain percentage of the precipitation in the basin is finally stored in the storage lake. This relation is expressed by the term ‘inflow efficiency’ that is not equal to the hydrological runoff coefficient. Contrarily, it is only a coarse estimation for that part of the rainfall in the basin that makes its way all through the catchment and turns into stored water. This inflow efficiency Eff_{inflow} (-) is estimated to be 0.2 in normal times and 0.15 in dry years.

All in all, the inflow term I_{month} is calculated as:

$$I_{month}\ (l) = A_{source} \cdot P_{month} + A_{catch} \cdot P_{month} \cdot Eff_{inflow} \qquad (5.6)$$

where A_{source} (m²) is the area of the storage lake, A_{catch} (m²) the catchment area and P_{month} (l/m²) the precipitation in this month.

Temperature, humidity and global radiation are the only meteorological data available for estimating potential evaporation. This limits the number of applicable equations, since the more complicated equations need too many unknown parameters. Therefore, the comparably simple, but tried and tested equation of Haude (1958, cited after Dyck and Peschke, (1995)) is applied which was used within the WAVES project as well. According to Haude, the potential evaporation ETP_{Haude} (mm/d) is calculated based on the saturation deficit at 2 pm:

$$ETP_{Haude}\ (mm/d) = k \cdot (E - e)_{2pm} \qquad (5.7)$$

where k is an empirical factor (-), the so called Haude factor, E is the saturation vapour pressure at 2 pm (hPa) and e is the actual saturation at 2 pm (hPa). The values for the empirical Haude factor, that have to be determined for each month and each region individually, are given in Table 5.17 (Külls, 2005, personal communication). Different empirical equations exist to estimate the saturation vapour pressure based on the temperature. In this case, the frequently used Magnus-equation is used (Dyck and Peschke, 1995):

$$E_W\ (T)\ (hPa) = 6.11 \cdot 10^{(7.5 \cdot T)/(237.3+T)} \qquad (5.8)$$

where E_W (T) is the saturation vapour pressure above water (hPa) and T is the air temperature (°C). Since vapour pressure and saturation vapour pressure at 2 pm are asked for, the temperature at this time T_{2pm} (°C) has to be estimated first based on the available daily mean temperatures T_{av} (°C) and equation 5.9 (Külls, 2005, personal communication).

$$T_{2pm}\ (°C) = 1.14 \cdot T_{av} + 1.91 \qquad (5.9)$$

Table 5.17: Haude factor (mm/d) for each month

Monat	1	2	3	4	5	6	7	8	9	10	11	12
	0.3	0.3	0.32	0.34	0.38	0.38	0.36	0.34	0.32	0.3	0.3	0.29

Based on this estimation, the loss through evaporation is calculated by:

$$L_{evap}\ (l) = ETP_{Haude} \cdot days \cdot A_{source} \qquad (5.10)$$

where ETP_{Haude} (mm/d) is the monthly average of the estimated daily potential evaporation, days is the length of the month (-) and A_{source} (m²) is the area of the storage lakes. Since the evaporation from a lake is considered, it seems right to assume that the actual evaporation equals the potential evaporation. However, the most likely varying area of the storage lake due to variations in the water level may cause a certain error that cannot be excluded based on the available data. The resulting evaporation values (see Table 5.19) are very close to empirical values. High losses due to evaporation in all the major dams, from 2000 up to 2500 mm/a, are assumed (Hydroisotop, 2002). Calculating this value for the dams and the reference year with normal rainfall reveals an evaporation value of 2155 mm/a.

For the estimation of the infiltration into the soil on the ground of the dam it is necessary to estimate the material of the ground and the associated infiltration rate. The resulting formula for the loss through infiltration L_{inf} (l) is:

$$L_{inf}\,(l) = Inf_d \cdot days \cdot A_{dam} \qquad (5.11)$$

where Inf_d is the daily infiltration (l/m²), days is the length of the month (-) and A_{dam} is the catchment area (m²). In this case, an infiltration rate corresponding to the infiltration of clay loam is chosen, namely $2 \cdot 10^{-8}$ l /(m² · s) or $1.73 \cdot 10^{-3}$ l / (m² · d). Bringing together the different parts of the equation results in the following equation for the newly built input of a month:

$$Input_{month}\,(l) = (A_{dam} \cdot P_{month} + A_{catch} \cdot P_{month} \cdot Eff_{inflow} - ETP_{Haude} \cdot A_{dam} - Inf_d \cdot days \cdot A_{dam}) \cdot Eff \qquad (5.12)$$

The results of these estimations are summarized in Table 5.19. A comparison between the estimated values for the dam Vareza do Boi (dam number 6) and the empirical data for this dam (see Table 5.16) reveals an acceptable degree of congruence. The yearly capacity of the dam is calculated to be $5.1 \cdot 10^7$ m³ per year. Campos et al. (2003) mention a corresponding mean annual value of $4.3 \cdot 10^7$ m³, although it is called inflow and not capacity in their case.

Wells and waterholes

Wells and waterholes are both fed by groundwater. Therefore, the estimation of the monthly built input $Input_{month}$ is based on the estimation of the subsurface catchment of the sources A_{catch} (m²) and of the groundwater recharge r_{gw} (-) in the area.

$$Input_{month}\,(l) = A_{catch} \cdot P_{month} \cdot r_{gw} \qquad (5.13)$$

where P_{month} the precipitation in this month (l/m²). The calculation of the groundwater recharge relies on empirical data. According to Hydroisotop (2002), the direct recharge in years with an average precipitation is about 25 mm/a. This result is obtained if 3.27% of the monthly rainfall recharges the groundwater, thus the coefficient is 0.0327. In dry years, the groundwater recharge is estimated to be only 1 mm/a. The resulting coefficient is 0.0013. Surely, it is possible to withdraw more than the recharged water out of a well, if it is used in a non-sustainable way. However, taking into account the crystalline geology, the amount of water to be withdrawn is limited. Moreover, it is a complicated matter to model the effect of falling water levels and assuming an unlimited capacity for the wells and waterholes would favour them unrealistically at the expense of the other sources. Therefore, the yearly built amount of groundwater recharge is implemented as the maximum capacity of the wells and the waterholes.

Table 5.18 and Table 5.19 summarize the capacities that are obtained by these estimations. It includes the starting capacities, as used in the model and the numbers of persons that can be provided by this source.

Table 5.18: Estimated yearly water supply by cistern, waterhole and well

	Cistern	**Waterhole**	**Well**
$Input_{year}$ (m³) = maximum capacity C_{max} (m³)	15	62.5	625.0
$Input_{day}$ (l)	-	171.2	1712.3
Input in dry years (m³)	15	2.5	25
Starting capacity C_{start} (m³)	3.75	15.6	156.5
Yearly inflow normal years $I_{y,n}$ (m³)	32.5	-	-
Yearly inflow dry years $I_{y,d}$ (m³)	18.2	-	-
Minimum number of persons supplied[a] (-)	0.6	1.1	11.4
Maximum number of persons supplied[b] (-)	1.8	3.4	34.2

a) Assuming a high daily water use (150 l/(capita · d) and 18.25 m³/(capita · a)) and the rainfall of a normal year
b) Assuming a low daily water use (50 l/(capita · d) and 54.75 m³/(capita · a)) and the rainfall of a normal year

Table 5.19: Estimated yearly water supply by dams

Class	**1**	**2**	**3**			
ID	1	2	3	4	5	6
Yearly total input (m³)	$3.5 \cdot 10^6$	$5.4 \cdot 10^7$	$9.5 \cdot 10^9$	$1.5 \cdot 10^{10}$	$3.8 \cdot 10^{10}$	$1.0 \cdot 10^{11}$
Loss by infiltration (m³)	$1.3 \cdot 10^6$	$2.2 \cdot 10^7$	$5.3 \cdot 10^9$	$7.9 \cdot 10^9$	$2.0 \cdot 10^{10}$	$2.3 \cdot 10^{10}$
Loss by evaporation (m³)	$3.8 \cdot 10^2$	$6.3 \cdot 10^3$	$1.6 \cdot 10^6$	$2.3 \cdot 10^6$	$6.0 \cdot 10^6$	$6.9 \cdot 10^6$
Yearly capacity C_{year} (m³)	$1.44 \cdot 10^3$	$2.08 \cdot 10^4$	$2.73 \cdot 10^6$	$4.65 \cdot 10^6$	$1.13 \cdot 10^7$	$5.08 \cdot 10^7$
Starting capacity C_{start} (m³)	$7.22 \cdot 10^2$	$1.04 \cdot 10^4$	$1.36 \cdot 10^6$	$2.32 \cdot 10^6$	$5.67 \cdot 10^6$	$2.54 \cdot 10^7$
Min.number of persons supplied[a] (-)	260	380	50,000	85,000	210,000	930,000
Max.number of persons supplied[b] (-)	790	1,100	150,000	250,000	620,000	2,800,000

a) Assuming a high daily water use (150 l/(capita · d) and 18.25 m³/(capita · a)) and the rainfall of a normal year
b) Assuming a low daily water use (50 l/(capita · d) and 54.75 m³/(capita · a)) and the rainfall of a normal year

Costs of the water

Data about the costs for water out of the different water sources is taken from research work done within the WAVES project (de Araújo et al., 2003). The costs are separated into investment costs and costs for operation and maintenance of the source. It is important to clarify which of the costs the consumers have to bear, because only these costs are meant to influence their decisions. The waterholes and the dams are assumed to be financed completely by the users, i.e. they have to pay both kinds of costs. The same is assumed for the cisterns, however, it is thought to be an interesting scenario to evaluate how the situation changes, if the users have to account for the operation and maintenance costs of the cisterns only. For the dam, it is assumed that the investment costs are public, not private costs. In Table 5.20, the costs that are chosen for the modelling are printed in bold type.

Table 5.20: Costs for investment, maintenance and operation of the water sources (de Araújo et al., 2003)

Source	**Estimated investment costs (US$/m³)**	**Estimated operation & maintenance costs (US$/m³)**	**Estimated total costs (US$/m³)**
Cistern	0.567 *	0.029	**0.596**
Dam	0.064	**0.004**	0.068
Waterhole	0.005 **	0.004	**0.009**
Well	0.046	0.027	**0.073**

* Assumption: 20-year lifetime, three fillings each year, yearly interest rate of 6%
** Own estimation

5.4.3 Agents

Water use agents

The behaviour of the water user agents is based on their three attributes monthly income, household size and location within the system. The location of the agents in conjunction with the spatial distribution of the water sources determines which sources are available for an agent and how far he has to travel to reach it. For the monthly income, no empirical data exists in the questionnaire. A monthly income is therefore allocated randomly to all agents, based on a normal distribution with the average income in Ceará of 215 US$ as mean value. As lower boundary, a value of 90 US$ is assumed being the governmental defined minimum income. Since the economic values indicate severe poverty, it is not likely that the modelled families have considerable savings at their disposal. Therefore, in each month an income value is assigned to each agent, without a start credit or the possibility to make savings. The household size is known for the 'empirical' agents. The corresponding data for the other agents is created randomly, assuming a normal distribution with an average household size of 5.4 and a standard deviation of 2.2, as in the empirical data. After creating the agents, 'empirical' and 'randomised' agents are not treated differently.

The first step in the behaviour of the agents is choosing which of the existing sources they consider to use. In the current version of the model, this is implemented simply by determining for each agent the specimen of each of the four categories of water sources closest to the place where the agent lives. The assumption is that in reality each water user considers all different kinds of sources because of their specific advantages and disadvantages. He knows the specimens that are closest to his place and considers solely these.

In a second step, each agent ranks the four closest water sources according to his preferences. Since this is one of the most complicated parts of the model, it is described in more detail further below in this chapter. Naturally, each agent tries first to get water out of his preferred source. Now, as a third step, it is tested if the credit of the agent is sufficient to pay for the water out of this source. Therefore, the water demand of the agent's household has to be calculated by multiplying the size of the household with the assumed water use per person. Thereby, it is differentiated between the demand for drinking water and water for domestic use. The demand for drinking water, called basic water demand as well, is assumed to be 5 litres per day and capita and to be critical for the surviving of the person. Only if it is satisfied, the agent tries to get more water for domestic purpose. Thereby, the demand is subject to flexibility, as described later on. The water demand of the household is multiplied with the costs of the preferred source and compared to the credit of the agent. If the credit is sufficient, the water demand is compared to the capacity of the source. If this is sufficient as well, the agent takes all the demanded water out of this source. Otherwise, if the credit is high enough, but the capacity of the source is not, the agent takes the rest of the water from the source. After that, he tries the other sources one after another until he manages to find one that provides the rest of its water demand. If the credit is not sufficient, the agent tries the next source and finally all the sources until he finds one that is cheap enough so he can afford it.

