Summary

Finding a strategy that allows economically efficient drinking water production in regional supply systems at minimal environmental cost is often a complex task. In order to determine the optimal spatial production configuration, a systematic trade off among costs and benefits of possible strategies is required. Such a trade-off involves the handling of pronounced non-linear relations between quantitative aspects of strategies and their corresponding impacts. We developed a computer-based methodology for multiple objective optimisation of drinking water production by combining 'Min Cost Flow' and Genetic Algorithms (GA). The impact of production strategies is assessed by environmental, economic and geo-hydrologic modelling. Finding the optimal solution requires valuation of objective categories by translating impacts into a common scale and/or by definition of constraints that are specific for a particular category. If the impact of a category cannot be converted a priori to a common scale, a Pareto frontier of non-inferior solutions is calculated. Thus, the interdependency of impact categories can be clarified and decision makers and stakeholders are facilitated in the selection of appropriate production strategies. The approach was implemented in a GIS-based decision support system in order handle all spatial relations efficiently and to offer decision makers an adequate access to the methodology.

Groundwater quality prediction studies are frequently carried out within the framework of drinking water supply in order to assess the future composition of groundwater that will be pumped at production wells. These prediction studies help to assure a safe supply of drinking water in the future. Regional drinking water companies typically exploit numerous pumping wells and need to decide on research priorities for these wells as budgets are limited. Assessment of the uncertainty of prediction studies has been a scientific topic for many years, particularly when numerical models are used as predictive tools. Sophisticated techniques for the quantification of the uncertainty of model results have been developed over the past decades. In sharp contrast to the progress on the level of model uncertainty is prioritisation of prediction studies still generally based upon 'expert judgement'. Very few studies have focussed on the question how uncertainty of predictions on the composition of pumped groundwater should be used for management decisions on research priorities. However, deciding on these research strategies has become more complex, due to the increased size and interdependency of regional drinking water supply systems. Consequently, there is a need for decision support methods in order to avoid sub-optimal strategies.

This report presents a framework that is based on the above-mentioned methodology for multiple-objective optimisation of drinking water production. It enables decision support for allocation of research priorities to groundwater quality prediction studies. Rational research strategies on groundwater quality prediction seek to minimize the risk of well failure due to contamination of groundwater (breakthrough). There are 3 elements that form the basis of our approach:

- the quantification of risks for drinking water supply due to groundwater pollution
- an operational quantification of the reliability of predictions
- the anticipated marginal precision efficiency of additional prediction studies

The minimal negative impact of well failure in both economic and environmental terms is assessed by using genetic algorithms.

General Project Data

Project title:	PRESYS-GQ: Demonstration of a Groundwater Quality Prediction System for Impact Assessment of Landuse Development on Sustainable Drinking Water Production LIFE96ENV/NL/230
Project location:	Production well Roosteren, Limburg Province
Region/country:	Province of Limburg, The Netherlands

Beneficiary's full name and address:

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Project manager:	Dr. Paul P. Schot
Duration:	1-6-1997 - 1-6-2001 (48 months)
Total costs:	425,053.04 Ecu
Contribution by LIFE:	212,526.51 Ecu

Presys-GQ Organisation Chart

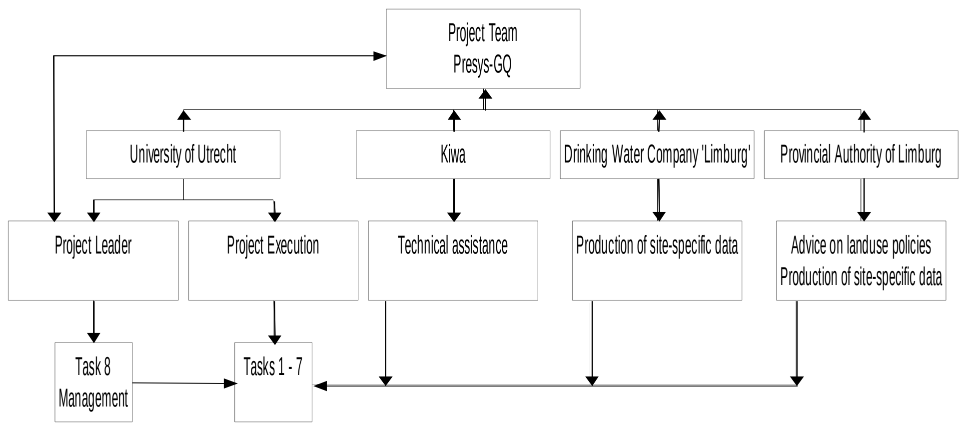

Figure 1: Organization chart PRESYS-GQ Project.

Organizational Structure

Participants of the project: **Tasks:**

University of Utrecht	all main tasks
Kiwa	technical assistance
Drinking Water Company Limburg	production of site-specific data
Provincial Authority Limburg	advice on land use strategies production of site-specific data

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1. Project description

1.1. Background

This report forms part of the PRESYS-GQ project, which is focussed on the environmental aspects of drinking water supply. Utrecht University carries out the project in cooperation with Drinking Water Company Limburg (WML), the Provincial Authorities of Limburg Province and Kiwa Onderzoek en Advies(Figure 1).
The quality of groundwater has deteriorated in many regions over the past decades due to agricultural and industrial pollution. Well failures due to the breakthrough of pollutants consequently have become more frequent. Besides, national and international standards for drinking water quality have become more stringent. As a result, drinking water companies need to spend substantial budgets on monitoring and prediction of groundwater quality. Rational and consistent methods are needed in order to spend available budgets efficiently.

During Phase A of the project, a case study on groundwater flow and transport of groundwater solutes was carried out. State-of-the-art groundwater quality prediction techniques have been applied, varying from simple to complex. Results of the case study indicated that the application of complex, advanced numerical transport models for prediction of groundwater quality at Pumping Station 'Roosteren' lacked sufficient precision[1], due to a combination of three factors:

- complex processes (many sub-processes)
- high variability of soil and groundwater properties and conditions
- limited data availability

Due to the insufficient precision of simulation results it was decided that it would be unwise to carry out further research directed at application and development of numerical process models that are meant to simulate chemical reactions during groundwater transport at an even more detailed and refined level. In stead, we focussed on the development of a method that allows:

- rational and efficient prioritisation of groundwater quality prediction studies
- integrated economic and environmental optimisation of production strategies

The method was implemented in a GIS-based decision support system in order handle all spatial relations efficiently and to offer decision makers an adequate access to the developed methodology.

1.2. Objectives and project phases

General objective of the PRESYS-GQ Project is the development of a groundwater quality prediction system which can be used by actors relevant for the drinking water supply and which can facilitate an integrated decision making. This system should be accessible for experts as well as non-experts.
The project consists of three phases. The relation between phases and tasks is described in the following paragraph.

