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INTEGRATED WATER RESOURCES MANAGEMENT IN ALPINE REGIONS:

DEVELOPMENT AND APPLICATION OF METHODOLOGIES FOR THE ANALYSIS OF PRESENT AND FUTURE CONDITIONS

DISSERTATION

EINGEREICHT AN DER LEOPOLD-FRANZENS-UNIVERSITÄT INNSBRUCK

FAKULTÄT FÜR BAUINGENIEURWISSENSCHAFTEN

zur Erlangung des akademischen Grades

“DOKTOR DER TECHNISCHEN WISSENSCHAFTEN“

Innsbruck, November 2009

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ACKNOWLEDGEMENT

First of all I would like to thank my supervisor, Prof. Wolfgang Rauch, for his continuous support and guidance throughout the years I worked on this thesis. I am always amazed in his ability in managing time – and keeping a positive attitude - within the many different things he works on. His interest in and openness to different scientific topics and their interrelation within the water sector were very valuable to this work.

I would also like to thank Prof. Hans Zojer, who kindly accepted to review my dissertation. He initiated the Competence Network Water Resources (CNET) in which framework my dissertation is situated. With this respect I also thank the people of *Wasser Tirol*, for an excellent cooperation within the project, and all other business partners - *Illwerke-Wassermanagement*, *W.E.I.Z., Wintertechnik Engineering* and *Bergbahnen St. Jakob*. I also greatly acknowledge their funding of the project, as well as the other funding institutions (www.waterpool.org). The *Doktoratsstipendium* of the University of Innsbruck supported this work during its last 1.5 years, for which my gratitude. Additionally, the presentation of scientific results at several international conferences was made possible by funding from several institutions, like the *ÖFG* (*Österreichische Forschungsgemeinschaft*), the IWA (International Water Association) and the *Dekanat der Fakultät für Bauingenieurwissenschaften*. I would like to thank all colleagues at the Institute, particularly the ones that also worked on the project to make it successful: Stefanie, Michael and Irene, as well as Gülay.

The print and publication of this work was made possible by means of the grant "*Druckkostenzuschuss für österreichische Dissertationen*" from the University of Innsbruck, for which my gratitude.

The continuous support of my wife Silvia has been invaluable, off course.

KURZFASSUNG

Diese Dissertation betrifft die Entwicklung (und Anwendung) von Methoden um die Nachhaltigkeit der Bewirtschaftung von Wasserressourcen und deren Nutzung in einem alpinen Umfeld – sowohl heute als in Zukunft - zu testen, und dies im breiterem Kontext vom integrierten Wasserressourcenmanagement (IWRM). Diese Methoden situieren sich innerhalb eines Workflows, welcher die Struktur dieser Arbeit formt. Sie bieten die Möglichkeit zur Analyse einer räumlich und zeitlich differenzierten Wasserbilanz zwischen verfügbaren Wasserressourcen und die verschiedene Wasserbedarfsträger im alpinen Kontext. Als Endresultat ergibt dies die Erstellung 1) einer Wasserbilanzierungskarte und 2) einer Wasserversorgungssystemvulnerabilitätskarte, welche kombiniert mit Alpinen Naturgefahren eine Risikokarte ergibt. Der Workflow mit den resultieren EUS (Entscheidungsunterstützendes System) oder *DSS (Decision Support System)* Karten situiert sich im Pfeiler „Management Instrumente" von IWRM – welche essentielle Methoden und Tools für einem Bewirtschaftungsplan eines Flusseinzugsgebiet entsprechen. Um rationale und informierte Entscheidungen zwischen verschiedene Aktionen auf der Einzugsgebietsebene machen zu können, müssen Entscheidungsträger die richtigen Tools zur Verfügung haben. Damit können derzeitige und zukünftige verfügbare Wasserressourcen, Wasserbedarf und resultierende Wasserdefizite und -Überschusse evaluiert und vorhersagt werden. Die Diskussion in dieser Dissertation beschränkt sich auf Management von Wasserquantität. Weil die zeitliche und räumliche Variation von sowohl Wasserressourcen (Oberflächengewässer, Quellen und Grundwasser) als Wasserbedarf (Haushalte, Gemeinde, Landwirtschaft, Industrie, Energie, Beschneiung, Bewässerung, …) in Gebirgsregionen sehr hoch ist, erfordert die Analyse und Quantifizierung von diesen Elementen speziell geeignete Methoden.

Der Workflow wurde für das Pilotgebiet Kitzbühel Raum in den Österreichischen Alpen entwickelt und getestet, welches 19 gemeinden in 4 Einzugesgebiete gelegen beinhaltet. Er zielt auf eine Anwendbarkeit in den verschiedenen Gebirgsregionen der Welt. Große Teile der Forschung dieser Dissertationen wurden im Rahmen des Kompetenznetzwerk Wasserressourcen GmbH (KNET) ausgeführt. Projekterarbeitungen und –Resultaten wurden kontinuierlich bei den Wirtschaftspartnern implementiert, angewandt und evaluiert. Verschiedene wissenschaftliche Artikel (Paper) wurden erfasst: 1 Buchkapitel, 1 Konferenzbeitrag und 6 Zeitschriftartikel. Die Dissertation ist als ein zusammenfassender Text mit den Artikeln als integrales Teil aufgebaut. Anders gesagt, die Arbeit ist eine Mischung einer Monographie und eine kumulative Dissertation.

Kapitel 3 behandelt die Abgrenzung vom Pilotgebiet, die räumliche Skala für welche die Methodik im Wesentlichen anwendbar ist und die Wichtigkeit von Wasser in Berggebiete. Dieses letzte Thema wurde hauptsächlich in Paper A und speziell für das Einzugsgebiet der Donau – in welchem die Kitzbühel Region gelegen ist – im ersten Kapitel von Paper B behandelt. Kapitel 4 bietet eine Übersicht von erforderliche Daten und deren Verfügbarkeit. Kapitel 5 analysiert die Hydrologie des Untersuchungsgebietes mittels dem semiflächendifferenzierten hydrologischen Model PREVAH für den Referenzzeitraum (1961-1990), und behandelt die Wasserverfügbarkeit für ein Normal- und Trockenjahr mittels Behalt von ökologisch erforderliche Wassermengen. In Kapitel 6 wird der Bedarf der verschiedenen Wasserbedarfsinteressenten ermittelt. Paper C präsentiert eine Methodik für die Berechnung von räumlich aufgelösten Wasserbedarfswerten in Rasterzellen für jeweiligen Zeitschritt – für Haushalte, Gemeinden, Industrie und Landwirtschaft (ohne Pflanzenbau). Als anderer wichtiger Wasserbedarfsinteressent wurde die Beschneiung identifiziert. Kapitel 7 – zu welchem die Papers D und E sich beziehen – beschreibt den verschiedenen Schritten die zu eine regionalen Wasserbilanz und die beiden DSS Karten führen. Kapitel 8 zeigt die Effekte von möglichen Zukunftsszenarien (demografische Änderungen und verschiedene Klimawandel-

szenarien) auf die Bewirtschaftung von Wasserressourcen und deren Nutzung in der Kitzbühel Region. Die Papers F, G und H beziehen sich zu diesem Kapitel.

Wasserressourcenmanagement in der Kitzbühel Region ist im Wesentlichen nachhaltig, sowohl heute als in Zukunft. Infolge Klimawandel und demografische Wandel werden eine Änderung in räumliche und zeitliche Wasserverfügbarkeit und ein Anstieg in Wasserbedarf vorhergesagt. Jedoch, wenn richtig bewirtschaftet – e.g. mittels Speicherteiche für die Beschneiung und Notverbindungen zwischen den verschiedenen Wasserversorgungssystemen – werden keine regionalen oder lokalen Defizite auftreten. Ökologisch erforderliche Wassermengen in Flüsse und Bäche des Untersuchungsgebiets werden behalten. Für das Trinkwasserversorgungssystem werden einige Komponenten vom Leitungsnetz für Alpinen Naturgefahren mit einem Risikopotential bewertet. Diese Stellen sollten für eine lokale Analyse herangezogen werden und wenn notwendig sollten Präventivmaßnahmen genommen werden.

Allerdings sind viele Gebirgsregionen in der Welt und ihre umliegende wasserabhängige Ebenen bereits heute von großen Wasserproblemen betroffen. Diese werden im 21. Jahrhundert, infolge Bevölkerungswachstums, schnelle Urbanisierung und Industrialisierung, Umweltschäden, ineffiziente Wassernutzung und Armut (ökonomische Wassermangel), verschärft durch Klimawandel, nur in Herausforderung zunehmen. Mit dem präsentierten Workflow und ihre eingebaute Methoden werden wichtige Management Tools für diese Gebirgsregionen geliefert. Mittels diesen können die verschiedenen Interessengruppen im Entscheidungsprozess aufgenommen werden und die richtigen Entscheidungen für ein nachhaltiges Wasserressourcenmanagement für heute und die Zukunft getroffen werden.

ABSTRACT

This dissertation focuses on the development (and application) of methodologies to test the sustainability of alpine or mountainous water resources management for present and future conditions, within the wider concept of IWRM. These methodologies fit within the framework of a workflow, which forms the structure of this work. They provide the possibility to achieve a temporally and spatially distributed assessment of the water balance between available water resources and the different water demand stakeholders in an alpine context. This results finally in the generation of 1) a water balance map and 2) a water supply system vulnerability map which combined with Alpine natural hazards gives a risk map. The workflow with its resulting DSS maps is situated in the pillar “management instruments” of IWRM, essential methods and tools in order to achieve river basin plans. In order to make rational and informed choices between alternative actions at the basin level, it is important for decision makers to have the right tools (management instruments) to evaluate and predict current and future water availability and demand, and resulting deficits and surpluses. The discussion in this dissertation is limited to water quantity management. As the temporal and spatial variation of both water resources (surface water, springs and ground water) and water demand (domestic, municipality, agriculture, industry, energy, snowmaking, irrigation …) is very high in mountainous regions, the analysis and quantification of the latter require specific methodologies.

The workflow is developed and tested within the case study area of the greater Kitzbühel region in the Austrian Alps, encompassing 19 municipalities located in 4 catchments. It aims at being applicable for different mountainous regions of the world. Large parts of the research of the dissertation were conducted within the framework of the Competence Network Water Resources (CNET or KNET). Project developments and results were continuously implemented, applied and evaluated within the know-how of the business partners. Several papers were written and published during the duration of this dissertation, and they support the scientific value of this work. In total 8 papers are included: 1 book chapter, 1 conference proceedings and 6 journal papers. The dissertation is structured as a summarising text, with the papers as an integral part of the dissertation. In other words, this work is a mixture of a monograph and a cumulative dissertation.

Chapter 3 discusses the delineation of the case study area, the spatial scale for which the methodology is primarily applicable and the importance of mountain water. The latter topic is generally discussed in paper A and particularly for the Danube river basin – in which the Kitzbühel region is located – in the first section of paper B. Chapter 4 provides an overview on required data and their availability. Chapter 5 analyses the hydrology of the case study area by means of the semi-distributed hydrological model PREVAH for the reference period (1961-1990), and discusses the water availability for a normal and dry year whilst maintaining environmental flows. Within chapter 6 the water demand for the different stakeholders is assessed. Paper C presents here a methodology for the calculation of grid cell spatially distributed water demands – for domestic, municipal, industrial and agricultural (without crop production) purposes – for any time step. As other major water demand stakeholder snowmaking is identified. Chapter 7 – to which the papers D and E relate - describes the different steps that lead to a regional water balance and the two DSS maps. Chapter 8 shows the effect of possible futures (demographic changes and different climate change scenarios) on the water resources management of the Kitzbühel region. Papers F, G, H relate to this chapter.

Water resources management in the Kitzbühel region proves to be generally sustainable, both at present and in future. Due to climate change and demographic changes there will be

a change in spatial and temporal water availability and an increase in water demands. However, when managed properly – e.g. by using reservoirs for technical snowmaking and emergency connection pipes between different water service undertakings – neither regional nor local water deficits will occur. Environmental flows in the rivers and streams of the project area are maintained. For the water supply distribution system some risky areas with respect to alpine natural hazards were identified. These locations should be analysed in detail and when necessary protection measures constructed.

However, many mountainous regions of the world and their dependent lowlands already today face large problems. These will only become more challenging in the 21st century, due to population growth, rapid urbanisation and industrialisation, environmental degradation, inefficient water use and poverty (economic water shortage), all aggravated by climate change. With the presented workflow and its methodologies, important management tools for these mountainous basins are provided to include the different stakeholders in the decision process and to make sustainable water resources management decisions for now and in future.

LIST OF INCLUDED PAPERS

A **Vanham, D.,** Rauch, W. (2009) Mountain water and climate change. In: Climate Change and Water - International Perspectives on Mitigation and Adaptation. Joel Smith, Carol Howe and Jim Henderson (Ed.), page 21-40, ISBN 9781843393047.

B **Vanham, D.,** Rauch, W. (2009) Retreating snowpacks under climate change: Implications for water resources management in the Austrian Alps, in: Improving Integrated Surface and Groundwater Resources Management in a Vulnerable and Changing World, Proceedings of JS.3 at the Joint IAHS & IAH Convention, Hyderabad, India, 6-12 September 2009, IAHS Publ. 330, 231-238.

C **Vanham, D.,** Millinger, S., Pliessnig, H., Rauch, W. (2009) Rasterised water demands: methodology for their assessment and possible applications. *Submitted to Water Resources Management.*

D **Vanham, D.,** Fleischhacker, E., Rauch, W. (2008) Technical Note: Seasonality in alpine water resources management – a regional assessment. Hydrology and Earth System Sciences, 12(1), 91-100.

E Möderl, M., **Vanham, D.,** De Toffol, S., Rauch, W. (2008) Potential impact of natural hazards on water supply systems in Alpine regions. Water Practice and Technology 3/3, doi:10.2166/wpt.2008.060.

F Laghari, A.N., **Vanham, D.,** Rauch, W. (2009) To what extend does climate change result in a shift in alpine hydrology? A case study in the Austrian Alps. *Submitted to Hydrological Sciences Journal.*

G **Vanham, D.,** Fleischhacker, E., Rauch, W. (2009) Impact of snowmaking on alpine water resources management under present and climate change conditions. Water Science and Technology – WST, 59 (9), 1793-1801, doi:10.2166/wst.2009.211.

H **Vanham, D.,** Fleischhacker, E., Rauch, W. (2009) Impact of an extreme dry and hot summer on water supply security in an alpine region. Water Science and Technology – WST, 59 (3), 469-477, doi:10.2166/wst.2009.887.

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1 INTRODUCTION

1.1 INTEGRATED WATER RESOURCES MANAGEMENT (IWRM)

Integrated water resources management (IWRM) is a systems approach to water management, recognising the need to manage the entire water cycle and its interconnectivity.

During the preparatory conferences for the UN Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992, the concepts underlying Integrated Water Resources Management were for the first time widely debated (Savenije and Van der Zaag, 2008). The concept was first introduced within one of these conferences - the International Conference on Water and the Environment (ICWE, 1992) - in Dublin, which led to the Dublin Principles. The water interest of the UN is fragmented over WMO, WHO, FAO, UNESCO, UNDP, UNEP and UNICEF (Savenije and Van der Zaag, 2008). Important steps in the process towards more coordination have been the formation of the Global Water Partnership (GWP) and the World Water Council (WWC), which both have the aim to coordinate the implementation of IWRM principles and practices worldwide. The WWC concentrates on raising awareness at political levels, whereas GWP aims at the implementation of IWRM concepts at the operational level. Together they have been the driving force behind the World Water Forums in The Hague (2000), Kyoto (2003), Mexico City (2006) and Istanbul (2009).

Some definitions of IWRM have been proposed by the GWP (GWP and INBO, 2009) and (Pollard, 2002), among others:

- The GWP defines IWRM as *a process that promotes the co-ordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems*.

- Pollard (2002) defines IWRM as *simultaneously a philosophy, a process and an implementation strategy to achieve equitable access to and sustainable use of water resources by all stakeholders at catchment, regional and international levels, while maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits.*

The Dublin Principles state that IWRM implies (ICWE, 1992):

- an inter-sectoral approach
- the representation of all stakeholders
- the consideration of all physical aspects of the water resources
- considerations of sustainability and the environment

Accordingly, approaches to IWRM do not regard the ecosystem as a “user” of water in competition with other users, but as the base from which the resource is derived and upon which development is planned (Jewitt, 2002).

Due to the nature of water, IWRM has to take account of the following four dimensions: 1) water resources; 2) water demand; 3) the spatial scale and 4) the temporal scale (taking into account the temporal variation in availability of and demand for water resources) (Savenije and Van der Zaag, 2008). The values underlying the IWRM concept are well captured by the three E's proposed by (Postel, 1992): equity, ecological integrity (or environmental sustainability) and efficiency. Implementing an IWRM process based on these values is in fact, a question of getting the "three pillars" (Figure 1-1) right: moving towards an environment of appropriate policies, strategies and legislation for sustainable water resources development and management; putting in place the institutional framework through which the policies, strategies and legislation can be implemented; and setting up the management instruments required by these institutions to do their job (Jønch-Clausen, 2004).

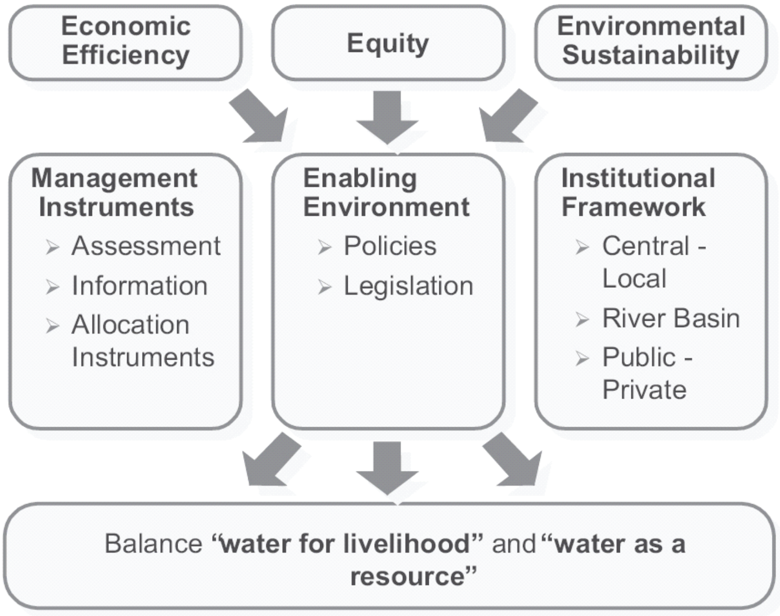


Figure 1-1: The "three pillars" or three-dimensional framework of IWRM: Enabling Environment, Institutional Framework and Management Instruments (Jønch-Clausen, 2004)

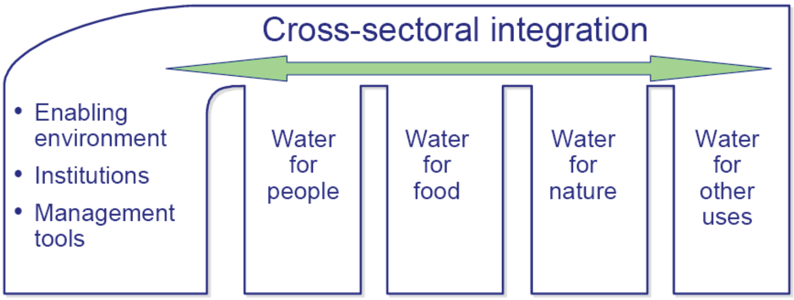


Figure 1-2: IWRM and its relation to sub-sectors (Jønch-Clausen, 2004)

At the basin level, IWRM can be defined as a process that enables the co-ordinated management of water, land and related resources within the limits of a basin so as to optimise and equitably share the resulting socioeconomic well-being without compromising the long-term health of vital ecosystems. Any formal or informal entity that manages water resources at the basin scale can be referred to as basin organisation (GWP and INBO, 2009). Although formal basin organisations are part of the public sector (including different government stakeholders/authorities), for water to be managed effectively, a wide range of stakeholders like community groups, economical sectors, non-governmental organisations and private enterprises, need to be involved. Different government stakeholders/authorities have to be involved, because land management, which covers planning, forestry, industry, agriculture and the environment, is usually governed by policies not connected to water policy and is managed by separate parts of an administration. In different parts of the world various types of river basin organizations are implemented (GWP and INBO, 2009): basin commissions or basin authorities, basin directorates or agencies and basin associations. In the European Union (EU), international basin commissions are co-ordinating the implementation of the Water Framework Directive in riparian EU member states. Examples are the International Commission for the Protection of the Danube River (www.icpdr.org) and the Ruhr Association (www.ruhrverband.de). In other regions of the world examples are the Murray–Darling Basin Authority (www.mdba.gov.au), the Mekong River Commission (www.mrcmekong.org) and the Changjiang (Yangtze) Water Resources Commission (www.cjh.com.cn/eng).

The role of IWRM will vary depending on the development stage of the country (Jønch-Clausen, 2004). Developing countries, countries in transition and developed countries will all have different ways of implementing the IWRM process and derive different benefits. Developing countries will in particular see sound water resources management as a factor in addressing poverty, hunger, health and environmental sustainability. Countries in transition may see IWRM as a rational approach to improvement of their resource management thus assisting the continued development of their economies. Developed countries may find valuable inspiration in the IWRM processes and sometimes chose to design their own variety as has happened in the case of the EU Water Framework Directive (WFD).

The WFD provides a European policy basis at the river basin scale. The river basin management and planning process prescribed in the WFD is an adaptation of the IWRM principles (GWP and INBO, 2009), involving all physical domains in water management, sectors of water use, socio-economics and stakeholder participation. The European Water Framework Directive imposes the development of basin plans in Europe, forcing riparian countries to work together on the development and management of their river basins.

There are two general approaches to planning and management in river basins. One is from the top down, often called command and control. The other is from the bottom up, often called a grass-roots approach. Both approaches can lead to an integrated plan and management policy (Loucks and van Beek, 2005):

> *1. Top-Down Planning and Management*: Over much of the past half century, water resources professionals have been engaged in preparing integrated, multipurpose ‘master’ development plans for many of the world’s river basins. These plans typically consist of a series of reports describing all aspects of water resources management and use, in which alternative management options are identified and evaluated. On the basis of these evaluations, the preferred plan is presented. Using this approach there is usually little if any active participation by interested stakeholders. In today’s environment, where publics are calling for increasing participation in planning and management activities, top-down approaches are becoming less desirable or acceptable.

2. *Bottom-Up Planning and Management*: Within the past decade water resources planning and management processes have increasingly involved the active participation of interested stakeholders – those affected in any way by the management of the water and land resources. Experiences of trying to implement plans developed primarily by professionals have shown that, even if such plans are technically flawless, they have little chance of success if they do not take into consideration the concerns of affected local stakeholders and do not have their support. Water resources management should thus involve sufficient public participation of so that a) valuable local information and technical inputs are identified and utilized, b) the interests of all affected groups are identified and taken into account, and c) local water users feel a part of the river basin plan and accept their responsibilities for operation and maintenance.

IWRM is now a well known and widely accepted concept throughout the world. A clear vision is that water governance, management and use cannot be considered independently if the goal is water resources sustainability. Both developed and developing countries are reforming their water resources planning policies and laws. European Union members, for example, are implementing the Water Framework Directive. Many middle- and low-income countries in Africa, Asia and South America are engaging in reform, focusing on principles of IWRM. Various types of river basin organizations have been implemented throughout the world. However, a recent UN survey on the progress towards 2005 targets for IWRM and water efficiency plans (UN-Water, 2008), concluded that a lot of work still needs to be done.

1.2 IWRM IN ALPINE REGIONS: SCOPE OF THE DISSERTATION

This dissertation focuses on the development (and application) of methodologies to test the sustainability of alpine or mountainous water resources management for present and future conditions, within the wider concept of IWRM. These methodologies are situated in the pillar “management instruments” of IWRM as presented in Figure 1-1. The two other pillars - Enabling Environment and Institutional Framework – are not part of this dissertation.

The main focus of the dissertation is the development and application of methodologies within the context of a workflow in order to achieve a temporally and spatially distributed assessment of the water balance between available water resources and the different water demand stakeholders in an alpine context. As the temporal and spatial variation of both water resources (surface water, springs and ground water) and water demand (domestic, municipality, agriculture, industry, energy, snowmaking, …) is very high in mountainous regions, the analysis and quantification of the latter require specific methodologies. Temporal and spatial variations of mountainous water resources are high due to the effect of rain accumulation at high altitudes, specific hydrogeology, and the storage of water in the form of snow and ice. On the other hand water demand is generally concentrated in the valleys, and the demands of the different stakeholders fluctuate over the seasons of the year. By means of the presented workflow a detailed water balance - temporally and spatially distributed – can be generated for an alpine region for the current and future situations (including climate change considerations). Additionally a methodology is presented to test the vulnerability of an alpine water supply system. The workflow is developed and tested within the case study of the greater Kitzbühel region in the Austrian Alps, but aims at being applicable for different mountainous regions of the world.

River basin management plans (RBMP) are an important means to reach IWRM. Basin organisations aim at developing and implementing such a plan. Within the EU WFD, the development of a river basin plan is obligatory. This dissertation is situated in pillar “management instruments” (Figure 1-1) of IWRM, essential methods and tools in order to achieve river basin plans. In order to make rational and informed choices between alternative actions at the basin level, it is important for decision makers to have the right tools (management instruments) to evaluate and predict current and future water availability and demand, and resulting deficits and surpluses. However, it has to be stressed that planning is a continuing sequential process (Loucks and van Beek, 2005). Water resources plans need to be periodically updated and adapted to new information, new objectives, and updated forecasts of future supplies, demands, costs and benefits. A final solution to a water resources planning problem rarely exists: plans and projects are dynamic. They evolve over time as facilities are added and modified to adapt to changes in management objectives and in the demands placed on the facilities.

UNESCO for example proposes a pentagram as a tool for comparing alternative plans (Figure 1-3). A pentagram can be used to illustrate a set of decision variables such the ‘triple-bottom line’, which assesses economic, social and environmental success as indicators of sustainable development. This enables stakeholders to compare the potential success of proposed plans.

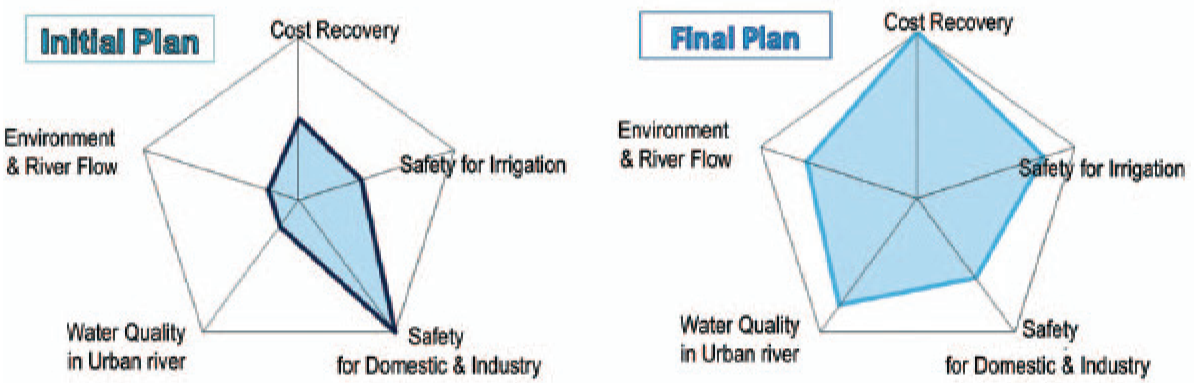


Figure 1-3: A pentagram as tool for comparing alternative river basin management plans. Source: (UNESCO, 2009b)

The discussion in this dissertation is limited to water quantity management. Clearly the regimes of flows, velocities, volumes and other properties of water quantity will affect the quality of that water as well. Moreover, from the perspective of IWRM, quantity and quality aspects should be considered jointly. However, unless water quantity management strategies are based on requirements for water quality, water quality measures do not normally affect water quantity. For this reason it is common to separate analytical approaches of water quantity management from those of water quality management (Loucks and van Beek, 2005). For the case study area Kitzbühel region, water quality is – presently - not an important issue. Source water is of good quality (as it comes from the mountains) and all used water is treated by water treatment plants. However, when attempting to predict the impacts of any management policy on both water quantity and quality, both quantity and quality models are needed.

Also the International Commission for the Protection of the Danube River or ICPDR (www.icpdr.org) aims at developing, implementing and (future) updating a river basin management plan. The Alps form a large and hydrological important part of the Danube basin, as well as the Carpatian mountain range. The case study area greater Kitzbühel region is located within the Danube basin. The developed methodologies and resulting findings can contribute significantly to the Danube RBMP. It also has to be stressed that RBMP of subbasins and their respective catchments can also be developed, within the wider framework of a basin RBMP. This means that the methodologies and results of this dissertation have the potential to contribute to more regional or local RBMP within the Danube RBMP. The resulting DSS maps of the dissertation can be used as management tool for stakeholder involvement (Figure 1-4).

Figure 1-4: Stakeholder involvement in a river basin management plan. Source: (Loucks and van Beek, 2005)

1.3 PROJECT CONTEXT

1.3.1 COMPETENCE NETWORK WATER RESOURCES (CNET - KNET)

Large parts of the research of the dissertation were conducted within the framework of the Competence Network Water Resources (CNET or KNET – Kompetenznetzwerk Wasserressourcen)(www.waterpool.org). Over 75 commercial and research partners in Austria, Italy, Slovenia and Croatia are part of the network, which is made up of six central network hubs, with 45 sub-projects. Within the network hub “Netnode 2 - Sustainable Water Supply in Mountain Areas”, the sub-project “Work package 2.1.2 - Water supply and precautionary logistic systems” functioned as a framework for most of the research results presented in this dissertation.

Figure 1-5: Netnode 2 meeting, 22. June 2006 in Innsbruck (Foto © R. Ebenbichler)

Table 1-1: Work Package 2.1.2 „Water supply and precautionary logistic systems“ in CNET

Business partners	**Research partner**	**Project duration**
• Wasser Tirol (www.wassertirol.at) • Illwerke-Wassermanagement (www.illwerke.at) • W.E.I.Z. (www.w-e-i-z.com) • Wintertechnik Engineering (www.wintertechnik.at) • Bergbahnen St. Jakob (www.bergbahnen-stjakob.at)	Working Unit Environmental Engineering, Institute of Infrastructure, University of Innsbruck	09/2004 – 06/2008
Content:	Methodology for the analysis and forecasting (prediction) of integrated water supply and precautionary logistic systems (resources, technical supply systems and demand) in alpine regions; research of the water cycle with respect to artificial snowmaking	
Research areas	1) Pilot area greater Kitzbühel region; verification areas 2) Bregenzer Wald and 3) Weizer region; 4) Defereggental (Eastern Tyrol)	

The sub-project “Work package 2.1.2” involved one research institute and five business partners (Table 1-1). Funding was provided by different governmental institutions in combination with the business partners. The work package aimed at the development of a methodology for the analysis and forecasting of the total alpine water system, composed by the sub-elements water resources, water demand and water supply systems (Fleischhacker, 1994). Project developments and results were continuously implemented, applied and evaluated within the know-how of the business partners, resulting in so-called competence build-up. The partners were in this way provided with the knowledge to apply developed methodologies on other project areas themselves.

Figure 1-6 Researchers of the University Innsbruck within work package 2.1.2; (from left to right) D. Vanham, S. Millinger, M. Möderl and W. Rauch (Foto © R. Ebenbichler)

1.3.2 LIST OF PUBLICATIONS AND REPORTS

Table 1-2 gives a list of publications and reports that relate to this dissertation. Many – but not all – originate within the framework of the CNET project.

Table 1-2: List of publications and reports related to this dissertation

Journal Articles

Vanham, D., Fleischhacker, E., Rauch, W. (2009) Impact of an extreme dry and hot summer on water supply security in an alpine region. Water Science and Technology – WST, 59(3), 469-477.

Vanham, D., Fleischhacker, E., Rauch, W. (2009) Impact of snowmaking on alpine water resources management under present and climate change conditions. Water Science and Technology – WST, 59(9), 1793-1801.

Vanham, D., Millinger, S., Pliessnig, H., Rauch, W. (2009) Rasterised water demands: methodology for their assessment and possible applications. *Submitted to Water Resources Management*.

Laghari, A.N., **Vanham, D.**, Rauch, W. (2009) To what extend does climate change result in a shift in alpine hydrology? A case study in the Austrian Alps. *Submitted to Hydrological Sciences Journal.*

Vanham, D., Rauch, W. (2009) Climate Change and its Influence on Mountain Snow Covers: Implication for Drinking Water in the European Alps. The International Journal of Climate Change: Impacts and Responses.

Vanham, D., Fleischhacker, E., Rauch, W. (2008) Technical Note: Seasonality in alpine water resources management – a regional assessment. Hydrology and Earth System Sciences, 12(1), 91-100.

Möderl, M., **Vanham, D.**, De Toffol, S., Rauch, W. (2008) Potential impact of natural hazards on water supply systems in Alpine regions. Water Practice and Technology 3/3.

Möderl, M. De Toffol, S. **Vanham, D.** Fleischhacker, E. Rauch, W. (2008): Abschätzung des Risikos von Naturgefahren für Wasserversorgungssysteme auf Basis der Systemvulnerabilität. In: Österreichische Wasser- und Abfallwirtschaft 9-10, 149 - 155.

Series

Zwolsman, G., **Vanham, D.**, Fleming, P., Davis, C., Lovell, A., Nolasco, D., Thorne, O., de Sutter, R., Fülöp, B., Staufer, P., Johannessen, A. (2009) Climate change and the water industry – Practical responses and actions. Perspectives papers on Water and Climate Change Adaptation No.10, World Water Council, IUCN and IWA.

Conference proceedings

Vanham, D., Rauch, W. (2009) Retreating snowpacks under climate change: Implications for water resources management in the Austrian Alps, in: Improving Integrated Surface and Groundwater Resources Management in a Vulnerable and Changing World, Proceedings of JS.3 at the Joint IAHS & IAH Convention, Hyderabad, India, 6-12 September 2009, IAHS Publ. 330, 231-238.

Vanham, D., Rauch, W. (2009) Climate Change and its Influence on Mountain Snow Covers: Implication for Drinking Water in the European Alps. International Conference on Climate Change: Impacts and Responses, 9-11 January 2009, Pune, India.

Möderl, M., **Vanham, D**., De Toffol, S., Rauch, W. (2008) Potential impact of natural hazards on water supply systems. Proceedings of the 6th World Water Congress, Vienna, Austria, 8-12 September 2008.

Vanham, D., Fleischhacker, E., Rauch, W. (2008) Impact of an extreme dry and hot summer on water supply security in an alpine region. Proceedings 11th international specialized conference on watershed and river basin management, Budapest, Hungary, 4-5 September 2008.

Vanham, D., Fleischhacker, E., Rauch, W. (2008) Impact of snowmaking on alpine water resources management under present and climate change conditions. Proceedings 4th Biennial International Young Water Professionals Conference, Berkeley, USA, 16-18 July 2008.

De Toffol, S., **Vanham, D.,** Laghari, A.N., Rauch, W. (2008): Investigations of Climate Change Effects on Public Water Supply in Alpine Regions. Proceedings of IFAT 2008 – Sustainable Water Management in response to 21st century pressures, 5.–9. May 2008, Munich.

Rauch, W.; Ebenbichler, R.; Fleischhacker, E.; Lek, I.; Millinger, S.; Möderl, M. und **Vanham, D.** (2008): WP 2.1.2: Alpine Wasserversorgungs- und Vorsorgelogistik. In: Tagungsband zur Internationalen Fachtagung „Wasserressourcen und deren Bewirtschaftung – Die Bedeutung von Netzwerken“, Graz, 22.-23 April 2008, p. 82-88.

Vanham, D., De Toffol, S., Fleischhacker, E., Rauch, W. (2009) Water demand for snowmaking under climate change conditions in an alpine environment. In: Borsdorf, A.; Stötter, J.; Veulliet, E. (Hrsg.): Managing Alpine Future. Proceedings of the Innsbruck Conference 15-17 October 2007. IGF-Forschungsberichte, Band 3, Wien.

Vanham, D., Millinger, S., Heller, A., Pliessnig, H., Möderl, M. und Rauch, W. (2007). GIS-gestütztes Verfahren zur Erhebung und Analyse der Trinkwasserversorgungsinfrastruktur im alpinen Raum am Beispiel des Großraumes Kitzbühel. In: Strobl, J., Blaschke, T. & Griesebner, G. (eds.): Angewandte Geoinformatik 2007 - Beiträge zum 19. AGIT-Symposium, Salzburg, 3-6 Juli 2007, 832-837, Heidelberg (Wichmann Verlag).

Diploma theses and dissertations

Millinger, S. (2008) Wasserversorgungsinfrastruktur im Großraum Kitzbühel - Erhebung, Erfassung und Analyse mit einem geographischen Informationssystem. Diplomarbeit, Institut für Geographie, Leopold-Franzens-Universität Innsbruck, 126 S., Innsbruck

Vanham, D. (2009) Integrated water resources management in alpine regions: development and application of methodologies for the analysis of present and future conditions.- Phd Thesis in Progress, University of Innsbruck, Innsbruck.

Möderl, M. (2009) Modelltechnische Analyse von Netzwerksystemen der Siedlungswasserwirtschaft. - Phd Thesis, University of Innsbruck, Innsbruck.

Reports

Vanham, D. et al. (2008) Endbericht, Netzknoten 2, Work Package 2.1.2 „Alpine Wasserversorgungs- und Vorsorgelogistik“, Universität Innsbruck, Wasser Tirol, W.E.I.Z., Vorarlberger Illwerke, Bergbahnen Sankt Jakob, Wintertechnik Engineering, 30.06.2008, Innsbruck.

A listing of reports written in the context of the project can be found in:

Rauch, W.; Ebenbichler, R.; Fleischhacker, E.; Lek, I.; Millinger, S.; Möderl, M. und **Vanham, D.** (2008): WP 2.1.2: Alpine Wasserversorgungs- und Vorsorgelogistik. In: Tagungsband zur Internationalen Fachtagung „Wasserressourcen und deren Bewirtschaftung – Die Bedeutung von Netzwerken“, Graz, 22.-23 April 2008, p. 82-88.

2 STRUCTURE OF THE THESIS AND DEVELOPED WORKFLOW

2.1 WORKFLOW

Figure 2-1 shows the positioning of the developed workflow in this dissertation within the framework of IWRM. Within IWRM, management instruments (Jønch-Clausen, 2004) are the elements and methods that enable and help decision makers to make rational and informed choices between alternative actions (Figure 1-1 and Figure 2-1).

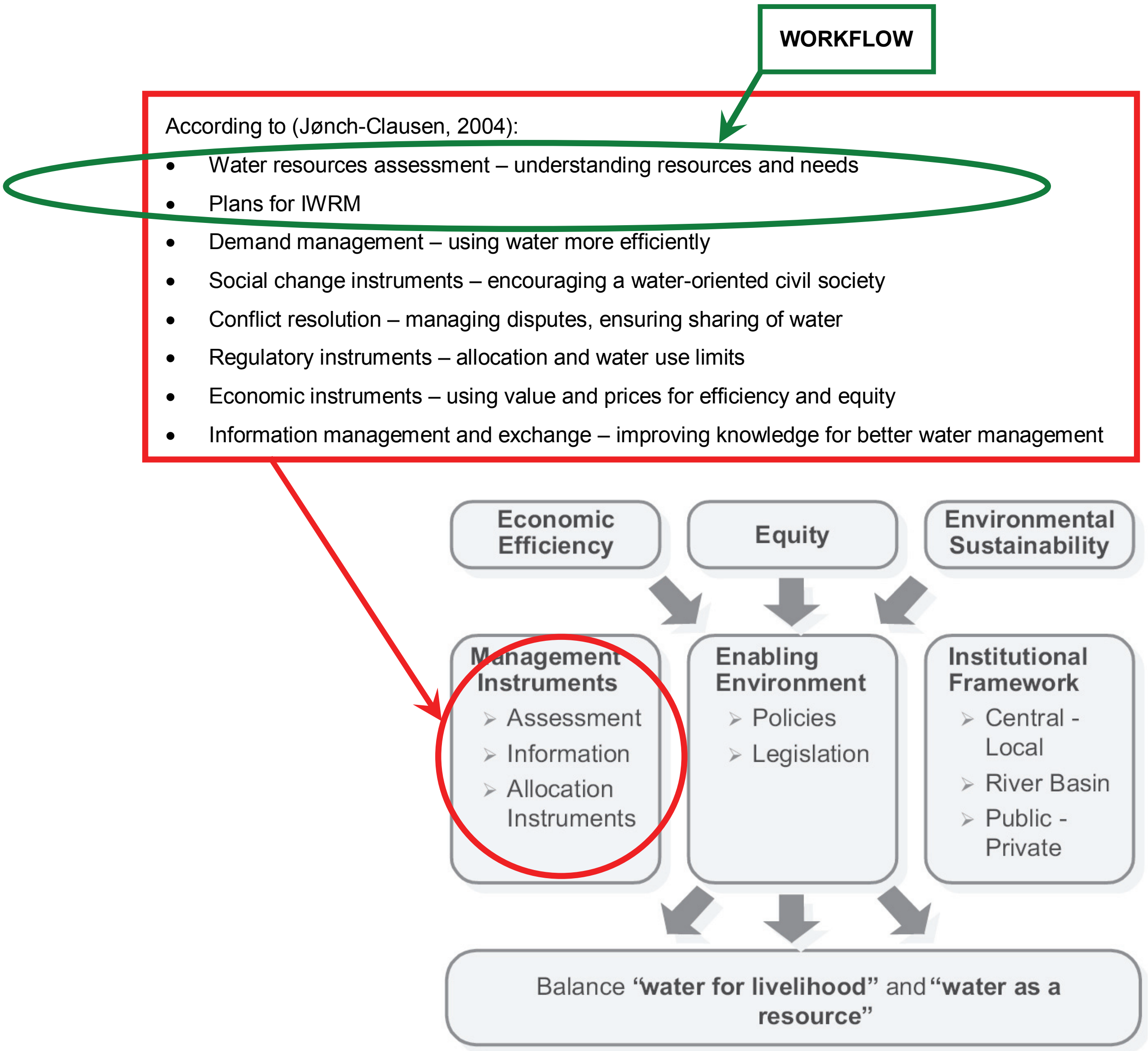


Figure 2-1: Positioning of the developed workflow within the "pillar" Management Instruments of IWRM according to (Jønch-Clausen, 2004)

Figure 2-2 shows the developed workflow with schematically the topics of the different papers positioned within. The synthesis of the developed methodologies and different steps results in firstly a water balance map and secondly a water supply systems vulnerability map, which combined with Alpine natural hazards, gives a risk map. These maps are important tools to test an alpine project river basin on its sustainability both at present and for possible future scenarios. The different steps will be discussed in the following chapters.

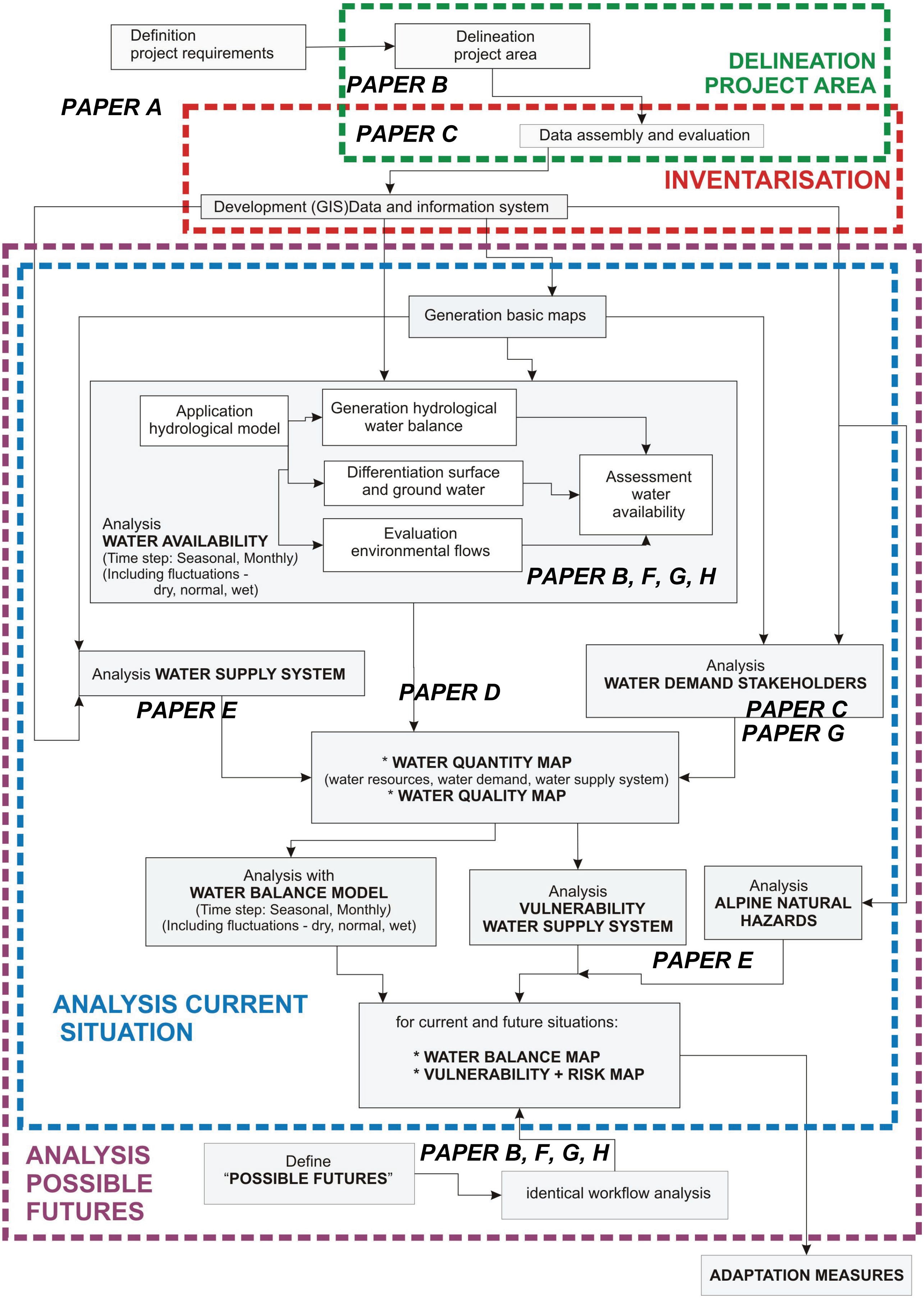


Figure 2-2: Developed workflow to achieve 1) a water balance map and 2) a water supply system 2a) vulnerability map and 2b) Alpine natural hazards risk map

These papers cover large parts of the presented methodology. They were written and published during the duration of the dissertation, and they support the scientific value of this work. The dissertation is structured as a summarising text, with the papers as an integral part of the dissertation. In other words, this work is a mixture of a monography and a cumulative dissertation. A detailed overview of the included papers is given in the following chapter 2.1. In total 8 papers are included: 1 book chapter, 1 conference proceedings and 6 journal papers. They are discussed in more detail in the following chapters of the dissertation.

A central focus within the different steps of the workflow is the inclusion of both the spatial and temporal distribution in available water resources and water demand. Especially in mountainous areas this is very important.