If the agent gets all the water he demands, he will not undertake any action until the next time step starts. If he happens not to have enough credit to pay for his water demands or not to find a suitable source at all, he will stay without water for now. It is assumed that in such a case the neighbours support each other, although this kind of interaction is not explicitly implemented in the model. However, the state of the agent is monitored by the government. In the case that more than one third of the water users do not get any water at all, the government supplies 20 l per capita and day to all the agents free of charge via the water trucks. Such a water truck delivers in drought times in average 20 L per capita and day at an average cost of 6.65 US$/m³ (de Araújo et al., 2003). Compared to the other sources of water with costs of clearly less than 1 US$/m³, this kind of water supply is extraordinarily expensive. Since the government has to pay for this water, this source is only used if no other option is left. In the model, the water trucks are consequently not implemented as a regular source of water, but as a mean of emergency supply. The costs for the government by this water supply are added up and are an indicator for the quality of the water supply system, since of course it is the aim of the government to keep its costs as low as possible. A system in which this kind of supply is not necessary, not even in times of exceptional drought, would be desirable for both, government and water users. Although the water users get the water of the water trucks free of charge, it should not be their favourite source of supply since they depend on the government, only get a low share of water and often have to travel far to reach the distribution points.

Decision model

As mentioned before, the decision of the water users for certain water sources is meant to be influenced by the quality of the water in the source, the distance to the source, the costs of the water and the part of capacity that is already consumed. To implement such a decision making process, the values of the different water sources in these categories have to be defined or estimated first. Afterwards, these values are subject to a rating in order to obtain comparable values and calculate the index of preference. In this rating, values from 1 to 4 are assigned to all three factors, whereby a higher rating value indicates a higher preference of the agent for this water source (Table 5.21). For example, the cheapest water source is rated in the cost rating with the value 4, the most expensive one with 1. In the current implementation of the model, the index value expressing the attitude of an agent towards a water source is obtained by multiplying the rating values of Distance D, Costs C, Water quality W and Remaining capacity RC (see equation 5.14). Since each of these rating values is in the range of 1 to 4, the index I ranges from 1 to 64. The highest index value calculated for an agent indicates its preferred source.

$$I = D \cdot C \cdot W \cdot RC \ [-] \tag{5.14}$$

Table 5.21: Rating for the three influential factors on decision about water source

	Parameter				
Rating	**Distance D (-)**	**Costs C (US$/m³)**		**Water quality W TDS (mg/l)**	**Remaining Capacity RC (%)**
4	0	Waterhole	0.009	< 500	75 – 100
3	0 - 1	Dam	0.004	-	50 – 75
2	1 - 5	Well	0.073	500 < x <1500	25-50
1	> 5	Cistern	0.596	-	0-25

The distance between an agent and a water source is calculated in the grid. It is not trivial to transform these values into distances in reality. It can be assumed that transferring the ESRI ArcView grid into the multi-agent model causes no distortion. Therefore, the distance calculated between two neighbouring points in the Repast grid should equal the distance between the mid points of the corresponding raster cells in the ArcView grid, corresponding to 950 m in reality. Comparing the resulting distances to data from the questionnaire, the impression was that the calculated distances are rather high, but there was not enough data for a reliable conclusion.

A reason may be that the water user mention only distances to sources they really use and that may be the closest ones only. Moreover, one has to keep in mind that this distance is calculated between the mid points of the raster cells, but the objects (water sources or agents) may be located somewhere in this cell. For a grid size of 950 x 950 m², the error has theoretically a maximum of $\sqrt{2} \cdot 950$ m, that is about 1350 m. However, for the rating this error is less important, since the error is not systematic, but the same for all the sources. The range of the distance for the rating categories is indicated in Table 5.21.

For the ranking of water quality, the estimation corresponds already with a rating system, assigning a value of 4 to water of good quality and the value 2, if the quality is acceptable (value 2). The ranking of the costs is achieved by simply placing the water sources into an order according to their empirical costs for 1 m³ of water. The source with the lowest costs per cubic meter, i.e. the dam, achieves the highest value (see Table 5.21). The remaining capacity RC is based on the relation between the current capacity of a source and its maximum capacity. If the actual capacity makes up a high percentage of the maximum capacity, the source has a higher preference than otherwise.

Flexibilty

The water demand of the agent depends on the actual state of the water resources, thereby realizing some sort of feedback mechanism between agents and resources. This is implemented by calculating the daily water demand per person based on the remaining capacity RC (%), as described in the previous section, and the equation given below (Figure 5.10). This equation is based on the assumption that the water demand is not unlimited, but has a maximum level, the maximum demand D_{max} (l). With a D_{max} of 150 l, the maximum total consumption per person is assumed to be 155 l per day, taking into account the basic water demand of 5 l per day. The other determining parameters in the equation are the flexbility of the demand F_{dem} (l) expressing the range in which the water demand may vary and the inertness i(-), expressing the degree of variation in the flexibility:

$$D_{Per} = D_{max} - (F_{dem} \cdot \exp(- i \cdot RC)) \qquad (5.15)$$

For the inertness, a value of four is assumed, for the flexibility 145 l. Among the possible implementations, this flexibility is chosen because it corresponds to some basic assumptions about the water demand, e.g. the existence of a maximum demand. Another assumption is that the demand varies slowly for capacities of 50 to 100% and rather high variations for lower capacities, going back to zero, if there is no capacity left.

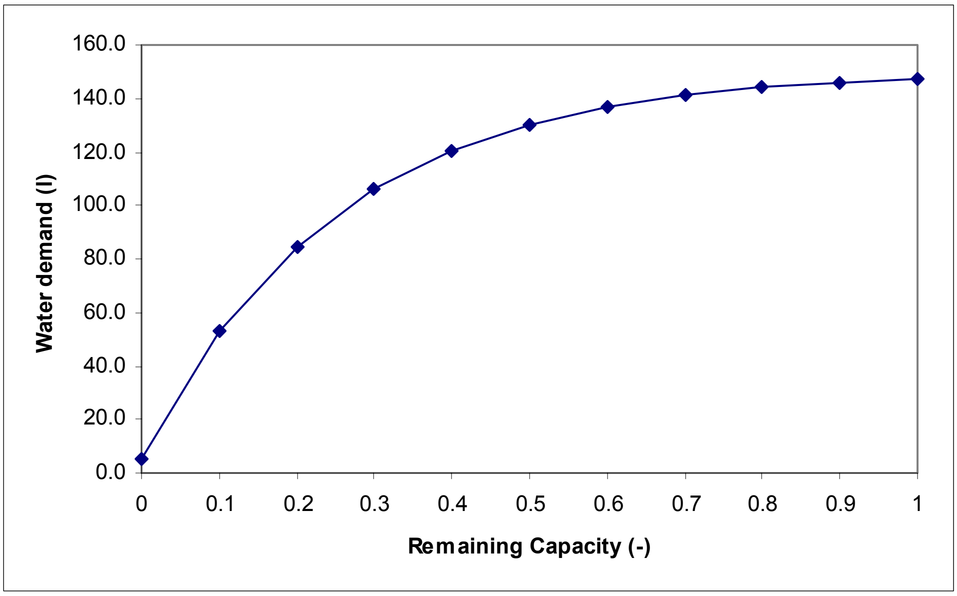

Figure 5.10: Graph of the flexibility

City agent

The water user agents and the city agent compete for water to satisfy their daily water demand. The city uses as water sources the four major dams that are accessible to the water use agents as well and the 20 urban wells whose use is limited to the city agent. Corresponding to the approach for the water users, it is differentiated between water demand for drinking purposes and domestic use. It is assumed that the city satisfies its basic demand out of the urban wells, whereby about 49000 m³ are taken out of the well, assuming a demand of 5 l per capita and day. In addition, the city agent tries to satisfy its water demand for domestic use out of the dams. As for the water user agents, this demand is meant to be flexible depending on the remaining capacity of the water source, as described in the previous section. In times when the dams do not deliver sufficient water for even the minimum demand for domestic use of 20 l per capita and person, the rest of the water is taken out of the wells. Contrarily to the rural wells, the capacity of the urban wells is not limited to the yearly capacity. Since the urban wells are deeper, they are meant to tolerate high variations in withdrawals quantities better. However, the capacity of the wells is monitored in order to control whether the use of well water is unrealistically high. A conceptual problem is distributing the demand between the different wells and dams. Because the wells are not differentiated, the water demand is distributed equally between the individual wells. For the dams, the situation is another, since they have different capacities. Distributing the demand equally would mean that the capacity of the greater dams is not used sufficiently. However, it is likewise unrealistic to assume that the total capacity of the dams is used at once. Therefore, out of each dam cell 90% of the capacity is used in one time step, whereby the actual percentage value is easy to change. The demand that is left is distributed between the remaining dam cells. Regarding the competition between city and water users for the resources, the city is implemented in every time step before the agents consume their water, i.e. the city always wins.

Government agent

The functionality of the government agent is described already in the context of the water use procedure of the water use agents. Its only activity is to decide whether the water trucks are needed to deliver the water to the agents and to monitor how much cost this programme causes.
With the time step of a month the problem arises to realize a realistic representation in this rather low resolution. In the version chosen, the government checks at the end of a time step if a supply by water trucks is necessary. If so, the agents get water for each day in this month, so to say belated. An alternative approach would be to provide water in the next time step, if there is a shortage in the previous step. However, when there is a drought situation, a month is thought to be too long for the people to be without drinking water and this version is moreover easier to realize since the usual activities of the agents are not affected.

5.4.4 Organisation of the model

The organisation and execution of the model is based on functionality provided by the Repast software. More precisely, Repast offers a general main class (SimModelImpl.java) that is extended by the main class of the Tauá-Model (WaterUseModel.java). This means that some methods have to be defined within the class WaterUseModel that are necessary for organizing and executing the model, e.g. a 'setup'-method, a 'buildModel'-method and a 'step'-method. In the building-method, the necessary elements of the model are implemented. For example the data is read in (e.g. agents and water sources) or the relevant objects are initialised (e.g. the government and the grids for storing the data). The main purpose of the setup-method is to reset all the parameters of the model to its original state. It is called between two runs of the model in order to prepare the model for the next run. Additionally, the class WaterUseModel is responsible for displaying all the information in the way the modeller wants it to be. The buildDisplay-method is responsible for all the actions concerning display of information, i.e.

mainly creating and specifying displays, background maps and graphs. One of the most important parts of the model is the step-method, since it specifies all the actions that are undertaken at each time step. In the case of this model, it goes through the whole list of agents and calculates the water use of the agents, their preferred sources and finally which sources they actually use. However, it is important to schedule these actions of the model together with the other activities such as updating displays and graphs. This is done in the buildSchedule-method. Finally, the begin-method is called when the run of the model is started in order to call these different methods in the right order. Besides, the WaterUseModel.java contains some methods that concern the content of the model, but not the organization of it, e.g. the calcWaterSupply-method monitoring how many of the users do not have sufficient water supply. The source code of the model is available from the CD-ROM that comes with this thesis and the software used is described in Table A 3 in the annex.

5.4.5 Resulting structure

To summarize the structure of the model, Table 5.22 gives an overview on some of its features and attributes, following the structure of (Weiss, 1999) (see also Table 3.1).

Table 5.22: Description of important features and attributes of the realized multi-agent system

	attribute	**implementation**
agents	number	4700 water user agents; 1 city agent; 1 government agent
	uniformity	3 types of agents; water users slightly heterogeneous (income, household size, infrastructure)
	goals	homogeneous (maximise water quality and quantity)
	architecture	reactive, but goal-driven
	abilities (sensor, effectors, cognition)	rather simple
interactions	frequency	rather low
	persistence	short-term
	level	indirect
	variability	fixed
	purpose	competitive
environment	predictability	unforeseeable (precipitation, resources)
	accessibility and knowability	limited to the water sources in the neighbourhood (agents without knowledge about system)
	dynamics	comparably fixed (dynamic of rainfall, but resources not nested)
	diversity	medium (low number of different sources, but high number of specimen)
	availability of resources	restricted

5.5 Results

5.5.1 Number and length of runs

Before running the model, it has to be determined how many years are to be simulated in one run and how many runs are needed for modelling one scenario. Generally it is expected that the variation within and between different runs will be comparably low. The only random parameters are the income of the agents and the spatial distribution of most of the agents, cisterns and waterholes. However, it is not expected that these random distributions will influence the outcome of the model substantially, considering the high number of agents, cisterns and waterholes. To prove this assumption, the variance in multiple runs of the model is analysed.

