Energie & Umwelt /
Energy & Environment
Band / Volume 339
ISBN 978-3-95806-177-4

Energie & Umwelt
Energy & Environment
339

M. Andjelov, Z. Mikulič, B. Tetzlaff, J. Uhan & F. Wendland
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Member of the Helmholtz Association

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Schriften des Forschungszentrums Jülich
Reihe Energie & Umwelt / Energy & Environment Band / Volume 339

Forschungszentrum Jülich GmbH
Institute of Bio- and Geosciences
Agrosphere (IBG-3)

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ISSN 1866-1793 ISBN 978-3-95806-177-4

Bibliographic information published by the Deutsche Nationalbibliothek.
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Publisher and Distributor:	Forschungszentrum Jülich GmbH Zentralbibliothek 52425 Jülich Tel: +49 2461 61-5368 Fax: +49 2461 61-6103 Email: zb-publikation@fz-juelich.de www.fz-juelich.de/zb
Cover Design:	Grafische Medien, Forschungszentrum Jülich GmbH
Printer:	Grafische Medien, Forschungszentrum Jülich GmbH

Schriften des Forschungszentrums Jülich
Reihe Energie & Umwelt / Energy & Environment, Band / Volume 339

ISSN 1866-1793
ISBN 978-3-95806-177-4

The complete volume is freely available on the Internet on the Jülicher Open Access Server (JuSER) at www.fz-juelich.de/zb/openaccess.

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Foreword

Groundwater is a resource of utmost strategic importance for Slovenia and Germany providing drinking water of good quality to its population. For decades, management of this key resource has received the highest priority of our national hydrological services. In the framework of the service activities in both countries, groundwater status in terms of quantity and quality has been observed and studied systematically for more than 50 years. In the eighties of the last century the first models for groundwater recharge assessment at local and regional scale were developed. However, long time assessment of groundwater status and estimation of groundwater recharge for heterogeneous hydrogeology systems of entire countries were not available. In this respect the GROWA model, developed at the Agrosphere Institute of Research Centre Jülich, was one of the first groundwater recharge models that was applicable at the level of river basins and Federal States in Germany. The transfer and application of the GROWA model to groundwater systems of the Republic of Slovenia was a pioneering effort, establishing for the first time a groundwater recharge model covering the whole territory of Slovenia and not focusing on individual aquifers only, being the practice in Slovenia before.

The GROWA-Slovenia project is an outstanding example of an excellent cooperation among EU member States. The potential of the GROWA model for Slovenia was first identified during a TAIEX (Technical Assistance and Information Exchange instrument) seminar on groundwater modelling in Ljubljana, which was organised by the Directorate-General Enlargement of the European Commission and the Hydrogeological Analysis Division of Slovenian Environment Agency. As a follow-up to this seminar, a bilateral research cooperation project between Slovenian Environment Agency and Agrosphere Institute of Research Centre Jülich to determine groundwater recharge in Slovenia was established.

It is a special privilege and honour in our capacity as director general of Slovenian Environment Agency and director of Agrosphere Institute of Research Centre Jülich to introduce the results of this research cooperation. As documented in this monograph, the results of GROWA-Slovenia have supported both, the strategic groundwater planning at Slovenian Environment Agency with regard to the implementation of the EU Water Framework Directive and the implementation of the national water legislation in Slovenia. At the level of the different operational activities and tasks of the various branches of Slovenian Environment Agency the GROWA model results have been used for the regional water resources assessment, e.g. by establishing annual groundwater balances for entire regions or as a reference for the day-by-day groundwater resources management.

We believe that the cooperation between Slovenian Environment Agency and the Agrosphere Institute of Research Centre Jülich, is a very good example of joint bilateral actions in meeting common future challenges in the field of water resources management. Having this in mind, we do look forward with confidence to the results of the cooperation with regard to reactive nitrate modelling in soil and groundwater. For this purpose the DENUZ / WEKU model system developed at the Agrosphere Institute for assessing reactive nitrate transport in soil and groundwater has already been transferred and applied for the entire Republic of Slovenia.

Just recently, a cooperation project has started aiming at the transfer and application of the mGROWA model system to Slovenia. mGROWA is a further development of the GROWA model for assessing water balance components in daily time steps. In this project, both partners will jointly develop a snow module to be included in the mGROWA model. The subsequent implementation of this new mGROWA-SI model developed at the Slovenian Environment Agency is a big new milestone of strategic importance as the upgraded mGROWA will promote the development of the Slovenian hydrological service, e.g. by enabling improved products like a near real time hydrological water balance assessments.

Joško Knez
Director General
Slovenian Environment Agency

Prof. Dr. Harry Vereecken
Director of Agrosphere Institute at
Research Centre Jülich

Executive summary

The overall goal of the project was to analyse groundwater recharge in Slovenia based on the water balance model GROWA, which was developed for the management of water resources and nutrients in German river basins and / or Federal States. The goal was to analyse the possibilities of the transfer and applicability of the model system to river basins in Slovenia, respectively to the Alpine, Dinaric, Mediterranean and Pannonian conditions.

For this purpose Slovenian-German cooperation between the Slovenian Environment Agency (ARSO) and Research Centre Jülich, Agrosphere Institute (IBG-3) was initiated. Focus of the first project period was the compilation of a Slovenia wide data base for the GROWA model. This was followed by an area-covering implementation of GROWA in Slovenia and the validation of the GROWA model results. More recently, GROWA model has been used to support water resources management issues on national scale. Regular stays of Slovenian guest scientists in the Agrosphere Institute during the whole time of the project, was an indispensable basis for reaching the goals of the Slovenian-German cooperation.

GROWA input data on climate, hydrology, soil, hydrogeology, topography and land use were collected in different Slovenian institutions. A lot of effort had to be given to this initial step of the project. The majority of these data sets have been available for the whole of Slovenia in digital format. As GROWA is a GIS-based model, input data were prepared for processing in GIS platform prior to their use in the model simulations. Finally, area covering databases were created for the whole Slovenian territory (Chapter 3). In this way comprehensive, thematically consistent and geographically uniform databases have been developed. Independent of the GROWA project these data bases could be used for further investigations in Slovenia.

The most important runoff components considered in GROWA model, i.e. total runoff, direct runoff and groundwater runoff (groundwater recharge), were modelled as long-term annual averages for 100 m x 100 m grid cells for the hydrologic reference period 1971 – 2000 as a function of climate, soil, geology, topography and land use conditions. The mean long-term annual total runoff is the difference between mean annual precipitation and real evapotranspiration. Taking the spatial distributed total runoff values for the grid cells as starting points, direct runoff values and groundwater runoff values are separated using base flow indices, (BFIs). BFIs determine the ratio of groundwater recharge to total runoff. In case BFI values are high, groundwater runoff is prevailing. Otherwise, the predominating runoff component is direct runoff.

Results of water balance calculations for the hydrological period 1971 – 2000 (Chapter 4) have shown that runoff displays considerable differences between the Slovenian macro regions. In general, Slovenia is characterized by different physical-geography conditions and heterogeneity with regard to water resources. The median of the calculated total runoff is about 720 mm/a, but a considerable variation within the country occurs. While the central parts of Slovenia show total runoff values between 400 and 1200 mm/a, total runoff in the Pannonian basin lies in the range of 200 – 400 mm/a only. Values highly above average are modelled for the alpine regions in the northern and especially north-western parts of Slovenia, the peaks there even exceed 2500 mm/a. The regional differentiation is strongly determined by the precipitation patterns, showing a significant decrease from the Alps-Dinaric mountain range barrier to the north-east with the minimum in Pannonian basin.

Runoff separation has shown that groundwater runoff (groundwater recharge) is the dominating runoff component in parts of the Alpine-Dinaric area with karst hydrogeology (BFI >0.5) and most of all in the areas of alluvial plains with intergranular porosity having BFIs >0.8. To the contrary, in the Eastern Alps, where metamorphic and igneous rocks prevail, direct runoff is dominant, displaying BFI values <0.2. This situation is due to the low water storage capacity of the geological formations which cause high interflow portions.

While total runoff is predominantly influenced by regional precipitation patterns, groundwater recharge is influenced additionally by hydrogeologic site conditions. The median value of groundwater recharge in Slovenia is about 250 mm/a. The territory of Slovenia can roughly be delineated in three regions of prevailing groundwater recharge rates: high groundwater recharge occurs along the Alps-Dinaric mountain range whereas lower groundwater recharge rates occur in the Mediterranean region to the south-west and the Pannonian region to the north-east. In the Alps-Dinaric mountain range with high precipitation rates and high BFIs in the karstified carbonate rocks the groundwater recharge is above 500 mm/a with peaks above 700 mm/a. In the Mediterranean region groundwater recharge rates display a wide range between 50 mm/a and 400 mm/a, comprising low values at the sites where flysch occurs and high values at sites where karstified carbonate rocks occur. In the north-eastern half of the country groundwater recharge is generally in the range of 50 mm/a to 300 mm/a with recharge below 50 mm/a in the most north-eastern part of Slovenia in the Pannonian basin. All alluvial plains display high BFIs (>0.8), which is considerably higher than the BFIs of the hard rock areas. Consequently, groundwater recharge rates in the alluvial plains are significantly higher than the groundwater recharge rates of the adjacent hard rock areas.

A lot of effort has been put in validating and verifying the model results (Chapter 5). For this purpose pool of data from 95 gauging stations was available for a comparison of modelled values against gauged runoff values. The mean deviation between gauged and modelled total runoff was about 15%, for the groundwater recharge this was in the range of 21%. Both comparisons can be regarded as a satisfying agreement of the GROWA modelled results with the observed values from gauging stations. By this, the transferability of the GROWA model principle to Slovenian site conditions has been proved.

The validation process revealed that the modelled as well as the gauged groundwater recharge rates in karst areas are in the range of 50 – 60% of total runoff only, although it is well known that all percolation water having passed the root zone enters the karst aquifer systems. This apparent contradiction reflects the different definitions of water quantity of underground karst systems in hydrological and hydrogeological sense. While in the hydrogelogical sense all the water in the underground rock mass is regarded as groundwater, in the hydrological sense the same quantity of water is further separated into fast and slow runoff components. Accordingly, in the hydrologic definition only the slow runoff component is considered as groundwater recharge.

The area differentiated mean long-term total runoff, direct runoff and groundwater recharge values determined with the GROWA model are an indispensable basis for the actual water resources management in Slovenia. So far the results have already been used:

- for the preparation of a Slovenian River Basin Management Plan,
- for the assessment of available groundwater and the licensing of water withdrawal rights to groundwater users,
- in the framework of the required annual reviews of the groundwater quantitative status according to EU Water Framework Directive,
- for yearly reporting of Slovenian water balance to European Environment Agency and other international institutions,
- as a basis for the impact assessment of climate change,
- as a tool used in groundwater pollution vulnerability,
- for assessing diffuse nutrient inputs into groundwater and surface waters according to runoff components.

More detailed examples for this kind of evaluations can be found in chapters 6 and 7.

1 Introduction

1.1 Background

With regard to the essential aims of the EU Water Framework Directive (Directive 2000/60/EC, 2000), which requires the long-term protection of water resources and the enhancement of the quantitative status of water resources, the promotion of sustainable water management strategies is of great importance. A fundamental problem with the implementation of the EU Water Framework Directive (WFD) is the applicability of the sustainability principle by using suitable measures against the background of ecological and economical boundary conditions. In the framework of this policy implementation, the pillars of sustainable water management, i.e. a reliable water balance and data on degree of use of available water are needed for the assessment of quantitative status of water resources. A “good quantitative status of groundwater” is achieved once the mean long-term groundwater abstraction is lower or equal to the available groundwater resources. The special professional challenge in the process of sustainable water management is the assessment of available groundwater resources, which is according to the definition in the WFD derived from “the long-term annual average rate of overall recharge of groundwater”. Hence, information about mean long-term groundwater recharge can be regarded as the most important parameter for assessing quantitative status of groundwater.

Under the WFD and Slovenian Water Act (Official Gazette of the Republic of Slovenia 67/02, 2002***),*** a total of 21 groundwater bodies have been delineated in Slovenia (Official Gazette of Republic of Slovenia 65/03, 2003; Official Gazette of Republic of Slovenia 63/05, 2005). According to WFD a groundwater body is defined as a distinct volume of groundwater within an aquifer or system of aquifers, which is hydraulically isolated from nearby groundwater bodies. In practise, groundwater bodies are the groundwater management units used for reporting groundwater status to the EU and implementing programmes of measures related to groundwater.

Only ten years ago hydrogeologists have faced professional challenges to assess for the first time renewable and available groundwater resources for the newly defined groundwater bodies. At that time total runoff was determined (Kolbezen & Pristov, 1998; Frantar ed., 2008), but not separated in order to determine the groundwater runoff component. The first attempt to assess the quantitative status of groundwater water bodies was based on the analysis of river baseflows and critical levels of groundwater using data from the Slovenian Environment Agency’s (ARSO) national hydrologic monitoring network of surface waters and groundwaters (Andjelov et al., 2006). These results of the assessed available groundwater resources of Slovenia for the period 1990 – 2001 were in good compliance to previous hydrogeological studies of assessing so called “dynamic groundwater reserves” (Drobne et al., 1976; Kranjc Kušlan, 1995). However, this first assessment was not able to address the high spatial variability of hydrogeological conditions within the groundwater bodies and the spatial variability of groundwater recharge quantities respectively.

Accordingly, area differentiated information about groundwater recharge rates within the 21 groundwater bodies was not available, although this information is essential for the sustainable groundwater planning and management.

Aware of this lack of information the general idea for a German-Slovenian cooperation project was generated in the framework of a Seminar on groundwater modelling – Water Framework Directive in January 2008, which was organised by the Slovenian Environment Agency (ARSO) and the Technical Assistance Information Exchange Instrument (TAIEX) of European Commission – DG Enlargement (Mikulič & Andjelov eds., 2009).

The overall goal of the cooperation between the Slovenian Environment Agency (ARSO) and Research Centre Jülich (FZJ), Agrosphere Institute (IBG-3) was to assess groundwater recharge in Slovenia on a country-wide level as a support for the nationwide groundwater management. In contrast to the implementation of several local or regional models, it was the general idea to apply an area differentiated water balance model which covers the whole territory of Slovenia.

There was a common understanding between ARSO and FZJ that assessment of groundwater recharge rates should be performed based on the water balance model GROWA, which was developed and used for the management of water resources and nutrients in German river basins and / or Federal States (Kunkel & Wendland, 2002, 2006; Bogena et al., 2003; Tetzlaff et al., 2004; Kunkel et al., 2006; Wendland et al., 2008). Thus, the determination of the most important water balance components: total runoff, direct runoff and especially groundwater recharge are quantified in a consistent and comparable way, taking into account all the relevant information about climate, soil, geology, etc. which is available in digital form on a national level.

1.2 Project goals

The overall goal of the cooperation project between the Slovenian Environment Agency (ARSO) and Research Centre Jülich (FZJ), Agrosphere Institute (IBG-3) was to quantify groundwater recharge for the whole territory of Slovenia using GROWA model. To reach this goal a lot of effort had to be given to the set-up of a comprehensive, thematically consistent and geographically uniform databases of the GROWA model including area-differentiated data on climate, hydrology, soil, hydrogeology, topography and land use.

The cooperation project was carried out in five consecutive steps and comprised the following tasks:

1. to set-up a uniform and consistent nationwide GIS input data base consisting of climate, soil, geology, topography, land use data etc.
2. to carry out a nationwide water balance study with the aim to quantify the renewable water resources – the total runoff

3. to separate total runoff into the runoff components: direct runoff and groundwater recharge
4. to calibrate the model and validate the model results by using national data base of measured runoff from gauging stations
5. to assess options for a further model development.

1.3 Area of investigation: Republic of Slovenia

Area of Slovenia is 20,273 km^2, with a total population about 2 Millions. It is located at the meeting point of four major European geographical regions: the Alps, the Dinaric Mountains, the Pannonian Basin and the Mediterranean – Adriatic Sea, see Figure 1-1 (Gams et al., 1995; Perko, 1998). Whereas only 2.7% of Slovenian territory comprises settlement areas, ca. one third of the country is used for agriculture, mainly in the north-east. More than 58% of the country however is covered with forests (CLC, 2000) and in some areas with woodland scrub. Consequently, Slovenia is one of the most forested countries in Europe, after Finland and Sweden.

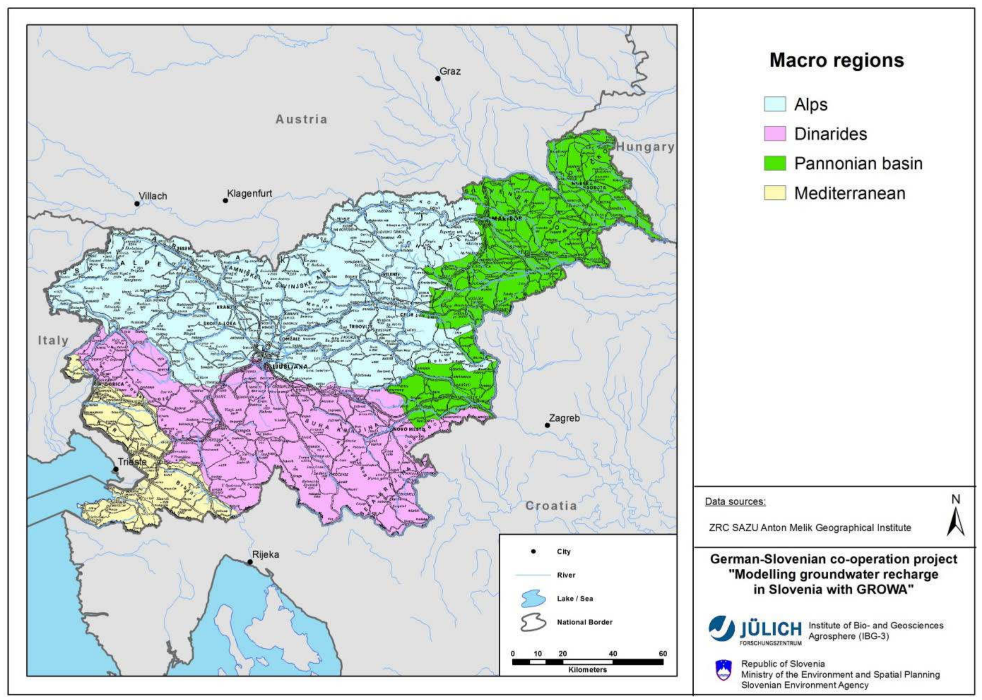

Figure 1-1: Main macro regions in Slovenia (Gams et al., 1995; Perko, 1998).

Slovenia's climate is diverse: a temperate continental climate in the central and eastern region, an alpine climate to the north-west and a sub-Mediterranean climate in littoral region in the south-west. This leads to major differences in the amount of precipitation received across the country. The highest level is in the Dinaric-Alpine zone, with more than 2,600 mm annual precipitation at mountain barrier of the upper

Posočje and Mount Snežnik area. Mean annual temperatures in the majority of the country are in the range 8° to 10°C.

Slovenian macro-regions, as defined according to climatological, geographical, geological and landscape – ecological characteristics are presented on Figure 1-1. The **Alps** occupy the northern part of Slovenia. They consist of several physiographic and geologic parts: the Julian Alps, Karavanke, Savinja Alps and Pohorje. The Julian and Savinja Alps are built predominantly of carbonate rocks with karst phenomena that strongly influence relief, erosion, vegetation and hydrology. The Karavanke and Pohorje on the contrary are mostly built of metamorphic and volcanic rocks, which produce rich soils with very dense vegetation cover. The Fore-Alps occupy the central part of Slovenia. They are divided by the Kranj-Ljubljana valley into eastern and western part. Geologically these terrains belong to the so called Inner Dinarides, in which clastic sediments like shale, marl and sandstone predominate. Mixed forests and grasslands with a lot of cultivated land are abundant in this area. The exception is the area south of the Idrija fault i.e. Banjščice, Trnovski gozd and Nanos, which is built mostly of carbonate rocks. Therefore, there we have a typical karst relief with karstic hydrological regime.

Geographically, *sensu stricto* the **Dinarides** occupy the Southern part of Slovenia. Geologically, the area belongs to the so called Outer Dinarides. Predominantly, they consist of carbonate rocks limestones and dolomites except in some areas at the coast that consist of flysch deposits. Carbonate rocks areas represent the well known dinaric karst region, where vegetation cover consists of mixed forest to broad leaf wood and grasslands with very scarce cultivated land only.

Inner depressions are embedded within the previously described regions. The largest are the Ljubljana-Kranj valley and Celje valley. The Ljubljana-Kranj valley is filled up with clay, sand and gravel of fluvio-glacial and limno-glacial origin. The Celje valley represents a flat land of fluvial and proluvial origin of sediments.

The **Pannonian basin** occupies the eastern part of Slovenia and represents a pattern of broad flat-lands and hilly regions. The flat-lands represent in fact broad river valleys filled up by alluvial deposits: sand, gravel and clay. Hilly regions are mostly built of clastic sediments, such as marls and sandstones. The land of Pannonian basin is highly cultivated, especially in the Mura and Drava plains, as well as Krško plain in the lower Sava valley.

The **Mediterranean** macro region, where air temperature is not below freezing point in coldest months of the year, occupies south western part of Slovenia in the immediate vicinity of the Bay of Trieste. This macro region is known for specific temperate climate vegetation not found in the rest of the country. Geologically, it consists of flysch in the low hill areas and carbonate rocks in the karst plateaus. From the karst plateau the terrain descends over escarpment down to the Adriatic seaside. Part of this macro region is also region of Kras (in German Karst), i.e. the area which gave a name to the science of karst in the nineteenth century. The karst plateaus are almost without any surface water, while in the flysch there is a dense network of streams and rivers.

Hydrologically, Slovenia is divided by a continental watershed, i.e. the Adriatic Sea – Black Sea watershed (Figure 1-2). About 81%, precisely 16,423 km2, of the country is located within the Danube River Basin District, which in turn represents about 2% of the entire Danube catchments area. Two big Danube tributaries flow through the country: first the Sava river together with its major tributaries, the Kolpa and the Savinja, and second the Drava river with its tributary, the Mura. The Adriatic Sea River Basin District, consists of the Soča and Adriatic Rivers river basins. Detailed description of the Slovenian catchments areas concerning land use as well as climatological, pedologic and geological characteristics is given in Chapter 3.

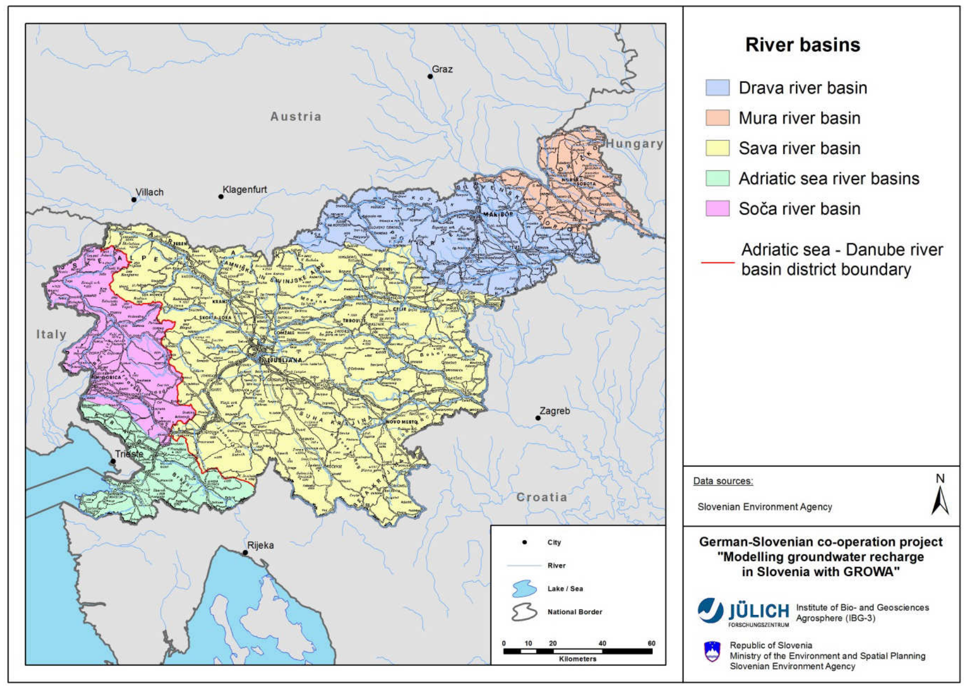

Figure 1-2: Major hydrological basins of Slovenia (ARSO, 2010b).

In Slovenia the river network is very dense with 1.33 km of river channels per square kilometre, amounting to total length of 26,989 km. However, only 46 rivers are longer than 25 km, being about 22 % of the hydrographic network. Rivers exceeding 100 km in length include the Sava – 221 km, Drava, Kolpa and Savinja. While on average, Slovenian rivers form a very dense network it is not distributed equally over the Slovenian territory. In areas of impermeable and poorly permeable rocks, the network density is very high. A sparse network, or somewhere no river network, occurs in all regions where percolation water can infiltrate freely into the underground, i.e. in the karstified carbonate rocks in the Mediterranean, Dinaric and the Alps macro regions, as well as in alluvial plains (Figure 1-3). The high karst plateaus, for example, have no river network at all. Similar conditions are found in the karstic Alpine area, but areas without rivers are not so extensive there. The central part of the gravel flatlands, such as at Kranjsko polje, Sorško polje, Ljubljansko polje and Dravsko polje, also show sparse networks.

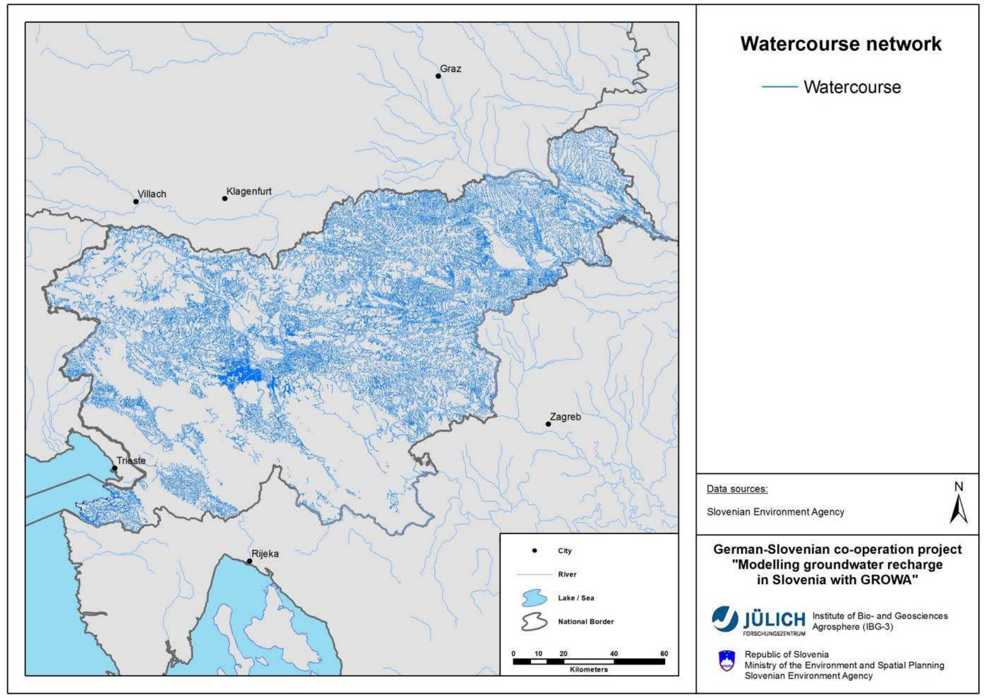

Figure 1-3: Watercourse network of Slovenia (rivers, streams, drainages).

The most important source for drinking water in Slovenia is groundwater accounting for approximately 97% of the population supply. Slovenia currently has sufficient water resources to provide continuous drinking water supply to its population, although its supply will become a limiting factor in some areas due to increasing water consumption and the anticipated economic development. Water Protection Zones have been defined to protect key aquifers and now cover almost a quarter of the country.

1.4 Basic hydrologic definitions

The hydrologic cycle begins with the evaporation of water from the surface of oceans, lakes, rivers, marshes etc., as well as from land surface. As moist air is lifted, it cools and water vapour condenses to form clouds. Moisture is transported around the globe until it returns to the surface as precipitation (Figure 1-4).

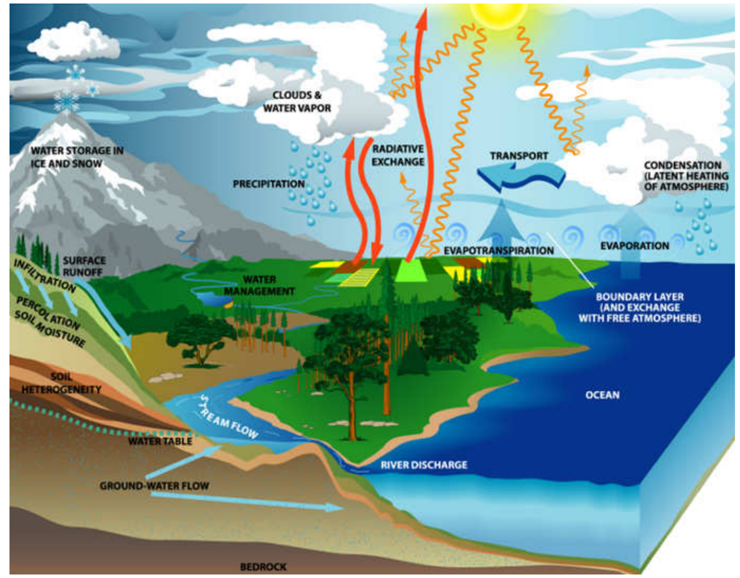

Figure 1-4: General concept of hydrologic cycle (Tutorvista, 2015).

In the terrestrial system water from precipitation reaches the ground, where one of following processes may occur:

1. Water may evaporate directly from the soil surface (evaporation) or the canopy (interception) back into the atmosphere.
2. Water may penetrate the soil surface and is released back into the atmosphere through transpiration by plants or the soil itself (transpiration).

Processes 1) and 2) are addressed as evapotranspiration, which can be addressed as the total release of water vapour from a well defined terrestrial area.

3. Water is flowing away to surface waters without penetrating the soil surface (surface runoff, syn. overland flow).
4. Water may penetrate the soil surface and become subterranean runoff (interflow, drainage runoff and groundwater runoff / groundwater recharge).

In the end all runoff components end up in terrestrial surface waters (Figure 1-4), like rivers and lakes, from where they are carried back to the oceans again, where the cycle begins again. The entire water volume Q_{total}, flowing away from an area can be derived from the water balance equation:

$$Q_{total} = P - ET_a + \Delta S \qquad (1\text{-}1)$$

Q_{total}	: Total runoff (mm/a)
P	: Precipitation (mm/a)
ET_a	: Actual evapotranspiration (mm/a)
ΔS	: Change in storage (mm/a)

In case of long-term considerations *ΔS* can be neglected and ***total runoff*** Q_{total} can be separated into different runoff fractions, which enter surface waters after different residence times. This comprises the runoff components surface runoff, interflow, drainage runoff, groundwater recharge / groundwater runoff.

According to DIN 4049-3 ***surface runoff*** (Q_O) corresponds to the part of runoff, which reaches surface water without having passed through the soil column. After a precipitation event, surface runoff reaches the surface waters within several hours (Baumgartner & Liebscher, 1990). In Peschke (1997) and Schwarze et al. (1991) this runoff fraction is addressed as „fast direct runoff".

The fraction of runoff which has infiltrated vertically into the soil may reach the aquifer or a less permeable layer above the aquifer itself, i.e. still within the unsaturated zone. In the latter case the infiltrating water flows towards the next receiving surface water along the maximum slope of the impermeable layer. In DIN 4049-3 (DIN, 1994) this runoff component is addressed as ***interflow*** *(Q_I)*, which reaches the receiving surface water after a short time gap after the precipitation event. In general the residence time of the interflow in the underground lies in the range of one to several days. As can be seen from Figure 1-5 the flow time of Q_i is longer than the flow time of Q_o, thus contributing to a later rise and a later fall of the hydrograph.

Figure 1-5: Runoff components according to Struckmeier (1997).

In Germany the "Interflow" is often further differentiated into the *"Retarded (slow) Interflow"* and the *"Immediate (fast) Interflow"*, wherein the latter one is by far the more important volume fraction according to Baumgartner & Liebscher (1990). In Peschke (1997) and Schwarze et al. (1991) the interflow on the other hand, is addressed as the „retarded direct runoff".

Another runoff component attributed to the direct runoff component is ***drainage runoff***. This runoff component summarizes all runoff fractions which reach surface waters via artificial drainage systems, like ditches and drainages. Typically, such features are to be found in lowland areas and areas in which perched water in the soil occur. With regard to their residence times drainage runoff lies in the same range as the interflow.

According to DIN 4049-3 the sum of surface runoff, drainage runoff and interflow is indicated as ***direct runoff*** (Q_D). In this way direct runoff comprises all runoff components which reach surface waters shortly after a runoff generating rainfall event.

According to DIN 4049-3 ***groundwater recharge*** *(GW_{neu})* designates the volume of water which percolates through the unsaturated zone and reaches the aquifer. Hence, groundwater recharge occurs at the top of the water saturated zone, i.e. the upper aquifer (Figure 1-6). In case longer time periods are considered, there is a balance between the groundwater recharge infiltrating into an aquifer and the related ***groundwater runoff*** (Q_G), amounting to the runoff component seeping into the surface waters from the aquifers. Hence, in case of a long-term consideration the groundwater recharge of a region corresponds to its groundwater runoff. According to DIN 4049-3 this runoff component is addressed as ***base flow*** (Q_B).

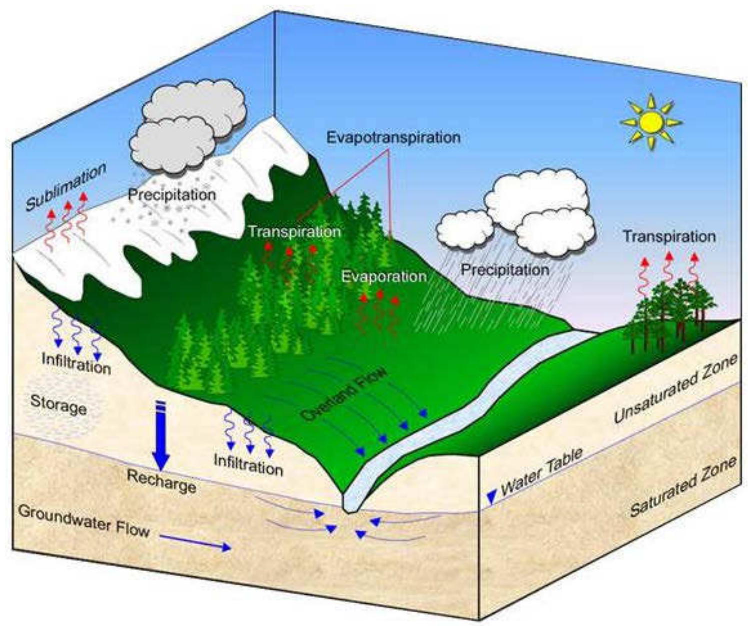

Figure 1-6: Groundwater recharge (solid blue downward arrow) as a part of hydrologic cycle.

As the residence times of base flow, i.e. groundwater runoff, are significantly higher than the residence times of the direct runoff components, its contribution to the river discharge is largely constant throughout the year. Hence, in dry weather periods base flow is the only runoff component which feeds a river. Accordingly, the water volume which can be observed in rivers during low flow conditions, typically during summer months, are a good indicator of the groundwater borne runoff. In practice, river discharges observed during dry periods are often used to separate direct runoff fractions from groundwater runoff fractions (Wundt, 1958; Kille, 1970) in case the anthropogenic impact on water balance, e.g. groundwater withdrawal, is low or negligible.

Peschke (1997) and Schwarze et al. (1991) differentiate the base flow into „short-term baseflow" (retarded interflow) and "long-term baseflow" which corresponds to a great extent to the groundwater runoff, and hence to the groundwater recharge:

$$GW_{recharge} = P - ET_a - Q_D \qquad (1\text{-}2)$$

$GW_{recharge}$	: Mean long-term groundwater recharge	(mm/a)
P	: Mean long-term precipitation	(mm/a)
ET_{al}	: Mean long-term actual evapotranspiration	(mm/a)
Q_D	: Mean long-term direct runoff	(mm/a)

The separation of total runoff into the main runoff fractions, direct runoff and groundwater runoff, the latter corresponding to groundwater recharge, is a prerequisite for the determination of groundwater recharge rates.