2.2 INCLUDED PAPERS

2.2.1 A: BOOK CHAPTER

Vanham, D., Rauch, W. (2009)

Mountain water and climate change.

In: Climate Change and Water - International Perspectives on Mitigation and Adaptation. Joel Smith, Carol Howe and Jim Henderson (Ed.) page 21-40, ISBN 9781843393047.

Mountains are a water reservoir for many regions in the world. Numerous river basins rely strongly on their mountainous parts for water, due to the effect of rain accumulation at high altitudes, specific hydrogeology, and the storage of water in the form of snow and ice. The latter is true for regions with substantial seasonal snowpacks and glaciers. Climate change will affect mountain hydrology significantly, with important consequences for the water availability both in upstream and downstream parts of river basins. This paper gives an overview of possible effects in river basins throughout the world. An extensive literature overview is made, and different regional and world maps are displayed. Within the workflow this book chapter describes the typical spatial and temporal fluctuations of Alpine hydrology and water demand, as well as the importance of many mountain regions for the surrounding lowlands. It sets a framework for the first step of the workflow, i.e. the definition of the project requirements.

2.2.2 B: CONFERENCE PROCEEDINGS

Vanham, D., Rauch, W. (2009)

Retreating snowpacks under climate change: Implications for water resources management in the Austrian Alps.

in: Improving Integrated Surface and Groundwater Resources Management in a Vulnerable and Changing World, Proceedings of JS.3 at the Joint IAHS & IAH Convention, Hyderabad, India, 6-12 September 2009, IAHS Publ. 330, 231-238.

This paper presents a synthesis of different steps within the workflow. However, these steps are described in more detail in the following **papers C, D, F, G** and **H**. The first part of the paper situates the topics of paper A within the project region of this dissertation. More specifically three different hydrological regimes (two mountainous and one lowland) within the Danube River basin are described. Their importance for Integrated

Water Resources Management (IWRM) within the whole river basin is discussed. One of these hydrological regimes – a non-glacerised mid mountain region in the Austrian Alps – is the case study area of this dissertation. The disproportionate hydrological influence of the Alps is demonstrated for the Danube River basin, especially during summer, late spring and early autumn.

2.2.3 C: JOURNAL PAPER

Vanham, D., Millinger, S., Pliessnig, H., Rauch, W. (2009)

Rasterised water demands: methodology for their assessment and possible applications.

Submitted to Water Resources Management.

In this paper a methodology for the calculation of grid cell spatially distributed water demands is presented. As case study the Kitzbühel region was chosen. Austria is one of few countries within the European Union that provides data of the population and housing census of 2001 in a raster format, with resolutions of 125m, 250m, 500m, 1000m and 2500m. From these available data, population and employment raster data were used for the analysis. Based upon the latter and a calibrated related rate of water use (litre per unit per time interval), rasterised yearly and winter water demands were calculated. Included are the different water demand stakeholders: population of principal and secondary residence, tourist overnight stays, employment activities (industries, small trade, schools, hospitals, administration, …) and agriculture. Apart from detailed spatially distributed information, this methodology can also be used for different time steps (yearly, seasonal, monthly, weekly, daily, hourly). The rasters are independent of political entities like countries or municipalities. They provide the possibility to reaggregate water demands on political entity levels to the river basin scale. They can be used in studies for landscape and urban planning and a wide range of water resources management and hydraulics related studies. Within the workflow they are essential for the generation of both the water balance and the water supply system vulnerability map. For the latter they are necessary for the transposition of cell water demand values to respective pipe sections of the water distribution network.

2.2.4 D: JOURNAL PAPER

Vanham, D., Fleischhacker, E., Rauch, W. (2008)

Technical Note: Seasonality in alpine water resources management – a regional assessment.

Hydrology and Earth System Sciences, 12(1), 91-100.

Alpine regions are particularly affected by seasonal variations in water demand and water availability. Especially the winter period is critical from an operational point of view, as being characterised by high water demands due to tourism and low water availability due to the temporal storage of precipitation as snow and ice. The clear definition of the winter period is thus a minimum prerequisite for water resource management in alpine regions. This paper presents a GIS-based multi criteria method to determine the winter season. A snow cover duration dataset serves as basis for this analysis. Technical snow-making and (winter) tourism were identified as the two major seasonal water demand stakeholders in the study area. Winter was defined as the period from December to March. A clear distinction between the different seasons is a must for any integrated assessment. A seasonal time step for the analyses in the workflow is a minimum.

2.2.5 E: JOURNAL PAPER

Möderl, M., **Vanham, D.,** De Toffol, S., Rauch, W. (2008)

Potential impact of natural hazards on water supply systems in Alpine regions.

Water Practice and Technology 3/3, doi:10.2166/wpt.2008.060.

This paper describes the methodology for the generation of the water supply system 1) vulnerability map and 2) Alpine natural hazards risk map, as presented in the workflow. The approach serves for the definition of zones with low, medium and high potential risk by combining vulnerability and hazard maps. This approach enables the possibility to accomplish prevention measures on risky sites. A management support tool (VulNetWS – Vulnerability of Water Supply Networks) is developed which quantifies vulnerability based on hydraulic and quality simulations assuming component failure of each single WSS component. Hazards of flooding, landslide, debris flow and avalanches are calculated and categorized in potential low, medium and high hazard zones. For this analysis different GIS data sets (e.g. Austrian hazard zone maps, HORA "Flood Risk Zoning") are used. The methodology is presented by applying it upon an alpine region encompassing the municipality of Kitzbühel and 4 neighbouring municipalities. The combination of vulnerability and hazard is summarized using a risk matrix that highlights a zone of 0.42 square kilometres within the study area as being potentially risky. The production of a water demand raster – as described in **paper C** – is an essential step in the generation of the vulnerability map.

2.2.6 F, G, H: JOURNAL PAPERS

Laghari, A.N., **Vanham, D.,** Rauch, W. (2009) – **paper F**

To what extend does climate change result in a shift in alpine hydrology? A case study in the Austrian Alps.

Submitted to Hydrological Sciences Journal.

Vanham, D., Fleischhacker, E., Rauch, W. (2009) – **paper G**

Impact of snowmaking on alpine water resources management under present and climate change conditions.

Water Science and Technology – WST, 59 (9), 1793-1801, doi:10.2166/wst.2009.211.

Vanham, D., Fleischhacker, E., Rauch, W. (2009) – **paper H**

Impact of an extreme dry and hot summer on water supply security in an alpine region.

Water Science and Technology – WST, 59 (3), 469-477, doi:10.2166/wst.2009.887.

In these three papers the semi-distributed hydrological modelling system PREVAH is applied for the case study area to assess its water availability (see step *analysis water availability* in the workflow), both for the baseline period 1961-1990 as in future scenarios (the middle and end of the 21st century). A differentiation in surface and ground water is made and environmental flows are analysed, all on a seasonal and/or monthly basis. The quantification of the effect of climate change on the hydrological water balance components within a catchment is invaluable for future planning within the water sector. These three papers predict a shift from a rainfall-snowmelt dominated flow regime to a rainfall dominated flow regime in future for the case study area. A future decrease in snow accumulation and a shortening in snow cover duration is observed, an effect that increases with lower altitudes and differs between the winter months. Due to the shortening of the winter season, a change in seasonality of river flows and available water resources (ground and surface water) occurs. There will be an increase in winter flow, and a decrease in spring, summer and autumn flow. The typical low flow period during winter shifts to a low flow period during late summer and autumn.

Paper F focuses on the quantification of uncertainty of future climate change projections. As the regional effect of global warming is highly uncertain, the provision of quantitative estimates with error bands is essential. Many studies only take one or a very limited sample of climate-change scenarios into account. In this paper the hydrological response to 13 different regional climate change model scenarios for the end of the 21st century within the catchment of the Kitzbüheler Ache (one of four catchments of the case study area of the dissertation) is investigated. The results show a shift in hydrology as described in the previous paragraph. However, the magnitude of the effects depends strongly on the choice of the scenario. The uncertainties are presented for a monthly and seasonal time step.

Paper G focuses on the impact of snowmaking as a water demand stakeholder on a regional water balance. A regional water balance (water demand-water resources) is analysed for the case study area, for the reference situation and a future climate change scenario (2°C warming). In addition to the changes in hydrology, the water demand for improvement snowmaking increases, especially in the month of March. However, December proved to be the critical month due to the large amounts of water required for base snowmaking both now and in future. These results stress the necessity of reservoir storage for base snowmaking on a regional level. Water availability during other months but winter is sufficient to fill these reservoirs.

Paper H focuses on the impact of both the extreme hot and dry summer of 2003 and the PRUDENCE CHRM climate change scenario summer for 2071–2100 on the monthly water balance within the case study area. Climate change will induce an increasing drought risk in western and southern Europe and a resulting increase in water stress. In both summer scenarios total flow and ground water recharge decrease substantially, due to the decrease in precipitation and increase in evapotranspiration. However, regional water availability is still sufficient to serve all water demand stakeholders. Especially springs are very vulnerable to these climatological conditions; average local groundwater recharge is reduced by 20% up to 70% within both scenarios. Due to the hydrogeological characteristics of the case study area and the typical small structured alpine water supply infrastructure, local deficits can occur. But also groundwater aquifers in the valleys show a decrease in water availability. These results are supported by observations made in 2003 throughout Austria and Switzerland.

3 PILOT AREA

3.1 INTRODUCTION

After the definition of the project requirements, the first step within the workflow (Figure 2-2, page 12) is the delineation of the project area (Figure 3-1).

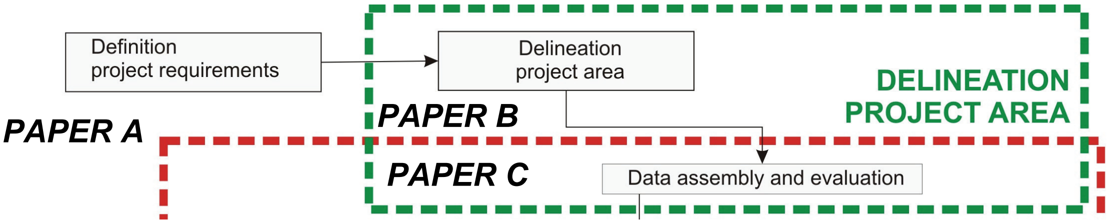


Figure 3-1: Different steps within the workflow regarding the delineation of the project area

3.2 DELINEATION OF THE CASE STUDY AREA: THE KITZBÜHEL REGION IN THE AUSTRIAN ALPS

3.2.1 SPATIAL SCALE

The presented workflow with its methodologies aims at producing management instruments for IWRM on the river basin or catchment level (Figure 2-1, page 11). The spatial scale for which the methodology is primarily applicable is therefore the macro level (Figure 3-2 and Figure 5-2 page 35). Some presented methodologies can also be transferred to the meso level, like the assessment of the vulnerability of the water supply system and the resulting water supply system 1) vulnerability map and 2) Alpine natural hazards risk map (**paper E**). However, the resulting DSS maps are tools that can be used for a regional analysis, not for a local analysis (micro level). Once decisions are made for the regional level, local problems and solutions can be addressed.

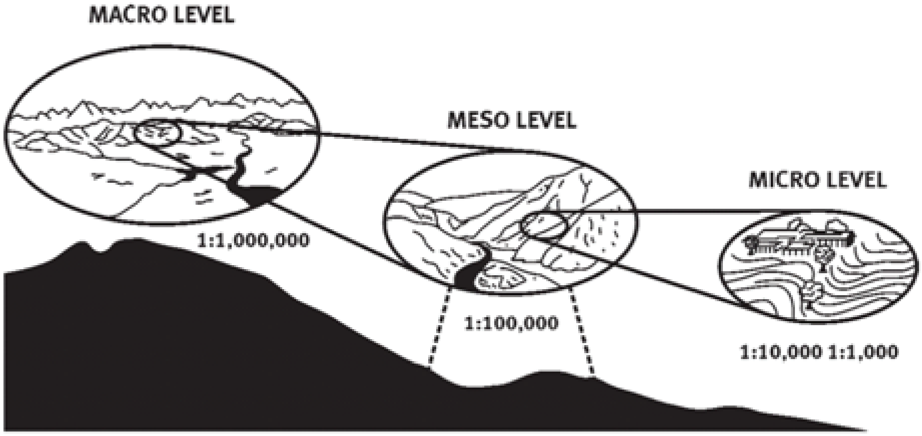


Figure 3-2: Diagrammatic representation of macro-, meso- and micro-level natural water resource systems in a basin management framework. A macro-level system deals with part of a geographical zone, such as a river basin. A meso-level system deals with a river valley within a basin. A micro-level system deals with a relatively uniform ecological and hydrological unit. Source: (Hooper, 2005)

3.2.2 THE IMPORTANCE OF MOUNTAIN WATER

As IWRM implies the whole river basin, the effect of undertaken water management measures within a case study area that is located in an upstream part of the basin on lower lying areas has to be taken into account. This is especially important for river basins with a mountainous part, as in many regions of the world mountains have a water tower function for their surrounding lowlands. This topic is generally discussed in **paper A** (Vanham and Rauch, 2009c) and particularly for the Danube river basin in **paper B** (Vanham and Rauch, 2009a).

By definition of (Meybeck *et al.*, 2001), mountains and higher-altitude areas make up about 25 % of global continental surface excluding Antarctica and Greenland. These 25 % of the Earth's total land area account for 32 % of surface runoff. However, depending on the climate zone, mountain discharge can represent temporarily up to 95 % of total river basin flow, when surrounding lowlands are characterised by a dry climate (Viviroli *et al.*, 2003; Viviroli *et al.*, 2007). Examples of such wet islands in dry climate zones include the Hindu-Kush-Himalayas mountain range for the Indus river basin or the Rocky Mountains for the Colorado river basin. (Viviroli *et al.*, 2007) generated a world map displaying different Earth system mountain types, hydrologically distinguished according to the contributing potential of a mountain cell (resolution of 0.5˚ × 0.5˚) to the respective analysis basin's lowland runoff. The authors show that more than 50 % of mountain areas have an essential or supportive role for downstream regions. The European Alps are an example for Earth system mountain type III - medium or high contributing potential to a wet lowland area – for the Rhine, Rhone, Danube and Po river basins.

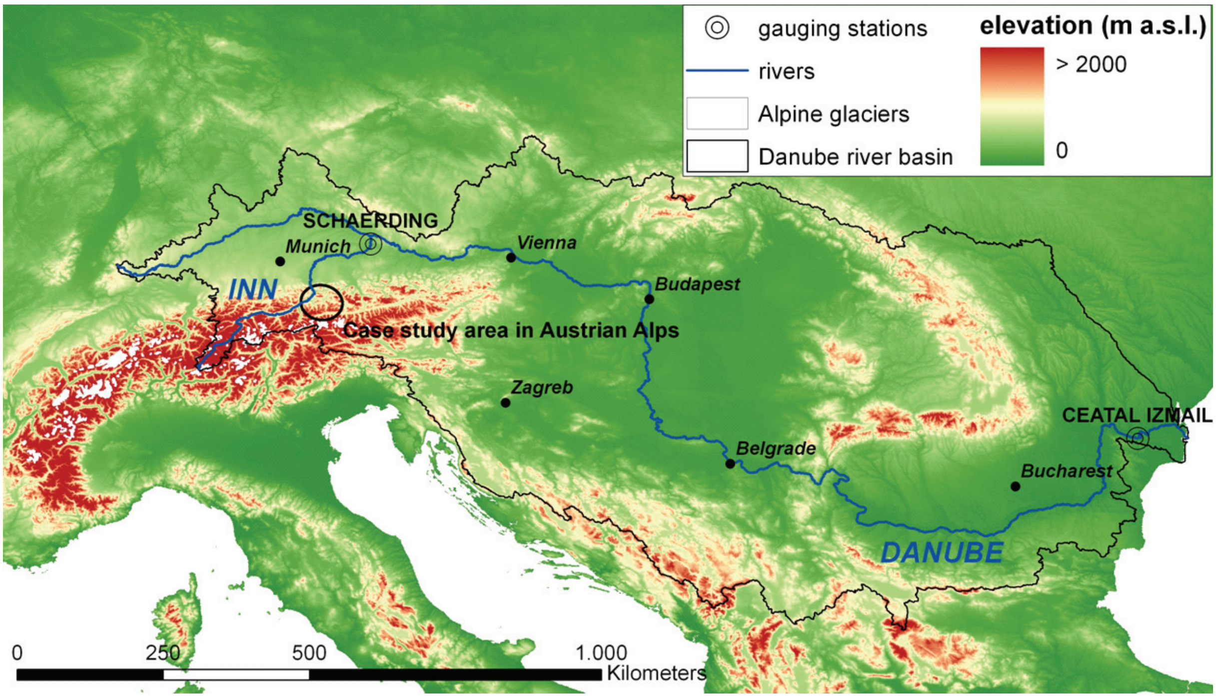


Figure 3-3: Location of the case study area in the Danube river basin (Vanham and Rauch, 2009a). Location of the gauges *Schärding* on the Inn and *Ceatal Izmail* on the Danube. Source: paper B (Vanham and Rauch, 2009a).

(Weingartner *et al.*, 2007) stated that with a mean contribution of 26% of the total discharge, the mountain region of the Danube system (10% of total area) supplies 2.6 times more water than might be expected on the basis of surface area alone. The mountainous part of the Danube thus plays a distinctive role in the hydrology of the whole river basin. The disproportional influence of the largely alpine Inn catchment (up to gauge “Schärding”) to the total Danube basin (up to gauge “Ceatal Izmail”) shows large variations on a monthly basis (Figure 3-4). The latter gauge is located at the Danube’s entrance into its extensive delta, which flows into the Black Sea. Figure 3-3 shows the location of both gauges. It has to be stressed that water for certain stakeholders like irrigation is consumed (consumptive use) from the Danube River before it reaches gauge Ceatal Izmail. The areal proportion of the Inn River catchment is only 3.2%, but its mean contribution to total discharge ranges from a minimum of 6.6 in the winter months to a maximum of 18.5 in August. Expressed in disproportional influence - mean contribution related to surface area - these values range from 2.1 to 5.8. The hydrological processes that cause these observations are discussed in chapter 5 - Water availability (page 33 and following).

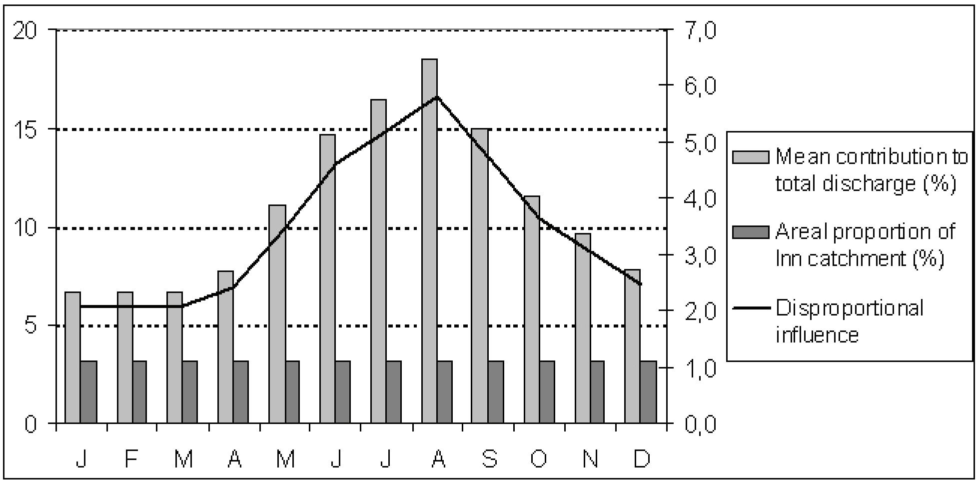


Figure 3-4: Monthly contribution of the Inn catchment (gauge “Schärding”) to total Danube discharge (gauge “Ceatal Izmail”) (1961–1990) (primary Y-axis); and disproportional influence (mean contribution related to surface area) of the Inn catchment (secondary Y-axis). Data source: GRDC, 56058 Koblenz, Germany. Source: paper B (Vanham and Rauch, 2009a).

The mountain water of the case study area thus plays an important role in water availability downstream. Whenever a project area is defined to assess its WRM, the whole river basin has to be regarded when making management decisions.

3.2.3 DELINEATION OF THE CASE STUDY AREA

IWRM should be implemented on the river basin level, however political entities (e.g. continent, country, state, district, municipality, …) often do not coincide with natural borders (catchment, basin, subbasin, …). The Kitzbühel region is located in the eastern part of the Province of Tyrol in the Austrian Alps (Figure 3-5). Historically and geographically it can be identified as an entity. To delineate the project area, the catchments that coincide with the affected municipalities are chosen. A hydrological model is used to analyse the available water both currently as under climate change conditions. This means that a time series of measured flows - representative for the project aims - for calibration should be available. Therefore the boundaries of the catchments are defined by available gauging stations. In the case of the case study area four basins are selected (Figure 3-5). These gauging stations are presented in Figure 5-3 (page 36). Daily flow measurements are available from 1961 on. The study area is located in the north-eastern part of the Alps (Figure 3-3 and Figure 3-5). It is therefore characterised by a continental climate and not so much influenced by the Mediterranean like e.g. the Southern Alps.

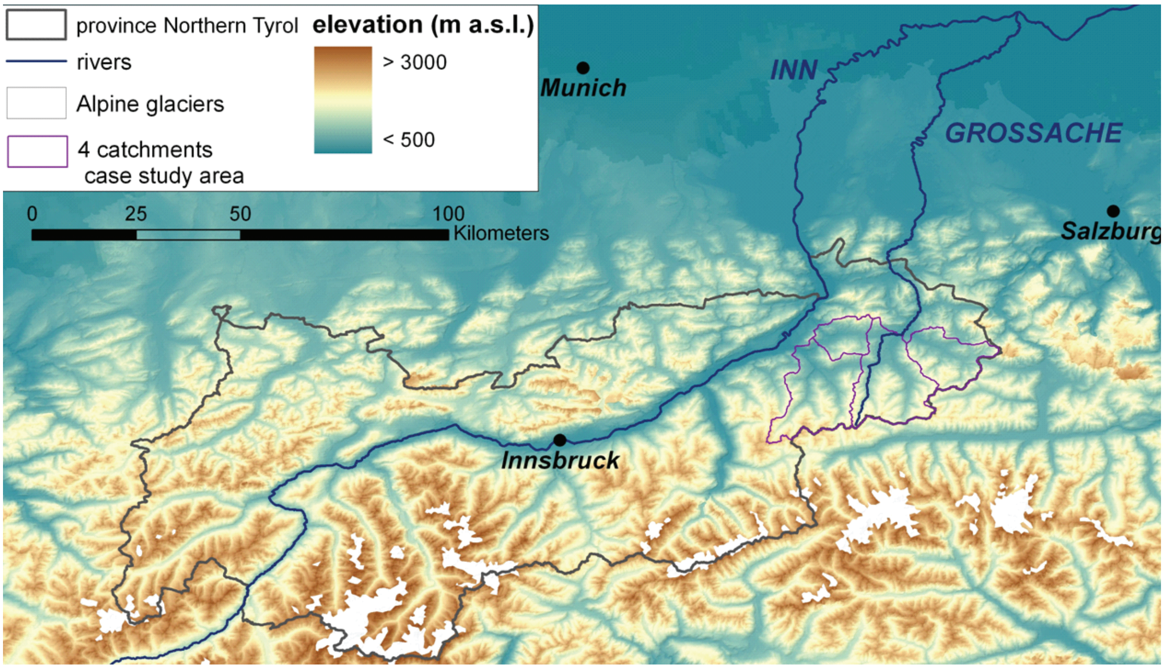


Figure 3-5: Location of the four catchments of the case study area within the Austrian province of Tyrol (the map displays North Tyrol without East Tyrol)

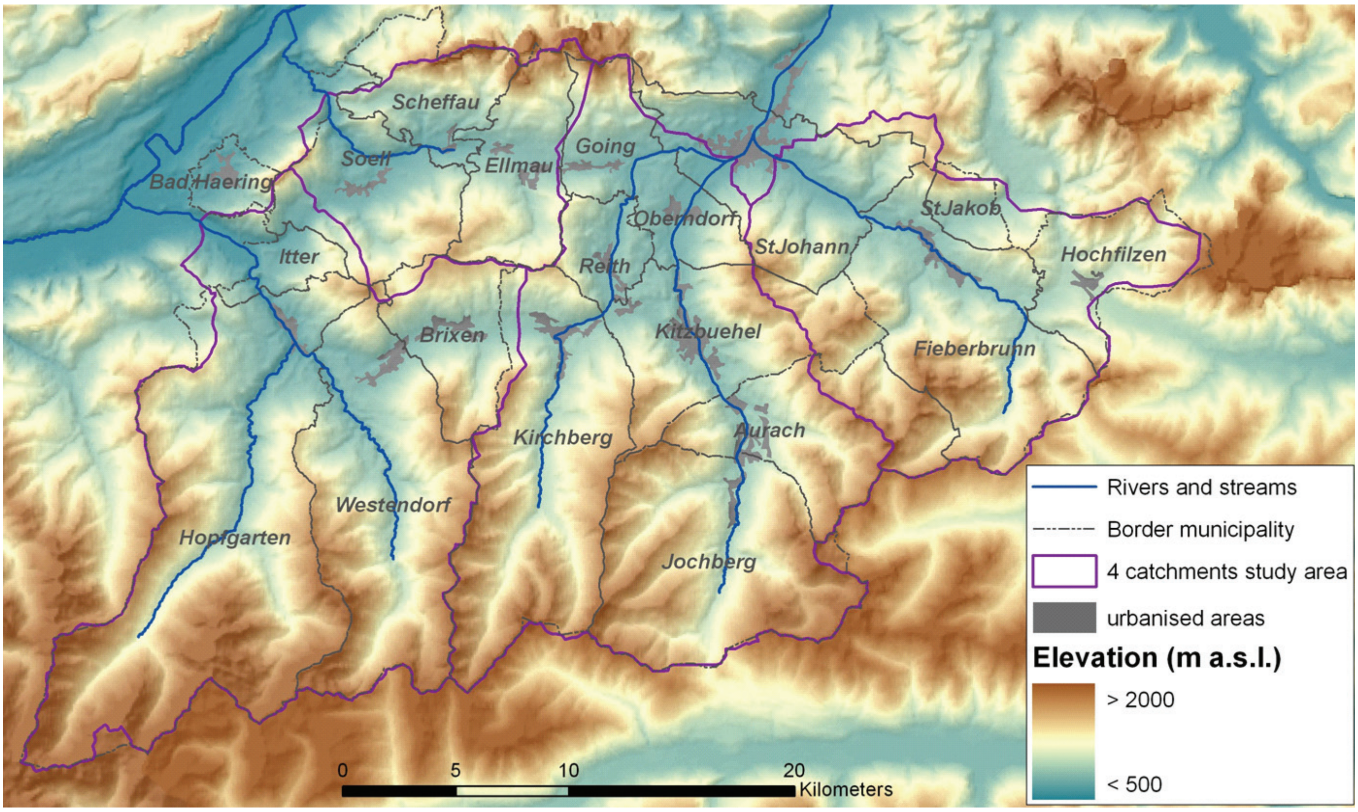


Figure 3-6: The four catchments and 19 municipalities of the case study area

In total the administrative borders of 19 municipalities coincide roughly with the borders of these four catchments (Figure 3-6). Most municipalities have a rural character. Only Kitzbühel and Sankt Johann have a more urban character. The part of the valley between Sankt Johann and Kitzbühel has a larger concentration on industry and small trade as compared with the remaining study area. The elevation ranges from approximately 450 m a.s.l. to 2500 m a.s.l.

Figure 3-7: View from the town centre of Kitzbühel (foreground) to the Kaiser mountain range (background) in the northern part of the case study area (Foto © Tirol Atlas)

Figure 3-8: Kitzbühel in winter with the famous „*Hahnenkamm*“ ski slope in the background (Foto © Niederstrasser - Kitzbüheler Alpen Marketing GmbH)

4 DATA AVAILABILITY AND ORGANISATION

4.1 INTRODUCTION

After the delineation of the project area, the following step within the workflow (Figure 2-2, page 12) is the acquisition of data and the implementation of a (GIS)-data and information system (Figure 4-1). GIS-data and the use of GIS-software (in this case ArcGIS) play a central role within the workflow which results in DSS-maps.

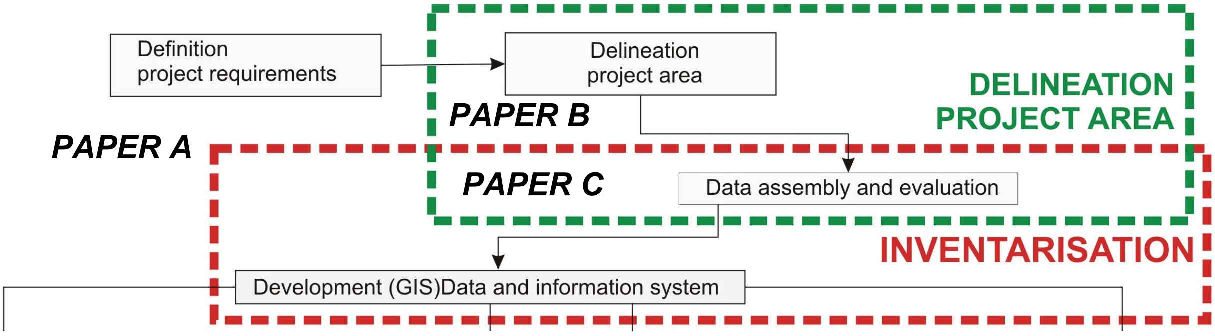


Figure 4-1: Following steps within the workflow regarding data assembly and evaluation

The following Table 4-1 gives an overview of the publications and reports related to the CNET-project which discuss the topic "*data availability and organisation*". Within this chapter of the dissertation this topic is generally discussed, however for a detailed description these references should be consulted.

Table 4-1: Publications and reports related to the CNET-project in which the topic "*data availability and organisation*" is discussed

Type	Title	Reference
Journal Article	**PAPER C**: Rasterised water demands: methodology for their assessment and possible applications.	(Vanham *et al.*, 2010)
Conference Proceedings	Gis-gestütztes Verfahren zur Erhebung und Analyse der Trinkwasserversorgungsinfrastruktur im alpinen Raum am Beispiel des Grossraumes Kitzbühel	(Vanham *et al.*, 2009e)
Conference Proceedings	WP 2.1.2: Alpine Wasserversorgungs- und Vorsorgelogistik.	(Rauch *et al.*, 2008)
Diploma Thesis	Wasserversorgungsinfrastruktur im Großraum Kitzbühel - Erhebung, Erfassung und Analyse mit einem geographischen Informationssystem.	(Millinger, 2008)
Report	Endbericht, Netzknoten 2, Work Package 2.1.2 „Alpine Wasserversorgungs- und Vorsorgelogistik"	(Vanham *et al.*, 2008b)

One of the most time and energy consuming steps within a river basin management analysis project is the acquisition of data, especially when modelling is involved. Therefore the project requirements or expectations should be clearly visualised, in order not to waste time and resources on data collection which afterwards proves to have been unnecessary. Data should not be collected in an exhaustive way. When the necessary data are not available, it may be possible to deduce the required information from other data. For example, land use maps can be generated from satellite images.

Especially for GIS-data the required resolution has a large influence on their availability. Data with high (dense) resolutions tend to be much less accessible than data with low (coarse) resolutions. The spatial scale of the project (Figure 3-2 page 17 and Figure 5-2 page 35) therefore plays an essential role in the minimum data resolution. As the presented workflow and applications are applicable for the macro- (water balance map) and meso-level (water balance and water infrastructure vulnerability map), very detailed geographical information on the micro level (e.g. cadastral maps) are not necessary. Such data could have a supportive function, but when not easily available, it can be chosen not to acquire them.

As dominating factors to choose the raster resolution of the project are the area of the catchments of the hydrological model and the availability of data. Different authors (Fekete *et al.*, 2001; Shrestha *et al.*, 2006; Vazquez *et al.*, 2002; Zappa, 2002) analysed the effect of grid size on predictive uncertainty and an optimal grid resolution for (semi-) distributed hydrological modelling. The challenge is to determine a scale above which spatial variability can be neglected. Selecting a higher resolution brings with it heavy tasks of data acquisition, defining the model parameter values, complex and time-consuming calculations and large memory space requirements on the computer. On the other hand, selecting a lower resolution greatly reduces the workload but risks leading to poor results due to lack of consideration of important spatial features - especially in Alpine regions. (Zappa, 2002) summarised the results of different authors and fitted a curve through the recommendations he found in literature (Figure 4-2). This curve can be used for rough estimates on an appropriate grid size.

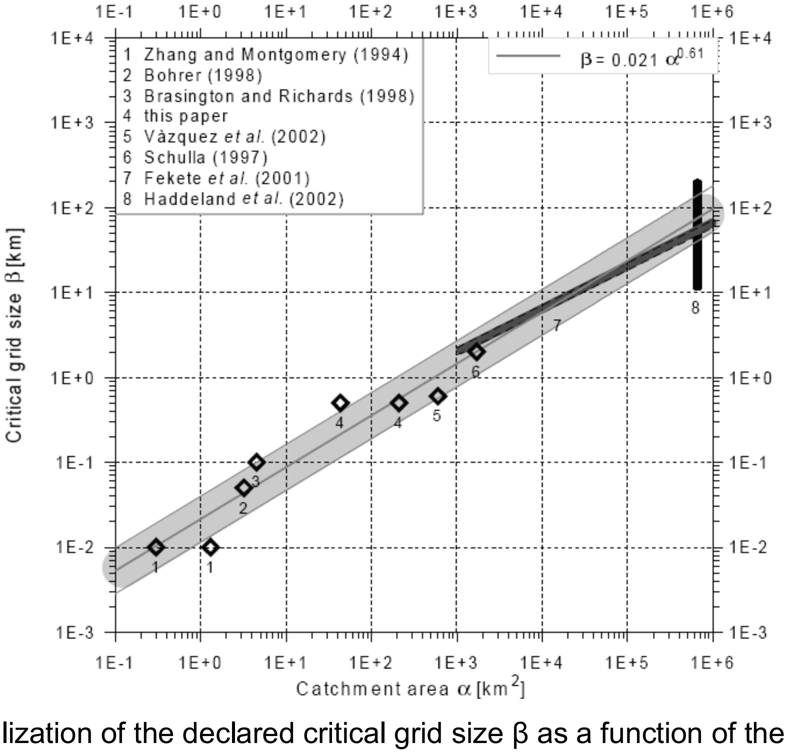


Figure 4-2: Visualization of the declared critical grid size β as a function of the catchment area α. Source: (Zappa, 2002)

The median area of the four case study catchments is approximately 244 km^2. According to Figure 4-2 the optimal hydrological modelling grid size is about 500m.

As resolution for the project 250 m was chosen, as many data are available in their densest resolution in 250 m (e.g. the gridded population census of 2001 for the calculation of rasterised water demands – see **paper C** and chapter 6.2.2 – and the CORINE land use dataset). Particular data (like the digital elevation model – DEM) are also available in denser resolutions.

For this fine grid resolution certain disadvantages in data accuracy need to be taken into account. An example is the gridded population census of 2001 dataset. For the Austrian dataset some data are not given when a raster cell contains only one element for privacy protection reasons. This is e.g. possible in sparsely populated areas, where only one house is located within a grid cell. A disadvantage thus has to be taken into account, as the sum of raster values can differ from the absolute value (Kaminger and Meyer, 2007). This is also the case for other countries that provide the 2001 census data on a raster level. The methods to ensure statistical confidentiality and therefore the resolution of the available data generally differ between these countries (Szibalski, 2007). For example, in Switzerland census data are offered already in a 100-metre grid. Austria uses a lower threshold of 125 meters. In Finland and Norway, the threshold is 250 meters. Estonia publishes grid maps with a minimum resolution of 500 metres. Sweden modifies data in order to make single persons unrecognizable. In Switzerland raster cells with low population values are only made available in a classified way (for example 1 to 3).

Data accessibility tends to differ amongst countries but also smaller political entities (states or provinces, municipalities …). Because of (recent) fragmentation of data over many organisations and because of (recent) financial independence of some of these organisations, data availability in Austria is quite restricted and often subject to payment (e.g. particular climatological data of the ZAMG or gridded population census data of Statistics Austria). Other countries like the US tend to have a more open access policy on data availability. There is also a differentiation in the accessibility of data according to the institution that wants to use the data. Research institutions often are provided with free-of-charge data for research purposes whereas e.g. consultancy companies have to pay for the same data.

Proper and well-arranged data storage and organisation is an important issue within the assessment of water management plans (and the workflow of this dissertation), as more than one person with different scientific backgrounds will have to deal with these data through the course of the project. Also the involvement of different stakeholders in the analysis, evaluation and implementation of river basin plans needs an organised database. As the situation in a river basin changes continuously, so will river basin management plans and their related databases. Data sharing amongst stakeholders during coordination is critical because it builds common understanding amongst those involved (UNESCO, 2009a). It is vital that individual stakeholders make decisions and act based on shared information. Within the scope of the CNET-project a database structure was developed, primarily with the focus of interaction between the different specialists working on the project. For the involvement of stakeholders in the process a modified database could be considered, for example with a link to the internet for easy accessibility. In this case data policies of the different institutions that provided data need to be considered

4.2 DATA AVAILABILITY

4.2.1 OVERVIEW

Typical for the assessment of river basin plans, data in following three categories are required:

- ***Natural factors***: geology, climate, hydrology, water quality, geomorphology, environment/ecology, etc.
- ***Social factors***: population and its dynamics, standards of living, social customs, land use, water use, etc.
- ***Economic factors***: working population, industrial activities, etc.

This workflow of this dissertation however deals with a selected part within the assessment of river basin plans. An overview of required data for the analysis of the workflow is given in the following Table 4-2. The discussion in this dissertation is limited to water quantity management, thus so are the data in the table. Data for water quality analyses for example are not listed in this table.

Table 4-2: Overview of data required for the workflow

Purpose	Dataset	Type
Analysis water availability	digital elevation model (DEM)	geodataset
	land use map	geodataset
	soil map	geodataset
	hydrogeology map	geodataset
	climatological data: temperature, relative humidity, wind speed, global radiation, sunshine duration	time series (daily), location stations (geodataset)
	hydrological data: precipitation, river discharge, snow cover duration	time series (daily), location stations (geodataset)
	Springs	time series, location (geodataset)
	ground water zones	location (geodataset)
	rivers, lakes, catchments	location (geodataset)
	Glaciers	location (geodataset), general data
Analysis water demand	political borders: province, district, municipality …	geodataset
	land use map/Zoning plan	geodataset
	statistical data on population, employment, industry, overnight stays, agriculture, …	statistical data
	gridded population and housing census data	geodataset
	operating data from water supply undertakings	operating data (time series)
	Water Book - a register containing all water rights	location of water rights (geodataset), allocated amounts (statistical data)
	technical snowmaking: area of ski slopes with and without snowmaking, operating data from mountain railway companies	Geodataset, operating data (time series)
	irrigation: irrigated areas, details on crops	location (geodataset), general and operation data

	reservoirs for different purposes (e.g. hydropower)	location (geodataset), operating data
Analysis water balance map	Results from the balancing of water availability and water demand. Required data are listed under "*Analysis water availability*" and "*Analysis water demand*"	
Analysis vulnerability water supply system and risk map	Water supply system: location water pipe distribution network of the different municipalities, with attribute data (e.g. diameter)	location (geodataset), general data
	Alpine natural hazards flooding, landslide, debris flow and avalanches: flooding map (e.g. HORA), land use map, hazard zone map	geodatasets

For the project the funding partner *Tiroler Landesregierung* (the administration of the province of Tyrol), and especially its geo-information department TIRIS (*Tiroler Raumordnungs-Informationssystem*), proved to be a major source for data acquisition. TIRIS provides a list of data they offer on their website (http://tiris.tirol.gv.at).

4.2.2 WATER AVAILABILITY

As a hydrological model is necessary for the analysis of water availability in the workflow (to achieve a spatially and temporal distributed water balance and to assess future conditions), the required data list for the analysis of water availability is rather extensive (Table 4-2). As discussed in the introduction of this chapter, the selected raster resolution of the project is 250 m.

An elementary dataset is a **digital elevation model (DEM)** of the case study area. For the project area, TIRIS provided a DEM with resolution 10 m. The administration of Tyrol is currently working on a laser scanning DEM for the whole province, but as previously discussed, this fine resolution is unnecessary for the project. For coarser resolutions, many institutions provide DEMs free of charge:

- the Institute for Environment and Sustainability of the Joint Research Centre (JRC) of the European Commission offers a 90 m DEM-grid for the whole European Alps area in the framework of the ECALP project (http://eusoils.jrc.ec.europa.eu/projects/alpsis/Ecalp_data.html).
- the US Geological Survey offers since the year 1996 GTOPO30, a global DEM with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometre) (http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html).
- since June 2009 the Ministry of Economy, Trade and Industry of Japan (METI) and the National Aeronautics and Space Administration (NASA) jointly offer the global ASTER GDEM with an exceptional fine grid resolution of 30 m. For all mountainous ranges in the world a high resolution grid is thus now available free of charge and easily downloadable from the Web (http://www.gdem.aster.ersdac.or.jp/search.jsp).

For **land use** the CORINE Landcover dataset – derived from satellite images - was used in the project. Two different types of CORINE Land Cover can be identified. Firstly the national CORINE Land Cover data base, collected by national teams, on a scale of 1/100.000. Users interested in extracts of this data base should direct their requests to the National Reference Centre. In the case of Austria this is the *Umweltbundesamt*, on which website the dataset is discussed in detail and can be ordered (http://www.umweltbundesamt.at/umwelt/raumordnung/flaechennutzung/corine). The whole European Land Cover data base is the result of the integration of national databases. Data has been converted to the European reference system and has been generalised to a minimum mapping unit of 25 ha with 44 classes of land cover grouped within a three-level nomenclature. Datasets are available in a 100 m grid, a 250 m grid and a 1 km grid. They can be downloaded directly from the data service webpage of the European Environment Agency (http://dataservice.eea.europa.eu/dataservice), under the keyword *CLC2000* or *Corine Land cover 2000* (http://dataservice.eea.europa.eu/dataservice/available2.asp?type=findkeyword&theme=clc2000). For this project the CORINE land cover dataset in a resolution of 250 m was used.

The land use according to the CORINE land cover dataset for the case study area is shown in Figure 4-3 and Figure 4-4. Forest is by far the most important land use in the study area, encompassing almost 50 % of the total area. Alpine meadows at higher elevations and pastures at lower elevations cover also large areas. Percentages of urbanised areas are small and restricted to the valleys. Bare rock can only be found at mountain tops.

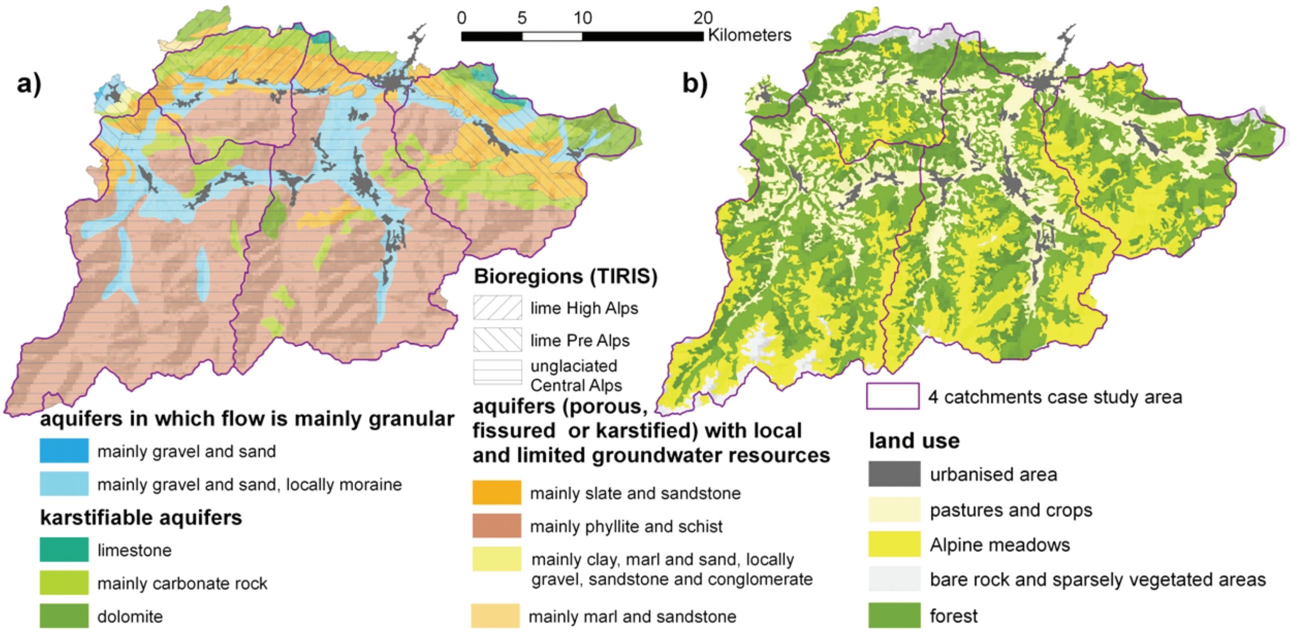


Figure 4-3: a) Hydrogeology and b) land use in the case study area. The hydrogeological dataset was obtained from the digital Hydrological Atlas of Austria. The land use dataset is the CORINE-dataset in a resolution of 250 m.

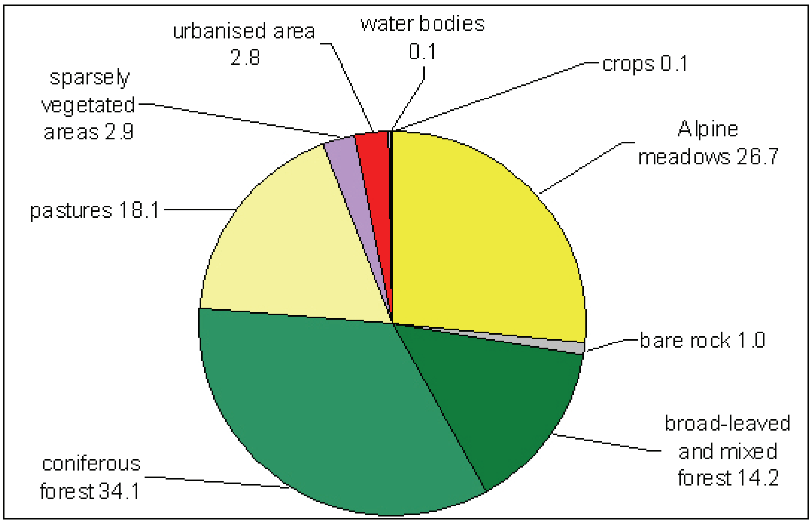


Figure 4-4: Percentages of land use in the case study area according to CORINE. Forest is by far the dominating land use, followed by Alpine meadows (26.7%) and pastures (18.1%) in the valleys. Urbanised areas (2.8%) are constraint to the valleys.

As **soil map** the soil geodataset from the digital Hydrological Atlas of Austria (Peticzka and Kriz, 2003) was used. Other soil maps are provided by the Joint Research Centre (JRC) of the European Commission over the European Soil Data Centre (http://eusoils.jrc.ec.europa.eu/data.html). A worldwide soil map is provided by the FAO – the FAO digital soil map of the world (www.fao.org/ag/agl/agll/dsmw.htm), which is based on the FAO/UNESCO Soil Map of the World, original scale 1:5,000,000.