Table 5.23 shows the results for important output variables in ten different runs of the model. As expected, the differences are low, especially compared to the uncertainties of the model. For example, a standard deviation of 0.5 for an average annual consumption of about 22 m³ per person indicates a rather stable output of the model. Since it is the aim of the model to capture the dynamics of the system, such small deviations from the mean value are not important. Consequently, for the exploratory application within this research work, single runs are considered sufficient. This decision might not be reasonable for an application of the model with a different focus.

Table 5.23: Variation in the output of the model in ten runs

	Total costs for water trucks (US$)	Average water consumption (m³/(capita · a))	Users without sources (%)	Consumers using one source (%)	Consumers using two sources (%)	Consumers using three sources (%)
Mean	757089	21.7	52.7	32.8	12.4	2.1
Std.dev.	3819	0.5	0.9	0.6	0.6	0.2
Min.	751768	21.2	51.0	31.9	11.2	1.9
Max.	763999	22.6	53.9	33.8	13.2	2.5
Range	12231	1.4	2.9	1.9	2.0	0.6

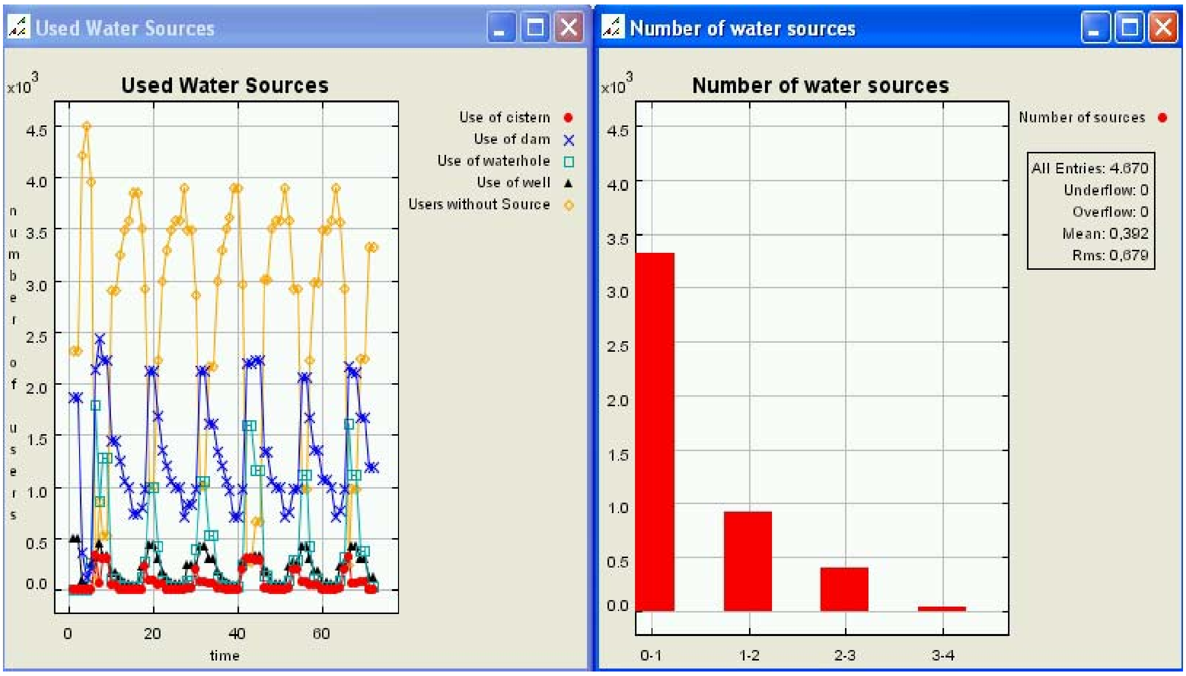

Figure 5.11: Model output for a simulated period of six years: number of users for the different sources and change in time (left) and number of water sources used per agent in a time step (right, last time step)

Concerning the duration of the simulation, it is not considered reasonable to model several consecutive years. Since the variation in the precipitation in the area is very high, several years with the same precipitation are unlikely. However, because of the high uncertainties involved in estimating the starting capacities, it was decided to model 24 months and to interpret only the second year. Nevertheless, the basic version of the model was run for a longer period at first in order to check the plausibility of the assumption. As Figure 5.11 shows, the behaviour of the model is similar for all years except for the first one. The pattern of used sources is similar for the years 2 to 6 and the distribution of numbers per user at the end of the sixth year is very similar to the pattern at the end of the second year (see Figure 5.13).

5.5.2 Result of the basic version of the model

First of all, the model is run with the standard parameter as described above (see also Table 5.31). Figure 5.12 and Figure 5.13 illustrate the output and the user interface of the model at the end of the second year.

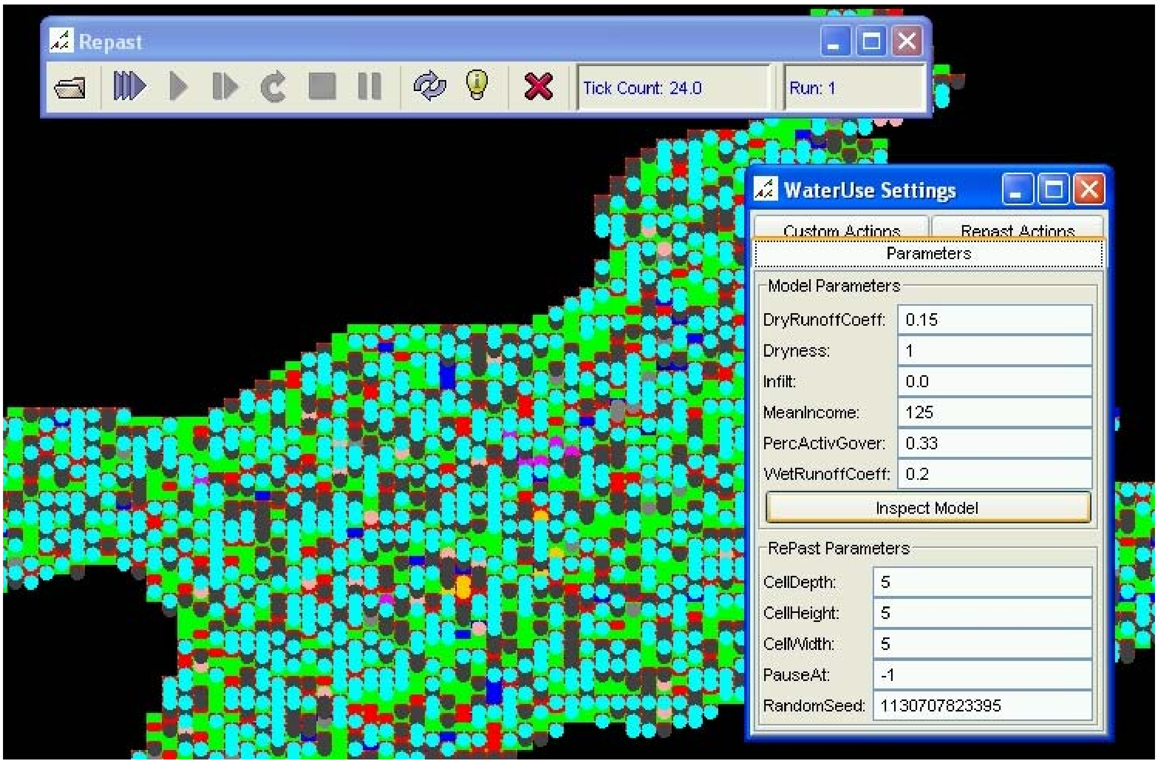

Figure 5.12: Background map and Graphical User Interfaces

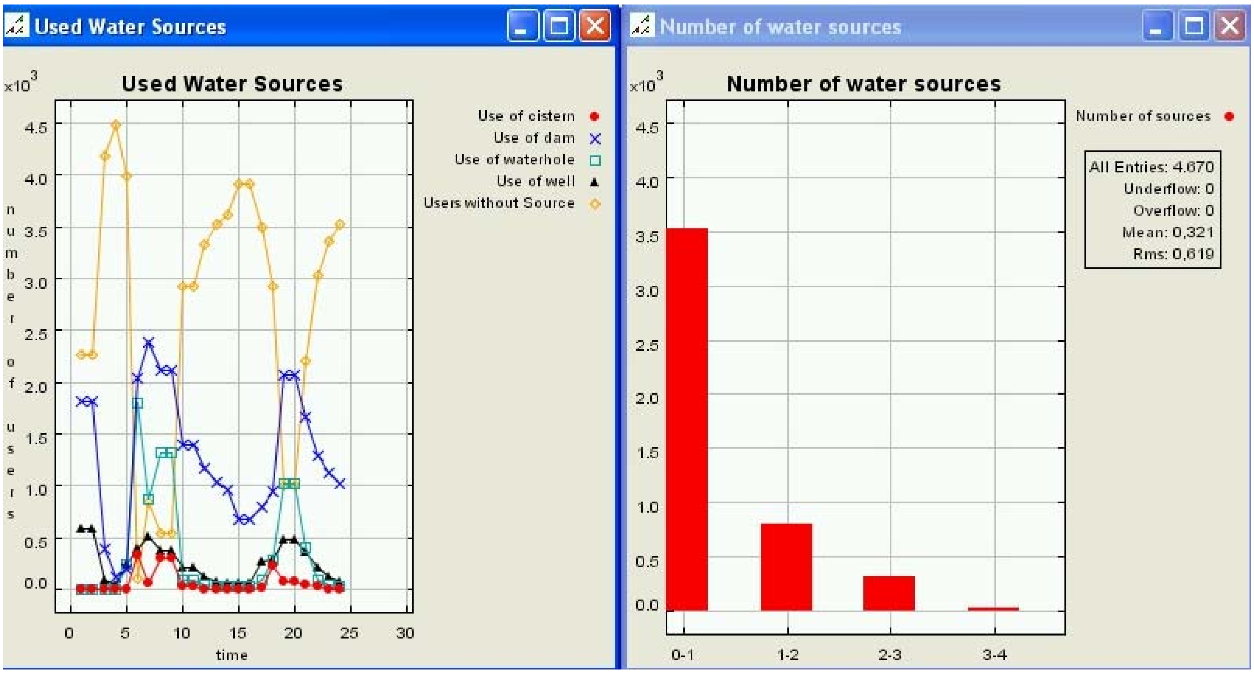

Figure 5.13: Original output of the model at the end of the second year

The first interesting question is whether any trends can be identified in the percentage of agents using a certain source, e.g. a seasonal trend (Figure 5.14). Apparently, the highest number of water users does not use any source at all. However, towards the middle of the year the number of users without sources decreases, whereas the uses for all the other sources increase. Almost all the time the dams are the favoured source, but waterholes are also rather frequently used from April to August. Cisterns and wells are less favoured sources, and almost not used at all throughout the year.