2 Description of the GROWA model

2.1 State of the Art in hydrologic modelling on a nationwide scale

The development of hydrologic models started in the 60s with the Stanford Watershed Model (Crawford & Linsley, 1966). Up to now, the number of models and model systems as well as the number of different model concepts has grown considerably, as indicated in the survey given by Singh (1995). Most of the models have been developed for a specific scale and the simulation of a specific aspect of the hydrologic cycle. Physically based models like PRMS (Leavesley et al., 1985), TOPMODEL (Beven et al., 1995) or SHE (Abbot et al., 1986), for instance, have been developed for the application in micro- to mesoscale watersheds. The application of these models in areas like the Republic of Slovenia, which covers an area of ca. 20,300 km^2, is limited not only due to the lack of input data needed to run these models, but also because of regionalisation issues (Blöschl & Kirkby, 1996).

The problem of applying small-scale models to large catchments areas has led to the development of models especially designed for macroscale applications. These models differ significantly to micro- and mesoscale models with respect to the representation of the relevant processes and the spatial and temporal resolution. The RHINEFLOW model (Kwadijk, 1993), for instance, calculates the water balance for the Rhine basin using a more integrated approach on a monthly basis. The HBV-model (Bergström, 1995) is a more deterministic approach using daily resolution, applicable to larger areas. For modelling the long-term groundwater recharge in large catchments areas or regions empirical models turned out to be sufficient (see. Dörhöfer & Josopait, 1981; Renger & Wessolek, 1996; Meinardi, 1994; Kunkel & Wendland, 2002; DeWit et al., 2000). These models allow a reasonable determination of the long-term water balance as a function of the interaction between the actual land cover and climatical, pedological, topographical, and hydrogeological conditions.

In the mid-90s Kunkel & Wendland started to develop the distributed hydrological model GROWA (Kunkel & Wendland, 1998, 2002), which focuses on the main runoff components: direct runoff and groundwater runoff. GROWA model was used in the following years in the framework of national and international research projects:

- Developed 1996 – 1998 in the framework of the BMBF research priority „Elbe-Ecology“
- Since 1999: Cooperation with Lower Saxony's Federal Agency for Mining, Energy and Geology (LBEG) and application of model results in Environmental information system NIBIS
- 2001-2003 Further development for „Hamburg Metropolitan Region“

- Since 2002: Cooperation with the Federal Environment Agency of the Federal State of North Rhine – Westphalia (LANUV) and application of model results in Environmental information system HYGRIS
- 2006 – 2009: Application and further development of GROWA for the Federal State of Saarland, in the framework of EU – LIFE – Project WAgriCo, in the framework of FGG – Weser Project AGRUM in Weser catchment funded by the Federal Agricultural Ministry
- Since 2009: Application and further development of GROWA for impact analyses of climate change related issues, i.e. in the framework of the EU project CLIMB and the BMBF research Priority KLIMZUG.

The GROWA model (Kunkel & Wendland, 2002) has been applied to regions ranging typically between mesoscale river basins of approximately 1,000 km^2, up to entire Federal States, and to macroscale transboundary river catchments of 100,000 km^2 and more (Wendland et al., 2003; Bogena et al., 2005). GROWA is a grid based model consisting of several modules for determining the long-term annual averages of the main water balance components as shown in Figure 2-1: actual evapotranspiration, total runoff, direct runoff (surface runoff, interflow, drainages) and groundwater recharge. As input data it requires spatial distributed input data sets, like soil physical parameters, land cover, topography climatic data, etc.

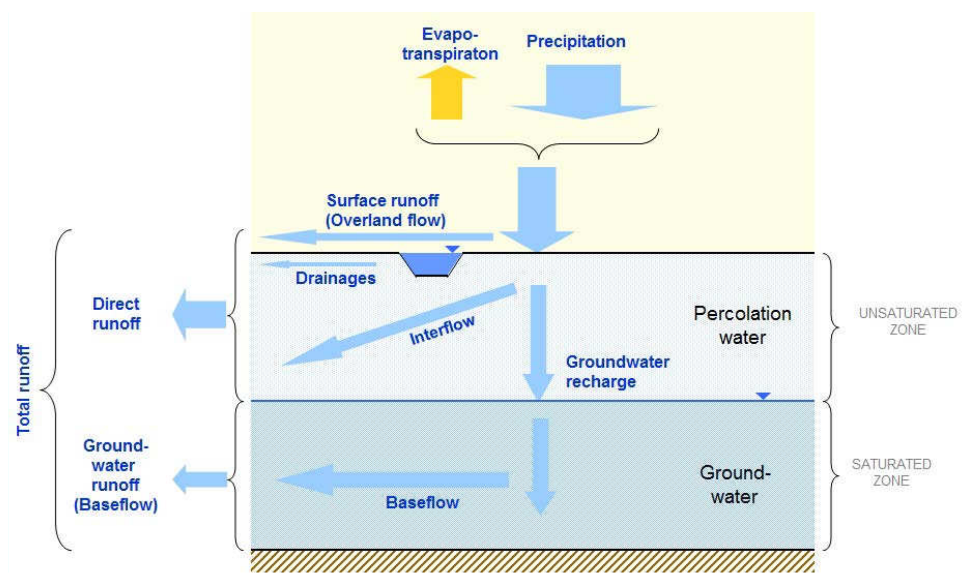

Figure 2-1: Water balance components considered in GROWA model (adapted from Wendland et al., 2010).

In recent years GROWA importance has been emphasized by further development of applications to an area-covering recalculation of natural long-term groundwater availability in the Federal States of Bremen, Hamburg, North-Rhine-Westphalia and Lower-Saxony (Kunkel et al., 2006). It has been used for practical water resources management related issues, e.g. for issuing the grants of water withdrawal rights to public water suppliers and for the required quantitative status reviews of the groundwater bodies of Lower-Saxony according to the EU Water Framework Directive (Tetzlaff & Wendland 2008; Tetzlaff et al. 2009a). Amongst others the GROWA-model has been implemented in the methodological data base (NIBIS) (Heineke et al., 1999) of the Geological Survey of the Federal State of Lower Saxony. Additionally, GROWA model results are used to simulate runoff as a prerequisite for nutrient transport modelling (Tetzlaff & Wendland, 2012; Tetzlaff et al., 2013b; Andjelov et al., 2014).

Well known and established hydrologic models have been in use in Slovenia for decades, but there is no tradition of using them in water balance studies. However, their use has been focused mostly on modelling flood events. Precipitation-runoff model HEC 1 has been introduced into university curriculum in 1990s (Brilly, 1993), and later on into routine practice at national hydrologic service for flood forecasting as described by Kobold (2015). The first use of HBV model (Lindström et al., 1997) in Slovenia was for flash flood forecasting in the Savinja River basin (Kobold & Brilly, 2006) and later on for modelling the Sava River discharge (Primožič et al., 2008), the largest river in Slovenia.

The locally developed conceptual hydrological models for groundwater balance studies have been introduced into Slovenian practice early in the 1990s at the Hydrometorological Institute of Slovenia, the predecessor of Slovenian Environment Agency. The first model was developed for the Dravsko polje alluvial aquifer, being important for water supply of Maribor, the second largest city in the country. It enabled separation of mean water balance components for the entire aquifer for the long term period: precipitation, evapotranspiration, direct runoff and groundwater runoff (Steklasa & Mikulič, 1990). Later on conceptual models have been developed for all of the twenty major alluvial aquifers in Slovenia (Mikulič, 1992). In this framework a comprehensive map of these alluvial aquifers of Slovenia has been derived. This map was later upgraded under consideration of geometry, boundary conditions and hydrogeology (Mikulič, 1997; Mikulič & Savić, 2012), but unfortunately use of the conceptual models for groundwater balance studies has been rather sporadic and restricted only to some alluvial aquifers (Mikulič et al., 2000).

According to Brilly and Gorišek (1999), the first numerical groundwater modelling in Slovenia dates to 1978 and was carried out by the Laboratory of Fluid Mechanics at Ljubljana University. One of the early published papers on groundwater modelling is from the 1980s (Brilly, 1989) for the Ljubljansko polje alluvial aquifer, which is supplying drinking water to Slovenian capital Ljubljana. This model calculated groundwater flow through the aquifer and determined portions of groundwater recharge from precipitation infiltration to the groundwater, drainage from the Sava river and interflow from the surrounding hills. The use of numerical models increased with the time. At present, commercial numerical groundwater models, like MODFLOW (Harbaugh, 2005;) and FEFLOW (Diersch, 2014) are nowadays routinely used by Slovenian hydrogeology professionals at the level of alluvial aquifers in Slovenia (Vižintin & Mikulič, 2009; Souvent et al., 2014), as well as for solving geotechnical problems (Vižintin et al., 2009) and for water balance assessment of deep transboundary thermal aquifer (Rman et al., 2014).

The examples of the following hydrological and hydrogeological studies may help to frame the context of water balance assessment practice in Slovenia so far.

On nationwide scale two water balance hydrological studies were carried out, each for a thirty years period: the first one at the Hydrometeorological Institute of Slovenia (Kolbezen & Pristov, 1998) and the second one at the Slovenian Environment Agency (Frantar ed., 2008). Both studies were based on the national database of meteorological and hydrological service monitoring, separating long term precipitation into evapotranspiration and total runoff. While Kolbezen & Pristov (1998) assessed potential evapotranspiration only, the study by Frantar ed. (2008) assessed actual evapotranspiration.

The first attempt to determine a groundwater balance of the whole country has been made in 1970s by Drobne et al. (1976). In this study the total groundwater runoff amount for Slovenia has been assessed as the so called dynamic groundwater reserves (more detailed explanation is in Chapter 6). More recent studies in this context have been performed by Brenčič et al. (1998, 2005) by lumping together groundwater runoff into two porosity types of aquifers (alluvial and karst), and breaking down total groundwater reserves of these two types to the potential and available quantities, as well as to the amount of groundwater abstraction.

Apart from these nationwide groundwater balance studies, there were also some early groundwater quantity assessments in the 1980s and 1990s on a scale of particular alluvial aquifers (Žlebnik, 1982, 1991). In these studies, groundwater quantity was calculated as a groundwater flow through characteristic cross sections of the aquifers.

Consequently, all hydrological modelling and water balance assessments in Slovenia prior to the period of implementing Water Framework Directive didn't include area differentiated and at the same time nationwide applicable model approaches to calculate total runoff and to derive direct runoff and groundwater runoff components.

Groundwater quantity assessment on the nationwide scale in the framework of implementation of Water Framework Directive was for the first time performed at national hydrological service of Slovenian Environment Agency (Andjelov et al., 2006). Groundwater quantities were assessed on the level of groundwater bodies. The need for an area differentiated regional assessment of groundwater resources led to the idea to implement GROWA water balance model in Slovenia (Wendland et al., 2009a), as a necessary upgrade to the previous infiltration map approach.

As the GROWA model has been developed, calibrated and validated for German site conditions, the applicability for Slovenian site conditions was not guaranteed a priori. However, the modular architecture of the model, as described in the following chapters, allows adapting individual modules in the case of discordance between modelled and measured values.

2.2 Calculation of actual evapotranspiration and total runoff

As described in Chapter 1.4 total runoff for a long-term period is calculated by subtracting evapotranspiration from precipitation amount. Precipitation data are usually reliable data sets obtained from well developed meteorological networks. Data on evapotranspiration are not measured in general, so one of the core challenges of GROWA is the realistic representation of area differentiated actual evapotranspiration rates.

2.2.1 Flat unsealed areas with deep water tables

The method of Renger & Wessolek (1996) allows a calculation of the annual actual evapotranspiration (ETa_{RW}) for flat unsealed areas with deep water tables (Eq. 2-1).

$$ETa_{RW} = a \cdot P_{wi} + b \cdot P_{su} + c \cdot \log\left(W_{pl}\right) + d \cdot ET_o + e \qquad (2\text{-}1)$$

ETa_{RW}	: Actual evapotranspiration according to Renger & Wessolek (1996) [mm/a]
a,b,c,d,e	: Land use specific coefficients [-]
P_{wi}, P_{su}	: Winter and summer precipitation [mm/a]
W_{pl}	: Plant available soil water content [mm]
ET_o	: Potential evapotranspiration [mm/a]

The landcover enters in Eq.2-1 via the land use-specific coefficients of regression a…e, which are listed in Table 2-1. For arable land, grassland and coniferous forest the regression constants according to Renger & Wessolek (1996) are used. For deciduous forest constants according to Renger & Strebel (1980) are used. It has to be noted that in this case, instead of the half-year levels of precipitation, only the mean annual precipitation is considered and that the plant available volume of soil water is not taken into account. In order to determine the mean actual evapotranspiration of vegetation-free barren land, a simple approach of Proksch (1990) is applied. This method was derived from lysimeter results for different soils (DVWK, 1996) and takes into account only the annual level of precipitation.

The annual sum of the potential evapotranspiration, ET_o, relates to the method of Haude (1954). However, the FAO (Food and Agriculture Organization) recommends the grass reference evapotranspiration as an internationally uniform standard (Allen et al., 1994). The grass reference evapotranspiration is based on the Penman-Monteith relation (ATV-DVWK, 2002) and was determined nationwide by Wendling (1995) on the part of the German Meteorological Services (DWD).

Table 2-1: Land use-specific regression coefficients for the calculation of actual evapotranspiration according to Renger & Wessolek (1996), Renger & Strebel (1980) and Proksch (1990)

Land cover	**a**	**b**	**c**	**d_{Haude}**	**e**
Arable land[1]	0.08	0.39	153	0.12	-109
Pastures[1]	0.10	0.48	286	0.10	-330
Coniferous forest[1]	0.29	0.33	166	0.19	-127
Deciduous forest[2]					
Vegetation-free areas[3]	0.047	0.047	0	0.02	430.1
	0.074	0.074	0	0	59.2

In the case that the grass reference evapotranspiration according to Wendling (1995) is used, the regression constant *d* must be modified as follows (Kunkel & Wendland, 1998):

$$d_{Wendling} = 0.926 \cdot d_{Haude} \quad (2\text{-}2)$$

The empirical actual evapotranspiration calculation method of Renger & Wessolek (1996) is based on the physical approach of Rijtema (1968). In order to cover the small-scale variability of soils and vegetation, it takes a large number of site factors into account. However, this method is restricted to flat unsealed areas with deep water tables, where the mean soil percolation rate corresponds to the mean groundwater recharge. Hennings (Hennings ed., 2000) specifies a maximum slope gradient of 3.5 % as the application limit for this method. In addition, climatologically restrictions have to be considered. For agricultural areas, the annual precipitation should not exceed 800 mm and for forests a value of 1300 mm should not be exceeded. If these conditions are not fulfilled, the calculation approach according to Renger & Wessolek (1996) cannot be directly used.

In order to ensure a universal application, Kunkel & Wendland (1998, 2002) extended the methodology of the Renger-Wessolek equation. The modifications include the consideration of topography, groundwater influence and sealing.

2.2.2 High relief terrains

In high relief terrains, the actual evapotranspiration level is additionally affected by the relief factors: slope and aspect. This influence can be taken into account in the form of a correction factor f_h for Renger-Wessolek actual evapotranspiration ETa_{RW}:

$$ETa_{relief} = f_h(\alpha,\varphi)\cdot ETa_{RW} \tag{2-3}$$

ETa_{relief} : Actual evapotranspiration in high relief terrains [mm/a]

A relevant investigation in hilly regions was performed by Golf (1981), whose results were generalized by Kunkel and Wendland (1998):

$$f_h(\alpha,\varphi)=\varphi\left[1.605\cdot 10^{-2}\cdot \sin(\alpha-90)-2.5\cdot 10^{-4}\right]+1 \tag{2-4}$$

α : aspect [°]

φ : slope [°]

In Figure 2-2 the dependence of the correction factor on aspect and slope is shown in the form of a graph. It can be clearly seen that the evapotranspiration on southerly exposed slopes predominates that on northern slopes.

Thus, for example, a 16 % higher evapotranspiration level is found for southerly exposed slopes with a slope inclination of 10° than in flat ground. For northerly exposed slopes with a slope inclination 10°, in contrast, an evapotranspiration level is found which only corresponds to 84 % of the value for flat area. These differences increase with rising slope inclination. Due to the additive correlation between precipitation and actual evapotranspiration in the calculation of the total runoff level, this may lead to a considerable modification of the runoff levels under certain conditions.

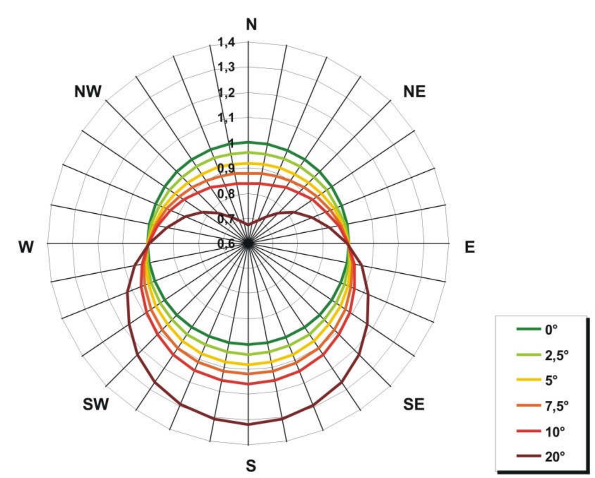

Figure 2-2: The value of the Golf factors fh depending on slope and aspect.

2.2.3 Groundwater-affected areas

For areas affected by groundwater, the application of Eq. 2-1 leads to an underestimation of the actual evapotranspiration level, since due to the capillary rise, water is constantly available for the evapotranspiration process. It is therefore assumed that the actual evapotranspiration corresponds to a maximum evapotranspiration:

$$ETa_{gw} = ET_{\max} \tag{2-5}$$

ETa_{gw} : Actual evapotranspiration of groundwater affected sites [mm/a]

ET_{max} : Maximum evapotranspiration [mm/a]

The maximum evapotranspiration represents a modification of the potential evapotranspiration, which in turn reflects an evapotranspiration value calculated for the theoretical condition of grass vegetation with 12 cm height. The actual level of evapotranspiration for other land use types, however, can clearly deviate from this value. The maximum evapotranspiration (ET_{max}), which can be lower or higher than the potential evapotranspiration, depends on the type and height of vegetation. The maximum evapotranspiration is calculated from the potential evapotranspiration (ET_o) using the parameter f (ATV-DVWK, 2002):

$$ET_{\max} = f \cdot ET_o \tag{2-6}$$

The values for the parameter f were determined via regression equations as a function of land use, vegetation height and available field capacity of the soil on the basis of lysimeter and gauge data for different site conditions (ATV-DVWK, 2002). Glugla et al. (1999) assumes that the actual evapotranspiration in lysimeters with sufficient moisture availability, i.e. with high soil-internal capillarity and thus high capillary water rise into the evapotranspiration-affected soil zone, corresponds to the maximum evapotranspiration:

$$f = \frac{ET_{\max}}{ET_o} \approx \frac{ETa_{lysimeter}}{ET_o} \tag{2-7}$$

$ETa_{lysimeters}$: measured evapotranspiration of the lysimeter with sufficient moisture availability [mm/a]

A value for f = 1.51 +/- 0.76 was obtained for lysimeters with soils from deep loess (ATV-DVWK, 2002).

For sealed and vegetation-free barren land areas, Glugla et al. (1999) compared the evapotranspiration values of vegetation-free lysimeter sites with the grass reference evapotranspiration after extensive precipitation events. For areas with deciduous and coniferous forest, observed data from non-weighable lysimeters were used. The actual evapotranspiration results from the difference between corrected precipitation and measured percolation. In this way, Glugla et al. (2002) derived the following correlation:

$$ET_{\max} = \frac{ETa}{0.8} \tag{2-8}$$

On the basis of Eq. 2-8, the parameter f for flat regions was calculated as a function of soil properties and plant rotation age (ATV-DVWK, 2002). The plant rotation age corresponds here to the stand age to the time of felling. The respective value for f thus corresponds to the average over all development stages up to the stand age upon felling. Figure 2-3 shows the dependence of the parameter f on the soil type and the respective rotation age.

Figure 2-3: Long-term means of the parameter for deciduous (broad-leaved) and coniferous forests and different soil types depending on the turnover rate.

Hence, in determining the maximum evapotranspiration for groundwater affected sites the influence of different land use categories is taken into account by the correction factor f (Eq. 2-9):

$$ET_{\max} = f \cdot ET_o \tag{2-9}$$

The equations for calculating the parameter f are listed in Table 2-2. The related parameters (e.g. average vegetation height of the plant stand) and UA (average rotation age of the plant stand) were estimated on the basis of the landcover categories of the landcover data CORINE.

Table 2-2: Land use-specific equations for the calculation of parameter f according to ATV-DVWK (2002).

Landuse classes		**Equations**
Urban fabric		$f = 0.8$
Open spaces	$\Theta_{nFK} \leq 8.5$ Vol.% =>	$f = 0.8$
	$\Theta_{nFK} \geq 8.5$ Vol.% =>	$f = 0.0186 * \Theta_{nFK} + 0.6419$
Pasture (12 cm)	$\Theta_{nFK} \leq 11$ Vol.% =>	$f_{12cm} = 0.0125 * \Theta_{nFK} + 0.7108$
	$\Theta_{nFK} \geq 11$ Vol.% =>	$f_{12cm} = 0.2866 * \ln(\Theta_{nFK}) + 0.6419$
Pasture (varying)	5 cm < $z_B \leq$ 20 cm =>	$f_k = 0.0676 * \ln(z_B) + 0.8321$
	$z_B \geq$ 20 cm =>	$f_k = -0.7 * 10^{-5} * z_B^2 + 0.37 * 10^{-2} * z_B + 0.9661$
		$f = f_k(z_B) * f_{12cm}$
Arable land		$f = 0.221 * \ln(\Theta_{nFK}) + 0.431$
Deciduous forest (Broad-leaved forest)	**Sandy soils** ($\Theta_{nFK} \leq 16$ Vol.%)	
	UA ≤ 90 years =>	$f = 0.84 + 0.25 * 10^{-2} * UA + 0.508 * 10^{-3} * UA^2 – 0.233 * 10^{-4} * UA^3 + 0.422 * 10^{-6} * UA^4 – 0.3494 * 10^{-8} * UA^5 * 0.10946 * 10^{-10} * UA^6 = f_{SL1}$
	UA > 90 years =>	$f = 1.038 + 0.49 * 10^{-3} * UA + 0.155 * 10^{-5} * UA^2 – 0.1686 * 10^{-8} * UA^3 = f_{SL2}$
	Loamy soils ($\Theta_{nFK} > 16$ Vol.%)	
	UA ≤ 90 years =>	$f = 1.05 * f_{SL1}$
	UA > 90 years =>	$f = 1.05 * f_{SL2}$
Coniferous forest	**Sandy soils** ($\Theta_{nFK} \leq 16$ Vol.%)	
	UA ≤ 130 years =>	$f = 0.8 + 0.2694 * 10^{-1} * UA + 0.63924 * 10^{-3} * UA^2 – 0.8052 * 10^{-5} * UA^3 – 0.5785 * 10^{-7} * UA^4 – 0.223 * 10^{-9} * UA^5 + 0.356 * 10^{-12} * UA^6 = f_{SL1}$
	UA > 130 years =>	$f = 1.35 + 0.108 * 10^{-2} * UA + 0.178 * 10^{-5} * UA^2 = f_{SL2}$
	Loamy soils ($\Theta_{nFK} > 16$ Vol.%)	
	UA ≤ 130 years =>	$f = 1.03 * f_{SL1}$
	UA > 130 years =>	$f = 1.03 * f_{SL2}$

2.2.4 Urban areas

Due to the variability in the building and settlement structure, it is very difficult to take the influence of sealing in urban regions into account. Presently, a number of studies dealing with this topic are available, but most of them created non-transferable results.

The present methodology is based on studies by Wessolek & Facklam (1997), who investigated the influence of sealing on groundwater recharge in the Berlin area. Accordingly, a correction factor is introduced by Kunkel & Wendland (1998) that reduces evapotranspiration in sealed regions (Eq. 2-10).

$$ETa_{urban} = ETa_{RW} - f_v \cdot G \qquad (2\text{-}10)$$

ETa_{urban}	: Actual evapotranspiration of urban areas [mm/a]
G	: Degree of sealing [%]
f_v	: Correction factor [-]

The correction factor f_v was determined by a comparison between the actual evapotranspiration calculated according to Eq. 2-1 for a hypothetically unsealed situation and the evapotranspiration resulting after Wessolek & Facklam (1997) for the Berlin area (Kunkel & Wendland, 1998). A value of 3.44 was thus found for f_v. According to ATV-DVWK (2002), fractions of the sealed area can be derived using the CORINE nomenclature.

2.3 Deriving groundwater recharge

The groundwater recharge is determined in the GROWA model by separating the calculated total runoff into the components of direct runoff and baseflow. According to Peschke (1997) on a long-term average the baseflow component essentially corresponds to the groundwater recharge. Following Dörhöfer & Josopait (1980) and Hennings (2000), the baseflow is separated by so-called "baseflow indices" (BFI). In this way, the groundwater recharge, $GW_{recharge}$, is expressed as a relative fraction of the total runoff, Q_{total}:

$$GW_{recharge} = BFI \cdot Q_{total} \qquad (2\text{-}11)$$

The BFI values are dependent on specific site conditions and are assumed to be nearly constant on a long-term average. In order to enable a differentiated calculation of the groundwater recharge for the total area of Slovenia, the BFI values must be spatially distributed to the entire area. A three-step procedure was adopted for this purpose, which will be explained in more detail in the following.

2.3.1 Determining BFI values from measured runoff data

In a first step, observed discharge data were used to determine the BFI values arising in the respective catchment areas. In order to achieve an adequate determination of the BFI values the discharge data of a large number of catchments has to be analysed. The catchment-area-related BFI values (BFI_{basin}) are determined according to the following relation:

$$BFI_{basin} = Q_G / MQ \tag{2-12}$$

MQ : Mean annual discharge [m³/sec]

Q_G : Groundwater discharge [m³/sec]

In order to determine the groundwater-bearing runoff Wundt (1958) proposed a method in which the groundwater runoff is derived from the monthly low-water discharges (MoLR) of a prolonged series of years (MoMLR-method):

$$Q_G \approx MoMLR = \sum_i^n MoLR_i / n \tag{2-13}$$

In a first approximation, the MoMLR value reflects the groundwater flow of a river for sites that are not significantly anthropogenic affected and which are located in unconsolidated rock regions. In this case the MoMLR value is an appropriate measure of the groundwater recharge for a catchment area. The applications of the GROWA model to the Elbe catchment area (Kunkel & Wendland, 1998) and to Lower Saxony (Dörhöfer et al., 2001) have proved that plausible baseflow fractions can be determined in such regions with the MoMLR-method.

In solid rock regions, however, the MoMLR-values do not correspond to the mean groundwater recharge, since the monthly low-water discharges contain significant fractions of direct runoff (surface runoff and interflow), which are also covered by the MoMLR-method. For this reason, following Kille (1970) and Demuth (1993), a method was applied to the solid rock regions, which allows a reduction of the MoMLR values by the interflow fraction.

The graphical Kille-method is a modification of the Wundt-method, the individual MoMLR values being arranged in ascending order. In this way, a cumulative frequency is obtained which, according to Demuth (1993), can be divided into two types (type I S-shaped, Type II parabolic). The Kille method can only be applied to type I, the linear section of the distribution being used for fitting a straight line. The MoMLR value reduced by the interflow (MoMLRr) is read in the middle of the distribution on the y-axis according to Kille and corresponds to the mean groundwater recharge.

This procedure was taken up by first forming the cumulative frequency from the MoMLR values as was done by Kille (1970) and Demuth (1993). With the aid of a regression analysis, the linear section of the cumulative frequency is then determined by iteratively reducing the domain of definition of the MoMLR values. For this purpose, first of all the maximum and then the minimum MoMLR values are omitted in the each iteration step. This procedure is completed, when a maximum coefficient of determination of the regression straight line is reached.

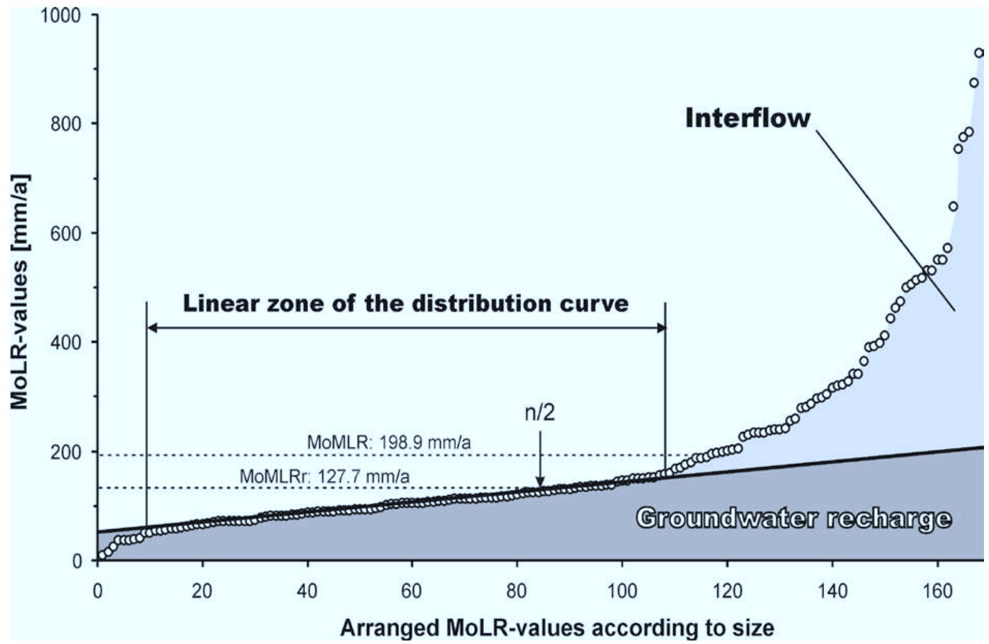

Figure 2-4: Separating the interflow component from groundwater recharge (MoMLRr-method).

Finally, the MoMLRr-value is calculated by means of the gradient m, the number of MoLR-values n and the axis intercept y_0:

$$MoMLRr = m \cdot \frac{n}{2} + y_0 \qquad (2\text{-}14)$$

The example of the Rebbelroth (Agger) gauge in Figure 2-4 illustrates the difference from the Wundt method. If the MoMLR method after Wundt is used, a very high value (198.9 mm) is obtained for the groundwater recharge level. As can be seen in Figure 2-4, this results from the relatively large fraction of exceedingly high MoMLR values, which may exhibit high fractions of direct runoff e.g. due to snowmelt or during periods of heavy precipitation. If the MoMLRr method is used, a value of 127.7 mm is determined by eliminating the direct runoff fraction, which corresponds much better to the actual groundwater recharge in the catchment area of the Rebbelroth gauge (Bogena et al., 2003).

2.3.2 Identification of runoff effective site conditions

After having derived the regional averages of the BFI values for the considered catchment areas on the basis of the runoff data, the next steps are the disaggregation and the transfer to regions for which no suitable gauge data are available. Therefore runoff-effective regional features and parameters are taken into account.

For this purpose, a hierarchical approach is used (Figure 2-5), in which the value of a site condition is considered to be exclusively determining for the BFI value. Further site parameters are only considered if the primary site condition is not relevant. A total of 41 different site features have been defined, to each of which a BFI value is assigned:

- Two sealing classes for separating the groundwater recharge in urban regions according to their degree of sealing,
- Twenty six classes for including the influence of the geology on groundwater recharge in solid rock regions,
- One class to include the influence of artificially drained areas in unconsolidated rock regions,
- Four classes to differentiate the influence of the depth to groundwater on groundwater recharge in unconsolidated rock regions,
- One class to reproduce water logging influences on groundwater recharge in unconsolidated rock regions,
- Seven classes for including the influence of the different slope gradients on groundwater recharge in unconsolidated rock regions.

Figure 2-5: Site characteristics that determine groundwater recharge in GROWA.

The hierarchical approach is consequently divided into five steps. First of all, it is assumed in each area element or each grid cell that groundwater recharge is negligible for the sealed fraction. It is then verified for the remaining fraction of the area element whether there is a significant artificial drainage, e.g. pipe or ditch drainage. If this is the case, a corresponding BFI value is estimated. In the case that a detailed information concerning sealing and the remaining land cover is not available, e.g. if the CORINE Land cover data are used, a representative value for the whole area element is used.

If the actual grid cell shows neither sealing condition nor artificial drainage, a differentiation into consolidated rock and unconsolidated rock regions is carried out. In the unconsolidated rock areas, the depth to the groundwater table and the water logging tendency as well as the slope gradient are considered. In the solid rock regions, the hydrogeological rock properties are regarded as the decisive runoff-effective site property.

The degree of sealing is identified using the Landcover data (CLC, 2000) (Chapter 3.2). The hydrogeological properties were taken from hydrogeological maps provided by GeoZS (OGK1, 1967-98; Buser & Draksler, 1993; Buser, 2010; Prestor et al., 2004, 2005) (Chapter 3.4). The soil-physical and topographic data for the unconsolidated rock regions were taken from the Digital Soil Information System (PKS, 2007) and are calculated on the basis of the DMV 100 digital terrain model (GURS, 2000), respectively (Chapter 3).

2.3.3 Attribution of area differentiated BFI values

The application of the GROWA model to the Elbe catchment area (Kunkel & Wendland, 1998) and to Lower Saxony (Dörhöfer et al., 2001) has shown that the use of BFI values from the literature (Table 2-3) leads to realistic groundwater recharge rates in unconsolidated rock regions.

Table 2-3: BFI-values of the unconsolidated rock areas according to Dörhöfer & Josopait (1980), Hennings (2000) and Wessolek & Facklam (1997).

Degree of sealing	**Groundwater depth**	**Water logging tendency**	**Slope**	**Baseflow indices**
	> 2 m	No water logging	< 1 %	1
	1.3 – 2 m	1 (very low)	1 – 3.5 %	0.9
I (10 – 45 %)				0.82
			3.5 – 7 %	0.67
			7 – 10 %	0.59
	0.8 – 1.3 m	2 (low)	10 – 13 %	0.5
	0.4 – 0.8 m	3 – 4 (medium – high)	13 – 15 %	0.44
	< 0.4 m	5 (very high)	> 15 %	0.4
II (45 – 75 %)				0.33
III (75 – 90 %)				0.28
IV (>90 %)				0.2

Kunkel & Wendland (1998) established that the BFI values specified in table 2-3 cannot be used for the solid rock regions, since the influence of the geological conditions predominate by far the influence arising from soil properties in solid rock regions. Gabriel & Ziegler (1989) and Schwarze et al., (1991) come to the same conclusion.

Hence, separating runoff fractions in solid rock regions should take the particular importance of the geological conditions into account. For this reason, Kunkel & Wendland (1998) used typical permeability ranges of solid rock aquifer typologies as the central parameter for separating the base flow in solid rock regions.

Table 2-4 shows typical hydraulic conductivity classes and BFI values determined in a GROWA application by Bogena et al. (2003) in a solid rock area in Germany. As can be seen the BFI values increase with increasing hydraulic conductivity values.

As the petrographic properties and the regional hydrological and hydrodynamic conditions can be regarded as the major geogenic factors influencing groundwater recharge in solid rock areas (Wendland et al., 2005) it can be expected that aquifers or groups of aquifers with similar petrographic properties display similar or comparable hydrodynamic and hydrologic conditions (Appelo and Postma, 2005) irrespectively of state borders.

Table 2-4: Classification of the hydrogeological properties of hard rocks and associated BFI-values according to Bogena et al. (2003).

Hydrogeological class	Permeability	k_f-value	Baseflow Indices
I	very high	> 10^{-2} m/sec	0.9
II	High	> 10^{-3} – 10^{-2} m/sec	0.6
III	Medium	> 10^{-4} – 10^{-3} m/sec	0.57
IV	Moderate	> 10^{-5} – 10^{-4} m/sec	0.3
V	Low	> 10^{-7} – 10^{-5} m/sec	0.29
VI	very low	> 10^{-9} – 10^{-7} m/sec	0.18
VII	extremely low	< 10^{-9} m/sec	0.12

We therefore assume that the BFI values assessed for aquifer typologies in Germany will not contrast significantly from the BFI values in Slovenia, as long as the aquifer typologies show similar petrographic properties. For this reason the BFI values determined by Bogena et al. (2003) have been considered as suitable starting points for assessing BFI values for Slovenia.

Figure 2-6 summarizes the procedure in the GROWA model for determining the baseflow fractions.