The **hydrogeology map** was also retrieved from the digital Hydrological Atlas of Austria (Schubert, 2003). This map is a simplification of the hydrogeological map of Austria in scale 1:500,000 (Schubert *et al.*, 2003). Figure 4-3 shows the hydrogeological situation in the case study area, which can generally be divided in two major areas: the karstifiable lime Alps in the northern part – predominately the Kaiser mountain range - and the unglaciated central Alps in the rest of the case study area.

As **climatological data** temperature time series (daily) are essential. They have to be applied for with the responsible institution; in this case the Administration of the Province of Tyrol (www.tirol.gv.at) and/or the ZAMG (www.zamg.ac.at). TIRIS provides the geodataset of the measurement stations. In order to calculate evapotranspiration according to Penman-Monteith (Monteith, 1975) (see chapter 5.2), daily time series on relative humidity, wind speed, global radiation and sunshine duration are required. These are provided by the ZAMG (liable to costs). If for a certain project area these are not available, evapotranspiration can also be calculated with simple formulae that do not require these data.

As **hydrological data** daily time series of precipitation and river discharge – a prerequisite in the study - for Austria can be obtained (downloaded) from the website EHYD (http://gis.lebensministerium.at/eHYD), provided by the Hydrographical Service (*Hydrographischer Dienst*) of Austria. For missing values (time frames) or stations the Administration of the Province of Tyrol (www.tirol.gv.at) should be contacted. TIRIS and the Hydrological Atlas of Austria provide the geodatasets of the measurement stations. Snow cover duration time series can be obtained from the Administration of the Province of Tyrol (www.tirol.gv.at).

Time series of discharge data of selected **springs** can be downloaded from EHYD. However, this applies to a very small number of springs. For discharge time series and a geodataset on the location of springs - in the so called *Wasserwirtschaftsdatenbank (WWDB)* - the Administration of the Province of Tyrol (www.tirol.gv.at) should be contacted. Additionally municipalities maintain supplementary discharge data on springs.

A rough geodataset on the delineation of **groundwater zones** can be obtained from the Hydrological Atlas of Austria. A detailed groundwater zone map for Tyrol was produced by (Anderle, 1978), and can be obtained in a digital form from the Administration of the Province of Tyrol.

Vector datasets on **rivers and catchments** for the whole of Europe were created by the Joint Research Centre (JRC) of the European Commission in the *CCM River and Catchment Database*. These data can be downloaded directly from the data service webpage of the European Environment Agency (http://dataservice.eea.europa.eu/dataservice), under the keyword *vector data > European river catchments*. For Austria digital data are also available in the Hydrological Atlas of Austria, and high resolution data can be obtained from TIRIS. By means of a hydrological model or GIS-software, catchments can also be delineated.

There are no **glaciers** within the case study area. However, due to their hydrological importance in many mountainous areas of the world, general data availability is given. For Austria glaciers are available as a digital geodataset in the Hydrological Atlas of Austria (Gattermayr *et al.*, 2003). On a European level they are classified as a separate land use within the CORINE land cover geodataset. On a world scale a digital geodataset is the DCW (Digital Chart of the World) glacier layer (Raup *et al.*, 2000) provided by the GLIMS Geospatial Glacier Database (http://glims.colorado.edu/glacierdata/).

4.2.3 WATER DEMAND

Geodatasets on **political borders** (province, district, municipality …) and a **zoning plan** were obtained from TIRIS.

Statistical data on population, employment, industry, overnight stays, agriculture, … can be obtained from the statistical department of the Administration of the Province of Tyrol (www.tirol.gv.at > Department of Statistics - www.tirol.gv.at/buerger/statistik-tiris/statistik/) or on a national level from Statistics Austria (www.statistik.at).

A prerequisite for some analyses in this study is the **gridded population and housing census data of 2001**, as provided by Statistics Austria (www.statistik.at). Details on this geodataset are described in **paper C** (Vanham *et al.*, 2010). The acquirement of these data is subject to payment. Gridded population data are also provided in a worldwide raster with a resolution of 1 km by CIESIN (CIESIN, 2005) (www.ciesin.org). A raster dataset on population density disaggregated with the Corine land cover 2000 dataset in a resolution of 100 m for the whole of Europe can be downloaded directly from the data service webpage of the European Environment Agency (http://dataservice.eea.europa.eu/dataservice), under the keyword *raster data > Population density disaggregated with Corine land cover 2000*.

Operating data from water supply undertakings were obtained by means of a questionnaire. Operating data for larger water supply undertakings can also be obtained from the ÖVGW (only Kitzbühel and Sankt Johann) or Statistics Austria (*Statistisches Jahrbuch österreichischer Städte – Raumwirtschaft*). The latter only provides operating data for Kitzbühel, Sankt Johann and Hopfgarten. A detailed description of the data availability for operating data can be found in (Millinger, 2008).

A geodataset with the location of the water rights of the **Water Book** - a register containing all water rights granted in the province of Tyrol - was obtained from TIRIS. The attribute table of this geodataset contains information on the type of water use (e.g. snowmaking, hydropower, …) and the official Water Book number (*Wasserbuch Postzahl*). It does not contain information on the allocated water right amount. To obtain these amounts, the responsible department of the Administration of the Province of Tyrol (Water right or *Wasserrecht*) has to be contacted. The actual application for every water right, which has to be accompanied with a detailed study, can be found in an analogue form at the Water Right dependencies of the districts (Bezirke). For the case study area Kitzbühel region, the Water Book dependencies can be found in the district buildings of Kitzbühel and Kufstein.

For **technical snowmaking** a geodataset of the ski slopes, with attribute table information whether the slope has technical snowmaking infrastructure or not, was obtained from TIRIS. Maximum water rights can be obtained from the Water Book. Actual operating data have to be applied for from mountain railway companies.

Data on **irrigation** (irrigated areas, details on crops) have to be applied for at responsible departments of the Administration of the Province of Tyrol. Maximum water rights can be obtained from the Water Book. Within the CORINE land use dataset irrigated areas are defined as separate land use class. A European irrigated areas geodataset based upon the latter is provided by (Wriedt *et al.*, 2009a) Global geodatasets on irrigated area are provided by different institutions, like the FAO (Siebert *et al.*, 2007; Siebert *et al.*, 2005) or the IWMI (www.iwmi.cgiar.org). The official website of the FAO dataset is www.fao.org/nr/water/aquastat/irrigationmap/index.stm. Although irrigation is not present in the case study area, a detailed description on this topic can be found in chapter 6.2.3 (page 49 and following).

The geodataset of the Water Book provided by TIRIS, also includes the location of **reservoirs** for different purposes (e.g. hydropower or technical snowmaking).

4.2.4 WATER SUPPLY SYSTEM VULNERABILITY AND RISK MAP

In order to generate the water supply system vulnerability and risk map, following datasets are essential:

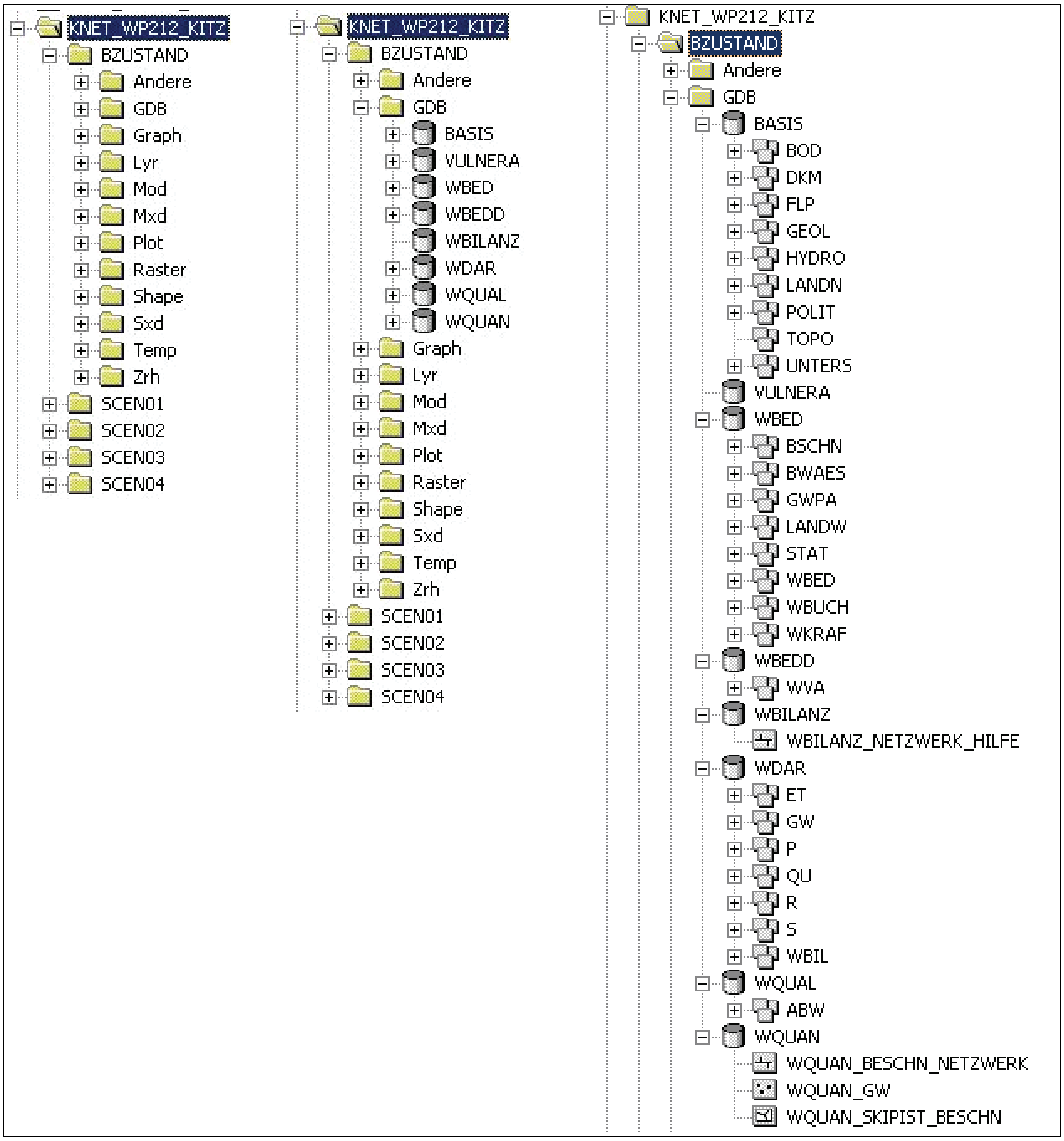
- gridded population census data (described above)
- water supply distribution system
- Data for the analysis of alpine natural hazards (e.g. HORA dataset)

For a detailed description on the data availability for the analysis of alpine natural hazards it is referred to **paper E** (Möderl *et al.*, 2008a). Within this paper also the data requirements and specifications regarding the water supply distribution system are described. In Austria detailed data (e.g. geographical location of pipes, diameter of pipes …) on the water supply system of a water supply undertaking (generally the municipality) are not centralised, but can only be obtained from the undertaking itself. General data (e.g. which springs and groundwater wells serve the system, which reservoirs are there, …) are currently being centralised for Tyrol by the administration of the province of Tyrol. For a detailed description on the data availability and accessibility regarding the water supply distribution system it is referred to (Millinger, 2008).

4.3 DATA ORGANISATION

Acquired data are organised in a (GIS-) data structure. This structure was developed in cooperation with the business partners and there implemented. Especially with the partner *Wasser Tirol* a regular exchange took place. The base data structure was installed on one of their computers, and regularly updated as soon as new data and results were available. In different folders data/information such as geographical data, times series (e.g. discharge times series) or modelling results are saved within the structure.

The (GIS)-data organisation structure (Figure 4-5) is divided into three levels. The first level refers to the different scenarios within the analysis: existing situation (*BZUSTAND*) and different scenarios like demographic increase or climate change scenarios (*SCEN01, SCEN02* …). This folder level contains different subfolders according to the type or format of the data: the Geodatabase (*GDB*), modelling analyses and results (*Mod*), ArcGIS project files (*Mxd*), prints or plots (*Plot*), geographical raster data (*Raster*), time series (*Zrh*) … The second level refers to the different steps within the workflow (Figure 2-2 page 12): base maps (*BASIS*), analysis water availability (*WDAR*), analysis water demand (*WBED*), analysis water supply system (*WBEDD*), analysis water quantity (*WQUAN*) and quality (*WQUAL*) maps, analysis water balance map (*WBILANZ*) and analysis water supply system vulnerability map (*VULNERA*). This same structure repeats itself within every sub-element of level 1. The third level contains the actual data and information. For example within the folder *WDAR* of the Geodatabase (*GDB*) in Figure 4-5 the third level contains the elements ET (ev potranspiration), GW (ground water), P (precipitation), QU (springs), R (discharge), S (snow) and WBIL (hydrological water balance). Within these elements actual geographical information on these topics is contained.



- KNET_WP212_KITZ
  - BZUSTAND
    - Andere
    - GDB
    - Graph
    - Lyr
    - Mod
    - Mxd
    - Plot
    - Raster
    - Shape
    - Sxd
    - Temp
    - Zrh
  - SCEN01
  - SCEN02
  - SCEN03
  - SCEN04

- KNET_WP212_KITZ
  - BZUSTAND
    - Andere
    - GDB
      - BASIS
      - VULNERA
      - WBED
      - WBEDD
      - WBILANZ
      - WDAR
      - WQUAL
      - WQUAN
    - Graph
    - Lyr
    - Mod
    - Mxd
    - Plot
    - Raster
    - Shape
    - Sxd
    - Temp
    - Zrh
  - SCEN01
  - SCEN02
  - SCEN03
  - SCEN04

- KNET_WP212_KITZ
  - BZUSTAND
    - Andere
    - GDB
      - BASIS
        - BOD
        - DKM
        - FLP
        - GEOL
        - HYDRO
        - LANDN
        - POLIT
        - TOPO
        - UNTERS
      - VULNERA
      - WBED
        - BSCHN
        - BWAES
        - GWPA
        - LANDW
        - STAT
        - WBED
        - WBUCH
        - WKRAF
      - WBEDD
        - WVA
      - WBILANZ
        - WBILANZ_NETZWERK_HILFE
      - WDAR
        - ET
        - GW
        - P
        - QU
        - R
        - S
        - WBIL
      - WQUAL
        - ABW
      - WQUAN
        - WQUAN_BESCHN_NETZWERK
        - WQUAN_GW
        - WQUAN_SKIPIST_BESCHN

Figure 4-5: (GIS)-data organisation structure with first level (left), second level (middle) and third level (right)

5 WATER AVAILABILITY

5.1 INTRODUCTION

When the data are assembled and implemented in the (GIS)-data and information system, water availability can be analysed (Figure 5-1). Within the workflow the use of a (semi-)distributed hydrological model is required, in order to:

- spatially and temporally distribute the different water balance components;
- separate surface from ground water;
- have the possibility to evaluate the impact of climate change or changing land use on the water balance components (and therefore water availability).

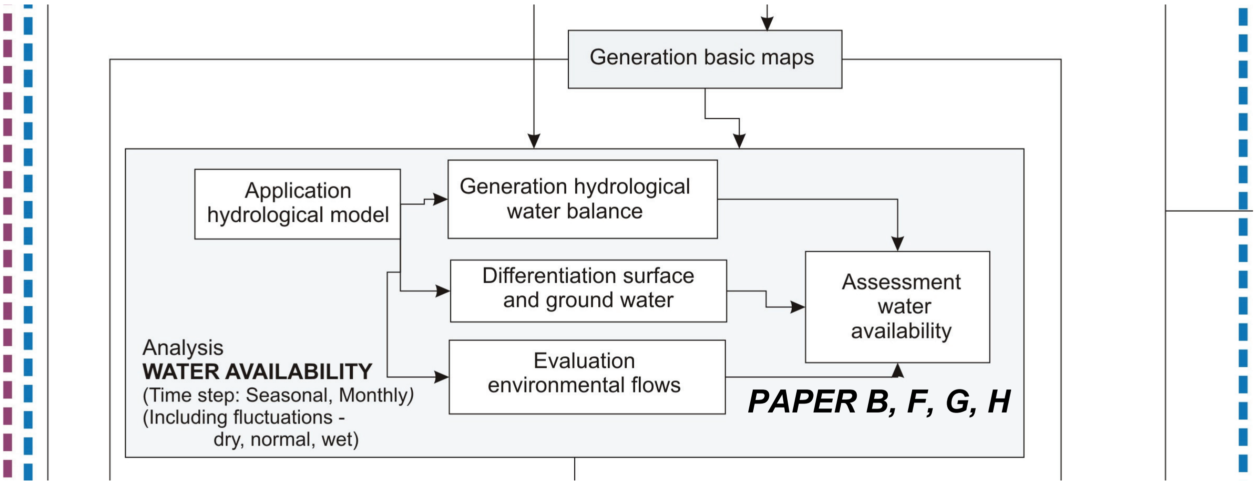


Figure 5-1: Following steps within the workflow regarding the analysis of water availability

Approaches to IWRM do not regard the ecosystem as a “user” of water in competition with other users, but as the base from which the resource is derived and upon which development is planned (Jewitt, 2002). A goal of IWRM should be to maintain, and whenever necessary, restore ecosystem health and biodiversity. This means that environmental flows - the flow regime needed to maintain environmental functions in a river ecosystem - are a prerequisite in the rivers. Available water therefore equals total flows minus environmental flows.

5.2 HYDROLOGICAL BALANCE MODELLING

5.2.1 THE HYDROLOGICAL BALANCE EQUATION

The components of a hydrological water balance are precipitation (P), runoff (R), evapotranspiration (ET) and change in water storage (dS): Under specific hydrogeological conditions, in particular in karstic areas, natural underground inflow and outflow (I) must also be taken into account. The equation for the water balance is therefore:

$P = R + ET + dS - I$ (Equation 5-1)

For the case study area the component I can be neglected. Part of the case study area is karstic (see the hydrogeology map Figure 4-3 on page 27), more particularly the northern parts of the catchments of the Weißache and Kitzbüheler Ache (Figure 5-3 page 36). However, another study in the CNET-project (Benischke *et al.*, 2008a; Benischke *et al.*, 2008b), which analysed the groundwater recharge in the Kaiser mountain range, indicated that for the area of the two affected catchments the underground water flows generally coincide with the surface catchment boundaries delineated according to topography.

5.2.2 HYDROLOGICAL MODEL

As hydrological model the semi-distributed model PREVAH (PREcipitation-Runoff-EVApotranspiration HRU Model) is used. The model implements a conceptual process-oriented approach and has been developed especially to suit conditions in mountainous environments with their highly variable environmental and climatic conditions, including a snow and glacier module. PREVAH uses physically based algorithms for the majority of process descriptions. For a detailed description it is referred to (Viviroli *et al.*, 2009). For research institutions the model is freely available.

Two types of external input data are required to run PREVAH: 1) Physiographical information for the hydrological response units (HRUs) and 2) Meteorological input. Of the detailed listing of data required for the assessment of available water in Table 4-2 (page 25), following data are required for the hydrological model: a digital elevation model (DEM), a land use map, a soil map, precipitation and temperature data, river discharge data for calibration of the model. In order to calculate evapotranspiration according to Penman-Monteith (Monteith, 1975), extensive meteorological input (relative humidity or water vapour pressure, global radiation, wind speed and sunshine duration) data at high temporal resolution are required. This is however not a limitation since more simple evapotranspiration formulae are also available in the model and allow for application in regions where meteorological observations are scarce. Snow cover duration as indicated in Table 4-2 is not required as input for the model, however can function as verification for snow covers simulated by the snow module of the model.

PREVAH contains a number of tuneable parameters which are used to adjust the model to the conditions prevailing in a specific catchment. In practice, this means that the agreement between observed and simulated hydrographs has to be maximised by selecting a suitable set of such parameters. This is referred to as model calibration and is a key process in the application of hydrological models. Calibration is particularly difficult due to inherent limitations and uncertainties (input data, model structure, basin characteristics, process understanding and scaling issues), as a consequence of which a number of local optima exists rather than a global optimum. Model calibration is therefore a complex task and has received considerable attention over the years (Viviroli *et al.*, 2009).

Although PREVAH was selected within the workflow as hydrological model due to its specification for mountainous river basins, other models can also be used. In (Viviroli *et al.*, 2009) a short overview of other distributed hydrological models is given. For a comprehensive review of the large number of models available today, it is referred to (Reggiani and Schellekens, 2005; Singh and Woolhiser, 2002; Singh and Frevert, 2006; Todini, 2007). A well known approach is the system SHE (Système Hydrologique

Européen), developed by the Danish Hydraulic Institute DHI, the Institute of Hydrology at Wallingford (UK) and SOGREAH (France) (Abbott *et al.*, 1986a, b). SHE has since evolved into a robust physically-based model, available as MIKE-SHE (Refsgaard and Storm, 1995) and SHETRAN (Ewen *et al.*, 2000). The limitation to its practical use is the large requirement for data and computational time. Other possible models include the Water balance Simulation Model-ETH (WaSiM-ETH), a fully distributed model with a highly physical description of hydrological processes (Klok *et al.*, 2001) and the TOPographic Kinematic APproximation and Integration (TOPKAPI) model, a fully distributed and physically based hydrologic model (Liu and Todini, 2002). Also the semi-distributed hydrological model Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 1998) could be used. All these models are applicable for mountainous areas and have a snowmelt module. The choice which model an institution will use is off course dependent on the resources it has (financial resources, computer hardware infrastructure and human resources that have experience in using the model). The Institute of Water Resources Management of Joanneum Graz for example used in the framework of the CNET-project the MIKE-SHE model for the assessment of ground water recharge in the Kaiser mountain range (Benischke *et al.*, 2008a; Benischke *et al.*, 2008b), which is part of the case study area of this dissertation.

The following Figure 5-2 shows the application range of hydrological models at different spatial and temporal scales. As also discussed in chapter 3.2.1 (page 17), the spatial scales for which the methodology is primarily applicable are the macro and meso level.

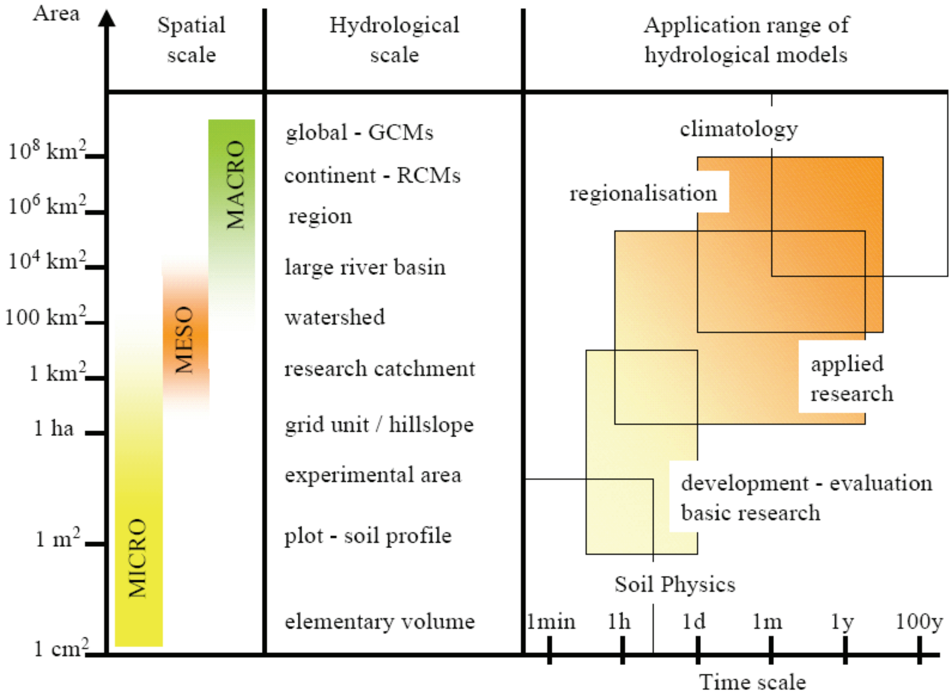


Figure 5-2: Application range of hydrological models at different spatial and temporal scales. Source: (Zappa, 2002)

5.2.3 MODELLING THE CASE STUDY AREA

For the case study area four different catchments (Table 5-1, Figure 5-3, Figure 5-4) had to be modelled. These catchments generally coincide with the municipalities of the project area and were selected based on available gauging stations (see chapter 3.2.3 - Delineation of the case study area – page 19).

Table 5-1: Characteristics of the four catchments of the case study area. Table adapted from (Vanham *et al.*, 2009c)

Name river	Name gauge	Code	Area	Elevation (m a.s.l)			Water balance components (mm)		
			(km^2)	average	min	max	P	ET	R
Brixentaler Ache	Bruckhäusl	BRIX	320	1326	519	2427	1500	430	1070
Kitzbüheler Ache	St Johann i.T.	KITZ	323	1291	662	2314	1571	450	1121
Fieberbrunner Ache	Almdorf	FIE	189	1228	664	2330	1741	436	1305
Weißache	Kaiserwerk	WEI	102	1083	570	2255	1419	480	939
Case study area		CASE	934	1268	519	2427	1565	444	1121

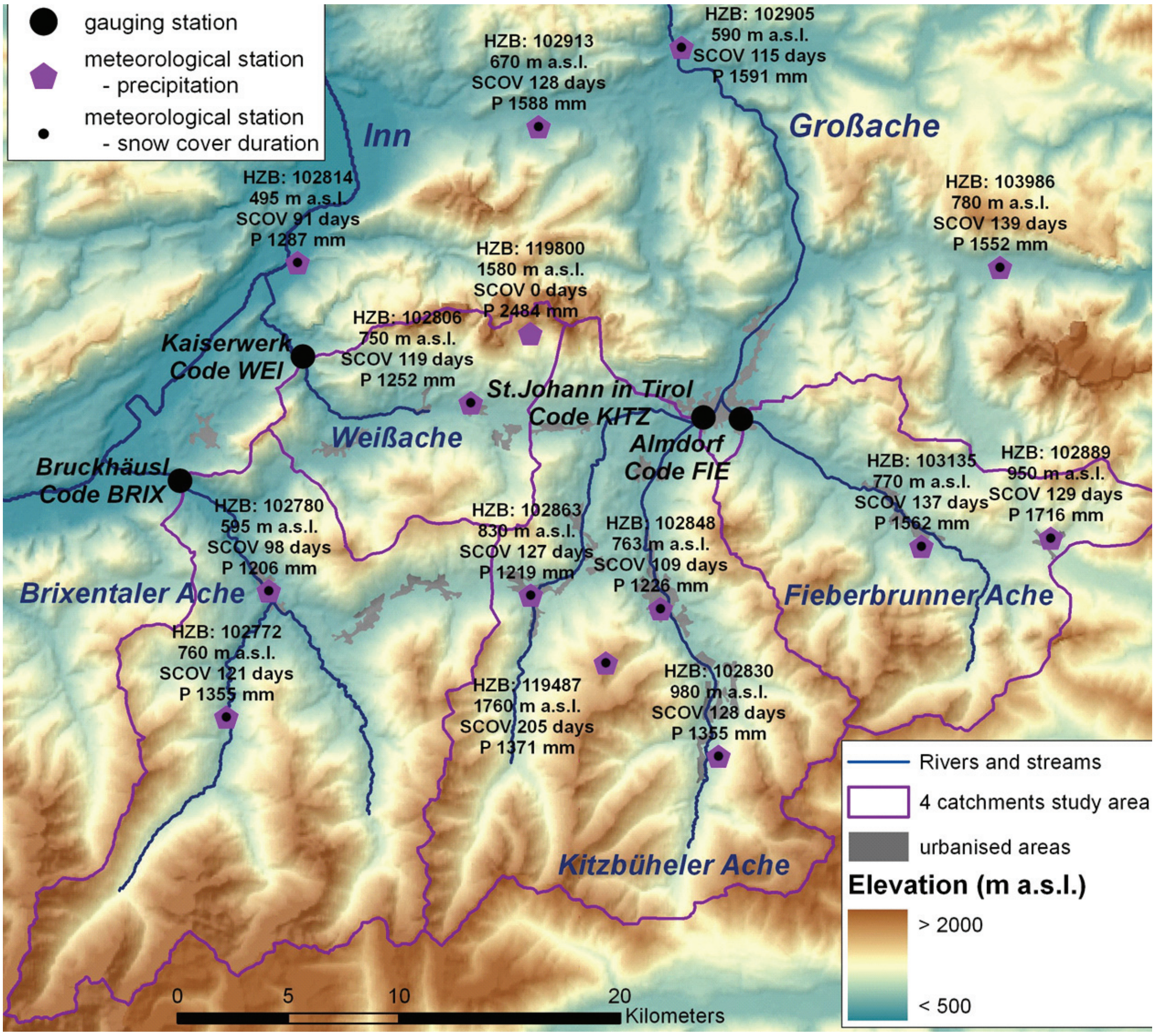


Figure 5-3: The four catchments of the case study area with their gauging stations and the meteorological stations used in the study with precipitation (P) and snow cover duration (SCOV) values. For the station with the HZB number 1119800 (Gruttenhütte, on the southern slope of the Kaiser mountain range) no snow cover measurements are available.

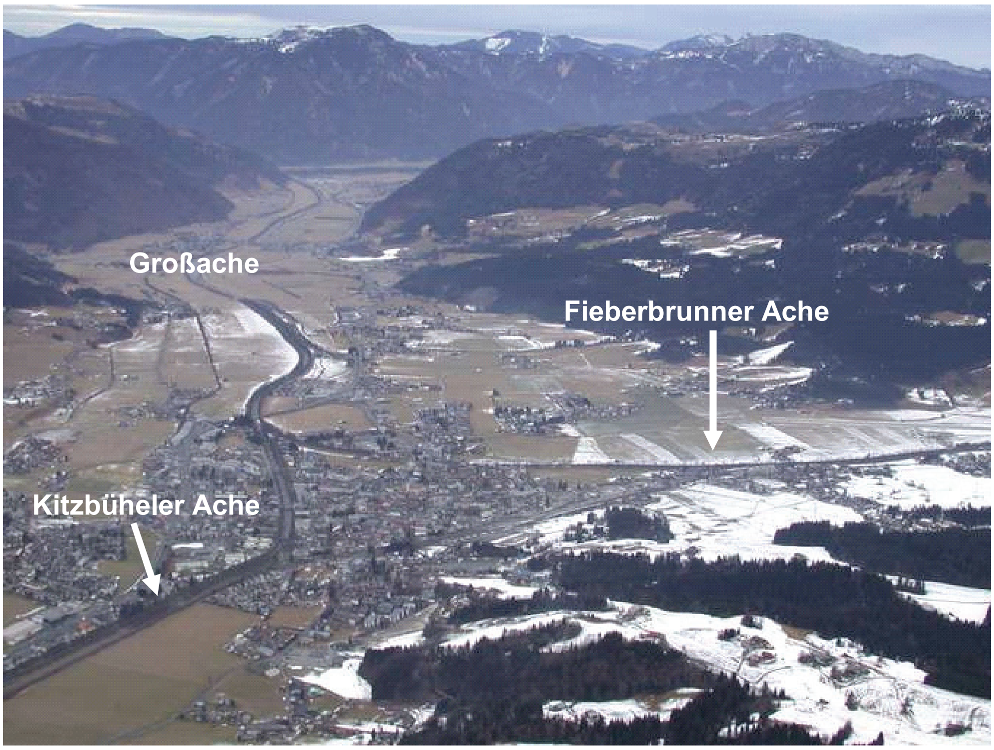


Figure 5-4: Confluence of the Kitzbüheler Ache and Fieberbrunner Ache into the Großache in Sankt Johann, view to the north (Foto © Tirol Atlas)

Different climatological stations were used for the model, in order to represent precipitation and temperature elevation-dependent gradients which are typical for mountainous regions. At high altitudes rain tends to accumulate, which is known as the orographic effect. Temperature decreases with increasing altitudes. Climatological measuring stations at higher altitudes are however underrepresented (as in almost any station network in mountains). Therefore it is advisable to include as many measurements from stations at high altitudes as are available.

In the case of the study area long precipitation and temperature time series were only available for the station with HZB number 1119800 (Gruttenhütte, elevation 1580 m a.s.l. on the southern slope of the Kaiser mountain range) and the station with HZB number 119487 (Hahnenkamm-Ehrenbachhöhe, elevation 1760 m a.s.l., located on the Hahnenkamm mountain top above the centre of Kitzbühel). Both stations are displayed in Figure 5-3. Although the station *Hahnenkamm-Ehrenbachhöhe* is located higher than the station *Gruttenhütte*, its mean annual precipitation value for the period 1961-1990 is much lower (1371 mm for *Hahnenkamm-Ehrenbachhöhe* and 2484 mm for *Gruttenhütte*). The orographic effect is thus much higher around the steep (see also Figure 3-7, page 21) Kaiser mountain range in comparison with the mountains in the southern part of the case study area, which have not such a steep topography. The local common knowledge of the Kaiser mountain range as a water tower is hereby confirmed. It is clear that the spatial interpolation of precipitation values has to represent this distribution. Figure 5-5 a) shows this distribution after interpolation with the algorithm GRADGRID (Bucher *et al.*, 2004). Within the PREVAH hydrological model similar interpolation modules are used.

As a reference or baseline period for the modelling the WMO climate normal period from 1961 to 1990 was chosen. The modelling time step is daily. Climatological input series are daily values.

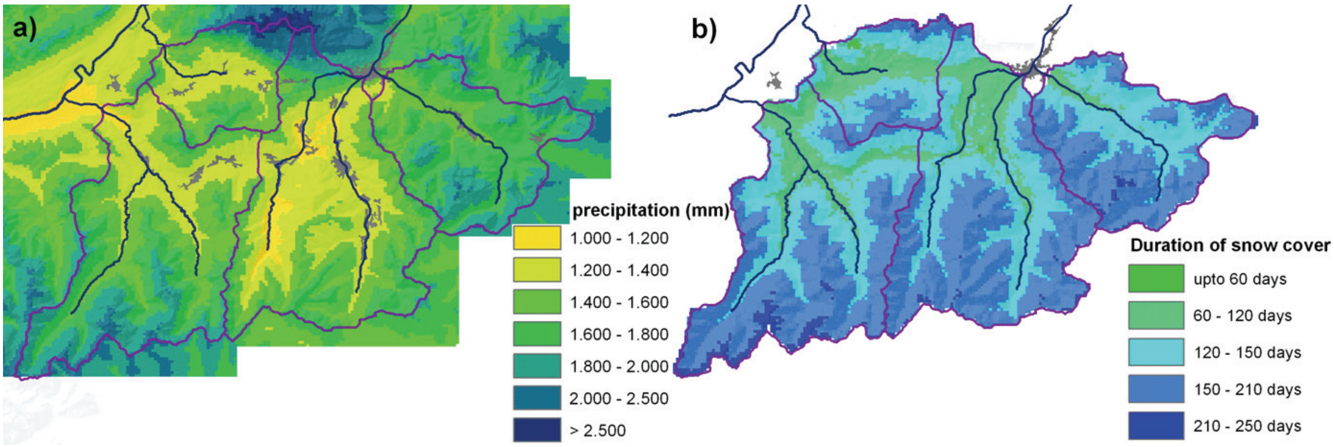


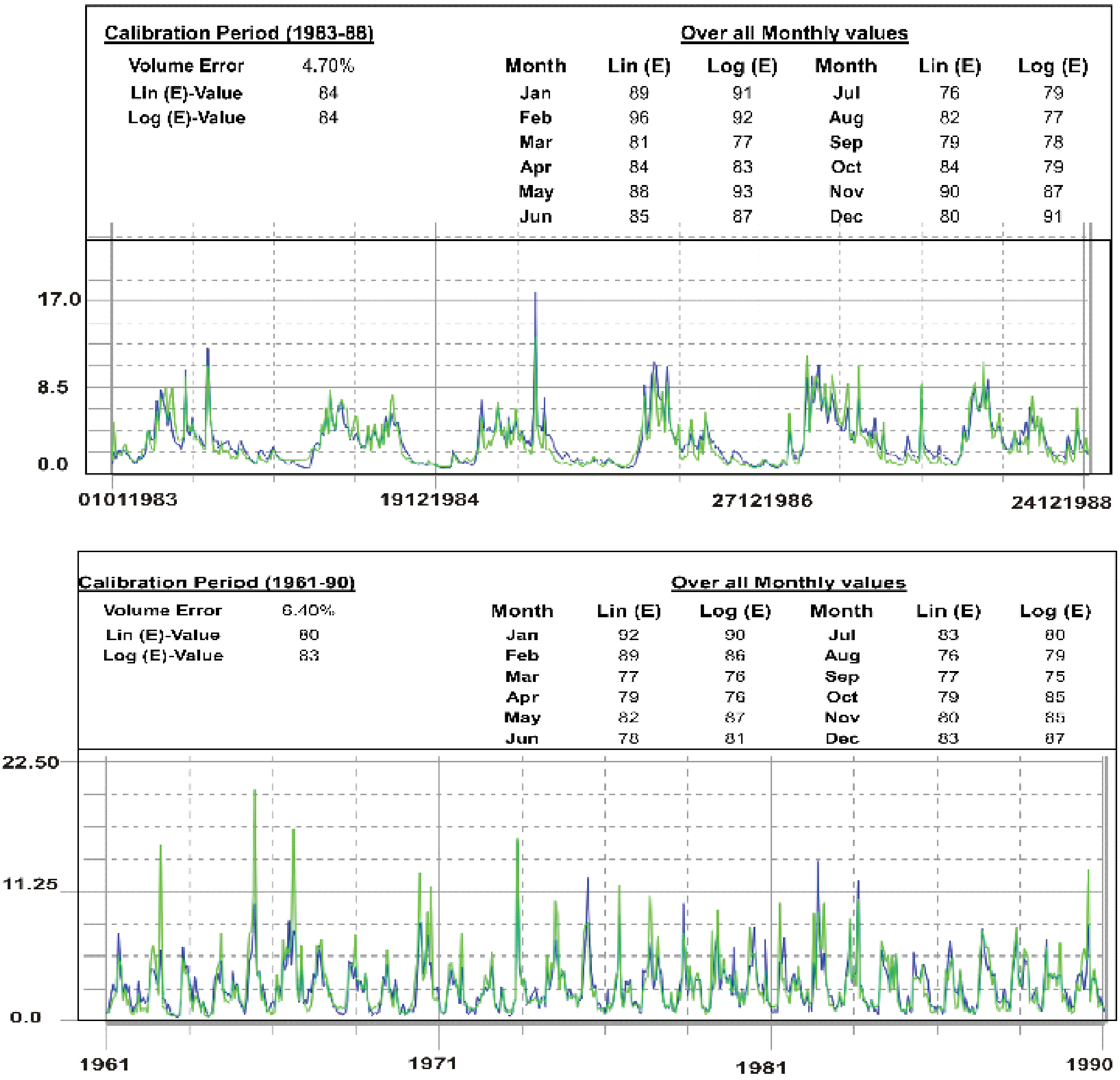
Figure 5-5: a) Mean annual precipitation (mm) as interpolated by GRADGRID (Bucher *et al.*, 2004) and b) mean annual duration of snow cover (days) as modelled by PREVAH in the case study area for the reference period 1961-1990

Potential and real evapotranspiration, soil- and vegetation specific, were calculated according to Penman-Monteith (Monteith, 1975). Therefore daily time series on relative humidity, wind speed, global radiation and sunshine duration were acquired from the ZAMG. Snow accumulation and snow melt are addressed according to (Hock, 2003).

The model was calibrated with the daily flow time series of the reference period 1961-1990 measured at the 4 gauging stations of the corresponding catchments. This period has the advantage that no snowmaking was implemented at that time, therefore no water stored in reservoirs. In addition medium or large reservoirs for irrigation or power generation do not exist in the study area. Consumptive water use in the case study area is also minimal (see in more detail in chapter 6 - Water demand). Irrigation for example, a large consumptive water user, is not present in the catchments. As there is no significant water storage or consumptive water use in any of the four catchments, the measured gauge flows represent the natural flow and can therefore be used directly for calibration of the model. A special emphasis in the calibration of the model was put on base flow analysis, as all demand stakeholders – apart from snowmaking – are served with spring or groundwater. In addition the modelled snow cover duration grids were compared with the measured snow cover duration values (at the stations displayed in Figure 5-3).

An example of the calibration process is given in **paper F** (Laghari *et al.*, 2010) for the catchment of the Kitzbüheler Ache. The model was calibrated over the 1983-88 period and validated over 30 years (baseline period 1961-90). PREVAH's calibration scheme combines three standard efficiency scores with three different temporal ranges: Linear (E_{lin}) and logarithmic (E_{log}) Nash–Sutcliffe efficiency (Nash and Sutcliffe, 1970) as well as the volumetric deviation are assessed over the entire calibration period and in their annual and monthly variations (Viviroli et al., 2009). Figure 5-6 shows the observed and with PREVAH simulated mean daily flow for the calibration (1983-88) and validation (control period 1961-90) periods. The volumetric deviation for the whole calibration period is about 4.7%, the linear (E_{lin}) and logarithmic (E_{log}) Nash–Sutcliffe efficiencies are both 84. The values thus show good agreement between observed and simulated flows. Also in the monthly variations the E_{lin} and E_{log} values are between minimum 77 and maximum 96. The model thus simulates the seasonal hydrological behaviour well.

For the validation period the volumetric deviation is about 6.4%, E_{lin} is 80 and E_{log} is 83. Also in the monthly variations the E_{lin} and E_{log} values are high. These values are the lowest in spring, during the period of snowmelt, and also during summer (July-September), the period of typical heavy thunderstorms. But even here the lowest value is 75.


Calibration Period (1983-88)

Volume Error	4.70%
Lin (E)-Value	84
Log (E)-Value	84

Over all Monthly values

Month	Lin (E)	Log (E)	Month	Lin (E)	Log (E)
Jan	89	91	Jul	76	79
Feb	96	92	Aug	82	77
Mar	81	77	Sep	79	78
Apr	84	83	Oct	84	79
May	88	93	Nov	90	87
Jun	85	87	Dec	80	91

Calibration Period (1961-90)

Volume Error	6.40%
Lin (E)-Value	80
Log (E)-Value	83

Over all Monthly values

Month	Lin (E)	Log (E)	Month	Lin (E)	Log (E)
Jan	92	90	Jul	83	80
Feb	89	86	Aug	76	79
Mar	77	76	Sep	77	75
Apr	79	76	Oct	79	85
May	82	87	Nov	80	85
Jun	78	81	Dec	83	87

Figure 5-6: Observed and simulated daily discharge at the Kitzbüheler Ache catchment outlet (gauge station St Johann i.T) for the calibration (1983-88) and validation (1961-1990) periods. Source: (Laghari *et al.*, 2010)

Resulting water balance components (mm) for the reference period in the four catchments and the case study area are presented in Table 5-1 (page 36). Generally one third of total annual precipitation evapotranspirates, whereas two thirds are total runoff. The mean annual duration of snow cover varies from less than 60 days (2 months) in the valleys up to more than 210 days (7 months) on selected mountain tops (Figure 5-5, page 38). As discussed previously, the quantity of these different water balance components is very dependent on elevation. Figure 5-7 shows the modelled mean annual components versus elevation for the whole case study area. Precipitation in the form of rain and snow (snow water equivalent) increases with altitude, evapotranspiration decreases with altitude (as does temperature), and as a result specific runoff decreases with altitude.

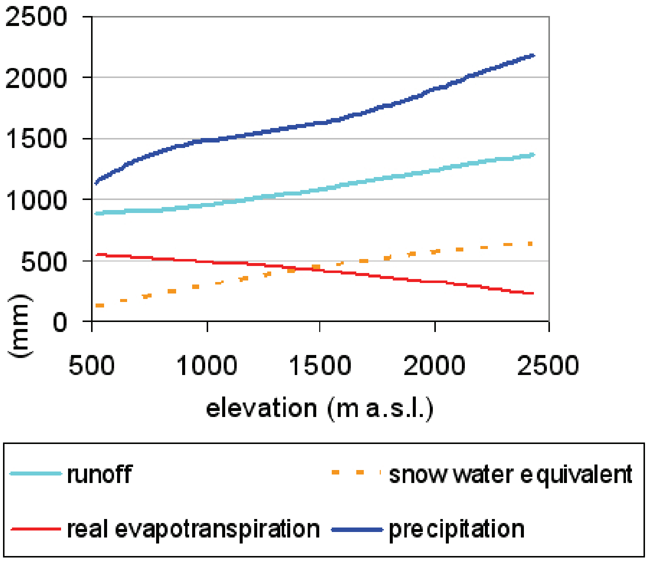


Figure 5-7: Mean annual water balance components versus elevation in the case study area for the reference period 1961–1990 (Vanham and Rauch, 2009a)

These hydrological processes are the cause for the observations discussed in chapter 3.2.2 - The importance of mountain water (page 18 and following). To support this notion on the importance of mountain water results the average monthly water balances (period 1961–1990) of three catchments (Figure 5-8) within the Danube River basin are compared. The first catchment is the strongly glacerised upper Ötztal up to the gauge “Huben”, with an average altitude of 2625 m a.s.l. (min. 1185 and max. 3770 m a.s.l.). The second is the non-glacierised Brixentaler Ache catchment up to the gauge “Bruckhäusl”, with an average altitude of 1326 m a.s.l. (min. 519 and max. 2427 m a.s.l.)(Table 5-1 page 36). This catchment is one of the four catchments of the case study area. The third catchment is the Kamp catchment up to the gauge “Stiefern”, with an average altitude of 613 m a.s.l. (min. 263 and max. 1015 m a.s.l.).

The water balance components of the three catchments (Figure 5-9) show clear differences both in average yearly and monthly amounts. Precipitation is much higher and evapotranspiration much lower in the two mountainous catchments due to the effect of temperature decrease with altitude. This results in a more effective runoff generation in the mountainous catchments as compared to in the lowlands. The discharge difference between the two mountainous catchments and the lowland catchment is particularly large in spring and summer, when snowmelt and glacier melt occurs. For the high altitude and glacerised catchment of the Upper Ötztal, maximum snowmelt occurs some weeks later in the year compared with the mid-mountain catchment of the Brixentaler Ache. Maximum glacier melt occurs during summer (July–August). For the Brixentaler Ache maximum snowmelt occurs during spring (April– June). In winter a large proportion of precipitation is stored as snow (dS in Figure 5-9 is positive), thereby reducing the runoff from mountainous regions substantially. The typical low flow period is winter. The late spring and summer runoff from the Alps arrives at a time of low flows in the lowlands, during which evapotranspiration can exceed precipitation. As generally the largest water demands (municipalities, trade and industry, agriculture, cooling water, etc.) are concentrated in the lowlands, the Alps can be defined as a very important seasonal water tower within the Danube river basin.