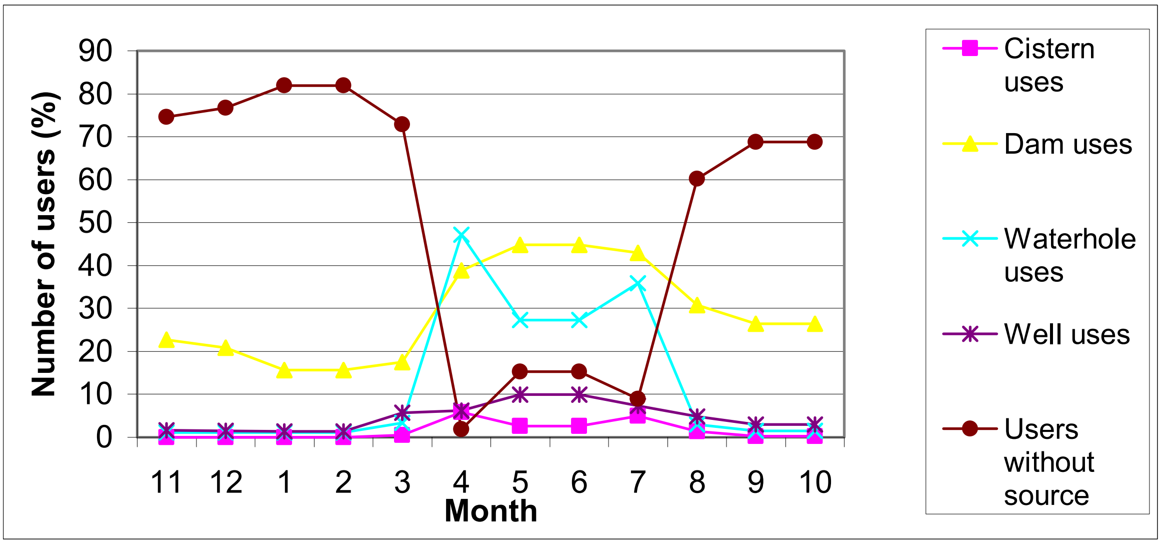

Figure 5.14: Percentage of all agents using the different sources

To understand the dynamics of the system better, Figure 5.15 illustrates the variation in some key characteristics of the system (see also Table 5.24). It shows that the average consumption per capita and day as well as the number of sources used show almost exactly the same pattern. The pattern resembles the precipitation regime to some degree, with two months delay and a lower peak, whereas the trend in the number of persons without any water source is contrary to consumption and number of sources.

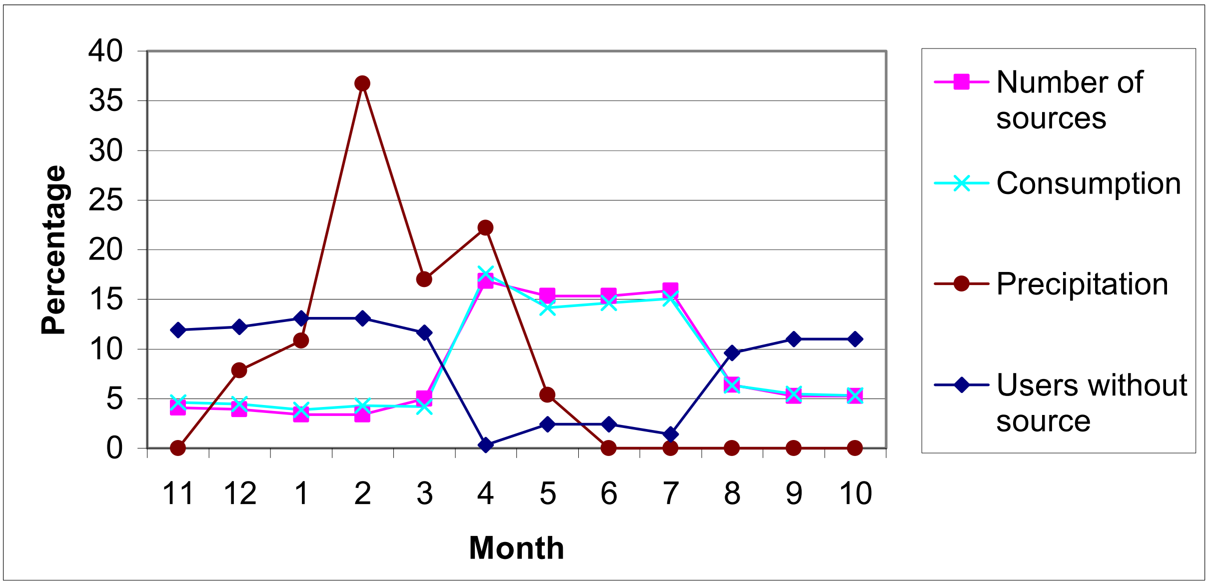

Figure 5.15: Monthly variation of important characteristics of the system (all values given as percentage of their annual value)

On the average, the agents consume 60 l of water per capita and day out of averagely 0.6 sources (Table 5.25), whereby the water trucks do not count as water source and their water supply is not included into the calculation of the daily consumption. The water trucks supply the local population in eight of the 12 months and the government has to pay about 750,000 US$ in the year in total, i.e. 62700 US$ on average per month (Table 5.24 and 5.25). The water consumption in the city is higher, averagely 136 l per day and capita.

Table 5.24: Annual sum for the consumed water and the costs for water trucks

Rural consumption (10^3 m³/a)	Cistern	10
	Dam	338
	Waterhole	118
	Well	45
	Total	**511**
Urban consumption (10^3 m³ /a)	Dams	1276
	Wells	49
	Total	**1325**
Cost water trucks (US$)	Total costs	752000

Table 5.25: Monthly values for the output variables of the model

Month	Precipitation (mm)	Average number of sources	Total Cost (US$)	Consumption per day (l)	Urban consumption per day (l)
11	0	0.3	93250	34	128
12	60	0.3	96359	31	125
1	83	0.2	96359	24	122
2	281	0.2	96359	27	135
3	130	0.4	87034	30	113
4	170	1.2	0	125	141
5	41	1.2	0	105	144
6	0	1.2	0	108	149
7	0	1.2	0	109	142
8	0	0.5	96359	50	146
9	0	0.4	93250	41	146
10	0	0.4	93250	40	141
Mean	**-**	**0.6**	**62685**	**60**	**136**
Std.dev.	**-**	**0.4**	**46367**	**39.0**	**11.5**

Water balance

From a hydrological point of view, it is important to ensure that the results of the model are not contradictory to the water balance. Table 5.26 provides an overview on the water balance based on the assumptions of (Hydroisotop, 2002). The values are to be compared with the capacities that are built in the modelled sources in a year with normal rainfall (Table 5.18 and Table 5.19). About 70 million m³ of water are available to the users in the sources represented in the model in a normal year, i.e. 2.4% of the input through precipitation in the area (3 billion m³). At the same time, the maximum demand of the modelled agents is 2.8 million m³ in one year (Table 5.27). All in all, it seems that resources and demand on the one hand and capacities of the modelled water sources and natural resources on the other hand are in a reasonable relation to each other. Furthermore, the capacity of the dams seems reasonable compared to the total runoff; so does the capacity of wells and waterholes compared to the total groundwater recharge and the capacity of the cisterns to the precipitation input. However, the water balance does not equal the amount of water available for human consumption, since it does not consider the water quality. Especially the annual groundwater recharge is not completely of sufficient water quality.

The comparison between the consumption in the modelled year and the maximum capacities of the sources reveals a high variation between the different sources (Table 5.28). Only about 2.5% of the water resources in all dams are used, but about 50% of the resources in waterholes and rural wells. In total, only about 3 % of the available water is consumed. For the urban wells, no maximum capacity is assumed.

Table 5.26: Water balance of Tauá (for an area of 3940 km²) (Hydroisotop, 2002)

	(mm/a)	**(10^6 m³/a)**
Annual total precipitation	741	2920
Annual total groundwater recharge	1	4
Real evaporation	595	2344
Runoff	145	571

Table 5.27: Maximum annual capacities and demand in the model

		(10^3 m³/a)	**Assumptions**
Max. annual capacity	Cistern (max. capacity)	48.5	Number: 1541 Yearly input per cistern: 31.5 m³
	Dams	$6.95 \cdot 10^4$	Sum of yearly input of all dams
	Waterholes	263	Number: 4203 Yearly input per waterhole: 62.5 m³
	Rural wells	87.5	Number: 140 Yearly input per well: 625 m³
	Urban wells	500	Number: 20 Yearly input per well: 2500 m³
	Total	**$7.04 \cdot 10^4$**	
Max. Demand		$2.84 \cdot 10^3$	Number: 51937 $demand_{max}$: 150 l/(capita · day)

Table 5.28: Comparison between consumption in the model and maximum capacity

	Consumption (m³)	**Max. yearly capacity (m³)**	**Percentage of capacity used (%)**
Cistern	$1.03 \cdot 10^4$	$4.85 \cdot 10^4$	21.2
Dam (total)	$1.61 \cdot 10^6$	$6.95 \cdot 10^7$	2.3
Waterholes	$1.18 \cdot 10^5$	$2.63 \cdot 10^5$	44.9
Rural wells	$4.48 \cdot 10^4$	$8.75 \cdot 10^4$	51.2
Urban wells	$4.86\ 10^4$	-	-
Total	**$2.27 \cdot 10^6$**	**$7.04 \cdot 10^7$**	**3.2**

Comparison with empirical data

Moreover, the output of the model can partly be compared with the empirical data. First, the number of users for each source in model and reality is compared (Table 5.29). For all sources, the number of users in the model is far smaller than in reality, except for the water trucks not mentioned by interviewees. The second comparison addresses the number of sources for each water user (
Table **5.30**). Corresponding to the number of users per source, the number of sources per user is in the model far below the value in reality. The average number of sources per person is 2.2 in the survey data (standard deviation 0.88) and 0.6 in the output of the model (standard deviation: 043).

Table 5.29: Number of users for the different water sources

	Model output (%)	**Survey data (%)**
Cistern	1	33
Dam	29	75
Water hole	9	90
Well	5	17
Water truck (no sources)	55	0

Table 5.30: Number of users with a certain number of sources used

	Number of users (%)	
Number of used water sources	**Model output**	**Survey data (general use)**
0	52	1
1	34	21
2	12	42
3	2	31
4	0	6

5.5.3 Scenarios

The variation of the model parameters can be used for exploring the behaviour of the system under certain conditions.

Parameters

Two groups of parameters can be identified whose variation may influence the output of the model; the parameters of the physical environment on the one hand and the parameters related to the agents' behaviour and the water consumption on the other hand (Table 5.31).

The effect of the parameters in the first category is mainly to increase or decrease the amount of water available to the water users. They either determine the input into the water resources, such as the Inflow Efficiency and the Recharge coefficient or the loss from the sources, e.g. the evaporation from the storage lakes or the assumed efficiency of dams and cisterns. In contrast, the second category of parameters is demand oriented, i.e. changes in the parameter influence the water demand of the agents.

Table 5.31: Parameters in the model that might be varied for creating scenarios (highlighted: variables set as parameters in the model)

Category	Attribute	Parameters	Standard value
Parameters related to natural resources	Precipitation	Input file	see Table 5.13
	Inflow	Dam: Inflow Efficiency	normal years: 0.2 dry years: 0.15
		Recharge	normal years: 0.0013 dry years: 0.0327
		Efficiency (cistern/dam/waterhole/well)	0.85 / 0.65 / 1.0 / 1.0
	Losses	Dam: Infiltration Dam: Evaporation (Haude)	0.0017 see Table 5.17
	Price of the water (US$/m³)	costCubic (cistern/dam/waterhole/well)	0.596/0.004/0.009/0.073
	Size of the storage	Max. capacity	see Table 5. 18
Parameters related to water consumption	Flexibility of water use	luxury (D_{max})	150
		inertness (i)	4
		flexibility (F_{dem})	145
	Basic water demand	basicDemanPerson	5
	Income	meanIncome (US$) lowestIncome (US$)	215 41.6
	Threshold for governmental action	agents without water	33 %

To test the behaviour of the model, it is useful to vary these parameters and analyse the effects of the variations on the results. Repast provides the possibility to specify parameter files that allow for the systematic variation of one or more parameters. Furthermore, Repast provides the option to vary single variables through its Graphical User Interface (GUI). However, to keep the GUI clear, not all variables that could be varied within scenarios are implemented as parameters. Instead, these variables can be changed within the source code of the model.

Climatic scenario

Considering that the study area is regularly affected by droughts, the obvious thing to do is to investigate the behaviour of the system in dry years. Two changes in the model are necessary for this scenario. First, the input data has to be changed in order to import the precipitation data of the dry year. Second, the wetness indicator has to be adapted, so that the values for dry years are used for some of the parameters, e.g. for groundwater recharge and inflow efficiency.