- **Standard Model Construction**
  - tasks 1, 2, 3
  - task 6 partly
- **Decision Support System Construction**
  - tasks 4, 5
  - task 6 partly
- **Dissemination**
  - task 7
  - task 6 partly

In phase A, simulations of groundwater flow and transport of chloride and nitrate in groundwater were carried out for a case study located in the south of The Netherlands (Figure 2). Results of these studies indicated that more advanced transport simulations would become too speculative because of the limited availability of data, as compared to the spatial and temporal variability of geohydrologic properties in the case area. It was also found that a systematic approach for the evaluation of reliability and accuracy of model results was needed in order to answer the question how precise model results

[1] Precision of groundwater quality predictions comprise *accuracy* and *reliability*

should be. In order to answer the latter question the content of phase B of this project was changed. In stead of simulation of groundwater transport by even more advanced models, it was decided to develop a methodology and computer-based procedure that can assist in answering the question which accuracy and reliability of simulation results is needed for a specific case.
In phase B the following tasks are distinguished:

- Development of a generally applicable decision support model for sustainable regional drinking water supply (task 4)
- Application of the decision support model to a case area (task 5)

For tasks 1, 2 and 3 separate technical reports describe the tasks, methods and results in detail (Vink&Schot 1997,1998,1999).
This report pertains to the results of the aforementioned task 4: Development of a decision support model for sustainable regional drinking water supply. The figures that illustrate the functionality of the decision support system are based upon data that originate from the case area of this project. Some data are fictive and merely constructed in order to clarify the functionality of the decision support system.
All project tasks that were carried out until present are concisely described in the following paragraphs.

Figure 2: Location of the case area

1.3. Description of task 1 (Technical report 1)

Aim:

- Construction of a groundwater flow model of the selected case-area.

Method:

- Groundwater modelling software code MODFLOW.

Activities:

- Selection of a representative case-area.
- Collection of site-specific data as input for MODFLOW.
- Simulation of groundwater levels.
- Calibration of model by comparing simulated water levels with observed water levels in monitoring wells.
- Calculation of streamlines and delineation of the groundwater recharge area.
- Technical report T1.

1.4. Description of task 2 (Technical report 2)

Aim:

- Simulation of conservative transport of chloride in the case-area.

Method:

- Simulation of groundwater fluxes in the case area by means of the groundwater modelling software code MODFLOW.
- Simulation of chloride transport in the case area by means of the groundwater transport software code MT3D96.
- Chemical analyses of water samples.

Activities:

- Collection of site-specific data on chloride deposition over time.
- Collection of water samples for chemical analyses.
- Simulation of groundwater fluxes over time after refining the groundwater model, which has been constructed during the execution of task 1. (MODFLOW).
- Simulation of transport of chloride in the saturated zone over time (MT3D96).
- Calibration of chloride transport by comparison of simulated with observed chloride concentrations.
- Writing technical report T2.

Relation to other tasks:

- The construction of the flow model during task 1 forms the basis for flow simulations of task 2.
- The adapted flow model constitutes input for tasks 3,4,5 and 6.

1.5. Description of task 3 (Technical report 3)

Aim:

- Simulation of non-conservative transport of nitrate in the case-area, using the flow model from task 2.

Method:

- KIWA-code for leaching of contaminants from unsaturated zone.
- Groundwater transport software code MT3D using a decay factor to account for denitrification.

Activities:

- Collection of site-specific data on nitrate input over time in relation to land use.
- Simulation of leaching of nitrate ions from unsaturated zone over time.
- Simulation of transport of nitrate in the saturated groundwater zone using decay factor in MT3D.
- Calibration of nitrate transport by comparison of simulated with observed nitrate concentrations in production or observation wells.
- Technical report T3.

Relation to other tasks:

- Results constitute input for tasks 6 and 7.

1.6. Description of task 4 (This report)

Aim:

- Development of a computer-based instrument for integrated impact assessment of drinking water strategies.

Functionality:

- Assist in the evaluation of groundwater quality management strategies
- Support integrated evaluation of regional drinking water strategies
- Support communication between drinking water companies and governmental authorities
- Assist in optimisation of use of resources and minimization of negative environmental impacts

Method:

- Avenue GIS computer programming (ArcView)

Activities:

- Functional model design
- Technical model design
- Implementation
- Technical report T4.

Relation to other tasks:

- Results constitute input for tasks 5, 6 and 7.

1.7. Contents of the report

A general description of the PRESYS-GQ project and of the tasks related to this report is described in Chapter 1 of this report. Chapter 2 contains an introduction to decision support systems in the framework of regional drinking water management. The structure and functions of the decision support system can be found in Chapter 3. The figures that illustrate the functionality of the decision support system are based upon data that originate from the case area of this project. Some data are fictive and merely constructed in order to clarify the functionality of the decision support system.

2. Decision support for regional drinking water supply

2.1. Introduction

Over the last decades, complexity of regional drinking water supply has increased. This development is caused by a number of tendencies:

- Increasing scarcity of land with low pollution risk;
- Increasing scarcity of unpolluted groundwater;
- Increasing awareness of the need to protect the environment

Scarcity of caption zones with unpolluted groundwater and low pollution risk
Some decades ago only two criteria determined the choice of the location of a groundwater pumping station: geo-hydrological properties of the subsoil and the distance that had to be covered from the well to the consumers. Since then many more criteria came into play. Groundwater quality deteriorated and the occupation of land for industry, intensive agricultural production, highways and urban zones increased sharply. These types of land use do not represent the ideal conditions for the location of a drinking water production well; the risk of groundwater pollution is relatively high. In order to prevent pollution of groundwater that is destined for drinking water production, governmental regulations limit the types of land use that are admissible in groundwater protection zones. These zones represent areas in which infiltrated water is likely to end up in a well within 25 years. As the risk for pollution of groundwater became more manifest, the need for monitoring groundwater composition and predicting future developments of groundwater quality have become more important.

Awareness of the need to protect the environment
'Natural' vegetation became better protected over the past years. Authorities have recognized its ecological value and taken measures for a more effective conservation. Vegetation in wetlands and other 'wet' ecosystems often depends on a high groundwater level. Pumping groundwater for drinking water production may cause a lowering of the groundwater level and thus endanger groundwater dependent vegetation. Whether or not provincial authorities are willing to grant permission for extraction of groundwater is nowadays strongly dependent on the impact of pumping on natural vegetation. Also, regional authorities became more reluctant in granting permissions to 'mine' old, unpolluted groundwater, as this forms a scarce environmental capital. The location of pumping stations and the way production is organised have also an impact on the use of energy and chemicals that are involved in the production of drinking water. These environmental criteria have been added to strictly economical considerations. Developments that were briefly mentioned here-above have gradually changed drinking water supply in the Netherlands and in many other densely populated areas in the world from a relatively simple to a highly complex process. Production strategies need to be evaluated with respect to a complex chain of costs and impacts. Advanced computer-based systems, such as the decision support system that is described in this report, offer a useful instrument for assessment of the economical and environmental impact of production strategies.

2.2. Objectives

The objective of this project task is the development of a computer-based instrument for integrated impact assessment of drinking water strategies. The instrument will be implemented within a Geographic Information System (GIS).

The instrument can be used to:

- assist in the evaluation of groundwater quality management strategies
- support integrated evaluation of regional drinking water strategies
- support communication between drinking water companies and authorities
- assist in optimisation of use of resources and minimization of negative environmental impacts

2.3. Target groups

Target groups for the decision support system are:

- Drinking water companies (strategy makers, technicians)

- Authorities (strategy makers, technicians)
- Universities, research institutes, consulting engineers (researchers, technicians, students)

For any of these groups the decision support system may function as a tool for analyses and assessment of strategies related to drinking ware supply. The decision support system also may function as an instrument to improve communication and visualization. For universities it may function to familiarize students with environmental aspects of regional drinking water supply and the inevitable trade-offs that go with it.