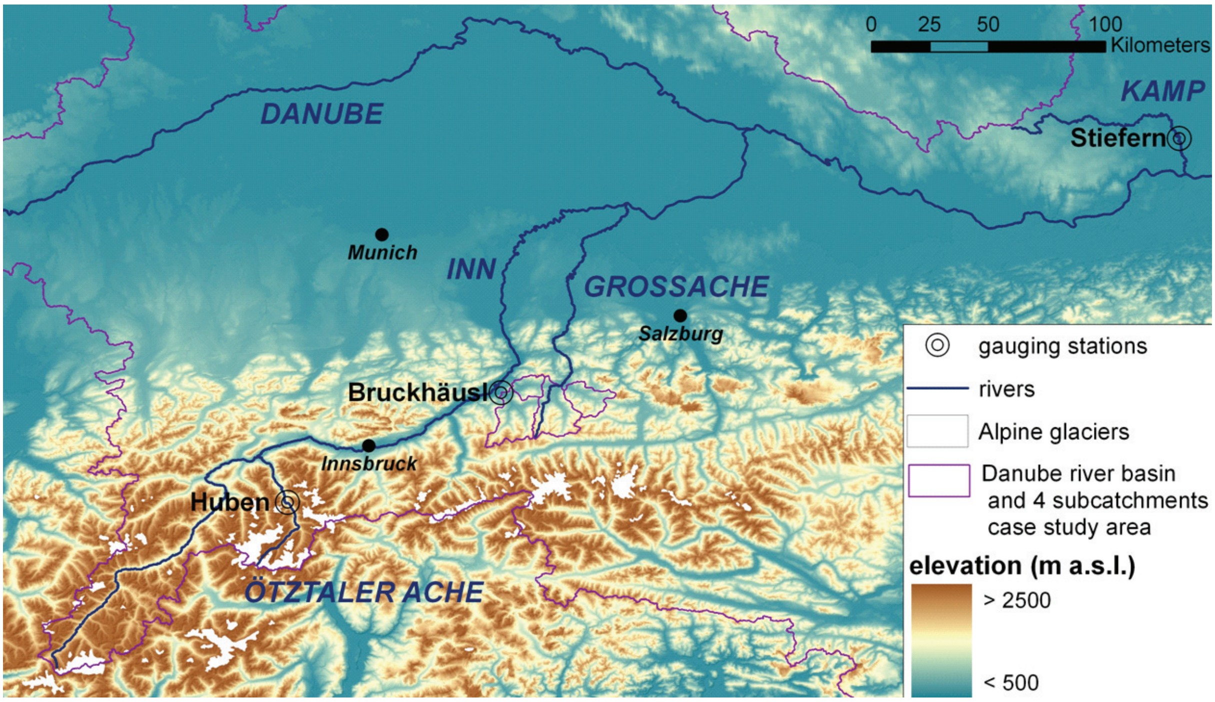


Figure 5-8: The four different subcatchments of the case study area, of which two drain to the Inn and two to the Großache. Location of the gauges “Huben” on the Ötztaler Ache, “Bruckhäusl” on the Brixentaler Ache and “Stiefern” on the river Kamp (Vanham and Rauch, 2009a)

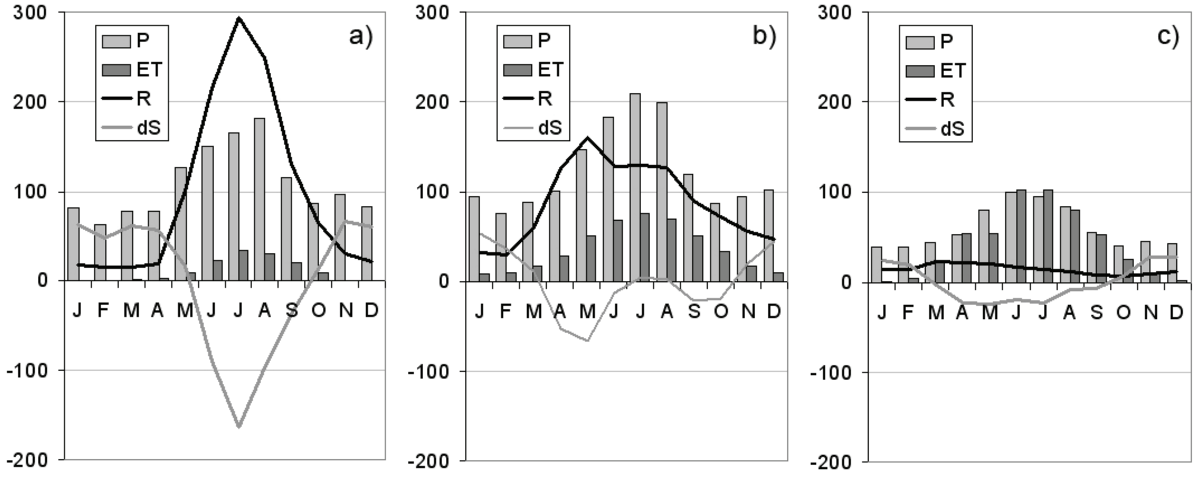


Figure 5-9: Monthly average water balance components (mm) for the period 1961–1990 for: (a) the catchment of the Ötztaler Ache up to gauge “Huben”, (b) the catchment of the Brixentaler Ache up to gauge “Bruckhäusl”, (c) the catchment of the Kamp up to gauge “Stiefern”. Data source, (a) and (c): Hydrological Atlas of Austria. Source: (Vanham and Rauch, 2009a)

5.3 ENVIRONMENTAL FLOWS (EF)

Approaches to IWRM do not regard the ecosystem as a “user” of water in competition with other users, but as the base from which the resource is derived and upon which development is planned (Jewitt, 2002). Therefore, in order to evaluate the available water resources, environmental flows (EF) have to be defined. The notion of environmental flow - the flow regime needed to maintain environmental functions in a river ecosystem - is an attempt to find a compromise between productive uses and some protection threshold.

A global review by (Tharme, 2003) of the status of EF methodologies revealed the existence of some 207 individual methodologies, recorded for 44 countries within six world regions. These could be differentiated into hydrological, hydraulic rating, habitat simulation and holistic methodologies, with a further two categories representing combination-type and other approaches.

Hydrological EF methodologies are by far the most common used, as they are the simplest methodologies. They rely primarily on the use of hydrological data, usually in the form of naturalized, historical monthly or daily flow records, for making EF recommendations. They are often referred to as fixed-percentage or look-up table methodologies, where a set proportion of flow, often termed the minimum flow, represents the environmental flow requirements intended to maintain the freshwater fishery, other highlighted ecological features, or river health at some acceptable level, usually on an annual, seasonal or monthly basis. Holistic methodologies address the flow requirements of the entire riverine ecosystem, based on explicit links between changes in flow regime and the consequences for the biophysical environment. Recent advancements include the consideration of ecosystem-dependent livelihoods.

According to (Smakhtin, 2007; Smakhtin *et al.*, 2006; Smakhtin, 2001; Smakhtin and Anputhas, 2006) EFs should mimic natural patterns of flow variability in a river. All components of the natural hydrological regime have a certain ecological significance. High flows with return periods of 5 to 2 years ensure channel maintenance and riparian wetland flooding. Moderate flows occurring 30–60% of the time may be critical for cycling of organic matter from river banks and for fish migration. Low flows in the 70–95% exceedence range are important for fish spawning, algae control and use of the river by the local people. Maintaining the full spectrum of naturally occurring flows in a river is, however, hardly possible on account of water resources development (Smakhtin, 2007). Magnitude, frequency and duration of some or all flow components is modified and the suite of acceptable flow limits for such modifications can ensure a flow regime capable of sustaining some target set of aquatic habitats and ecosystem processes. EFs can therefore be seen as a compromise between river basin development on the one hand and maintenance of river ecology on the other.

(Tharme, 2003) states that Q_{95} is frequently applied as EF in Europe at a seasonal level. Therefore the monthly Q_{95} (daily values) is in this study chosen as EF. Q_{95} represents the daily average flow in a specific month that is exceeded 95 % of the time. In many legislations the abstraction of certain percentages of natural Q_{95} flow is (temporally) approved. An example is Switzerland (BUWAL, 2004), where water abstractions that result in a cumulative reduction of Q_{95} up to 20% can be approved. However, Switzerland is one of few countries in the world that have required the provision of a minimum flow for each individual stream type in their national policies and legislation (Dyson *et al.*, 2003). The Swiss Water Protection Act establishes specific flow values for different average flow rates, which must be maintained or increased in certain cases, depending on geographic and ecological factors.

5.4 AVAILABLE WATER

When assessing the available water in the catchments of the case study area, a differentiation between surface water and ground water (recharge) needs to be made. All water demand stakeholders in the Kitzbühel region use groundwater (springs and groundwater zones), except for snowmaking, which uses predominately surface water. A differentiation between these two sources of water results from the hydrological model. The model provides 250 m spatial and temporal distributed rasters for total flow, surface flow and base flow (groundwater). Simulated monthly flows for the whole case study area are presented in Figure 5-10. The base flow represents groundwater flow. Q_{95} and Q_{80} were defined statistically based on the simulated flows. Q_{80} represents the daily average flow in a specific month that is exceeded 80 % of the time, and is defined as a flow occurring during dry years. As a test groundwater recharge for the catchment BRIX was calculated according to (Kille, 1970), a methodology recommended by (Bogena *et al.*, 2005) and (Kling, 2006) for the assessment of ground water recharge in alpine areas without the use of a hydrological model. Results were generally in accordance to those simulated by the model.

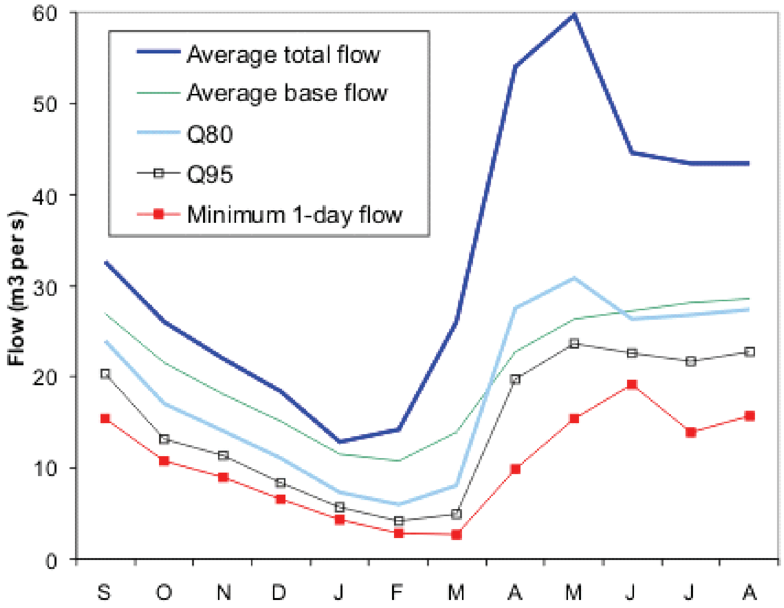


Figure 5-10: Simulated flows (in m^3 per s) for the reference period 1961-1990 for the whole case study area. Source: (Vanham *et al.*, 2009c)

The monthly base flow index (BFI) - the ratio of base flow to total flow – is presented in Table 5-2. The table shows the high contribution of base flow to total flow (BFI values of 0.8 and larger) during the autumn and winter months. During spring BFI values are the lowest due to snowmelt water. During summer months BFI values are about 0.6. Much precipitation falls in short storms and discharges as surface water when soils are fast saturated.

Table 5-2: Monthly base flow index (BFI) – ratio of base flow to total flow

Month	S	O	N	D	J	F	M	A	M	J	J	A
BFI	0.83	0.83	0.82	0.82	0.89	0.76	0.53	0.42	0.44	0.61	0.65	0.66

Total monthly available water for a normal and dry year is presented in Figure 5-11. Average monthly available water resources are defined as total flow minus Q_{95}. Average monthly dry year available water is represented by the difference between Q_{95} and Q_{80}. Of the total average flow R of 1121 mm (Table 5-1, page 36) for the case study area, 708 mm (63%) is base flow. This means that more than half of the total flow from the area is ground water. Also 504 mm (45%) is Q_{95}, 639 mm (57%) is Q_{80}. More than half of the total flow is defined as available water during a normal year (617 mm or 55%) but only 12 % (135 mm) is defined as available water during a dry year. Of the available water during both a normal and dry year, about 40% is accounted to the snowmelt period in spring (March to May).

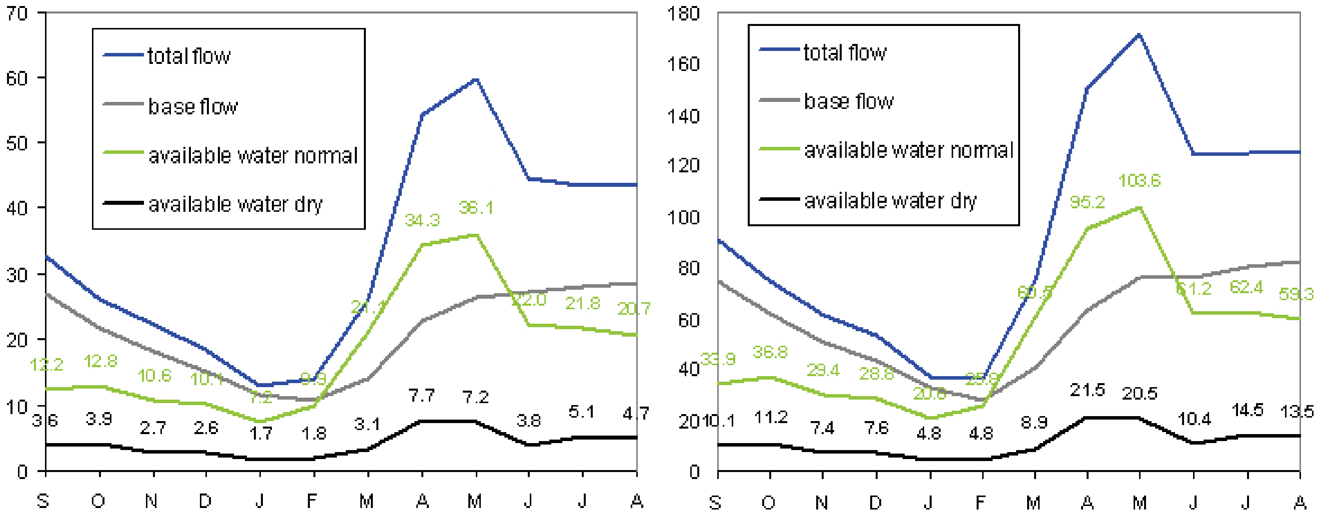


Figure 5-11: Monthly available water for a normal and dry year in m^3 per s (left) and mm (right) in the case study area for the reference period (1961-1990)

6 WATER DEMAND

6.1 INTRODUCTION

When the data are assembled and implemented in the (GIS)-data and information system, water demand of the different stakeholders can be analysed (Figure 6-1). In **paper C** a methodology for the calculation of grid cell spatially distributed water demands – for domestic, municipal, industrial and agricultural (without irrigation) purposes - is presented. In **paper G** a methodology for the calculation of the water demand for snowmaking is presented.

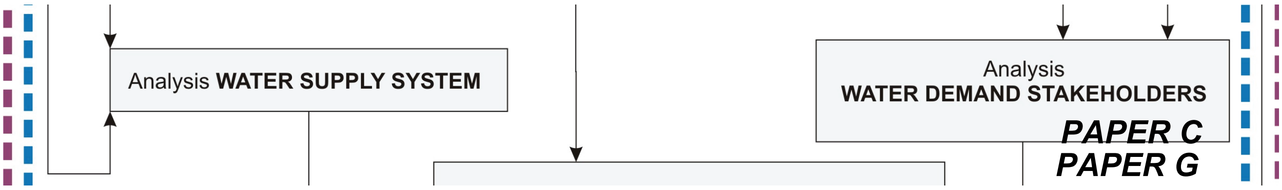


Figure 6-1: Positioning of the step “Analysis water demand stakeholders” within the workflow

Table 6-1: Publications and reports related to the CNET-project in which the topic “*water demand*” is discussed

Type	Title	Reference
Journal Article	**PAPER C**: Rasterised water demands: methodology for their assessment and possible applications.	(Vanham *et al.*, 2010)
Journal Article	**PAPER G**: Impact of snowmaking on alpine water resources management under present and climate change conditions.	(Vanham *et al.*, 2009c)
Conference Proceedings	Gis-gestütztes Verfahren zur Erhebung und Analyse der Trinkwasserversorgungsinfrastruktur im alpinen Raum am Beispiel des Grossraumes Kitzbühel	(Vanham *et al.*, 2009e)
Conference Proceedings	WP 2.1.2: Alpine Wasserversorgungs- und Vorsorgelogistik.	(Rauch *et al.*, 2008)
Report	Endbericht, Netzknoten 2, Work Package 2.1.2 „Alpine Wasserversorgungs- und Vorsorgelogistik“	(Vanham *et al.*, 2008b)

6.2 DIFFERENT WATER DEMAND STAKEHOLDERS

6.2.1 OVERVIEW

Generally following water demand stakeholders can be distinguished:

- **Domestic water demand** or household demand
- **Municipal water demand**: The water requirements of the commercial sector (shops, department stores, hotels, …) and for the services sector (hospitals, of-

fices, schools and others). This water demand thus includes tourism (overnight stays), a very important sector in the European Alps.

- **Industrial water demand**
- **Agricultural water demand:** In this study agricultural activities which are generally water fed by the public municipal water supply system, i.e. 1) persons employed in the agricultural sector and 2) water consumption of livestock are discussed. Rainfed and irrigated crop production are major water demand stakeholders, but they are of minor or no importance in the case study area.
- **Rainfed and irrigated crop production (water for food):** In many regions of the world by far the largest water user. However, there is no irrigation in the case study area and the rainfed crop area is not significant (0.1%, see Figure 4-4 page 28).
- **Energy**: Hydropower, ground water heat pumps, cooling water (e.g. nuclear energy production)
- **Technical snowmaking:** A major water demand stakeholder in the European Alps.
- **Other activities:** Fisheries, recreation (e.g. paddling, lake recreation), thermal water, religious activities, …

When water demand is discussed, the important distinction between non-consumptive and consumptive use needs to be made. Non-consumptive use is water use that returns to the system. With consumptive use the water leaves the system. More particularly, (Falkenmark and Lannerstad, 2005) define "*consumptive or depletive water use*" as evapo(transpi)ration with a vapour flow leaving the basin not available for reuse (until re-precipitated elsewhere through moisture recycling). Consumptive use of water can also be defined as use that results in returning water to the atmosphere, rather than back to streams or groundwater. About 80% to 90% of the water abstracted for domestic, municipal and industrial purposes will usually be returned to the system as wastewater (Loucks and van Beek, 2005). About 95% of cooling water is also typically returned to the basin, the rest is evaporated. Irrigation however, is a typical consumptive water user. Water losses in irrigation canals and the return of unused water can be seen as non-consumptive use as the water stays within the system. Technical snowmaking is generally a non-consumptive water user, as the produced snow normally stays within the system (except for snow evaporation). Also evaporation losses from reservoir storage for snowmaking – according to (de Jong *et al.*, 2009) a large concern in the European Alps - are consumptive use. In river basin studies, the total demand (both consumptive and non-consumptive) has to be taken into account, as this amount is actually withdrawn from the system (Loucks and van Beek, 2005). The water not used will be returned to the system, possibly at another location, in a future time period and containing more pollutants because of its use. Especially for shorter times steps the consideration of both is thus essential. When dealing with monthly time steps, water for technical snowmaking can be regarded as a consumptive use (as it remains hydrologically immobilized as snow). However on a yearly basis, technical snowmaking is a non-consumptive water user.

Another important distinction can be made between so-called blue and green water. Blue water is the water in rivers and ground water. Irrigation-based agriculture is linked to this water. Green water is the water that leaves the system through evapotranspiration – evaporation from soils and water surfaces and transpiration from plants. Rainfed agriculture is linked to green water. A more detailed discussion on rainfed agriculture (green water demand) is fiven in chapter 6.2.3 (page 49).

6.2.2 PAPER C: DOMESTIC, MUNICIPAL, INDUSTRIAL AND AGRICULTURAL WATER DEMAND IN A RASTER GEODATASET

Paper C (Vanham *et al.*, 2010) presents a methodology for the calculation of grid cell spatially distributed water demands for the stakeholders domestic, municipal, industrial and agricultural (without irrigation) water use.

To obtain such a grid, the number of units of the detailed population and housing census raster – originating from the population and housing census of 2001 (Statistics Austria, 2008), as described in chapter 4.2.3 page 29 - are multiplied with a rate of water use (litre per unit per time interval) for the different stakeholders. These water use rates are obtained from literature – e.g. (DVGW, 1972; Hoch, 2007; Mutschmann and Stimmelmayr, 2007; Trifunović, 2006) - and calibrated with operating data from the water supply undertakings in the study area. For the different stakeholders following (census raster) data are used:

- **Domestic water demand**: population of principal and secondary residence
- **Municipal and industrial water demand without tourism (overnight stays)**: number of persons employed in the different sectors (industries, small trade, schools, hospitals, administration, …). A differentiation between on the one hand the commercial sector and the services sector and on the other hand industry is very complicated within the list of ÖNACE-classes used in the paper to differentiate amongst people employed in different classes. Therefore the paper identifies municipal and industrial water demands together. Within the commercial sector tourism in the form of overnight stays is calculated separately.
- **Municipal water demand restricted to tourism (overnight stays)**: tourist overnight stays
- **Agriculture (without rainfed and irrigated crop production):** Persons employed in the agricultural sector and livestock units (LUs)

This methodology can be used in different spatial resolutions and for different time steps (yearly, seasonal, monthly, weekly, daily, hourly). The generated rasters provide the advantage that they are independent of political entities like countries or municipalities. They provide the possibility to re-aggregated water demands on political entity levels to the river basin scale. For the detailed methodology and results the paper in the Annex should be consulted.

As in detail discussed in the following chapter 7.2 (Analysis water supply system, page 58), the 19 municipalities of the case study area are served by 24 major water supply undertakings (see Table 7-1, page 59). As described, the methodology can calculate water demands for any time step. **Paper D** (Vanham *et al.*, 2008a) indicates that a water balance between water demand and available water resources should be analysed at least on the seasonal level in alpine areas. Winter is identified as a critical period. The seasonality analysis – described in the following chapter 7.3, page 60 – defines winter for the reference period as the period from December to March. Figure 6-2 displays the total calculated water demand (l per s) during the winter period for the different water demand stakeholders for each municipality. Also the demand for the stakeholders not connected to one of these major undertakings within the project area is shown. The total average winter water demand is 251 l per s. The total average annual water demand is 219 l per s. These values do not take water losses into account, as water demands were calibrated according to service data without water losses (the water sold to the customer was given in the questionnaire)(Vanham *et al.*, 2010). Water losses in the case study area can be estimated to be about 10 %, based upon the service data given by the municipalities in the questionnaire. This means that the total average water demands inclusive water losses are estimated at 276 l per s in winter and 241 l per s annually. The proportions of the different water demand stakeholders as described in **paper C** (Vanham *et al.*, 2010) to total water demand are displayed in Figure 6-3. Population of secondary residence and agriculture present only a small fraction of total water demand, whereas population of principal residence, persons employed and overnight stays present the large stakeholders. The proportion of overnight stays is clearly larger during winter than as an annual average. In other terms domestic water demand accounts for approximately 40 % of total water demand, municipal and industrial water demand 50 % and agriculture 10 %.

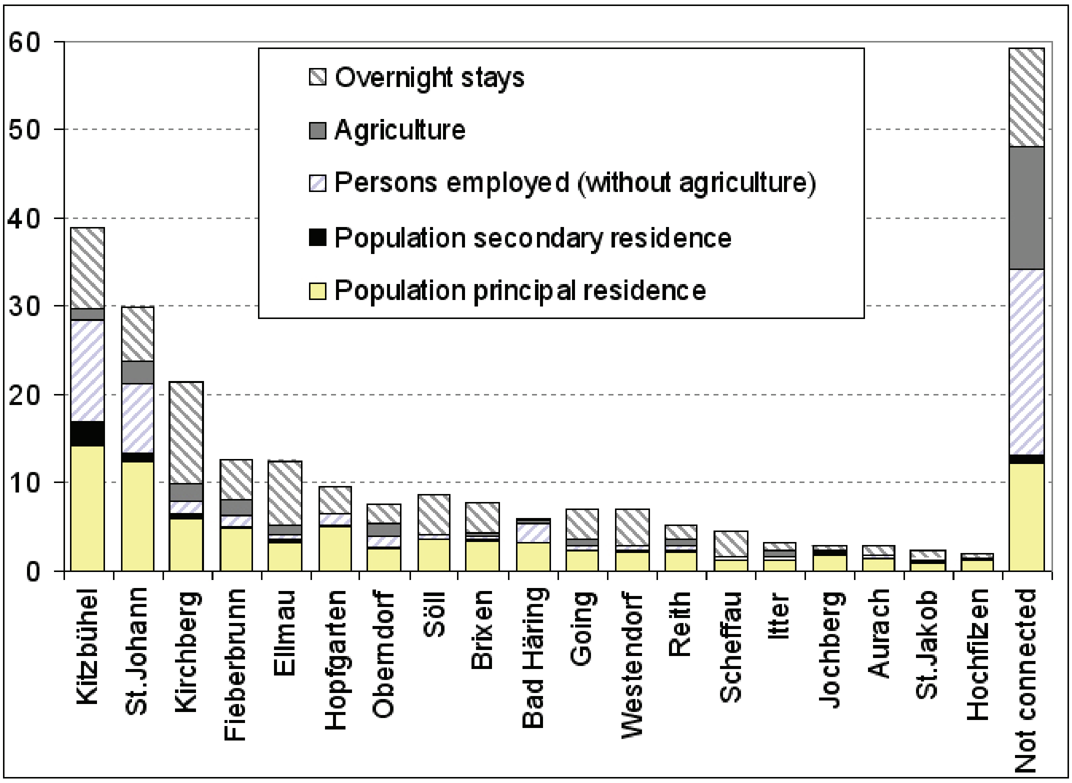


Figure 6-2: Total calculated winter water demand (l per s) for the different water demand stakeholders connected to the 24 major water supply undertakings for each municipality. Also the water demand for the stakeholders not connected to one of these major undertakings within the project area is shown.

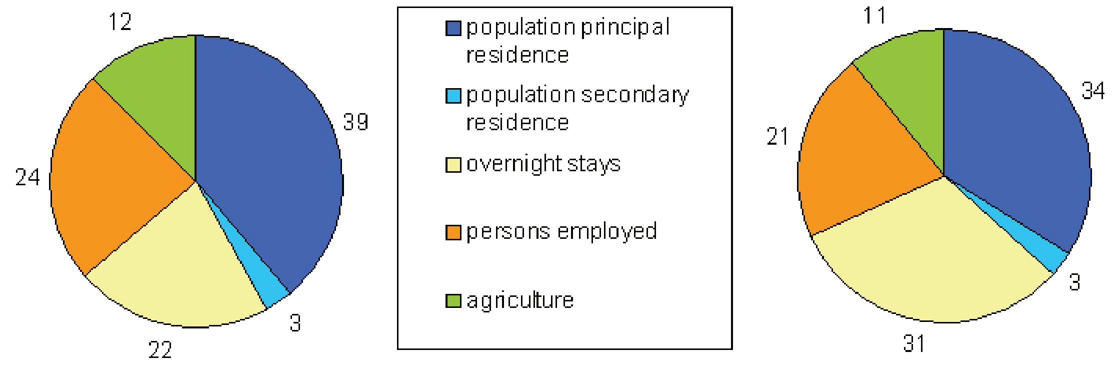
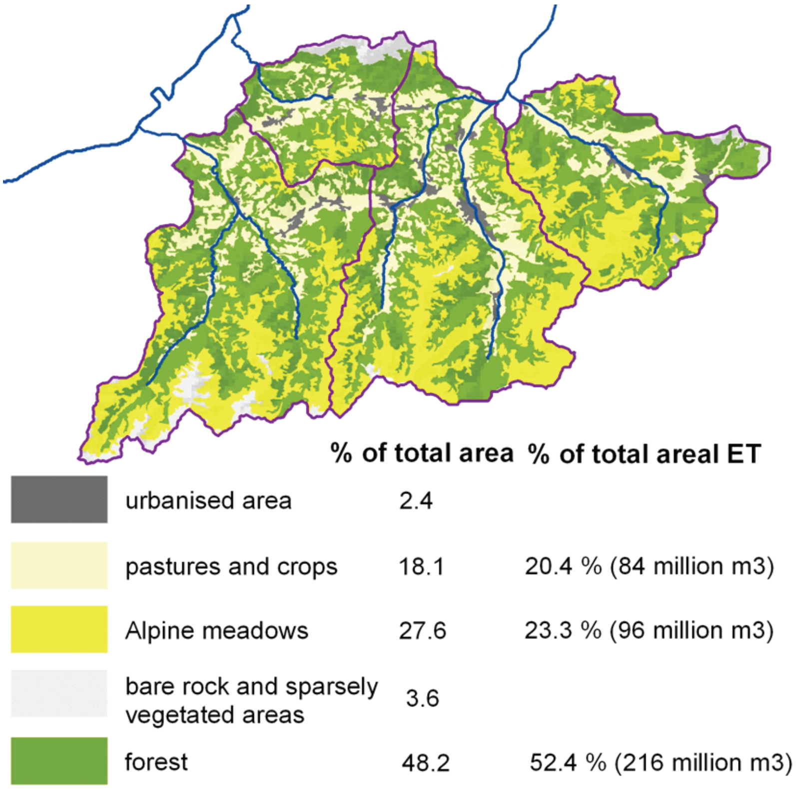


Figure 6-3: Proportions of different water demand stakeholders on the total average annual (left) and winter (right) water demand

6.2.3 AGRICULTURE (WATER FOR FOOD): RAINFED AGRICULTURE (GREEN WATER) AND IRRIGATION (BLUE WATER)

Few people are aware that rainfed agriculture is by far the largest worldwide (green) water user. This is a consumptive (evapotranspiration) water use. Global food production consumes approximately 6,800 km^3/yr of water (Falkenmark and Rockström, 2006; Shiklomanov, 2000). Of this amount, 1,800 km^3/yr is consumed for irrigated crop production - which water planners generally refer to as the totality of water used in agriculture -, whereas the remaining 5,000 km^3/yr is consumption by the world's rain-fed agriculture. According to (Siebert and Döll, 2009), for the period 1998–2002, the global value of total crop water use was 6685 km^3/yr, of which blue water use was 1180 km^3/yr, green water use of irrigated crops was 919 km^3/yr and green water use of rainfed crops was 4586 km^3/yr. Also (Hoff *et al.*, 2009) indicate that green water use in global crop production is about 4–5 times greater than consumptive blue water use. (Liu *et al.*, 2009) indicate that about 80% of the amount of water in food production was from green water.

The following Figure 6-4 shows the evapotranspiration amounts for the 3 major land use classes in the case study area. Different authors indicate that green water has to be accounted for in IWRM with respect to food production. The crop land area is neglectible; however the pastures in the valleys and the Alpine meadows are the grazing food for the livestock units (LU) in the case study area. They make up about 44 % of the total annual evapotranspiration in the 4 catchments. In summer cattle graze on the Alpine meadows, in winter they are in stables in the valleys. In spring and autumn they reside on the pastures in the valleys. During summer the hay and straw from the valleys is stored for winter. Whether the total area is required for the LU, is not part of this study. However, it can be seen that the green water demand for (parts of) the pastures and Alpine meadows could be regarded as a separate agricultural water demand within the case study area.



		% of total area	% of total areal ET
⬛	urbanised area	2.4	
▨	pastures and crops	18.1	20.4 % (84 million m3)
🟨	Alpine meadows	27.6	23.3 % (96 million m3)
⬜	bare rock and sparsely vegetated areas	3.6	
🟩	forest	48.2	52.4 % (216 million m3)

Figure 6-4: Annual evapotranspiration (ET) amounts for the major land use classes (period 1961-1990)

Irrigation is in many regions of the world the largest blue water demand stakeholder, also in mountainous areas and lowlands dependent on mountain water. The latter situation is for example true in the Po basin in Italy, in the Indus and Ganges-Brahmaputra (Vanham and Rauch, 2010) river basins in South Asia - as described in **paper A** (Vanham and Rauch, 2009c) - or for the Cauvery basin in India (Vanham *et al.*, 2009a). A global map of the proportional freshwater withdrawal of the three sectors agriculture, industry and domestic use (Figure 6-5), shows that in many countries of the world (especially in countries with a warmer climate) irrigation is the predominant water demand stakeholder. In the EU for example, there is a strong regional difference (Wriedt *et al.*, 2009b). In the Mediterranean region irrigated agriculture is a major water user accounting for more than 60% of total blue water abstractions (e.g. Spain 64 %, Greece 88 %, Portugal 80 %). In Central and Northern European countries agricultural water abstractions account for less than 1% of total abstractions (e.g. Belgium 0.1 %, Germany 0.5 %, Netherlands 0.8 %). In these regions, irrigation is supplementary and used to optimize production in dry summers, especially when water stress occurs at a sensitive crop growth stage. In countries like Pakistan or India, more than 90 % of all water withdrawals are accounted to irrigation.

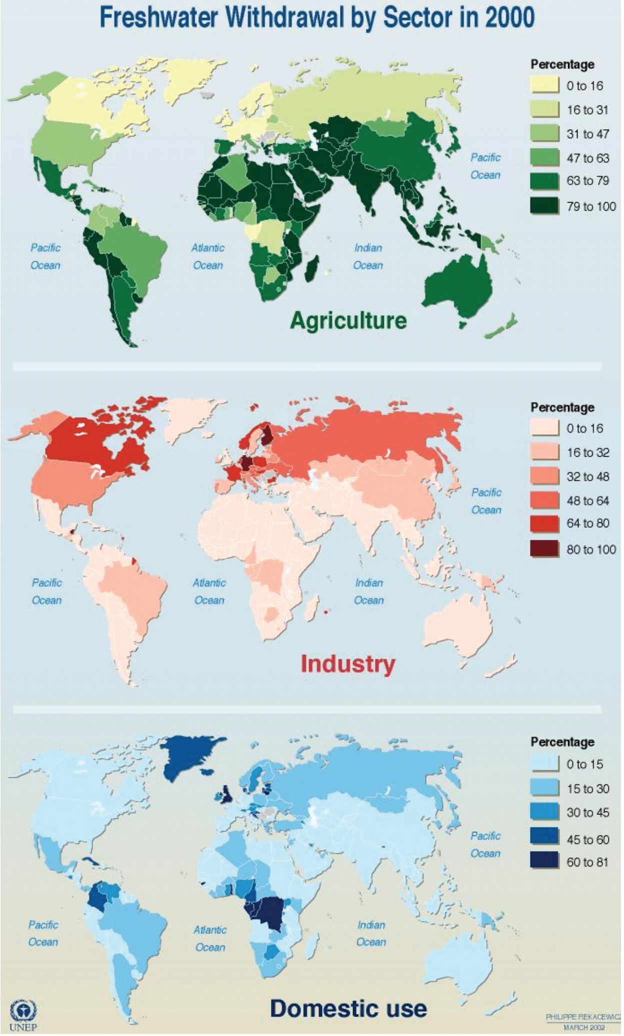


Figure 6-5: Freshwater withdrawal (blue water) in % in 2000 by the sectors agriculture, industry and domestic use. Source: (WRI, 2000), provided by UNEP, Grid Arendal, http://maps.grida.no/theme/freshwater.

Steadily increasing demand for agricultural products to satisfy the needs of a growing worldwide population is the main driver behind agricultural water use. Also economic development, in particular in emerging market economies, is translating into demand for a more varied, water-intensive diet, including meat and dairy products (UNESCO-WWAP, 2006). To meet these future food needs, pressure to develop new supply sources or increase water allocation to agriculture will continue. Countries like India and China, with their already present day huge populations, population increase, rapid industrialization and urbanization and higher standards of living (and altered food preferences) could move from food self-sufficiency to (massive) food imports (Falkenmark and Lannerstad, 2005). This alternative is sometimes referred to as virtual water flow, as the imported food represents a consumptive use of water resources in another country. This will put an extra burden as virtual water export on river basins throughout the world (Allan, 1998; Chapagain and Hoekstra, 2008; Hoekstra and Chapagain, 2007; Kumar and Singh, 2005; Oki and Kanae, 2004).

Although irrigation is not present in the case study area, the topic is generally discussed as the presented methodology aims to be applicable for any river basin with a significant mountainous part. Irrigation is a consumptive water user, as the water is evapotranspirated by the crops and therefore lost from the basin. In order to calculate irrigation water demands, the standard modelling approach is based on the FAO guideline to estimate crop water requirements (Allen *et al.*, 1998). In the primal equation crop water demand (crop evapotranspiration) is calculated by multiplying reference evapotranspiration (ETo) over a standard grass surface with a crop coefficient, which varies according to the different phenological stages of the crop. Net irrigation requirements per unit irrigated area are then calculated as difference between the crop-specific evapotranspiration and the effective precipitation. These can be calculated for wet, normal and dry conditions.

This FAO approach was implemented in different field scale models, e.g. CROPWAT (Smith, 1992) and ISAREG (Pereira *et al.*, 2003). The combination of GIS and field scale soil water balance models allows estimating irrigation water demands in irrigation districts and at regional scale. The spatially distributed model GISAREG (Fortes *et al.*, 2005) applies ISAREG to multiple fields and irrigation districts. A GIS-based approach was developed by (Portoghese *et al.*, 2005) for regional assessment of net irrigation requirements in Southern Italy. Based on the FAO approach, it calculates monthly water balances on raster data with a spatial resolution of 1 km. At global scale, the WaterGAP model (Döll and Siebert, 2002; Döll *et al.*, 2003) implements the FAO approach at daily time steps to estimate irrigation requirements at a spatial resolution of 0.5°. GEPIC (Liu, 2009; Liu *et al.*, 2007) is a large-scale implementation of the EPIC model that has been applied to simulations of crop growth and water productivity at continental and global scale and runs at a spatial resolution of 0.5°. (Wriedt *et al.*, 2009b) use a spatially distributed implementation of the EPIC model to calculate irrigation water requirements in Europe in a 10 km grid.

6.2.4 ENERGY

Water is used in river basins for hydropower, ground water heat pumps and cooling water (e.g. nuclear energy production). In the Alps and other mountain areas in the world hydropower is a large water demand stakeholder. There are two kinds of hydroelectrical power plants: run-of-river power stations and storage power stations. In Austria the existing hydropower system generates in average 42,000 GWh electrical energy per year (Pirker, 2003). About two thirds from run-of-river power stations and one third from storage power stations. Storage power stations are off course concentrated in the mountains. The largest run-of-river power stations can be found on the Danube and its larger tributaries (like the Inn).

In the case study area Kitzbühel region small run-of-river power stations can be found locally on the rivers. There are no significant storage power stations. However, on reservoirs built for other purposes (e.g. snowmaking) energy can be additionally generated. Nonetheless this is not the primal function of the reservoirs in the case study area. Ground water heat pumps are also present. The water demand for energy is however not assessed separately in the case study area, as it is very small, regarded as a secondary advantage for other water demands and as run-of-river power stations are water availability driven (Pirker, 2003).

There is a lot of ambiguity in the sustainability of dams/reservoirs on rivers for hydropower generation. Positive effects are the generation of green house gas neutral electricity and the possibility of multifunctional purposes like the storage for irrigation water, flood management, recreation, fisheries, navigation and economic impulses for the region. An example of a multifunctional reservoir is the Tarbela Dam on the Indus river (located on the foot of the Himalayas), which provides not only for hydropower but for many other water demands (e.g. irrigation water) as well. On the other hand hydroelectrical power plants change the river flow regime significantly, with negative effects to the natural ecological system. Wetlands are often negatively affected as well as fish migration; flood plains are often not inundated any more and in deltas there can be seawater intrusion in the groundwater. There can be downstream environmentally damaging impacts due to fluctuating peak hydro releases. Often the (energy producing) life time of dams is very short due to rapid sedimentation of the reservoir. This sedimentation can also lead to increased water velocities downstream and resulting erosion. Dam construction often requires the resettlement of many people (e.g. the Three Gorges Dam on the Yangtze river in China). Critics argue that when climate change reduces inflows to reservoirs in key parts of the world, turning to hydropower as a solution is nonsensical (Pittock, 2008). However, it is generally accepted – also by some environmental organisations like WWF – that modest hydropower expansion is required. Globally, for large hydropower plants, some 740 GW have been installed, and an economically feasible potential of some 1530 GW remains, of which 120 GW is being built now and a further 445 GW is planned (Pittock, 2008). Expansion of hydropower facilities is underway in countries like China, India, Iran, Turkey and Brazil. An example of dam ambiguity poses the Mekong river (Molle *et al.*, 2009). The Mekong is relatively "underdeveloped" in terms of storage infrastructure. Some see this as a lost opportunity for energy generation, dry season irrigation and flood control. Yet the Mekong Basin is also the world's largest freshwater fishery, producing 17% of the world total. With some 1700 species of fish, the Mekong is the second most ichtyofaunally biodiverse river basin in the world, and most of these species (70%) are migratory and hence vulnerable to the blocking effect of dams

When hydropower is important in the basin, it should be regarded as a separate water demand stakeholder.

As stated in chapter 3.2.2 (page 18), mountain waters can be essential for their downstream lowlands. These waters are often used for cooling water for nuclear power and other thermal power. A good example is the Rhine river, in which water from the Alps contributes significantly to spring and summer flows in the lowlands, where cooling water is a large demand stakeholder – see **paper A** (Vanham and Rauch, 2009c). This should be accounted for when water management decisions in mountainous upstream catchments are considered.

6.2.5 PAPER G: WATER DEMAND FOR TECHNICAL SNOWMAKING

Within **paper G** (Vanham *et al.*, 2009c) and (Vanham *et al.*, 2009d) the topic of technical snowmaking and its impact as a water demand stakeholder on the water balance of the case study area is discussed in detail. A methodology for the calculation of its water demand is presented.

Owing to less natural snow reliability as a result of climate change on the one hand, and the demand of higher standards by winter tourists on the other hand, the production of artificial snow in ski resorts has increased substantially and is likely to increase further in future (Vanham *et al.*, 2009c). During the past 20 years, the production of technical snow has become increasingly important in many ski areas of the world (OECD, 2007). In Austria today, 60 % of the total ski slopes are covered by technical snow (Fachverband der Seilbahnen Österreichs, 2009). With winter tourism being economically very important in the Alps and other mountain regions of the world and snowmaking constantly increasing, its impact as a water demand stakeholder on the total water system is an essential issue to be addressed.

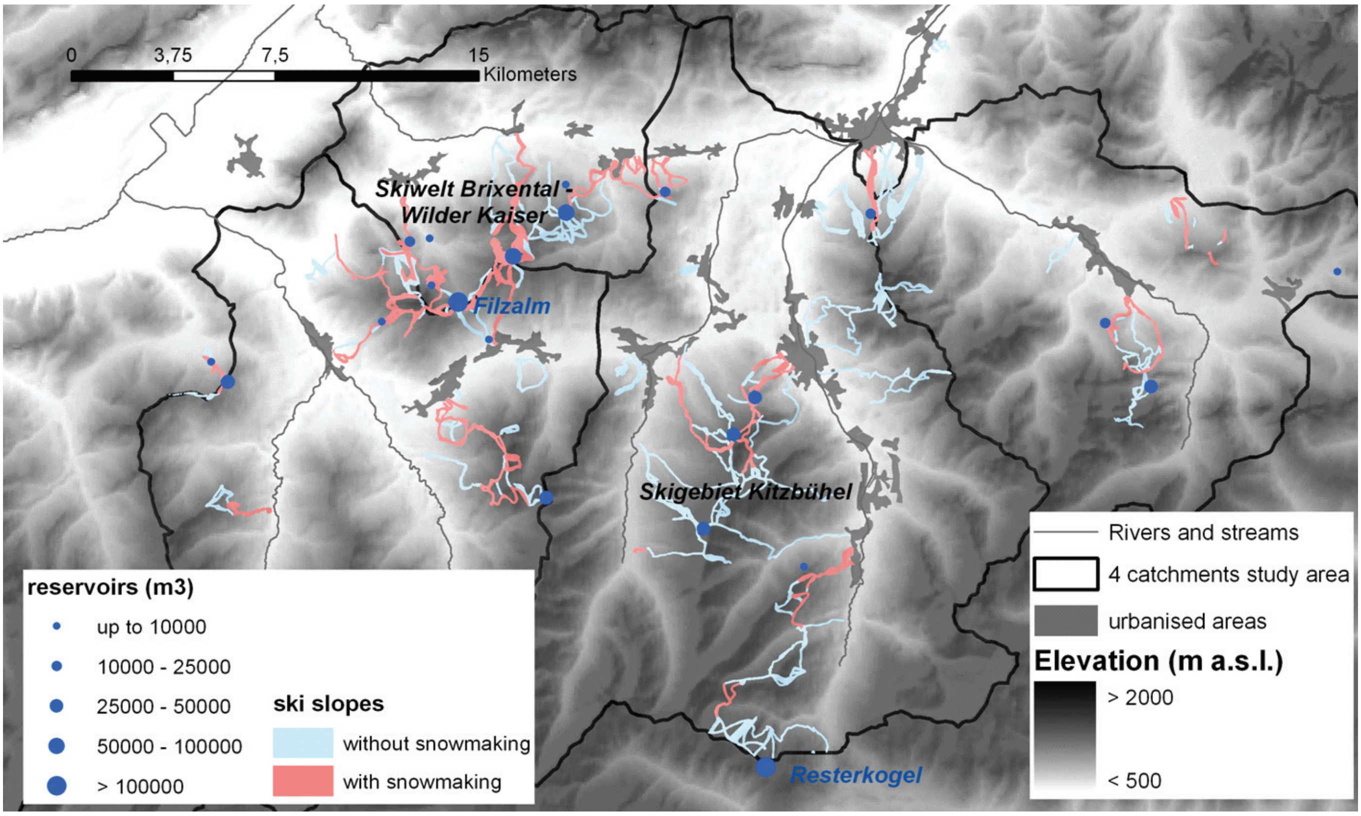


Figure 6-6: Location of ski slopes with and without technical snowmaking capacity (with capacity: 882 ha of the total ski slope area of 2,117 ha). Reservoirs for snowmaking are also indicated with their storage volume (in m^3).

Figure 6-6 shows the location of the ski slopes within the case study area. Currently 882 ha have technical snowmaking capacity, of a total of 2117 ha. The two largest ski regions are the *Skiwelt Brixental – Wilder Kaiser* and the *Skigebiet Kitzbühel*. At the time of this project the area with snowmaking capacity increased (e.g. within *Skiwelt Brixental – Wilder Kaiser*). However, in the analysis it is assumed that the total ski slope area has snowmaking infrastructure in order to analyse a maximum water demand (Vanham *et al.*, 2009c). This can be justified due to that fact that the ski slope area with snowmaking capacity is continuously increasing and is likely to do so further in future. Also the reservoirs within the case study area are displayed, of which two (the reservoir *Filzalm* with a storage volume of 170,000 m^3 and the reservoir *Resterkogel* with a storage volume of 180,000 m^3) are amongst the largest in Austria. A photograph of both reservoirs is displayed in Figure 6-7. This figure also displays the cumulative elevation range for all ski slopes within the case study area, with a minimum of about 600 m a.s.l. and a maximum of about 2000 m a.s.l. This is rather low for the European Alps. About 50 % of the ski slopes are located at an elevation lower than 1300 m a.s.l. For operation of ski resorts the (Swiss) 100-day rule was suggested by (Witmer *et al.*, 1986) stating that for the successful operation of a ski area, a sufficient snow cover (snow depth of minimum 30 cm) should last at least 100 days per season. For the present day situation in Switzerland, this rule is fulfilled for natural snow-reliability at an altitude above 1,200–1,300 m a.s.l. (Laternser and Schneebeli, 2003). For the Western part of Austria, including Tyrol, the same altitude is identified as the baseline of natural snow-reliability (Wielke *et al.*, 2004). An overview of this altitude for different alpine regions in 5 alpine countries is given in (OECD, 2007). According to this rule, snowmaking is necessary below the baseline of natural snow-reliability.