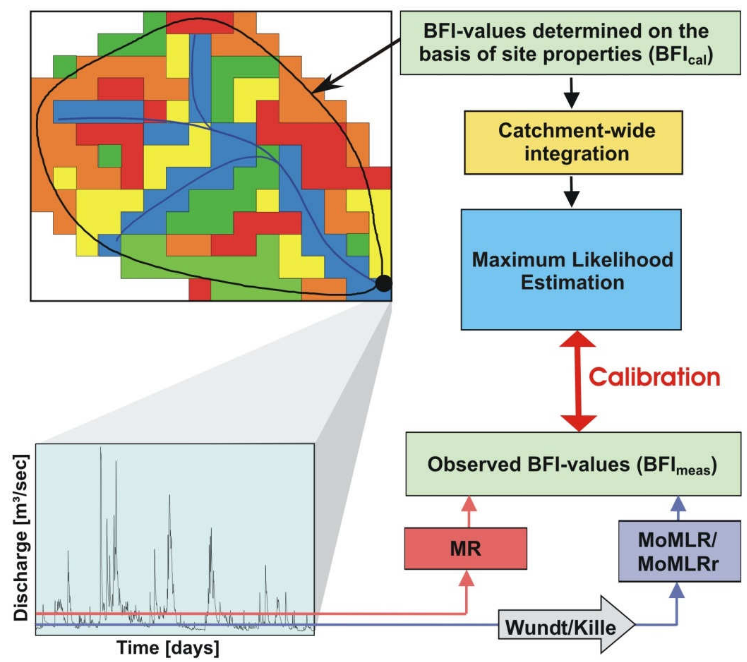

Figure 2-6: Procedure in the GROWA model for BFI calibration.

The calibration is performed in a catchment-area-related manner. For this purpose, the relative area fractions (a_i) of the individual site parameters in each region under investigation were multiplied by the respective (BFI_i), added up and compared with the baseflow indices observed (BFI_{meas}):

$$BFI_{meas} = MoMLR(r) / MR \xleftrightarrow[compared\ with]{} BFI_{cal} = \sum_{i=1}^{n} BFI_i \cdot a_i \qquad (2\text{-}15)$$

where MR denotes the measured long-term average total runoff. The sum runs here across all the 41 site features distinguishable, e.g. in the unconsolidated rock regions across the categories of groundwater and water logging influence shown in 2-3 and of the slope gradient. In a next step, the baseflow indices of the twenty six site features in solid rock are varied in a continuous iteration process by maximum likelihood method (Sorooroshian et al., 1983), until the sum of the square deviations between calculated and measured baseflow fractions assumes the lowest value (Eq. 2-16).

$$\sum_{j=1}^{n} (BFI_{meas} - BFI_{cal,j})^2 = Min \qquad (2\text{-}16)$$

2.4 Summary of the GROWA model features and input layers

GROWA model flow chart (Figure 2-7) gives an overview of separating input precipitation into main water balance components: actual evapotranspiration, total runoff, direct runoff and groundwater recharge. It calculates net water balance, originating only from precipitation at modelled area for a hydrological year from November 1st to October 31st.

Main general features of the GROWA model are as follows:

- Model architecture: Modular
- Scale of application: 100 – 500,000 km²; from small catchments to regions and states
- Spatial resolution: Variable – dependent on input grid
- Temporal resolution: Year
- Input data type: Digital data – maps
- Potential evapotranspiration: Penman-Monteith equation
- Actual evapotranspiration: Renger-Wessolek equation
- Runoff separation: Base flow indices – BFI
- Results: Total runoff, percolation water, direct runoff (surface runoff, interflow, drainage runoff), groundwater recharge
- Validation: Gauged runoff at gauging stations (MQ, MoMNQ)
- Implementation: C++; GIS – linkages to ArcView

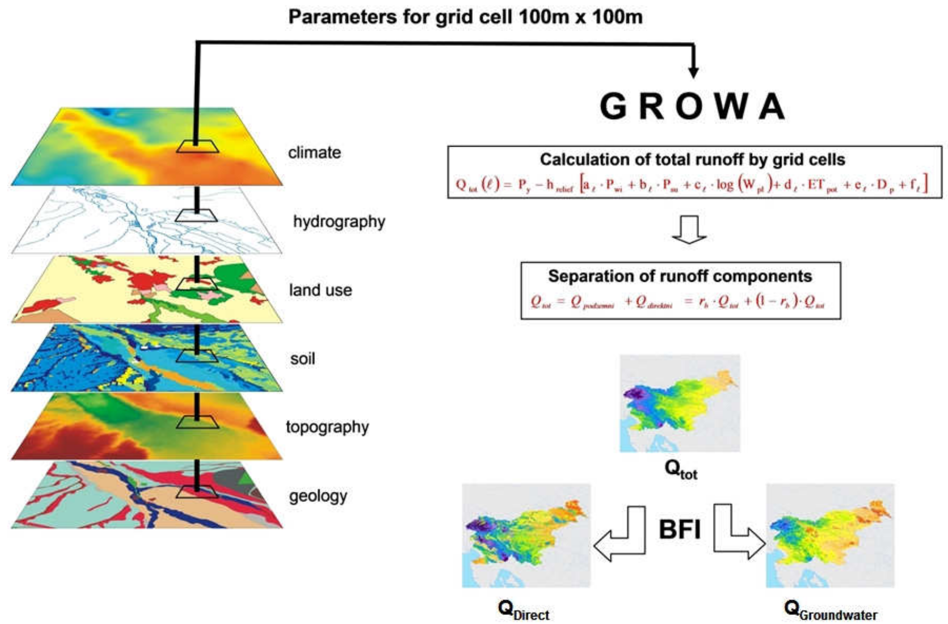

Figure 2-7: The GROWA-SI model input data layers and calculation flow chart (adapted from Kunkel & Wendland, 1989, 2002).

In groundwater recharge model of Slovenia the input data were prepared and water balance components were calculated for 100m x 100m grids. In this way the Slovenian territory is subdivided into 2,027,300 elementary computation units, for which the water balance components are determined individually.

The GROWA model implementation to Slovenia displays some specific features arising from the site conditions of the Alps, Dinaric, Pannonian and Mediterranean macro regions, which are different from the German conditions. In the process of defining BFIs for runoff separation as well as in the verification of the runoff separation the so-called Index of Development and Persistence of the River network IDPR has been introduced, which is described in detail in Chapter 3.4. Because of these modifications, the GROWA model for Slovenia is refered to GROWA-SI in the following chapters, describing the model implementation and wider use of the results in Slovenian hydrological practice.

3 Data preparation and regionalization

The GROWA-SI model was implemented in order to determine the water balance for the entire Republic of Slovenia. For the application of the GROWA-SI model spatially distributed climatic, hydrological, pedological, topographic and hydrogeological basic data were prepared. The datasets used for this study are described in this chapter with respect to data source, methodology and precision. Furthermore, this section includes explanations with regard to special data processing steps and the description of specific regional features. All the databases used in this study originate from the state authorities and the University of Ljubljana (Table 3-1).

Table 3-1: Database of the GROWA water balance model.

	Data base	Scale / spatial resolution	Data source
Climate data (1971-2000)	Precipitation (May - October) Precipitation (November -April) Potential Evapotranspiration	100 X 100 m	Slovenian Environment Agency (ARSO), Meteorology Office
Soil cover	Land use category	25 ha	CORINE data base
Soil data	Soil types Soil texture Effective field capacity for arable land	1:25,000	Ministry of Agriculture, Forestry and Food (MKGP) University of Ljubljana, Biotechnical Faculty,Centre for Soil and Environment Science
Soil data	Effective field capacity Influence of perched water Rooting depth	1:25,000	Derived; based on pedo-transfer functions
Groundwater data	Depth to groundwater	1:25,000	Slovenian Environment Agency (ARSO), Hydrology and State of the Environment Office
Drainage	Artificially drained areas	1:25,000	Ministry of Agriculture, Forestry and Food (MKGP)
Relief	Digital elevation model(DMR 100)	100 X 100 m	Surveying and Mapping Authority of the Republic of Slovenia (GURS)
Topography	Slope inclination Slope aspect	100 X 100 m	Derived; based on digital elevation model
Geology	Geological map Hydrogeological map	1:100,000 1:500,000	Geological Survey of Slovenia (GeoZS)
Hydrologic data	Catchment areas Daily runoff (1971 – 2000)	1:25,000	Slovenian Environment Agency (ARSO), Hydrology and State of the Environment Office
Base maps	River network, political boundaries, towns etc.	1:25,000	The Surveying and Mapping Authority of the Republic of Slovenia (GURS)

The climate parameters were processed by the Meteorology Office of Slovenian Environment Agency ARSO, (ARSO, 2010a). The pedological parameters were derived by the University of Ljubljana, Biotechnical Faculty, Centre for Soil and Environmental Science and by Ministry of Agriculture, Forestry and Food (MKGP, 2007). Hydrogeological maps were made available by the Geological Survey of Slovenia (Prestor et al., 2006). The digital elevation model (DMR), used as a database for topographic site conditions, originates from the Surveying and Mapping Authority of the Republic of Slovenia (GURS, 2000). Observed runoff data at gauging stations were made available by the ARSO, Hydrology and State of the Environment Office (ARSO, 2010b). Data on artificially drained areas were provided by the Ministry of Agriculture, Forestry and Food (HMO, 2007). Detailed explanations concerning the individual data bases are to be found in ARSO Information System (ARSO, 2011). All data were embedded in the Geographic Information System ArcView© and in the Access database system. Data storage as well as analysis and the evaluation of results took place in ArcView©.

3.1 Climate data

All climate data were provided by the Meteorology Office of Slovenian Environment Agency ARSO (ARSO, 2010a) as digital datasets for the hydrologic period 1971-2000:

- mean precipitation in the hydrological six summer months
- mean precipitation in the hydrological six winter months
- average annual potential evapotranspiration

Area-wide climate data model input were derived from the 201 climate and precipitation stations of ARSO meteorological monitoring network. Precipitation values were interpolated at ARSO using universal kriging method (Cressie, 1993). The predictors in the deterministic part of the model were relative altitude in the NE direction, longitude and latitude. Empirical variogram was fitted with anisotropic spherical variogram model and on the basis of cross-validation procedure, while influential surrounding was set to 35 km. With this method initially monthly values of the period 1971-2000 were assessed. Subsequently, the average annual precipitation for the hydrological six summer months (1971-2000) and the average annual precipitation for the hydrological six winter months (1971-2000) were derived by averaging and adding up the basic grids of monthly precipitation (Nespor et al., 1999; Dolinar et al., 2006). The dataset for the potential evapotranspiration was derived in analogous manner.

Precipitation

The method for determining the water balance values in the GROWA-SI model incorporates the average precipitation amounts in the hydrological six summer months and hydrological six winter months (Renger & Wessolek, 1996). In order to describe the precipitation conditions in Slovenia, the mean annual precipitation

(Figure 3-1), the mean precipitation of the hydrologic summer months (Figure 3-2) and winter months (Figure 3-3), as well as the ratio between summer and winter precipitation (Figure 3-4) of the reference period 1971-2000 will be dealt with in more detail in the following.

The spatial distribution of mean annual precipitation for the reference period 1971–2000 (Figure 3-1) is closely related to the synoptic situation with South-Western wet winds. This meteorological situation causes heavy precipitation due to orographic effect in the Alpine-Dinaric mountainous ridge which extends from NW to SE part of the country. Precipitation values of more than 1,600 mm/year are limited to the western mountainous part of the country. Accordingly, the highest values are detected in the Julian Alps in the NW of the country, where the annual precipitation sum exceeds 3,200 mm/a. The secondary maximum is located around Mt. Snežnik region in Dinaric Mountains, where precipitation exceeds 2,600 mm yearly. There is a very steep gradient in precipitation amount at the Dinaric edge, where in only 10 km distance the annual precipitation increases from 1,600 mm up to 2,600 mm. Going further towards the NE, precipitation decreases slowly and at the most NE part of the country precipitation doesn't exceed 900 mm per year.

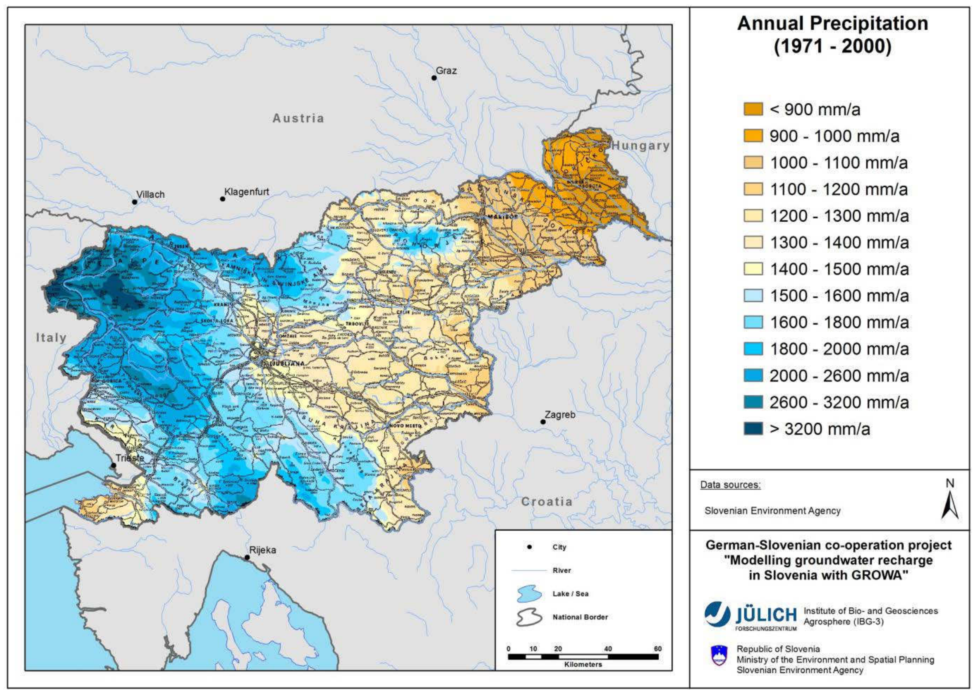

Figure 3-1: Mean annual precipitation sum of precipitation in Slovenia (1971 – 2000).

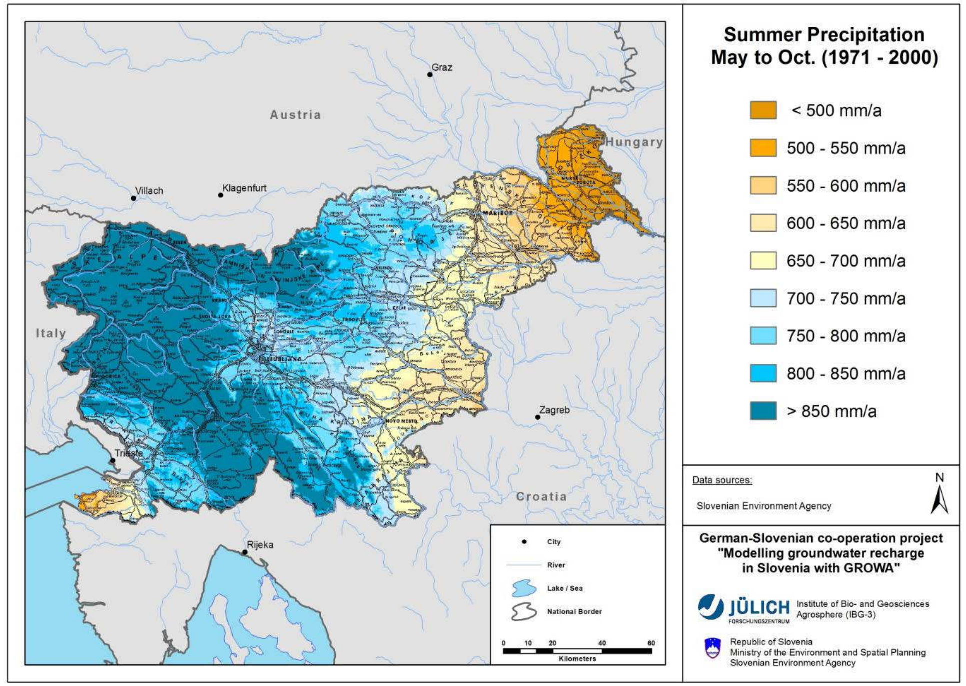

Figure 3-2: Summer precipitation in Slovenia, months between May and October (1971-2000).

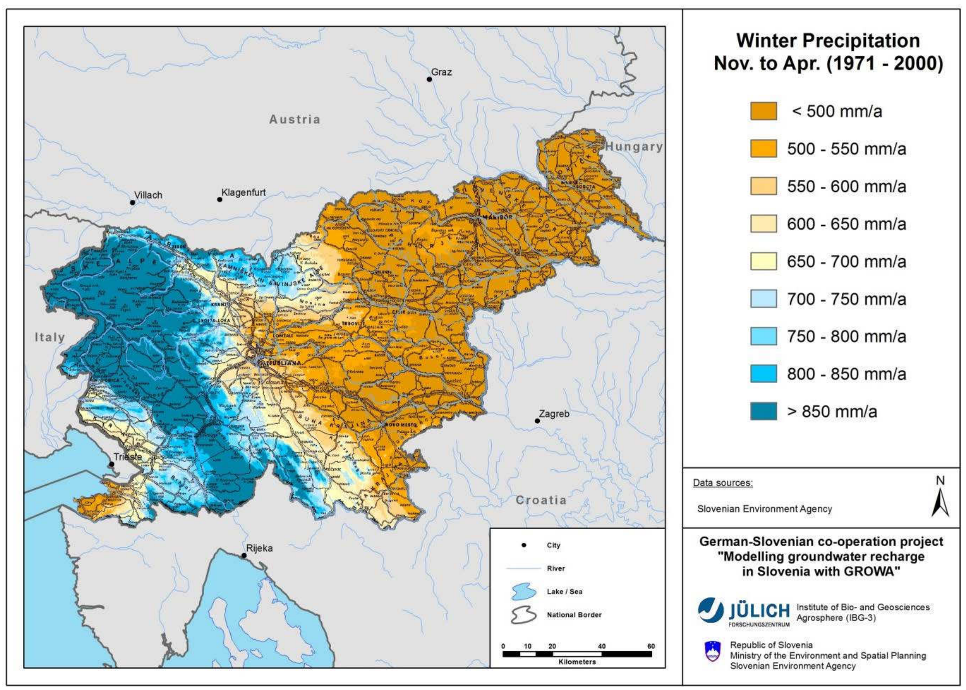

Figure 3-3: Winter precipitation in Slovenia, months between November and April (1971-2000).

The months between May and October represent the hydrological summer months whereas the months between November and April represent the hydrological winter months. The mean value of winter precipitation in the period 1971-2000 is around 650 mm per year (Figure 3-2) whereas summer precipitation is on average around 825 mm per year (Figure 3-3). It can be seen from these maps that summer precipitation is significantly higher than winter precipitation. Also, the high precipitation amounts are more evenly distributed across the country in summer, while in winter the high precipitation is mostly limited to the afore described Alpine-Dinaric mountain barrier in the west.

Figure 3-4 shows the ratio of winter and summer precipitation for the period 1971-2000. At a ratio of 100% the precipitation amount in the hydrological summer months is the same as in the hydrological winter months. Summer precipitation predominates at values below 100% and winter precipitation at values above 100%. The precipitation ratios range from below 60% to above 110%. From the map it becomes clear that winter precipitation is clearly predominant in less than 10% of Slovenian territory only, specifically in an area along the Alpine-Dinaric mountain barrier. In contrast, summer precipitation is predominant in more than 90% of Slovenia and thus coincides with the period of the highest evapotranspiration.

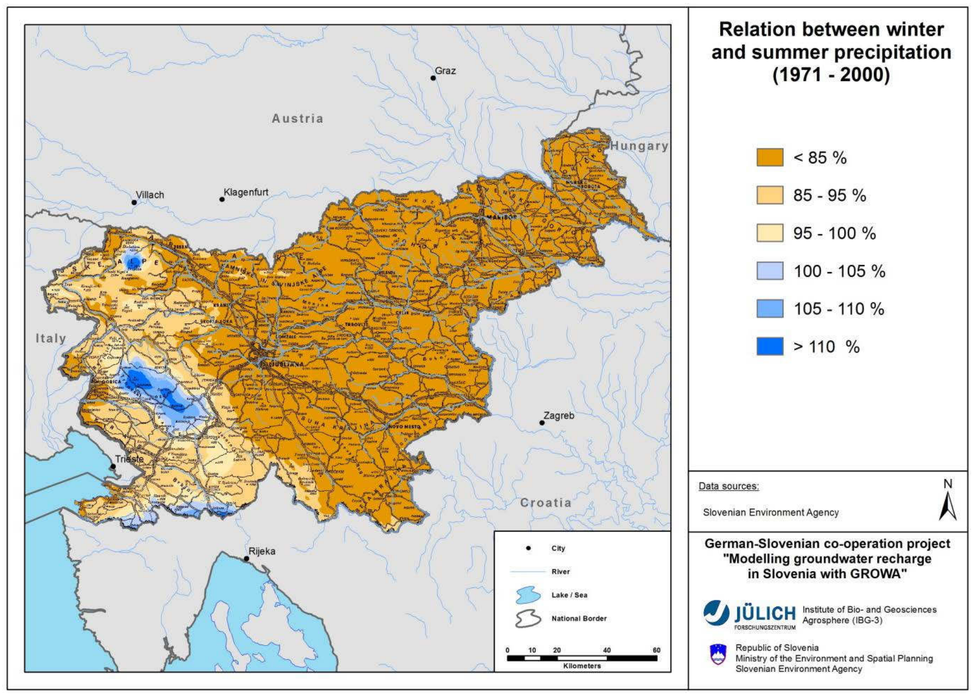

Figure 3-4: Ratio between winter and summer precipitation (1971-2000).

Potential evapotranspiraton

Due to the high instrumentation effort to measure evapotranspiration, models are used all over the world in order to determine evapotranspiration rates on a country level. The potential evapotranspiration describes the evapotranspiration amount under given climatic conditions that may arise from a defined soil surface in the case of unlimited water availability. In order to enable a uniform calculation, the boundary conditions (vegetation, land use and soil properties) must be defined. The FAO (Food and Agriculture Organization) recommends the grass reference evapotranspiration, which is based on the Penman-Monteith relation (Allen et al., 1998, 2000).

Accordingly, the average potential evapotranspiration (ET_0) for the period 1971-2000 was calculated by ARSO for the individual climate station of Slovenia. For this purpose the potential evapotranspiration was calculated on the basis of the Penman–Monteith equation (Monteith, 1965) from the daily measurements of air temperature, wind speed, air humidity and net radiation at 33 meteorological stations equally distributed all over Slovenia. Subsequently, the values calculated for the individual climate station were regionalized in order to get an area covering map. For interpolation universal kriging was used (Cressie, 1993).

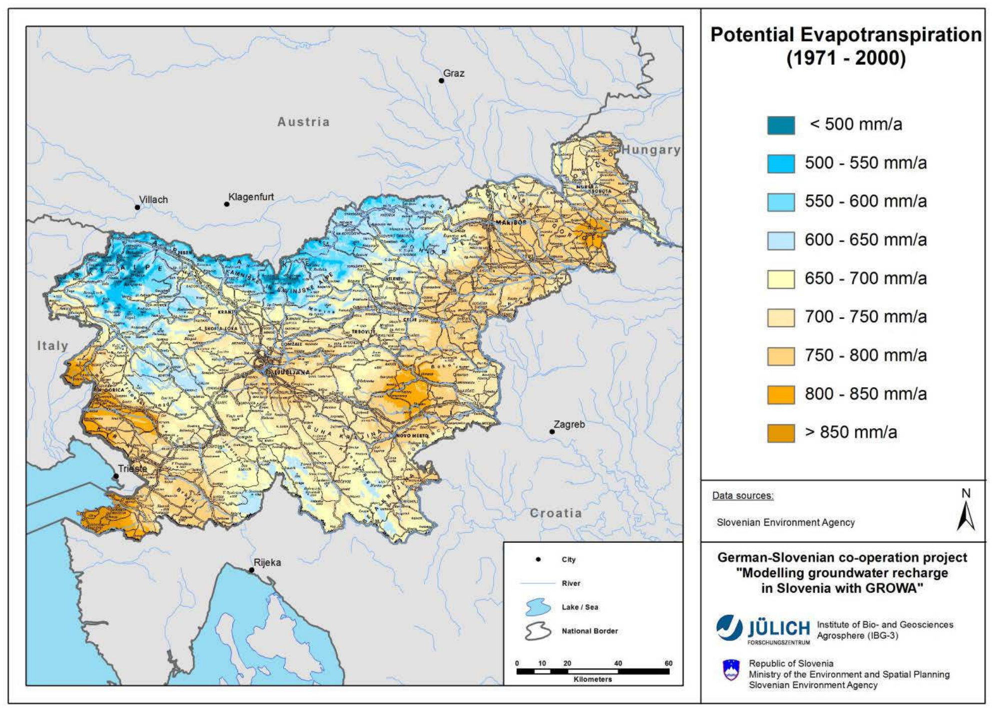

Figure 3-5: Mean annual potential evapotranspiration in Slovenia (1971-2000).

Figure 3-5 shows the potential evapotranspiration determined as described above. The highest potential evapotranspiration with values above 800 mm/a can be found in the Mediterranean macro region, specifically in the vicinity of the coastal area and in the west of Nova Gorica region. Spatial distribution shows decrease of potential evapotranspiration to the north. Accordingly, the lowest rates of average potential evapotranspiration, with values less than 500 mm/a, occur in parts of the Alps macro region in north-western and nothern part of Slovenia. In the central part of Slovenia values between 700 to 750 mm/a can be found. Further to the east potential evapotranspiration ranges between 750 and 800 mm/a predominate, reflecting the increasing influence of continental climate conditions.

3.2 Land cover data

The land cover data used in this study were determined by the Slovenian Environment Agency ARSO, within the framework of the EU programme CORINE (Coordination of Information on the Environment) (CEC, 1994). The aim of this programme was to establish uniform and comparable land cover data for the entire European Union area. For the first time land cover in Slovenia was determined according to the CORINE concept in the year 1995. In 2003, ARSO elaborated a new CORINE Land Cover (CLC) map for Slovenia (EEA, 2011). This database was created from satellite imagery of the year 2000 and is comparable with the land use data determined by twenty-nine other European countries. The concept of CORINE Land Cover contains 44 land cover categories, of which 33 occur in Slovenia. Table 3-2 shows the total area and fraction of these CORINE land cover categories for Slovenia in the year 2000 (CLC, 2000).

The GROWA-SI model differentiates between the following land cover units: paved areas/urban fabric, vegetation-free areas/open spaces, grassland/pasture, arable land, deciduous forest, coniferous forest and water surface (see Chapter 2, Table 2-2). Hence, for the calculation of actual evapotranspiration in the GROWA-SI model, the more differentiated CORINE Land cover categories were allocated to the corresponding land use units required by the GROWA model. For this purpose, the 33 categories that occur in Slovenia according to CORINE Land Cover were subsumed under these land use groups. In case of heterogeneous land cover an allocation on the basis of a recommendation by ATV-DVWK (2002) has been applied. The related key used for this allocation is shown in Table 3-3.

The frequency distribution obtained on the basis of GROWA-SI adapted land use grouping is shown in Figure 3-6. In general, land use categories in Slovenia reflect to a great extent relief: altitude, inclination, and exposition (aspect), as well as climate and soil conditions. The most common type of land cover is forests, which cover about 58% of the land surface. By this, Slovenia ranks amongst the most forested countries in Europe. Arable land comprises ca. 29%, of which ca. 1% are special crops: vineyards, orchards, berry plantations, olive groves and hop plantations. Grasslands sum up to 8%, whereas only 2.4% of Slovenian territory is urban area. Smaller portions are classified as rock surface and vegetation-free barren land 1.5%, as well as water areas and wetlands 0.6%.

Table 3-2: Land cover classes of CORINE Land Cover in Slovenia (CLC, 2000).

ID	CORINE Land cover class	Total area (km^2)	Percentage of the area (%)
1.1.1	Continuous urban fabric	1.90	0.01
1.1.2	Discontinuous urban fabric	432.58	2.04
1.2.1	Industrial or commercial units	68.10	0.32
1.2.2	Road and rail networks and associated land	20.84	0.10
1.2.3	Port areas	2.00	0.01
1.2.4	Airports	6.65	0.03
1.3.1	Mineral extraction sites	13.40	0.06
1.3.2	Dump sites	3.60	0.02
1.3.3	Construction sites	6.57	0.03
1.4.1	Green urban areas	5.03	0.02
1.4.2	Sport and leisure facilities	14.30	0.07
2.1.1	Non-irrigated arable land	1,165.70	5.48
2.2.1	Vineyards	166.03	0.78
2.2.2	Fruit trees and berry plantations	36.31	0.17
2.3.1	Pastures	1,218.31	5.73
2.4.2	Complex cultivation patterns	2,860.78	13.46
2.4.3	Land principally occupied by agriculture, with significant areas of natural vegetation	1,893.78	8.91
3.1.1	Broad-leaved forest	4,707.79	22.15
3.1.2	Coniferous forest	2,564.59	12.07
3.1.3	Mixed forest	4,657.29	21.91
3.2.1	Natural grassland	221.33	1.04
3.2.2	Moors and heathland	235.05	1.11
3.2.3	Sclerophyllous vegetation	1.69	0.01
3.2.4	Transitional woodland-shrub	497.33	2.34
3.3.1	Beaches, dunes, sands	6.34	0.03
3.3.2	Bare rocks	190.33	0.90
3.3.3	Sparsely vegetated areas	126.08	0.59
3.3.5	Glaciers and perpetual snow	0.36	0.00
4.1.1	Inland marshes	26.93	0.13
4.2.1	Salt marshes	2.21	0.01
4.2.2	Salines (saltworks)	5.32	0.03
5.1.1	Water courses	64.92	0.31
5.1.2	Water bodies	29.78	0.14

Table 3-3: Percentages of the land cover units of the CLC classes used in the GROWA-SI model, as well as the parameters plant height (Z_G) and turnover rate (UA), according to ATV-DVWK (2002).

CLC class	Paved areas [%]	Open space [%]	Pasture		Arable land [%]	Deciduous forest		Coniferous forest		Waters [%]
			[%]	Zg [cm]		[%]	UA [a]	[%]	UA [a]	
1.1.1	80		10	12		10				
1.1.2	35		20	12	20	15				
1.2.1	85		10	12		10				
1.2.2	50	20	20	12		5				
1.2.3	80	10	10	12		10				
1.2.4	30		70	12						
1.3.1		70	25	12						5
1.3.2		80	20	12						
1.3.3	20	80								
1.4.1			50	12		50				
1.4.2	15		60	12	5	10 10	100 30			
2.1.1					100					
2.2.2						100	20			
2.3.1			100	20						
2.4.2			35	20	40	25	10			
2.4.3			35	20	40	15	50	10	50	
3.1.1						100	155			
3.1.2								100	85	
3.1.3						50	155	50	85	
3.2.1			100	12						
3.2.2			50	20		50	50			
3.2.4						50	15	50	10	
3.3.1		100								
3.3.3		50	50	12						
4.1.1			50	20	40	10	50			
4.1.2			100	20						
5.1.1										100
5.1.2										100

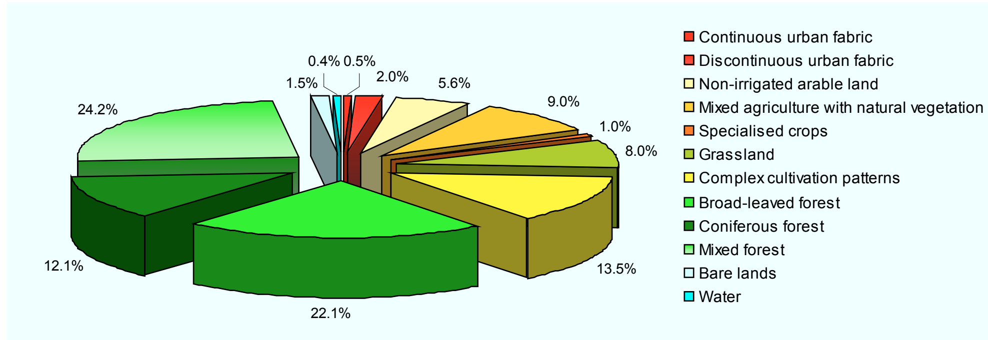

Figure 3-6: Percentages of area of the land cover units in Slovenia according to ATV-DVWK (2002).

The assessment of the land use change between 1995 and 2000 performed at ARSO came to the conclusion that the change affected less then 1% of the country territory. The largest change detected was in forest classes CLC 3.1.1 and 3.2.4 (KOS, 2011; EIONET, 2011a). In total, only 48 polygons were detected in which a land use change had taken place. The related area is less than 800 hectares. Therefore, it can be concluded, that land cover changes between 1995 and 2000 will not have a big influence on the overall Slovenian water balance.

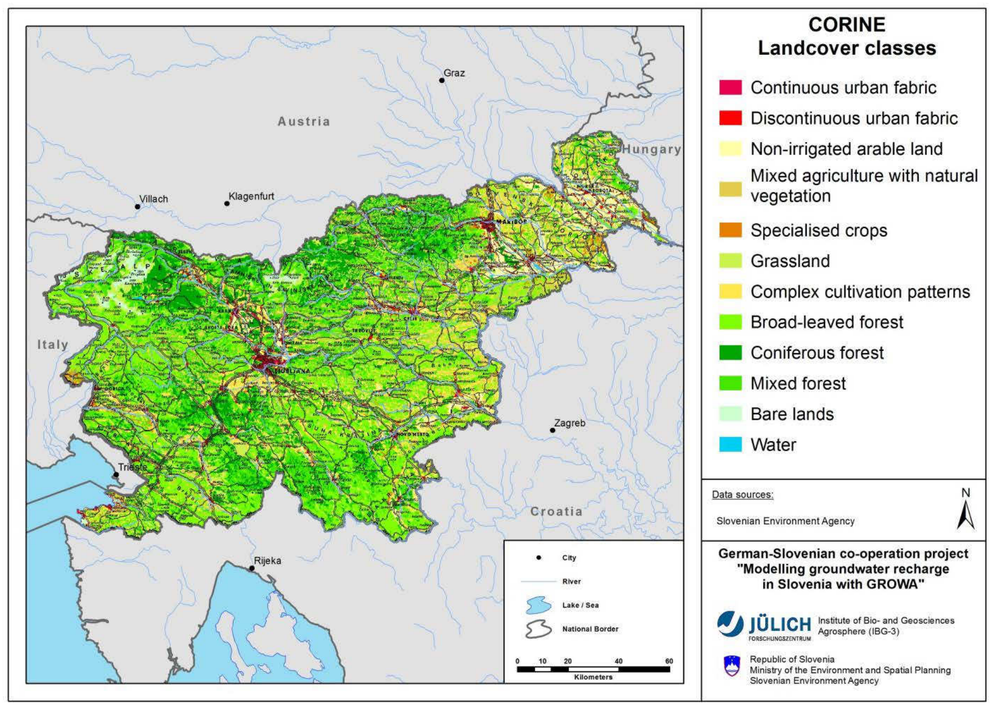

Figure 3-7: The CORINE Landcover units in Slovenia (CLC, 2000).

Figure 3-7 shows the spatial distribution of the land cover units occurring in Slovenia. The predominance of the forests distributed across the whole country is evident. Cultivated fields on the other hand, greatly dominate only in the plains of the

Pannonian macro region where they occupy some half of the surface. At the plains of the Alps macro region they occupy merely a good quarter, while in the Alpine mountains cultivated fields comprise only 0.5% of the surface and on the Dinaric plateaus just 1.5%.

In hilly and mountainous areas, grassland is an important land category. Land class of specialised crops like hop plantations in the Savinja plain, olive groves of the Mediterranean, vineyards and orchards in the Mediterranean and Pannonian hills, cover small highly scattered areas only, so that they can barely be identified in the map. In contrast, forests cover 80% of the Dinaric plateaus. Population and economic activity represent the greatest pressure on the land cover of the plains, above all in the plains of the Alpine region. There, almost 20% of the territory is urbanized area. Barren land category with no or meagre vegetation, like heather and mountain meadows and rock surfaces amounting in total to 1.5 %, is a significant land category in the high mountains of the Alps, the only Slovene region with land above the upper tree line.

Apart from the predominance of forests, the rest of the territory exhibits a great variability of land cover, often changing at small distance. Monocultures are rare and they do not cover continuous large uninterrupted areas. High variability and lack of large monoculture areas arise both from the physiography of the territory and socioeconomic pattern of the society. On one hand land use variability is greatly influenced by different climate types: Alpine, Mediterranean and continental Pannonian. On the other hand, regarding the socioeconomic factor, big landowners are extremely rare, while small plots of land are predominant, leading to intricate land use pattern.

3.3 Soil data

Soil properties estimated by the pedotransfer functions concern biological, chemical, mechanical and hydrological properties of soils. They allow use of the Soil Geographical Database as input for modelling in many domains such as crop yield forecasting, climate change impacts, erosion risk assessment and many others (Jones et al., 2005).