2.4. A GIS-based decision support system

The reason to implement the decision support system in a GIS environment originates from the complex structure of data. Since most data possess a spatial property it is considered that a geographic information system (GIS) is the most fruitful way to explore and analyse the subject. Well-developed visualization functions belong to a good GIS. These functions greatly contribute to the accessibility of the issues discussed.

A decision support system (DSS) can be viewed as "an integrated, interactive computer system, consisting of analytical tools and information management capabilities, designed to aid decision makers in solving relatively large, unstructured problems" (1995, Watkins and McKinney). Computer-based systems that comply with this definition have been developed since the appearance of the first personal computers. In the field of water management there is an increasing number of DSS available.

The management and planning of drinking water supply is an issue that affects many different organisations and authorities. Due to the scarcity of space and other resources there are often strongly conflicting objectives between and within organisations that operate in densely populated areas. The issues may be related to economic costs of production, occupation of space, limitations for land use, environmental costs and risks for human health. In this context a DSS can be very useful, not only as a tool for optimising the use of resources, but also for improving the process of communication and negotiation among and within the parties concerned. The intranslatability of the spatial aspect in water management issues makes it difficult to appraise plans on a basis of merely lumped, cumulative scalar quantities. By integrating GIS and decision support systems an improvement of access to information can be achieved. "Decision makers may become active participants in a regional planning analysis, rather than selectors among a few, pre-planned alternatives" (Jones, 1998).

The reason to construct a decision support system is related to the complexity and great quantity of data, but also to the fact that the use of such a system implies the formulation of explicit decision rules and knowledge. These properties improve the value of a decision support system for communication and analyses. Results can be visualized with great flexibility; presuppositions of results are explicit and accessible. The impact of drinking water production strategies can be assessed clearly and fast.

Analyses by means of such an instrument can throw also some light to questions such as:

- Where is additional knowledge most needed?
- To which processes and relations are results most sensitive?
- Which values and presuppositions are decisive?

2.5. Regional drinking water supply

Regional drinking water supply essentially consists of a number of locations where drinking water is needed and a number of locations where drinking water is 'produced'. These sites are interconnected by a transport network. The basic components of drinking water supply consist of pumping, purification, transport and finally consumption (Figure 4).

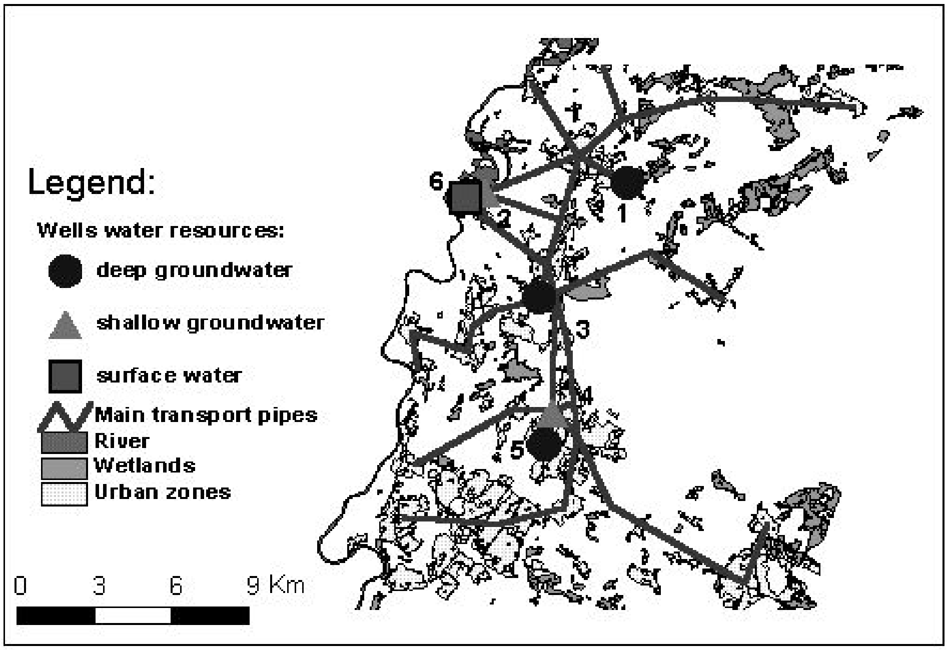

Figure 3 Map of a regional drinking water supply system

At pumping stations groundwater is pumped out of the subsoil and purified in order to make it suitable for human consumption. From pumping stations the water is distributed to the locations where it is needed by means of a transport network. An example of a basic configuration of pumping stations, consumption locations and a main transport network is displayed in Figure 3.

Generally, supply systems have spare capacity available in order to respond to fluctuations of demand and also as an ‘insurance’ to technical failure of system components. The presence of spare capacity implies the existence of a ‘decision space’ and hence a need to formulate strategies for the allocation of production rates to the available production units. Different strategies result in different economic and environmental efficiency. Both types of efficiency may vary considerably because of the spatial variability of relevant factors. Transport distances between pumping wells and the locations where the water is required also affect production efficiencies strongly.
A production strategy defines the way in which the required capacity is distributed over the available wells. The impact of a strategy would consist of production costs and transport costs in a ‘basic’ system where only these costs are relevant. (Figure 6). Every particular distribution of discharges over the available pumping stations results in a different impact. If drinking water supply would be as simple as sketched here-above, optimal allocation of resources would imply a consideration of pumping and transportation costs only, as these costs would determine the principal impact of production strategies. From such a viewpoint it would be evident that pumping stations should be located close to locations where the drinking water is needed. Transport costs would then be minimal.
In reality, optimal management of resources is not as simple as just described. The impact of production strategies covers many more aspects than just production and transport costs (Figure 58). The strategy of drinking water companies has to fit within the strategy framework of local authorities (Figure 5). Provincial authorities define a strategy framework for drinking water supply with respect to pollution risks. A part of the caption zone[2] is declared *groundwater protection zone.* Types of land use that may endanger groundwater quality are limited in existing groundwater protection zones. Locations for pumping stations are thus restrained by existing or planned types of land use in the projected groundwater protection zone.

[2] A caption zone of a well refers to the area from which infiltrated rainwater is likely to be pumped up in the well, eventually.