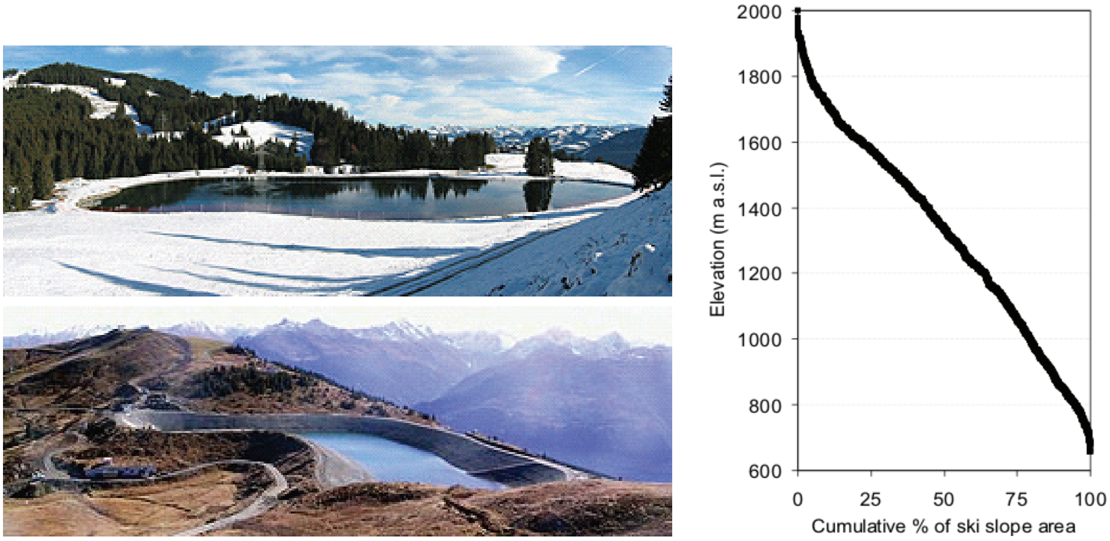


Figure 6-7: (Upper left) reservoir Filzalm; (lower left) reservoir Resterkogel; (right) cumulative elevation range for all ski slopes within the case study area Source: (Vanham *et al.*, 2009c)

The water demand for snowmaking is calculated based upon the area of ski slopes, according to a methodology described by (Pröbstl, 2006), who evaluated the water demand for the production of artificial snow in different Bavarian (Southern Germany) and Tyrolean ski regions in similar altitudes as the project area of this study. As a ground rule 2.4 m^3 of snow is generated from 1 m^3 of water. For the base snowing at the beginning of the winter season, a snow height of 30 cm is chosen, corresponding to 120 litre water per m^2. This minimal critical height for skiing (Elsasser and Bürki, 2002; Scott *et al.*, 2003) was assumed for base snowmaking in both the reference and the climate change scenario. For improvement snowmaking during the remaining winter season 120 percent of the base snowing is assumed (Pröbstl, 2006).

First the technical snowmaking water demand for the installed 882 ha was calculated. This results in a base snowmaking demand for 30 cm at the beginning of the winter season of 1.06 million m^3, and an improvement snowmaking demand (120 % of base snowmaking) of 1.27 million m^3. The sum is 2.33 million m^3. These values are presented in (Vanham *et al.*, 2009d). The total reservoir volume within the case study area (0.9 million m^3), divided over app. 20 reservoirs, is capable of storing almost the whole base snowmaking volume. The calculated 2.3 million m^3 is approximately identical to the total water rights approved within the case study area in the *Water Book*. This confirms that the applied methodology is also used for the water right applications of the mountain railway companies within the Kitzbühel region.

In **paper G** (Vanham *et al.*, 2009c) a maximum water demand for all ski slopes (2,117 ha) is calculated. The resulting values are displayed in Table 6-2.

Table 6-2: Maximum water demand for snowmaking for the total area of existing slopes (2117 ha). Source: (Vanham *et al.*, 2009c)

	10^6 m^3	m^3 per s
Average yearly natural snow cover water equivalent	8.76	
Base snowmaking (restriction to 5 days in December)	2.50	4.75
Improvement snowmaking	3.05	
of which in December	0.92 (30%)	0.34
of which in January	0.60 (20%)	0.22
of which in February	0.60 (20%)	0.22
of which in March	0.92 (30%)	0.34
Total water demand snowmaking	5.55	5.88

Figure 6-8: View on the ski region *Skiwelt Brixental – Wilder Kaiser* (Photo © TVB Wilder Kaiser)(left) and view on a snowmaking device (right).

6.2.6 WATER DEMAND FOR OTHER ACTIVITIES

Other water demand related activities include fisheries, recreation (e.g. paddling, lake recreation), sports (e.g. golf), thermal water, religious activities (e.g. ritual washing in India) etc. Within the case study Kitzbühel region water related summer recreation (swimming, paddling, lake recreation) can be identified as a noticeable water demand stakeholder. Two recreation lakes in the region are the Schwarzsee in Kitzbühel and the Thiersee in Scheffau, which are generally fed by precipitation and groundwater. As in the analysis environmental flows are regarded as prerequisite (monthly Q_{95}), this water demand is not assessed separately. An analysis of the lakes fluctuations and its relationship to water demand could however be done. For the golf sports areas within the region, watering of the grass fields (irrigation) during dry periods (spring to autumn) can present a temporary water demand. This water demand is however not included in the analysis, but can be calculated according to the methodology described in chapter 6.2.3 (page 49).

7 DSS MAPS

7.1 INTRODUCTION

When water availability (chapter 5) and water demands (chapter 6) are assessed and the water supply system implemented in the (GIS)-data and information system, the water quantity map can be generated (Figure 7-1). The workflow also presents the generation of a water quality map, however the discussion in this dissertation is limited to water quantity management. By means of a regional and local water balance model, a water balance map can then be generated. By means of the analysis of the water supply system and its vulnerability and the interaction with Alpine natural hazards, a water supply system vulnerability map and Alpine natural hazards risk map can be generated. The methodology for the latter map(s) is described in **paper E** (Möderl *et al.*, 2008a) and (Möderl *et al.*, 2008b). These maps can be generated for any time step. A general time step is a yearly one. However, as discussed before, in alpine regions at least seasonal water balance time steps should be addressed. The winter season – a critical period in alpine water resources management due to low water availability and high water demands – is in **paper D** (Vanham *et al.*, 2008a) defined as the period from December to March for the case study area Kitzbühel region. The clear definition of the winter period is a minimum prerequisite for water resource management in alpine regions. In the following text the methodologies will be presented for a yearly and/or seasonal (winter) time step.

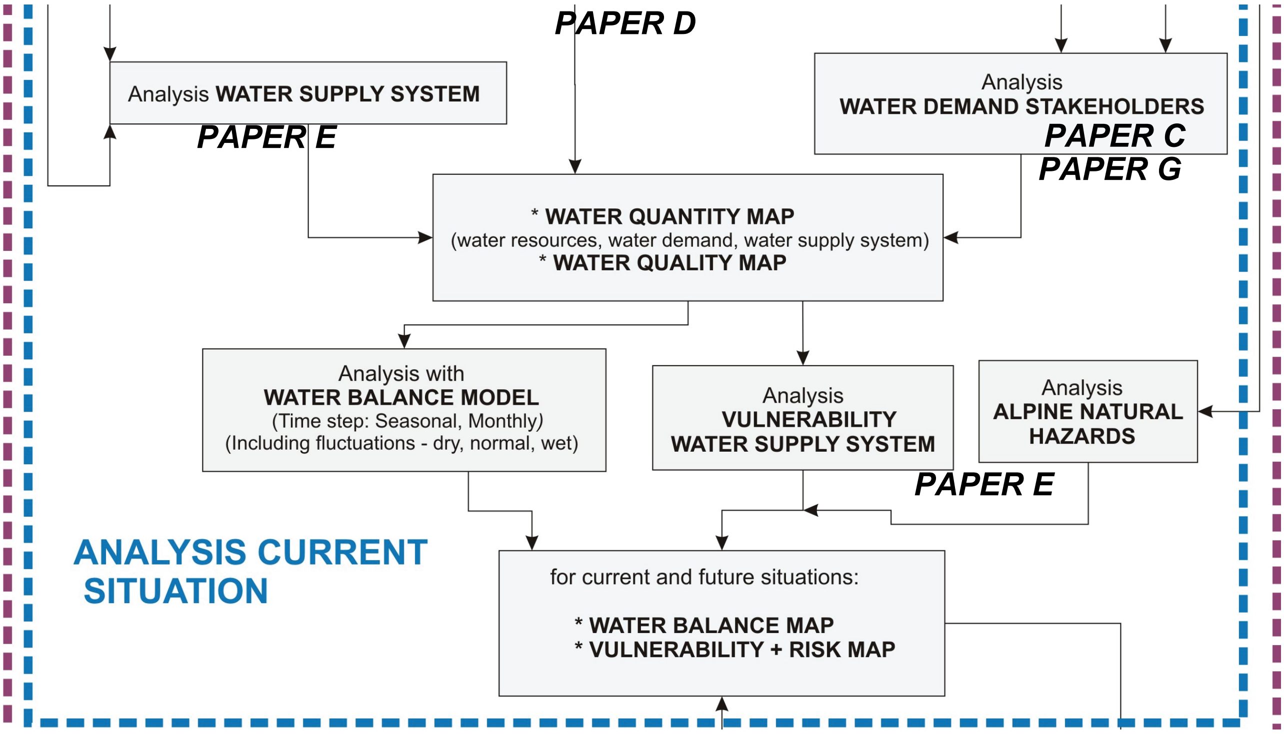


Figure 7-1: The following steps within the workflow regarding the generation of 1) a water balance map and 2) a water supply system 2a) vulnerability map and 2b) Alpine natural hazards risk map

7.2 ANALYSIS WATER SUPPLY SYSTEM

The acquisition of the geographical and attribute data on the water supply system is a very time and energy consuming task, as discussed in chapter 4.2.4 page 30 and (Millinger, 2008). In order to analyse water demands as presented in **paper C** (Vanham *et al.*, 2010) –described in chapter 6.2.2, page 47 – the service zone area border needs to be identified. The identification of the geographical location of the water supply system is very helpful here, however not necessary when the border of the service area is known. For the definition of the winter season according to **paper D** (Vanham *et al.*, 2008a) – as discussed in the following chapter 7.3 – it has to be known which springs and groundwater wells serve which service zones. Again, when this information is known (e.g. from the Water Book or by means of a questionnaire filled out by the municipality) the acquisition of the geographical water supply system data is not necessary. However, these data are a prerequisite for the assessment of the water supply system vulnerability map and Alpine natural hazards risk map (**paper E**). When these data are not available and cannot be acquired, the map cannot be generated. Then the DSS map of this dissertation reduces itself to the water balance map.

In the European Alps, drinking water supply systems are characterised by a local, small structured infrastructure. Water supply is generally organised on a municipality basis. In Austria for example a total of 7600 public water supply undertakings provide the national population of 8.1 million inhabitants with drinking water (Schönback *et al.*, 2004). A map of the average population served per water supply undertakings (Figure 7-2), shows significant differences among selected countries in Europe. Alpine countries like Austria and Switzerland are characterised by an average low number of people served per undertaking. Water supply undertakings in Northern European countries with a flat topography like the Netherlands, Belgium and England on the contrary, serve on average a large number of people. Germany and France present on a national scale a situation between these two extremes. However, on a regional level the small structured water supply undertakings are concentrated in the mountainous parts of these countries, whereas large undertakings are concentrated in the lowlands.

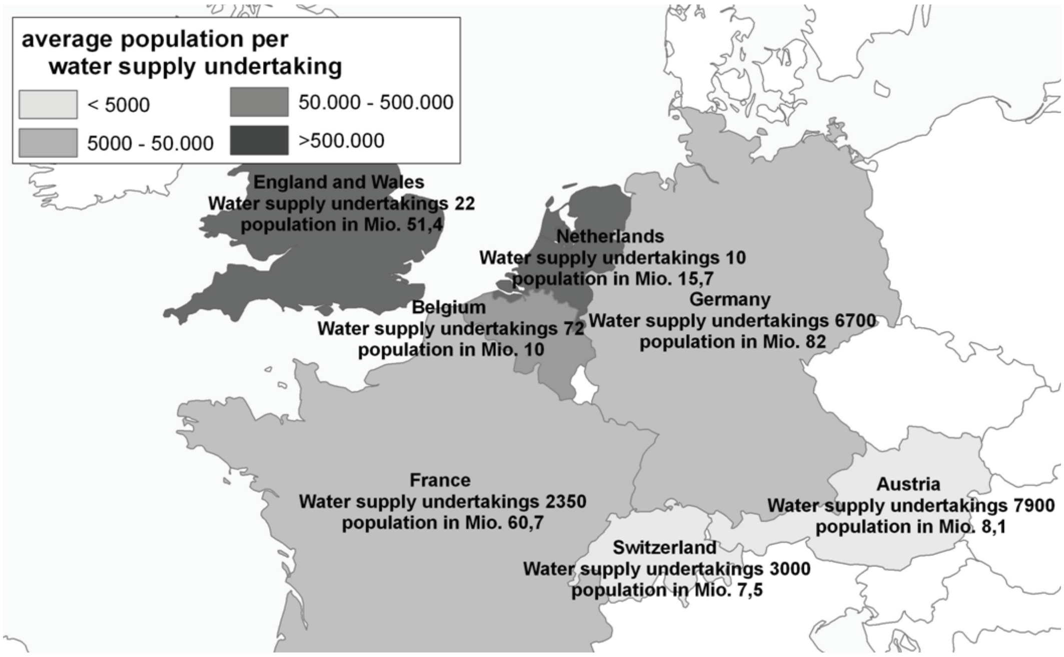


Figure 7-2: Average population per water supply undertaking in selected European countries. Source (Vanham and Rauch, 2009b)

The 19 municipalities of the Kitzbühel region are served by 24 major water supply undertakings, as listed in Table 7-1. In the **papers C** (Vanham *et al.*, 2010) and **D** (Vanham *et al.*, 2008a) the municipality of Kirchdorf is included in the analysis. However, this municipality is not part of the final case study area of the dissertation. About 10 % of the population are not connected to these 24 water supply undertakings. Typically for the Alps, springs are the first source for public drinking water (average 80%), followed by ground water (average 20%). Some municipalities are only served with spring water, some only with ground water. The amount of use of ground and spring water was obtained by means of a questionnaire. Surface water is not used for drinking water purposes.

Table 7-1: Water supply characteristics in the case study area. Table adapted from **paper C** (Vanham *et al.*, 2010) and **paper D** (Vanham *et al.*, 2008a)

municipality	inhabitants	public drinking water supply (%)		Major water supply undertaking	Connection % principal residence
		spring water (%)	groundwater (%)		
Aurach	1203	80	20	1	88
Brixen	2574	100	0	1	93
Fieberbrunn	4180	100	0	2	87
Going	1730	100	0	1	96
Hochfilzen	1109	100	0	1	83
Hopfgarten	5266	95	5	3	69
Itter	1060	100	0	1	93
Jochberg	1540	100	0	1	84
Kirchberg	4958	80	20	1	91
Kitzbühel	8571	80	20	1	96
Oberndorf	1944	40	60	2	97
Reith	1595	0	100	1	91
St.Jakob	635	20	80	1	100
St.Johann	7959	80	20	1	91
Westendorf	3454	100	0	2	43
Bad Häring	2265	70	30	1	100
Ellmau	2524	100	0	1	92
Scheffau	1211	100	0	1	77
Söll	3364	80	20	1	75
total	57142	80	20	24	87

Figure 7-3 shows the water supply pipe network (without house connections) in the case study area. Also the springs and groundwater wells that feed each supply network are shown. Many municipalities are served by several springs. Groundwater is predominately used in the valley Aurach to Sankt Johann, where groundwater zones are significant. For springs the average winter discharge is shown in the size of the dot representation (range from less than 1 to more than 15 l per s). For groundwater wells the size of the respective dot represents the approved water right as taken from the Water Book. For a detailed analysis and description of the water supply system of the case study area it is referred to (Millinger, 2008). In this work amongst others the diameter size and material for all pipe sections are given.

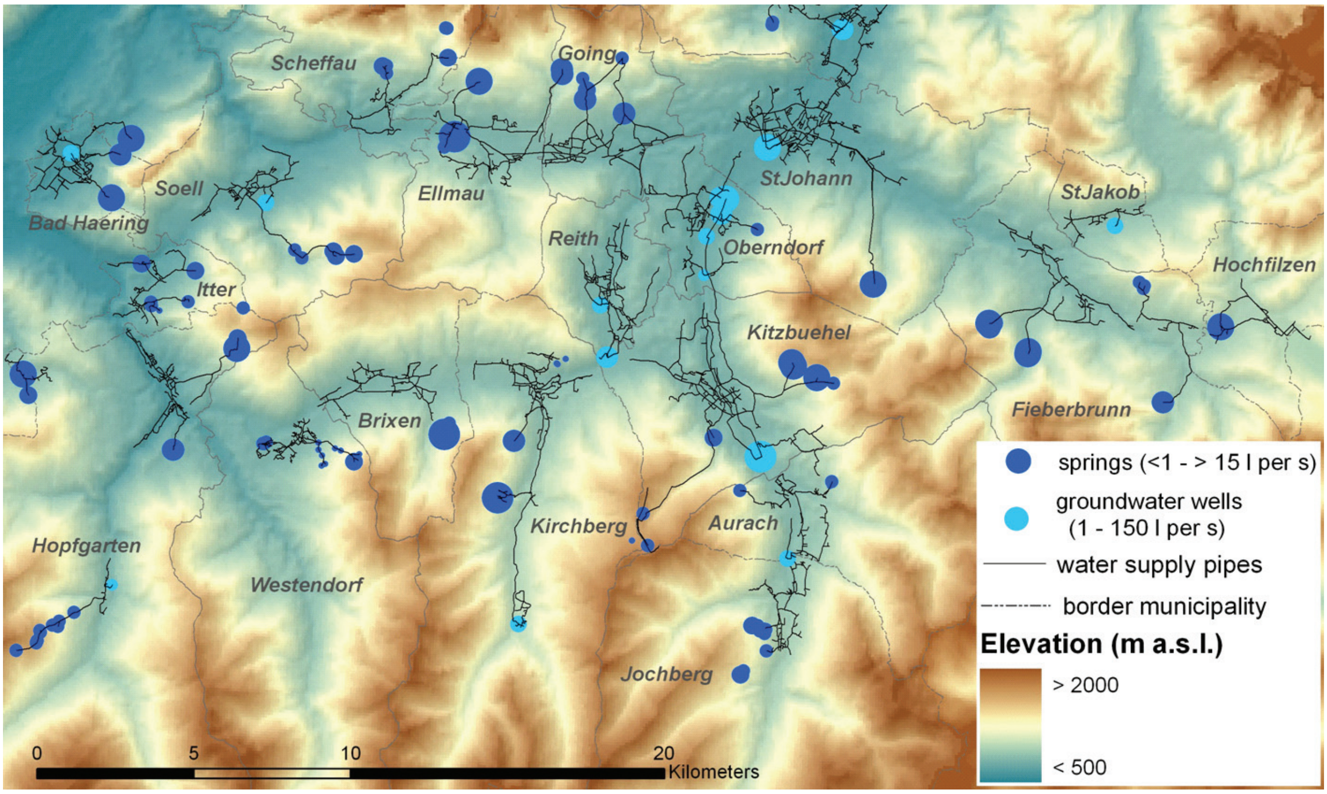


Figure 7-3: Water supply pipe network (without house connections) for the 24 main water supply undertakings in the Kitzbühel region.

7.3 SEASONALITY – PAPER D (VANHAM *ET AL.*, 2008A)

The paper presents a GIS-based multi criteria method to determine the winter season. A snow cover duration dataset serves as basis for this analysis. Water demands and the springs that serve them have to be identified, quantified and geographically localised in order to be able to assess the seasonality analysis. Technical snowmaking and (winter) tourism were identified as the two major seasonal water demand stakeholders in the study area. Winter was defined as the period from December to March. For a detailed description of the methodology it is referred to the attached paper.

Basically the methodology is based upon the following four equations. These equations weigh a start and end date for the winter season based upon a snow cover start (SCOV6190_S) and end date (SCOV6190_E) raster of the case study area. The first two equations (Equations 7-1 and 7-2) make a weighting for the seasonal water demand stakeholders technical snowmaking and tourist overnight stays. The third equation (Equation 7-3) makes a weighting for the base water demand. The last equation (Equation 7-4) makes a weighting of the start and end dates acquired in the three previous equations.

$$T_{snow} = \sum T_i \, (A_i / A_{snow}) \qquad \text{Equation 7-1}$$

$$T_{tour} = \sum \left(\left(\sum T_j \, (Q_j / Q_k)\right) (O_k / O_{tour}) \right) \qquad \text{Equation 7-2}$$

$$T_{base} = \sum \left(\left(\sum T_j \, (Q_j / Q_k)\right) (I_k / I_{base}) \right) \qquad \text{Equation 7-3}$$

$$T_{wbal} = D_{snow} \, T_{snow} + D_{tour} \, T_{tour} + D_{base} \, T_{base} \qquad \text{Equation 7-4}$$

The GIS-based analysis of Equation 7-1 is visualised in Figure 7-4. In this Equation T_{snow} is the weighted day for all ski regions and T_i the selected day for a specific ski region i in the snow cover start date (SCOV6190_S) or end date (SCOV6190_E) raster. A_i represents the ski slope area with snow making for a specific ski region i. A_{snow} is the ski slope area with snow making for all ski regions within the study area.

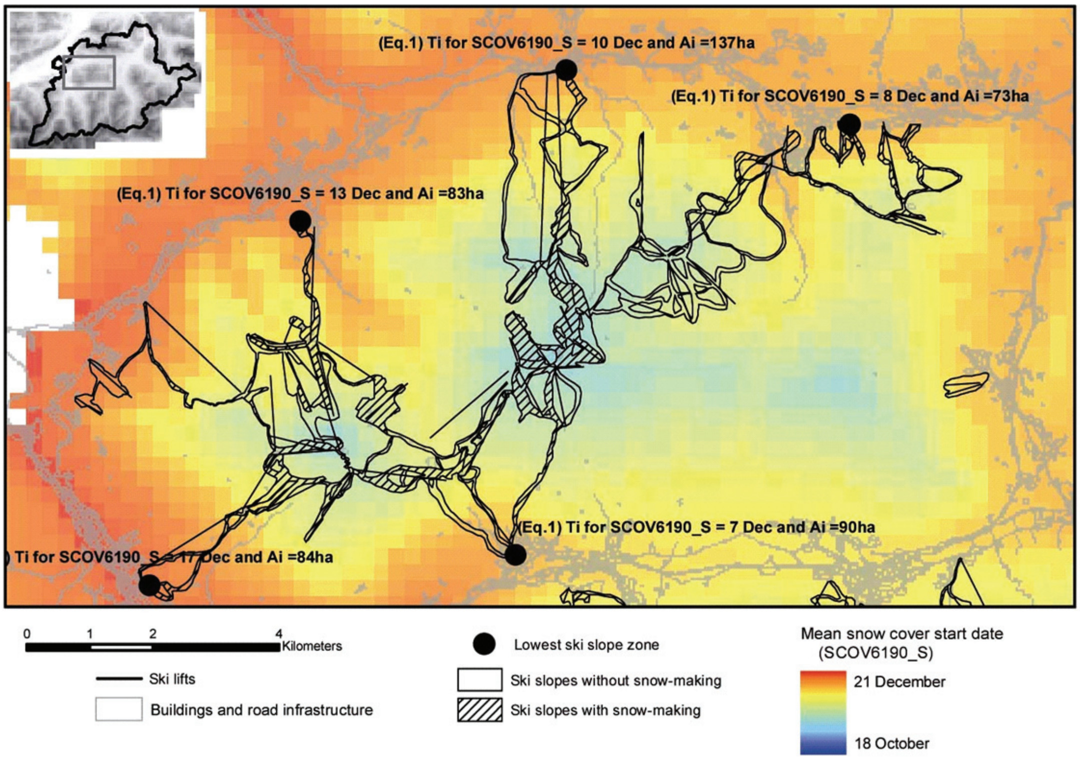


Figure 7-4: Location of the interconnected ski region “skiweltWilder Kaiser-Brixental” in the study area, with indication of ski slopes with snowmaking and their lowest topographic zone. The values for T_i and A_i in Equation 7-1 for the mean snow cover start date raster (SCOV6190_S) are given.

A visualisation of Equation 7-2 and Equation 7-3 is given in Figure 7-5. Within Equation 7-2, T_{tour} is the weighted day in the snow cover start date (SCOV6190_S) or end date (SCOV6190_E) raster for all public water supply systems that are (partly) served by spring water within the study area. T_j is the selected day for a specific spring j, that provides the water supply system of municipality k with water. Q_j is the mean winter (January–February) flow of spring j . Q_k is the sum of mean winter flows of all springs that provide the water supply system of municipality k with water. O_k represents the number of overnight stays connected to the water supply infrastructure for a specific municipality k (partly) served by spring water. O_{tour} represents the number of overnight stays connected to the water supply infrastructure for all municipalities in the study area (partly) served by spring water. Within Equation 7-3, T_{base} is the weighted day in the snow cover start date (SCOV6190_S) or end date (SCOV6190_E) raster for all public water supply systems that are (partly) served by spring water within the study area. $\sum T_j\,(Q_j\,/Q_k)$ represents the same factor as in Equation 7-2. I_k represents the number of inhabitants connected to the water supply infrastructure for a specific municipality k (partly) served by spring water. I_{base} represents the number of inhabitants connected to the water supply infrastructure for all municipalities in the study area (partly) served by spring water.

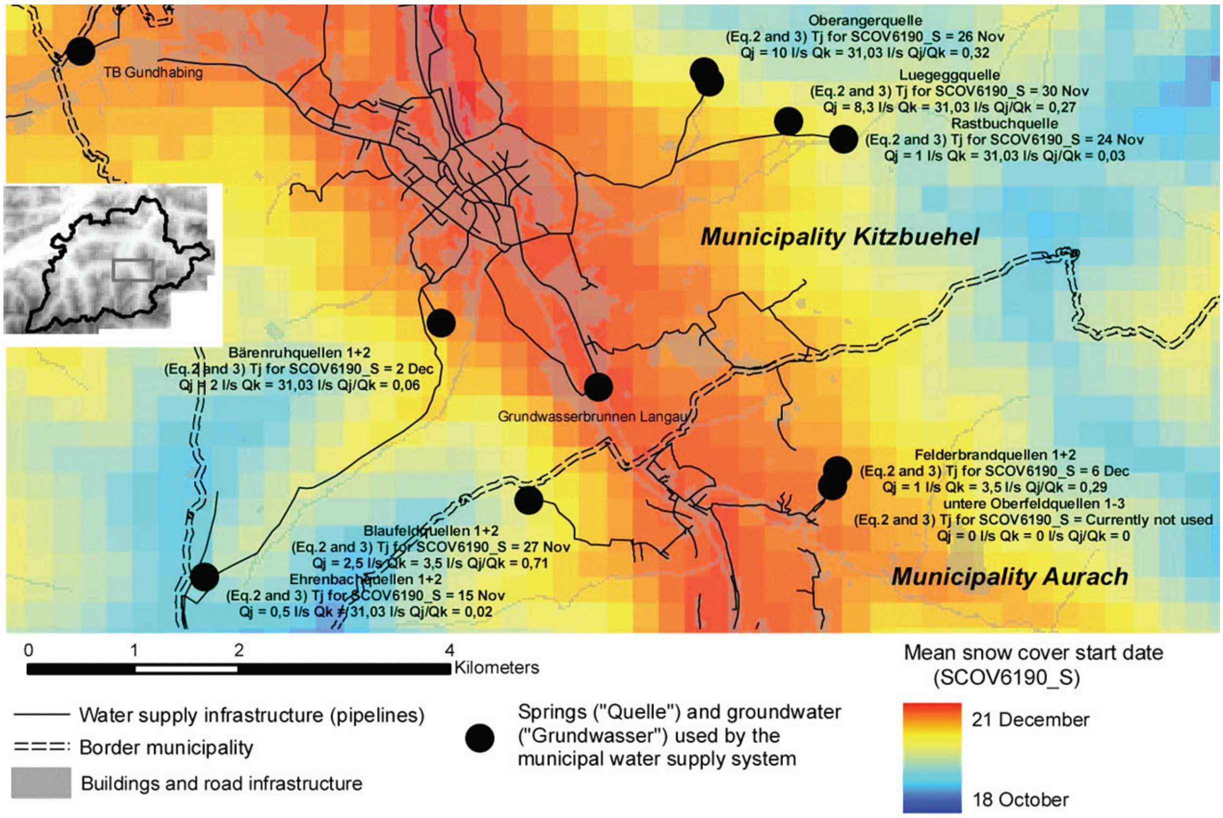


Figure 7-5: Schematization of parts of the infrastructure (water pipe distribution network, springs and groundwater wells) of the public water supply systems of the municipalities Kitzbühel and Aurach. The values for T_j , Q_j , Q_k and Q_j /Q_k in Equation 7-2 and Equation 7-3 for the mean snow cover start date raster (SCOV6190_S) are given. For Equation 7-2 O_k is about ten times higher for the municipality of Kitzbühel compared to Aurach, resulting in a larger impact on T_{tour}. For Equation 7-3 I_k is about seven times higher for the municipality of Kitzbühel compared to Aurach, resulting in a larger impact on T_{base}.

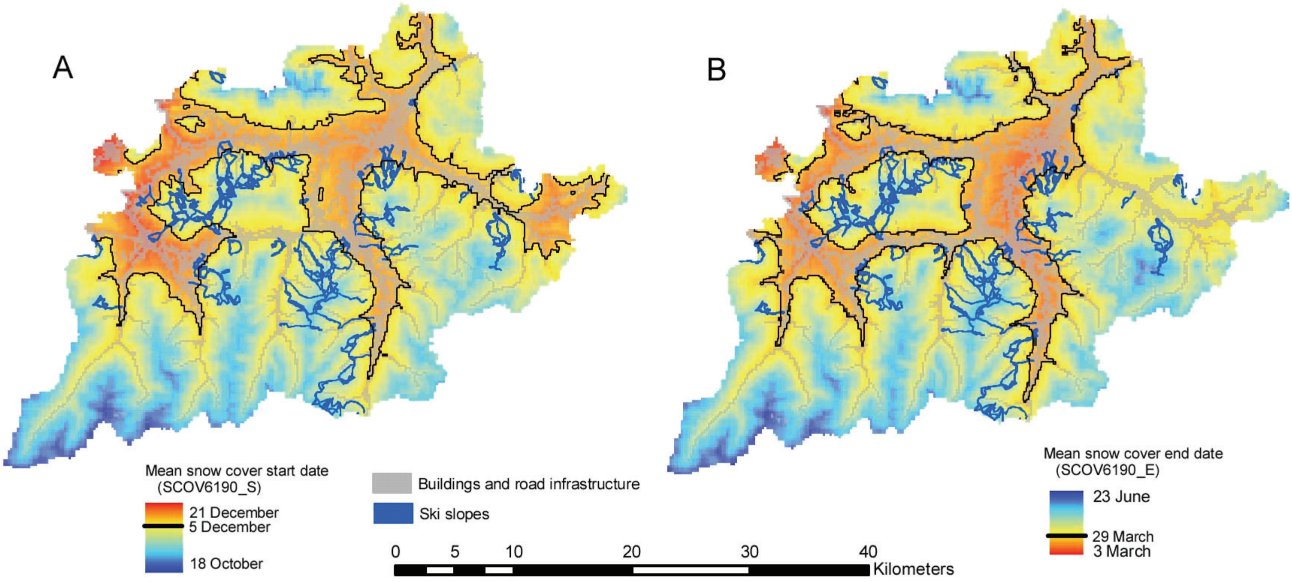


Figure 7-6: Weighted start of the winter season 5 December (a) and weighted end of the winter season 29 March (b) for the study area Kitzbühel region (including Kirchdorf), as the result of Equation 7-4. Source (Vanham *et al.*, 2008a).

The weighted analysis results in the 5 December and the 29 March as key dates for defining the winter season (Figure 7-6). For practical reasons, it can be stated that the winter months are December to March.

7.4 WATER QUANTITY MAP

The water quantity map presents all water demand stakeholders and available water resources (groundwater, springs and surface water). The map can be generated for any time step. By means of this map, it is possible to visualise water flows from water resources to water demand stakeholders (e.g. springs to water supply undertaking, surface water from streams to reservoirs for technical snowmaking or directly to ski slopes …). Also quantitative amounts are visible, whereby first visual assessments on possible deficits can be made. This map is the base for the water balance map, which shows the results of a network-based water balance analysis in different water demand and availability nodes.

Figure 7-7 shows a zoom on the water quantity map of the case study area, and Figure 7-8 shows the legend of the map. It is for example visible that the four major springs east of Kitzbühel (Oberangerquelle, Unterangerquelle, Luegeggquelle and Rastbuchquelle) – that feed the water supply service zone of the town of Kitzbühel – have a cumulative winter discharge of 27.6 l per s (10+8.3+8.3+1 l per s). The average water demand in winter for the service zone is 38.8 l per s. The map thus shows that in winter Kitzbühel needs its groundwater wells to provide its service zone with enough water. It is for example also visible that the ski region Kitzbühel to the west of Kitzbühel and Aurach, has three large reservoirs for technical snowmaking (cumulative volume of 33,000+32,600+36,600 m^3) which are interconnected and fed by different sources (red and green arrows). The total ski slope area with technical snowmaking capacity amounts to 116.9 ha, which implicates a base snowmaking water demand volume of 0.541 m^3 per s or 140,300 m^3 and an improvement snowmaking demand of 0.02 m^3 per s. In other words, the three reservoirs are able to store most of the water for base snowmaking at the beginning of the winter season.

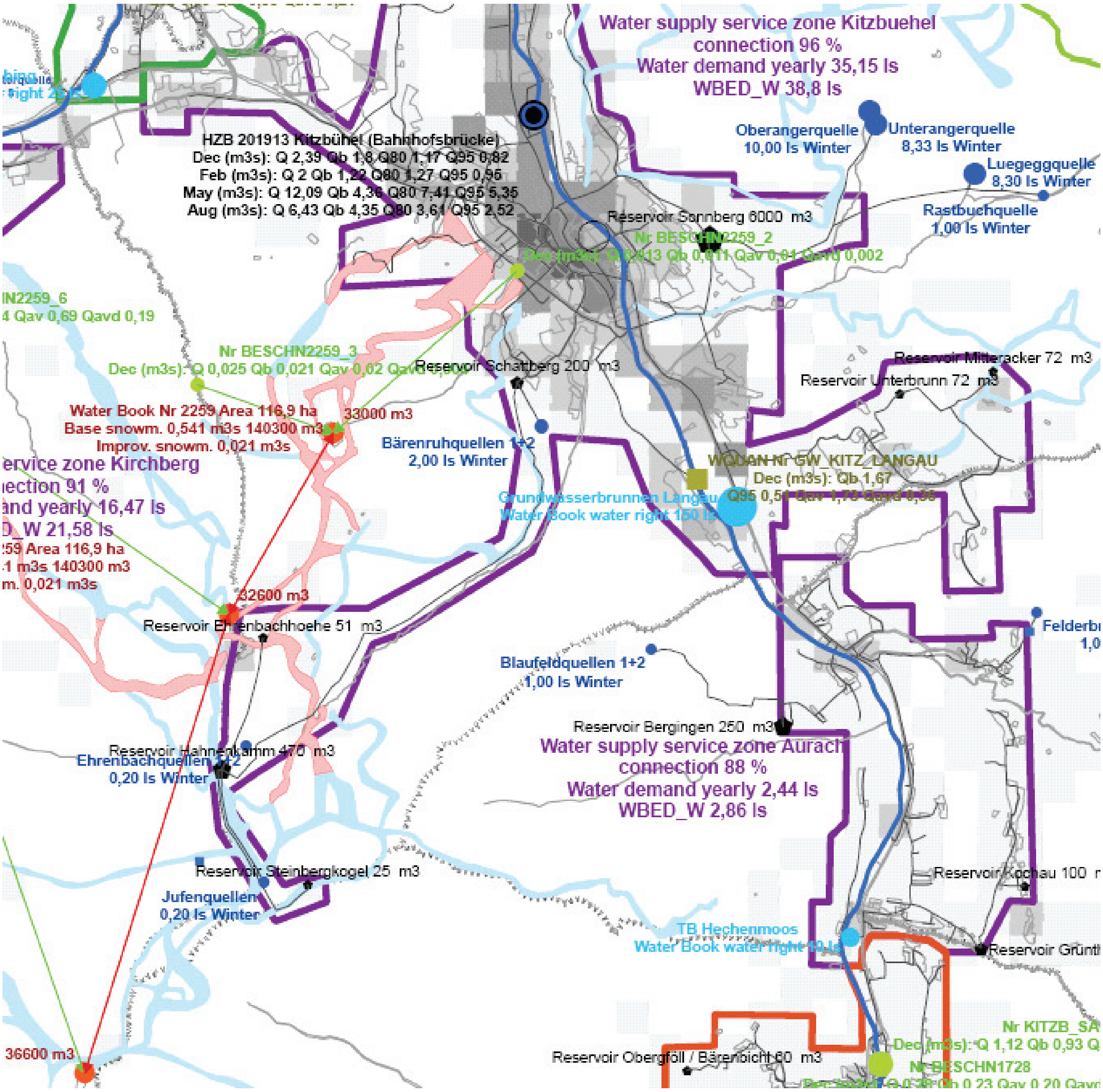
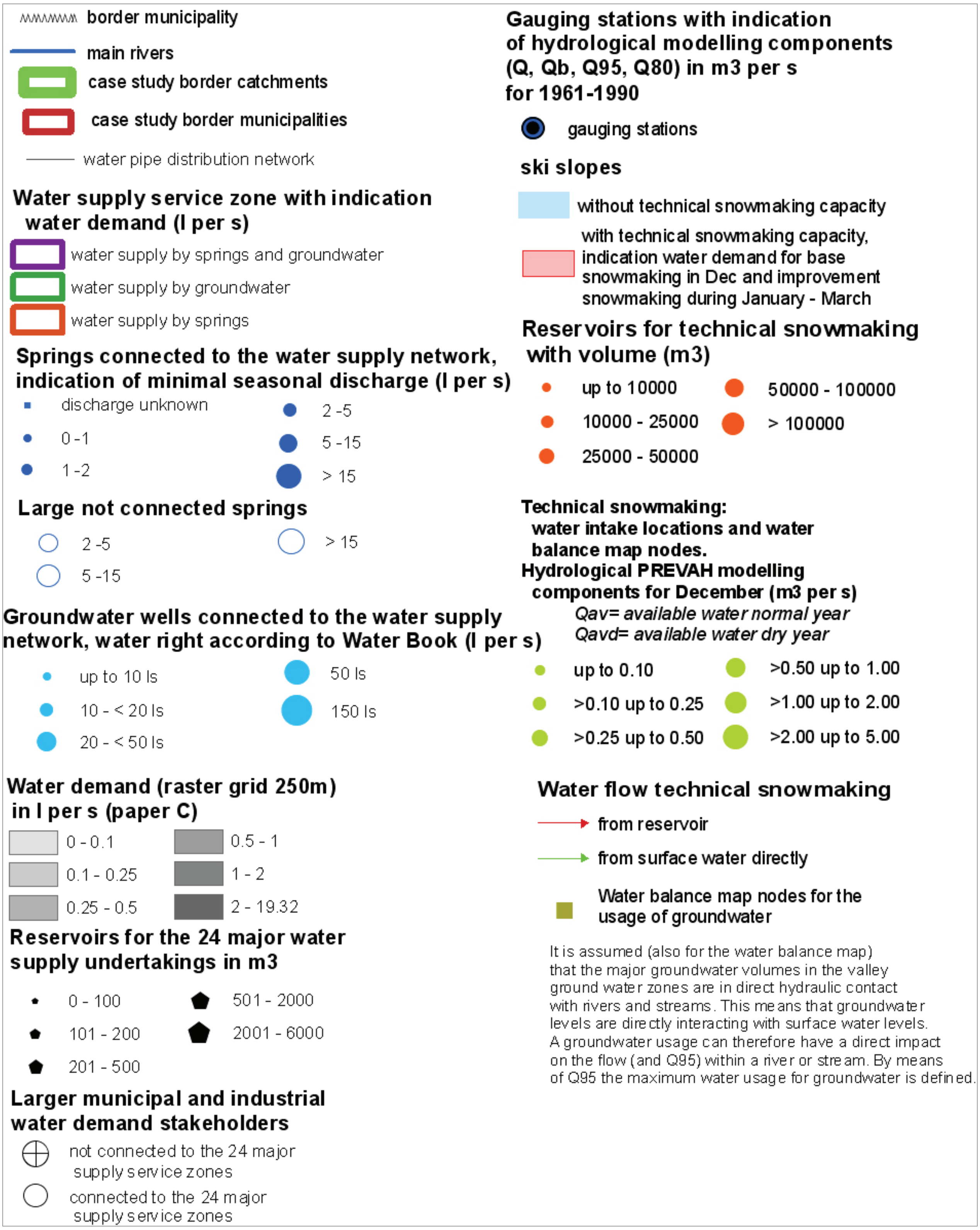


Figure 7-7: Zoom of the original A0-Size water quantity map



〰 border municipality

― main rivers

🟩 case study border catchments

🟥 case study border municipalities

― water pipe distribution network

Water supply service zone with indication water demand (l per s)

▢ water supply by springs and groundwater

▢ water supply by groundwater

▢ water supply by springs

Springs connected to the water supply network, indication of minimal seasonal discharge (l per s)

- ▪ discharge unknown
- ● 0 - 1
- ● 1 - 2
- ● 2 - 5
- ● 5 - 15
- ● > 15

Large not connected springs

- ○ 2 - 5
- ○ 5 - 15
- ○ > 15

Groundwater wells connected to the water supply network, water right according to Water Book (l per s)

- ● up to 10 ls
- ● 10 - < 20 ls
- ● 20 - < 50 ls
- ● 50 ls
- ● 150 ls

Water demand (raster grid 250m) in l per s (paper C)

- ▨ 0 - 0.1
- ▨ 0.1 - 0.25
- ▨ 0.25 - 0.5
- ▨ 0.5 - 1
- ▨ 1 - 2
- ▨ 2 - 19.32

Reservoirs for the 24 major water supply undertakings in m3

- ⬟ 0 - 100
- ⬟ 101 - 200
- ⬟ 201 - 500
- ⬟ 501 - 2000
- ⬟ 2001 - 6000

Larger municipal and industrial water demand stakeholders

⊕ not connected to the 24 major supply service zones

○ connected to the 24 major supply service zones

Gauging stations with indication of hydrological modelling components (Q, Qb, Q95, Q80) in m3 per s for 1961-1990

◉ gauging stations

ski slopes

🟦 without technical snowmaking capacity

🟥 with technical snowmaking capacity, indication water demand for base snowmaking in Dec and improvement snowmaking during January - March

Reservoirs for technical snowmaking with volume (m3)

- ● up to 10000
- ● 10000 - 25000
- ● 25000 - 50000
- ● 50000 - 100000
- ● > 100000

Technical snowmaking: water intake locations and water balance map nodes.
Hydrological PREVAH modelling components for December (m3 per s)
Qav= available water normal year
Qavd= available water dry year

- ● up to 0.10
- ● >0.10 up to 0.25
- ● >0.25 up to 0.50
- ● >0.50 up to 1.00
- ● >1.00 up to 2.00
- ● >2.00 up to 5.00

Water flow technical snowmaking

→ from reservoir

→ from surface water directly

■ Water balance map nodes for the usage of groundwater

It is assumed (also for the water balance map) that the major groundwater volumes in the valley ground water zones are in direct hydraulic contact with rivers and streams. This means that groundwater levels are directly interacting with surface water levels. A groundwater usage can therefore have a direct impact on the flow (and Q95) within a river or stream. By means of Q95 the maximum water usage for groundwater is defined.

Figure 7-8: Legend of the water quantity map

7.5 WATER BALANCE MAP

7.5.1 REGIONAL WATER BALANCE

A regional water balance between available water resources and water demand within the Kitzbühel region results in the assessment whether deficits or surpluses occur for a certain time step within the whole region.

Figure 7-9 shows the regional water balance for an annual time step (reference period 1961-1990) for the case study area. The average annual domestic, municipal, industrial and agricultural demand includes 10% water losses (219 l per s + 10%), as described in chapter 6.2.2. Technical snowmaking on all ski slopes (2117 ha) of the case study area is assumed, to represent a maximum water demand (see Table 6-2, page 56). The figure shows that for an average hydrological year (normal year) no regional deficits occur for an annual time step. Environmental flows are maintained and water demands are met. Water availability is much larger than water demand.