All pedological parameters for GROWA-SI modelling were taken from the soil map of Slovenia on a scale of 1:25,000 (PKS, 2007). The scale of this map gives an overview of the soils in Slovenia and their regional significance with adequate precision (Lobnik et al., 2006). Figure 3-8 shows the spatial distribution of the main soil types in Slovenia, Figure 3-9 shows the related frequency distributions.

Rendzic Leptosol is the most widespread soil type, covering ca. 26% of the territory. They form on the slopes of carbonate rocks, i.e. limestones and dolomites, and prevail in 44% of the territory of Slovenia. This soil is not only washed down the slopes, but it can also be found in the cave systems of the karst areas.

Rendzic Leptosol transformed into Chromic Cambisols, many of them colluvial, predominate on less steep slopes, on the bottom of dolinas, or at the footslopes, occurring in ca. 12% of the Slovenian territory. The two most widespread soil types besides Rendzic Leptosols are Dystric Cambisols with 21% and Eutric Cambisols with 16% total area. Dystric Cambisols form on siliceous parent materials like volcanic, clastic and igneous rocks, and are usually found in mountainous regions.

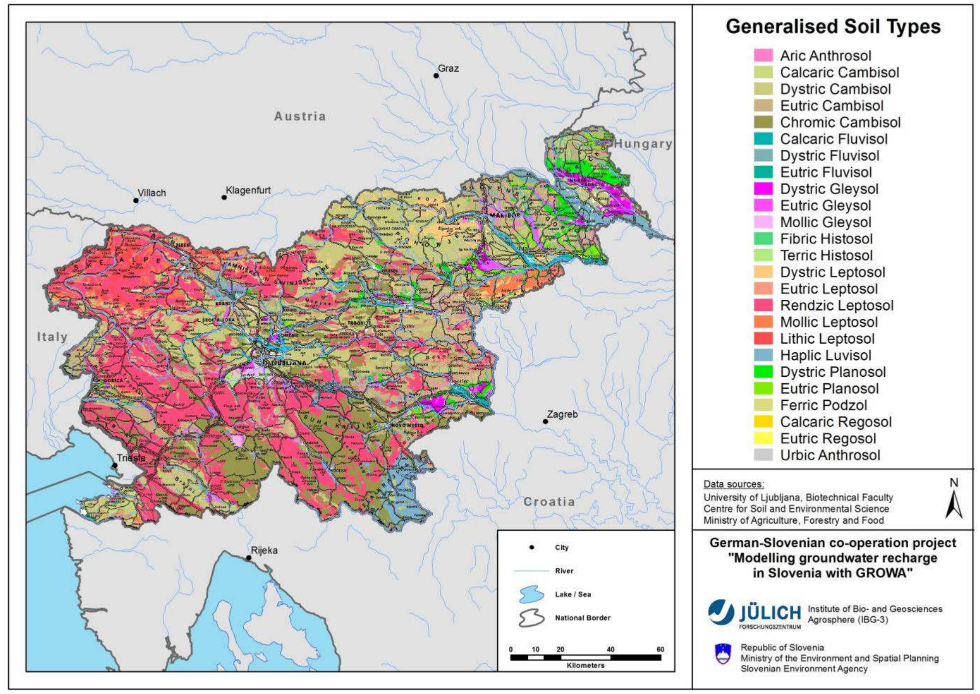

Figure 3-8: Soil map of Slovenia; generalised according to the FAO classification.

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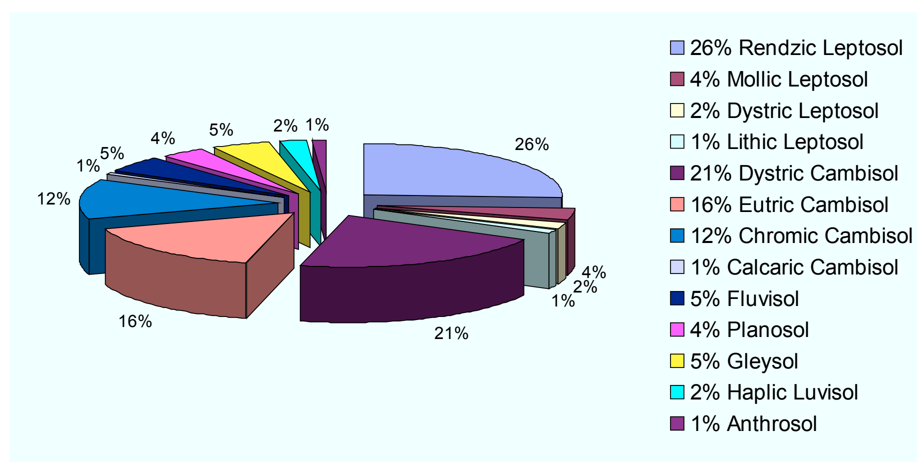

Figure 3-9: Frequency distribution of the main soil types in Slovenia.

On steeper slopes, Dystric Cambisols are replaced by Dystric Leptosols (2%). In contrast, Eutric Cambisols, are often found at the bottom of basins and valleys or in terraced hilly regions in case of mixed siliceous-carbonate parent rock. Mollic Leptosols form on the same kind of parent rock, however they are less widespread (ca. 4%). Calcaric Cambisols with pedogenic nodules can be found on marly parent materials in drier eastern and south-western Slovenia. Haplic Luvisols form by translocation of clay and pedogenic Fe compounds, but are less widespread than expected (ca. 2%). Several soil types can be found in tectonic basins and flat areas. Fluvisols, Eutric, Dystric and Calcaric are common along the rivers and cover more than 5% of Slovenian territory. Hydromorphic soils occur in these areas as well, they cover almost 9% of Slovenia. Eutric and Dystric Planosols are soils with stagnant meteoric water. In summary, Cambisols (45%) and Leptosols (35%) represent the most widespread soil types in Slovenia. These two soil types reflect the mountainous character of most of the country, which prevents the further development and differentiation of the soils (Vidic et al., 1998).

The water and matter balance are particularly governed by pedological factors. For example, the evapotranspiration rate is controlled by the water stored in the root zone, the so-called plant available soil water content (W_{pl}). This soil hydrological parameter enters in the calculation of water balance with the GROWA model (Chapter 2). Information about the available field capacity, effective rooting depth and capillary rise is required to derive this parameter.

Slovenian soil data base describes each soil unit by the soil type, the initial rock type with its stratigraphy, and the soil type stratification. The soil type stratification contains quantified information on the soil texture, humus and lime contents as well as the thickness for each layer (Tič & Vrščaj, 2002). In order to make this information compatible for the GROWA-SI modelling, Slovenian soils profile information from 1,500 profiles was transformed into German soil texture classes (Figure 3-10). For a specific soil type, texture of each layer in the profile was transformed into German texture class. For example 3 layers of eutric cambisol of distinguished profile texture were transferred into classes defined as Lt3-Tu2-Tu2 (Rupreht, 1999).

According to the German soil texture classification (Ad-hoc-AG Boden, 2005) the soil texture triangle is divided into 31 texture classes: seven clay classes, ten loam classes, seven silt classes and seven sand classes. The boundaries of the texture classes are shown in Figure 3-10. For each texture class values on porosity depending on soil compaction are provided. Additionally, correction factors for high organic contents are available. On this basis, in conjunction with characteristics from the pedological mapping instructions (AG Boden, 1994), the effective field capacity values are derived.

T = clay, S = sand, U = silt, L = loam; 2= slight, 3 = medium, 4 = high

Figure 3-10: Definition of the German soil texture classes according to Ad-hoc-AG Boden (2005).

Effective field capacity of the root zone

The **effective field capacity** represents the part of the field capacity that can be reached by vegetation and specifies the soil water stored in the medium-size pores with tensions of pF 1.8 to 4.2. It is the most important soil-physical parameter that enters in the calculation of actual evapotranspiration according to the GROWA model (Chapter 2) and, therefore it is of special importance.

An area covering soil map of Slovenia, showing effective field capacity for the entire territory was not available when the project started. Therefore, the effective field capacity for the soils occurring in Slovenia was assessed in two subsequent steps. Initially, the 1:25,000 map of effective field capacity for arable land below a topographical elevation of 700 m as developed by Zupan et al. (2008) was used. By this data sets information about effective field capacity was available for ca. 30% of the country without further processing.

For the remaining 70% of the Slovenian territory however, such an indication of effective field capacity was missing and had to be generated in the second step. This was done using the 1:25,000 Slovenian soil map (PKS, 2007). The 1,500 individual soil units of this map were evaluated predominantly with regard to the designation of the soil texture portions sand and silt. This was followed by the determination of the effective field capacity using the pedo-transfer functions developed by German Federal Agency for Geosciences and Raw Materials (AG Boden, 1994) and according to the "Official German Hand Book for Soil Mapping" (Ad-hoc-AG Boden, 2005). Finally, the derived effective field capacity values were connected to the related soil polygons. In this way effective field capacity according to German classification was made available for ca. 65% of the soil polygons.

For the remaining 5% of the soil polygons, for which no soil profile was available, the effective field capacity information from polygons, for which effective field capacity values were already derived was transferred to the polygons with similar combinations of soil type and geology. In this way effective field capacity values for all soil types occurring in Slovenia were derived, so that in the end a data layer of effective field capacity was developed for the whole country.

The **depth of the root zone** is a soil parameter which defines the depth from which water stored in a soil may be used by plants for water uptake and therefore for the transpiration process. The rooting depth is land-use dependant. For a given soil type, the value of rooting depth is decreasing in following order: from trees to arable land and to grassland.

Rooting depth was assigned according to "Official German Hand Book for Soil Mapping" (Ad-hoc-AG Boden, 2005). For flat areas (0-2% slope), following designation was applied:

- 1.5 m: forest
- 0.8 m: arable land
- 0.6 m: grassland
- 0.1 m: construction sites, deposits etc.

However, as Slovenia displays a lot of mountainous areas, such "ideal" rooting depths are hardly achieved. Depending on the slope gradient in %, the rooting depth values designated above were adapted according to (AG Boden, 1994) as follows:

- 2.0 - 3.5% slope: 10% depth reduction
- 3.5 - 7.0% slope: 20% depth reduction
- 7.0 - 9.0% slope: 30% depth reduction
- 9.0 -18.0% slope: 50% depth reduction
- >18.0% slope: bulk reduction to 0.1m depth.

The **effective field capacity of the root zone** is obtained from the sum of the effective field capacity per soil type layer across the mean effective rooting depth. Within the framework of this study, the land cover categories of arable land, pasture and forest were distinguished using CORINE land cover dataset (CLC, 2000). The calculation of the effective field capacity of the root zone is performed separately for each land use category according to the designations above.

Figure 3-11 shows the available field capacity of the root zone. In Slovenia, soils of high effective field capacity of the root zone are often associated with the soils occurring in the central part of country. Especially for the chromic cambisol and the luvisol, mean available field capacities above 200 mm are frequent. The opposite, low effective field capacities of the root zone are to be found in mountainous regions of Slovenia. There, values below 15 mm are frequent due to the very small soil thicknesses.

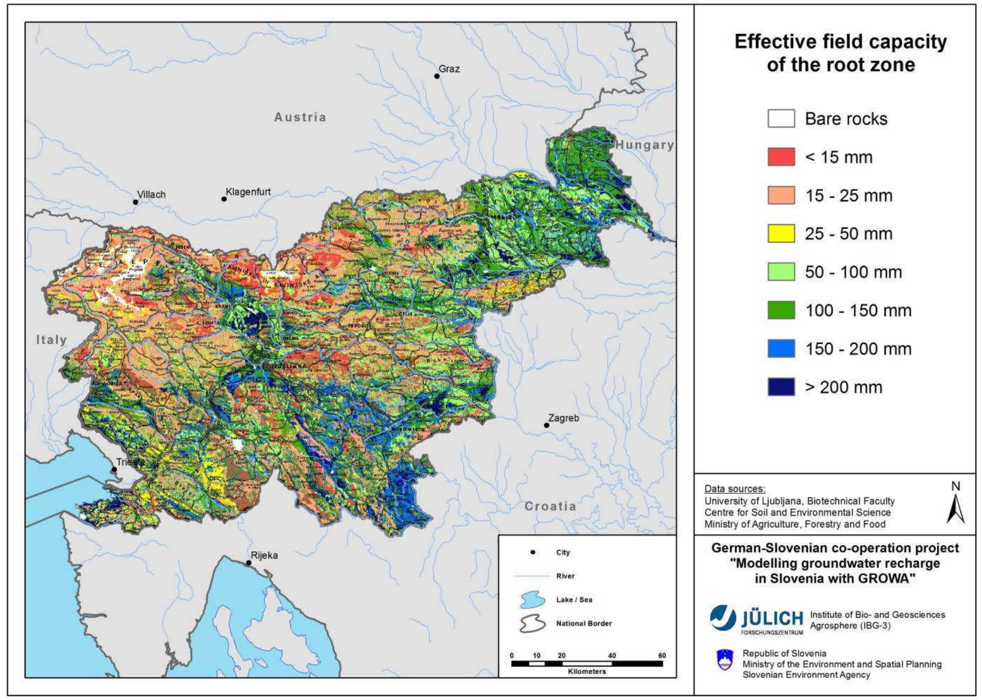

Figure 3-11: Effective field capacity of the root zone.

Groundwater level

The groundwater table close to the surface determines the development and properties of soils and thus influences their function for agricultural use or need for melioration. The groundwater level varies more or less strongly during a year as a function of weather, the substratum, the terrain location and vegetation. The groundwater level can be anthropogenically influenced by subsidence, drainage, recipient regulation, groundwater withdrawal, industry and mining (Uhan & Mikulič, 1996; Mikulič, 2004).

Several informations have been used to derive a groundwater level map for Slovenia (Mikulič ed., 2000; Uhan ed., 2004) as a data layer showing groundwater levels is missing in the digital Slovenian soil map 1:25,000. First of all, information from the digital “wetland map” was used (EIONET, 2011b; Beltram, 2005; Krajnc & Andjelov, 2006). This data layer was merged with area designations of groundwater influence in Slovenian soil map 1:25,000. For this purpose information on gleysols and histosols of FAO-classification and on hipogley from Slovenian classification were used (Tič & Vrščaj, 2002; PKS, 2007). Both data layers corresponded to each other to a large extent, thus proving the reliability of the classification.

In a consecutive step the depth of groundwater was allocated to the “wetlands” using CORINE Land cover map and information from National Slovenian Groundwater Monitoring Network for the derivation of mean groundwater levels:

- 0 - 0.4 m: wetlands and swamps according to CORINE
- 0.4-0.8 m: wetlands and forest according to CORINE
- 0.8-1.3 m: wetlands and agricultural according to CORINE
- 1.3 m: wetlands and construction, rocks, quarries according to CORINE

Figure 3-12 shows the mean depth to the groundwater in centimetres below ground level. All areas, which were not classified as wetlands or not having soil types listed in paragraph above, have been designated as a groundwater-free soils. For all these areas it can be expected that the groundwater table is deeper than 1.3 m.

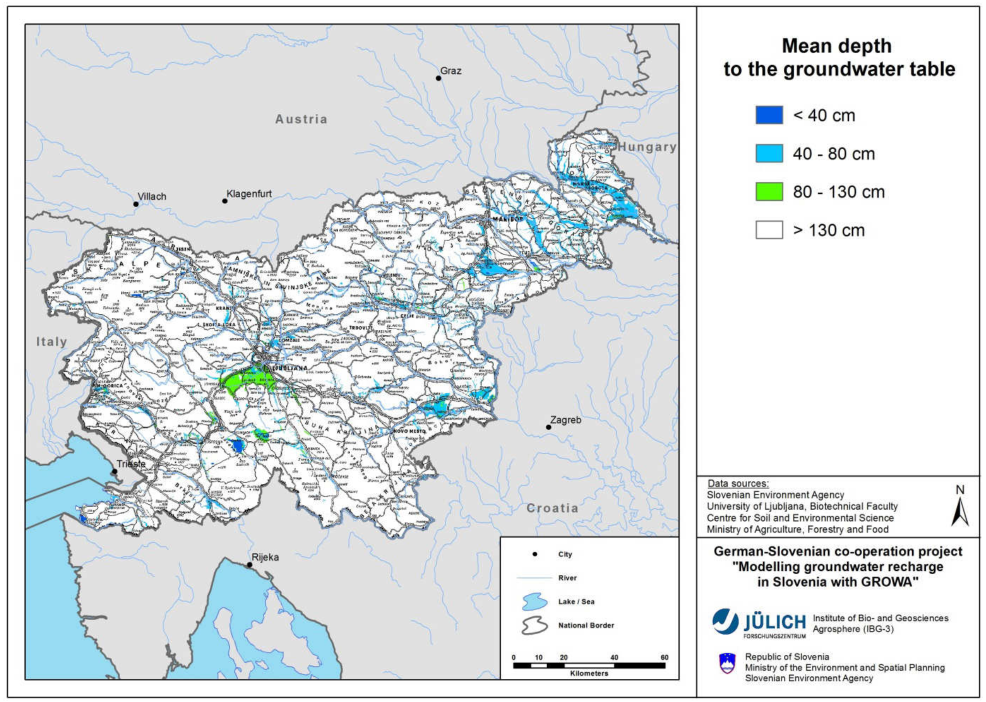

Figure 3-12: The mean depth to the groundwater table.

From Figure 3-12 it can be seen that the areas with high water table are limited only to some specific parts of the country. In total ca. 5.4% of Slovenia territory is dominated by groundwater influenced soils, like Eutric, Dystric and Mollic Gleysols and Histosols in marshy areas. Sites like that are widespread in the plains of the rivers Ledava, Pesnica, Polskava, Savinja, Krka, Pšata and Ljubljanica. In the upper

Sava river plains, in contrast, hardly any site is groundwater-affected, the only exception being extensive Ljubljana marshes.

Waterlogging tendency

Water logging tendency has an influence on the soil water balance, i.e. on evapotranspiration and runoff generation, and hence has been considered in the GROWA-SI model. As a general rule, a certain soil type with a perched water influence has a tendency to evaporate more water than the same soil type without water logging tendency.

For the derivation of a Slovenian water logging map, the digital Slovenian soil map 1:25,000 has been used, attributing waterlogging tendency to the Planosols according to FAO classification and to the Pseudogley according to Slovenian classification (Tič & Vrščaj, 2002; PKS, 2007).

Figure 3-13 shows the area of waterlogging of perched- and retained-water-affected soils. Strongly affected soils are predominantly located in the central and eastern parts of Slovenia with flat as well as hilly relief comprising ca. 4.6% of the entire country territory.

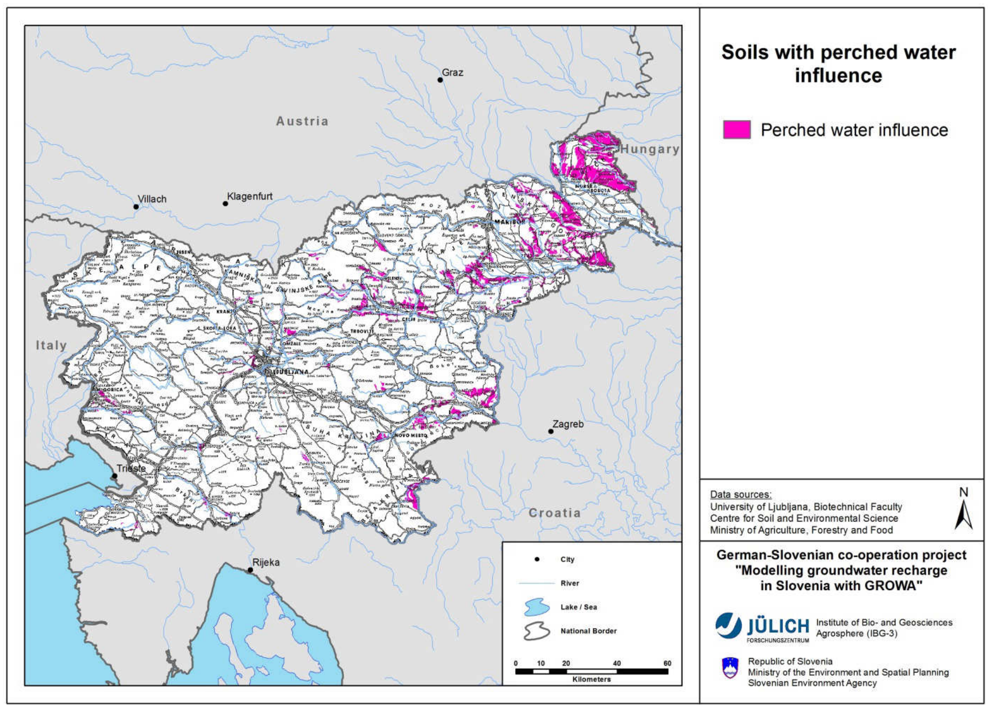

Figure 3-13: Soils with perched water influence.

3.4 *Hydrogeological data*

Hydrogeological data provide information on groundwater flow through consolidated and unconsolidated rocks. In the GROWA-SI model such information was used for spatial-related interpretation of the relevant runoff components.

Within the framework of the present study, different data bases have been used, which have been all incorporated in the information system “Database of hydrogeological data to define groundwater bodies of Slovenia” (BHP), developed by the Geological Survey of Slovenia as part of the activities for the European Water Framework Directive implementation (Prestor et al., 2006):

- Geological map (OGK1, 1967-1998; Buser, 2010)
- Aquifer Typology map (Drobne et al., 1976; Prestor et al., 2005)
- Hydrogeological map (Prestor et al., 2004)
- IDPR (Index of Development and Persistence of the River network) map (Mardhel et al., 2004)

In the following, at first the individual data bases are discussed in detail. This is followed by the introduction of the map of hydrogeological properties which has been developed in this project as an input data layer for the GROWA-SI model.

Geological map

For the present study the synthetic geologic map of geological units for Slovenia has been compiled, resulting in 30 different lithostratigraphic units. The stratigraphic division was done by taking into account the surface-near occurrence of the rock formations. The division of lithostratigraphic units according to their geological age was made by using the data both of the Basic geologic map of Yugoslavia 1:100,000 (OGK1, 1967-98) and the Geologic map of Slovenia 1:250,000 (Buser, 2010). Geological overview map (Figure 3-14) shows a nation-wide area distribution of the lithostratigraphic units in Slovenia, based on digitized data from both maps.

Figure 3-15 represents the spatial portions of the most important stratigraphic units in Slovenia shown in Figure 3-14. Quaternary rocks spread over 24% of the territory. In valleys they consist mainly of clay, sand and gravel, whereas in highland regions slope debris and moraine deposits predominate. Tertiary–Quaternary rocks cover only 2.6% of the territory and mainly represent clay and sand deposits. Tertiary rocks: marl, clay, sandstone, conglomerate and limestone cover one fifth of the territory 21%. Cretaceous rocks occupy 14.5% and consist of limestone and dolomite predominantly, flysch deposits being less common. Jurassic rocks, mainly limestone and dolomite, cover 8.2% of the territory. Triassic rocks cover 21.5% of Slovenian territory and are formed mainly by dolomite, limestone and less regular sandstone, marl, claystone and pyroclastic rocks. Paleozoic rocks spread over ca. 8% of the

Slovenian territory. They comprise mainly sandstones and conglomerates, as well as igneous and metamorphic rocks.

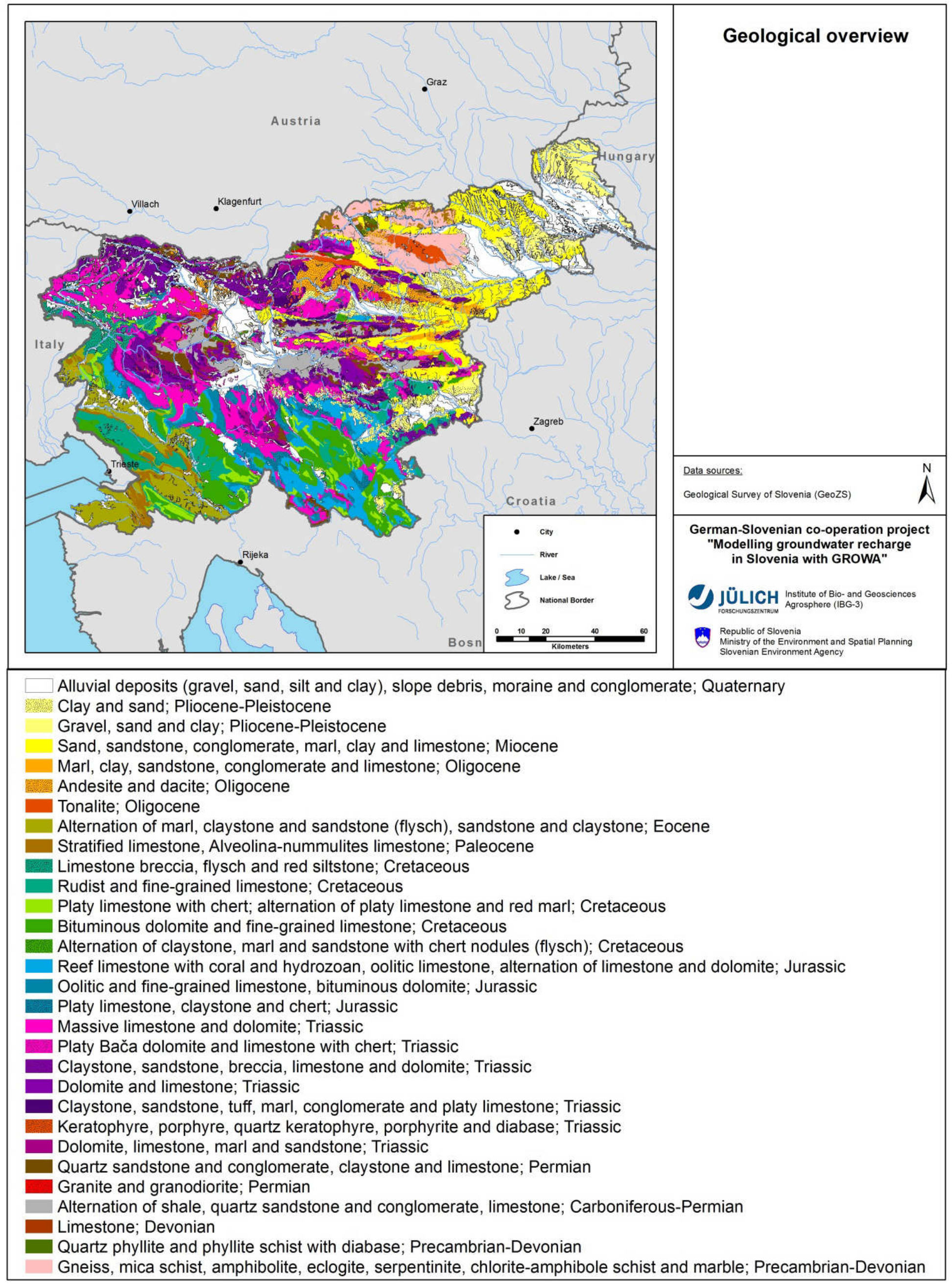

Figure 3-14: Geological overview of Slovenia, compiled from basic geological map of SFRJ 1:100,000 (OGK1, 1967-1998) and basic geological map of Slovenia 1:250,000 (Buser, 2010).

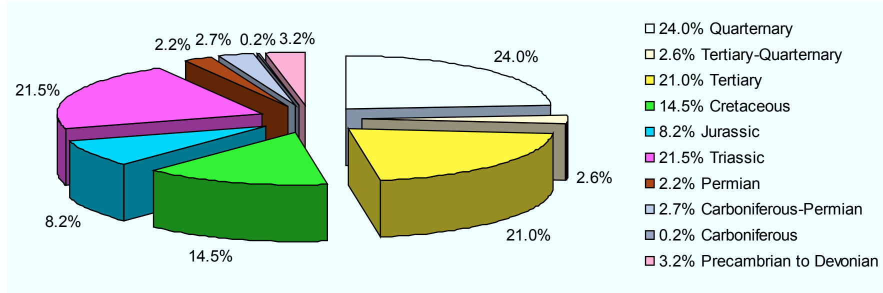

Figure 3-15: Frequency distribution by area of the most important stratigraphic units in Slovenia.

Pleistocene and Holocene gravel and sand sediments represent the most important groundwater bearing formations in Slovenia. They predominate in the river valleys (see Figure 3-14) (Drobne et al., 1976). At Kranjsko polje, Sorško polje, Ljubljansko polje and Ljubljansko barje plains in the upper Sava river, sediments reach a thickness over 100 m. Shallower are the river sediments in the tectonic depressions of Krško-Brežiška kotlina of the lower Sava river and Spodnja Savinjska dolina: thickness there is on average ten to twenty metres of Quaternary gravel and sand sediments. The Quaternary sediment of the Dravsko polje of the Drava river aquifer is only sporadically thicker than 20 m. The situation is quite similar at by area the largest alluvial aquifer, along the Mura River.

Apart from sand and gravel aquifers, there are groundwater bearing layers in limestones, dolomite limestones, sandstones and marls of the Mesozoic age. Karst porosity is typical for the limestone layers, which had been fractured due to the tectonic movements, and were later karstified. Aquifers with high karst porosity are located at the large continuous areas in the western and southern parts of Slovenia, from the Julian Alps to the Dinaric karst. For the dolomite layers, above all, fissure porosity is characteristic. Less water-abundant layers with low permeability are located in the carbonates in the area of Idrija and Škofjeloško hribovje, between Ribnica and Ljubljansko barje, on Gorjanci mountain and south from Kočevje. The thickness of the aquifers with karst and fissure porosity can reach several hundred or even over a thousand metres. Sandstones, claystones and marls are occurring in the central part, and in the south-western and north-eastern part of Slovenia, of which only the marls are locally important for water supply. Around 7% of Slovenian territory comprise of igneous, pyroclastic and metamorphic rocks. These rock types can predominantly be found in the eastern part of the Alps macro region and display low to no groundwater bearing properties.

Aquifer Typology

Information about aquifer typology is used in the GROWA-SI model in order to determine groundwater recharge, as the lithologic character and the hydrodynamic properties of rock complexes are more important for the assessment of groundwater recharge in an area than it is their stratigraphic position (Wendland et al., 2008). The geological entities that can transmit and accumulate groundwater are aquifers with intergranular, fissured and karst porosity.

Based on the geological overview (Figure 3-14) an aquifer typology map was derived applying the German LAWA classification system (Drobne et al., 1976; Prestor et al., 2005). This classification takes into account the type of rock porosity. For this purpose the rocks near the surface have been subdivided into the aquifer typology classes: intergranular porosity - unconsolidated rocks predominantly, fissured porosity - hard rocks predominantly, karst porosity - limestones and dolomites, and special cases - low permeability rocks. In case of areas, where very complex hydrogeological systems with small scale changing lithologies occur, only the prevailing rock type was considered for the designation of aquifer typologies. Furthermore, the expert knowledge of geologists has been incorporated. The resulting aquifer typology map and the frequency distributions of the rock types according to LAWA classification are shown in Figure 3-16 and Figure 3-17 respectively.

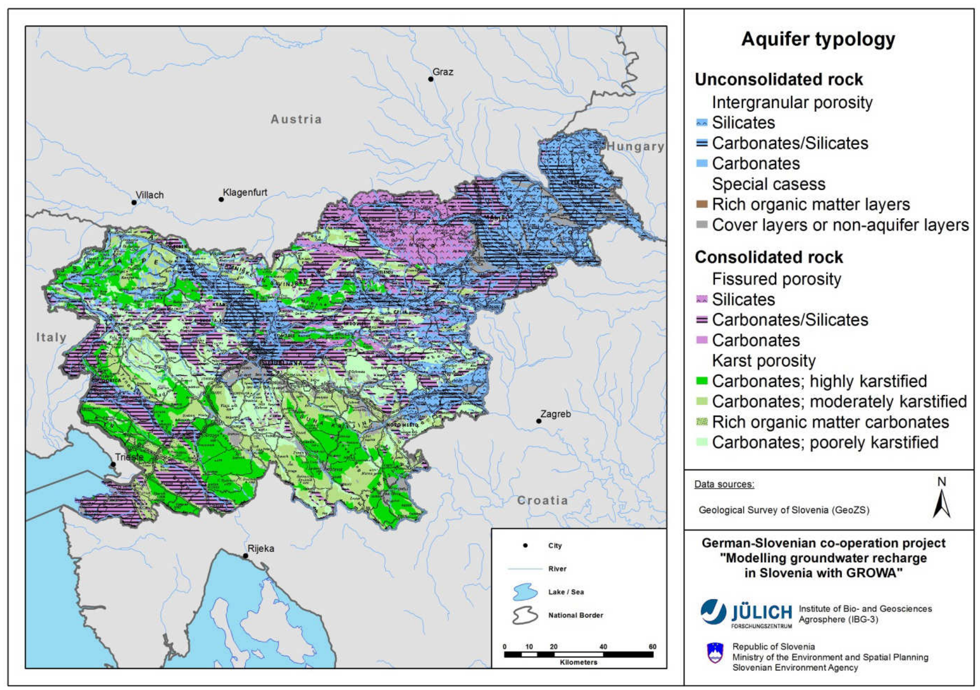

Figure 3-16: Aquifer typology in Slovenia according to LAWA classification (Prestor et al., 2005).

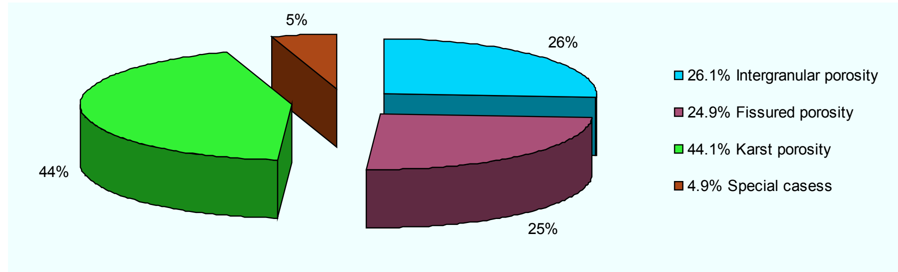

Figure 3-17: Frequency distribution of rock types in Slovenia according to LAWA classification.

From Figure 3-17 it is seen that prevailing intergranular porosity occurs in 26% of Slovenia, whereas fissured rock porosity is predominant in 25% of the territory. Karst porosity predominates in 44% of the country. The special cases, i.e. impermeable rocks, represent merely 4.9% of the territory. Aquifers with intergranular porosity, also called alluvial aquifers, are from the Tertiary and Quaternary age. Larger rivers have deposited layers of flatland gravel and sand into tectonic depressions. They are found in the central, eastern and north-eastern parts of Slovenia. Such flatland regions are, for example, in the valleys of the rivers Sava, Savinja, Krka, Mura and Drava. Aquifers with karst and fissure porosity are in areas of carbonate rocks, mostly limestone and dolomite from the Mesozoic age. They can be found in the northern, north-western, western and southern parts of Slovenia, mostly in the Alps and Dinaric macro regions. These are the mountainous karst regions of the Julian Alps, the Karavanke, the Kamnik and the Savinja Alps, as well as the karst regions of Notranjska, Dolenjska and Primorska.

Hydrogeological map

Figure 3-18 shows the water-bearing rock strata in Slovenia derived by Geological Survey based on geological map OGK1 (1967-98) (Figure 3-14) according to IAH standard, which is based on hydraulic conductivity of the aquifer (Prestor et al., 2004).

The coefficient of hydraulic conductivity of the Quaternary deposits frequently range between $1x10^{-5}$ m/sec and $5x10^{-3}$ m/sec, depending on the lithologic character of the sediments. Semisolid sandy rocks form productive aquifers. A primary fast flow system, similar to a karst aquifer, can be differentiated from a secondary flow system having a more effective retention. These rocks have hydraulic conductivity ranging from $1x10^{-7}$ m/sec to $1x10^{-5}$ m/sec. Much higher hydraulic conductivity is to be expected for the limestones and dolomites due to karstitication, mostly more than $5x10^{-3}$ m/sec. The groundwater in metamorphic consolidated rocks of the Pohorje Mountain flows mainly through a system of tight fissures. Therefore, these rocks have in part extremely low coefficient hydraulic conductivity, less than $1x10^{-9}$ m/sec, governed by the opening of the fissures.