Table 5.32 compares the most important output variables for the basic model and for the climatic scenario. As expected, the consumption of water out of the rural resources is obviously lower in dry years than in years with average precipitation and the water trucks are used in all months of the dry years. Surprisingly, the water consumption in the city per person and day is substantially higher than in the reference year. However, this is meant to be an error in the model code. If the dams are not providing sufficient water, the citizens in the city attempt to get more water out of the wells. The capacity of the wells is not limited in this case, but apparently the demand neither. The average consumption is in consequence higher than the generally assumed maximum daily demand of 150 l. However, the urban wells are not available for the rural population and the groundwater consumption in the wells does not exceed the yearly groundwater recharge in the area, so the error does assumingly not affect the modelling of the rural water consumption noticeably.

Table 5.32: Output variables for the basic model and the two realized scenarios

		Basic model	**Climatic scenario**	**Economical scenario**
Input	Annual rainfall (mm)	765	428	765
	Mean income (US$)	215	215	45
	Lowest income (US$)	90	90	15
Consum (10^3 m³)	Cistern	10.3	4.2	9.75
	Dam (rural)	$3.38 \cdot 10^5$	57.2	331
	Waterhole	118	0.002	119
	Well (rural)	44.8	1.09	43.6
	Total rural	511	62.5	504
	Dam (urban)	$1.28 \cdot 10^3$	672	$1.28 \cdot 10^3$
	Wells(urban)	48.6	1.5	48.6
	City total	$1.32 \cdot 10^3$	$2.13 \cdot 10^3$	$1.32 \cdot 10^3$
	Total	$\mathbf{1.84 \cdot 10^3}$	$\mathbf{2.20 \cdot 10^3}$	$\mathbf{1.83 \cdot 10^3}$
Water trucks	Total costs (US$)	752	$1.15 \cdot 10^3$	$7.58 \cdot 10^5$
	Number of month with water trucks	8	12	8
Average consumption per day (without water trucks)(l)	Rural	60	7.8	59
	Urban	136	220	136
Number of sources	Yearly average	0.6	0.1	0.6

Figure 5.16 demonstrates that the dynamic of the system is generally reduced by the very high number of water users without any source. A small peak in the number of users of cisterns and dams occurs around July. The same peak appears for the number of sources used and the daily consumption (Figure 5.17). Again, the peak appears with some delay after the highest precipitation in April and after the rainy season, but is very steep and short in this scenario.

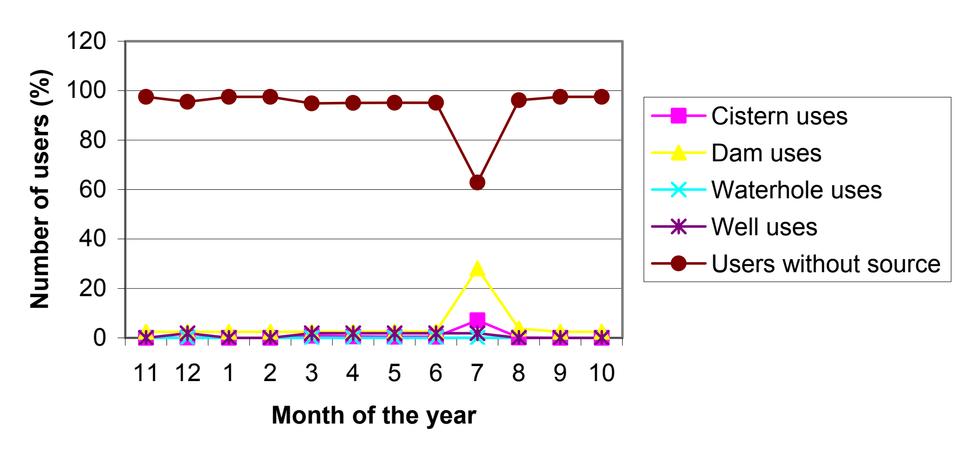

Figure 5.16: Percentage of users for the different water sources

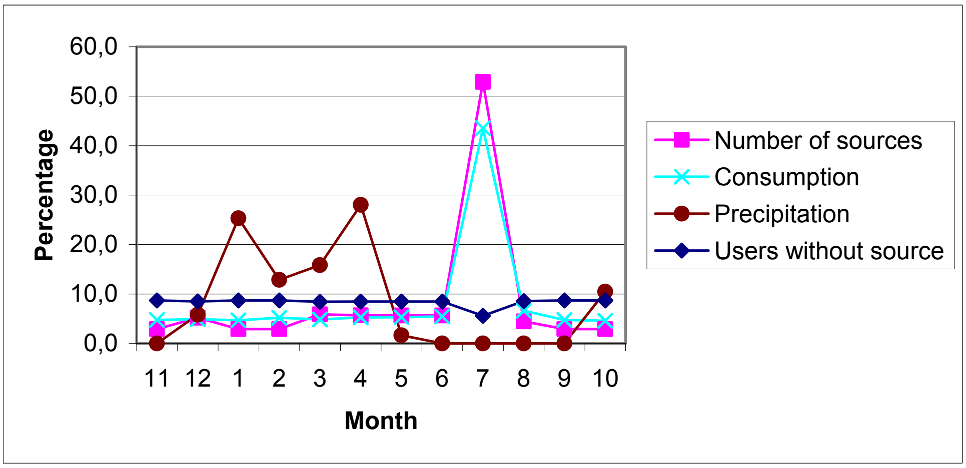

Figure 5.17: Monthly variation of important characteristics of the system (all values given as percentage of their annual value)

The question is whether this is an error in the model or appears systematically. For this purpose, a graphical representation of a model run of six years is given in Figure 5.18, despite the discussion above. Interestingly, such peaks occur regularly, but not every year. In the other years, two very small peaks appear instead. Compared to the basic model, the behaviour in the long term is less stable in this scenario.

The only empirical data available for this scenario is related to the number of users per source (Figure 5.16) and the corresponding comparison is given in Table 5.33. The difference between empirical data and model output is high, due to the exceptionally high number of persons without source of water in the model. An explicit comparison with the water balance is not necessary, since the basic version showed no conflict between water consumption and water balance and the water consumption is even lower in this scenario.

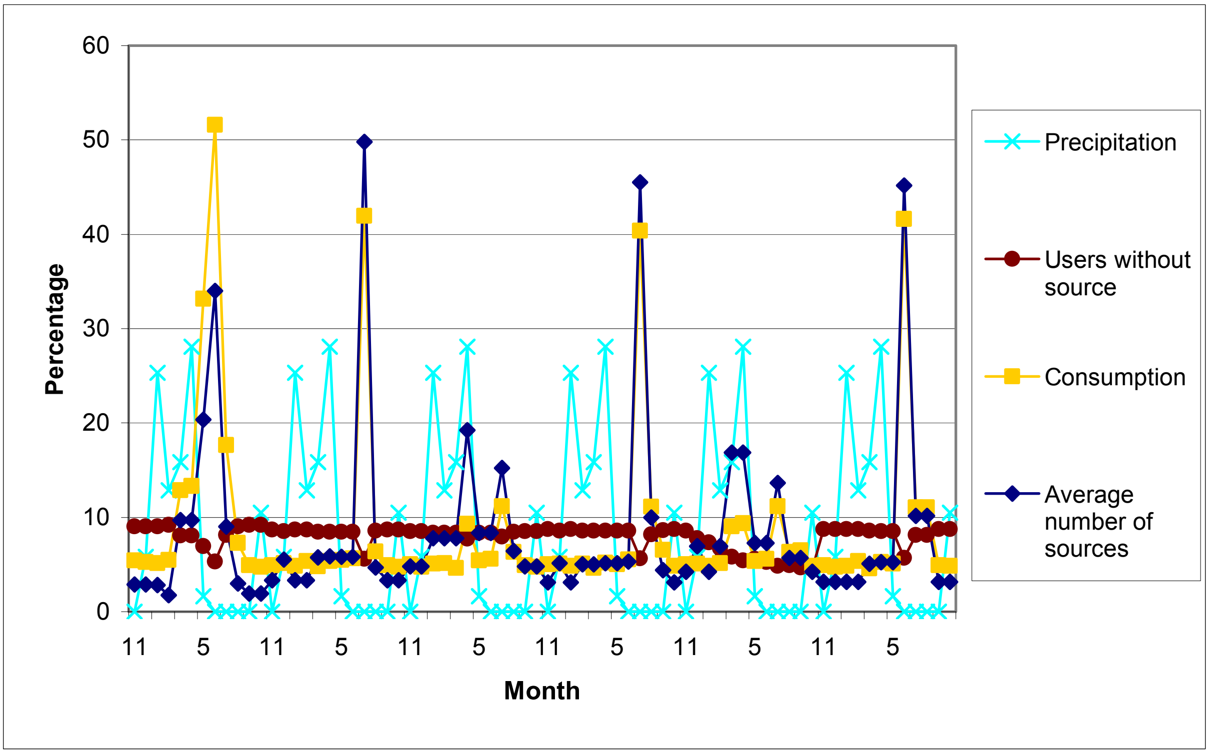

Figure 5.18: Monthly variation in important characteristics in the system in a run of six years

Table 5.33: Empirical data for the water sources used in droughts

	Number of users (%)		
	Model output	**During droughts**	
Water sources	-	Drinking Water	Domestic Use
dam	4.7	20.8	25.0
well	0.9	2.8	5.6
cistern	0.8	9.7	1.4
water hole		19.4	25.0
water holes in rivers	0.0	6.9	9.7
Water truck	-	22.2	13.9
No source	93.5	8.3	11.1

Economic scenario

The income distribution in the basic version of the model is conservatively based on the average income in Ceará, 215US$, as well as on the assumption that the citizens earn at least the governmentally fixed minimum income of 90 US$. However, this may apply to the citizens in the cities and to officially employed workers, but not to the poor rural population. Instead, it is assumed that 85% of the population live in total poverty, i.e. earns less than 50% of minimum income (de Oliveira et al., 2003).

A scenario is realized that reduces the average income to 45US$ and the minimum income to 15 US$. In this case, 50% of the population earn not more than half of the minimum income. Apparently, the model output is not different from the output of the basic version. The graph indicating the yearly distribution of number of users per source for the scenario (Figure 5.19) seems to be identical to the corresponding illustration for the basic scenario (Figure 5.14). Moreover, all the model outputs of the scenario are very close to the output of the basic version of the model.

However, a statistical analysis is necessary to see whether this assumption is true. For this purpose, the r^2 value, the square of the correlation coefficient, is calculated for the most significant output variables. The squared correlation describes the relation of variance in common between two variables. The r^2 values are very high, between 0.993 and 1.0, and Table 5.34 shows some of these values. The variables of the two simulations, the scenario and the basic model, share consequently at least 99.3% of their variation. It can thus be assumed that there is no significant difference between them. Further analyses of the scenario, e.g. considering the water balance or comparison with empirical data, are not necessary.

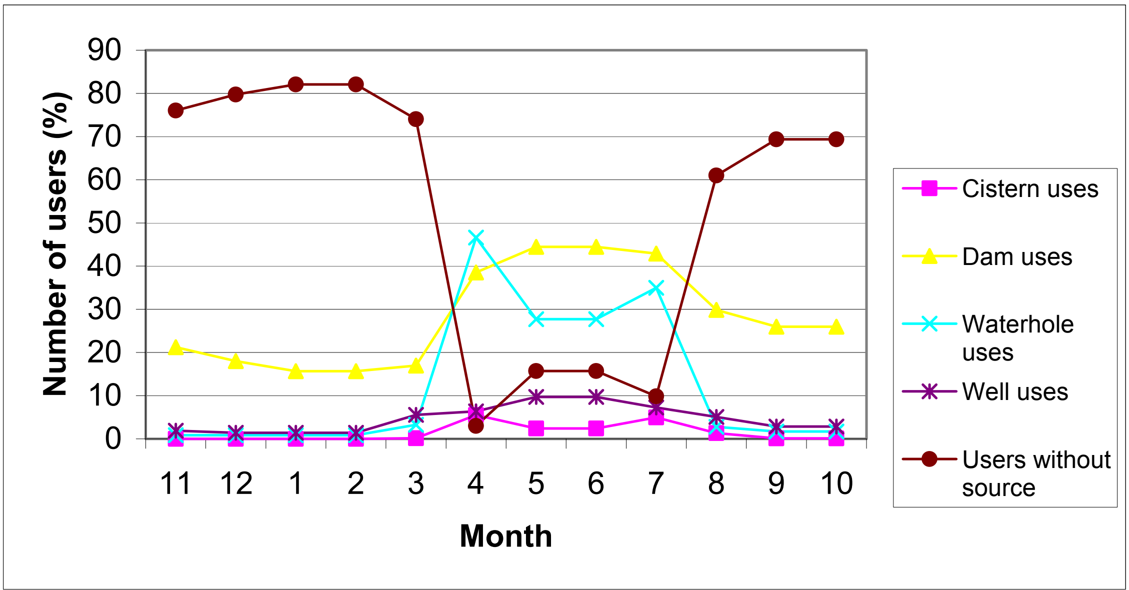

Figure 5.19: Percentage of water users for the different water sources

Table 5.34: r^2 values for the selected output variables of the model

CisternUses	DamUses	Waterhole	Well	NoUser	totalCost	averageConsum
0.9962	0.9954	0.9995	0.9975	0.9994	1.0	1.0

Possible scenarios

Beside these implemented scenarios, other scenarios are possible, mainly by changing the parameters related either to water consumption or to natural resources. Of course, the behaviour or the quantities of the resources can be modified, e.g. the assumptions concerning the maximum capacity of the resources or all the parameters that increase the capacities in the water sources.