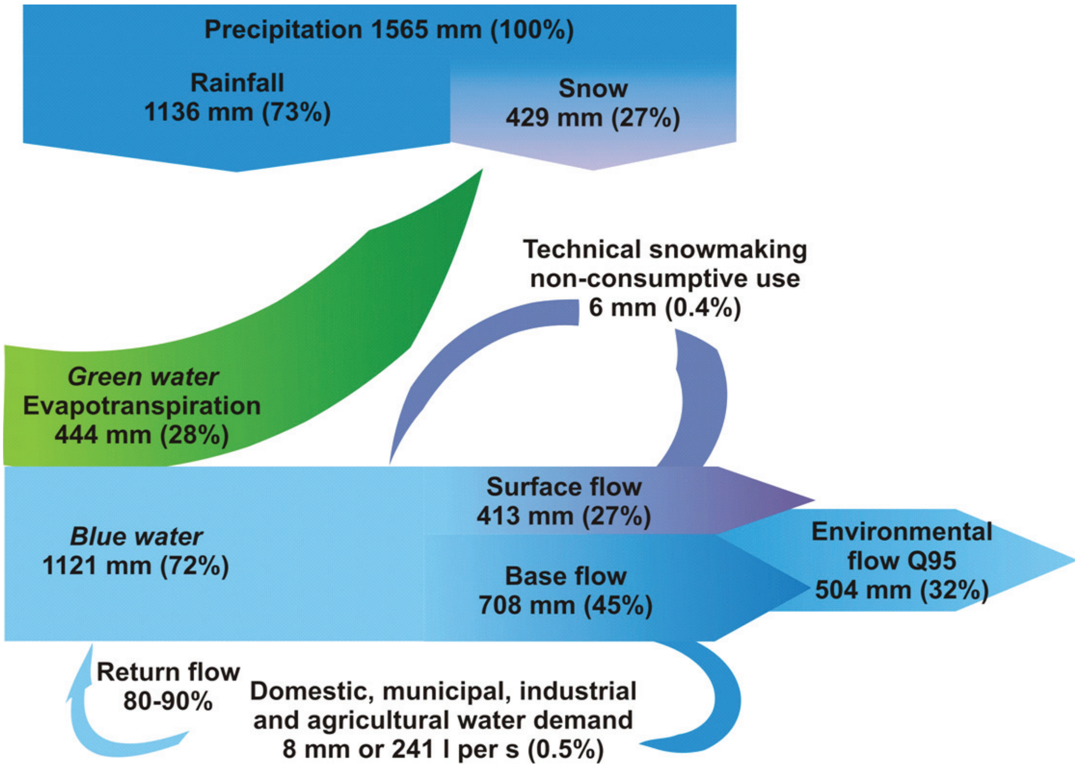
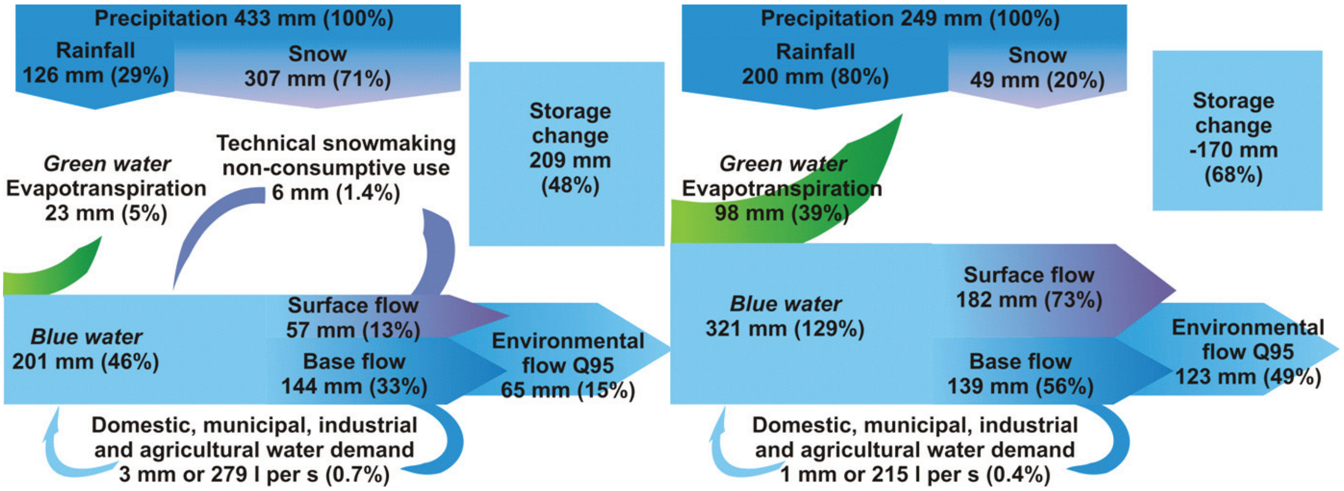


Figure 7-9: Regional water balance, average yearly time step (reference period 1961-1990), with maximum technical snowmaking for 2117 ha (all ski slopes). Domestic, municipal, industrial and agricultural demand includes 10% water losses.

However, as described in previous chapters, the temporal aspect is essential in alpine water resources management. Therefore a regional water balance should minimally be made for a seasonal time step. Table 7-2 presents the different seasons for a water balance assessment within the Kitzbühel region. The winter season is in **paper D** (Vanham *et al.*, 2008a) defined as the period from December to March for the case study area Kitzbühel region. Based upon the reference period hydrological characteristics and fluctuations in water demand (due to e.g. tourist overnight stays), the remaining three seasons are defined as displayed in the table.

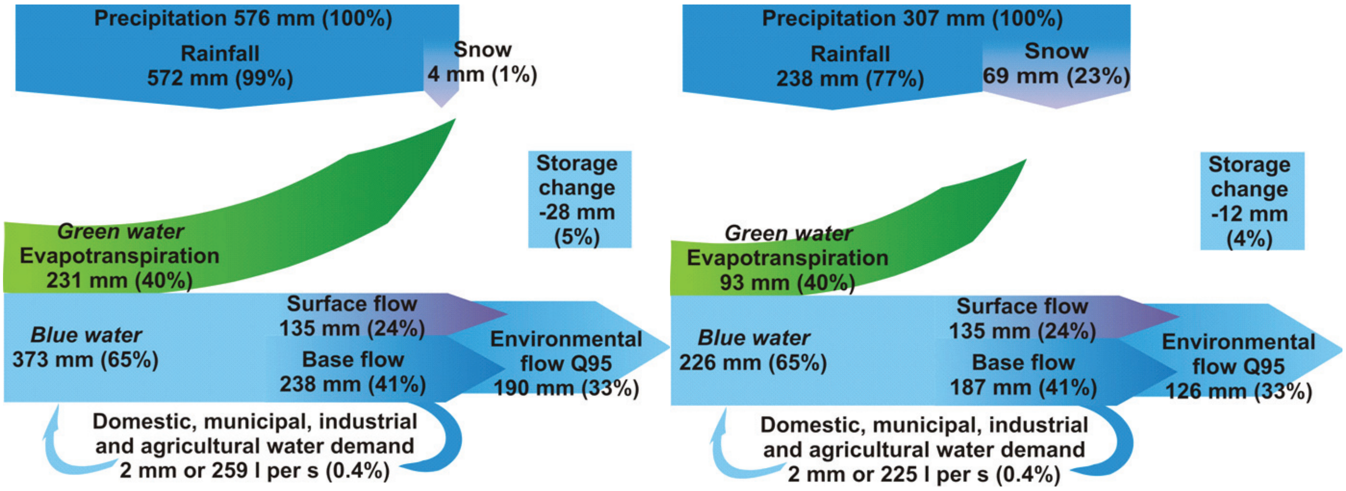
Table 7-2: Definition of the seasons for a balance between water availability and demand in the Kitzbühel region

season	months
winter	December – March (DJFM)
spring	April – Mai (AM)
summer	June – August (JJA)
autumn	September – November (SON)



a) winter (DJFM)

b) spring (AM)



c) summer (JJA)

d) autumn (SON)

Figure 7-10: regional water balance for the four seasons (reference period 1961-1990)

Figure 7-10 shows the regional water balance within the case study area for a seasonal time step. For none of the four seasons water deficits occur on a regional level. Water availability (with maintaining environmental flows) of ground and surface water is for each season higher than water demands. During winter and autumn water availability is generally the lowest, and during spring water availability is the highest due to snow melt. Water demands are the highest during winter (technical snowmaking and tourist overnight stays) and summer (tourist overnight stays). For the latter period increased water usage (e.g. for garden watering, swimming pools …) is not accounted for.

A monthly regional water balance is presented in Figure 7-11 for a normal and dry hydrological year (definition see chapter 5.4). The monthly available water is shown (see Figure 5-11, page 44) as well as the water demand of all stakeholders. For the stakeholder technical snowmaking all ski slopes are considered (2,117 ha) and it is assumed that base snowmaking occurs within 5 days during December, resulting in a temporary water demand of 4.75 m^3 per s (see Table 6-2 page 56). A detailed description of this assessment can be found in chapter 6.2.5 and **paper G** (Vanham *et al.*, 2009c). The regional water balance analysis shows no deficits or critical values for a normal year. However, the month of December is identified as a critical time for a dry year due to the large amount of water required for base snowmaking. This stresses the necessity of reservoir storage of water for base snowmaking on a regional level (under the assumption that the total ski slope area of 2,117 ha has snowmaking infrastructure). The analysis also shows that enough water is available in other months on a regional level to fill these reservoirs.

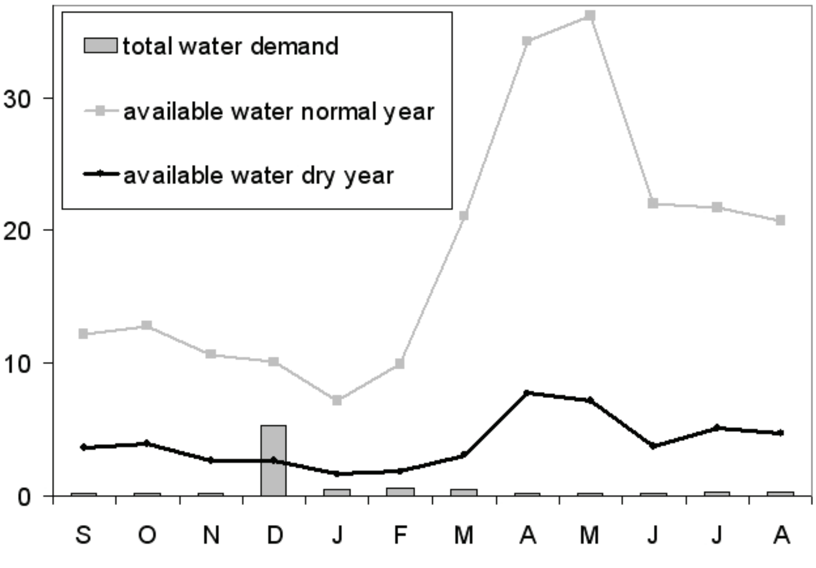


Figure 7-11: Monthly water balance in m^3 per s for the reference period (1961-1990). Base snowmaking is restricted to 5 days. Figure adapted from **paper G** (Vanham *et al.*, 2009c).

In the current situation - in which 882 ha of the ski slopes have artificial snow infrastructure - a total reservoir volume of 0.9 million m^3 (divided over 20 reservoirs) is installed, capable of storing almost the whole base snowmaking volume. A detailed description on the reservoir situation in the case study area can be found in chapter 6.2.5. Many of these reservoirs are filled with river water in the snow melt months of April and June (water rights are attributed to this period in the Water Book). Taking into account evaporation losses, additional filling in autumn is a possibility.

It is clear that water balance deficits on a local level within the case study area can be more pronounced. Depending on local water availabilities and water demands, the other winter months - especially March - could also become problematic due to high water demands for improvement snowmaking. The potential for reservoir installation and/or water allocation can be technically or economically restricted. Therefore other adaptation strategies - like the restriction of skiing and snowmaking to higher altitudes - could be considered, as described in **paper G** (Vanham *et al.*, 2009c).

7.5.2 WATER BALANCE MAP

The regional water balance between available water resources and water demand within the case study area results in the assessment whether deficits or surpluses occur for a certain time step within the whole region. A regional water balance can thus be temporarily differentiated, but is not spatially differentiated. In order to assess spatial (or local) deficits/surpluses due to the interaction of natural and man-induced intra- and inter-catchment water flows, the water balance map is generated by means of a water resources management software tool.

Numerous models for the simulation of water resources management have been developed in the last years, e.g., AQUATOOL (Andreu *et al.*, 1996), MIKEBASIN (Danish Hydraulic Institute, 2009), RIBASIM (Delft Hydraulics, 2009), WaterWare (Fedra and Jamieson, 1996) and WEAP21 (Sieber and Purkey, 2007). Such river basin simulation packages support the development of a model schematization consisting of a network of nodes connected by links. The nodes represent water demands, reservoirs, dams, pumps, and so on. The links transport water between the different nodes. The network can be adjusted to provide the level of spatial and temporal detail required. The case study area is represented as a network schematization generally superimposed over a vector or raster map image. A recent comparison of such generalized river/reservoir system models is given by (Koch and Grünewald, 2009). A *river/reservoir system model* refers to a computer modelling system that simulates the storage, flow, and withdrawal of water in a system of reservoirs and river reaches. *Generalized* indicates that the computer modelling system is designed to be applied to a broad range of problems and locations rather than being site-specific and customized for a particular river system. Simple networks can however be calculated by means of a spreadsheet.

For the assessment of the water balance map of the Kitzbühel region the model MAGRET (*MAnaGement von WasserREssourcen innerhalb eines EinzugsgebieTes*) was used. This model was developed by the software company HydroIT GmbH. For each node within the model deficits and surpluses can be identified for a specific time step. For the Kitzbühel region a time step of 3 days was chosen, to include the critical period of base snowmaking during a period of 3 days. Water demands are based upon monthly water demands, and then interpolated to three days. Time series on flows and water availability (assuming that Q_{95} as environmental flow is a prerequisite) are available at any location within the case study area (resolution 250 m) owing to the distributed hydrological model PREVAH. These time series serve as an input for MAGRET in e.g. water withdrawal node elements for technical snowmaking. An example of such a node is the element BESCHN2259_3 (Figure 7-7, page 64), located at a stream within the ski region Kitzbühel. Reservoir storage is also simulated by the model through reservoir elements.

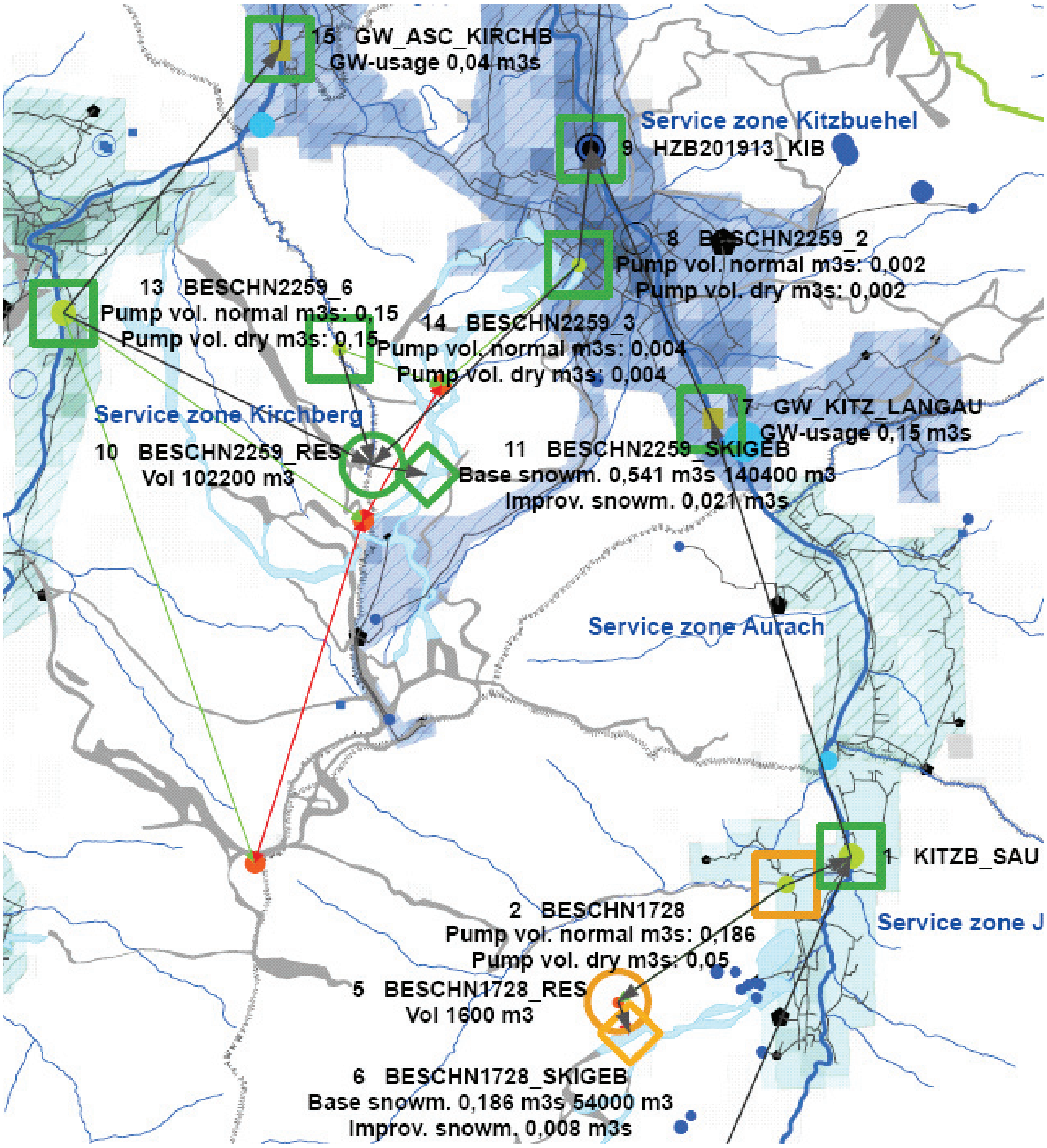


Figure 7-12: Zoom of the original A0-Size water balance map, indicating local deficits and surpluses for a normal and dry year (reference period 1961-1990)

Figure 7-12 shows a zoom of the water balance map of the case study area for the winter period of the reference period 1961-1990 and Figure 7-13 shows its specific legend. For the water supply service zones only surpluses were generated in the water balance for this specific period. The water supply zones and their spring sources were not specifically included as node elements, although this is advisable. They represent a primarily non-consumptive use for which 80-90 % of used water will return to the system after passing through a water treatment plant in a short time step (like three days). As mentioned, they should be included as node elements in the mode, but they were not to keep the first pilot model simple.

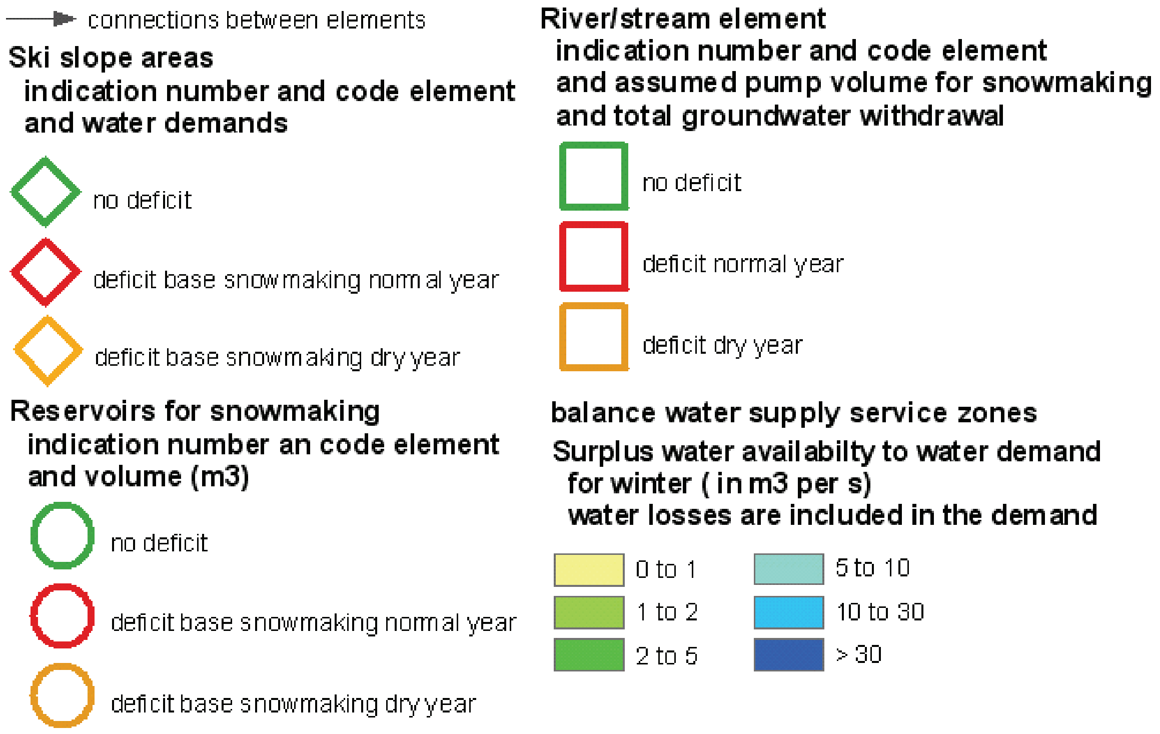
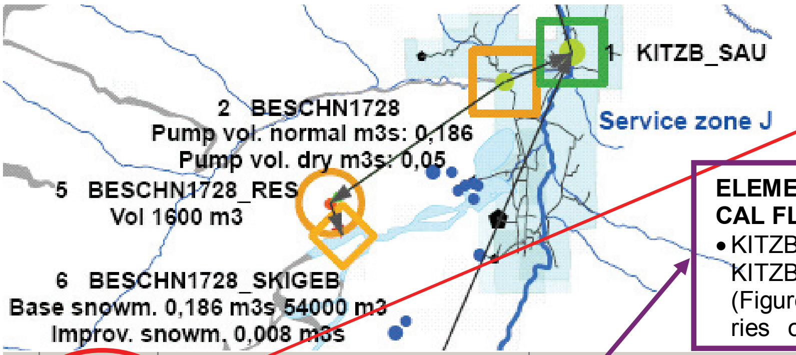


Figure 7-13: Legend of the water balance map

Most node elements for technical snowmaking did not show deficits in either a normal or dry year. However, locally some deficits were simulated for dry years and even normal years (in the ski region Brixental – Wilder Kaiser). It has to be said that pump volumes were theoretical values (with 1 m^3 per s set as maximum values due to technical pumping constraints) and not real service values. The latter were not available and have to be obtained from each individual mountain railway company. An example of a dry year deficit is shown in the southern region of Figure 7-12, more particularly in the elements 2, 5 and 6. The model showed that the restriction of the pumping volume to 0.05 m^3 per s in order to maintain the environmental flow in stream element 2 leads to a base snowmaking deficit in element 6 (the ski slope). The reservoir (element 5) proves to be not large enough to provide the base snowmaking volume restricted to three days. On the other hand the three reservoirs of the ski region Kitzbühel – discussed in chapter 7.4 based on Figure 7-7 – are modelled by means of one element (number 10, code BESCHN2259_RES) in Figure 7-12 and result in *no deficit* (green colour). Their cumulative volume (102,200 m^3) is smaller than the required base snowmaking volume (ski slope area, number 11, code BESCHN2259_SCHIGEB, 140,400 m^3). But during the three day time step, pumping from the different streams is able to refill the reservoirs sufficiently to provide the base snowmaking volume whilst remaining environmental flows within these streams. The fact that deficits for technical snowmaking were modelled is off course an important result of the water balance map. As next step – based upon this DSS map – a meeting with mountain railway companies should be organised in order to discuss this matter, include real service data and possibly update the map. This map is thereby an important DSS tool for such a meeting.

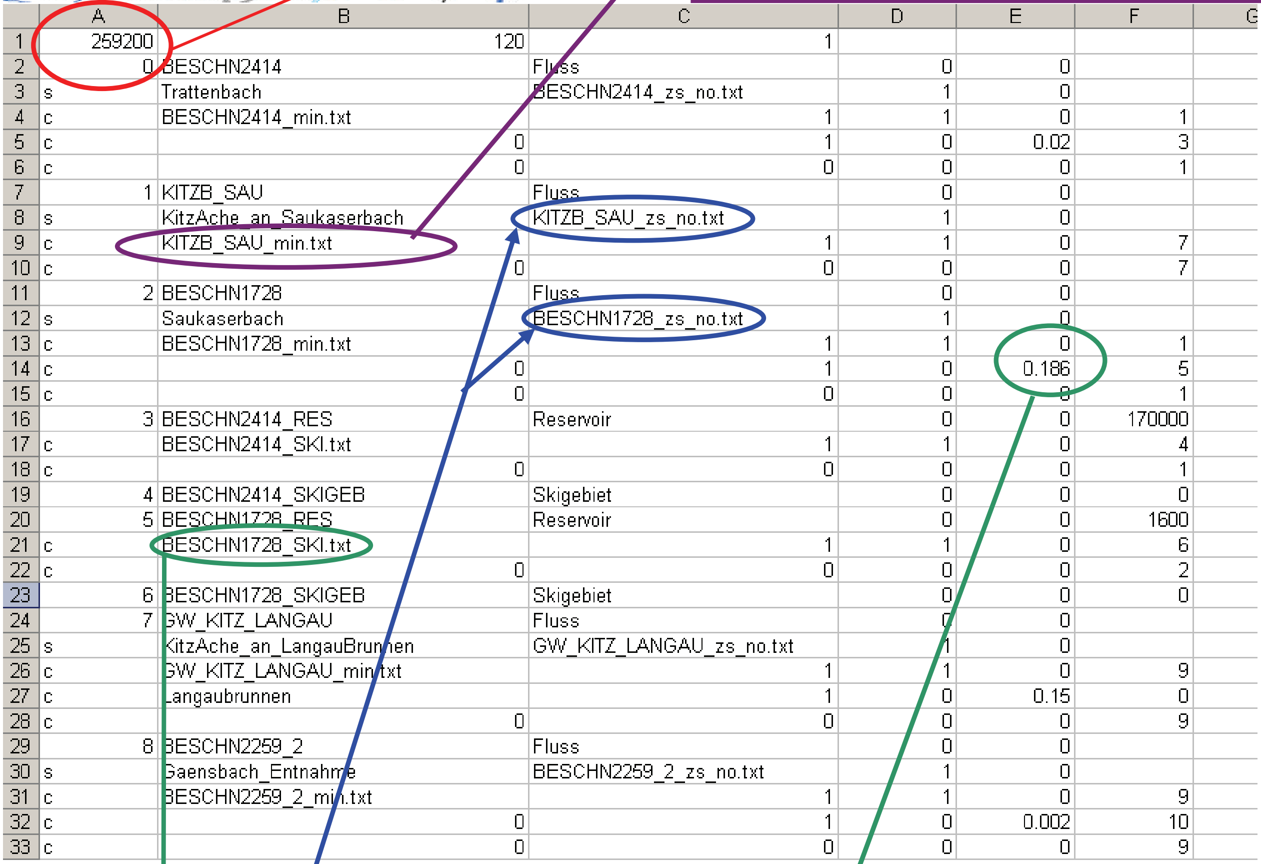
Figure 7-14 shows a spreadsheet of the MAGRET model in of the first 8 Elements in the model.

Time step 3 days = 259200 seconds



ELEMENT c (connection, column A) – ECOLOGICAL FLOW

- KITZB_SAU_min.txt for element number 1 KITZB_SAU flowing further to element number 7 (Figure 7-12) – column F. This .txt file is a time series of discharges respresenting the ecological



	A	B	C	D	E	F	G
1	259200	120	1				
2	0	BESCHN2414	Fluss	0	0		
3	s	Trattenbach	BESCHN2414_zs_no.txt	1	0		
4	c	BESCHN2414_min.txt	1	1	0	1	
5	c	0	1	0	0.02	3	
6	c	0	0	0	0	1	
7	1	KITZB_SAU	Fluss	0	0		
8	s	KitzAche_an_Saukaserbach	KITZB_SAU_zs_no.txt	1	0		
9	c	KITZB_SAU_min.txt	1	1	0	7	
10	c	0	0	0	0	7	
11	2	BESCHN1728	Fluss	0	0		
12	s	Saukaserbach	BESCHN1728_zs_no.txt	1	0		
13	c	BESCHN1728_min.txt	1	1	0	1	
14	c	0	1	0	0.186	5	
15	c	0	0	0	0	1	
16	3	BESCHN2414_RES	Reservoir	0	0	170000	
17	c	BESCHN2414_SKI.txt	1	1	0	4	
18	c	0	0	0	0	1	
19	4	BESCHN2414_SKIGEB	Skigebiet	0	0	0	
20	5	BESCHN1728_RES	Reservoir	0	0	1600	
21	c	BESCHN1728_SKI.txt	1	1	0	6	
22	c	0	0	0	0	2	
23	6	BESCHN1728_SKIGEB	Skigebiet	0	0	0	
24	7	GW_KITZ_LANGAU	Fluss	0	0		
25	s	KitzAche_an_LangauBrunnen	GW_KITZ_LANGAU_zs_no.txt	1	0		
26	c	GW_KITZ_LANGAU_min.txt	1	1	0	9	
27	c	Langaubrunnen	1	0	0.15	0	
28	c	0	0	0	0	9	
29	8	BESCHN2259_2	Fluss	0	0		
30	s	Gaensbach_Entnahme	BESCHN2259_2_zs_no.txt	1	0		
31	c	BESCHN2259_2_min.txt	1	1	0	9	
32	c	0	1	0	0.002	10	
33	c	0	0	0	0	9	

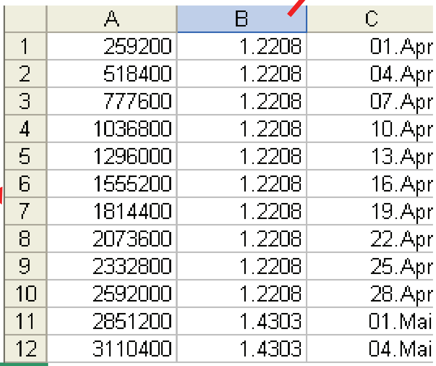
Figure 7-14: MAGRET model in spreadsheet of the first 8 Elements. The top-left figure is a section of Figure 7-12, displaying the elements 1, 2, 5 and 6.

Flow (m^3 per s)

Time step 3 days = 259200 s

FLOW TO ELEMENT

- KITZB_SAU_zs_no.txt: time series of discharge data within the subcatchment area between the preceding element and this element
- BESCHN1728_zs_no.txt: time series of discharge data within the subcatchment Saukaserbach upto element 2 (which is the first element on this stream). The time series start in April, as winter is finished and flows can fill the reservoirs for snowmaking.



	A	B	C
1	259200	1.2208	01.Apr
2	518400	1.2208	04.Apr
3	777600	1.2208	07.Apr
4	1036800	1.2208	10.Apr
5	1296000	1.2208	13.Apr
6	1555200	1.2208	16.Apr
7	1814400	1.2208	19.Apr
8	2073600	1.2208	22.Apr
9	2332800	1.2208	25.Apr
10	2592000	1.2208	28.Apr
11	2851200	1.4303	01.Mai
12	3110400	1.4303	04.Mai

- **DEMAND (constant):** 0.186 m^3 per s for element 2 - BESCHN1728 - as pumping volume during a normal year for the element number 5 BESCHN1728_RES (reservoir)
- **DEMAND (time series):** BESCHN1728_SKI.txt – time series water demand for snowmaking from the reservoir BESCHN1728

7.6 WATER VULNERABILITY AND RISK MAP

7.6.1 INTRODUCTION

The synthesis of the developed methodologies and different steps results apart from the water balance map in a water supply systems vulnerability map, which combined with Alpine natural hazards, gives a risk map (Figure 7-1, page 57). A detailed description of the methodologies leading to the water vulnerability and risk map can be found in **paper E** (Möderl *et al.*, 2008a) and its German version (Möderl *et al.*, 2008b).

For the water vulnerability and risk map, not the whole case study area was taken into account but it was focused on the valley of the five municipalities from Jochberg to Sankt Johann. A management support tool (VulNetWS – Vulnerability of Water Supply Networks) was developed which quantifies vulnerability based on hydraulic and quality simulations assuming component failure of each single water supply system (WSS) component. The approach serves for the definition of zones with low, medium and high potential vulnerability. Hazards of flooding, landslide, debris flow and avalanches are calculated and categorized in potential low, medium and high hazard zones. By combining the vulnerability and hazard maps, zones with low, medium and high potential risk are identified (risk map).

In order to assess the vulnerability of the water supply system, two extensive datasets need to be acquired: the water pipe distribution network with their diameter sizes and the gridded population and housing census dataset. Based upon the latter, a water demand raster needs to be generated – see chapter 6.2.2 page 47 and **paper C** (Vanham *et al.*, 2010). The generation of this raster was described for a resolution of 250 m; however for the water vulnerability map a resolution of 125 m is advisable. The pipe network VulNetWS simulation results of the water service zones of the five municipalities are evaluated by calculating three performance indicators (PI) for each component failure. The hydraulic quality (PI1) is assumed to be high if water supply pressure (p) in each junction is within a predefined range. In this study a sufficient pressure is assumed to be above 40 metres. The second indicator (PI2) estimates the vulnerability regarding water quality. As outlined by (Engelhardt *et al.*, 2000) the transport time of water in the pipe system (i.e. water age) is a suitable quality measure. Thus PI2 is calculated as being sufficient when the water age is beneath 48 hours. The third indicator (PI3) is the superposition of both criteria hydraulic vulnerability and vulnerability regarding water quality.

Table 7-3: Vulnerability categories according to performance indicator. Source (Möderl *et al.*, 2008a)

category	PI1 (-)	PI2 (-)	PI3 (-)
No	1	1	1
Low	1.00-0.75	1.00-0.75	1.00-0.75
medium	0.75-0.50	0.75-0.50	0.75-0.50
high	0.50-0.00	0.50-0.00	0.50-0.00

A zoom of the resulting vulnerability map is presented in Figure 7-15. The figure shows that according to the performance indicator (PI) 3 almost all pipes (and nodes) of the WSS of Kitzbühel and the two WSS of Oberndorf are low vulnerable. Certain sections show medium vulnerability whereas one particular section in the service zone Oberndorf Steinerbach shows high vulnerability. This service zone is only served by one groundwater well and no springs. It has to be noted that the two groundwater wells *Oberndorf Nord* and *Oberndorf Süd*, both located in Oberndorf, only serve the municipality of Kitzbühel.

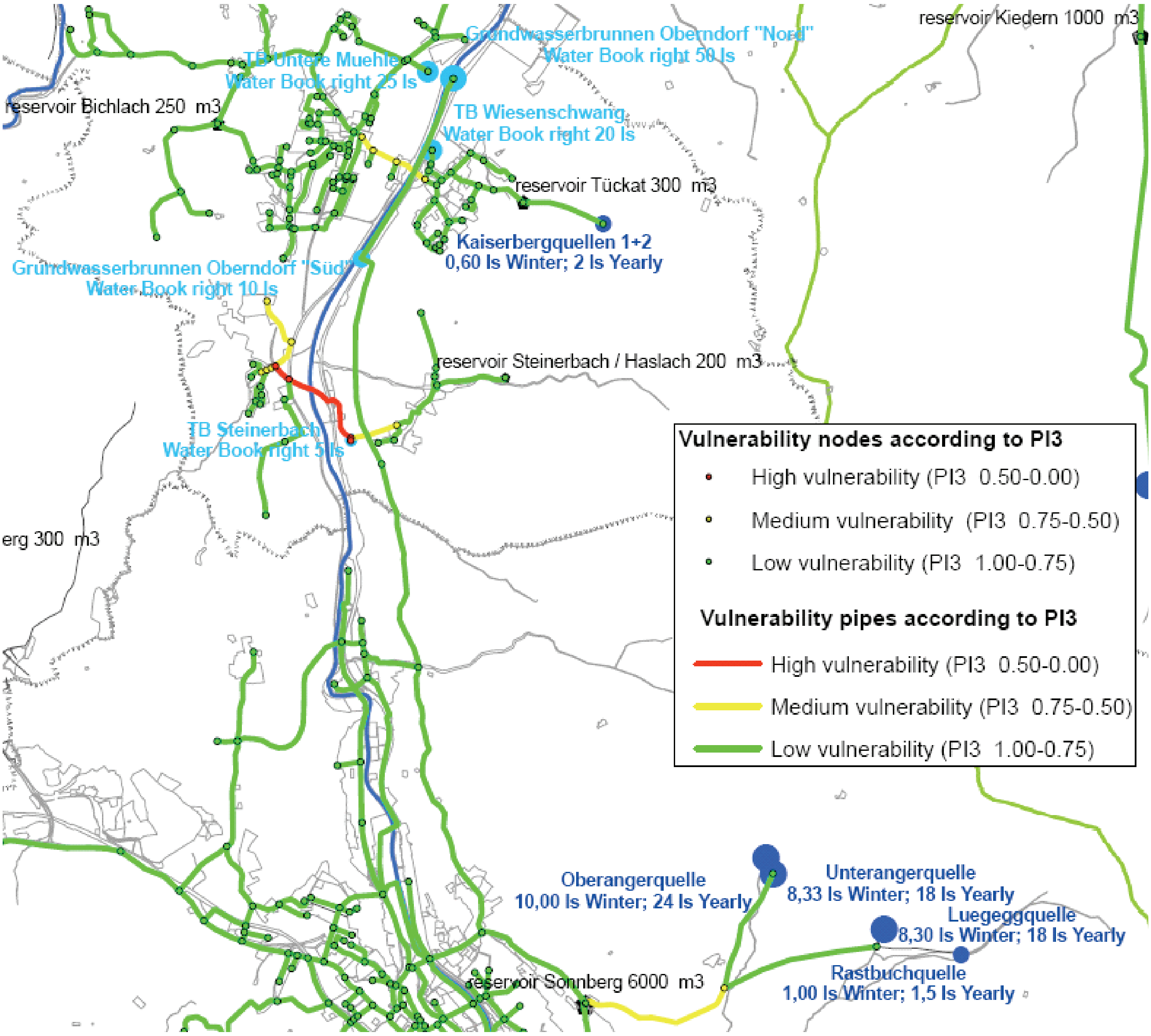


Figure 7-15: Zoom of the original A1-size water supply system vulnerability map (water supply systems of the municipalities Kitzbühel and Oberndorf) for yearly average water availability and demand

For the analysis of Alpine natural hazard, different GIS data sets (e.g. Austrian hazard zone maps and the HORA - *Flood Risk Zoning* - geodataset) are used. The detailed methodology for their categorization in potential low, medium and high hazard zones is described in (Möderl *et al.*, 2008a).

In Figure 7-16 both the WSS vulnerability and debris flow hazard for the water supply service area of Kitzbühel are shown. Risk occurs in the eastern part of the service area, due to a medium vulnerable pipe section (between the four main source springs and the reservoir *Sonnberg*) partly situated in a high debris flow hazard zone. This site is recommended for a further in-depth analysis and - if necessary - for preventive measures.

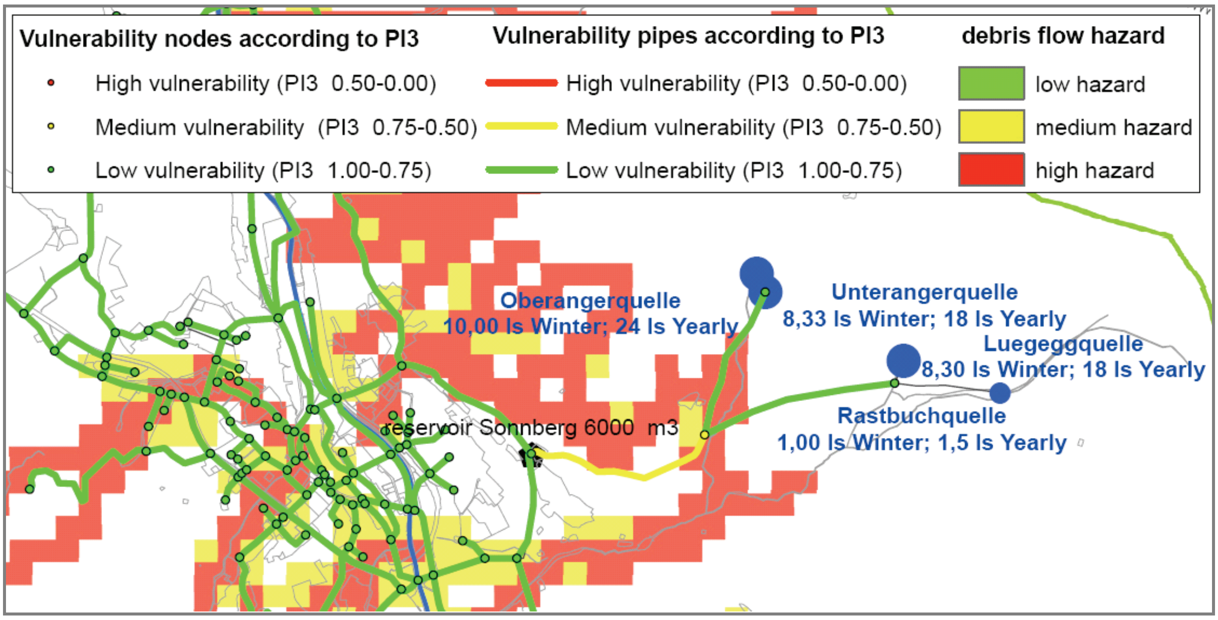


Figure 7-16: Water supply system vulnerability and debris flow hazard for the water supply service area of Kitzbühel

Using the presented methodology, the vulnerabilities of a water supply system can be identified and (if necessary) eliminated by technical measures, resulting in a higher supply security. Furthermore potential hazard zones can be located to construct protection measures at the proper sites. It has to be stressed that the applied methodology is a regional assessment, in which potential risky sites are identified for a larger area. In order to assess whether these sites are also risky locally, they have to be looked up in detail. This matter is visualised in Figure 7-17 for the area of the main groundwater well *taxa* that serves the water supply system of the municipality Sankt Johann. The high flooding hazard in a resolution of 125 m (Figure 7-17 a) coincides with the high vulnerable pipe section attached to the well. However, when the original flooding geodataset is mapped (Figure 7-17 b), it can be seen that the well is located on higher ground and is not affected by the flooding zones.

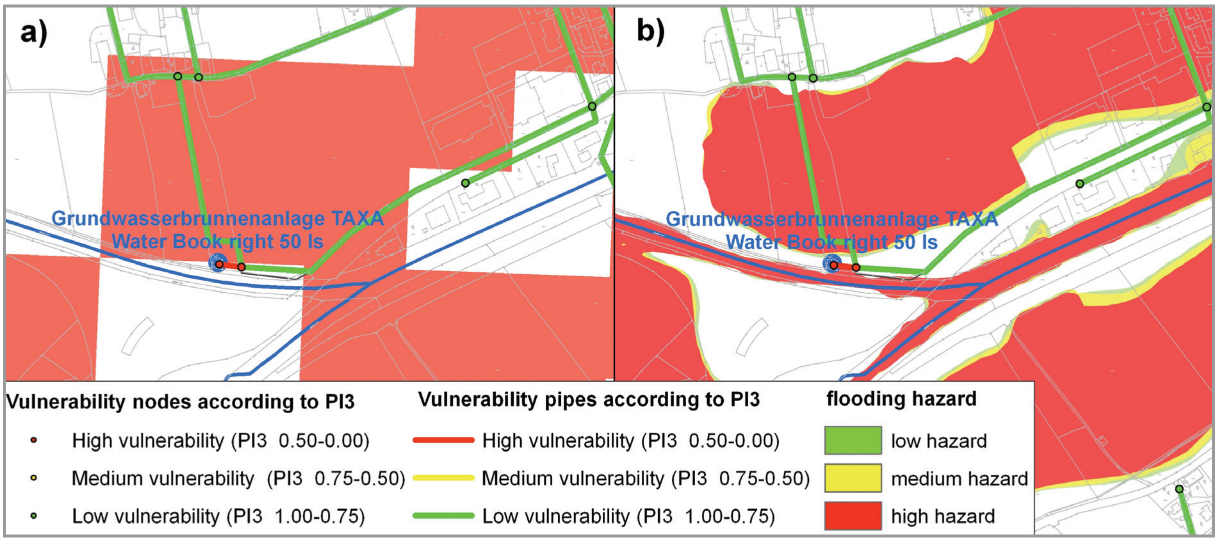


Figure 7-17: Area of the main groundwater well taxa that serves the water supply system of the municipality Sankt Johann, with a) the flooding hazard in a raster of 125 m and b) the flooding hazard in its original HORA feature class geodataset.

8 ANALYSIS FUTURE SCENARIO'S

8.1 INTRODUCTION

After analysing and implementing the different steps of the workflow for the present situation, a resulting water balance map and water supply system vulnerability (and risk) map for a certain time step are achieved. Different time steps (e.g. seasons or months) can result in different deficit/surplus identifications in the water balance map and/or different vulnerability and risk identifications in the respective water supply system vulnerability (and risk) maps. The world we are living in is not a static one. Changes upon water resources management in the river basins of the world in the 21st century will be substantial. Therefore case study dependent future scenarios need to be identified and defined. The developed workflow (Figure 2-2, page 12) needs to be analysed for these future scenarios (Figure 8-1), in order to provide for DSS tools to make adaptation and mitigation decisions amongst the different water demand stakeholders to be able to cope with future water management challenges. Within the workflow future changes in water availability and water demand can be quantified in a spatially and temporally distributed manner. The quantification of the effect of climate change e.g. on the hydrological water balance components within a catchment is invaluable for future planning within the water sector. The selected scenarios within this dissertation represent a population projection for 2031 and climate change projections for the middle and the end of the 21st century.

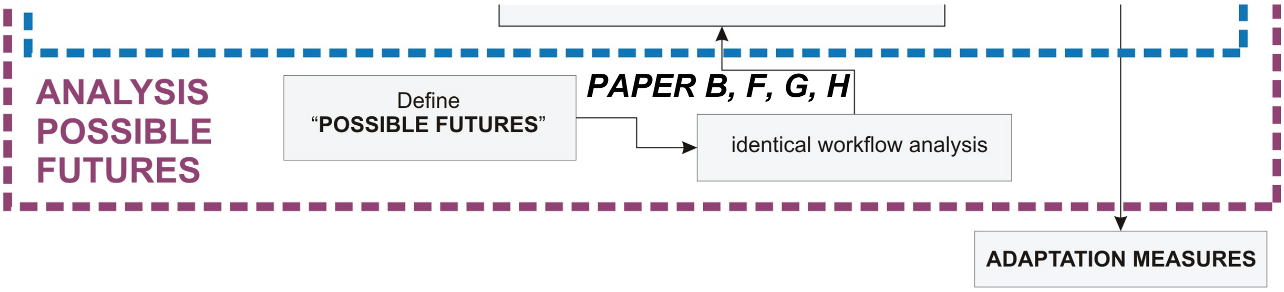


Figure 8-1: Different steps within the workflow regarding the analysis of future scenarios

Many regions in the world are facing major challenges in their water resources management sector within the 21st century. Water shortages are attributed to issues such as population growth, rapid urbanisation and industrialisation, environmental degradation, inefficient water use and poverty (economic water shortage). These problems are especially experienced by many developing and transition countries. Climate change – with its impacts on demand, supply and water quality - is a global phenomenon and is and will be experienced worldwide. Due to climate change, extreme events (e.g. droughts, flooding …) will occur more often. An extensive overview of the effects of climate change on the worldwide water cycle is given by (Bates *et al.*, 2008). **Paper A** (Vanham and Rauch, 2009c) gives a general overview on the effects of climate change on the hydrology and water management in the mountain ranges of the world and their dependent lowlands. Mountainous areas are particularly vulnerable to temperature and precipitation changes. Over the last century, glaciers throughout the world have shrunk considerably in size. On a seasonal level, both precipitation increases and decreases have been predicted for the different mountain ranges in the world. In the European Alps for example, an increase in winter precipitation but a decrease in summer precipitation is forecasted. Temperature increase however is likely to occur throughout the year in most regions of the world, resulting in increased snow and glacier melt. The consequences for river runoff will affect both the mountainous watersheds and the lowland regions that depend on them.

The topic of climate change effects on the water resources management in the case study area – described in this chapter – has been handled in **paper B** (Vanham and Rauch, 2009a), **paper F** (Laghari *et al.*, 2010)**, paper G** (Vanham *et al.*, 2009c) and **paper H** (Vanham *et al.*, 2009b).

Not the whole workflow is discussed in this chapter. The impact of future scenarios (climate change and demographic changes) will be discussed on water availability (chapter 8.3.2), water demand (chapter 8.3.3) and the regional water balance (chapter 8.3.4).

8.2 IDENTIFICATION POSSIBLE SCENARIOS

8.2.1 DEMOGRAPHIC CHANGES

Population growth is in many ways the most basic of pressures in water resources management because everyone requires at least some minimum of water related services (domestic, municipal and industrial water demands, water for food and energy). In countries like India and China population growth has a massive impact on pro capita water availability and possible (severe) water stress. In Austria however, population growth is not such a large issue. Figure 8-2 shows the population projection for 2031 for Austria. There is a strong regional difference, as both population growth and decline are predicted, dependent on the region. Within the case study area Kitzbühel region – for which the municipalities are located in the districts of Kitzbühel and Kufstein – a population increase is predicted. For the district Kitzbühel a value of 110 and for the district Kufstein a value of 115 relative to the index value 100 (year 2001) are predicted for 2031. These values increase from respectively 106 (Kitzbühel) and 108 (Kufstein) in 2011 to 108 (Kitzbühel) and 112 (Kufstein) in 2021. Data are only available at the district level and not the municipality level. Strong population increases as observed in the past century in Tyrol are not applicable any more.