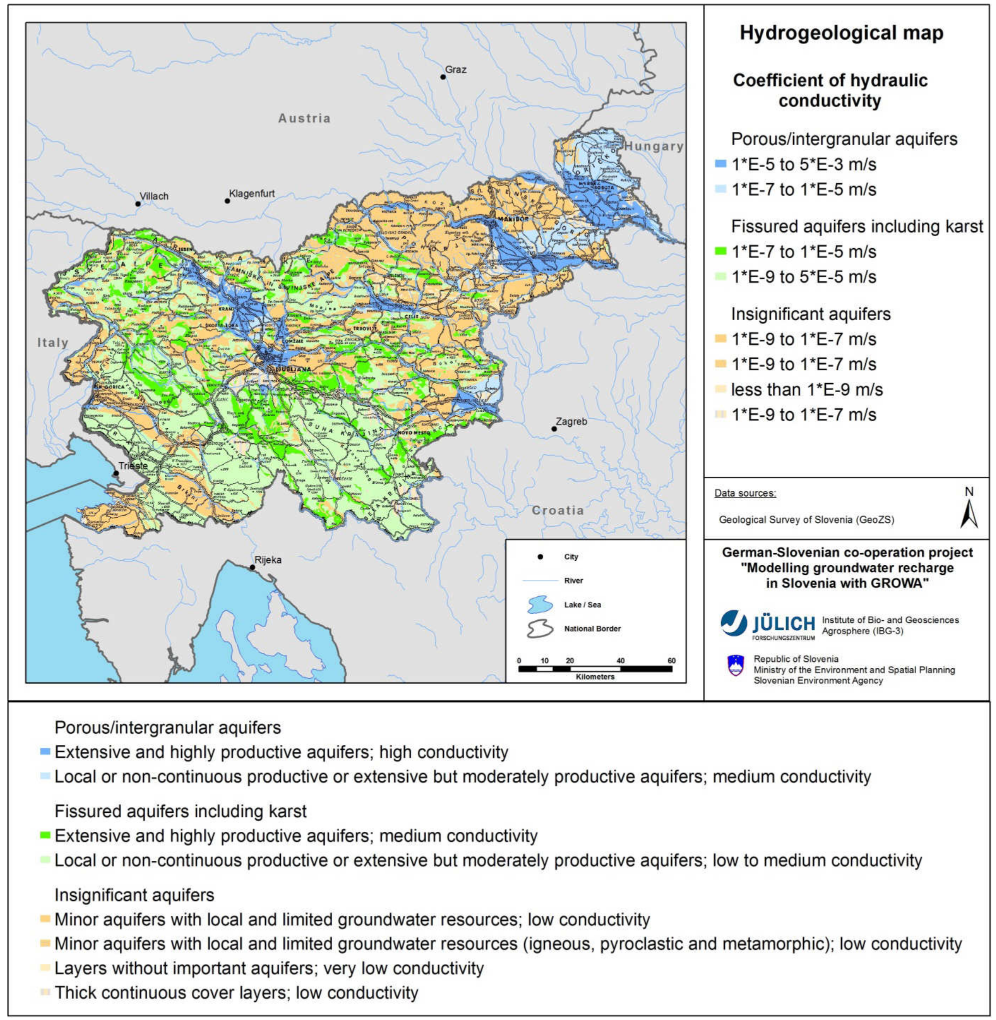

Figure 3-18: Hydrogeological map of Slovenia according to IAH classification (Adapted from Prestor et al., 2004).

IDPR map

Index of Development and Persistence of the River network, the so called IDPR index (Mardhel et al., 2004), is calculated in a complex process of evaluating the spatially distributed ratio between actual river network and the theoretical drainage network derived from digital relief model. The philosophy behind the method is that low density of the river network in a certain region is reflected in a low IDPR index, which itself indicates a high portion of infiltration and groundwater recharge respectively. In this way, regions with prevailing IDPR indices below 1 correspond to regions with a high portion of infiltration. Accordingly, an IDPR Index of 1 indicates a region, where the infiltration (groundwater recharge) and direct runoff are balanced, while IDPR indices higher than 1 correspond to areas where direct runoff is predominant. The IDPR concept was used in Slovenia in the process of deriving the infiltration map of Slovenia prior to the GROWA-SI project, being a part of the Map of aquifers and groundwater systems of Slovenia 1:250,000 (Prestor et al., 2005), produced for groundwater body delineation.

Figure 3-19 shows the IDPR indices calculated for Slovenia in spatial resolution of 100 m x 100 m.

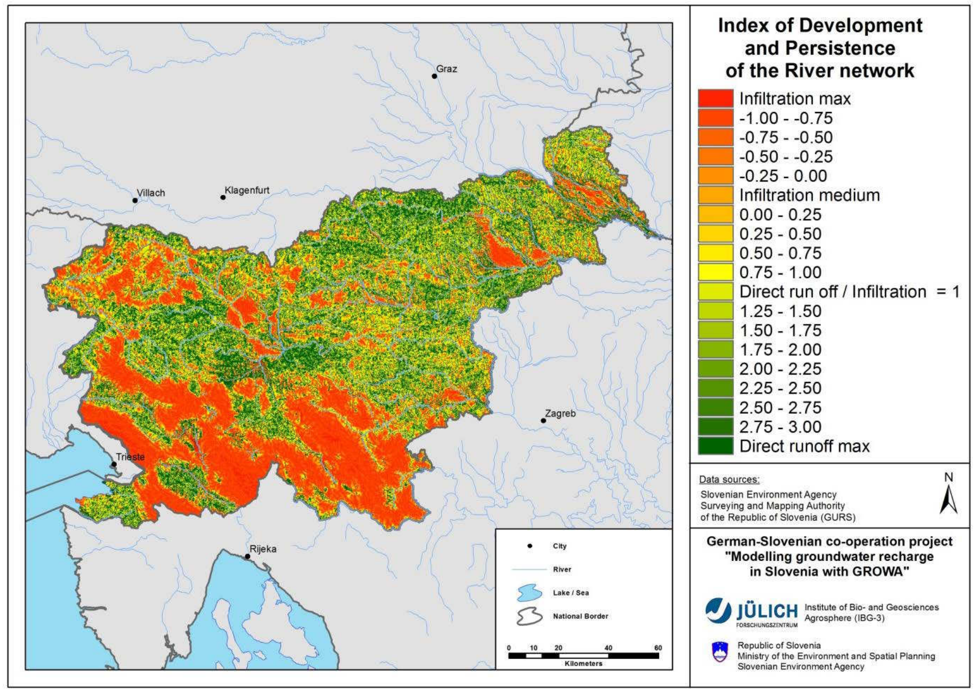

Figure 3-19: Map of IDPR values for Slovenia (adapted from Mardhel et al., 2004).

Figure 3-19 indicates that the highest water infiltration occurs in areas of karstified carbonate rocks, i.e. mostly in the Dinaric and the Alps macro regions, as well as in intergranular porosity alluvial aquifers along the major rivers. The lowest infiltration occurs in areas of flysch rocks of the Mediterranean macro region, at Pohorje mountain of igneous and metamorphic rocks in the east of the Alps macro region and in central Slovenia where Paleozoic claystones and quartz sandstones prevail.

Compared to the BFI concept used in the GROWA-SI project for assessing the portions of baseflow runoff (= groundwater recharge) in total runoff, it becomes evident, that the IDPR scale of indices is inverted to the scale of BFI values. Thus, regions with dominant infiltration (groundwater recharge) are represented by low values on the scale of IDPR indices (< 1) and high BFI values (0.7 – 1.0).

3.5 Topography data

Topography has a great influence on the regional water balance. Firstly, slope inclination and aspect are affecting the level of actual evapotranspiration and, secondly, the inclination serves as an input parameter for determining the baseflow fraction of total runoff (see Chapter 2). An area-wide digital relief model with a resolution of 100 m (DMR100) was made available by the Surveying and Mapping Authority of the Republic of Slovenia (GURS, 2000). On the basis of this relief model, the aspect and inclination were derived area-wide for Slovenia. The inclination calculated from the DMR100 (Figure 3-20) reflects the geological structures in Slovenia. Particularly flat regions with inclinations of less than 1% are the lowlands in the north-eastern part of Slovenia, which are often associated with the occurrence of unconsolidated rocks.

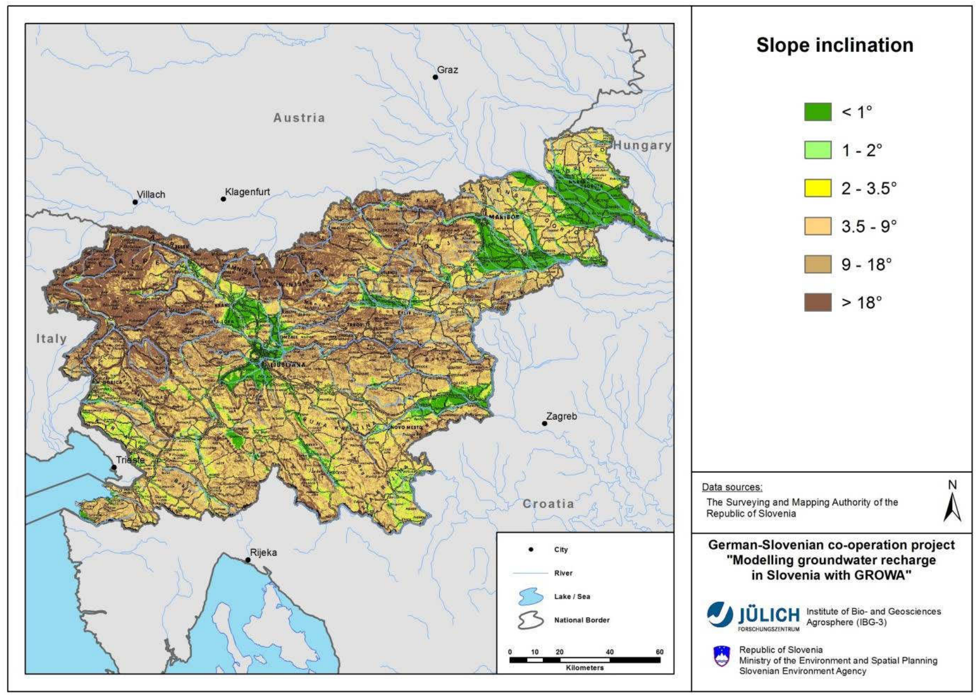

Figure 3-20: Slope inclinations in Slovenia.

The high erosion energy of the Alps relief clearly distinguishes itself from the lowland regions by gradients mostly above 3.5%. Here, on the one hand, the distribution of the differently erosion prone rocks, and, on the other hand, the river systems that deeply cut into the mountains are clearly reflected. The highest inclinations occur in the Julian Alps, Karavanke and Savinja Alps, where the maximum values can exceed 30%.

Figure 3-21 shows the aspect which also reflects the relief of the land surface in Slovenia in a high resolution manner. For example, the relatively broad valleys of the rivers Mura, Drava and Sava could be clearly distinguished from the highly resolved river systems in hilly and mountainous regions.

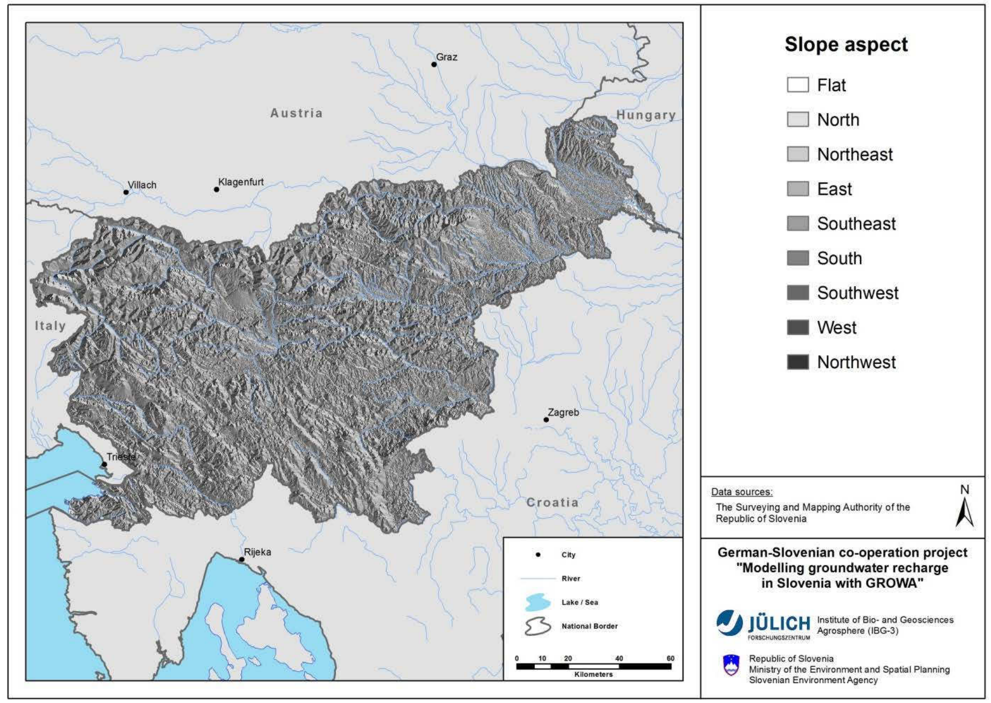

Figure 3-21: Slope aspects in Slovenia.

3.6 Discharge data

Runoff data from the Slovenian hydrological network of gauging stations were used for the calibration of the GROWA model and the final validation of the model results. Data were collected, processed and made available by national hydrological service of Slovenian Environment Agency (ARSO, 2010b). For the validation of GROWA model results a database was established, which contains daily means of discharge at gauging stations, covering catchment areas of more than 80% of Slovenia territory. Additionally, only gauges were selected with a continuous time series of measured data over ten years within the considered period 1971-2000. In this way a data base was created which comprises data of mean daily discharge from 95 catchments. The 95 gauges represent different sizes of catchment areas, from ca. 20 to ca. 10,000 km^2, and a wide range of climatological, geological and pedological site situations.

Mean long-term discharge values were used to validate mean long-term total runoff calculated by GROWA-SI (Chapter 5.1). Mean daily discharge values were used to derive monthly means for low flow runoff data (MoLR values) by Kille method (see Chapter 2.3.1), which were needed to calibrate and validate modelled groundwater recharge rates as described in Chapter 2.3.3 and Chapter 5. While data from all 95 gauging stations were used for validation of total runoff, for groundwater recharge calibration and validation only those gauging stations were used where data satisfied Kille method conditions. In Table 3-4 are listed all 95 catchments gauging stations considered, together with information on catchment area and mean annual discharge MQ used for total runoff validation.

Table 3-4: Gauging stations used for the validation of the GROWA model results for long-term period 1971-2000 (ARSO, 2010b).

ID	Gauging station	River	Catchment area [km²]	Observed mean annual total runoff MQ [mm/a]
1140	Pristava I	Ščavnica	273	238
1150	Branislavci	Turja	42	199
1220	Polana I	Ledava	208	224
1260	Čentiba	Ledava	857	233
1300	Martjanci	Martjanski potok	28	176
1310	Kobilje	Kobiljski potok	49	179
1350	Hodoš	Velika Krka	105	136
2220	Črna	Meža	95	751
2250	Otiški vrh I	Meža	551	701
2370	Dovže I	Mislinja	73	842
2390	Otiški vrh I	Mislinja	231	646
2420	Stari trg I	Suhodolnica	59	633
2530	Ruta	Radoljna	74	879
2600	Zreče	Dravinja	41	664
2640	Makole	Dravinja	302	495
2652	Videm	Dravinja	764	272
2670	Draža vas	Oplotnica	86	642
2720	Podlehnik	Rogatnica	57	451
2754	Tržec	Polskava	188	399
2830	Ranca	Pesnica	84	453
2880	Gočova	Pesnica	281	341
2900	Zamušani I	Pesnica	478	337
3060	Jesenice	Sava Dolinka	258	1,218
3100	Mojstrana I	Bistrica	46	1,678
3180	Podhom	Radovna	167	1,451
3220	Soteska I	Sava Bohinjka	288	2,008
3250	Bodešče	Sava Bohinjka	364	1,955
3465	Okroglo	Sava	1,201	1,379
3530	Medno	Sava	2,202	1,185
3650	Litija I	Sava	4,821	1,035
3725	Hrastnik	Sava	5,177	970
3850	Čatež I	Sava	10,186	834
4050	Preska	Tržiška Bistrica	121	1,239
4120	Kokra I	Kokra	112	1,164
4215	Žiri Ii	Poljanska Sora	54	1,301
4230	Zminec	Poljanska Sora	306	1,086
4270	Železniki	Selška Sora	104	1,233
4298	Vešter	Selška Sora	214	1,080
4400	Kamnik I	Kamniška Bistrica	195	1,163
4480	Nevlje I	Nevljica	82	677
4520	Podrečje	Rača	164	932

ID	Gauging station	River	Catchment area [km^2]	Observed mean annual total runoff MQ [mm/a]
4630	Zagorje I	Medija	97	710
4650	Žebnik	Sopota	48	811
4660	Martinja vas I	Mirna	164	513
4695	Jelovec	Mirna	270	492
4705	Orešje	Sevnična	40	525
4740	Rakovec I	Sotla	560	674
4790	Zagaj I	Bistrica	94	585
4970	Gradac	Lahinja	221	802
5080	Moste	Ljubljanica	1,763	1,010
5330	Borovnica	Borovniščica	35	1,031
5420	Iška	Iška	67	876
5500	Dvor	Gradaščica	79	922
5540	Razori	Šujica	47	911
6020	Solčava I	Savinja	64	1,082
6060	Nazarje	Savinja	457	1,133
6068	Letuš I	Savinja	530	1,148
6140	Celje II- brv	Savinja	1,189	829
6210	Veliko Širje I	Savinja	1,842	757
6220	Luče	Lučnica	58	1,359
6280	Velenje	Paka	63	549
6300	Šoštanj	Paka	131	557
6340	Rečica	Paka	205	595
6550	Dolenja vas II	Bolska	170	710
6630	Levec I	Ložnica	103	476
6690	Črnolica	Voglajna	54	510
6720	Celje II	Voglajna	202	516
6760	Grobelno	Slomski potok	49	457
6770	Polže	Hudinja	69	500
6790	Škofja vas	Hudinja	156	476
6835	Vodiško I	Gračnica	97	574
7030	Podbukovje	Krka	321	705
7070	Srebrniče	Krka	1,313	938
7160	Podbočje	Krka	2,238	731
7200	Mlačevo	Grosupeljščica	34	532
7220	Rašica	Rašica	58	830
7270	Meniška vas	Radešca	287	722
7310	Rožni vrh	Temenica	81	305
7340	Prečna	Prečna	294	460
7370	Klevevž	Radulja	48	610
7380	Škocjan	Radulja	108	521
7440	Sodražica	Bistrica	30	843
8030	Kršovec	Soča	158	2,268
8080	Kobarid I	Soča	437	2,551
8180	Solkan I	Soča	1,573	1,782
8455	Cerkno II	Cerknica	40	1,304
8480	Dolenja Trebuša	Trebuša	55	1,589
8500	Bača pri Modreju	Bača	142	1,481
8560	Vipava I	Vipava	132	1,565
8600	Miren	Vipava	590	928
9050	Cerkvenikov mlin	Reka	378	754
9210	Kubed II	Rižana	204	664

ID	Gauging station	River	Catchment area [km²]	Observed mean annual total runoff MQ [mm/a]
9280	Pišine I	Drnica	30	280
9300	Podkaštel I	Dragonja	93	506

4 Model results

The details associated with the basic GROWA model procedures are presented in section 2 and will not be repeated here. In this chapter the long-term annual averages 1971-2000 of water balance calculations with the GROWA model adapted to Slovenian site conditions (GROWA-SI) are presented. This chapter includes maps showing real evapotranspiration, total runoff, direct runoff and groundwater recharge. With regard to the presented runoff components it should be emphasized again, that the maps show the runoff of the individual runoff components generated in Slovenia for the basic grid cells 100m x 100m and do not include the water quantities of the rivers passing through Slovenia. Additionally, a statistical analysis for the main river basins and subbasins in Slovenia (see Figure 4-1) is carried out in order to provide an overview of their hydrological characteristics. For this purpose the arithmetic mean, the median, the 10 percentile and the 90 percentile are presented.

Chapter 4.3 contains an evaluation of the runoff ratio of the runoff components: direct runoff and groundwater recharge, which allows a more in-depth and more extensive assessment of the water balance situation in Slovenia.

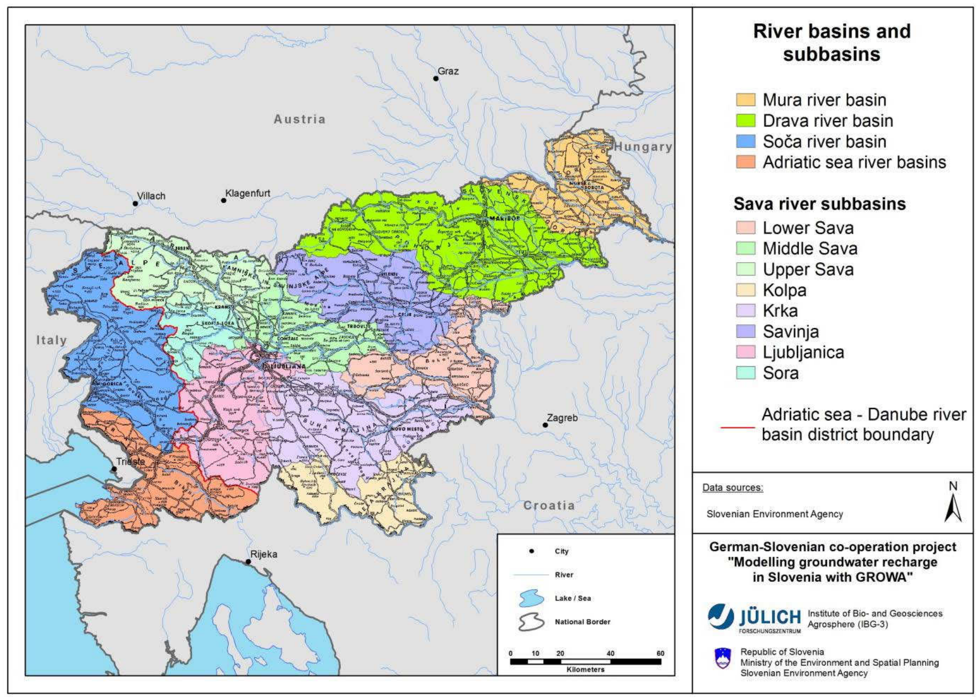

Figure 4-1: Main river basins and subbasins in Slovenia.

4.1 Actual evapotranspiration

Figure 4-2 shows the area distribution of actual evapotranspiration of the long term period 1971-2000 calculated in Slovenia. Actual evapotranspiration values show a great variability reflecting in general sense both the precipitation pattern and vegetation cover as it is e. g. represented for the Soča river basin in the west. In the Soča headwaters in the Julian Alps, where at high altitudes above tree line barren rocks prevail, actual evapotranspiration is low (<250 mm/a). Downstream of Bovec to the river outflow from Slovenia at Nova Gorica in the Mediterranean macro region thick forests in the Soča valley contribute to some of the highest actual evapotranspiration in the country (>800 mm/a). A belt of high actual evapotranspiration continues from Nova Gorica to the southeast to Brkini and Mt. Snežnik following high precipitation belt (compare Fig. 3-1 in Ch. 3). Apart from the high altitude belt in Julian Alps low actual evapotranspiration in the same range have been also modelled for the high altitude carbonate rock - lithosols in the Kamnik-Savinja Alps, where the lowest actual evapotranspiration rates, <250 mm/a, are bound to outcrop of barren rocks. Actual evapotranspiration below 400 mm/a, was calculated for the urbanised regions like Ljubljana.

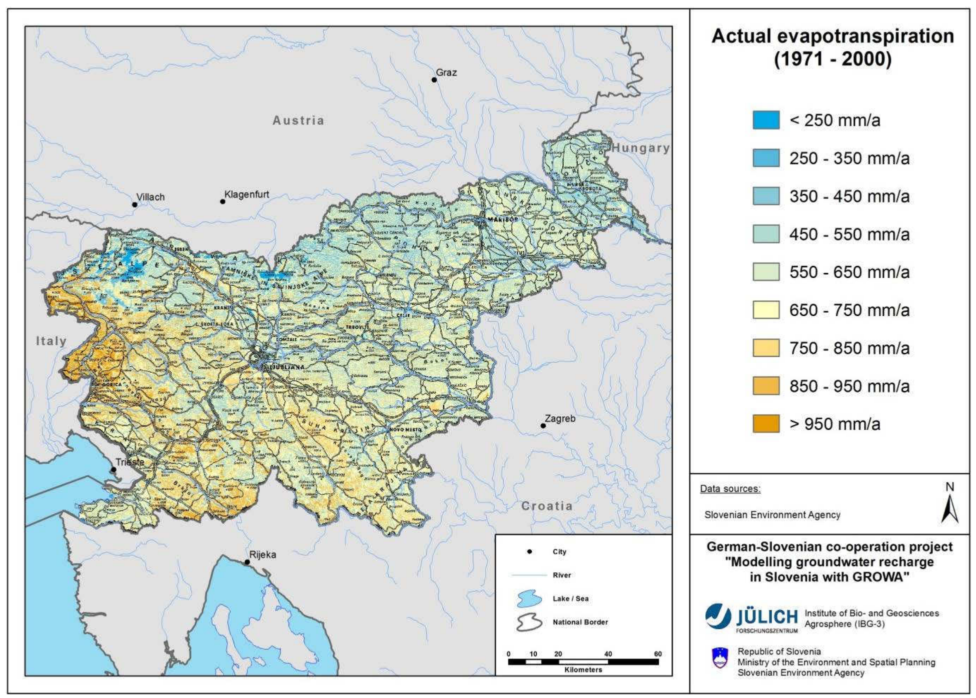

Figure 4-2: Calculated actual evapotranspiration in Slovenia.

In the lowland region in the north-eastern part of Slovenia in the Pannonian macro region, relatively low actual evapotranspiration values, i.e. 450 to 550 mm/a, were obtained for the arable lands, although the potential evapotranspiration is quite high, i.e., up to more than 750 mm/a. This is due to the low annual precipitation level of less than 900 mm/a.

At a smaller scale, especially in the hilly regions, there may be great differentiations of actual evapotranspiration depending on aspect and inclination. Thus, in the foothills of the Julian Alps, the Kamnik-Savinja Alps, Karavanke and at Pohorje mountain large differences in actual evapotranspiration can occur between northerly and southerly exposed slopes with otherwise identical characteristics.

In areas, where deciduous (broad-leaved) forests occur actual evapotranspiration rates are typically above 700 mm/a. The same actual evapotranspiration rates occur at the groundwater-affected sites of Ljubljana Marshes in central Slovenia, since there an additional supply from the groundwater takes place and, in addition, the water storage capacity of the soil is relatively high.

The frequency distribution of the calculated actual evapotranspiration in Slovenia (Figure 4-3) shows that about 65% of the values are in a range between 500 and 800 mm/a, while about 90% of values are in the range from 400 to 900 mm/a. The median value of the actual evapotranspiration rate is 644 mm/a. In the case of the actual evapotranspiration the arithmetic mean (643.6 mm/a) and the median (644.0 mm/a) are nearly identical due to the symmetrical distribution.

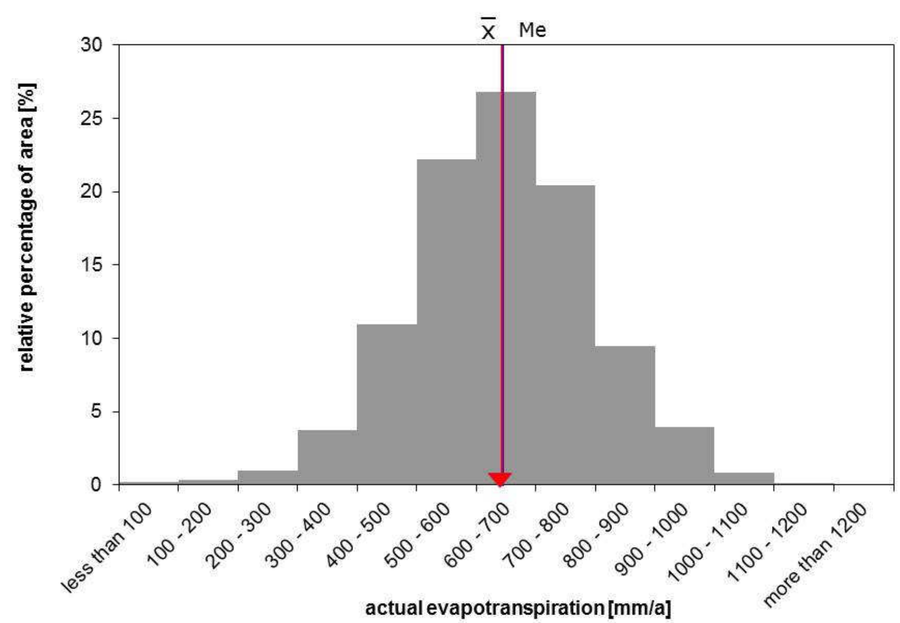

Figure 4-3: Frequency distribution of the calculated actual evapotranspiration in Slovenia.

The median values of the actual evapotranspiration for main Slovenian river basins is in the range between ca. 550 mm/a in the Mura basin and ca. 770 mm/a in the Soča river basin (Table 4-1). With regard to the centrals, 80% of the frequency distribution is in a quite narrow range for the Mura river basin (470 to 650 mm/a) and a wider range for the Soča river basin (470 to 970 mm/a).

Table 4-1: 10th percentiles, 90th percentiles and medians of calculated actual evapotranspiration in river basins and subbasins of Slovenia in mm/a.

	Catchment area [km^2]	10th percentile	90th percentile	Median
Sava river subbasins				
Lower Sava	1,334	463	772	637
Middle Sava	1,180	424	802	631
Upper Sava	1,527	337	777	607
Kolpa	1,103	513	840	691
Krka	2,252	507	817	676
Savinja	1,853	406	783	630
Ljubljanica	1,864	492	846	690
Sora	648	462	881	683
Sava river basin	11,759	452	813	654
Mura river basin	1,393	476	654	556
Drava river basin	3,271	427	726	594
Soča river basin	2,339	474	971	772
Adriatic rivers basin (without Soča)	1,512	519	898	704
Adriatic sea catchment	3,851	499	946	742
Black sea catchment	16,422	450	794	627
Slovenia	20,274	457	837	644

4.2 Total runoff

Regarding the total runoff generated, the territory of Slovenia can be broadly divided in three zones (Figure 4-4). In the Mediterranean macro region in the coastal region and in the classical Karst above the Trieste Bay to the Brkini, the total runoff is generally below 1,000 mm/a. In the belt of the west part of Dinaric Alps and the Alps in the northwest and the north of Slovenia occurs a high total runoff above 1,000 mm/a, mostly above 1,600 mm/a. Almost half of the country east of Ljubljana displays total runoff less than 1,000 mm/a, the values steadily diminish in north-eastern direction. Accordingly, in the lowland regions in the north-eastern part of Slovenia prevail total runoff values less than 400 mm/a. Values of less than 200 mm/a are to be found in the utmost north-eastern region of Goričko in the Pannonian macro region. The only exception in the east is Pohorje mountain range, being a part of the Alps macro region, where total runoff can reach ca. 1,500 mm/a. Generally, total runoff above 1,600 mm/a is predominating in the mountainous regions of the large parts of the Alps macro region. In the high Julian Alps values of even more than 2,500 mm/a can be reached, since it is the region of both the highest precipitation and at the same time of the lowest actual evapotranspiration. The urbanized regions in central part of Slovenia are characterized by total runoff between 600 and 800 mm/a.

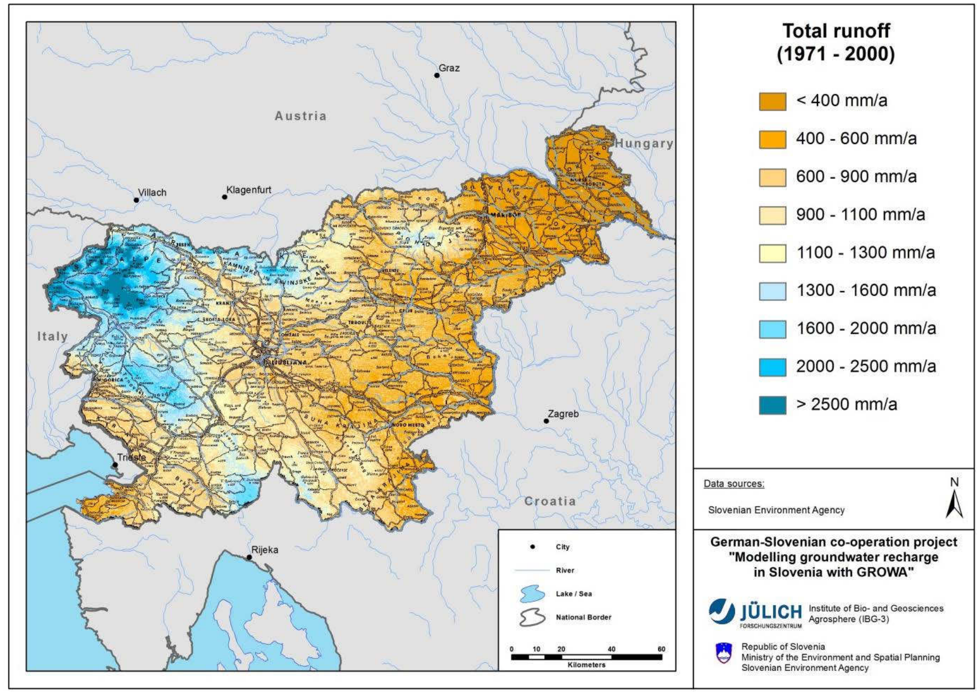

Figure 4-4: Calculated total runoff in Slovenia.

Figure 4-5 shows the frequency distribution of the generated total runoff in Slovenia. Frequency distribution exhibits a distinct positive skewness. Hence, there is a predominance of values in the lower classes, while values in higher classes occur with decreasing frequency. The maximum of the distribution is formed by the class of total runoff from 400 to 600 mm/a, in which is ca. 23% of the territory. Total runoff below 200 mm/a was calculated for only about 2% of the territory. Due to the positive skewness of the distribution of the total runoff, the median calculated for the whole Slovenia 717 mm/a, is ca. 100 mm/a lower than the arithmetic mean.

Table 4-2 shows the median as well the 10th percentile and 90th percentile of the total runoff distribution for the main river basins and subbasins of Slovenia. The medians of the total runoff values vary significantly among river basins. The Mura basin exhibits the lowest median value, ca. 250 mm/a. The highest median value of total runoff is for the Soča river basin, where it amounts to nearly 1,500 mm/a.

Also, the total runoff values at the 10th and 90th percentile within the same basin, display a wide scattering. Even in the climatically relatively homogeneous lowland region, e.g. the Mura basin, the difference between the 10th and 90th percentile value can amount to more than 190 mm/a. This reflects the high variability at small-scale of pedological and hydrological conditions as well as the land cover taken into account in the GROWA-SI model calculation.

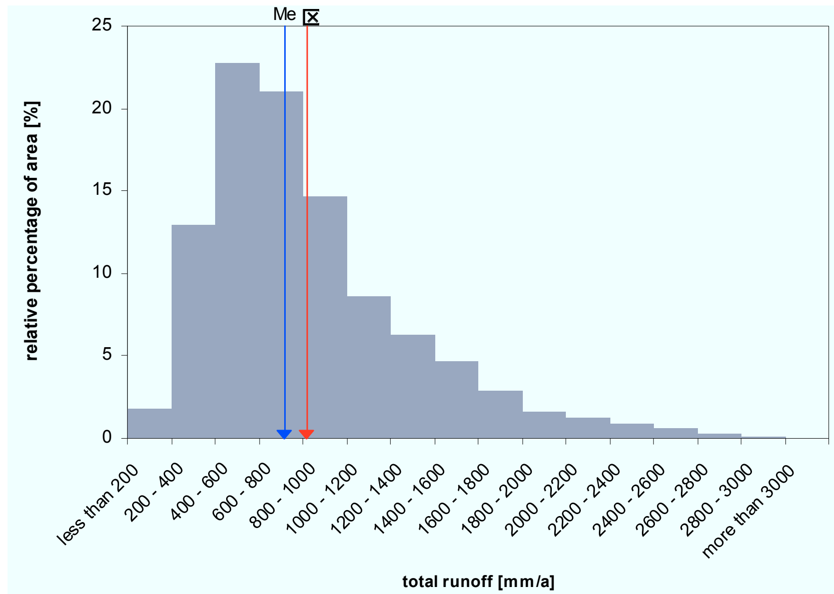

Figure 4-5: Frequency distribution of the calculated total runoff in Slovenia.