Concerning the agents, weighting the factors in the decision model, e.g. putting more weight on the influence of the distance, could help to explore which of the four factors determining the decisions of the agents is the most influential one. Furthermore, the water demand of the agents could be altered, exploring for example how the system behaves if some of the agents take very high amounts of water out of the system. In this way, the reaction of the system to industrial or agricultural water consumers could be explored. In addition, it may be interesting to see how the knowledge of the actual state of the water resources, i.e. the remaining percentage of the maximum capacity, influences the decisions and the consumption. In the actual implementation, the users are informed about the remaining water capacity of all the water sources except for the wells. In another scenario, the remaining capacities of all the water sources could be unknown; in still another scenario, a monitoring system for the wells could be established that results in knowledge about the state of the wells, too. A comparison between these three states could provide information on how such a monitoring would affect water consumption behaviour.

Other economic scenarios are possible, for instance changing the prices for the water. In the basic version of the model, the user have to pay the investment costs for the cisterns, which makes the water from the cisterns comparably expensive. Possibly their behaviour towards cisterns would change if the government or non-governmental organisations paid these investment costs.

5.6 Discussion

5.6.1 Discussion of the results

Basic version

Apparently, the water users do not get sufficient water in the basic model. The comparison with the empirical data shows that the number of water sources per persons is far too low. Moreover, the number of agents without any water sources is unrealistically high. Although it is known that the water in the area is scarce and that water trucks are necessary during the dry months and in droughts, it cannot be expected that they are in use for eight months in normal years.

One possible explanation is that the water resources represented are not sufficient. It is one of the ideas of the study that the resources implemented are not arbitrary, but correspond to the real situation. However, because empirical information is limited, this attempt requires a high number of assumptions. Erroneous assumptions could cause an unrealistic low provision of water. However, the comparison between the maximum capacity in the resources and the actual consumed amount of water indicates that there are far more resources in the system than the water consumers use. Especially the resources in the dams are hardly exploited. Consequently, it is more likely that an artefact in the model code or a wrong assumption in the model causes the low water consumption.

Moreover, the distribution of sources is not concurrent to the empirical data, especially cisterns and waterholes are not as frequently used in the model as they are in reality, according to the interviewees. Assumptions in the decision model are possibly responsible for this, by disadvantaging some of the water sources and producing wrong preference patterns for the agents. Clearly, the decision making process of the agents is one of the critical parts of the models; very important for the outcome of the model, but difficult to realize. For a further development of the model, the improvement of the decision model is one of the most important aspects.

Despite of these shortcomings of the model, its dynamic behaviour is promising. Apparently, the system reacts to the precipitation input. The preferences for the water sources are not always the same but depend on the time of the year. The number of sources used per water user and the average consumption per day correspond to each other, and show thereby the same trend as in the empirical data: The water users try all possible sources in order to get as much water as possible. However, the number of sources decreases in the drier times of the year, when their options are limited because not all the sources are usable all the time.

Climatic scenario

The analysis of the climatic scenario is of course hindered by the fact that the water supply is so unexpectedly low in normal years. Nevertheless, the water supply situation is clearly worse in dry years. This result is obvious in all relevant output variables, i.e. the decreased number of sources per user and amount of water consumed, the low consumption per capita and day and the more frequent use of water trucks.

However, there is one aspect in the dynamic of the system that cannot be explained. The generally very low consumption increases suddenly some time after the end of the rainy season without an obvious reason and for about two months only. Furthermore, this pattern is repeated every two years in a simulation of six years, whereas in the other years two very small peaks appear. But still the rainfall pattern is the same every year. Instead of such an unexpected rhythmic behaviour, a steady decrease in the consumption would have been more likely, since a drought period of six years should decrease the resources constantly. Nevertheless, it remains to clarify whether this effect is an artefact or an emergent behaviour.

Economic scenario

Apparently, economic factors do not determine the water consumption of the agents in the current version of the model. Although the decrease in the mean income from 215 to 45 US$ is substantial, the model output is not influenced at all. The water price surely affects the preferences for certain sources, but does not limit the actual consumption. A reason for this may be that the water users do not have to spend money for anything else than for water in the current version of the model. It may be more realistic to implement a more sophisticated economic model that considers other costs of the families as well.

5.6.2 Discussion of the model

Because the model is programmed object-oriented, it can be extended and modified easily. Changing the parameters, e.g. the capacities of the water sources or the intentions of the agents, enables the creation of scenarios, e.g. of future water problems related to the global change. Moreover, the model can be modified and refined. Like every model, the model contains some simplifications and assumptions, e.g. the exclusion of the hygienic conditions that may be changed in further versions of the model. Other possible extensions include the additional sources of water, e.g. rivers or public water supply, or an improved decision model.

Numerous extensions of the model that are possible but not yet implemented are summarized in Table 5.9. To address possible shortcomings of the model and potential improvements as well as further developments, the different aspects of the model are analyzed in the following section.

The behaviour of the agents is not very sophisticated yet and should be developed towards goal-directed behaviour. One possibility is to introduce a variable that expresses the satisfaction of the agent. The goal of its behaviour would then be to maximise this satisfaction value. In the current version, the goal of the agent is to get its daily needs of water, but such a satisfaction value could include other aspects as well, for example the effort necessary to get the water and the frustration about unreliable sources or negative consequences of the water use, such as diseases.

The agents are structured in a much too homogeneous matter, since it is reasonable to assume that intra-individual differences between real water are high. Differences between the agents could concern their intentions and their character, e.g. environmental awareness or the willingness to accept longer distances to get cleaner water. As discussed above, such an approach could be realized by weighting the aspects of the water sources differently.

Another urgent issue is the implementation of a better economic model. The actual distribution of income in the region may not be very realistic yet and the influence of the economic variables on the behaviour of the agents is only implemented in a rudimentary way. In the current version, water is only a public good used for satisfying the domestic use. Farming activities and industrial use are not included. This simplification is comparably realistic in Tauá where industry and agriculture are not important, except for animal husbandry. However, it limits the possibility to transfer the model to other rural areas and possibly the dynamic of the model as well. The dynamic of a water supply system may be greater if water is a mean for creating added value, i.e. if the agents earn money by using water, e.g. for irrigation purposes. Another interesting idea would be to extend the flexibility of the water demand to economic factors, i.e. the water demand per person depends not only on the remaining capacity of the water source, but also on the financial situation of the household.

The interaction of the agents in the model is implemented only indirect as use of the same source. This definitely oversimplifies the system. Important interactions include the influence of the neighbourhood on the actions of the agent, e.g. imitation, and cooperation of agents for exploiting new water resources, e.g. drilling of wells.

From a hydrological point of view, the current version of the model is not satisfactory yet. The uncertainties in the input data are high and the hydrological representation of the physical environment is still rather poor. Compared to other models, it is advantageous that the modelling of the water resources is not only based on empirical data, but also on hydrological assumptions about the processes involved. The disadvantage is that these assumptions do not consider detailed processes, e.g. the generation of runoff. The calculation of the storage in the dams for example represents inflow, evaporation and infiltration, as expected in regards to hydrology. However, the inflow is not implemented as runoff generation, since the necessary data is not available, but as rough estimation of the percentage of precipitation that reaches the storage lake. Therefore, an improved representation of the hydrological system, including the river network, elevation and catchment areas in conjunction with a more detailed consideration of hydrological processes is desirable.

However, it depends mainly on the research question which of the shortcomings of the model are most relevant and in which directions the model consequently has to be extended. A possible research question could address the best water supply system for a new settlement in an uninhabited area. Since the model represents single water users with basic decisions, it should be suitable for this purpose after some modifications, e.g. the inclusion of procedures for creating water sources, e.g. the drilling of wells.

Uncertainties in the model are related to the quality of the available data as well as to the process of simplification and the high number of assumptions consequently necessary. Maybe the most complicated task in setting up the model was to simplify the system for integrating it into the structure of the model and for finding suitable algorithms. Undoubtedly, simplifying the real system without ignoring important structures and interrelations is one of most difficult tasks in each attempt to model reality. However, it is even harder for a hydrologist to set up a model that includes the modelling of humans as well. Thereby it was tried not to introduce unnecessary assumptions in the model that are not justified either conceptually or empirically. If there was an uncertainty about one factor, e.g. about the statistical distribution of the income, the simplest solution was chosen, e.g. a normal distribution. This standard is introduced on the one hand of course to design a plausible model, but on the other hand owed to the philosophy of multi-agent modelling to base the model on the most essential rules. In order to live up to this standard when implementing human agents, it may be necessary to co-operate with social scientists for developing a more sophisticated version of the social aspects of the model.

A considerable part of the uncertainty is also related to the questionnaire that is unfortunately almost the only source of data. Although it is principally a seldom advantage to have such data, the questionnaire does not fulfil all expectations. Firstly, it lacks proper documentation is missing. Secondly, the structure of the questions is not uniform and can thus be criticized, e.g. some questions ask for domestic use only, whereas in another question animals and domestic use are summarized into one category. The main disadvantage is that the survey is probably too long and complicated for the interviewees, leading to a high number of missing values and possibly a certain percentage of incorrect answers. All these points limit the reliability of the data the model is based on.

In addition, the survey does not provide sufficient data to validate the model. Comparison between model and survey data has been used only for some sort of authentication of the model output. The result is that the water users in the model do not use the water sources sufficiently. Validation is one of the major shortcomings of the model, but it cannot be achieved due to a lack of data, time and suitable methodology, as discussed above.

It is seen as one of the advantages of the model that the modelling of the natural resources is based as much as possible on empirical data. At the same time however, this attempt creates one of the greatest problems in the model. Since not all the required data was available, some variables have to be implemented randomly, e.g. the income of all the agents or the location of most of the agents. Due to these random elements, the model cannot be expected to deliver a representation close to reality. Nevertheless, because of the large number of agents, the effect of the randomization is meant to lower than it would be for a smaller number of agents.

Regarding the software chosen, Cormas could perhaps have been an interesting alternative, since it is specialized on modelling of natural resources issues. Some of the functions that had to be programmed in the Repast software may also exist in the Cormas software. Predefined entities are for example a valuable tool as well as aggregating of cells to entities. However, less specialized software has the advantage that is easier to extend into different directions and that the greater user community leads to a faster and more ambitious development of the software. Moreover, since Repast is implemented in the common programming language Java and has a clear structure, it is easier for other modellers to work with an existing model.

Despite of all these criticisms, the model has innovative aspects and benefits as well. The literature review revealed many examples for multi-agent models concerning water resources. However, they all differ in some aspects from the model in this study. First, most of them address not purely water resources issues, but include other topics, such as farming or urbanization. Moreover, none of them addresses the simplest form of water supply system, namely water users with the choice for different sources. However, the task to represent the complexity inherent in such a simple water supply structure is ambitious enough, especially with a methodology with which the hydrological research community is not yet experienced. The extension of a tried and tested multi-agent model for modelling more complex issues is not a problem, due to the modular architecture of a model.

Another advantage does not concern the output of the model, but the modelling process itself.
The search for the most relevant processes related to water consumption caused an intensive reflection on the characteristics of water supply systems. One aspect emerged in the modelling process that had not been considered a priori, namely the question whether the consumers are aware of the state of their water resources, i.e. the percentage of the available water that they have already used. In the implemented monitoring process, the remaining capacities influence not only the preferences of the water users, but the amount of water they get out of a certain source as well, due to the flexibility of water demand. In this way, a sort of feedback mechanism is implemented between the actual and the future water. However, the influence of monitoring

on the preference for a certain source and the flexibility of water demand in this context seem to be interesting fields for further research that could benefit from multi-agent methodology.