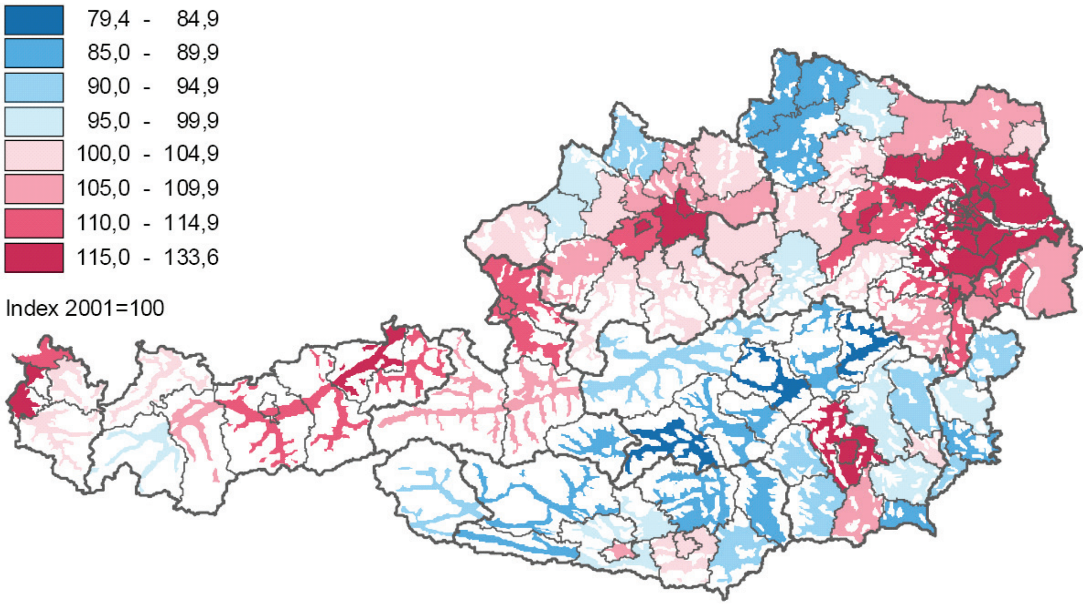


Figure 8-2: Population projection for 2031 (reference period 2001) for Austria, according to (ÖROK, 2004; Statistik Austria, 2006)

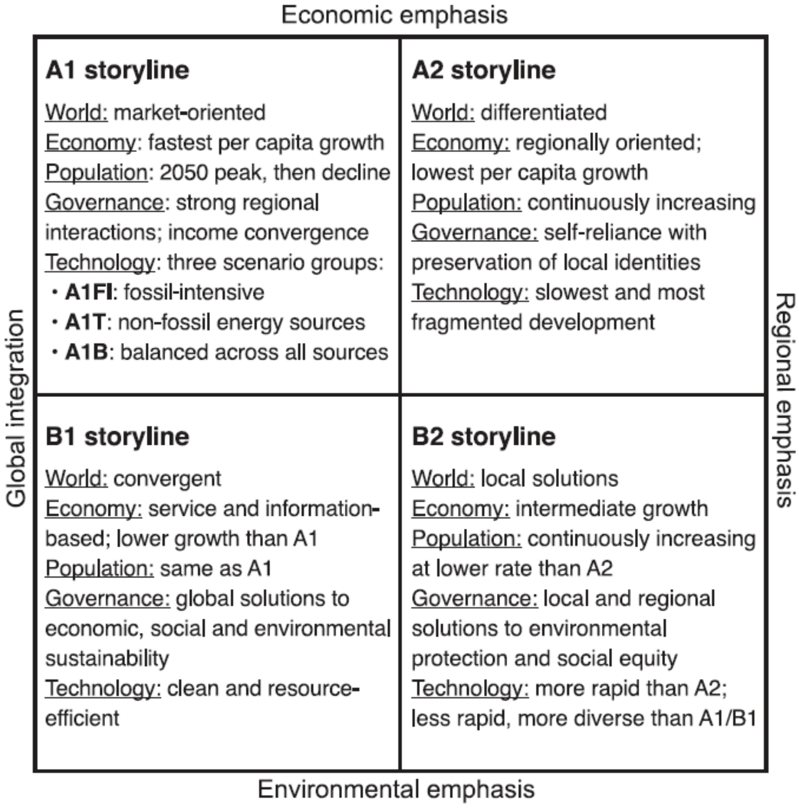
These demographic changes will have an influence on the water demand in the case study area, more particularly on the domestic, municipal, industrial and agricultural water demand – as discussed in chapter 6.2.2 (page 47) and **paper C** (Vanham *et al.*, 2010). The increase in water demand will be discussed in chapter 8.3.3 (page 86).

8.2.2 CLIMATE CHANGE

The Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report, released in 2007, concludes that based on historical observations, 'warming of the climate system is unequivocal' and this warming is very likely due to the observed increase in anthropogenic greenhouse gas (GHG) emissions. It is predicted with 'very high confidence' that the impacts of climate change on freshwater systems and their management will be primarily attributable to increases in temperature, rising sea levels and increased precipitation variability (Kundzewitz *et al.*, 2007). An increase in global mean temperature ranging from 1.4˚C to 5.8˚C for the end of the 21st century is predicted. Climate projections also show increases in globally averaged mean precipitation over the 21st century.

Mountainous areas are particularly vulnerable to temperature and precipitation changes (Beniston, 2003). In the European Alps for example, the 20th-century warming has been roughly three times the global average (Jungo and Beniston, 2001). Average temperatures are predicted to increase over the whole Alpine region. Climate models have difficulties representing precipitation in mountain areas. However, some general trends can be proposed with a precipitation increase during winter and a decrease during summer. A robust finding of hydrological impact studies is that warming leads to changes in the seasonality of river flows where much winter precipitation currently falls as snow. In most temperate mountain regions, the snowpack is close to its melting point, so it is very sensitive to changes in temperature. As warming progresses in the future, current regions of snow precipitation increasingly will experience precipitation in the form of rain. In these catchments earlier peak flows in spring are forecasted, as well as higher flows in winter and lower flows in summer (Barnett *et al.*, 2005; Beniston *et al.*, 2003; Eckhardt and Ulbrich, 2003). These observations were also made for the case study area Kitzbühel region, as discussed later in this chapter and in the **papers F** (Laghari *et al.*, 2010)**, G** (Vanham *et al.*, 2009c) and **H** (Vanham *et al.*, 2009b).

The four IPCC SRES - Special Report on Emissions Scenarios (Nakićenović and Swart, 2000) – storylines (Figure 8-3), which form the basis for many studies of projected climate change and water resources (Bates *et al.*, 2008), consider a range of plausible changes in population and economic activity over the 21st century. Among the scenarios that assume a world economy dominated by global trade and alliances (A1 and B1), global population is expected to increase from today's 6.6 billion and peak at 8.7 billion in 2050, while in the scenarios with less globalisation and co-operation (A2 and B2), global population is expected to increase until 2100, reaching 10.4 billion (B2) and 15 billion (A2) by the end of the century.



A1 storyline World: market-oriented Economy: fastest per capita growth Population: 2050 peak, then decline Governance: strong regional interactions; income convergence Technology: three scenario groups: • **A1FI**: fossil-intensive • **A1T**: non-fossil energy sources • **A1B**: balanced across all sources	**A2 storyline** World: differentiated Economy: regionally oriented; lowest per capita growth Population: continuously increasing Governance: self-reliance with preservation of local identities Technology: slowest and most fragmented development
B1 storyline World: convergent Economy: service and information-based; lower growth than A1 Population: same as A1 Governance: global solutions to economic, social and environmental sustainability Technology: clean and resource-efficient	**B2 storyline** World: local solutions Economy: intermediate growth Population: continuously increasing at lower rate than A2 Governance: local and regional solutions to environmental protection and social equity Technology: more rapid than A2; less rapid, more diverse than A1/B1

Figure 8-3: Summary characteristics of the four SRES storylines – based on (Nakićenović and Swart, 2000) – by (Bates *et al.*, 2008)

Projections of future climate change already exist, but are deficient both in terms of the characterisation of their uncertainties and in terms of their regional detail. To date, the assessment of potential impacts of climate change has generally relied on projections from simple climate models or coarse resolution Atmospheric-Ocean General Circulation Models (AOGCMs), neither capable of resolving spatial scales of less than ~300km (Jasper *et al.*, 2004). This coarse resolution limits their direct application in a detailed assessment of regional hydro-climatic change studies (Bronstert, 2004). The detailed spatial structure of variables like temperature and precipitation over heterogeneous surfaces e.g. the Alps are not presented. Therefore regional climate models (RCM) should be used. These are downscaling tools, adding detail to chosen general circulation model simulations. They have a much higher resolution than general circulation models and thus allow a more detailed assessment of a region's vulnerability to climate change. Most regional models have a resolution of 50 km or 25 km (Figure

8-4). This figure shows that these resolutions are necessary in order to represent the different weather regimes that influence the Alpine region (Figure 8-4). The EU PRUDENCE project (Christensen and Christensen, 2007) provides different regional downscaled scenarios – in resolutions 50 km or 25 km - for the European continent, representing the period 2071–2100 with respect to the baseline period 1961-1990. Another worldwide available RCM is PRECIS (Providing Regional Climates for Impacts Studies). PRECIS was designed by the Hadley Centre to be applied to any part of the world to generate detailed climate change predictions at a 50 km or 25 km scale. This model has been applied in regional hydro-climatic change studies in mountainous areas, like the Hindukush-Karakorum-Himalaya region (Akhtar *et al.*, 2008) and the Andes (Urrutia and Vuille, 2009).

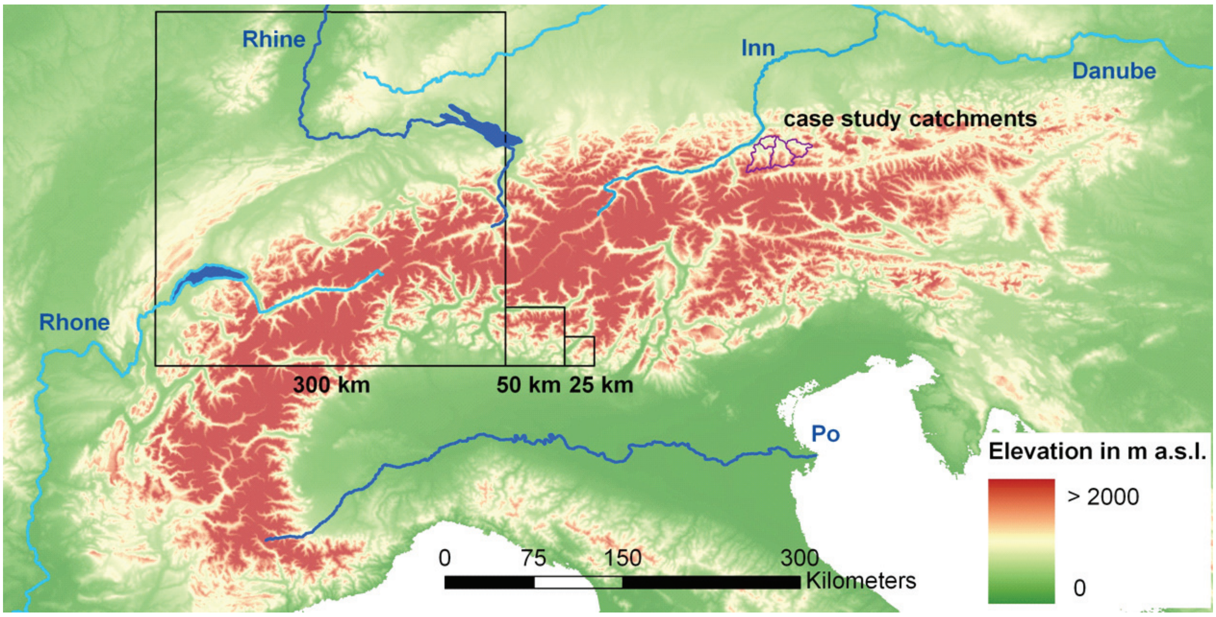


Figure 8-4: Raster resolutions 300 km, 50 km and 25 km superimposed on the Alpine region

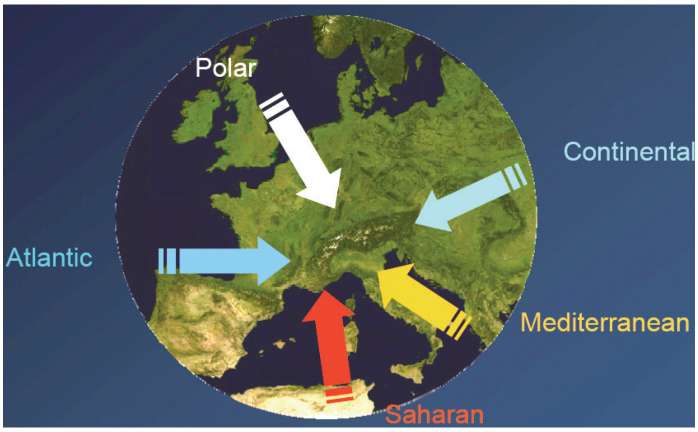


Figure 8-5: The Alps at the crossroads of numerous weather regimes. Source: (Beniston, 2006)

Estimates of future changes in climatic and hydrological conditions are complicated by an array of uncertainties related to the unknown future evolution of climate-forcing agents (emissions)(see Figure 8-3) and the limitations of the global to regional climate models used to project possible regional climate future (Jasper *et al.*, 2004). This means that a wide uncertainty band for the future evolution of the Alpine climate is a fact. The quantification of the effect of climate change on the hydrological water balance components within a catchment is invaluable for future planning within the water sector. Due to these uncertainties, the provision of quantitative estimates with error bands within the analysis is therefore important. This has been done in **paper F** (Laghari *et al.*, 2010) for the catchment Kitzbüheler Ache, one of the four catchments of the case study area Kitzbühel region. The paper bases its analyses on a set of 13 regional climate projections of the EU PRUDENCE project (Christensen and Christensen, 2007). This allows for the incorporation of uncertainties in the hydrological projections within the catchment at the end of the 21st century.

8.3 APPLICATION OF WORKFLOW FOR THE KITZBÜHEL REGION UNDER FUTURE SCENARIOS

8.3.1 INTRODUCTION

For the two selected future scenarios – demographic changes and climate change – the workflow for the Kitzbühel region should be applied. Only by assessing the workflow for the current and future situations and for different time steps, sustainable decisions regarding water resources management can be made. However, not the whole workflow is discussed in this chapter but only the most important changes in different steps are discussed. These workflow steps are water availability (chapter 8.3.2), water demand (chapter 8.3.3) and the regional water balance (chapter 8.3.4).

The topic of climate change effects on the water resources management in the case study area has been handled in:

- **paper B** (Vanham and Rauch, 2009a)
- **paper F** (Laghari *et al.*, 2010), which focuses on the quantification of uncertainty of future climate change projections. As project area the Kitzbüheler Ache, one of four catchments of the Kitzbühel region, was chosen.
- **paper G** (Vanham *et al.*, 2009c), which focuses on the impact of snowmaking as a water demand stakeholder on a regional water balance.
- **paper H** (Vanham *et al.*, 2009b), which focuses on the impact of both the extreme hot and dry summer of 2003 and the PRUDENCE CHRM climate change scenario summer for 2071–2100 on the monthly water balance within the case study area.

8.3.2 WORKFLOW STEP: WATER AVAILABILITY

8.3.2.1 Climate change scenarios

This chapter discusses the influence of different climate change scenarios on the hydrology and water availability in the case study area Kitzbühel region. This analysis is situated within the step *water availability* in the workflow (Figure 2-2 page 12). For such an analysis a hydrological model is required. In this case PREVAH was used.

- **For the whole study area** the impact of two climate change scenarios on the hydrology is investigated. As reference period the WMO climate normal period of 1961-1990 was chosen. Additionally the impact of the extreme hot and dry summer of 2003 on the hydrology of the case study area was chosen. Following climate change scenarios were chosen:
    - a 2˚C average temperature increase without precipitation change. This is a realistic scenario for the middle of the 21st century (2050)
    - the Climate High Resolution Model (CHRM) developed by the ETH Zürich under the A2 scenario (Christensen and Christensen, 2007). This scenario is valid for the end of the 21st century (2071-2100)
    - the extreme hot and dry summer of 2003
- **For the catchment Kitzbüheler Ache**, one of the four catchments of the case study area Kitzbühel region, the impact of 13 regional climate projections of the EU PRUDENCE project (Christensen and Christensen, 2007) on the hydrology is investigated. This analysis is described in detail in **paper F** (Laghari *et al.*, 2010).

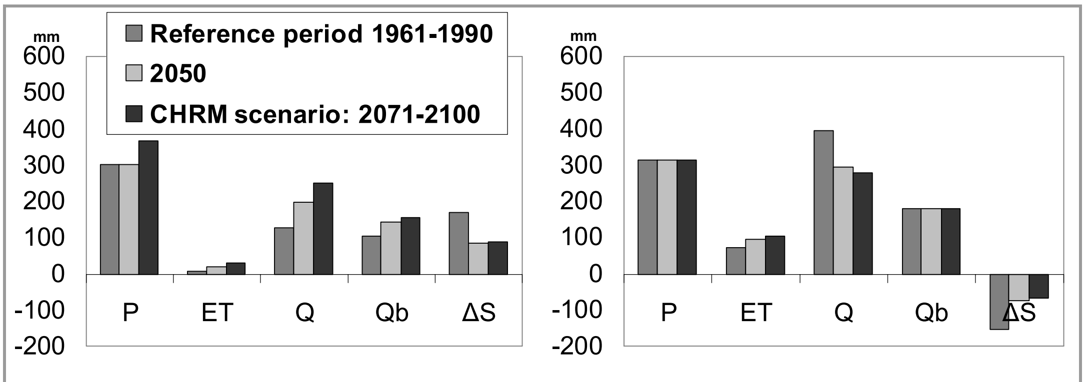
The CHRM model developed at the Institute for Atmospheric and Climate Science, ETH Zurich (IAC-ETHZ), derives from the former numerical weather prediction model, HRM, and has been modified to provide a RCM (Vidale *et al.*, 2003). The computational grid of the model is a regular latitude/longitude grid with a spatial resolution of 0.5° (about 50 km). The CHRM was validated for the region of the European Alps by (Vidale *et al.*, 2003) and (Frei *et al.*, 2003; Vidale *et al.*, 2003). (Vidale *et al.*, 2003) showed that the interannual variations in temperature are generally well represented and that precipitation is modelled better in relatively dry years, especially in summer.

A severe heat wave and accompanying drought over large parts of Europe in 2003 extended from June to August, raising summer temperatures by 3 to 5 ˚C in most of southern and central Europe and lowering precipitation substantially (Alcamo *et al.*, 2007). Many major rivers (e.g., the Po, Rhine, Loire and Danube) were at record low levels. This extreme climatic situation resembles simulations by regional climate models of summer temperatures in the latter part of the 21st century under the A2 scenario (Bensiton and Diaz, 2004). Therefore it provides information on the water supply security in an alpine environment within a future climate change summer. Also, (Schär *et al.*, 2004) state that at the end of this century (2071–2100) every second summer can be as hot (or even hotter) and as dry (or even drier) as the summer of 2003. Therefore the well document event of 2003 represents a unique chance to analyse future conditions. A detailed analysis of this climatic event in the case study area is presented in **paper H** (Vanham *et al.*, 2009b).

In order to calculate the effect of these climate change scenarios on the hydrology of the case study area, the model PREVAH was used. Average monthly relative precipitation and absolute temperature differences were extracted in GIS-raster format from the PRUDENCE project homepage. After calibration and validation of the reference period 1961-1990 model (see chapter 5 - *Water availability*), these monthly precipitation and temperature differences were incorporated within this simulation by means of the so-called delta approach often referred to as "*delta change*" (Graham *et al.*, 2007).

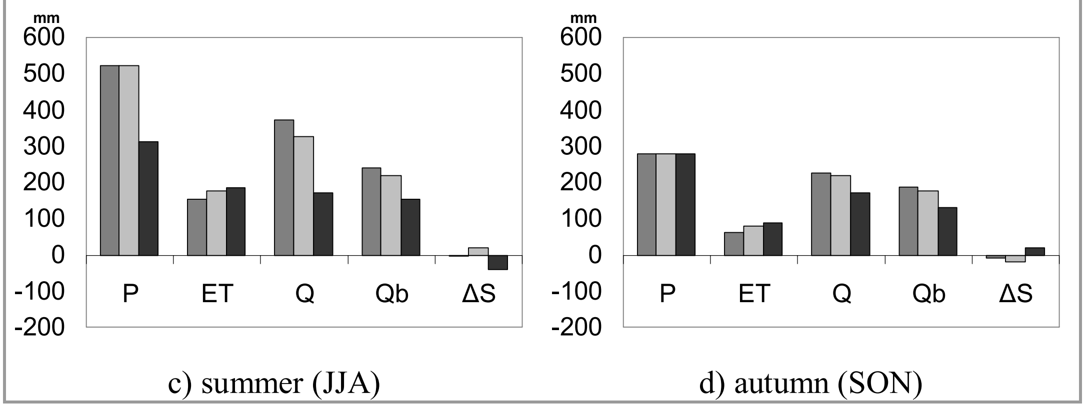
8.3.2.2 Impact of scenarios on hydrology and water availability

Figure 8-6 shows the resulting changes in water balance variables for the climate change scenarios 2050 and 2071-2100 for the four seasons. Typically for alpine regions ET is low in winter and the highest in summer. Due to the storage of water in the winter snowpack, ΔS is positive in winter and negative in spring (when the snowpack is released as melt water). ET increases for all seasons in 2050 and 2071-2100, due to the temperature increases. Total and base flow increase substantially in winter and decrease in spring, summer and autumn for the climate change scenarios.



a) winter (DJF)

b) spring (MAM)



c) summer (JJA)

d) autumn (SON)

Figure 8-6: Hydrological water balance variables for the reference period (1961-1990) and the climate change scenarios 2050 and 2071-2100 during a) winter, b) spring, c) summer and d) autumn. Source: (Vanham and Rauch, 2009b).

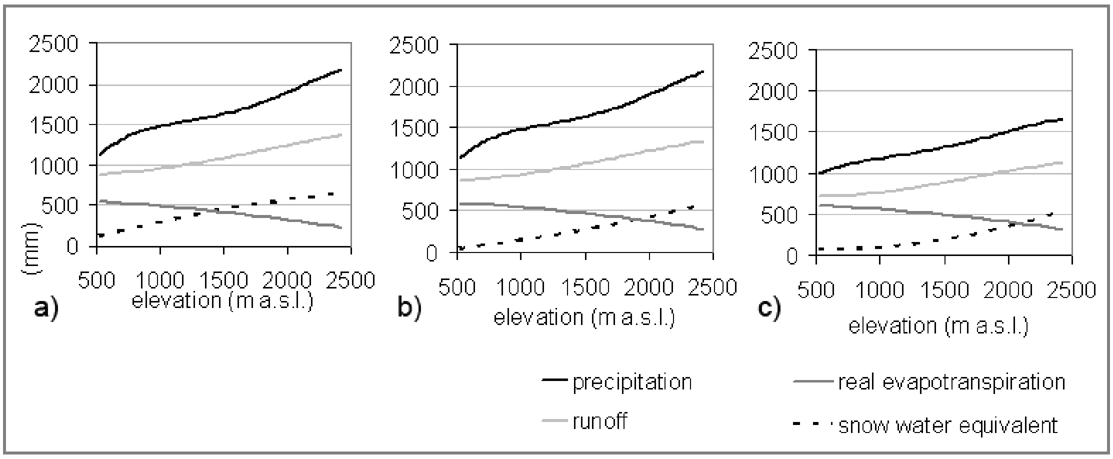


Figure 8-7: Mean annual water balance components versus elevation for the case study area for: (a) the reference period 1961–1990, (b) an average 2°C temperature increase, and (c) the CHRM scenario. Source: **paper B** (Vanham and Rauch, 2009a).

Figure 8-7 shows the elevation dependency of the water balance components both for the reference period (same as Figure 5-7, page 40) and the climate change scenarios. Precipitation in the form of rain and snow (snow water equivalent) increases with altitude, evapotranspiration decreases with altitude (as does temperature), and as a result specific runoff decreases with altitude. It is seen that evapotranspiration increases and runoff decreases within the climate change scenarios. Also the snow water equivalent decreases, however the effect is elevation dependent. Lower altitudes are more affected than higher altitudes.

This last observation is also shown in Figure 8-8 and Figure 8-9. The hydrological model indicates a substantial reduction in average annual snow cover duration and snow water equivalent, an effect that decreases with increasing elevation. Snow cover duration correlates strongly with snow accumulation (Beniston *et al.*, 2003). For the 2°C temperature increase scenario the natural average snow cover duration diminishes with approximately 40 days (15 % reduction) at an elevation of 2,000 m to 50 days (50 % reduction) at an altitude of 600 m (Figure 8-9 left and Figure 8-13). For the CHRM scenario a reduction up to 70 % in the valleys is observed (Figure 8-9 right). A 3-D visualisation of the reduction in snow cover duration for the CHRM scenario gives a good impression of the elevation dependency of this effect (Figure 8-10). These results correspond to the findings of other authors. A shortening of the winter season was also predicted in Switzerland by (Beniston *et al.*, 2003), who forecasted a reduction in snow cover duration of 15–20 days for each degree of wintertime warming. The shortening of the snow season concerns more the end (spring) rather than the beginning (autumn). Similar observations were made in Austria by (Hantel *et al.*, 2000).

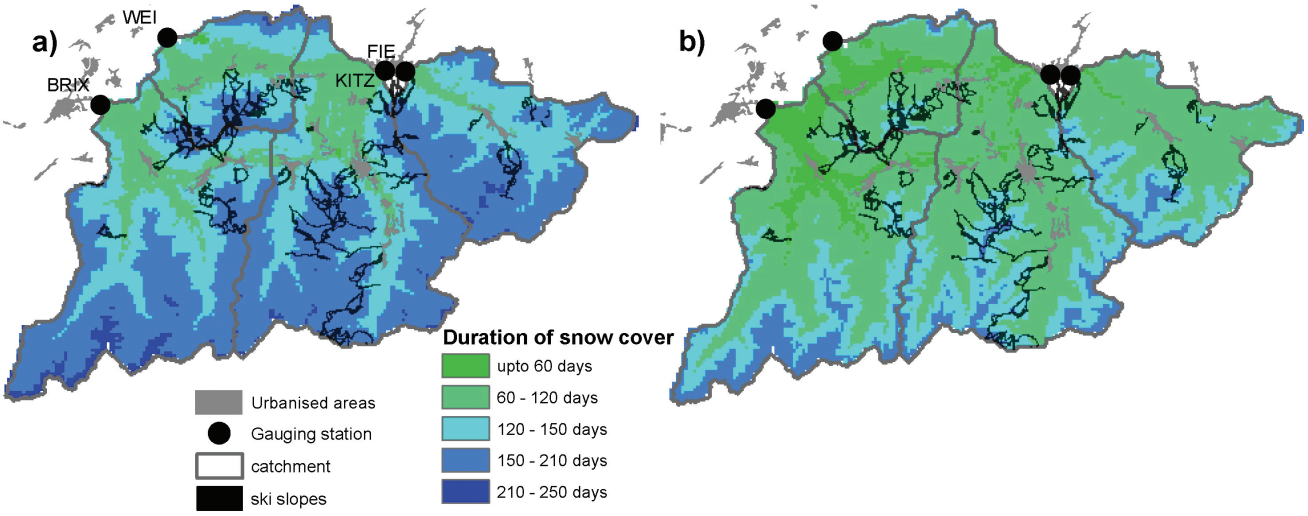


Figure 8-8: Average yearly snow cover duration in days for (a) the period 1961 to 1990 and (b) the assessed climate change scenario (average temperature rise of 28C without precipitation change). Source: **paper G** (Vanham *et al.*, 2009c)

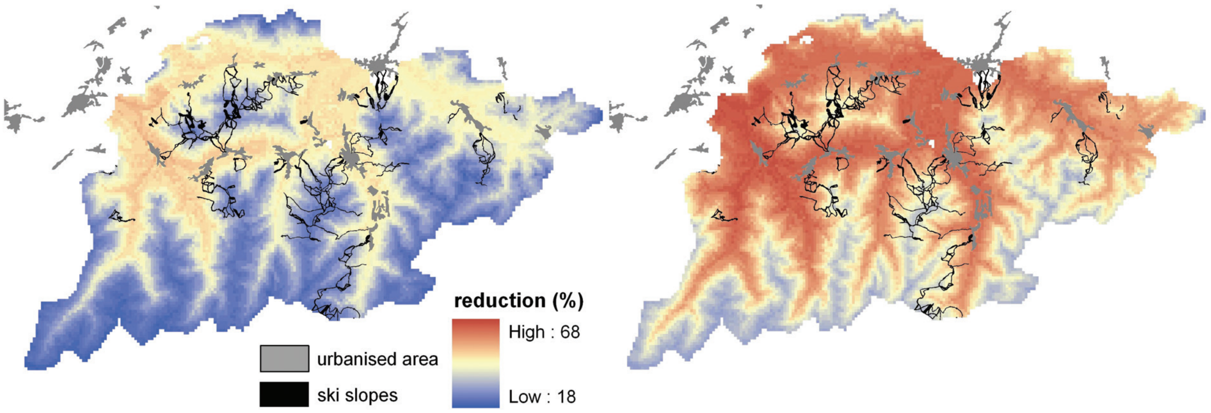


Figure 8-9: Reduction in average annual snow cover duration with respect to the reference period 1961–1990 for: (left) an average 2°C temperature increase, and (right) the CHRM scenario. Source: **paper B** (Vanham and Rauch, 2009a).

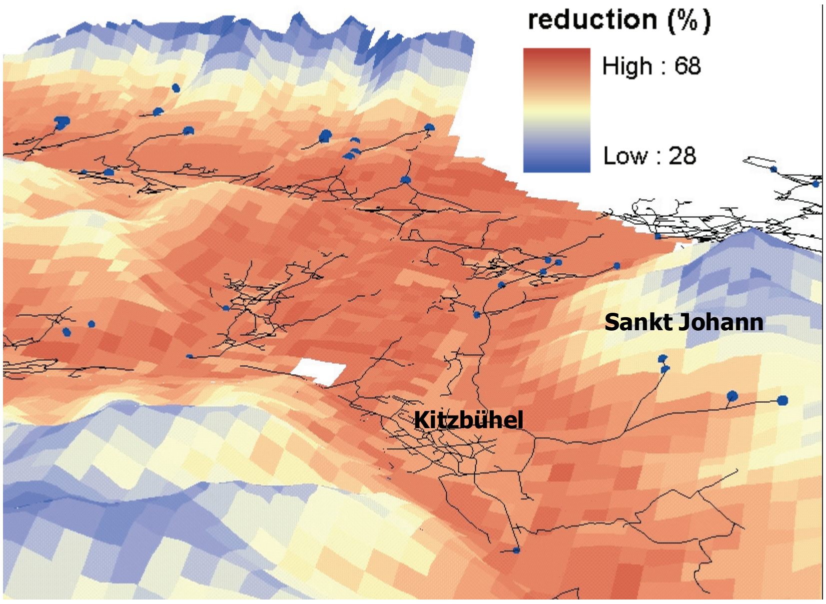


Figure 8-10: Reduction (%) in average snow cover duration over part of the case study area for the CHRM scenario with respect to the reference period. The black lines represent water distribution pipes, the blue dots represent springs and groundwater wells in the valleys. Source: (Vanham and Rauch, 2009b)

The most important effect of the climate change scenarios for IWRM is on the component runoff (and base flow). Figure 8-11 shows that a shift in flow seasonality occurs. Both total and base flow shift from the low flow period in winter to the low flow period in summer (and to a minor extend in autumn. As not so much water is stored as snow in winter anymore, the spring peak flows decrease and the natural reservoir effect of the snow cover decreases.

This shift in flow seasonality is shown on a monthly basis in Figure 8-11. The melt water peak in the reference period during spring is flattened out for the future scenarios as there is a shift in precipitation from snow to rain. Lowest flows shift from winter to summer and autumn.

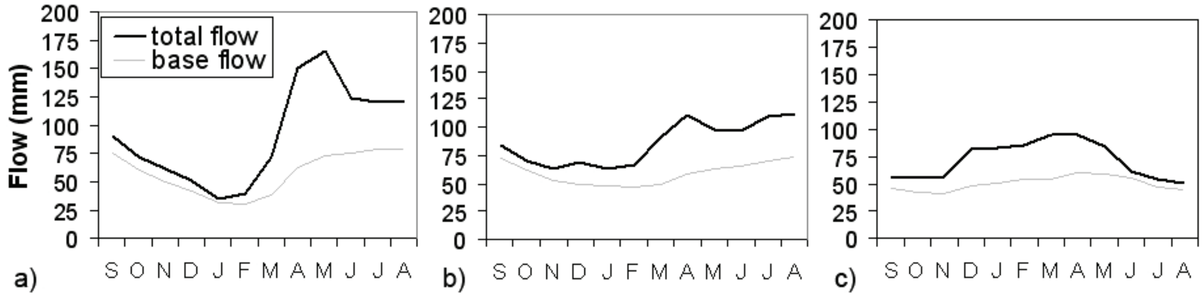


Figure 8-11: Mean monthly total and base flow in the case study area for: (a) the reference period 1961–1990, (b) an average 2°C temperature increase, and (c) the CHRM scenario. Source: **paper B** (Vanham and Rauch, 2009a).

In order to calculate available water for future scenarios, this change in flow seasonality is taken as existing situation in future. This means that the environmental flows (Q_{95}) are calculated based upon this new flow regime.

It has to be stated that these simulations included simplifications. The range of climate scenarios for example only included changes in precipitation and temperature, not in other meteorological variables like wind speed, relative humidity and radiation. Secondly, only mean values were considered. Possible shifts in the intensity and occurrence of extreme events were not taken into account. Thirdly, changes in vegetation due to climate change were not considered. Our simulations assumed a static description of the vegetation. However, especially in alpine regions with their heterogeneity in vegetation zones, shifts are likely to occur. The tree line for example is expected to rise due to global warming to higher altitudes.

8.3.3 WORKFLOW STEP: WATER DEMANDS

8.3.3.1 Domestic, municipal, industrial and agricultural water demand

The methodology to calculate the (rasterised) domestic, municipal, industrial and agricultural water demand is presented in chapter 6.2.2 and **paper C** (Vanham *et al.*, 2010). An increased future water demand due to demographic changes (chapter 8.2.1) is calculated within this chapter. It is representative for the year 2031. Further detailed projections are not available, so this scenario will be taken as representative for 2050 and the end of the 21st century (time range of the climate change scenarios). The increased water demand will only be calculated on a regional level, as there are some uncertainties in the analysis. Future demographic data are only available at the district level and not the municipality level. Therefore an overall increase of 10 % in population is assumed for the 19 municipalities of the Kitzbühel region. A new water demand raster is not calculated, as detailed spatial projections are required here. Literature that deals with this matter is e.g. (Krakover and Borsdorf, 2000) or (Durga Rao, 2005). Zoning plans of the municipalities should be analysed in detail, in order to geographically identify new housing areas and thereby new water demand areas. In order to assess a detailed water balance map and water supply system vulnerability map, these geographical analyses should be made.

The 19 municipalities of the case study area had a total population (principal residence) of 57,142 in the year 2001. For the year 2031 this population is projected to increase to 62,857. The same projection is made for the population of secondary residence. Figure 8-12 shows a linear relationship between population principal residence to persons employed for the municipalities of the case study area, except for two outliers (Kitzbühel and Sankt Johann). This relation and the number of people commuting show the urban character of the two latter municipalities, in contrast to the rural character of the 17 remaining municipalities. It can be stated that the rural communities are "self sufficient" in their people employed (they also have a net negative number in persons commuting – i.e. more people from these villages commute to other municipalities as reverse), whereas Kitzbühel and Sankt Johann attract persons employed from the surrounding villages. When this relationship is kept (i.e. about 3 persons employed per 10 inhabitants for the rural municipalities and about 7 persons employed per 10 inhabitants for the urban municipalities), a 10 % population increase results in a future 14,509 persons employed (from 13,190 in 2001) for the rural municipalities and 12,254 persons employed (from 11,140) for the urban municipalities. When other demand stakeholders are kept constant (e.g. overnight stays), future annual average water demand becomes 244 l per s (from 219) and winter water demand becomes 276 l per s (from 259) without water losses. For water losses an additional 10 % can be assumed.

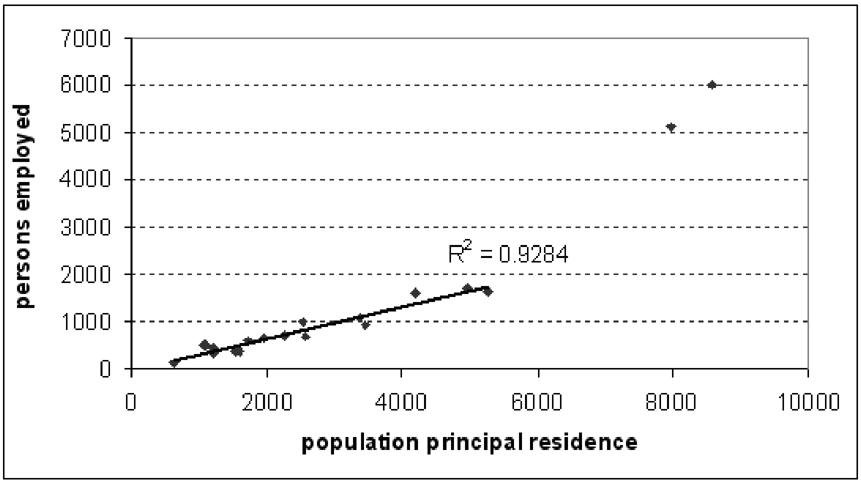


Figure 8-12: Relationship population principal residence to persons employed (without agriculture) for the 19 municipalities. The two outliers represent Kitzbühel and Sankt Johann.

These future water demands do not take the impact of climate change on water demand in account. It is e.g. expected that water demands will increase in future (hotter and dryer) summers due to more garden sprinkling, showering, swimming pool water etc. However, the methodology described in **paper C** (Vanham *et al.*, 2010) can take such increases in account. For a detailed analysis of future water demands these increases should be accounted for.

8.3.3.2 Water demand for technical snowmaking

Whether water demands for technical snowmaking will increase in future due to climate change is generally a matter of the elevation location of the ski slopes. As discussed in chapter 8.3.2.1, future snow reduction due to climate change increases with decreasing altitude. For an average temperature increase of 2°C (scenario for 2050) Figure 8-13 shows the reduction in average yearly number of days with snow cover for the whole case study area and for the ski slopes. Almost 100% of the existing ski slopes have a natural snow cover of about 4 months (120 days) in the reference period, more specifically from the end of November/beginning of December to the end of March/beginning of April. This snow line (minimum 4 months duration) corresponds to an elevation range between 750 and 1,000 m, depending on the aspect of the mountain slopes.

This observation is also shown in Figure 8-14 for the ski slopes (total area 900 ha) within the catchment KITZ, which represent the characteristics of all ski slopes within the whole study area due to their wide elevation range. This figure shows that 1) ski slopes at lower altitudes are more affected and 2) the impacts are least in January and February and most in April. In April skiing conditions are critical as the temperature leads to melting of the snow cover and makes snowmaking impossible likewise. The shortening of the snow season concerns more the end (spring) rather than the beginning (autumn).

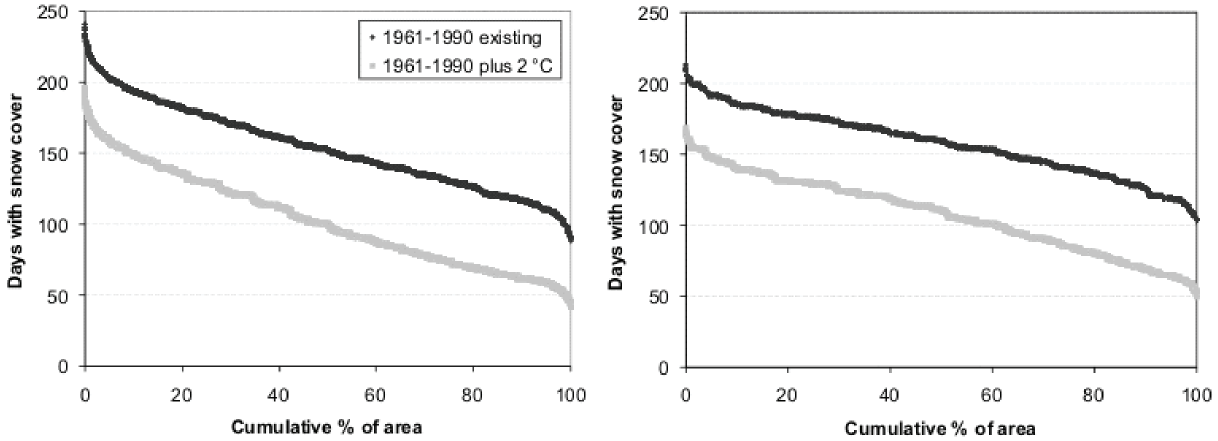


Figure 8-13: Average yearly number of days with snow cover for the existing and climate change scenario for the whole case study area (left) and for the existing ski slopes (right). Source: **paper G** (Vanham *et al.*, 2009c)

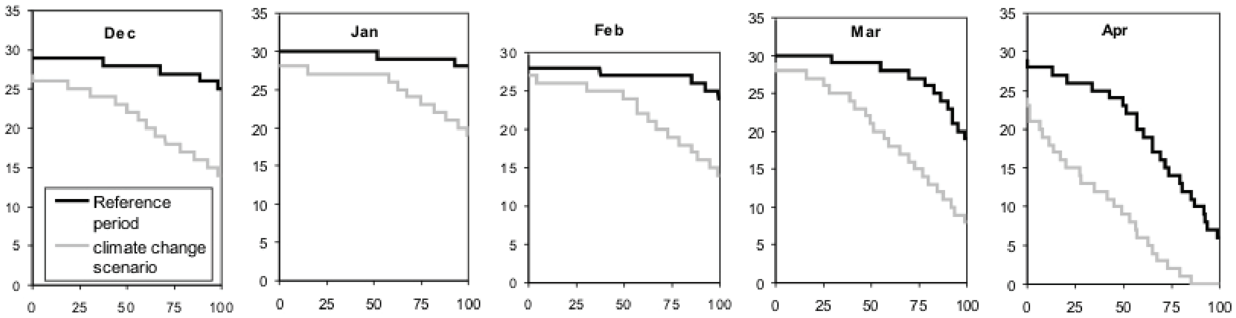


Figure 8-14: Average monthly number of days with snow cover for the existing and climate change scenario for the ski slopes (cumulative percentage of area) within the catchment KITZ. Source: **paper G** (Vanham *et al.*, 2009c)

It is clear that the reduction in natural snow cover leads to an increase in improvement snowmaking. How to quantify the additional water demand for improvement snowmaking under the climate change scenario is described in detail in **paper G** (Vanham *et al.*, 2009c). For the total area of existing slopes (2,117 ha) the water demand for improvement snowmaking increases from 3.05 million m^3 to 6.53 million m^3.

Climate change scenarios predict for the Alps both a temperature and precipitation increase during winter. Within the case study area the snowpack is close to its melting point, so it is very sensitive to changes in temperature. However, for very high altitudes (e.g. 3000 m a.s.l.) the increase in precipitation can compensate for the increase in temperature. In these high Alpine regions snow reduction can be reduced to zero. Additional snowmaking will not be necessary.

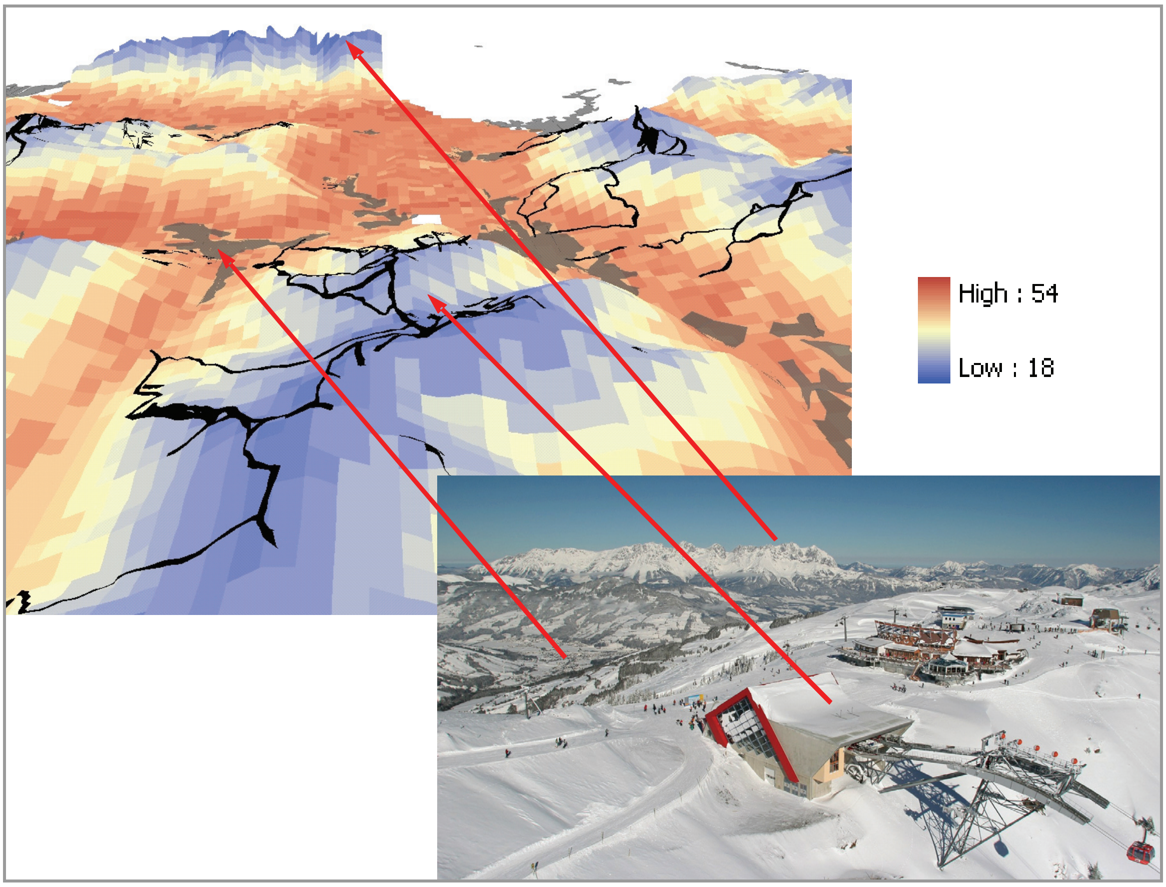


Figure 8-15: Reduction (%) in average snow cover duration over part of the case study area for an average 2˚C temperature increase with respect to the reference period. The ski slopes in the foreground belong to the ski region *Bergbahn Kitzbühel*. Source: (Vanham and Rauch, 2009b)

8.3.4 WORKFLOW STEP: REGIONAL WATER BALANCE

Within this chapter the impact of future scenarios (climate change and demographic changes) is discussed on the regional water balance of the case study area. The increased domestic, municipal, industrial and agricultural water demand (due to demographic changes) and increased water demand for technical snowmaking are balanced with the changed water availability for a monthly time step.