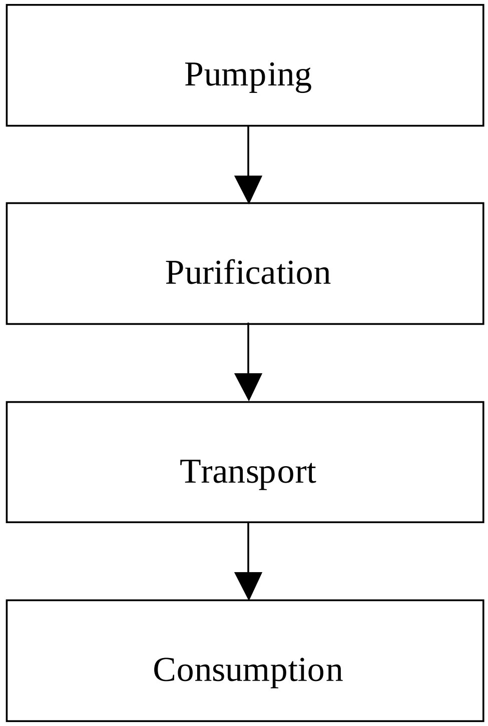

Figure 4 Basic components of drinking water supply

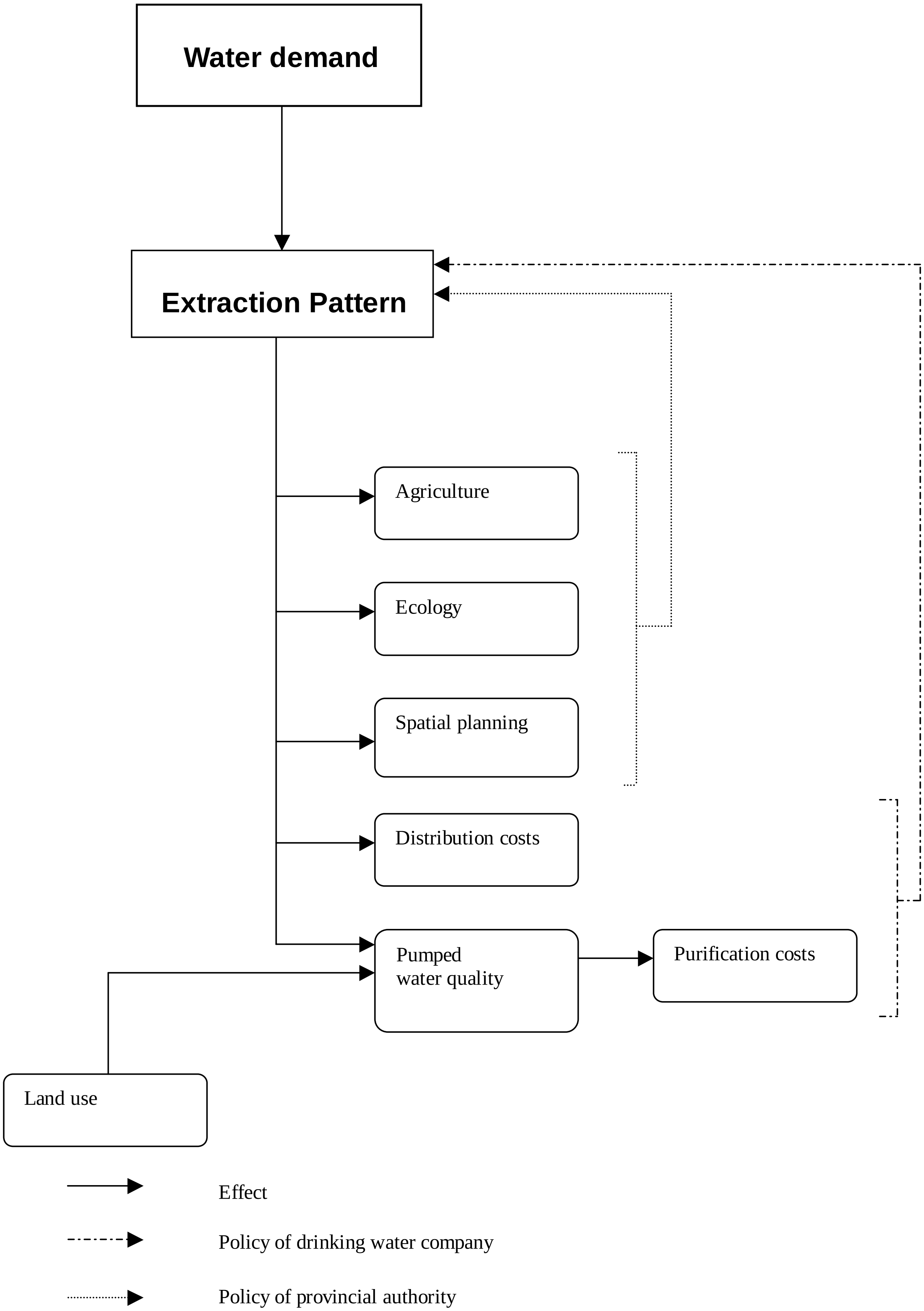

Figure 5 Basic impacts of regional drinking water supply

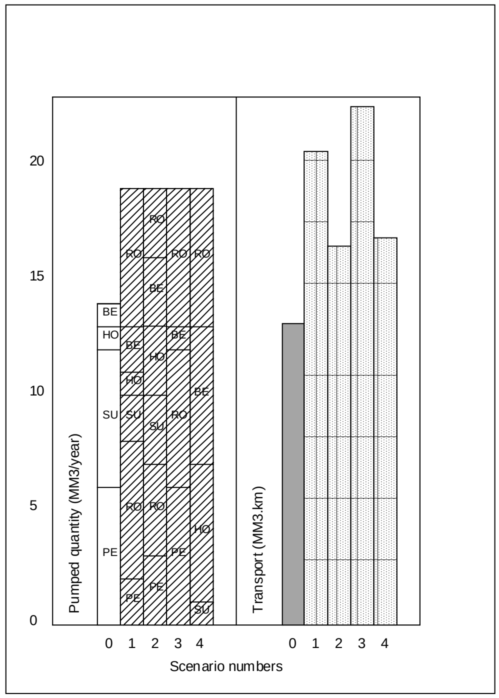

Figure 6 Evaluation of alternative production strategies for one impact category

Drawdown-induced impacts

Pumping of groundwater results in drawdown: a lowering of the groundwater level around a well. The higher the pumping discharge, the larger the drawdown. The geohydrological properties of the subsoil play a decisive role in the reaction of the groundwater level to pumping. Pumping in zones with low hydraulic transmissivity results in a much greater drawdown than in zones with highly permeable subsoils. A lowering of the groundwater level has a negative impact on natural vegetation that depends on groundwater. Agricultural production may also be affected by drawdown. Vegetation in wetlands and other regions with a high groundwater level is sensitive to even small changes of the groundwater level. In order to assess the impact of groundwater extraction on natural vegetation, hydrological impact has to be calculated first. The changes in hydrological conditions that are calculated can be used as input to ecological models which predict the ecological effects. The relation between discharge rate and the corresponding impact on ecology and agriculture is highly dependent on well specific conditions (Figure 7). Some wells are located near valuable and vulnerable natural vegetation whereas others may be located at a great distance. Many drinking water companies partly use surface water as a source for drinking water production. A lowering of the groundwater level obviously does not occur in those cases, but on the other hand are purification costs and sometimes transport costs much higher. Within existing regional frameworks for drinking water production, many alternative options for production may be possible. A different distribution of discharge rates over the available pumping stations may result in strong variations of corresponding environmental impact and total production costs. All these site-specific, mostly spatially determined factors invoke a highly complex system of relations, where often the best production strategy cannot be recognized without advanced analyses. Both the evaluation of suitable locations for new pumping stations and optimal production strategies for existing pumping stations are types of problems that are particularly suitable to be analysed by means of GIS-based tools.