Not only water resources research, but also hydrology may benefit from such an approach. Such a basic representation of water users may provide a framework to realize the connection between hydrological and socio-economic modelling. A representation of the water cycle in populated areas naturally has to include anthropogenic water consumption as well. As discussed before, most models emphasize only one of the aspects and more sophisticated agents are often the main focus of attention in multi-agent modelling. Although sophisticated agents are certainly necessary, simple agents may provide better means for a joint representation of hydrology and human behaviour at the moment. If a coupling of simple agents with a reliable representation of hydrological processes and water resources or with a hydrological model is successful, both agents and hydrological representation could be further developed in parallel.

5.7 Conclusions

Clearly, the greatest problem in the model is the insufficient supply for a high percentage of water users in normal years. If the tendency of a system towards one direction, in this case towards insufficient supply, is so high, it is harder to explore changes of behaviour, since changing into the preferred direction is almost impossible. In drought times, decreasing the water input into a system with an already low supply situation leads to a system that shows almost no dynamics. It seems reasonable to improve this aspect of the model before further, more complicated scenarios are modelled. However, analysing the system by changing the parameter values systematically is considered useful in order to find the reason for the low consumption of water in the system: especially all the parameters related to the decision-making of the agents and the amount of water resources need to be looked at. Even though this is a time-consuming procedure, it may be the best way to for improve and understand the model. Moreover, the agent-based model is still relatively simple in its current version. As discussed, important aspects are missing and some of the assumptions the model is based on are rather uncertain.

Nevertheless, the model shows some interesting features that are worth mentioning and that offer potential for further development. In contrast to other applications in water resources issues, the aim of this model is to represent a basic water supply infrastructure and to model the most basic agents, the water users. The dynamics of the output in the model are promising for this purpose. Despite of the problems mentioned above, the behaviour of the water users is reactive to the dynamic of the natural resources mainly based on the precipitation. It has been demonstrated that the water user prefer different water sources under different conditions and that they do not always succeed in reaching their goals to satisfy their basic water demand. The flexibility of water demand and the reactivity of the agents to the water level of the water resources are innovative features in multi-agent models of water resources. An additional quality of the model is the representation of the water resources based on their empirical distribution and hydrological assumptions, e.g. the water balance, even though this aspect has to be improved further.

Consequently, the merit of the model in its current version is possibly not to provide a sophisticated modelling tool, but a first step towards a new approach of representing water infrastructure that uses multi-agent modelling as a tool for crossing the border between hydrology, water resources research and socio-economic topics.

6 General Discussion

Discussing multi-agent modelling as a method and of its suitability for hydrology and water resources research is complicated by the lack of standards and the diversity in the research community. The term ‘multi-agent systems’ originates from the field of Distributed Artificial Intelligence and nowadays summarizes completely different approaches, fields of research and purposes of application. However, compared to applications in Artificial Intelligence and software engineering, the application of multi-agent modelling in the context of physical processes and natural resources is rather novel and experimental.

More applications are realized in water resources research than in hydrology. Still it seems that there are more possible kinds of applications in hydrology than the few currently applied. Hydrological processes could be either represented based on water particles as simple agents or by agents representing features of the water cycle, e.g. rivers or soil layers. Since almost no realisations exist for such approaches, it is difficult to evaluate what their specific problems are. Applications in water resources research seem to reach at a point where they could surely benefit from a standardization of methods and a systematic approach to the current limitations, e.g. the issue of validation.

General limitations of the methodology apply to both hydrology and water resources research. The most important ones are the lack of proper validation methods, problems with the appropriate representation of time and the distinction between emergence and artefacts. Moreover, some limitations are specific for modelling in hydrology and water resources research, mainly the inappropriate representation of the environment and the lack of integration of GIS methodology in most cases. Nevertheless, numerous advantages of the approach can be identified as well. Complex behaviour can be handled by reducing the system to its basic rules. Complexity emerges through entities that behave according to these rules and interact. If applied in the right way, the methodology is very flexible and has the capacity to integrate other methodologies, e.g. hydrological models or even GIS technology. Due to this flexibility and the discussed diversity of multi-agent system, it may be wrong to see them as a specific methodology. Instead, it may be more appropriate to consider them as a framework that follows a specific idea towards modelling. This idea has very different realizations and works well in combination with other approaches.

The modelled case study aims at studying a basic water supply system without public water supply, as it exits mainly in developing countries. Different kinds of water sources with their characteristics are represented as well as water user agents with their decisions for certain sources. Although the resulting model is comparably simple, it nevertheless captures some of the relevant dynamics of the system, e.g. the seasonal change in the preferences of the water users for the sources. Moreover, it addresses a water supply system in a new way in multi-agent modelling and introduces new issues into the research area, such as flexibility of water demand.

In spite of some limitations in the current version, the model opens possibilities for further applications, e.g. for developing a basic water supply structure in uninhabited areas or for exploring how an existing structure can be improved or extended. In the long term, similar models may for example provide support for international watershed management, where the different behaviour of water users with different cultural backgrounds could be modelled, e.g. in the Middle East or in Asia.

7 Conclusions

Despite all theoretical and practical problems and remaining uncertainties in the relatively young academic field of multi-agent modelling, the methodology seems to have a high potential. However, it is mainly the diversity of the approach that allows for such a general statement. Multi-agent modelling is not a narrow methodology that is limited to one application for which it may be suitable or not. Instead, it is a broader framework that offers different solutions for different contexts. Some researchers even argue that it may be a standard methodology one day, possibly as the successor of object oriented programming. "Perhaps as printed journals, with their static equations and figures, give way to electronic, hypertext journals and dynamic, downloadable model simulations, there will come a day when we will all wonder how we ever got along without agents " (Axtell, 2000, p. 18). If one does not want to be as prophetical it is at least reasonable to assume, according to the level of research discussed above, that "agent-based modelling can be understood as a field that has made significant progress and stands on the threshold of demonstrating its importance beyond the narrow confines of aficionados" (Bankes, 2002, p. 7200).

Consequently, the question may not be whether multi-agent modelling is suitable in the context of hydrology and water resources research or not. Instead, the question may be which of the possible approaches is most suitable. Water resources research benefits mainly from the natural ontology of agents for representing humans with their goals, attitudes and interactions, in this case all kinds of humans consuming water. Such an approach is chosen in the model of the water supply system in Tauá. In hydrology, applications may rely on simpler, but numerous agents, whereby the research is still in a very basic, experimental state. Moreover, the methodology is flexible enough to allow for different kinds of combinations, for example the coupling of multi-agent models with hydrological model. Partly, the methodology has to be modified or improved to meet the requirements of hydrology and water resources research better. However, a more detailed discussion of the possibilities and limitations of these different kinds of applications is beyond the scope of this thesis. Primarily, more practical applications are necessary for exploring the potential of the methodology intensely.

Models as the one developed in the practical part of this thesis provide doubtlessly a starting point for developing models that include humans into the modelling of the water cycle. Possible areas of application for such models and the resulting scenarios are numerous and various, especially in developing countries, where the problems are often equally caused by scarce resources and inappropriate human behaviour. In such cases, models applied as tools for decision support and consulting should ideally include both processes.

It is not possible at the moment to predict if the optimistic expectations for the future of multi-agent modelling are realistic or not. Nevertheless, it is definitely worth to watch the future development of the promising technology closely. Speaking of the challenges of the future related to assuring or initiating water supply for the world population, multi-agent modelling is of course not a solution for all problems. It can be a useful tool in research and practice that may help to integrate the modelling of natural resources and human behaviour. However, in order to cope with the challenges ahead, more is needed than just new modelling approaches, for example interdisciplinary workgroups, stakeholder involvement and political efforts.

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Glossary

Agent: autonomous entity with an agenda of its own. Each agent possesses the ability to act autonomously; a simple act of obedience to a command does not qualify an entity as an agent. An agent may interact or negotiate with its environment and/or with other agents and may make decisions.

Agricultural droughts: physiologically relevant deficiency in the water supply of plants.

Artificial Intelligence: intelligence exhibited by an artificial (non-natural, manufactured) entity. Such a system is generally assumed to be a computer. Although AI has a strong science fiction connotation; it forms a vital branch of computer science, dealing with intelligent behaviour, learning and adaptation in machines.

Bottom-up: individual parts of the system are specified in detail. The parts are then linked together to form larger components, which are in turn linked until a complete system is formed.

Cellular automata (CA): Uniform grid with cells representing individuals or collective entities. A uniform set of rules represent the 'laws' of the world and compute each cell's state from its own previous state and those of its close neighbours in time steps representing the advance of time.

Complexity: Systems are complex when they are composed of different entities with non-linear interactions.

Decision support system: software system that provides an overview on the data and the system in complex contexts and helps thereby the users to make decision. Possible purposes are summarizing, visualisation or scenario analysis.

Geographic Information System (GIS): software system that works as a tool for storage, visualisation, data processing and analysis of spatial distributed data.

Grid: a system of two sets of lines that intersect each other at a fixed angle, usually a right angle (i.e., a set of vertical lines and a set of horizontal lines).

Hydrological drought: a deficiency of available surface water or groundwater.

JAVA: commonly used programming language, object oriented and platform independent

Multi-agent system: System that combines various agents interacting which each other. They are situated in some sort of environment they react to or interact with. Different types of multi-agents are applied in various academic disciplines.

Monte Carlo Simulation: a class of computational algorithms for simulating the behaviour of various physical and mathematical systems; stochastic, usually by using random numbers.

Portable Grey Map (PGM): image file format that is relatively simple and quite common for image processing. The image data can appear in two different formats, either as ASCII data, which is just a list of values for each pixel or binary. Additionally to the image data, a .pgm-files consist of a header specifying if it is ASCII or binary data, the width and the height and the maximum value used in the image (for an 8bit image, this is set to 255).

Python: Python is an interpreted programming language, created in 1990. It is fully dynamically typed and uses automatic memory management. Python is developed as an open source project.

Stakeholder: all the parts of society, i.e. groups, institutions or companies with special interest in the discussed process.

Scenario: Modelling effort concerning future events. The purpose is not to provide an exact prediction of the future, as this is not possible, but a consistent view on possible future events.

TDS: Total dissolved solids; sum or all inorganic and organic particulate material. TDS is a measure of the mineral content of water.

Top down: in a top-down model, an overview of the system is formulated, without going into detail for any part of it. Each part of the system is then refined by designing it in more detail.

Tragedy of the commons: analogy used to illustrate the conflict for resources between individual interests and the common good. The term was coined by Garrett Hardin in 1968.

UML (Unified Modelling Language): programming language that is commonly used for the graphical representation and realisation of complex software projects.

Validation: process of determining that the behaviour of the model represents the real system to satisfactory levels of confidence and accuracy, which are determined by the intended application of the model and its application domain.

Verification: process of determining that a computational computer program that implements a model accurately represents the modeller's conceptual description and specification.