Table 4-2: 10th percentiles, 90th percentiles and medians of the calculated total runoff in river basins and subbasins of Slovenia in mm/a

	Catchment area [km²]	10th percentile	90th percentile	Median
Sava river subbasins				
Lower Sava	1,334	338	688	478
Middle Sava	1,180	510	983	696
Upper Sava	1,527	829	2,057	1,294
Kolpa	1,103	453	1,146	707
Krka	2,252	406	919	592
Savinja	1,853	444	1,058	660
Ljubljanica	1,864	639	1,381	993
Sora	648	809	1,502	1,158
Sava river basin	11,759	441	1,352	745
Mura river basin	1,393	159	351	258
Drava river basin	3,271	315	816	498
Soča river basin	2,339	832	2,245	1,494

Adriatic rivers basin (without Soča)	1,512	509	1,174	789
Adriatic sea catchment	3,851	643	2,059	1,151
Black sea catchment	16,422	319	1,245	645
Slovenia	20,274	342	1,483	717

4.3 Predominating runoff components

In the basic GROWA model procedure (Kunkel & Wendland, 2002) groundwater recharge is determined by separating the calculated total runoff into the components of direct runoff and groundwater recharge. According to Peschke (1997), the average groundwater recharge corresponds in long-term considerations essentially to the baseflow component. Following Dörhöfer & Josopait (1980), Hennings ed. (2000) and Kunkel & Wendland (2002), the baseflow component can be determined as a relative fraction of total runoff by so-called "baseflow indices" (BFI). In this way, groundwater recharge is expressed as a relative fraction of the total runoff. On the basis of the spatial distribution of the determined total runoff and the BFI values the regional predominating runoff component can be identified in an area differentiated way. In this case BFI values higher than 0.5 indicate that groundwater recharge is prevailing. Otherwise, in the case of BFI values lower than 0.5 the predominating proportion of total runoff is direct runoff. The process of BFI determination for Slovenian territory was modified in GROWA-SI, as described in following paragraphs.

In case of unconsolidated rocks BFI values for grid cells within the catchment were determined as described in Chapter 2.3.3 (see Table 2-3).

In case of hard rocks, in the GROWA-SI for the initial iteration step Slovenian classes of BFI based on Kennessey coefficient of permeability Cp (Kennessey, 1930) and corrected by IDPR indices had to be transferred to the BFI German classes (for German classes see Table 2-4 in Chapter 2.3.3). Later on, in the iterations of the calibration process relative relations between BFIs were checked by IDPR indices to get an overall adjusted set of values. In a special case of karstified carbonate rocks, data of Slovenian cave inventory (CAVE REGISTRY, 2012) and hydrogeological map of Slovenia according to LAWA classification (Figure 3-16) were used to adjust BFIs, so taking into account the degree of karstification.

For the calculation of BFI values of catchments in Slovenia the MoMLRr-method according to Kille (1970) was used. As described previously in Chapter 2.3.2, 41 different site properties for BFIs, were identified. Out of total 95 gauging stations (Table 3-4 in Chapter 3.6) used in calibration and validation of the GROWA-SI model results for total runoff, 46 stations were applied for calibration of BFI (Figure 4-6), while 27 out of remaining 59 stations were set aside and used later as an independent data set in validation of groundwater recharge (Tetzlaff et al., 2015). In this way, a set of BFI values was obtained, which leads to an optimal fit for the ensemble of catchment areas under consideration. This parameter set was then applied area-wide to the whole of Slovenia.

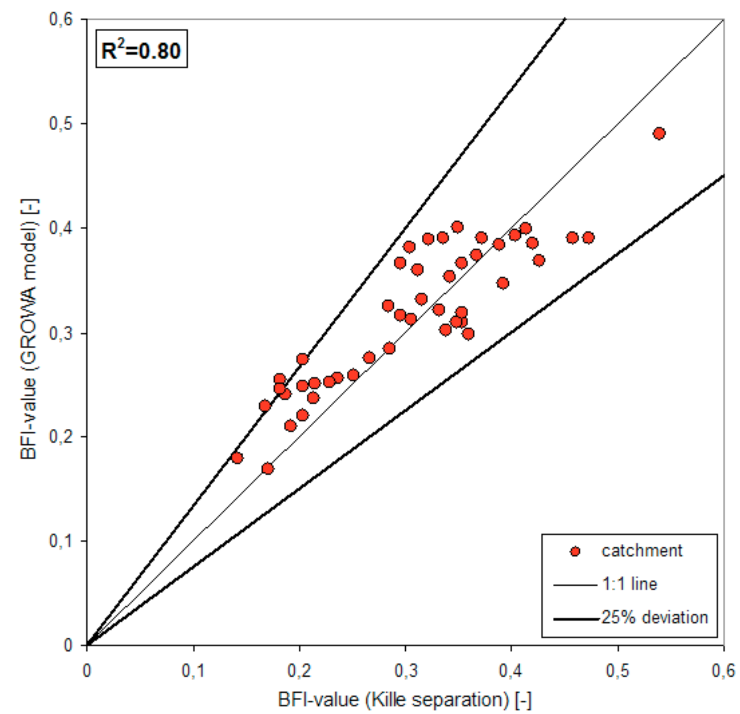

Figure 4-6: Comparison of measured and calculated BFI-values for the 46 catchment areas in Slovenia used for BFI calibration.

As it is shown by the correlation diagram in Figure 4-6, a good agreement between the baseflow fractions obtained from applying the 46 BFI values and the measured baseflow fractions of the total runoff is reached using the method presented. This is also documented by the coefficient of determination (R^2 = 0.80) and the mean residue, which amounts to 11.4 %.

Figure 4-7 shows the portion of groundwater recharge in total runoff (BFI-values). In the regions along the river plains with unconsolidated rocks, groundwater recharge is the dominating runoff component, reaching values significantly above 0.8. There, the main part of natural discharge to surface waters is groundwater flow.

In the consolidated rock regions of Slovenia a completely different discharge pattern can be found. In some consolidated rock areas, the proportion of direct runoff is much higher than the proportion of groundwater recharge. Most areas, where BFI values between 0.2 and 0.4 occur, coincide with the occurrence of Paleozoic non-carbonate rocks and Eocene flysch. There, the high proportion of direct runoff can be explained by the low water storage capacity of the rocks.

Water percolation in karstified carbonate rocks needs special profound detailed explanation. Due to the fact that hardly any interflow occurs in karst areas, all percolation water having passed the root zone enters the karst aquifer system. Hence, there total runoff should correspond to groundwater recharge. The baseflow from gauging stations in karst areas however turned out to be in the range of 50 – 60% of total runoff, thus indicating a direct runoff proportion in the range of 40 – 50%.

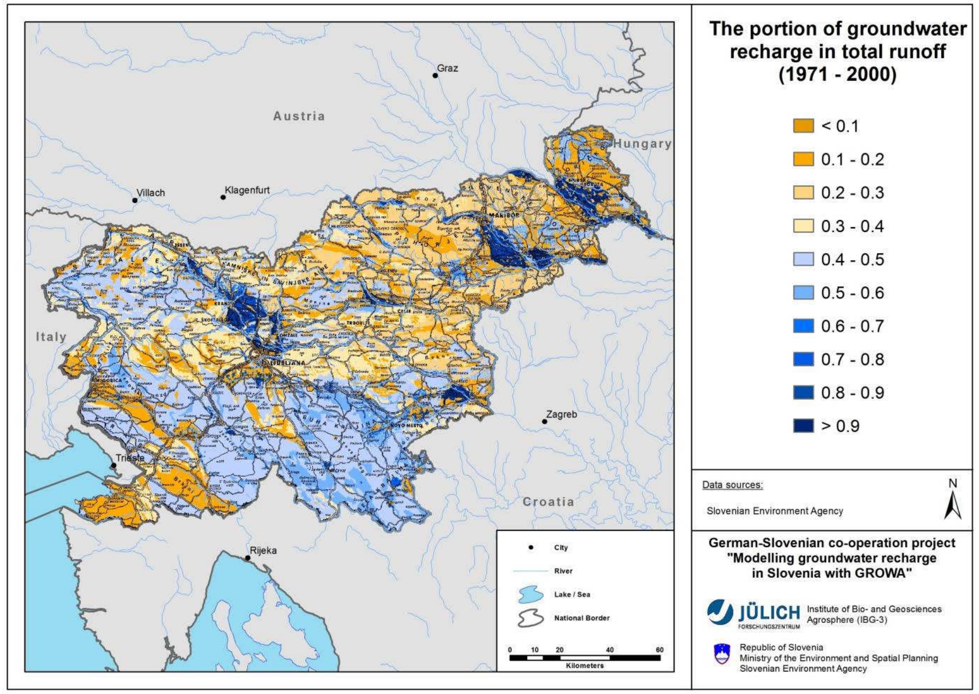

Figure 4-7: Proportion of groundwater recharge in total runoff (BFI-value).

A clear distinction should be made concerning water quantity of underground karst system. While in the hydrogelogical sense all the water in the underground rock mass is regarded as a groundwater, in the hydrological sense the same quantity of water is regarded as a component of the water balance which can be further separated into fast and slow runoff components. In hydrologic water balance modelling the dual porosity of karst systems plays important role. This duality is well investigated by tracer tests, the method most widely used in karst hydrogeology research.

Water flowing underground through the caves and conduits of karst system is fast runoff component, comparable to the direct runoff component of surface streams. This component has frequently turbulent flow and is well investigated by tracer tests as the first breakthrough curve. Due to the high flow velocity in the caves and conduits the transit time typically doesn't exceed several days to a couple of weeks.

However, the water passing through well drained fissures and fractures has a slow laminar flow and represents the groundwater recharge component in karst system. In tracer tests it appears as a retarded arrival of the tracer after several weeks or months.

To summarize, notwithstanding that the water of karst springs is hydrogeologically groundwater daylighting to the surface from the rock formations, the hydrological flow regime of the karst springs clearly needs water balance breakup of water discharge into direct runoff and groundwater recharge components.

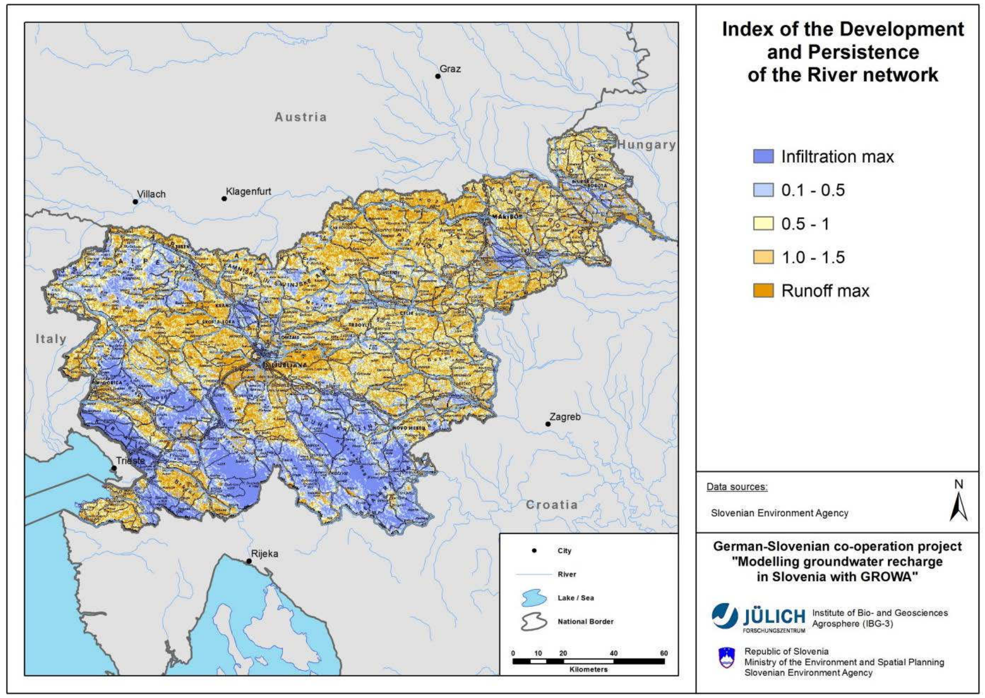

Figure 4-8: IDPR (Indice de Persistence et Développement des Réseaux) map of Slovenia (adapted from Mardhel et al., 2004).

Finally the map showing the portion of groundwater recharge in total runoff (Figure 4-7), has been compared to the map of area distributed IDPR indices (Figure 4-8). The good agreement of the spatial patterns in Figure 4-7 and Figure 4-8 can be regarded as an additional confirmation of the BFI value configuration developed for the GROWA-SI model for Slovenia by an independent method.

4.3.1 Direct runoff

The calculated direct runoff for Slovenia (Figure 4-9) follows similar spatial patterns as the total runoff shown in Figure 4-4. Again, in a curvilinear line, the belt of direct runoff with values about 1,000 mm, spreads along Alps-Dinaric mountain barrier from Mt. Snežnik (close to the border to Croatia) to the northwest to the Julian Alps and continues eastwards along Austrian border to Karavanke and Kamnik Savinja Alps. The Pohorje mountain range at the east of the Alps macro region has direct runoff about 500 mm. The rest of the country has direct runoff below 500 mm. The lowest direct runoff is at the northeast in the Pannonian macro region, amounting to less than 150 mm, the highest is in the Julian Alps, exceeding 1,200 mm.

However, the direct runoff spatial pattern diverges from that for the total runoff in karst areas and even more at alluvial plains where groundwater recharge component prevails (inspect Figure 4-7). In the alluvial plains of the Sava river, Savinja river, Drava river and Mura river values as low as 150 mm/a, or even lower, are dominant.

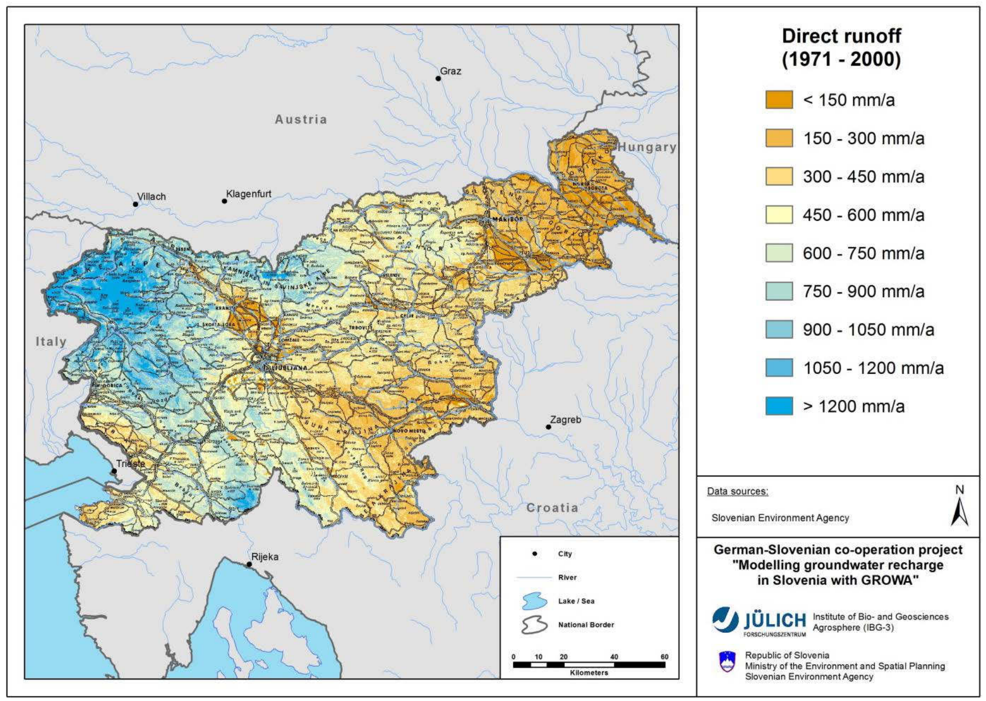

Figure 4-9: Calculated direct runoff in Slovenia.

Frequency distribution of the direct runoff values calculated for Slovenia is again positive skewed (Figure 4-10) as it was for the total runoff (compare Figure 4-5). Frequency maximum of the distribution is in the class from 300 to 450 mm/a, in which ca. 23% of the values are found. Median value of direct runoff for Slovenia is 465 mm. About half of all calculated direct runoff values are above 500 mm/a. The highest values can exceed 1,800 mm/a, in less than 0.4% of territory.

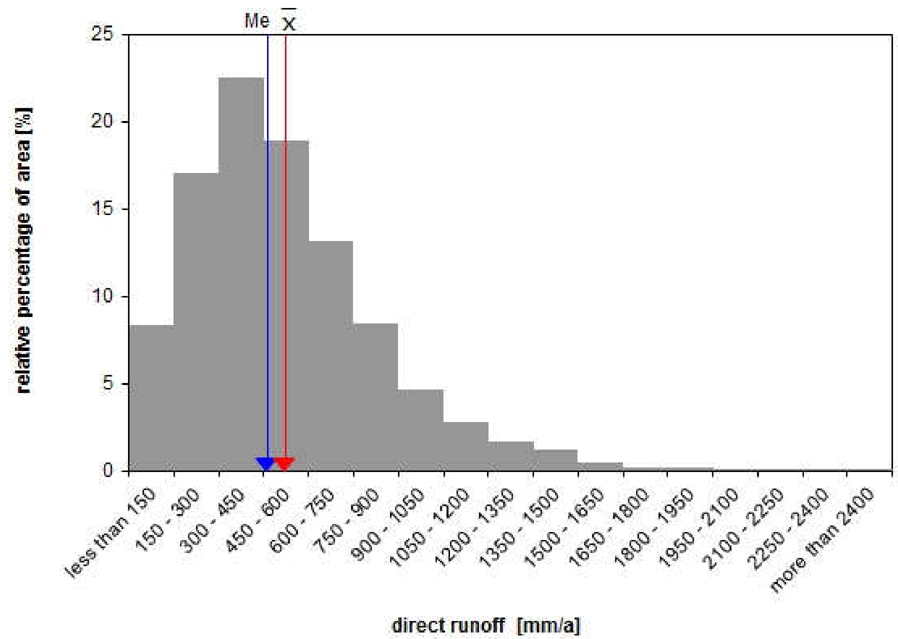

Figure 4-10: Frequency distribution of the calculated direct runoff in Slovenia.

Table 4-3 shows the 10th and 90th percentiles and medians of the calculated direct runoff values for the basins and subbasins in Slovenia. The direct runoff values of the main basins display a wide scattering. The lowest median with a value of 175 mm/a can be found in the Mura basin of the lowland region in the northeast in the Pannonian macro region. The 10th percentile for the Mura basin is as low as 9 mm/a.The highest value of 90th percentile is 1,399 mm/a in the Soča basin in the west. The highest medians are for the rivers with headwaters in Julian Alps, namely 928 mm/a for the Soča basin and 830 mm/a for the Upper Sava subbasin. In the climatically uniform and in terms of natural area relatively homogeneous lowland regions, the difference between the 10th and the 90th percentile calculated value is in the range less than 250 mm/a, whereas in the high altitude mountainous regions differences of typically more than 820 mm/a can occur.

Table 4-3: 10th percentiles, 90th percentiles and medians of the calculated direct runoff of the river basins and subbasins in Slovenia in mm/a.

	Catchment [km²]	10th percentile	90th percentile	Median
Sava river subbasin				
Lower Sava	1,334	176	489	339
Middle Sava	1,180	156	709	459
Upper Sava	1,527	317	1,388	830
Kolpa	1,103	219	633	383
Krka	2,252	181	557	338
Savinja	1,853	265	785	475
Ljubljanica	1,864	379	830	604
Sora	648	460	1,014	758
Sava river basin	11,759	211	865	469
Mura river basin	1,393	9	267	175
Drava river basin	3,271	107	622	367
Soča river basin	2,339	578	1,399	928
Adriatic rivers basin (without Soča)	1,512	331	829	520
Adriatic sea catchment	3,851	388	1,290	748
Black sea catchment	16,422	149	802	416
Slovenia	20,274	171	939	465

4.3.2 Groundwater recharge

Groundwater recharge modelling has been of core interest in this study, since the groundwater is a major source of drinking water supply for Slovenian population. The calculated median groundwater recharge with GROWA-SI model for Slovenia amounts to 247 mm/a (Table 4-4), which corresponds to 158.8 m^3/s or 6,859 l/capita/day in water supply units. In case the mean is considered, groundwater recharge is 195.2 m^3/s which corresponds to 304 mm/a and to 8,433 l/capita/day respectively. However, while this is quite an abundance of groundwater resource on national level, the regional groundwater recharge amount across the country shows a big spatial variability (Figure 4-11).

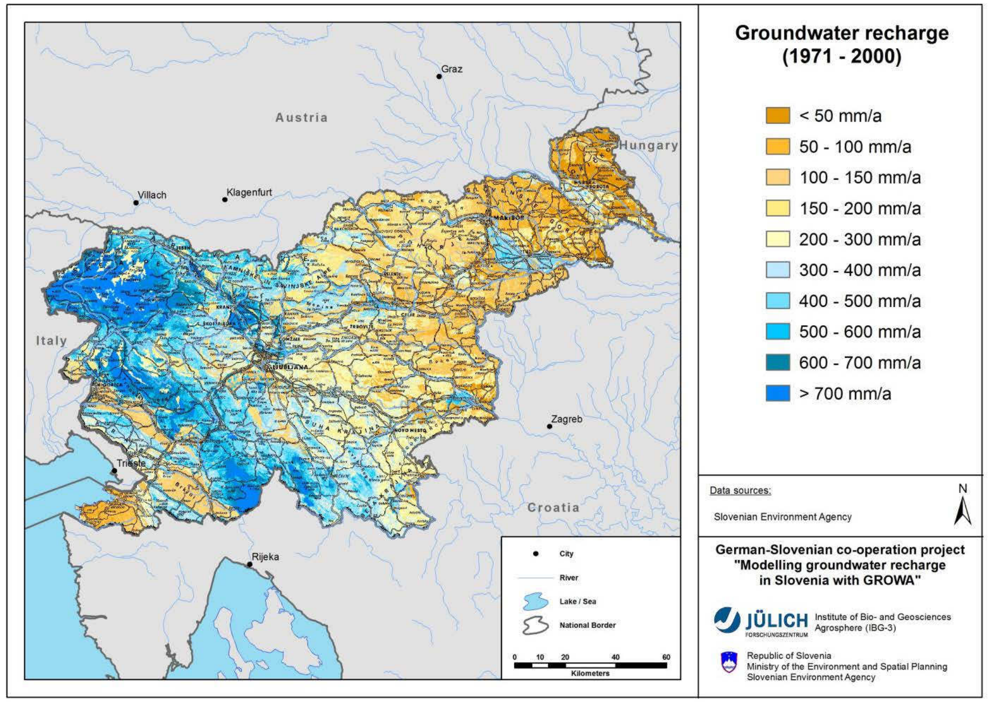

Figure 4-11: Calculated groundwater recharge in Slovenia.

Regarding modelled groundwater recharge rate for the long term reference period 1971-2000, territory of Slovenia can be generally delineated in three zones: one of high groundwater recharge and two adjacent zones of lower recharge rates. Within these three regional zones, there are variations influenced by the diversity of input data feeding the model.

High groundwater recharge rates have been calculated in the western part of the Dinarides macroregion and in the north-western part of the Alps macroregion. Elongated curvilinear shaped zone with rate >500 mm/a, and maximums exceeding 700 mm/a, is spreading from wider Mt. Snežnik area in the Dinarides next to Croatian border, into north-western direction across Trnovski gozd plateau to Julian Alps at Italian border, where it turns eastwards along Karavanke and Kamnik Savinja Alps range to the Ljubljana basin. Similarly, Ljubljana basin displays high groundwater recharge rates, due to high infiltration rates (BFIs) in the gravel sediments of the alluvial plains.

In the southwest of the country, i. e. the Mediterranean macro region, there is a zone of relatively low groundwater recharge in the range 50 – 400 mm/a. There, the influence of hydrogeology is clearly marked. In the area of flysch lithology with low BFI like in the Brkini range and along the coast, the recharge rate is in the range 50 – 200 mm/a. In the area of carbonate rocks with karst hydrogeology and high BFI, like classical karst region Kras and area at southwest foothills of the Brkini, the recharge rate is higher, amounting to 300 – 400 mm/a.

East of the western part of the Dinarides macro region and the north-western part of the Alps macroregion respectively, groundwater recharge is generally decreasing and reaches the lowest values (<50 mm/a) next to the Hungarian border in the Goričko region of the Pannonian macro region. East of Ljubljana, groundwater recharge exhibits commonly values in the range 100 – 300 mm/a. In this part of Slovenia, only the alluvial plains with unconsolidated gravel deposits display groundwater recharge rates in the range of 400 mm/a.

The frequency distribution of the groundwater recharge rates calculated in Slovenia is again positive skewed, as observed for the total runoff and direct runoff (Figure 4-12). The maximum of the distribution is formed by the class of 100-200 mm/a, in which is about a quarter of all the values. About two thirds of entire Slovenian territory has groundwater recharge rates in the range of 100 – 500 mm/a. About 16% of all values are in the class of less than 100 mm/a. Groundwater recharge rates above 700 mm/a, with about 6% of all values, play a minor role, occurring only in karstified mountains and high altitude vegetation-free sites.

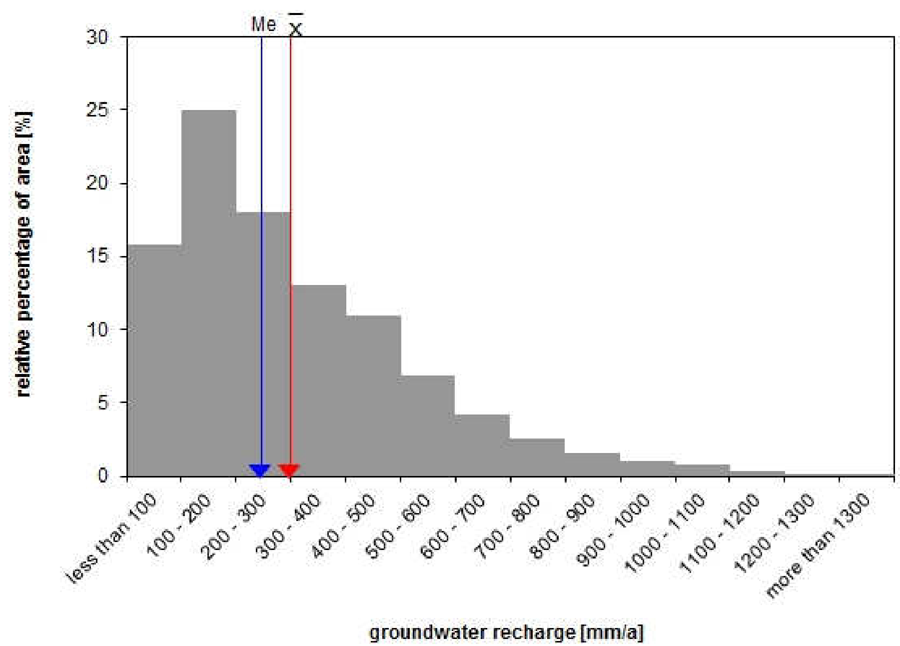

Figure 4-12: Frequency distribution of the calculated groundwater recharge in Slovenia.

Table 4-4 shows the 10th and 90th percentiles and medians of the calculated groundwater recharge rates of the basins and subbasins in Slovenia.

Table 4-4: 10th, percentiles, 90th percentiles and medians of the calculated groundwater recharge of the basins and subbasins in Slovenia in mm/a.

	Catchment [km^2]	10th percentile	90th percentile	Median
Sava subbasin				
Lower Sava	1,334	66	280	140
Middle Sava	1,180	120	484	243
Upper Sava	1,527	206	811	495
Kolpa	1,103	189	559	325
Krka	2,252	131	429	265
Savinja	1,853	83	405	169
Ljubljanica	1,864	141	643	423
Sora	648	193	647	417
Sava basin	11,759	104	575	280
Mura basin	1,393	23	257	61
Drava basin	3,271	62	332	141
Soča basin	2,339	143	936	552
Adriatic rivers basin (without Soča)	1,512	83	532	267
Adriatic sea catchment	3,851	108	855	413
Black sea catchment	16,422	72	525	225
Slovenia	20,274	78	608	247

The highest median value of all river basins is 552 mm/a occurring in the west of the country in the Soča basin, whose headwaters belong to the high precipitation Julian Alps, where karst is the major hydrogeological unit.

The Sava basin is situated in the central part of Slovenia and comprises ca. half of the area of entire country. There, the median groundwater recharge rates for subbasins are in a wide range between 140 and 495 mm/a. The median value for the Sava basin as a whole is 280 mm/a. The variability among subbasins can be explained by the hydrogeological site characteristics. The Sava basin is composed of Triassic and Jurassic carbonates, Permo-Carbonian, Oligocene, Miocene clastic rocks and Pleistocene sediments. Higher amount of precipitation in the Upper Sava and the Sora subbasins in the mountainous carbonate karst terrain results in high groundwater recharge rates of 495 mm/a and 417 mm/a respectively. High values are also found in the unconsolidated gravel sediments in Ljubljanska kotlina alluvial plain of the Upper Sava river subbasin, where the median of the groundwater recharge reaches 422 mm/a. Similarly, Ljubljanica subbasin with prevailing karst hydrogeology has a high median recharge rate of 423 mm/a, within which calculated groundwater recharge for Ljubljansko polje alluvial aquifer is lower, amounting to 362 mm/a. This result for Ljubljana aquifer is in line with some other water balance calculations (Andjelov et al., 2005). Down the Sava river watercourse precipitation amount decreases and proportion of less permeable rocks increases, resulting in decreasing groundwater recharge rate. Thus, the median for the Middle Sava subbasin is 243 mm/a, dropping to only 140 mm/a median value of the Lower Sava.

The lowest groundwater recharge rate among the river basins, is in the Mura river basin in the northeast of the country, with median value of 61 mm/a. In this basin low permeable marly and clayey deposits predominate in the hills surrounding alluvial deposits of the water bearing sand and gravel along the river. The small pore volume and the associated low hydraulic conductivity of these rocks in the hills lead to relatively high interflow rates. Therefore only a relatively small fraction of total runoff contributes to groundwater recharge. Additionally, this river basin is situated in the Pannonian Plain, thus receiving the lowest annual precipitation amount in Slovenia.

5 Model validation and verification

For validity check of the GROWA-SI model results for the entire Slovenia the modelled runoff was compared to runoff values measured at gauging stations. The procedure used is schematically shown in Figure 5-1.

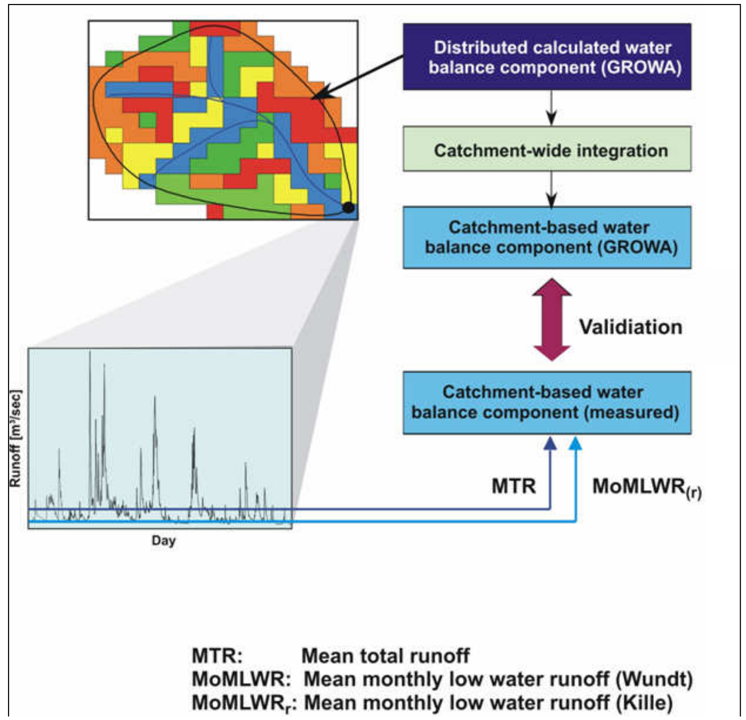

Figure 5-1: Procedure for the validating the simulated water balances by the GROWA-SI model.

First of all, the total runoff values calculated by the GROWA-SI model for the 100 m x 100 m grid cells have been integrated to gauge-related catchments areas, so called hydrometric catchments. Subsequently, these values have been compared to the gauged discharge of these catchments. Care should be taken here that the same reference period is used for both the modelled and the gauged discharge. If satisfactory agreement is achieved for a sufficiently large number of catchments areas, it may be assumed that representative information has been obtained with the underlying model. The validation of the model results was performed based on data sets from 95 gauged catchments areas (Table 3-4, Figure 5-2). The number of data sets used for validation of each water balance component is given in following chapters. Additionally, Figure 5-2 shows the total observed runoff at the 95 gauging stations as a mean long-term value in mm/a for the entire individual catchments.

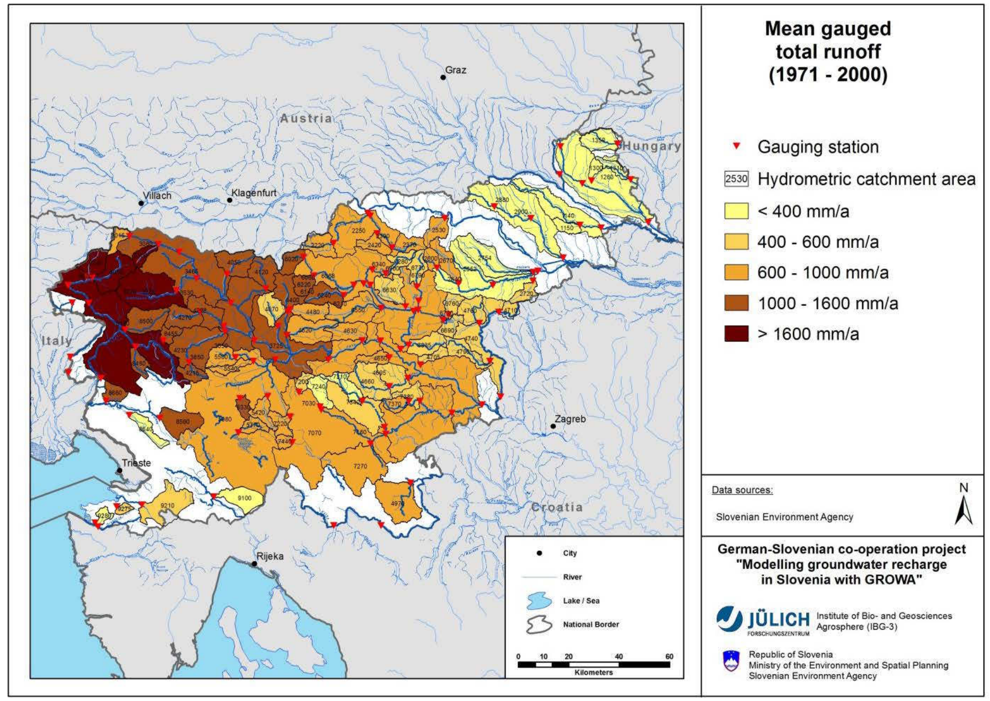

Figure 5-2: Discharge gauging stations and mean gauged total runoff in Slovenia.

Figure 5-2 shows that the mean gauged total runoff in the north-eastern part of Slovenia in Pannonian macro region is below 400 mm/a, whereas in the western part in the Alps macro region total runoff values above 1,600 mm/a are occurring.

5.1 Total runoff

For the validation of total runoff, runoff records from all 95 gauged catchments displaying time series of daily discharge of longer than 10 years were used. In this way more than 80% of the territory of Slovenia was covered. Not included were sub catchments along the rivers transiting through Slovenia, i.e. the Drava and Mura with anthropogenic influenced discharge, as well as the catchments in karst having unreliable drainage divides or underground flows to neighbouring countries for which discharge data was not available.

The total runoff modelled of the period 1971-2000 for the 100 m x 100 m grid cells was summed up for each of the 95 catchment areas and compared with the mean gauged total runoff (MTR in Figure 5-1) as shown in Figure 5-3.

The mean deviation is 15% and the correlation coefficient is 0.93. For 20 subcatchment areas the deviation between modelled and gauged values is less than 3%. In view of the data available and the size and heterogeneity of the region investigated, this represents an excellent agreement. For those catchments areas for which major deviations between calculated and gauged runoff values are observed, it must be examined in detailed studies whether the reasons for this are attributable to specific catchments-area-related features or to water management interventions not covered by the model.