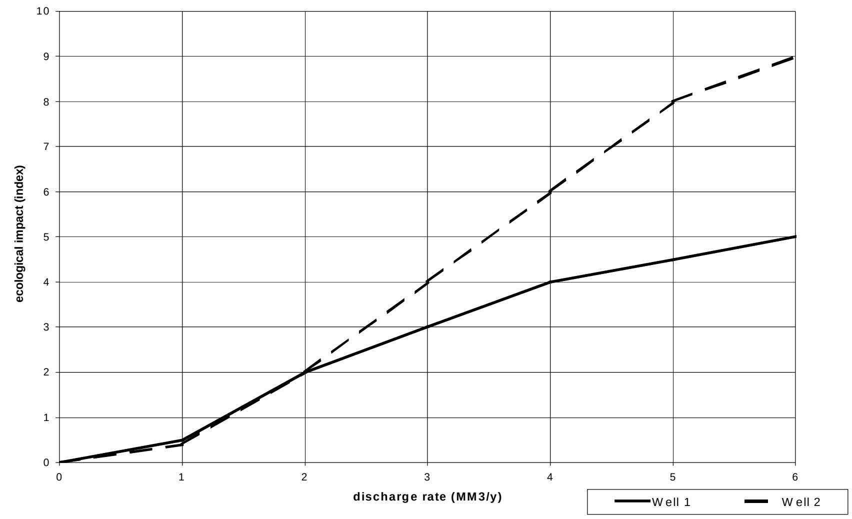

Figure 7 Discharge-impact relations of two different wells (example: ecological impact)

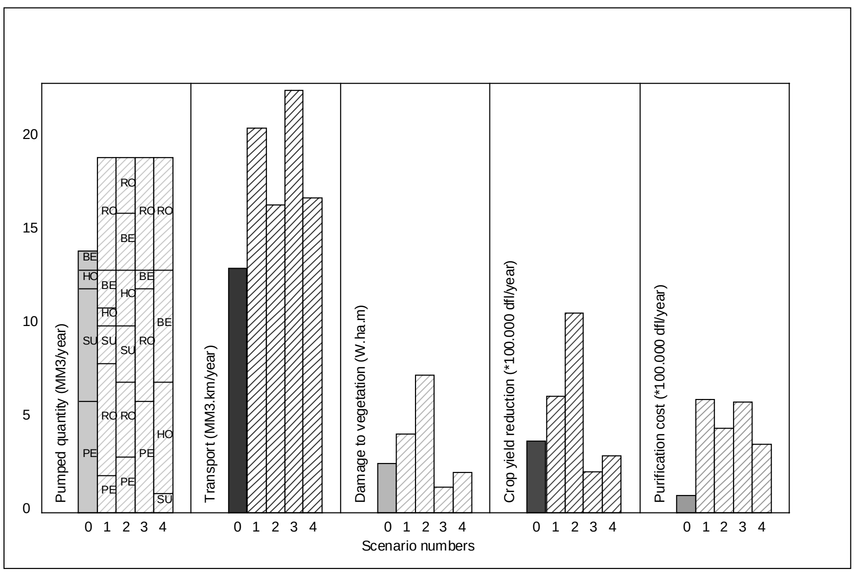

Figure 8 Evaluation of alternative production strategies for multiple impact categories

2.6. Optimisation of drinking water supply

Defining optimal strategies should be based on identification of relevant objectives (1), determination of the relation between strategies and impacts (2) and valuation of the various impacts (3). Valuation of impacts can be done by two different approaches:

- explicit approach, in which the impacts are all converted into a common scale;
- implicit approach, in which the valuation of impacts is expressed indirectly through constraints.

According to the explicit approach various impacts are translated into a common, often monetary scale. If we take damage to natural vegetation as an example, an explicit approach could consist of a valuation based on replacement costs. In that case the economic costs involved in creating a similar natural vegetation elsewhere would be the basis for valuing the impact. Explicit valuation is being criticised increasingly for its inability to reflect all relevant aspects in a meaningful way (Nijkamp, 1979). However, there are objective categories about which stakeholders have managed to agree on a translation of impacts into monetary terms. Alternatively, an implicit approach for value attribution could result in constraints of the type: the maximal drawdown induced by pumping may not exceed X cm in area Y. The latter approach offers a better possibility to take into account a variety of objectives without the risk of losing meaningfulness by translation into monetary terms, like in the explicit approach. Both approaches may be combined within one single optimisation. If decision makers cannot agree a priori on an either explicit or implicit valuation of objectives, then the interdependence between impacts of conflicting objectives can be expressed graphically by means of Pareto frontiers. Pareto frontiers are a well known concept in multi-objective optimisation theory and show graphically how optimal solutions depend on the valuation of conflicting objective categories. In our case it can display how economic cost and damage to vegetation are interrelated for optimal solutions. The Pareto frontier can thus be used as reference information by decision makers, as it marks the optimal solution as a function of a set of valuations.

Until recently, the pronounced non-linearity and interdependency of relations that play a role in regional drinking water production rendered it in practice unfeasible to optimise both economic and environmental objectives. To overcome this problem we have applied a genetic algorithm (GA) that enables optimisation and construction of Pareto frontiers by efficient handling of these non-linearities.

Genetic algorithms

Genetic algorithms (GA's) are based on the genetic processes of biological organisms. The concept of natural selection by survival of the fittest as stated by Charles Darwin in The Origin of Species plays a major role. Application of the principles of selection and mutation in computer programs was first proposed by Holland (1975). Since then, evolution programs have been applied successfully to a wide range of problems (Grefenstette 1990, Beasley et al. 1993). GA's work with a population of possible solutions to a problem. The performance of each member of the population is calculated in terms of fitness. The properties (genes) of the best performing ones are mixed with other solutions, leading to new members of the population that take the place of inferior members.

A disadvantage of any non-exhaustive, iterative technique like GA is that one never can be sure whether the global optima are identified sufficiently precise. We found that ‘circumstantial validation’ was possible in the theoretical cases we investigated. Solutions that correspond effectively to single objective optimisation are located at the extreme ends of the Pareto front. These single-objective solutions generally can be verified by analytical inspection of the systems impact relations. Circumstantial validation is then based on the assumption that the complete Pareto front represents truly non-dominated solutions if this is the case for the solutions at its extreme ends.

2.7. Prediction of groundwater quality

The importance of predicting the quality of pumped groundwater has increased since groundwater quality deteriorated. Prediction studies are carried out in order to reduce the risks of malfunctioning of drinking water supply. They form an early warning system that enables time for taking counter measures, in case some pollutant threatens a well. In case of a predicted crossing of a threshold concentration (breakthrough), several counter measures are possible:

Prevention of breakthrough:

- Influencing future composition of pumped groundwater by reducing the quantities of contaminants that enter the groundwater.
- Limitation of the transport of pollutants towards the well.

Compensation of breakthrough

- Installing supplementary capacity for purification of the groundwater.
- Installing alternative production wells, at sites where the groundwater is of a better quality.
- Transfer of needed production quantities to other (existing) production wells.

Either by changes in land use practices or by influencing the hydraulic regime of a particular polluting site, the transport of pollutants towards a well can be reduced. If these measures are successful,

production of drinking water at the endangered site can continue without further modifications of the production system.
Typically the greater part of the water particles that end up in the screens of a pumping wells have spend more than ten years in the soil since the moment of infiltration. Measures that are intended to improve the quality of pumped water therefore are not immediately successful. In the Netherlands drinking water companies have bought land in the caption zones of production wells in order to enable a change of the land use and thus achieve a reduction of pollutants entering the groundwater. Physical measures that prevent a further transport of pollutants to the well are sometimes implemented if a specific site causes pollution of groundwater. Modification of the pumping rate may also improve the quality of pumped groundwater.
Installing additional purification capacity enables a continuation of the use of a particular well for drinking water production. By means of purification, not all pollutants can be removed out of the groundwater successfully. In some cases either technical or economical considerations lead to a preference for closure of a well and installation of production capacity at other, more favourable sites.