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Annex

Table A 1: Overview of the applications discussed in chapter 3.5.1 and 3.5.2

Context	Area of research	Content of study	Author(s) (Year)	Comment
Physical processes	Modelling water flows	- model based on waterball agents	Servat (2002)	- bottom-up - scale effects
Water resources research	Urban water management	- Attempt to model natural resources management at the urban edge - Land and water dynamics, urbanization - Case study Sao Paolo, Brazil	Ducrot, R., Le Page, C., Bommel, C. and Kuper, M. (2004)	- farmer and urban owners as agents - decisions on use of the plots - explicit representation of urban processes
	Free access resources	SINUSE (Simulator of the water table and user interaction) - negotiate water demand management of a water table - case study: water table in Central Tunisia	Feuillette, S., Bousquet, F. and Le Goulven, P. (2003)	- farmers only as agents - interactions between farmers - based on field study, but realized with random distribution of entities - used only as research and experimental tool so far
	Participatory modelling, Urban water management	- Participatory modelling in conjunction with agent-based approaches - case study: Zurich, Switzerland	Hare, M., Medungo, D. Heeb, J. and Pahl-Wostl, C. (2002)	- aimed at developing new demand-oriented water management strategies - model-building-as-learning-process - part of the FIRMA project
	Participatory modelling, Urban water management	- The FIRMABAR Simulator - Urban Water Management with Artificial Societies of Agents	López-Paredes, A. Saurí, D. and Galán, J. (2005)	- families of agents - demand of families vs. delivery by water supply infrastructure - applied to cities in Spain - part of the FIRMA project
	Participatory modelling	- participative water management support - case study: French Drôme River basin	Abrami, G., Barreteau, O. and Cernesson, F. (2002)	- Agent-Group-Role approach - applies role playing games
	Role playing games	JogoMan: A Prototype Using Multi-Agent-Based Simulation and Role-Playing Games in Water-Management	Adamati, D.F., Sichman, J.S. and Rabak, C. (2005)	- land and water management in cities with high pressure of urbanization - social laboratory - CORMAS software
	RPG, agriculture	SHADOC: a multi-agent model to tackle viability of irrigated systems	Barreteau, O. and Bousquet, F. (2000)	- teaching and training tool - simulates farming decisions

	Integrated Watershed management	- Co-operative Ecosystem Management - sustainable and agreed strategy - Fraser River in British Columbia, Canada	Doran, J. (2001)	- conflicting stakeholder interests - exploring possible intervention strategies -highly abstract concept - heterogeneous agents grouped in a hierarchy
		- CATCHSCAPE model - impact of upstream water management on downstream farming systems - catchment in northern Thailand	Becu, N., Perez, P., Walker, A., Barreteau, O. and Le Page, C. (2003)	- simulates a whole catchment and farmer's individual decisions likewise - spatial distributed, including farmer's decisions - Cormas platform
	Lake management	- dynamics of a lake subject to phosphorus pollution - agents define input pollution	Carpenter, S.R., Brock, W. and Hanson, P. (1999)	- level of input pollution depends on agents' expectations about system dynamics of the system, markets and actions of other agent - agents adapt to changes
		- MIMOSE: agent based model of hydrological and limnological processes - represent potential polluters and local administration directly - case study: Lake Anderson	Möhring, M. and Troitzsch, K. G. (2001)	- based on a conventional computer model - farmer agents - a local government that applies different policies against the eutrophication of the lake.
	Decision support	- Agent-based decision support framework for water supply infrastructure rehabilitation and development	Davis, D.N. (2000)	- output: a ranking of the relative need of investments in different sectors
	Water resources and agriculture	- innovation diffusion for agricultural technologies - innovation as an alternative to migration	Berger, T. (2004)	- decision making in rural households in developing countries - different types of agents, based on their adoption behaviour (early vs. late adopters) - investigation on the connection between innovation and migration
	Economy	DAWN (distributed agents for water simulation) - influence-diffusion mechanism among water consumers - application to metropolitan area of Thessaloniki, Greece	Athnansiadis, I.N., Vartalas, P. and Mitkas, P.A. (2004)	- effects of a public conservation campaign on residential water demand influence-diffusion mechanisms - a community of interacting, autonomous, consumer agents and opinion leaders

Related topics	Hydrology and hydraulics	- Agent-based simulation of water flow for environment modelling in estuaries	Bertelle, C., Olivier, D., Tranouez, P. and Jay, V. (2000)	- integrating vortex methods - replacing coherent vortex structures by meta-vortex particles.
	Fluvial geomorphology	Modelling of the construction of the Rhone alluvial plain since 15 000 years BP	Teles, V., Bravard, J.P., De Marsily, G. and Perrier, E. (2001)	- no physically based equations and no representation of water - simple sedimentary rules - 'sediment' or 'erosion' entities
	Wastewater treatment	Modeling and Analysis of Biofilms Formation and Evolution in Wastewater Treatment Processes using Multi-Agent Systems	Lardon, L., Steyer, J.-P., Bernet, N. and Le Page, C. (2002)	- understanding fundamental mechanisms of biofilms. - inclusion of individual phenomena like cell-cell communication
Combined models		Agent-based simulation of human-influenced ecosystem: the hydraulic management of the Camargue	Franchesquin, N. and Espinasse, B. (2000)	- two interacting models (hydrologic model and the multi-agent social) - hydrologic model: hydro-salt state - social model: decisions on resources
		- Model of the water users within GLOWA Danube	Kneer, J., Ernst, A., Eisentraut, R., Nethe, M. and Mauser, W. (2003)	- only households in ACTOR module are agent-based - water consumption in household depends on objective as well as psychological parameters

Table A 2: Rating of the programming environments

General criteria		Cormas	NetLogo	Repast J	Repast Py	SeSam[a]
Programming Language	1 = Language specific to multi-agent modelling (e.g. NetLogo) 2 = Less common programming language (e.g. SmallTalk) 3 = Common programming language (e.g. Java)	2	1	3	2	3[b]
Source code	1 = Source code not available 2 = Source code available	2	1	2	2	2
Documentation	1 = Incomplete or no documentation 2 = Documentation in need of improvement 3 = Complete and user friendly documentation provided	3	3	2	2	2
Support	1 = No support though users and developers 2 = Support through active user community (mailing list, forum etc.)	1	2	2	2	2
User base	1 = Used only by the developers or never 2 = Used by a certain scientific community (e.g. in one country or in one academic discipline only) 3 = Established and recognized in a broad scientific community	2	3	3	3	2
Future viability	1 = The product is still maintained, but future seems uncertain and updates are rare 2 = Support and maintenance of the product seems assured for near future; updates are frequent	2	2	2	2	2
Modelling and Experimentation Criteria						
Ease of installation	1 = Installation requires general computing skills 2 = Installation easy for people with basic computing skills (setup supported) 3 = Installation easy for lay people (automatic setup)	1	3	2	2	3

Support for modelling	1 = Setup of model requires advanced programming skills 2 = Setup of model possible with basic programming skills 3 = Setup of model possible without programming knowledge	2	2	1	3	3
Ease of use	1 = Difficult to use even with strong programming skills 2 = Easy to use if modeller has knowledge of the programming language 3 = Graphical user interface usable by lay people	2	3	2	3	2
Support for simulation control	1 = no special simulation control (only functionality of programming language) 2 = Simple simulation control (user can only run the simulation) 3 = Advanced functionality (e.g. changing parameters in dependency on other parameters)	3	3	3	3	3
Support for experimentation	1 = No functions for control and recording of simulation series 2 = Simple functions for control and recording of simulation series (data recorder, graphs etc.) 3 = Advanced functions for control and recording of simulation series including parameter optimization algorithms	3	3	3	3	2
Modelling Options Criteria **a) concerning agents**						
Inter-agent communication	1 = No inter-agent exchange supported, must be programmed by the user 2 = Data exchange between agents is supported 3 = Complex data exchange processes can be programmed easily and computed rapidly	2	1	1	1	1

Generating agent population	1 = No procedure for automatically generating populations supported 2 = Data import supported: agents can be generated from data 3 = Agents can be based on simple statistical values (such as means and standard deviations)	2	1	2	1	1
Types of agent supported	1 = Only one type of agents 2 = Different types of agents supported (e.g. situated or not) 3 = Total flexibility of agent design	2	1	3	2	1
b) concerning environment						
Possible implementations	1 = Few and simple options for design of environment (e.g. only 2DGrid) 2 = Few, but advanced options for environment (e.g. Cellular Automata) 3 = Different options for implementing environment	3	1	3	1	1
Integration of GIS-components	1 = No possibility for implementation of GIS components 2 = Loose coupling (import and export of GIS data) 3 = More than loose coupling	2	1	2	3	1
Criteria related to hydrology and water resources research						
General degree of freedom for modeller	1 = Modeller is limited to options provided in the original software 2 = Modeller has some possibilities to extend functionality of the software 3 = Modeller is generally free to extend functionality	2	2	3	1	1
Integration of other software or sources	1 = No possibility for integrating any other software 2 = Limited capacity for integrating external software 3 = Easy integration of other software or packages	1	2	3	1	1
Innovative features relevant for hydrology	1 = No innovative technology 2 = One innovative feature for application in hydrology 3 = More than one special feature	2	3	1	1	1

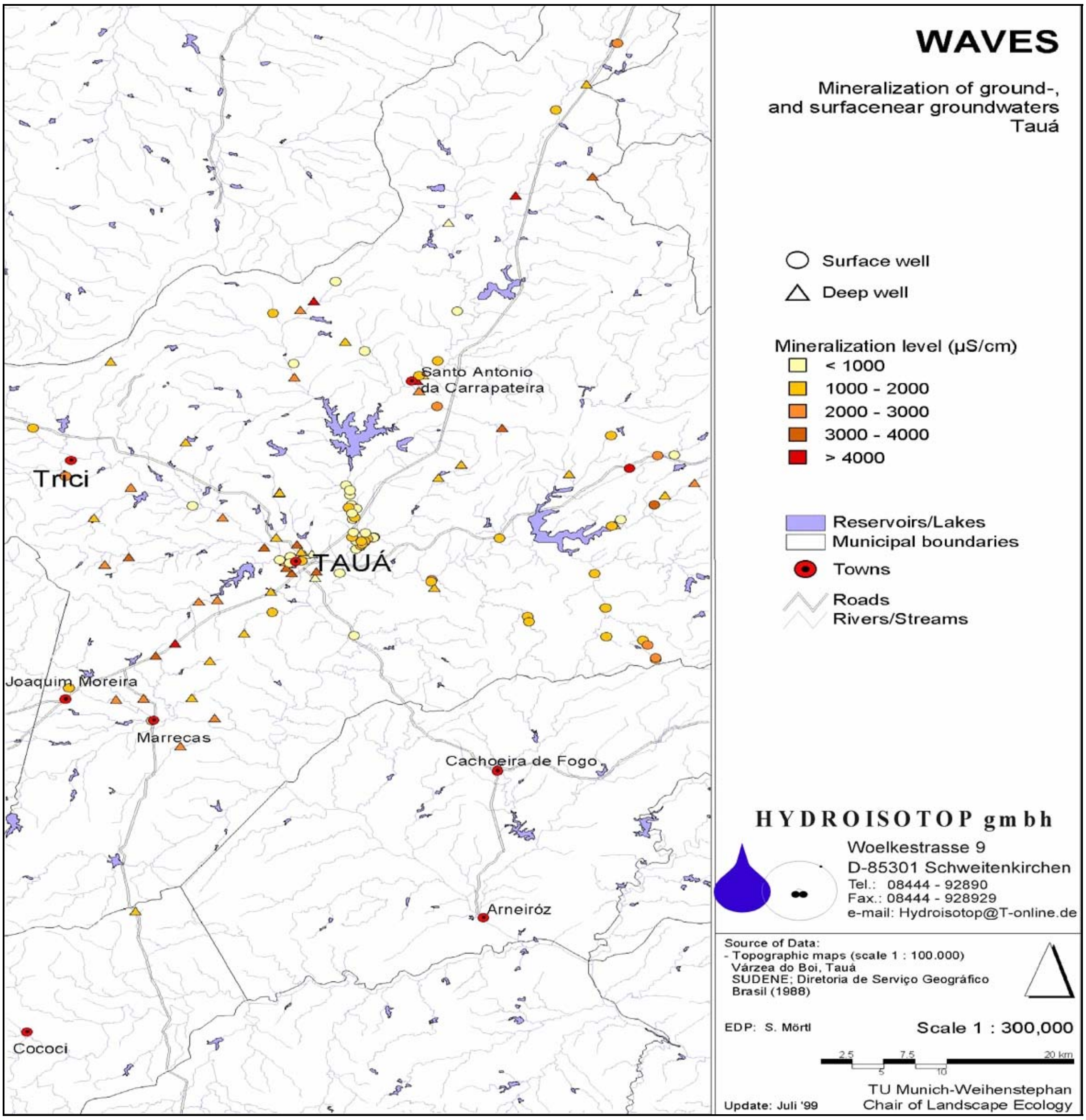

Figure A 1: : Map of Tauá including major infrastructure and some of the wells and dams (provided by Hydroisotop gmbH)

Table A 3: Software used for the modelling process

Software	Description	Version	Web Site
RepastJ	Multi-agent programming Environment	3.1	http://repast.sourceforge.net
Java	Java 2 Platform, Standard Edition; Version 1.4.2_08; Software Development Kit	J2SE v 1.4.2_08 SDK	http://java.sun.com
NetBeans	Programming Environment	IDE 4.1	http://www.netbeans.org