A monthly water balance (water demand–water availability) in m^3 per s for the climate change scenario for 2050 is presented in Figure 8-16. Also the water balance for the reference period is presented, identical to Figure 7-11 on page 68. Again – as for the existing situation – a deficit in the water balance during the month of December for a dry year is identified due to base snowmaking. Especially during January to March the total water demand increases substantially due to an increase in improvement snowmaking. However, on a regional level no other deficits are identified. Again the necessity for reservoirs for snowmaking is stressed and also quantified.

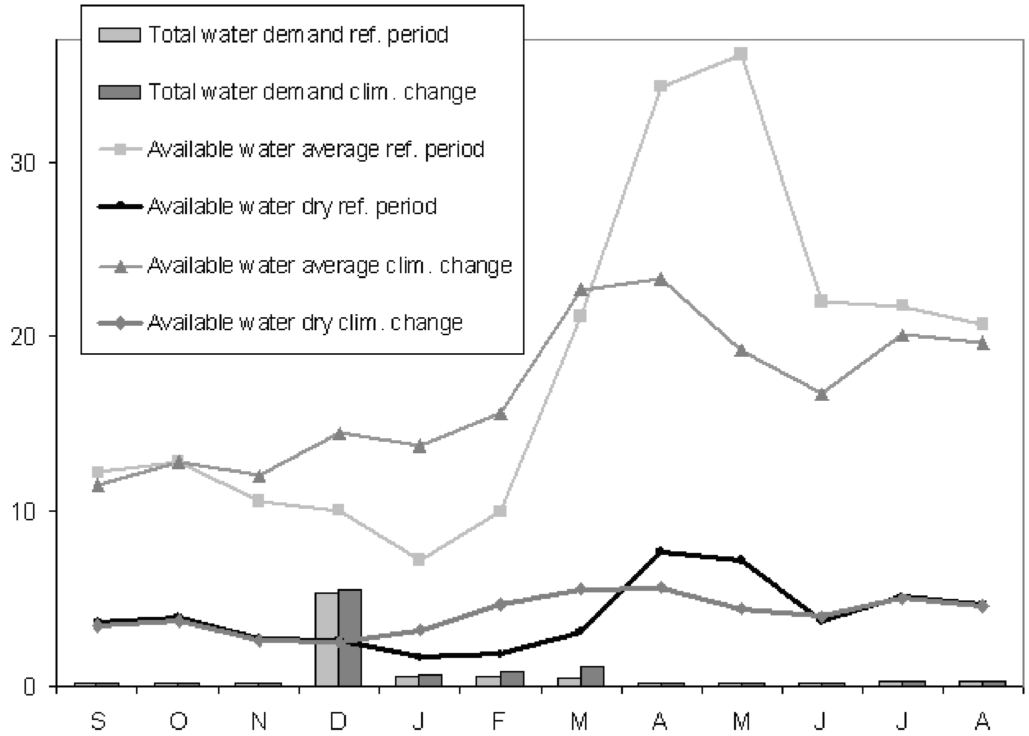


Figure 8-16: Monthly water balance (water demand–water availability) in m^3 per s for the reference period (1961-1990) and the climate change scenario for 2050. Base snowmaking is restricted to 5 days. Source: **paper G** (Vanham *et al.*, 2009c)

Another critical period for the water balance was identified as being a dry (and hot) summer. With respect to this situation, two scenarios were selected: the hot and dry summer of 2003 and an average summer under the CHRM scenario. These scenarios are discussed in detail in chapter 8.3.2.1 and **paper H** (Vanham *et al.*, 2009b).

The average monthly water balance of the summer months for the reference period shows that the water demand for all stakeholders can be easily met on a regional basis (Figure 8-17 left). This figure is a zoom of Figure 7-11 on page 68. The regional water balance for the summer of 2003 shows a deficit for the month of August (Figure 8-17 right), as the Q_{95} flow for the reference period equals the August flow in 2003. Theoretically – by defining the environmental flow as Q_{95}—no water is available. However, the regional water demand represents only 1.5% of this Q_{95} value, an amount largely acceptable on a regional scale. In many legislations higher values can be temporally approved (BUWAL, 2004), as already discussed in detail in chapter 5.3 - Environmental flows (EF). During the other summer months June and July of 2003, regional water availability was sufficient to meet water demands. Available groundwater in the CHRM climate change scenario proves to be sufficient to meet all the water demand stakeholders.

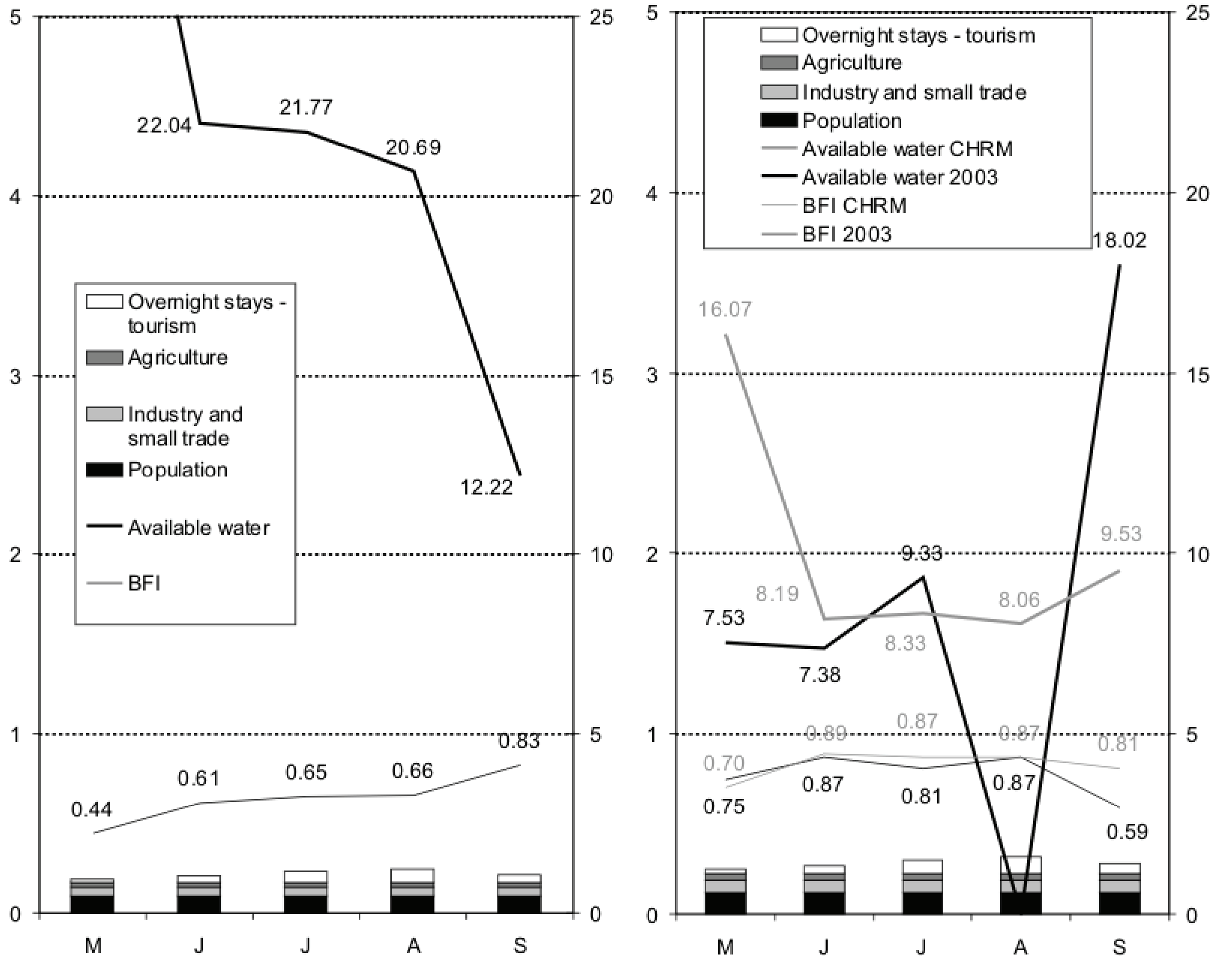
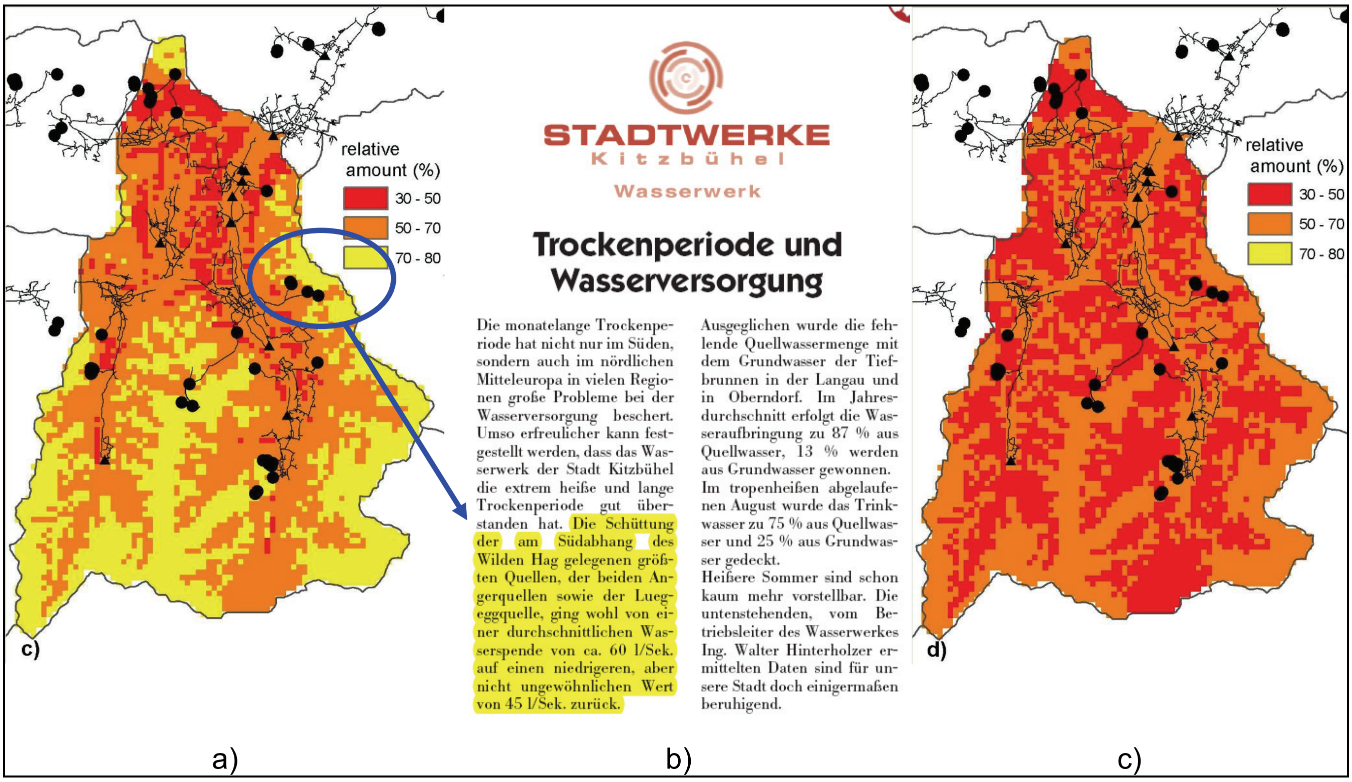


Figure 8-17: Regional monthly water balance during the summer months of the reference period (left) and the two summer scenarios (right). Values for water demand (m^3 per s) and BFI are related to the primary Y-axis (left), values for available water (m^3 per s) are related to the secondary Y-axis (right). Source: **paper H** (Vanham *et al.*, 2009b).

Although the regional water balance does not result in serious stress situations for future summer conditions, local deficits can occur. Figure 8-18 shows the reduction in groundwater recharge within the catchment Kitzbüheler Ache (KITZ) in the months of August for the summer of 2003 and the CHRM climate change scenario summer. Most of the springs that serve the water supply undertakings within the catchment KITZ, are located in the mainly phyllite and schist region of the Central Alps (see chapter 4.2.2 on hydrogeology). They are characterised by small average flows that react rapidly to rainfall due to small storage reservoirs and retention times. Average monthly ground water recharge reductions up to 70 % in both summer scenarios with respect to the reference period can therefore have a large impact on the water supply security of the different municipalities, as many have no groundwater wells and interconnection pipes between different systems are rare. An analysis of the water supply security during the summer of 2003 (BUWAL, 2004) showed that certain municipalities were only able to provide their service area with sufficient water due to interconnection pipes with other systems. Similar observations have been reported in Austria (Bogner, 2004). The detailed analysis of the flow time series of the spring "*Auebachquelle*" in the study area during the summer of 2003 showed a reduction of 60 % in spring flow with respect to the reference period (De Toffol *et al.*, 2008), and supports the results in Figure 8-18. Also a reduction in groundwater levels in the valleys was observed by the authors, with this effect being clearer for shallow aquifers in connection with the river systems.



STADTWERKE
Kitzbühel
Wasserwerk

Trockenperiode und Wasserversorgung

Die monatelange Trockenperiode hat nicht nur im Süden, sondern auch im nördlichen Mitteleuropa in vielen Regionen große Probleme bei der Wasserversorgung beschert. Umso erfreulicher kann festgestellt werden, dass das Wasserwerk der Stadt Kitzbühel die extrem heiße und lange Trockenperiode gut überstanden hat. Die Schüttung der am Südabhang des Wilden Hag gelegenen größten Quellen, der beiden Angerquellen sowie der Lueg-eggquelle, ging wohl von einer durchschnittlichen Wasserspende von ca. 60 l/Sek. auf einen niedrigeren, aber nicht ungewöhnlichen Wert von 45 l/Sek. zurück. Ausgeglichen wurde die fehlende Quellwassermenge mit dem Grundwasser der Tiefbrunnen in der Langau und in Oberndorf. Im Jahresdurchschnitt erfolgt die Wasseraufbringung zu 87 % aus Quellwasser, 13 % werden aus Grundwasser gewonnen.
Im tropenheißen abgelaufenen August wurde das Trinkwasser zu 75 % aus Quellwasser und 25 % aus Grundwasser gedeckt.
Heißere Sommer sind schon kaum mehr vorstellbar. Die untenstehenden, vom Betriebsleiter des Wasserwerkes Ing. Walter Hinterholzer ermittelten Daten sind für unsere Stadt doch einigermaßen beruhigend.

Figure 8-18: Relative groundwater recharge to the reference period in August in the catchment of the Kitzbüheler Ache for a) the year 2003 and c) the CHRM scenario. Figure adapted from **paper H** (Vanham *et al.*, 2009b)

An article in the local newspaper of the municipality Kitzbühel (Figure 8-18 b) described a measured flow reduction in the four springs east of Kitzbühel during the summer of 2003 of 25 %. The combined flow of these four springs reduced from 60 l per s to 45 l per s. This reduction amount was also simulated with the PREVAH model (Figure 8-18 a). For the CHRM climate change scenario (Figure 8-18 c) an even higher reduction in the same area of 50 to 30 % was simulated. The municipality of Kitzbühel did not have deficit problems during the summer of 2003 as it provides drinking water also with groundwater wells. In this summer period 75 % of the population was served with spring water and 25 % with groundwater. However, surrounding municipalities only have springs and no groundwater wells. With an increasing population for 2030, higher summer demands (due to garden watering …) and the absence of connection pipes between the different municipalities, local deficits can occur. A local analysis should be made. The distributed model PREVAH provides this possibility. During the CNET project process time, the different municipalities from Sankt Johann to Jochberg were actually already planning and discussing a possible implementation of an emergency connection pipe – based on the every day experience of their water supply undertakings.

9 CONCLUSIONS

9.1 AIMS, SCOPE AND STRUCTURE OF THE DISSERTATION

This dissertation focuses on the development (and application) of methodologies to test the sustainability of alpine or mountainous water resources management for present and future conditions, within the wider concept of IWRM. These methodologies are situated in the pillar “management instruments” (Figure 1-1, page 2) of IWRM, essential methods and tools in order to achieve river basin plans. In order to make rational and informed choices between alternative actions at the basin level, it is important for decision makers to have the right tools (management instruments) to evaluate and predict current and future water availability and demand, and resulting deficits and surpluses. The discussion in this dissertation is limited to water quantity management.

The ground structure of the dissertation is the development and application of methodologies within the context of a workflow (Figure 2-2, page 12) in order to achieve a temporally and spatially distributed assessment of the water balance between available water resources and the different water demand stakeholders in an alpine context. This results finally in the generation of 1) a water balance map and 2) a water supply system 2a) vulnerability map and 2b) Alpine natural hazards risk map. These maps are important tools to test an alpine project river basin on its sustainability both at present and for possible future scenarios.

As the temporal and spatial variation of both water resources (surface water, springs and ground water) and water demand (domestic, municipality, agriculture, industry, energy, snowmaking, irrigation …) is very high in mountainous regions, the analysis and quantification of the latter require specific methodologies.

The workflow is developed and tested within the case study area of the greater Kitzbühel region (Figure 3-6, page 20) in the Austrian Alps, but aims at being applicable for different mountainous regions of the world. Large parts of the research of the dissertation were conducted within the framework of the Competence Network Water Resources (CNET or KNET – Kompetenznetzwerk Wasserressourcen)(www.waterpool.org). Project developments and results were continuously implemented, applied and evaluated within the know-how of the business partners, resulting in so-called competence build-up.

Different papers were written and published during the duration of this dissertation, and they support the scientific value of this work. Figure 2-2 (page 12) shows schematically the topics of the different papers positioned within the workflow. In total 8 papers – numbered A to H - are included within the dissertation, of which 1 book chapter, 1 conference proceedings and 6 journal papers. Of the latter 4 are published, and 2 under review.

The different chapters within this dissertation generally present the different steps within the workflow. The following text gives a general overview of the content of the different chapters and the papers that relate to this content. The full paper citation is displayed after the chapter to which most of its content relates.

- **Chapter 3 - Pilot area**: One of the first steps in the workflow is described - the delineation of the case study area, the Kitzbühel region encompassing 19 municipalities located in 4 catchments. This chapter also discusses the spatial scale for which the methodology is primarily applicable - the macro and for some methodologies the meso level. Additionally the importance of mountain water is described. Many mountains have a water tower function for their surrounding lowlands. As IWRM implies the whole river basin, the effect of water management measures within an upstream located case study area on lower lying areas has to be taken into account. This topic is generally discussed in **paper A** (Vanham and Rauch, 2009c) and particularly for the Danube river basin – in which the Kitzbühel region is located – in the first section of **paper B** (Vanham and Rauch, 2009a). The disproportionate hydrological influence of the Alps is demonstrated for the Danube River basin, especially during summer, late spring and early autumn.

A **Vanham, D.,** Rauch, W. (2009) Mountain water and climate change. In: Climate Change and Water - International Perspectives on Mitigation and Adaptation. Joel Smith, Carol Howe and Jim Henderson (Ed.), page 21-40, ISBN 9781843393047.

B **Vanham, D.,** Rauch, W. (2009) Retreating snowpacks under climate change: Implications for water resources management in the Austrian Alps, in: Improving Integrated Surface and Groundwater Resources Management in a Vulnerable and Changing World, Proceedings of JS.3 at the Joint IAHS & IAH Convention, Hyderabad, India, 6-12 September 2009, IAHS Publ. 330.

- **Chapter 4 - Data availability and organisation**: After the delineation of the project area, the following step within the workflow is the acquisition of data and the implementation of a (GIS)-data and information system. GIS-data and the use of GIS-software (in this case ArcGIS) play a central role within the workflow which results in DSS-maps. One of the most time and energy consuming steps within a river basin management analysis project is the acquisition of data, especially when modelling is involved. This chapter explains why a project raster resolution of 250 m is chosen. An overview on required data and their availability is given. Proper and well-arranged data storage and organisation is an important issue within the assessment of water management plans (and the workflow of this dissertation). Within the scope of the CNET-project a database structure was developed, primarily with the focus of interaction between the different specialists working on the project. This (GIS-) data organisation structure is presented in the chapter (Figure 4-5, page 32).
- **Chapter 5 - Water availability**. Within this chapter the water availability in the case study area for the reference period (1961-1990) is assessed. The hydrological water balance is simulated by means of the semi-distributed model PREVAH. A hydrological model is necessary in the workflow in order to 1) spatially and temporally distribute the different water balance components; 2) separate surface from ground water; and 3) have the possibility to evaluate the impact of climate change or changing land use on the water balance components (and therefore water availability). The analysis with PREVAH for the reference period is part of the papers **B** (Vanham and Rauch, 2009a), **F** (Laghari *et al.*, 2010), **G** (Vanham *et al.*, 2009c) and **H** (Vanham *et al.*, 2009b). Also the topic of environmental flows and its impor-

tance for IWRM is described. Water availability – both for a normal and a wet year - is determined in the case study area by means of the modelling results and maintaining environmental flows.

- **Chapter 6 - Water demand**: Within this chapter the water demand of the different stakeholders is analysed. In **paper C** (Vanham *et al.*, 2010) a methodology for the calculation of grid cell spatially distributed water demands – for domestic, municipal, industrial and agricultural (without crop or green water requirements) purposes – for any time step is presented. In **paper G** (Vanham *et al.*, 2009c) a methodology for the calculation of the water demand for snow-making is presented.

C **Vanham, D.,** Millinger, S., Pliessnig, H., Rauch, W. (2009) Rasterised water demands: methodology for their assessment and possible applications. *Submitted to Journal of Hydrology.*

- **Chapter 7 - DSS Maps**: When water availability and water demands are assessed and the water supply system implemented in the (GIS)-data and information system, the water quantity map (Figure 7-7, p.64) is generated. A regional water balance between demand and available water resources is generated for a yearly (Figure 7-9, p.66), seasonal (Figure 7-10, p.67) and monthly (Figure 7-11, p.68) time step. In alpine regions at least seasonal water balance time steps should be addressed. The winter season – a critical period in alpine water resources management due to low water availability and high water demands – is in **paper D** (Vanham *et al.*, 2008a) defined as the period from December to March for the Kitzbühel region. The described methodology can determine the winter season for any mountainous case study area. As first DSS map, a water balance map (Figure 7-12, p.70) is generated with a water balance model. By means of the analysis of the water supply system and its vulnerability and the interaction with Alpine natural hazards, a water supply system vulnerability map (Figure 7-15, p.74) and Alpine natural hazards risk map are generated as second combined DSS-map. The methodology for these latter map(s) is described in **paper E** (Möderl *et al.*, 2008a). These maps can be generated for any time step.

D **Vanham, D.,** Fleischhacker, E., Rauch, W. (2008) Technical Note: Seasonality in alpine water resources management – a regional assessment. Hydrology and Earth System Sciences, 12(1), 91-100.

E Möderl, M., **Vanham, D.,** De Toffol, S., Rauch, W. (2008) Potential impact of natural hazards on water supply systems in Alpine regions. Water Practice and Technology 3/3, doi:10.2166/wpt.2008.060.

- **Chapter 8 - Analysis future scenario's**: In order to provide for DSS tools that support adaptation decisions amongst the different water demand stakeholders to be able to cope with future water management challenges, possible futures for the case study area need to be defined and analysed. Within this chapter the impact of a number of climate change scenarios and a demographic changes scenario is discussed on selected different steps of the workflow. The topic of the effect of these future scenarios on the water resources management in the case study area has been handled in **paper B** (Vanham and Rauch, 2009a), **paper F** (Laghari *et al.*, 2010)**, paper G** (Vanham *et al.*, 2009c) and **paper H** (Vanham *et al.*, 2009b).

F Laghari, A.N., **Vanham, D.,** Rauch, W. (2009) To what extend does climate change result in a shift in alpine hydrology? An example of the Kitzbüheler Ache catchment in the Austrian Alps. *Submitted to Journal of Hydrology.*

G **Vanham, D.,** Fleischhacker, E., Rauch, W. (2009) Impact of snowmaking on alpine water resources management under present and climate change conditions. Water Science and Technology – WST, 59 (9), 1793-1801, doi:10.2166/wst.2009.211.

H **Vanham, D.,** Fleischhacker, E., Rauch, W. (2009) Impact of an extreme dry and hot summer on water supply security in an alpine region. Water Science and Technology – WST, 59 (3), 469-477, doi:10.2166/wst.2009.887.

9.2 DEVELOPED METHODOLOGIES AND APPLICATION TO THE CASE STUDY ARE

The developed workflow functions as a framework for the different methodologies presented in this dissertation, and can therefore be regarded as the main achievement of this work. The description of the different steps within these methodologies provide for a kind of handbook that allows for the application of the workflow in any mountainous catchment in the world. A very useful IWRM management tool is thus created, which can be applied by any qualified or competent institution for a case study area of its choice. However, also the application to the Kitzbühel region and the obtained results provide invaluable information on the sustainability of water resources management in the Alps both currently and in future. These findings not only shed a light on the situation in the Kitzbühel region, but can be transposed to many mountainous regions in the world. Within this subchapter 9.2, a general overview on the methodologies and results for the chapters 5 to 8 is given.

Chapter 5 analyses the water availability in the 4 catchments of the case study area for the reference period (1961-1990) by means of the hydrological model PREVAH and the definition of environmental flows. Different climatological stations were used for the model, in order to represent precipitation and temperature elevation-dependent gradients which are typical for mountainous regions. The model was calibrated with the daily flow time series of the reference period 1961-1990 measured at the 4 gauging stations of the corresponding catchments. A special emphasis in the calibration of the model was put on base flow analysis, as all demand stakeholders – apart from snowmaking – are served with spring or groundwater. An example of the calibration process is given in **paper F** (Laghari *et al.*, 2010) for the catchment of the Kitzbüheler Ache. Resulting water balance components (mm) for the reference period (Table 5-1, p.36) show that one third of total annual precipitation evapotranspirates, whereas two thirds are total runoff. The quantity of these different water balance components is very dependent on elevation (Figure 5-7, p.40). The monthly base flow index (BFI) - the ratio of base flow to total flow – is presented in Table 5-2 (p.44). The table shows the high contribution of base flow to total flow (BFI values of 0.8 and larger) during autumn and winter. During spring BFI values are the lowest due to snowmelt water. The monthly Q_{95} (daily values) is in this study chosen as environmental flow. Q_{95} represents the daily average flow in a specific month that is exceeded 95 % of the time. Q_{80} represents the daily average flow in a specific month that is exceeded 80 % of the time, and is defined as a flow occurring during dry years. Total monthly available water for a normal and dry year is presented in Figure 5-11. Average monthly available water resources are defined as total flow minus Q_{95}. Average monthly dry year available water is represented by the difference between Q_{95} and Q_{80}.

Within **chapter 6** the water demand of the different stakeholders – domestic, municipal, industrial, agricultural, snowmaking - is analysed. There are no significant crop water requirements (rainfed or irrigation) in the Kitzbühel region and no significant water related energy production. **Paper C** (Vanham *et al.*, 2010) presents a methodology for the calculation of grid cell spatially distributed water demands for domestic, municipal, industrial and agricultural (blue water requirements for persons employed and livestock units) purposes. To obtain such a grid, the number of units of the detailed population and housing census raster – originating from the population and housing census of 2001 - are multiplied with a rate of water use (litre per unit per time interval) for the different stakeholders. These water use rates are obtained from literature - and calibrated with operating data from the water supply undertakings in the study area. Apart from detailed spatially distributed information, this methodology can also be used for different time steps (yearly, seasonal, monthly, weekly, daily, hourly). The rasters are independent of political entities like countries or municipalities. They provide the possibility to re-aggregate water demands on political entity levels to the river basin scale. Within the workflow they are essential for the generation of both the water balance and the water supply system vulnerability map. For the latter they are necessary for the transposition of cell water demand values to respective pipe sections of the water distribution network. Within the paper rasterised yearly and winter water demands were calculated, with winter defined as the period from December to March as described in **paper D** (Vanham *et al.*, 2008a). The total average winter water demand is 251 l per s. The total average annual water demand is 219 l per s. Including water losses of 10 % this comes to 276 l per s in winter and 241 l per s annually. Domestic water demand accounts for approximately 40 % of total water demand, municipal and industrial water demand 50 % and agriculture 10 %.

In **paper G** (Vanham *et al.*, 2009c) a methodology for the calculation of the water demand for technical snowmaking is presented. Currently 882 ha of a total ski slope area of 2117 ha in the case study area have technical snowmaking capacity. The two largest ski regions are the *Skiwelt Brixental – Wilder Kaiser* and the *Skigebiet Kitzbühel*. Figure 6-7 (p.55) displays the cumulative elevation range for all ski slopes within the case study area, with a minimum of about 600 m a.s.l. and a maximum of about 2000 m a.s.l. This is rather low for the European Alps. About 50 % of the ski slopes are located at an elevation lower than 1300 m a.s.l. The water demand for snowmaking is calculated based upon the area of ski slopes, according to a methodology described by (Pröbstl, 2006). For the installed 882 ha, a base snowmaking demand for 30 cm at the beginning of the winter season of 1.06 million m^3, and an improvement snowmaking demand (120 % of base snowmaking) of 1.27 million m^3 were calculated. The sum is 2.33 m^3. The total reservoir volume within the case study area (0.9 million m^3), divided over about 20 reservoirs, is capable of storing almost the whole base snowmaking volume. A maximum water demand for the total ski slope area of 2117 ha – as calculated in **paper G** – is 5.55 million m^3.

Chapter 7 presents the methodology to obtain the two DSS maps: 1) a water balance map and 2) a water supply system 2a) vulnerability map and 2b) Alpine natural hazards risk map. As discussed before, in alpine regions at least seasonal water balance time steps should be addressed. **Paper D** (Vanham *et al.*, 2008a) presents a GIS-based multi criteria method to determine the winter season. A snow cover duration dataset serves as basis for this analysis. The winter season – a critical period in alpine water resources management due to low water availability and high water demands – is defined as the period from December to March for the case study area Kitzbühel region.

First a regional water balance between water demand and available water resources is analysed. By means of a water balance model, a water balance map is then generated. The regional water balance is analysed for a yearly, seasonal and monthly time step. Figure 7-9 (p.66) shows that for an average hydrological year (normal year) no regional deficits occur for an annual time step. Environmental flows are maintained and water demands are met. For none of the four seasons water deficits occur on a regional level (Figure 7-10, p.67). A monthly regional water balance (Figure 7-11, p.68) for a normal and dry hydrological year shows no deficits for all months but December under dry conditions. This is due to the large amount of water required for base snowmaking. For the stakeholder technical snowmaking all ski slopes are considered (2,117 ha) and it is assumed that base snowmaking occurs within 5 days during December. This stresses the necessity of reservoir storage of water for base snowmaking on a regional level. The analysis – described in detail in **paper G** (Vanham *et al.*, 2009c) - also shows that enough water is available in other months on a regional level to fill these reservoirs.

A regional water balance can be temporarily differentiated, but is not spatially differentiated. In order to assess spatial (or local) deficits/surpluses due to the interaction of natural and man-induced intra- and inter-catchment water flows, the water balance map is generated by means of the water resources management software tool MAGRET. For each node within the model deficits and surpluses can be identified for a specific time step. For the Kitzbühel region a time step of 3 days was chosen, to include the critical period of base snowmaking during a period of 3 days. As for the regional water balance, both a hydrological normal year and dry year are considered. For the water supply service zones only surpluses were generated in the water balance for this specific period. In certain nodes deficits for technical snowmaking were modelled. Deficits can occur on a local level. As next step a meeting with mountain railway companies should be organised in order to discuss this matter, include real service data and possibly update the map. This map is an important DSS tool for such a meeting.

The second DSS-map is the water supply system vulnerability map, which combined with Alpine natural hazards, gives a risk map. The methodology is described in **paper E** (Möderl *et al.*, 2008a). In the European Alps, drinking water supply systems are characterised by a local, small structured infrastructure. Water supply is generally organised on a municipality basis. The 19 municipalities of the Kitzbühel region are served by 24 major water supply undertakings. About 10 % of the population are not connected to these 24 water supply undertakings. Typically for the Alps, springs are the first source for public drinking water (average 80%), followed by ground water (average 20%). Connection pipes between different service areas are very rare. For the water vulnerability and risk map, not the whole case study area was taken into account. It was focused on the valley of the five municipalities from Jochberg to Sankt

Johann. A management support tool (VulNetWS – Vulnerability of Water Supply Networks) was developed which quantifies vulnerability based on hydraulic and quality simulations assuming component failure of each single water supply system (WSS) component. The approach serves for the definition of zones with low, medium and high potential vulnerability. Hazards of flooding, landslide, debris flow and avalanches are calculated and categorized in potential low, medium and high hazard zones. By combining the vulnerability and hazard maps, zones with low, medium and high potential risk are identified (risk map). The combination of vulnerability and hazard is summarized using a risk matrix that highlights a zone of 0.42 km^2 within the study area as being potentially risky. Using the presented methodology, the vulnerabilities of a water supply system can be identified and (if necessary) eliminated by technical measures, resulting in a higher supply security. Furthermore potential hazard zones can be located to construct protection measures at the proper sites.

After analysing and implementing the different steps of the workflow for the present situation, a resulting water balance map and water supply system vulnerability (and risk) map for a certain time step are achieved. Different time steps (e.g. seasons or months) can result in different deficit/surplus identifications in the water balance map and/or different vulnerability and risk identifications in the respective water supply system vulnerability (and risk) maps.

Within **chapter 8** case study dependent future scenarios are identified and defined. The developed workflow needs to be analysed for these future scenarios, in order to provide for DSS tools to make adaptation decisions amongst the different water demand stakeholders to be able to cope with future water management challenges. Within this chapter the impact of future scenarios (climate change and demographic changes) is discussed on different steps of the workflow: the analysis of 1) hydrology and water availability (chapter 5), 2) water demand (chapter 6) and 3) the regional water balance (chapter 7). For the whole study area the impact of two climate change scenarios (for the time frames 2050 and 2071-2100) is investigated. Additionally the impact of the extreme hot and dry summer of 2003 was chosen. For the catchment Kitzbüheler Ache, one of the four catchments of the Kitzbühel region, the impact of 13 regional climate projections of the EU PRUDENCE project is investigated. The latter is discussed in detail in **paper F** (Laghari *et al.*, 2010).

The effect of these future scenarios on the water resources management in the case study area has been handled in **paper B** (Vanham and Rauch, 2009a), **paper F** (Laghari *et al.*, 2010)**, paper G** (Vanham *et al.*, 2009c) and **paper H** (Vanham *et al.*, 2009b). **Paper F** focuses on the quantification of uncertainty of future climate change projections. **Paper G** focuses on the impact of snowmaking as a water demand stakeholder on a regional water balance, for the reference period and a 2°c temperature increase (scenario for 2050). **Paper H** focuses on the impact of both the extreme hot and dry summer of 2003 and the PRUDENCE CHRM climate change scenario summer for 2071–2100 on the monthly water balance within the case study area.

The climate change scenarios have a substantial impact on the hydrology and water availability within the case study area. A shift from a rainfall-snowmelt dominated flow regime to a rainfall dominated flow regime is observed for the case study area. A future decrease in snow accumulation and a shortening in snow cover duration is simulated by the model, an effect that increases with lower altitudes and differs between the winter months. The shortening of the snow season concerns more the end (spring) rather than the beginning (autumn). Due to the shortening of the winter season, a change in seasonality of river flows and available water resources (ground and surface water) occurs. There will be an increase in winter flow, and a decrease in spring, summer and autumn flow. The typical low flow period during winter shifts to a low flow period during late summer and autumn.

In order to calculate available water for future scenarios, this change in flow seasonality is taken as existing situation in future. This means that the environmental flows (Q_{95}) are calculated based upon this new flow regime.

The future scenarios also lead to an increase in water demands within the case study area. For 2031 a population increase of 10 % for the case study is predicted due to demographic changes. Further detailed projections are not available, so this scenario is taken as representative for 2050 and the end of the 21st century (time range of the climate change scenarios). These changes lead to a future annual average domestic, municipal, industrial and agricultural water demand of 244 l per s (from 219) and winter water demand of 276 l per s (from 259) without water losses. For water losses an additional 10 % can be assumed. Whether water demands for technical snowmaking will increase in future due to climate change is generally a matter of the elevation location of the ski slopes. As the ski slopes in the Kitzbühel region are located rather low for the Alps, the water demand for improvement snowmaking on the total ski slope are (2,117 ha) increases from 3.05 million m^3 to 6.53 million m^3. A detailed analysis is presented in **paper G** (Vanham *et al.*, 2009c).

For the regional water balance, the increased domestic, municipal, industrial and agricultural water demand (due to demographic changes) and increased water demand for technical snowmaking are balanced with the changed water availability for a monthly time step. For 2050 – as for the existing situation – a deficit in the water balance during the month of December for a dry year is identified due to base snowmaking (Figure 8-16, p.90). Especially during January to March the total water demand increases substantially due to an increase in improvement snowmaking. However, on a regional level no other deficits are identified. Again the necessity for reservoirs for snowmaking is stressed and also quantified. Another critical period for the water balance was identified as being a dry (and hot) summer. The average monthly water balance of the summer months for the reference period shows that the water demand for all stakeholders can be easily met on a regional basis. The regional water balance for the summer of 2003 shows a deficit for the month of August as the Q_{95} flow for the reference period equals the August flow in 2003 (Figure 8-17, p.91). Theoretically - by defining the environmental flow as Q_{95} - no water is available. However, the regional water demand represents only 1.5% of this Q_{95} value, an amount largely acceptable on a regional scale. During the other summer months June and July of 2003, regional water availability was sufficient to meet water demands. Available groundwater in the CHRM climate change scenario proves to be sufficient to meet all the water demand stakeholders.

Although the regional water balance does not result in serious stress situations for future summer conditions, local deficits can occur. As an example, average monthly ground water recharge reductions up to 70 % for August in the catchment of the Kitzbüheler Ache in both summer scenarios were simulated with PREVAH. This can have a large impact on the water supply security of the different municipalities, as many have no groundwater wells and interconnection pipes between different systems are rare. With an increasing population for 2030, higher summer demands (due to garden watering …) and the absence of connection pipes between the different municipalities, local deficits can occur. A local analysis should be made. The distributed model PREVAH provides this possibility. During the project duration of this dissertation, the different municipalities from Sankt Johann to Jochberg were already discussing and planning a possible implementation of an emergency connection pipe – based on the every day experience of their water supply undertakings.

9.3 OUTLOOK

It can be said that water resources management in the Kitzbühel region is generally sustainable, both at present and in future. Due to climate change and demographic changes there will be a change in spatial and temporal water availability and an increase in water demands. However, when managed properly – e.g. by using reservoirs for technical snowmaking and emergency connection pipes between different water service undertakings – neither regional nor local water deficits will occur. Environmental flows in the rivers and streams of the project area are maintained. For the water supply distribution system some risky areas with respect to alpine natural hazards were identified. These locations should be analysed in detail and when necessary protection measures constructed.

However, many mountainous regions of the world already today face large problems like quantitative or qualitative water stress in their water management sector. In the 21st century different mountainous catchments and river basins are facing additional future challenges. Water shortages are attributed to issues such as population growth, rapid urbanisation and industrialisation, environmental degradation, inefficient water use and poverty (economic water shortage). These problems are especially experienced by many developing and transition countries, and are aggravated by climate change – with its impacts on demand, supply and water quality. Also the importance of mountainous catchments for the low-lying lands has to be taken into account. Water resources management practices in the mountainous part of a river basin will affect the lowlands, which are often characterised by high water demands due to larger population densities or extensive irrigation areas. Paper A gives a general overview on the importance of mountain water and the effects of climate change on the hydrology and water management in the mountain ranges of the world and their dependent lowlands. Paper B displays the importance of the European Alps – where the case study area is located – for the Danube river basin.

The developed workflow with its specific methodologies presents a valuable management tool which is applicable for any mountainous catchment. These methodologies and results can be applied by any competent institution. The sustainability of alpine or mountainous water resources management can be tested for any required time step. In order to make rational and informed choices between alternative actions at the basin level, it is important for decision makers to have the right tools (management instruments) to evaluate and predict current and future water availability and demand, and resulting deficits and surpluses. It also has to be stressed that planning is a continuing sequential process. Water resources plans need to be periodically updated and adapted to new information and new objectives. A final solution to a water resources planning problem rarely exists: plans and projects are dynamic. They evolve over time as facilities are added and modified to adapt to changes in management objectives and in the demands placed on the facilities. The developed methodologies and resulting findings can contribute significantly to the Danube river basin management plan

(RBMP). The International Commission for the Protection of the Danube River or ICPDR (www.icpdr.org) aims at developing, implementing and (future) updating a river basin management plan. The methodologies and results of this dissertation have also the potential to contribute to more regional or local RBMP within the Danube RBMP. The resulting DSS maps of the dissertation can be used as management tool for stakeholder involvement. Only by doing this, RBMP are likely to work. Water resources management should involve sufficient public participation so that a) valuable local information and technical inputs are identified and utilized, b) the interests of all affected groups are identified and taken into account, and c) local water users feel a part of the river basin plan and accept their responsibilities for operation and maintenance.

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A CURRICULUM VITAE

Personal information

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Nationality	Belgium (EU National)
Family status	Spouse Silvia Exenberger-Vanham (Austrian citizenship) 1 Son Raphael (4 years old)
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Education

2005-2009	**Phd** at the Institute of Infrastructure, Working Unit Environmental Engineering, University of Innsbruck, Austria (www.uibk.ac.at/umwelttechnik)
2000-2003	**Master in Water Resources Engineering** at the VUB (University Brussels), Belgium. IUP-WARE - **I**nter**U**niversitary **P**rogramme in **WA**ter **R**esources **E**ngineering (www.iupware.be) Masters thesis (2002-2003): Water balance of the Cutuchi river basin (Ecuador), for 2 scenarios of land development
1994-1997	Master **Engineer in environmental and applied agricultural sciences**, KUL - Katholieke Universiteit Leuven (Catholic University of Leuven), Belgium. (www.agr.kuleuven.ac.be/English/index.htm) Masters thesis (1996-1997): Influence of soil tillage and nitrogen fertilisation on the development and yield of „lentekoring“ (wheat) in the Swartland, South Africa. Research conducted at the Department of Agronomy, University of Stellenbosch.
1992-1994	Bachelor **Engineer in environmental sciences** at the University of Antwerp, Belgium (www.ua.ac.be)

Work experience

2005-current	**Project staff** in the water resources management group of the Institute of Infrastructure, Working Unit Environmental Engineering, **University of Innsbruck**, Austria (www.uibk.ac.at/umwelttechnik).
1999-2004	**Project engineer and GIS expert** within the river basin management working group **at IMDC**, Antwerp, Belgium (www.imdc.be). Manager of different projects. Work experience in different countries. Author and co-author of a wide range of project reports.
1998-1999	**Freelance GIS expert** at **Klenkhart and Partner Consulting**, engineering office, Innsbruck, Austria (www.klenkhart.at)
1997-1998	**Researcher** at **Department agronomy and pastures, University of Stellenbosch,** South Africa (http://www.sun.ac.za/agron/)

Research interests

- IWRM - Integrated Water Resources Management (water resources, water availability, water demand, water balance, water infrastructure, water security, water scarcity, water ecology)

- hydrology, mountain hydrology, snow hydrology, hydrology of the tropics and semi-tropics, hydrology of semi-arid and arid regions
- hydrological modelling, predictive modelling of water resources, water allocation models
- extreme events (drought, floods)
- water for food, virtual water, irrigation, green water
- climate change
- applied GIS, regionalization

Regional focus

- ***Europe***, with residency and work experience in Belgium and Austria
- ***South and South-East Asia***, with residency and work experience in India (Oct. 2008 – Aug. 2010)
- ***Southern and Eastern Africa***, with residency and work experience in South Africa (Sept.1996 – Dec. 1996 and Aug. 1997 – Mai 1998)
- ***South America***, with residency and work experience in Ecuador (Sept. 2001 – Oct. 2001)

Languages	Read	Write	Speak
Dutch, mother tongue	excellent	excellent	excellent
English	excellent	excellent	excellent
German	excellent	excellent	excellent
French	excellent	good	good
Afrikaans	excellent	good	good
Spanish	basic	basic	basic

Specialised computer skills

GIS	Different GIS-Software such as ArcGIS (and former ArcView), IDRISI
MIKE-BASIN	DHI Software for river basin management
ISIS	Wallingford software for hydrodynamic river modeling
PREVAH	Research software developed at the ETH Zurich, Switzerland, for the assessment of a catchment hydrological water balance (hydrological model)
PDM	Wallingford software, conceptual hydrological model

Graphical programs: Photoshop, CorelDraw

Member of

EGU	European Geosciences Union (www.egu.eu)
IWA	International Water Association (www.iwahq.org)

IWA specialist group on climate change

Editorial Board

Journal of Water and Climate, ISSN 2040-2244

Reviewer for

Water Research, ISSN 0043-1354
Water Science and Technology, ISSN 0273-1223

Other interests

- Professional photographer (winner different photo contests, publication popular articles with photographs, publication photo documentary book about transhumance in the European Alps)
- Research communication, popularisation of research to the general public – e.g. through articles in popular magazines with strong focus on graphical content

B PAPERS

A **Vanham, D.,** Rauch, W. (2009) Mountain water and climate change. In: Climate Change and Water - International Perspectives on Mitigation and Adaptation. Joel Smith, Carol Howe and Jim Henderson (Ed.), page 21-40, ISBN 9781843393047.

B **Vanham, D.,** Rauch, W. (2009) Retreating snowpacks under climate change: Implications for water resources management in the Austrian Alps, in: Improving Integrated Surface and Groundwater Resources Management in a Vulnerable and Changing World, Proceedings of JS.3 at the Joint IAHS & IAH Convention, Hyderabad, India, 6-12 September 2009, IAHS Publ. 330, 231-238.

C **Vanham, D.,** Millinger, S., Pliessnig, H., Rauch, W. (2009) Rasterised water demands: methodology for their assessment and possible applications. *Submitted to Water Resources Management.*

D **Vanham, D.,** Fleischhacker, E., Rauch, W. (2008) Technical Note: Seasonality in alpine water resources management – a regional assessment. Hydrology and Earth System Sciences, 12(1), 91-100.

E Möderl, M., **Vanham, D.,** De Toffol, S., Rauch, W. (2008) Potential impact of natural hazards on water supply systems in Alpine regions. Water Practice and Technology 3/3, doi:10.2166/wpt.2008.060.

F Laghari, A.N., **Vanham, D.,** Rauch, W. (2009) To what extend does climate change result in a shift in alpine hydrology? A case study in the Austrian Alps. *Submitted to Hydrological Sciences Journal.*

G **Vanham, D.,** Fleischhacker, E., Rauch, W. (2009) Impact of snowmaking on alpine water resources management under present and climate change conditions. Water Science and Technology – WST, 59 (9), 1793-1801, doi:10.2166/wst.2009.211.

H **Vanham, D.,** Fleischhacker, E., Rauch, W. (2009) Impact of an extreme dry and hot summer on water supply security in an alpine region. Water Science and Technology – WST, 59 (3), 469-477, doi:10.2166/wst.2009.887.