Reduction of Risk

Prediction studies can contribute to the *reduction of risks* of breakthrough by increasing the available time for counter measures. The first 2 options cited here-above are directed at prevention of the occurrence of breakthrough by affecting the *probability* that the event takes place. The other options are directed to a reduction of the *impact* of a breakthrough. Generally, if the available reaction time becomes less, the number of feasible options decrease and costs involved in counter measures increase. In the worst case the economic means for counter measures, the reaction time or the spare capacity within the system are insufficient and the supply is hampered.
Application of newly developed prediction tools such evoked the need for a quantification of the uncertainty of model results. Indeed, a statement with unknown certainty is useless. Assessment of the uncertainty of groundwater quality predictions forms an important issue in current scientific studies. A number of techniques was developed in order to quantify the uncertainty of model results (e.g. Gelhar, 1976, Dagan, 1982, Delhomme, 1979, Caselton & Luo 1992). This scientific progress and the continuous improvement of computer's calculation capacities will render application of these techniques practical and feasible in prediction studies.
In sharp contrast with the progress in the field of quantifying model uncertainty is prioritising prediction studies still generally based upon 'expert judgement'. Very few studies have focussed on the question how uncertainty of predictions on the composition of pumped groundwater should be used for management decisions on research priorities. Budget for prediction studies should be allocated on a basis of maximal reduction of risks of breakthrough, by enabling through counter measures that either the probability or the impact of a breakthrough is reduced. Prioritisation of prediction studies is necessary if research budgets are limited. The criterion for prioritisation should be directed at maximization of risk reduction. Deciding on these research strategies has become complex, due to the increased size and interdependency of regional drinking water supply systems. Consequently, there is a need for decision support methods in order to avoid sub-optimal strategies.
In this report, a systematic approach for the allocation of priorities to prediction studies is described. The risk of a breakthrough consists of two components: the *probability* that such an event would occur and the *impact* of a breakthrough to a regional supply system (Figure 11). The impact of a breakthrough of a well is related to costs and damages that would be involved in counter measures. Predictions of pumped groundwater quality cannot only enable a reduction of the impact of a breakthrough by increasing the available time to react to a threatening breakthrough, timely taken preventive counter measures can even reduce the probability of breakthrough of a contaminant.
If a well is crucial to the proper functioning of a regional supply system and there is not much spare capacity left then a sudden failure could endanger the supply of drinking water. The impact of a possible breakthrough of such a well consequently would be very high. On the other hand, a breakthrough of a well of which the production can easily be replaced by other production wells may have a relatively small impact on a regional drinking water supply system. Groundwater quality predictions are more needed for wells of which a malfunctioning would result in a high impact than for wells with minor impact in case of a breakthrough. The key for assessing the impact of malfunctioning of a well therefore lies in a quantification of all aspects that determine the impact of a breakthrough. The method for optimisation of drinking water production by means of genetic algorithms as is described in this report can be used to assess the optimal, i.e. minimized negative impact of well failure by determining the differences between optimal production configurations with and without a particular well.

Reliability – accuracy of predictions

Any prediction statement per definition lacks certainty, as it concerns the future. The reliability of a prediction statement signifies the probability that the prediction will come true. The usefulness of a prediction statement depends both on its reliability and accuracy. If a prediction statement is viewed in a stochastic context, the reliability of a statement is influenced by its accuracy. If the accuracy of a prediction statement that is based upon a certain analysis is reduced then its reliability will increase and vice versa. The exact relation between reliability and accuracy depends on the probability distribution of the stochastic variable. The required accuracy of a prediction is first of all related to the '*intervention concentration*': a threshold value that corresponds to a concentration that is no longer acceptable. A prediction statement should be sufficiently accurate in order to allow to distinguish between whether or not a concentration will exceed an 'intervention concentration'.

Improved precision of predictions yields to reduction of the risk of breakthrough by an increase of available reaction time. On average, the predicted moment of crossing the threshold concentration at a given confidence level will move towards the future if the accuracy of the prediction increases. The expectancy value of the 'new' crossing time can be used for the calculation of the risk reduction by translating the marginal increase of available reaction time into marginal reduction of risk.

Priority of prediction studies should thus be based on a trade off between required research costs for improvement of reliability and the corresponding expected reduction of risk.

3. Model description

3.1. Software environment

The decision support system operates within ArcView, a GIS tool of ESRI. ArcView is one of the leading GIS software packages for personal computers. The system is programmed in Avenue, the programming language within ArcView. The program can run under Microsoft Windows or Unix. The spatial decision support system (SDSS) that we constructed consists of a central module with an optimisation engine, coupled with a collection of impact models(Figure 9).

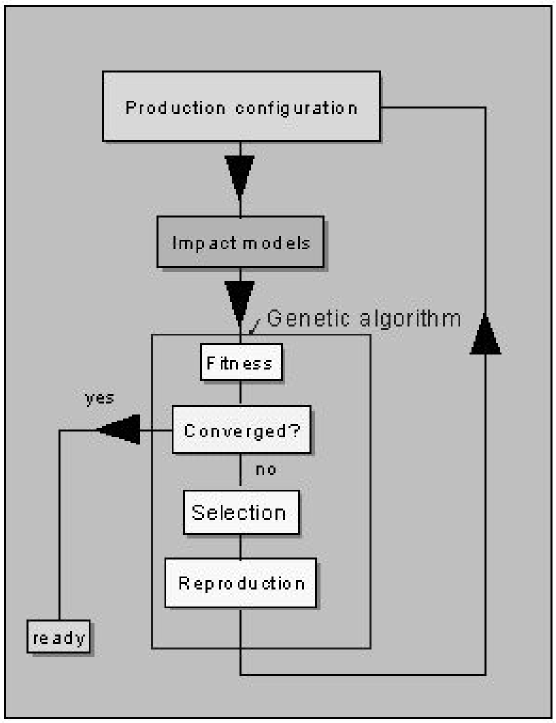

Figure 9 Flowchart of optimisation approach

3.2. Point objects

Production wells

Production wells are places where drinking water is being pumped from either groundwater or surface water. A well has a maximal and minimal discharge rate and a unit cost per volume. A spatially defined discharge-drawdown relation is defined for every source.

Purification stations

Purification stations are points with a maximal capacity and unit cost per volume. Mostly but not always they coincide with the location of production wells.

Consumption centres

Consumption centres are places where drinking water is used.. Usually a consumption centre represents a city or a village. A consumption centre has a fixed consumption quantity.

3.3. Line objects

Transport pipes

Transport pipes are line elements that are connected to sources, sinks, or other transport pipes. A transport pipe has a maximal discharge capacity and a unit cost per volume.

3.4. Polygon objects

Land use

The land use in a region is defined by attributes of polygons. These polygons may have one of the following qualifications:
Nature (currently not further specified);
Urban;
Water;
Agriculture (further specified according to the crop as used in LGN2, the digital land use map as composed by DLO-SC.