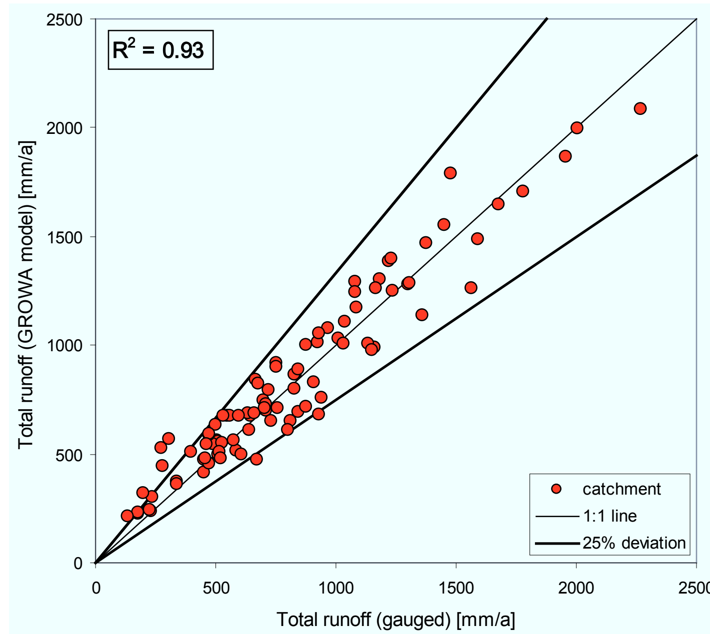

Figure 5-3: Comparison of gauged and modelled total runoff in Slovenia (95 catchments).

For verification purpose, the results of GROWA-SI model were compared to the previously performed water balance of Slovenia for the same long term period 1971–2000 (Frantar ed., 2008). That water balance analysed in great detail hydrometric catchments areas, to enable good comparison of modelled values to the values of measurements at gauging stations. However, the modelled total runoff was not separated to the components of direct and groundwater recharge, thus enabling comparison of total runoff only. The model was based on basic water balance equation, where the inputs were corrected precipitation and potential evapotranspiration by Hargreaves method (Hargreaves & Allen, 2003) modified by land use correction coefficients to obtain actual evapotranspiration.

The verification was performed in two steps. In the first step was checked area distribution of modelled values. Despite slightly different classes of values used on GROWA-SI map (Figure 4-4) and map of run-off in water balance of Slovenia (Frantar ed., 2008), visual inspection of total runoff maps by two models shows great similarity in area distribution. In this way area distribution of total runoff by GROWA-SI model was confirmed.

In the final step modelled values of total runoff for the same set of 95 catchments were compared (Figure 5-6). The mean deviation was 1.7 % and the correlation coefficient was 0.99, thus verifying GROWA-SI values of total runoff by modelled values in independently performed water balance of Slovenia (Frantar ed., 2008).

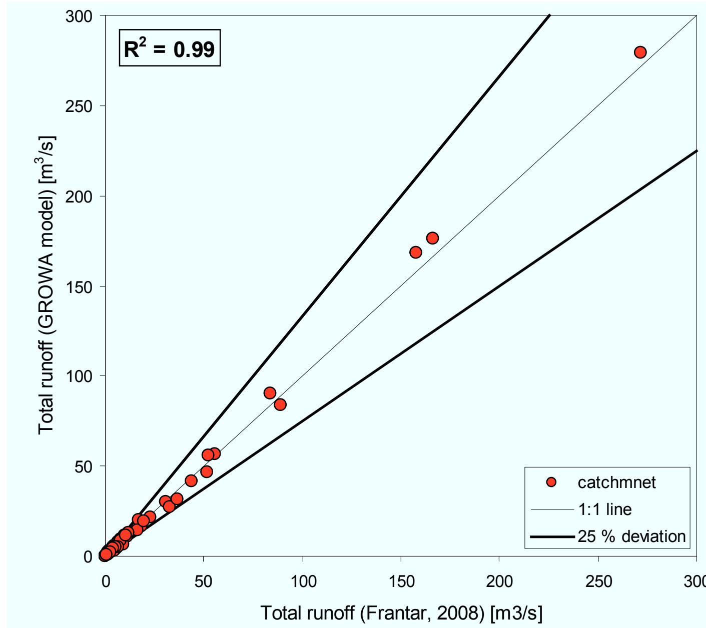

Figure 5-4: Comparison of GROWA-SI model results of total runoff with modelled total runoff by Frantar ed. (2008) for long term period 1971–2000.

5.2 Groundwater recharge and direct runoff

In validating the calculated groundwater recharge, it should be noted that the groundwater recharge only corresponds in the ideal case to the groundwater runoff, i.e. to the amount of water that feeds the recipients as spring discharge or base flow in a river basin. This is not always the case since a variety of natural and anthropogenic factors of influence may cause the groundwater recharge and the resultant groundwater runoff to deviate from each other.

Groundwater recharge can only indirectly be derived from the gauged runoff values (see Chapter 2.3). For this purpose MoMLRr method after Kille (1970) was applied, using data from 46 catchments out of total 95 catchments to calibrate BFI values as described in Chapter 4.3. The validation of groundwater recharge and direct runoff was done by data from additional 27 catchments from 95 catchments pool as an independent data set. In most cases, satisfactory agreement was found between modelled and gauged values, as was already the case for total runoff. The comparison of the gauged and modelled runoffs gives coefficients of correlation 0.94 for groundwater runoff (Figure 5-5) and 0.91 for direct runoff (Figure 5-6) respectively.

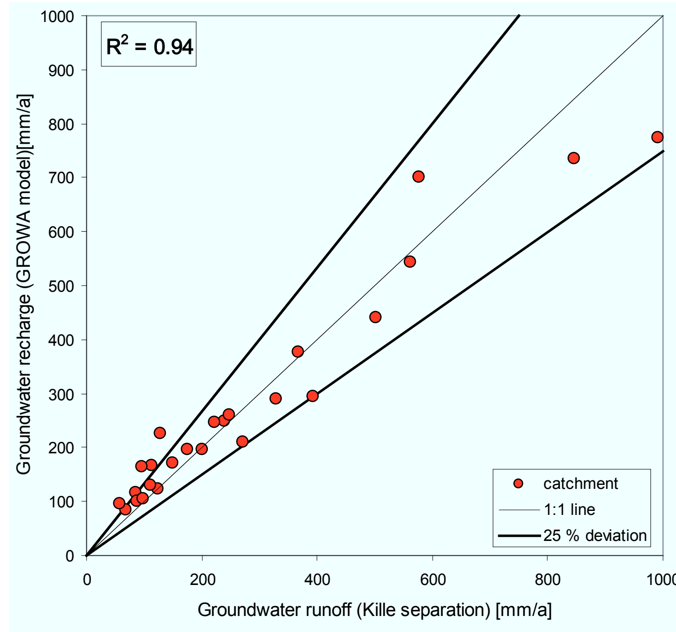

Figure 5-5: Comparison of gauged and modelled groundwater recharge in Slovenia (27 catchments).

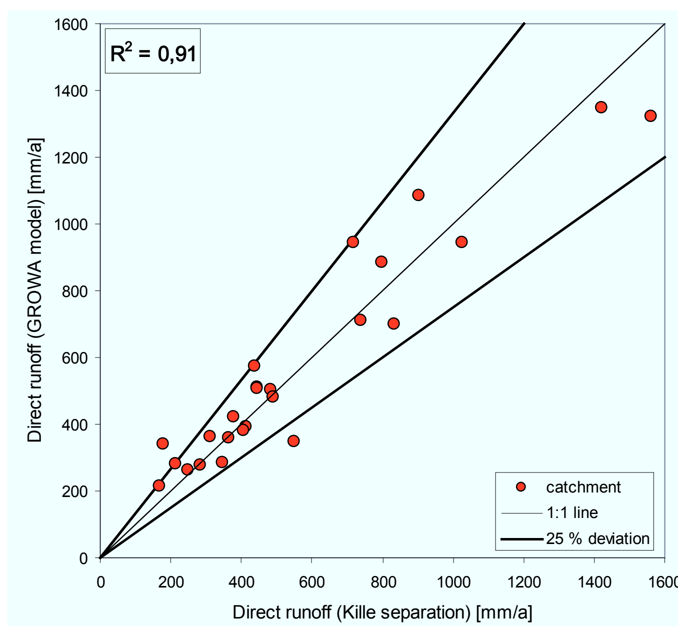

Figure 5-6: Comparison of gauged and modelled direct runoff in Slovenia (27 catchments).

However, the deviations were larger in comparison to those of the total runoff, because the scattering contributions of two submodels (total runoff modelling; separation of the runoff components) that were superimposed for the groundwater recharge and direct runoff. Consequently, the mean deviations across all the gauges used were 21.8% for direct runoff and 21.4% for the groundwater recharge respectively.

6 Water management implications of groundwater recharge assessment in Slovenia

As previously described in more detail, groundwater is a major source of public water supply in Slovenia. So, it is of importance to elaborate significance of GROWA-SI groundwater recharge model results to water management.

According to the EU-Water Framework Directive (Directive 2000/60/EC, 2000) and EU-Groundwater Directive (Directive 2006/118/EC, 2006), groundwater bodies are the geographical references for the quantitative and chemical status assessment, used in the process of groundwater management planning. For this purpose 21 groundwater bodies have been delineated. Table 6-1 characterizes these groundwater bodies in terms of size, and mean groundwater recharge in different units, whereas Figure 6-1 shows their location in Slovenia (Prestor et al., 2005; Official Gazette of Republic of Slovenia 63/05, 2005).

The delineation of individual groundwater body and groups of groundwater bodies was performed according to the guidelines of the EU-WFD. Above all, the characteristics of the surface-near lithological units have been considered in this regard like porosity, lithology, yield, area of catchments, flow lines, surface watersheds, withdrawal and water protection areas, and tracer experiments results. Slovenian groundwater bodies vary pretty much in area with a ratio of 1:30, ranging from about one hundred km^2 to more than three thousand km^2. Such a variability in size potentially poses quite a challenge in finding common policy for water management.

Table 6-1: Calculated mean groundwater recharge in reference period 1971 – 2000 for groundwater bodies in Slovenia.

ID	Groundwater body	Area	Groundwater recharge		
		km²	mm/a	m³/s	l/s/km²
	BLACK SEA CATCHMENT				
	SAVA BASIN				
1001	Savska kotlina in Ljubljansko Barje	774	401	9.8	12.7
1002	Savinjska kotlina	109	277	1.0	8.8
1003	Krška kotlina	97	312	1.0	9.9
1004	Julijske Alpe v porečju Save	783	589	14.6	18.7
1005	Karavanke	404	377	4.8	12.0
1006	Kamniško-Savinjske Alpe	1,112	295	10.4	9.4
1007	Cerkljansko, Škofjeloško in Polhograjsko hribovje	850	372	10.0	11.8
1008	Posavsko hribovje do osrednje Sotle	1,792	192	10.9	6.1
1009	Spodnji del Savinje do Sotle	1,397	156	6.9	4.9
1010	Kraška Ljubljanica	1,307	465	19.3	14.7
1011	Dolenjski kras	3,355	300	31.8	9.5
	DRAVA BASIN				
3012	Dravska kotlina	429	283	3.9	9.0
3013	Vzhodne Alpe	1,269	169	6.8	5.4
3014	Haloze in Dravinjske gorice	597	138	2.6	4.4
3015	Zahodne Slovenske gorice	756	102	2.5	3.2
	MURA BASIN				
4016	Murska kotlina	591	140	2.6	4.4
4017	Vzhodne Slovenske gorice	308	85	0.8	2.7
4018	Goričko	494	62	1.0	2.0
	ADRIATIC SEA CATCHMENT				
	ADRIATIC RIVERS BASIN				
5019	Obala in Kras z Brkini	1,589	294	14.8	9.3
	SOČA BASIN				
6020	Julijske Alpe v porečju Soče	818	760	19.7	24.1
6021	Goriška brda in Trnovsko-Banjška planota	1,443	434	19.9	13.8
	SLOVENIA	20,273	304	195.2	9.6

The distinction between aquifers with intergranular, karst and fissure porosity as described for aquifer typology (Figure 3-16) was used in order to further differentiate the 21 groundwater bodies identified (see Figure 6-1).

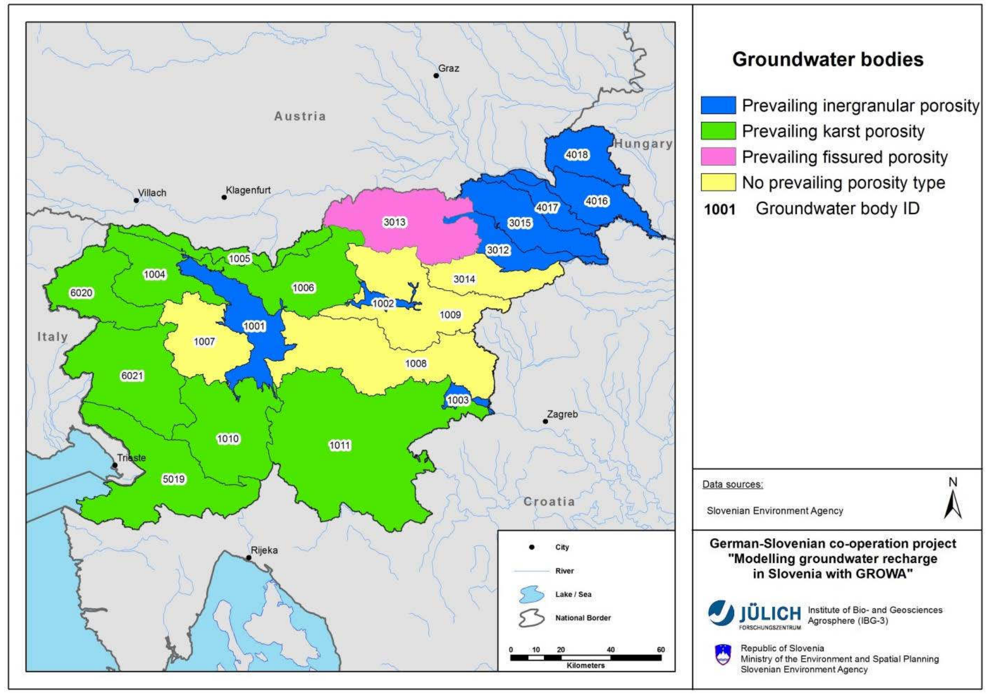

Figure 6-1: Delineation of groundwater bodies in Slovenia (after Prestor et al., 2005).

There are eight groundwater bodies with prevailing intergranular porosity aquifers, located mostly in eastern and north-eastern Slovenia. Eight groundwater bodies with prevailing karst porosity aquifers are mostly in south-western half of the country. Geographically positioned between these two groups are four groundwater bodies for which a dominant porosity type could not be established, since all three porosity type aquifers are present in nearly equal proportion. Only one groundwater body, located in northern Slovenia, comprise aquifers with prevailing fissure porosity.

Evaluation of groundwater recharge according to groundwater bodies

On national scale, the assessment with the GROWA-SI model shows that the mean groundwater recharge in Slovenia amounts to 195.2 m^3/s. The distribution of groundwater recharge rates according to the porosity types has revealed that most of the groundwater recharge in Slovenia occurs in karstified rocks, amounting to 112.2 m^3/s. Groundwater recharge in rocks with intergranular porosity amounts to 49.2 m^3/s and the least one is in fissured rocks with 33.8 m^3/s (Figure 6-2).

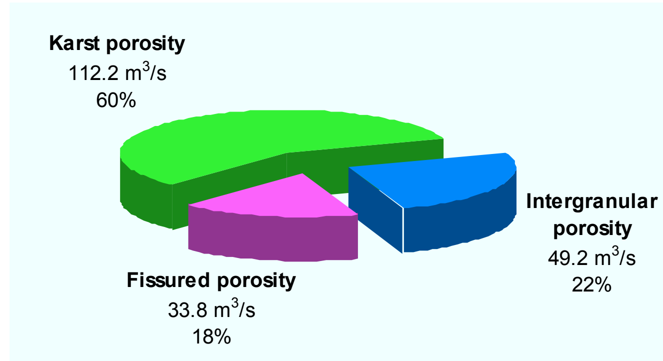

Figure 6-2: Distribution of groundwater recharge in Slovenia according to rock porosity type calculated by the GROWA-SI model.

Figure 6-3 shows the mean groundwater recharge in the groundwater bodies, whereas Figure 6-4 shows the specific groundwater recharge in the groundwater bodies. The latter indicates the mean groundwater recharge related to the size of the groundwater bodies. In this way the regional relevance of groundwater recharge is illustrated independent from the size of the groundwater bodies.

This is shown with the example of two neighbouring bodies: 1011 and 1003 in the Lower Sava River subbasin. Groundwater body 1011 is the largest in Slovenia, covering about one sixth of national territory (3,355 km^2). Accordingly, it has the highest absolute groundwater recharge, amounting to 31.8 m^3/s (Figure 6-3), which would at first guess qualify it as a prime water resource. The specific groundwater recharge of groundwater body 1011 is 9.5 l/km^2/s (Figure 6-4) indicating a reasonable amount of groundwater to be used. Closer analysis however shows that more than three quarters of this groundwater body consists of karst porosity, so that groundwater is not available area-covering, but at natural springs only far away from the major users. Consequently, the groundwater resource of groundwater body 1011 is not well exploitable. Additionally, high vulnerability of karst groundwater occasionally leads to pollution of springs and temporary closures of water supply.

The neighbouring groundwater body 1003 is the smallest in Slovenia, covering about 100 km^2 only. Accordingly, absolute groundwater recharge amounts to 1.0 m^3/s only (see Figure 6-3). The specific groundwater recharge is 9.9 l/km^2/s (Figure 6-4) similar to specific groundwater recharge of groundwater body 1011. However, due to the intergranular porosity of the alluvial aquifer and the good accessibility of groundwater due to shallow water table, it has great importance for that region as the water additionally is close to end users. The problem of that groundwater body, as being in highly urbanized and agriculture active area, is the protection of groundwater to pollution.

The two examples show that the groundwater recharge rates determined based on GROWA-SI model alone are not sufficient to implement groundwater management strategies. Parameters like the specific groundwater recharge as well as information about population and major water users in a groundwater body should be taken into account.

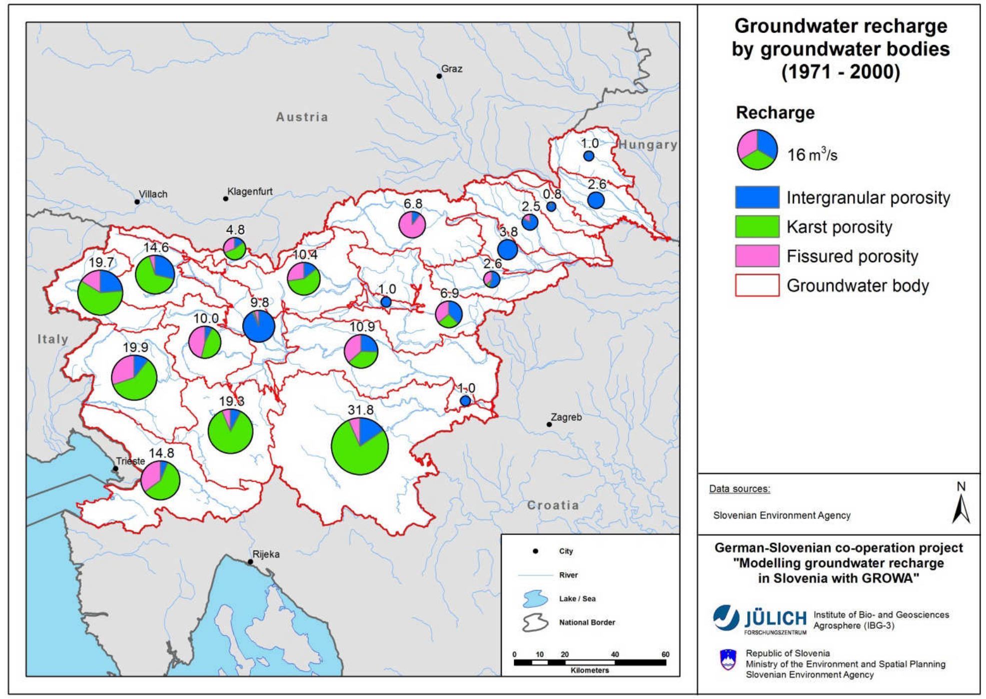

Figure 6-3: Groundwater recharge rates by groundwater bodies. The colours indicate the porosity type, the size of the circles indicate the absolute quantity per groundwater body.

All groundwater bodies with prevailing karst porosity show high specific groundwater recharge rates per groundwater body in the range from 9.3 l/km^2/s (groundwater bodies 1006 and 5019) up to 24.1 l/km^2/s (groundwater body 6020) which is the highest specific recharge in the country, as shown on Figure 6-4. Again however, these abundant groundwater resources are not easy accessible.

The karst groundwater bodies 6020 and 1004 in the Soča and Sava headwaters of the Julian Alps display absolute groundwater recharge per groundwater body of 19.7 m^3/s and 14.6 m^3/s respectively (see Figure 6-3). Both groundwater bodies show the highest specific groundwater recharge of all groundwater bodies in Slovenia, namely 24.1 l/km^2/s and 18.7 l/km^2/s (see Figure 6-4). They are located in nature protected areas, so that pollution is not an issue there. Due to their pristine nature, these resources can be considered as a very valuable “groundwater treasury” of Slovenia. Again, it should be taken into account that the groundwater resources of these karst groundwater bodies in the Alps are far away from densely populated areas and hence for the time being out of reach for end users. Additionally, exploitation of these groundwater resources will not only require a lot of technical effort due to the specific problems related to karst groundwater, but also a well balanced strategy to protect these vulnerable resource.

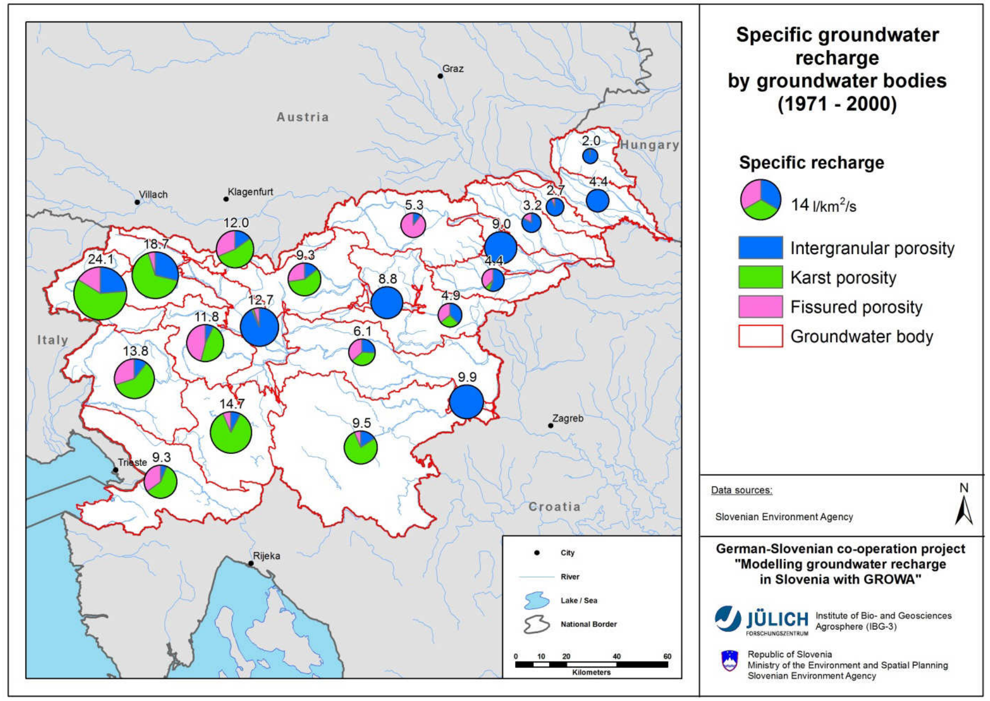

Figure 6-4: Specific groundwater recharge rates per groundwater bodies. The colours indicate the porosity type, the size of the circles indicate the specific quantity per groundwater body.

Another illustrative case study of difficulties of water management in karst is groundwater body 5019 in the Adriatic Sea river basin (without the Soča) in Mediterranean macro region. With groundwater recharge 14.8 m^3/s on groundwater body level and a specific groundwater recharge of 9.3 $l/km^2/s$ there should be enough water for the entire region. However, the major part flows underground to the springs in Trieste Bay in Italy, while in Slovenia there are only two point sources almost 30 km apart. These groundwater sources have been connected in an integral system of water supply. The large seasonal variability of groundwater recharge in karst with the lowest discharge in summer season causes frequently shortages in water supply. The two sources on Slovenian territory with low yield in summer season do not match the increased water consumption due to tourism load at the seaside. The regular water imports from Croatia can be regarded as a risk for future water supply in the region, especially in case climate change phenomena will increase.

Out of eight groundwater bodies with prevailing intergranular porosity five bodies correspond to alluvial aquifers. The aquifers are relatively shallow and flat and consist of gravel-sand alluvial deposits in tectonic depressions along major rivers: the Sava, Savinja, Drava and Mura. In spite of their relatively small surface area, these groundwater bodies represent the most important groundwater recharge areas in Slovenia due to the vicinity of large users: 1001 in the Upper Sava subbasin with 9.8 m^3/s, 1002 in the Savinja subbasin 1 m^3/s, 1003 in the Lower Sava subbasin also with 1 m^3/s, 3012 in the Drava basin 3.9 m^3/s and 4016 in the Mura basin with 2.6 m^3/s groundwater recharge, totalling to 18.3 m^3/s or 9.3 % of the whole country. These groundwater bodies are source for water supply of the capital Ljubljana, Maribor the second city in population, as well as regional centres Celje, Krško and Murska Sobota. In terms of specific groundwater recharge the intergranular porosity groundwater bodies are in range of 4.4 $l/km^2/s$ to 12.7 $l/km^2/s$, which is reliable source for water supply systems of listed cities.

However, alluvial aquifers of groundwater bodies 1002, 3012, and 4016 in eastern and north-eastern Slovenia, being areas of intensive agriculture production, are regularly over polluted by nitrates and sometimes by pesticides (Mihorko & Gacin, 2013).

The only groundwater body 3013 with dominant fissured porosity in magmatic and metamorphic rocks is in the Drava basin in eastern part of the Alps macro region having groundwater recharge of 6.8 m^3/s, and specific groundwater recharge 5.3 $l/km^2/s$. There are no big springs like in the karst groundwater bodies, and smaller water sources are pretty much dispersed.

The groundwater bodies 1007, 1008, 1009 and 3014 with no dominant porosity type in the Sava basin, Savinja subbasin and Drava basin, have groundwater recharge in the range 2.6 m^3/s to 10.9 m^3/s and specific groundwater recharge 4.4 $l/km^2/s$ to 11.8 $l/km^2/s$. These groundwater bodies are important for water supply of some small users only. Some parts of these bodies in eastern Slovenia locally experience frequent seasonal water scarcity.

Evaluation of temporal variation of groundwater recharge in groundwater bodies

Apart from described spatial variability of long term average groundwater recharge (Figure 6-3 and 6-4) to groundwater bodies, there are also pronounced differences among groundwater bodies in temporal variability from year to year. Temporal variation of groundwater recharge per groundwater body is analysed for the reference period 1971 – 2000 in order to indicate the natural deviation from the mean groundwater recharge in this period. For this purpose the coefficient of variation is determined. It is defined as the standard deviation normalized to the mean. This coefficient is a useful indicator for the stability of renewable groundwater resource.

Coefficients of variation of groundwater recharge for the individual groundwater bodies for the period 1971 – 2000 are shown in Figure 6-5. Temporally the most stable groundwater recharge is in the groundwater bodies 1010, 6021, 1007, 1004, 1005, 1001 and 1006. All of them are located in the western part of Dinarides and in the Alps and display coefficients of variation below 16%. These groundwater bodies are least affected in dry years, being fairly water abundant even during the most severe droughts in Slovenia.

The most vulnerable in terms of groundwater quantitative status are groundwater bodies with high coefficient of variation, i.e. about 30% or higher. Concerned are groundwater bodies 3015, 4017, 4016 and 4018 in the northeast of country in the Pannonian basin macro region. The droughts there are the most severe, and the variations from extremely dry to water abundant years are the highest. It is the great challenge of water management to secure stable water supply to this part of the country.

In general, more stable groundwater recharge can be expected for all groundwater bodies of the Soča basin, Adriatic Sea river basins and most of all for the groundwater bodies in the western part of the Sava basin. In the groundwater bodies of the Mura and Drava basins variability of groundwater recharge is higher due to the occurrence of dry periods and their influence on groundwater recharge. The high coefficient of variation indicates that these groundwater bodies are endangered in case of droughts.

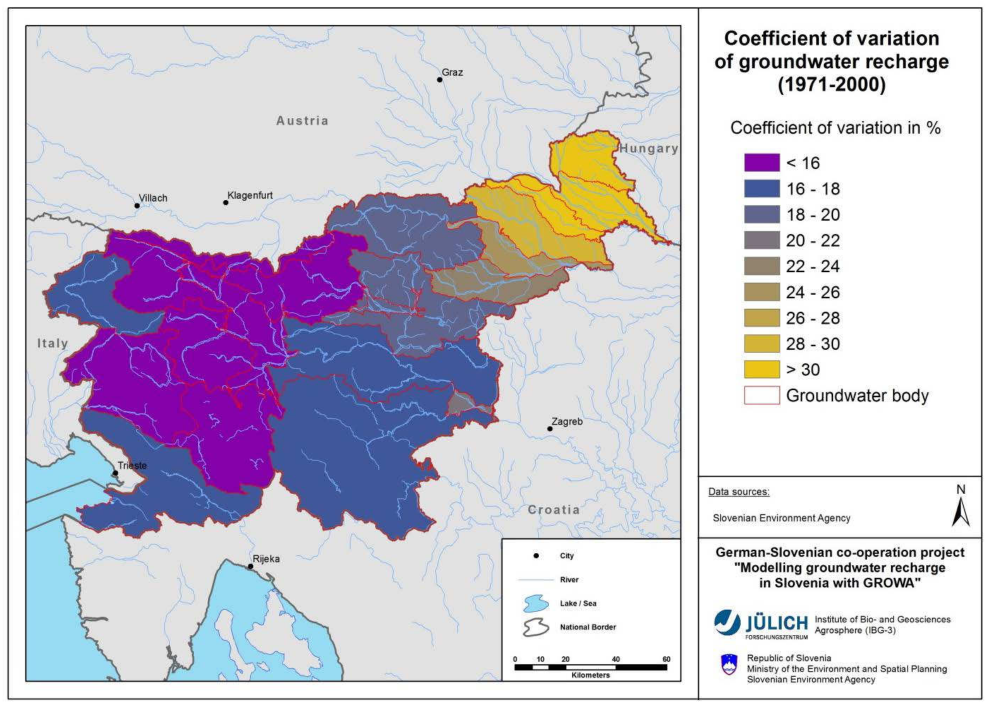

Figure 6-5: Coefficient of variation of groundwater recharge per groundwater body for the reference period 1971 – 2000.

Water management implications of groundwater resources according to porosity type of groundwater bodies (see Figure 6-1) have shown that the most important groundwater resources are in the groundwater bodies with intergranular porosity of alluvial aquifers. They are as a rule close to the big users, quite stable and technically easy to exploit. The groundwater resources least in quantity and least feasible for exploitation are in groundwater bodies where rocks with fissured porosity predominate. There, only local and dispersed sources of groundwater can be used. Groundwater in karst, while being abundant resource on terms of mean quantity is less reliable due to the high intra-annual variability. Additionally, groundwater availability in karst is restricted to springs sometimes far away from users. Last but not the least karst groundwater bodies are highly vulnerable to pollution.

Comparison of GROWA-SI approach on renewable groundwater resource with historical Slovenian studies on groundwater reserves

The GROWA-SI model results of area differentiated groundwater recharge bring a new insight into groundwater quantity of Slovenia. For the first time it moves focus from individual aquifers to the national territory as a whole, and from integrative groundwater reserves assessments for aquifers to water balance based groundwater recharge in high spatial resolution. Consequently, the modelled groundwater recharge values widely exceed the published assessments so far.

The first assessment in the seventies of the last century defined dynamic groundwater reserves of Slovenia to be 37 m^3/s taking into account low level water conditions and 25 m^3/s in extremely dry conditions (Drobne et al., 1976). In Slovenian hydrogeological practice two types of groundwater reserves were used: the static groundwater reserves have been defined as a volume of water present in the aquifer at all times, while the dynamic groundwater reserves have been the variable volume of groundwater. In practice, the latter should correspond to the yield of natural springs and flow from the aquifers into surface water recipients. Dynamic reserves of the assessment by Drobne et al. (1976) were calculated from groundwater flow by Darcy’s equation through characteristic cross sections of major alluvial aquifers, and by assessing the yield of major springs.

In the following years, assessments of groundwater reserves followed the procedure suggested in the legislation (Official Gazette of the SFRJ 34/79, 1979). In this approach, groundwater reserves were determined as exploitable reserves, based mostly on pumping tests, exploitation tests of the wells as well as by analysis of recession curves of the springs. In this way groundwater reserves were derived according to the same rules as for mineral resources. For this purpose the so-called certainty of the reserves has been determined and classified into categories. Again, assessments focused on individual aquifers important for the water supply only.

By the continuous exploration of aquifers since the 1980s, information and knowledge about the aquifers increased. The consideration of this data in the assessments of groundwater reserves has led to a gradual increase of total groundwater reserves for Slovenia as follows (Kranjc Kušlan, 1995):

1982: 43.6 m^3/s,

1989: 48.6 m^3/s,

1992: 49.9 m^3/s,

1995: 50.9 m^3/s.

The highest published assessment of dynamic groundwater reserves gives a total for Slovenia to be 55.2 m^3/s (Brenčič et al., 2005).

All the values of historical groundwater reserve assessments are not directly comparable to the GROWA-SI modelled groundwater recharge. First of all GROWA values have been calculated area-covering on national scale, whereas the groundwater reserves have been assessed taking into account individual aquifers only. Secondly, the groundwater reserve only considers the usable portion of groundwater in an aquifer. Both reasons lead to the fact, that the groundwater reserves (ca. 40 – 55 m^3/s) are significantly lower than the assessed groundwater recharge rates assessed by the GROWA-SI model (195.2 m^3/s).

The introduction of the GROWA-SI model into Slovenian hydrogeology practice means a move from the mining reserves evaluation approach, focused solely on individual groundwater resources, to the new water balance approach encompassing renewable groundwater for the entire country. The GROWA-SI model results give to the water managers a powerful tool for strategic regional groundwater resources use planning, while at the same time they are indispensable in EU-Water Framework Directive implementation.

7 Extended applications of GROWA-SI model in Slovenia

7.1 Groundwater quantitative status assessment annual report

Slovenian Environment Agency is a national authority responsible for national groundwater monitoring and implementation of Water Framework Directive - WFD through assessment of groundwater quantitative status. These activities have been carried out according to WFD which has been transposed into national legislation (Official Gazette of the Republic of Slovenia: Nos. 67/2002, 25/2009 and 31/2009).

Part of official national annual report on groundwater monitoring and groundwater quantitative status assessment is the evaluation of the ratio of groundwater abstraction in an individual year to long term available groundwater quantity. Long term available groundwater quantity ("Available Groundwater" in Figure 7-1) is calculated from GROWA-SI results for groundwater recharge ("Renewable Groundwater" in Figure 7-1) in the hydrologic period 1981 – 2010 (GROWA(30)-SI) , minus the groundwater quantity required for supporting good ecological status of surface waters (GROWA(05)-SI) being mean groundwater recharge of the five most dry years (Figure 7-2) and minus groundwater quantity to support groundwater dependent terrestrial ecosystems ($GW_{DTE\ Forest}$,+ $GW_{DTE\ Karst}$) as shown in Figure 7-1 (Mikulič et al., 2015).

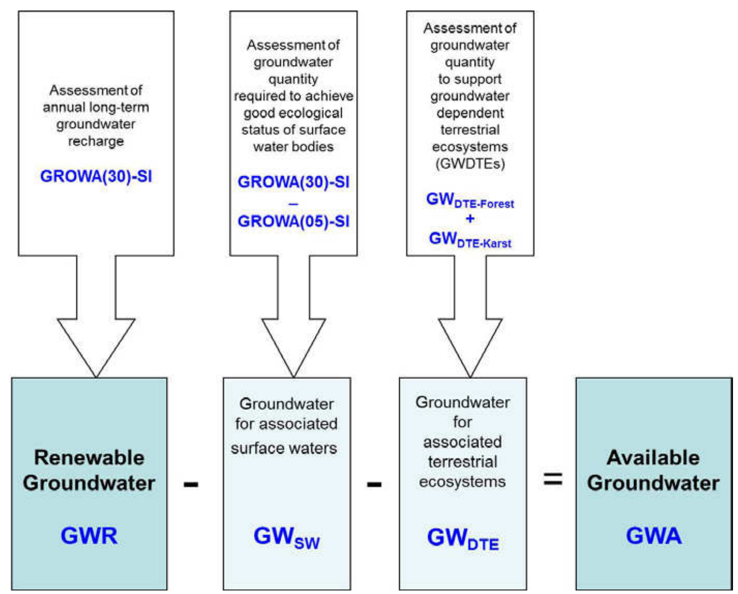

Figure 7-1: Deriving groundwater availability from renewable groundwater, e.g. from groundwater recharge modelled by GROWA-SI.