3.5. Raster objects

Groundwater level map

The groundwater level at the zero-scenario represents the distance between the groundwater level and the surface. It is stored in the format of a digital raster map.

Drawdown map

The drawdown map is calculated for every scenario and represents the cumulative drawdown induced by the pumping of the production wells. The degree of drawdown depends on the discharges of the various production wells.

3.6. Impact modules

The various impacts of strategies are quantified by category. The impact categories that we defined are:

- Pumping cost
- Purification cost
- Transport cost
- Agricultural yield reduction due to groundwater drawdown
- Natural vegetation impact due to groundwater drawdown

The impact models vary in complexity from simple linear relations such as those for economic costs, to complex non-linear impact models, such as the model for damage to vegetation by groundwater drawdown (Figure 10).

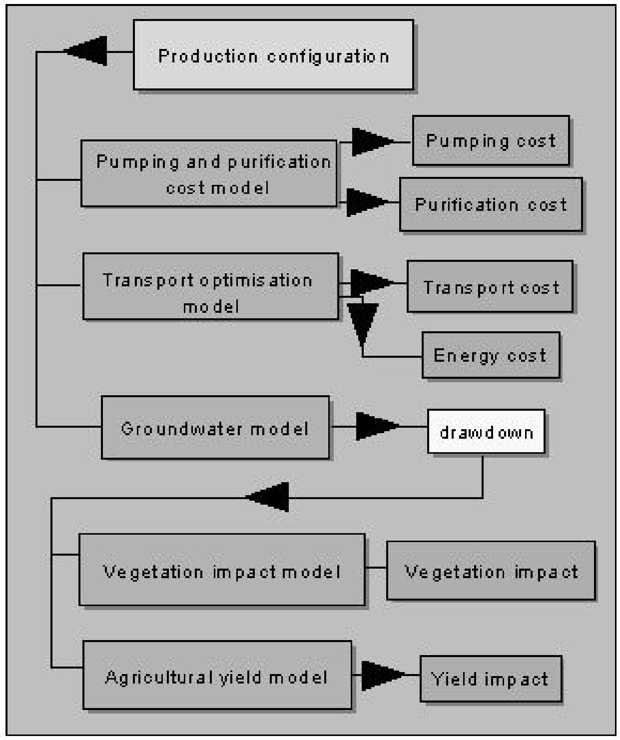

Figure 10 Flowchart of impact models

Drawdown calculation

Using GA as an optimisation technique for regional drinking water supply requires calculation times that are for many problems still too large for being practical. Impact calculations by means of geohydrological and ecological impact models are time consuming. It may typically require 1-5 minutes at a state of the art personal computer for a complete impact calculation. As to reduce the required calculation time we defined three levels of detail for drawdown-related impact calculations. The 'noisiness' of the impact functions is reduced stepwise during the optimisation process. Initially, impact functions are expressed as independent functions of well's discharge rates. This assumption presupposes that spatial impacts of different wells are independent and can be superposed. From the principle of superposition (e.g. Todd, 1980), the drawdown at any point in the area of influence caused by the discharge of several wells is equal to the sum of the drawdowns caused by each well individually. However, the principle of superposition does not take in account heterogeneities in the subsoil or non-linearities due to the presence of open water (ditches, rivers, lakes). These aspects may therefore introduce some error in the calculation of drawdown. Once the improvement of the fitness of generated solutions stagnates and near-optimal solutions for the initial fitness function have been found, the initial fitness function is replaced by a less noisy alternative. The superposition principle in the relation between drawdown and damage to agricultural yield or vegetation is then no longer assumed, but for calculation of total drawdown the superposition principle is still assumed to be correct. At the third stage, drawdown at locations that are within the area of influence of more than one well is no longer assumed to be superposable. For each solution a digital drawdown map is generated by a connected numerical groundwater model. The results of the calculation of drawdown are input to the decision support model, in the format of digital raster maps.

Vegetation impact calculation

The aforementioned total drawdown map of a scenario forms one of the ingredients for the calculation of the impact of drawdown to vegetation. Other sources of physical information form digital maps of

soils and of basic groundwater level. For each scenario a vegetation impact map is constructed in polygon format.
Currently, impact to vegetation is expressed in an index-based unit, based upon the following formula:

$$VI = D * V * K$$

Where:
VI: vegetation impact (-)
D: drawdown (m)
V: value of vegetation (-)
K: vulnerability of vegetation to drawdown (-)

V and K are classifications that are specific for a vegetation type. Currently both V and K are determined as a function of the distance of the groundwater level to the surface. Thus the attribution of value corresponds to general characteristics as conceived by ecologists.

Total vegetation impact:

$$TVI = \sum_{i=1}^{N} VI_i * A_i$$

Where
A_i: area of polygon(i)

Further development of the decision support model could comprise the implementation of a more refined ecological impact model.

Agricultural impact calculation

The map of total drawdown forms one of the ingredients for the calculation of the impact of drawdown agricultural production. Other sources of physical information form digital maps of soils and of basic groundwater level. For each scenario an agricultural impact map is constructed in polygon format.
The impact of pumping-induced drawdown on agricultural production is calculated according to

$$AI = D * AV * AK$$

Where:
AI: agricultural impact (-)
D: drawdown (m)
AV: value of crop (-)
AK: vulnerability of crop to drawdown (-)

Total agricultural impact:

$$TAI = \sum_{k=1}^{N} AI_k * A_k$$

Where
A_k: area of polygon(k)

Further development of the calculation of the agricultural impact could be achieved by implementation of the widely accepted method that was developed by the HELP Commission (1978). However, such an implementation is considered outside the scope of this project.

Production cost calculation

For each scenario total economic costs are calculated by summing up the various costs that are involved in the production process. The total costs consist of the following items:

- Pumping costs
- Purification costs
- Transport costs

Currently these costs can be defined linear to produced quantities of water. In principle the developed method of optimisation allows addition of any other relevant impact category that can be related to the discharge rates such as energy costs, use of deep groundwater (strategic reserves, environmental capital) or use of chemicals for purification.

3.7. Functions

Calculation of production costs and environmental impact

This function of the model consists of a calculation of the impact of a user defined production scenario. The user should define various costs and discharge rates of sources. The resulting financial and environmental costs will be calculated by the model and can be visualized as impact maps or charts.

Optimisation of production costs and environmental impact

The function 'Optimisation of production impact' makes the model determine the distribution of well extraction rates that results in a scenario with maximal benefits and minimal costs. The user should define for this options the importance that is attached to environmental impact as compared to production costs. Optimisation is not possible without a suitable quantification of environmental impact in terms of either financial costs or boundary conditions. Boundary conditions may consist of maximally acceptable values of vegetation damage, energy quantities or chemicals for purification. A definition of boundary conditions does not require to be expressed in financial terms, but can be specified in terms of the units of a impact category. For example, a user may define a maximal acceptable negative impact to vegetation in terms of the units that are used in the ecological model. Also it is possible to define a maximal allowable drawdown for specific sites or areas on the map. The latter option is not yet operational.

Impact assessment of source failure

Assessment of the impact of failure of production wells (‘breakthrough’) is closely related to groundwater quality management. The risk of breakthrough depends on *probability* and *impact* of such an event (see *Figure 11*). A prediction study on groundwater quality development may provide an early warning of a breakthrough. Thus, a reduction of the impact of a breakthrough can be achieved by gaining time for taking counter measures.
The minimized impact of breakthrough of a production well is calculated by optimising regional drinking water supply without this particular well. The production capacity of the disabled well will be optimally reallocated to other available wells.
This calculation offers the possibility to assess the vulnerability of a regional supply system to failure off any specific well (Figure 12).

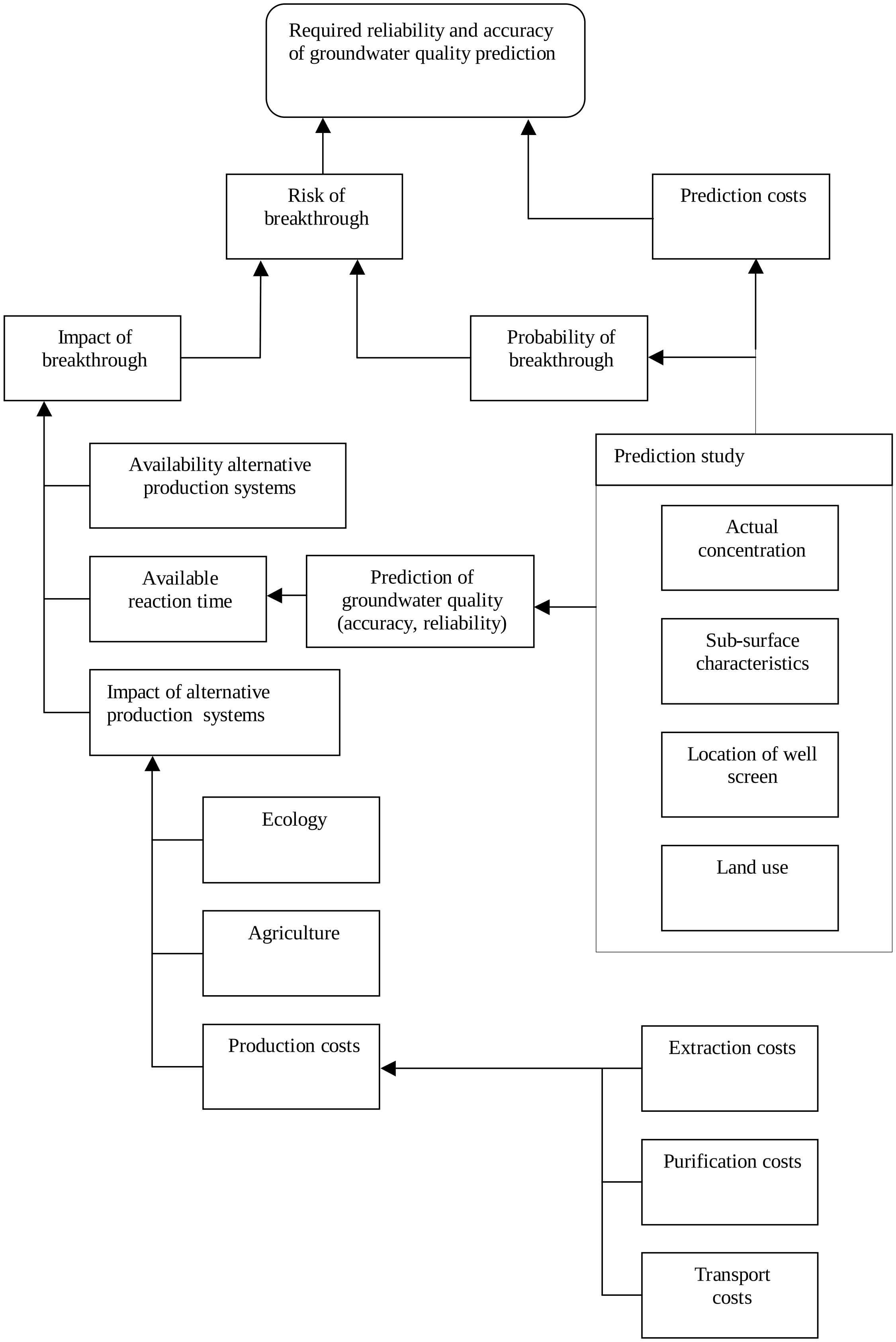

Figure 11 Required accuracy of prediction of pumped groundwater quality

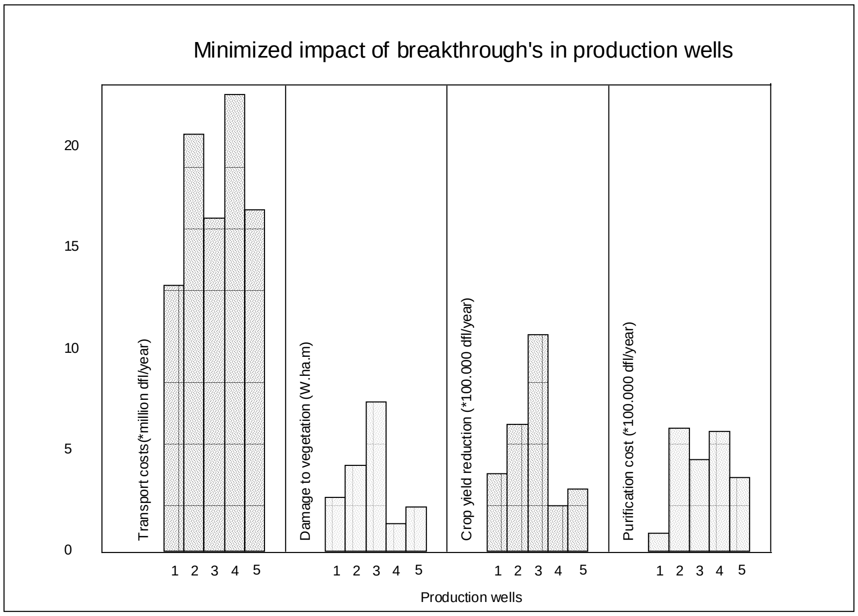

Figure 12 Minimized impact of well failure for 5 different wells

Calculation of well-specific costs and environmental impact as a function of discharge

Every production well displays a specific impact on costs and environment. Not only the relation between discharge and drawdown is well specific, but also the location of a well. The distance of the well to areas with valuable and vulnerable vegetation and to drinking water consumption locations is different for every well. By calculating the relation between costs and environmental impact for every well, the general ‘efficiency’ of a well in relation to the aforementioned categories can be assessed. These results allow an integrated comparison among different wells and can thus contribute to the evaluation of cost-efficient production scenarios, with minimal negative impact to environmental categories.

3.8. Visualization

Visualization options within the model consist partly of standard functions that are supplied within the standard ArcView® program. These possibilities comprise a great number of ways to visualize attributes of all map objects. A description of the functionality can be found in the ArcView reference manual (Esri, 1996).
A number of visualization functions were especially developed for this project:

Maps

Visualization options for maps are stated in the following:

Presentation of empirical data

- cross sectional presentation of lithological analyses
- cross sectional presentation of groundwater composition

Presentation of groundwater flow model results

- discharge dependent caption zone and travel times

- plane and cross sectional pathlines

Groundwater transport model results

- plane and cross-sectional groundwater composition

Charts

Charts can be created by the model either through the generic, standard chart option of ArcView, either by menu options that are especially developed for this application.

- Production scenario impact
- Source dependent discharge – impact relations

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