In calculating groundwater quantity needed for associated surface waters, modelled average groundwater recharge by GROWA-SI (05) for the five most dry years (Figure 7-2) in the reference period 1981-2000 is used (Schlüter, 2006), while the groundwater quantity needed for dependent terrestrial ecosystems was assessed by Geological Survey of Slovenia (Janža et al., 2014).

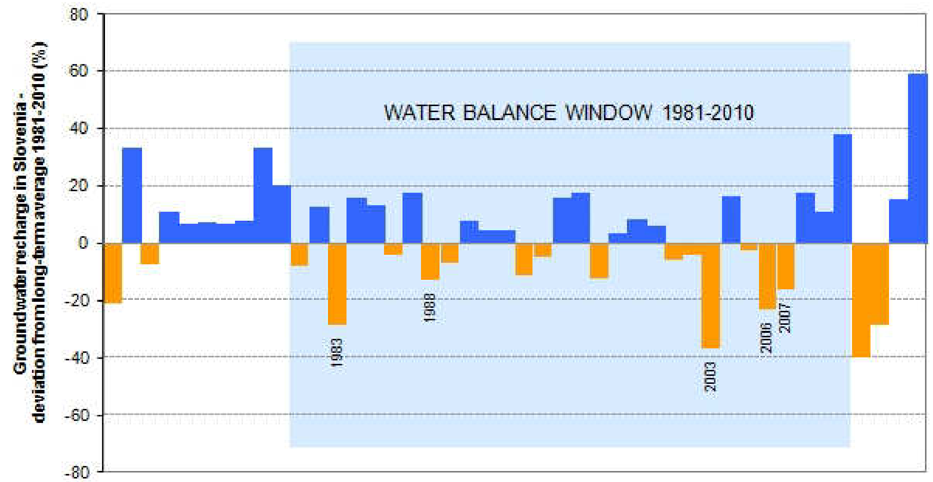

Figure 7-2: Defining five most dry years in reference time window (sliding 3 decades hydrological reference period) for calculating GROWA (05) groundwater recharge.

Evaluating the ratio of groundwater abstraction to the available groundwater quantity annually enables continuous assessment of groundwater abstraction pressure on groundwater bodies, being also an early signal in case more detailed analyses are needed for the six year cycles of river basin management plans.

An example of use of GROWA-SI for annual groundwater quantitative status assessment in the year 2013 is shown in Figure 7-3. On the map are shown nation-wide groundwater recharge rates in mm/a, the available groundwater per groundwater bodies by the size of the circles and ratio of groundwater abstraction to available groundwater both graphically and by percents. In this way a value of e.g. 10 means that 10 percents of long term average available groundwater is abstracted.

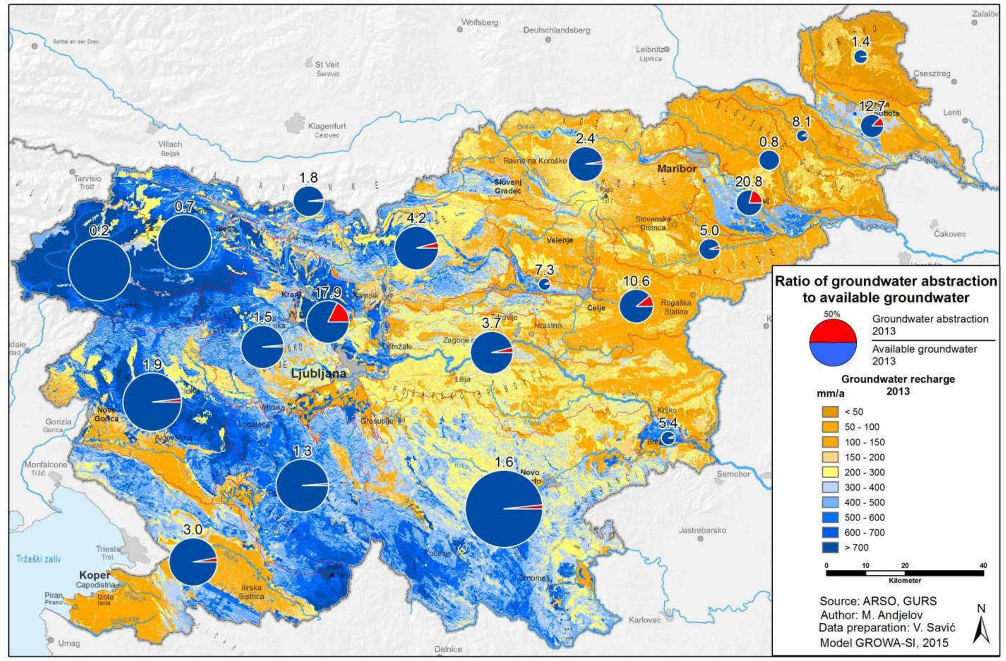

Figure 7-3: Ratio of groundwater abstraction to available groundwater in 2013 by groundwater bodies, together with groundwater recharge by GROWA-SI (Uhan ed., 2015a).

Figure 7-3 shows that the lowest pressure on groundwater quantity occurs in the Alps macro region karst groundwater bodies, where groundwater abstraction consumes less than 1% of the available groundwater. Opposite, largest pressure on groundwater quantity has been assessed for the groundwater bodies with intergranuar porosity located in the vicinity of big cities. But even in these alluvial aquifers the groundwater abstraction doesn't exceed one quarter of available groundwater (Uhan ed., 2015a).

7.2 River basin management plan

For the Second Slovenian River Basin Management Plan for the period 2015 – 2021 (MOP, 2015) at the first step mean annual groundwater quantities for 1981 – 2010 reference period have been determined based on GROWA-SI results on groundwater recharge (see Table 7-1 and Figure 7-4).

Table 7-1: Mean annual groundwater (GW) quantities for 1981-2010 reference period (Mikulič et al., 2015).

	Mean Slovenia (mm/a)	**Range by GW bodies (mm/a)**
Renewable GW (GWR)	289	57-723
GW for surface waters	67	17-168
GW for ecosystems	7	0-50
Available GW (GWA)	215	37-555

Mean annual renewable groundwater quantity (groundwater recharge) in Slovenia for 1981-2010 reference period, amounted to 289 mm/a, while the range of groundwater recharge determined for the 21 groundwater bodies was from 57 mm/a to 723 mm/a (Table 7-1). The available groundwater was derived according to the procedure suggested by Water Framework Directive, i.e. by reducing the renewable groundwater (Figure 7-1) by the quantity needed to maintain good ecological status of surface waters and the quantity needed to support groundwater dependent terrestrial ecosystems respectively. The resulting value of available groundwater 215 mm/a indicates that about three quarters of the renewable groundwater quantity in Slovenia can be used sustainably. Mean annual groundwater quantities converted into discharge, needed to enable comparison with groundwater abstraction, are shown in Figure 7-4.

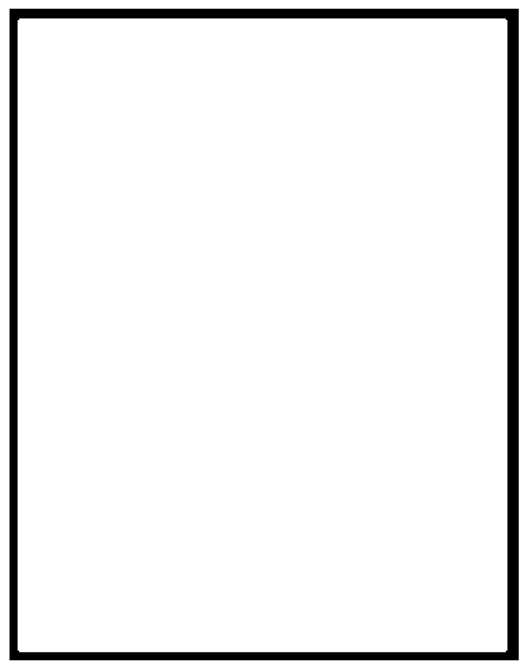

Figure 7-4: Mean annual renewable groundwater (GWR), available groundwater (GWA) and groundwater abstraction (ABSTR.) in Slovenia (Mikulič et al., 2015).

Discharge amounts to 185.5 m^3/s for renewable groundwater and to 135.2 m^3/s for available groundwater respectively (Figure 7-4). With an annual groundwater abstraction of 4.7 m^3/s, only 3.5% of the groundwater available in Slovenia on a national scale is exploited (Mikulič et al., 2015). However, as indicated in Table 7-1, the available groundwater quantities on a scale of groundwater bodies show a significant variation.

The Second Slovene River Basin Management Plan for the period 2015 – 2021 (MOP, 2015) comprises additionally data of GROWA-SI calculations for all groundwater bodies in Slovenia. Groundwater recharge derived from GROWA-SI model was used to determine the available groundwater in the groundwater quantitative status assessment. In this groundwater quantitative status assessment the ratio of groundwater abstraction for the period 2010 – 2013 to available groundwater quantity for the period 1981 – 2010 was calculated (Figure 7-5).

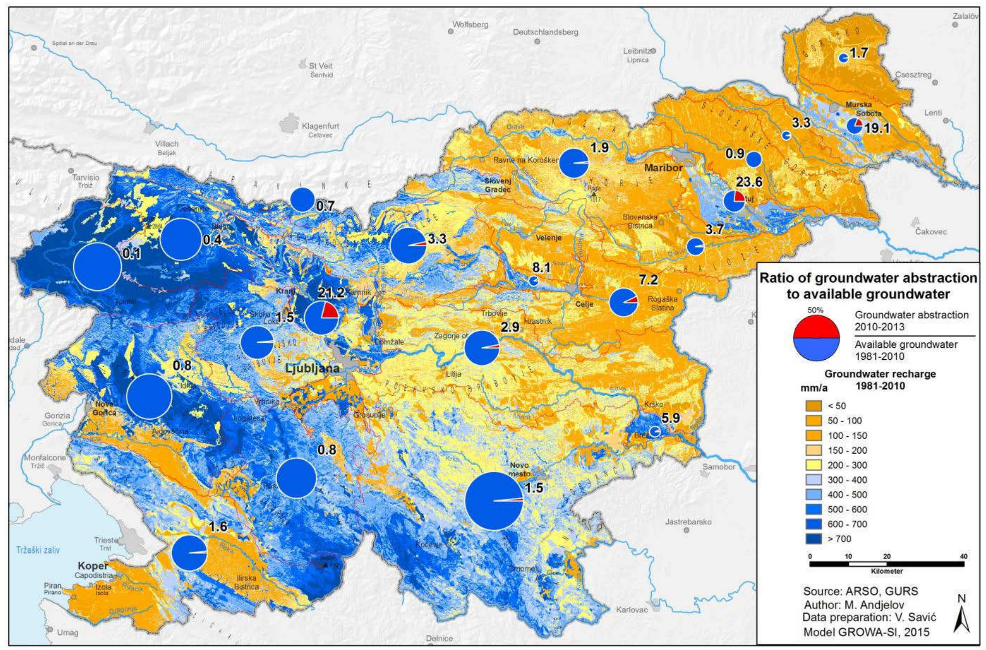

Figure 7-5: Ratio of groundwater abstraction (2010-2013) to mean long term available groundwater (1981-2010) by groundwater bodies, together with groundwater recharge by GROWA-SI (Uhan ed., 2015b).

The ratio of groundwater abstraction (2010-2013) to the mean long term available groundwater (1981-2010) shows a similar pattern to that described in Figure 7-3 for the ratio of groundwater abstraction to available groundwater for an individual year 2013. In this way, the ratio of groundwater abstraction (2010-2013) to mean long term available groundwater (1981-2010) indicates for the Alps macro region karst groundwater bodies, that groundwater abstraction seems in general to consume about 1% or even less of the available groundwater. In the same way the largest pressure on groundwater quantity is again assessed for the groundwater bodies with intergranuar porosity located in the vicinity of big cities Ljubljana and Maribor. There, abstractions are in the range between one fifth and one quarter of the available groundwater (Uhan ed., 2015b).

7.3 Water balance data for various EU and global institutions

Data on water balance components are an important part of supranational environmental information systems. Results for Slovenia of the water balance by GROWA-SI model are reported to European Environment Agency EEA and EUROSTAT/OECD in order to support the decision making processes and policy evaluation for the European Commission. In the process of environmental policies the water balance data, together with data on water abstraction and data on water use, are the core information for policy makers to implement and monitor the sustainable development of regions, member states and the EU. The water balance data are used by several institutions: European Environment Agency in Water Information System for Europe – WISE reporting, in OECD/Eurostat Joint Questionnaire and in Eurostat Regional Environmental Questionnaire**.** Data are reported on national and River Basin District - RBD level and are used as environmental indicators, for assessment of ecological status and trends, as well as to evaluate progress in achieving environmental policy objectives. The data are also used by EEA to assess Water Exploitation Index WEI+.

Since 2005, Slovenian Environment Agency regularly reports to the aforementioned European institutions on following water balance components, in recent years calculated by GROWA-SI:

- actual evapotranspiration,
- total runoff,
- groundwater recharge.

By data processing of member state contributions the European Commission, jointly with DG Environment, Joint Research Centre, Eurostat and the European Environment Agency fulfils official reporting requirements of EU water legislation. These data are incorporated in numerous thematic and synthetic reports on environmental indicators and water status in European Union (EEA, 2012a, 2012b, 2012c, 2014).

7.4 Groundwater recharge as an environmental indicator

Groundwater recharge modelled by GROWA-SI for individual years since 2011 is one of regularly published environmental indicators. It is published as VD-15 “Groundwater Recharge” at ARSO Website (KOS, 2015). Following graphics are derived from GROWA-SI model results:

- the graph of the yearly deviation of groundwater recharge from the mean of long term reference period 1981-2010 for all years since 1971 (Figure 7-6),
- the maps of area distributed groundwater recharge for the individual years (2011 to 2014), i.e. since implementation of GROWA-SI at ARSO (Figure 7-7), as well as
- the maps of yearly deviation of groundwater recharge from the mean of long term reference period 1981-2010 for the individual years since 2011 (Figure 7-8).

The deviation of groundwater recharge from the mean of the long term reference period 1981-2010 (Figure 7-6) is an important indicator of the groundwater regime variability from year to year. The graph shows that the variation has increased very much in the current decade. Thus both extremes, i.e. the driest year 2011 and the most water abundant year 2014 of the entire period since 1971, have occurred in the current decade. In case this pattern will continue, less constant groundwater recharge rates will pose in the future new challenge to the water management planning.

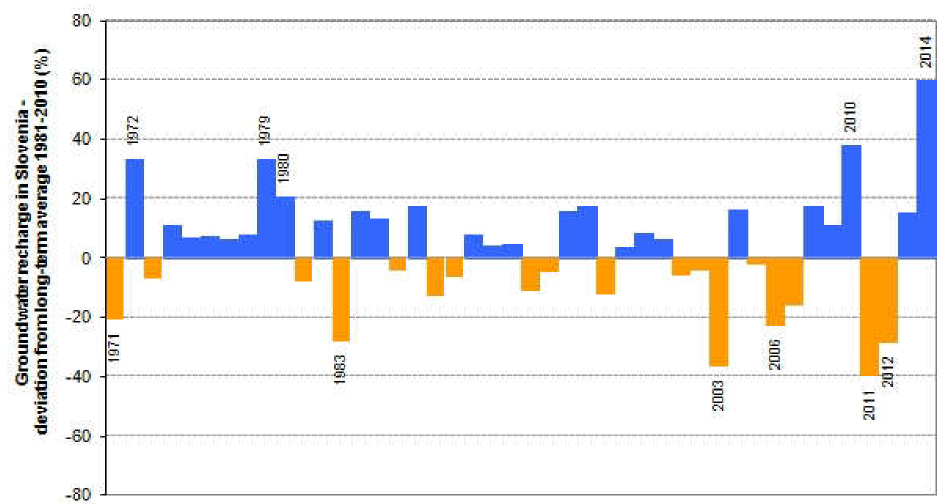

Figure 7-6: ARSO environmental indicator VD-15 “Groundwater Recharge”; deviation of yearly groundwater recharge by GROWA-SI from 1981-2010 mean.

The maps of groundwater recharge for individual years 2011 to 2014 (Figure 7-7) are prepared yearly since implementation of GROWA-SI at ARSO in order to inform interested public and relevant water management institutions on regional distribution of groundwater resources in previous year. The maps for the years 2011 to 2014 exhibit large regional variability of groundwater recharge between individual years, which was already discussed with the example of figure 7-6. The fact that there was a row of very wet and very dry years is presented here in its impact on regional groundwater recharge. Groundwater quantity among regions may deviate by factor of 5 and even more.

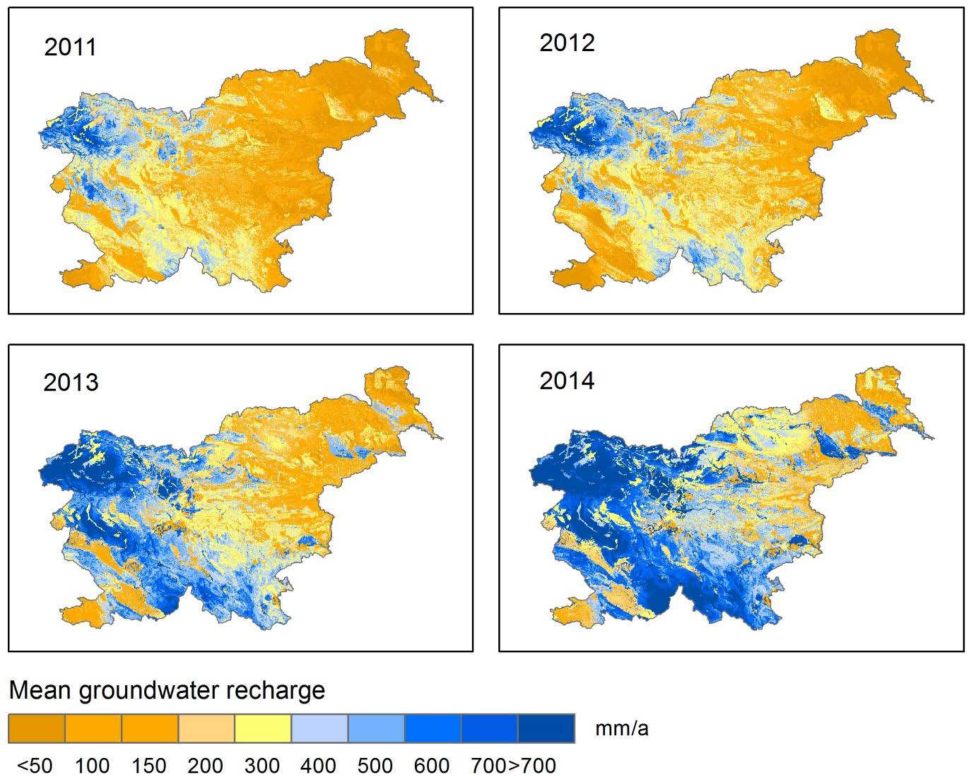

Figure 7-7: ARSO environmental indicator VD-15 “Groundwater Recharge”; groundwater recharge for individual years 2011 to 2014.

The maps of yearly groundwater recharge deviations from the long term reference period 1981 – 2010 (Figure 7-8) offer additional information for the whole country on regional water abundance distribution of the particular year. The deviation of mean annual groundwater recharge from the mean of the long term reference period 1981-2010 for the individual years since 2011 (Figure 7-8) shows that in the driest year 2011 (Figure 7-6) the large negative deviation in percents from the long term mean 1981 - 2010 was observed in majority of eastern half of the country, while in the dry year 2012 the large negative deviation was observed only in the Mediterranean macro region and in the north east of the Pannonian macro region. So in 2011 severe drought was experienced in large area of Slovenia, while in 2012 drought was local regional phenomenon with central parts of the country close to the normal situation. In 2014, the most water abundant year since 1971 (Figure 7-6), the positive deviation in groundwater recharge was more or less even, thus the entire country experiencing evenly distributed relative increase in water abundance.

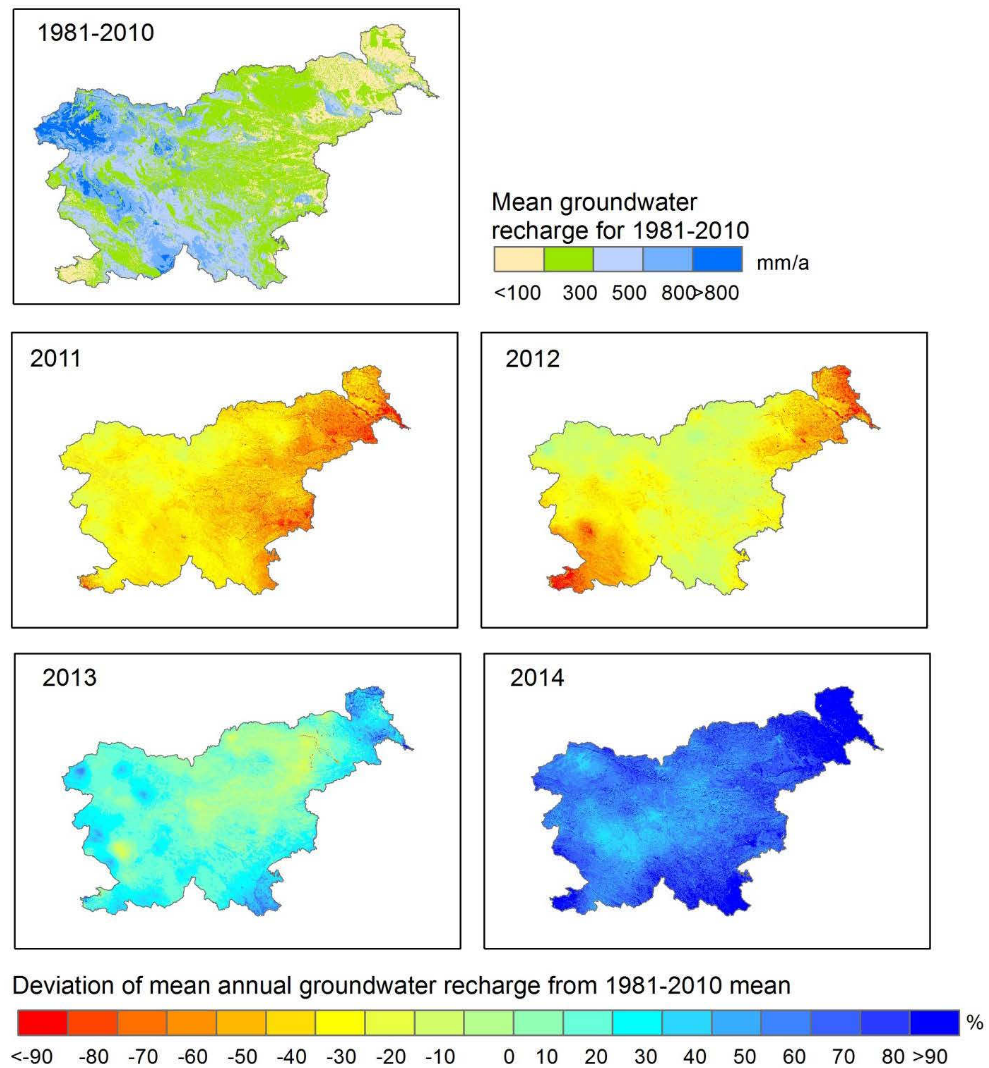

Figure 7-8: ARSO environmental indicator VD-15 “Groundwater Recharge”; groundwater recharge deviations from 1981-2010 mean, modelled by GROWA-SI for individual years since 2011.

The graphics of the environmental indicator VD-15 “Groundwater Recharge” and calculated groundwater recharge deviations from the normals offer valuable data to the interested public as well as to water planning managers.

7.5 Assessment of climate change impact on groundwater recharge

Climatological study of Slovenia for the 50 years period 1961-2010 shows an increase of mean annual air temperature by 1.7°C. Solar radiation duration and potential evapotranspiration increased too, while mean annual precipitation decreased up to 20% (Vertačnik, 2016). This climate variation has impacted water cycle by decrease of renewable groundwater resources (Andjelov et al., 2013).

Comparison of the mean annual groundwater recharge modelled by GROWA-SI for two 30 years periods, 1971-2000 and 1981-2010, showed a decrease of the mean annual recharge for Slovenia by 15 mm (Andjelov et al., 2013). This corresponds to a discharge of 9.6 m^3/s, which is more than twice as much as the current annual groundwater abstraction.

The climate change impact on groundwater recharge was studied for the Second River Basin Management Plan of 2015-2021. Impact was assessed by comparing the groundwater recharge rates of the thirty year period 2021-2050 to the groundwater recharge rates of the thirty year reference period 1981-2010. For the greenhouse gases emission forecast A1B scenario (IPCC SRES) was used. Climate change projections based on the A1B scenario were carried out in the European project ENSEMBLES. For this purpose regional climate models (RMCs) have been used. Results of ENSEMBLE project included the GROWA input parameters potential evapotranspiration and precipitation.

Expected interval of precipitation and potential evapotranspiration values from the model ensemble was assessed as 25^{th} percentile, median and 75^{th} percentile for 2021-2050. Each combination of precipitation and potential evapotranspiration of 25^{th} percentile, median and 75^{th} percentile for 2021-2050, was used as an input into GROWA-SI model runs, giving nine combinations (Figure 7-9).

The results compared to the 1981-2010 reference period show groundwater recharge quantity decrease in Slovenia by 8.7% for the most unfavourable combination (25^{th} percentile precipitation and 75^{th} percentile evapotranspiration) and an increase of the mean annual groundwater recharge by 6.5% for the most favourable combination (75^{th} percentile precipitation and 25^{th} percentile evapotranspiration). The GROWA-SI model run for median input values of precipitation and potential evapotranspiration resulted in 1% decrease of mean annual groundwater recharge.

Forecasted groundwater recharge was additionally analysed in the framework of predicted groundwater abstraction. Current trend of groundwater abstraction (MOP, 2015) extrapolated for ten years in advance showed 10% lower abstraction in 2025.

Since the projections to 2025 show stable population of Slovenia (EUROSTAT, 2014), the per capita groundwater consumption is expected to decrease. Consequently, a crisis in drinking water supply on national scale can most probably be excluded. However, uneven distribution of groundwater recharge and great seasonal variability will continue to pose problems in water supply in some parts of the Mediterranean and Pannonian macro regions. Possible future water shortages in these regions can be avoided by interconnecting local and regional water supply systems into an integrated network of national “Slovenian Water Stream” system (Mikulič, 2010).

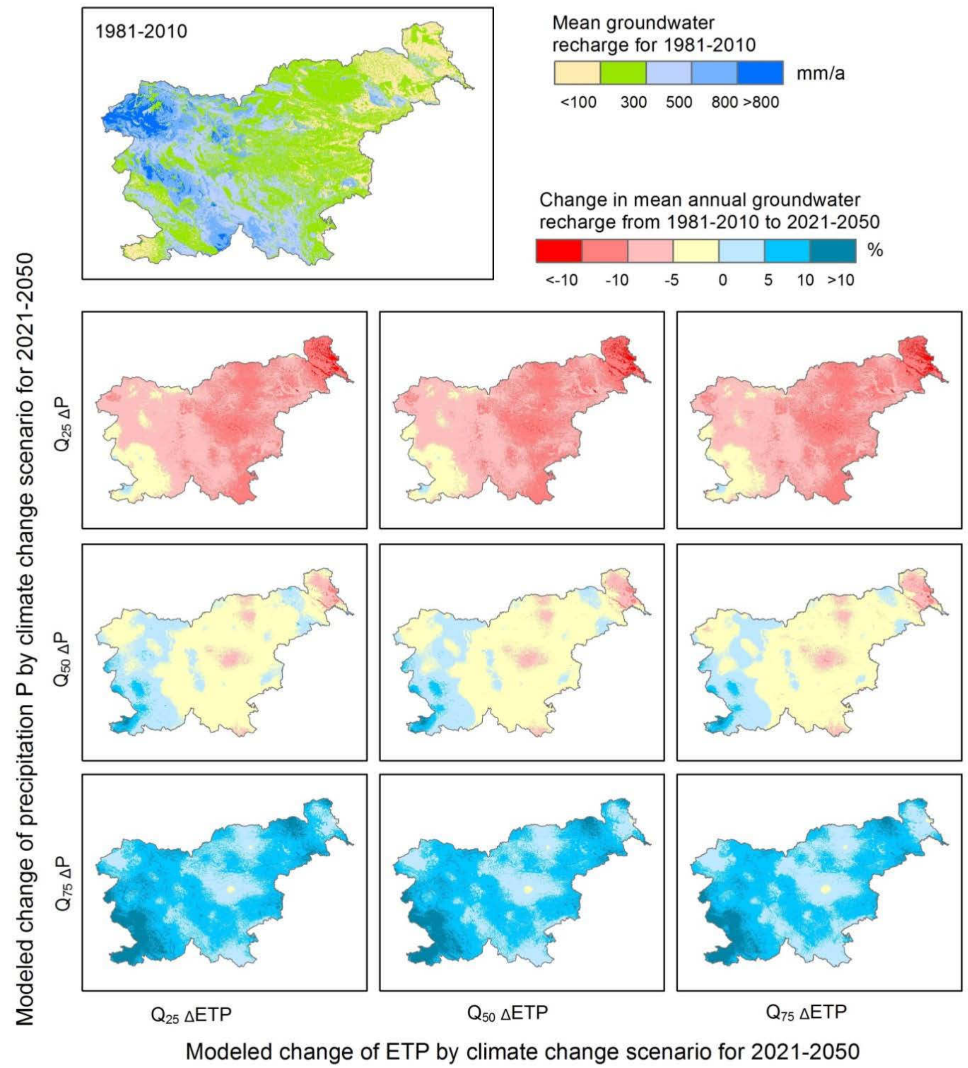

Figure 7-9: Deviations in groundwater recharge by GROWA-SI applying the 25th, median and 75th percentile of precipitation and potential evapotranspiration of climate change model ensemble for 2021-2050.

7.6 Groundwater recharge in data driven modelling of groundwater vulnerability to nitrate pollution

Anthropogenic nitrate pollution is also in Slovenia one of the major pressures to groundwater resources. After the transposition of Nitrate Directive (Directive 91/676/EEC, 1991) into Slovenian legal system, and based on the general assessment of the intrinsic groundwater vulnerability to pollution, the entire territory of Slovenia was proclaimed as nitrate vulnerable zone. Also, at the entire national territory it should have been followed by adopting of operational program of water protection to nitrate pollution from agriculture production (Official Gazette of the Republic of Slovenia 113/09, 2009). However, based on data of national immission monitoring for the First River Basin Management Plan (Bizjak ed., 2009a, 2009b) bad chemical status was assessed only for three groundwater bodies, covering 5.5% of national territory. The obvious discrepancy had to be resolved by area detailed analysis of groundwater vulnerability and tools for pollution probability assessment for area targeted program of measures.

The most commonly applied groundwater vulnerability assessments include map overlay methods of vector or raster systems, as well as parametric point count methods. These vulnerability maps offer only relative relations between estimated vulnerability classes and are difficult to validate by field data (Gogu & Dassargues, 2000). This led to a wider use of data-driven statistical models, based on area distribution of the pollution data, offering also characterisation of the pollution potential. The self-validation of models is governed by area distributed training points and the vulnerability itself is defined as a probability of the phenomena. One of these data-driven statistical models is Weight-of-Evidence (God, 1985), used in groundwater vulnerability case study of Spodnja Savinjska dolina.

Case study of Spodnja Savinjska dolina, close to the town of Celje in the Alps macroregion, is alluvial aquifer under heavy pressure by pollution from agriculture and urbanization. To assess aquifer vulnerability, data-driven Weights-of-Evidence model Arc-WofE (Kemp et al., 1999) was used (Uhan et al., 2011). Data of field measurements of nitrate pollution (Figure 7-10 map A) together with hydrological analysis and models (Figure 7-10 maps B, C and D) were integrated into the map of so called phenomena occurrence conditional probability for relative nitrate vulnerability as shown in Figure 7-10 map E (Uhan, 2012). Input layers into WofE model included the map of groundwater recharge by GROWA-SI (Andjelov, 2009), the map of nitrogen load in seepage water by DNDC model (Uhan, 2011) and the map of groundwater flow velocity by FEFLOW model (Vižintin, 2009) as evidential themes to calculate posterior probability. In each evidential theme calculated weights provide a measure of spatial association between the measured point values and the evidential theme. By evaluating the weights influence on change of prior probability relative classes of posterior probability of nitrate pollution have been defined, shown on map E in Figure 7-10. The highest nitrate pollution probability was found out to be in the central area of the aquifer with small depth of the soil cover and sand-gravel unsaturated zone, while the lowest probability was found to be at the aquifer periphery with anoxic conditions. According to the calculated confidence value the most important contribution on the final response theme in WofE was assessed for the groundwater recharge evidential theme from GROWA-SI model.

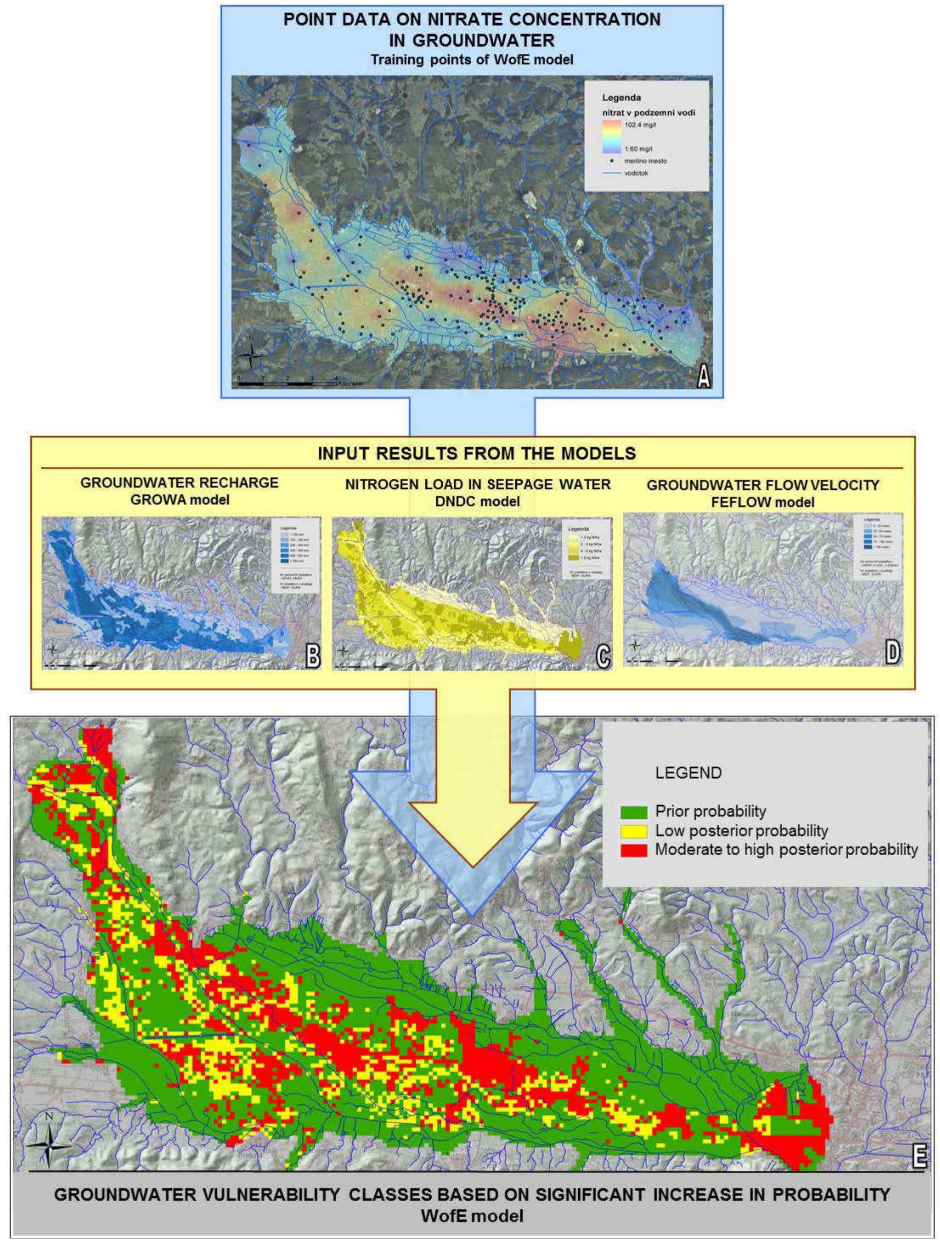

Figure 7-10: Model system for assessment of nitrate pollution probability and assessment of relative nitrate vulnerability by WofE data driven approach (Uhan, 2012).

7.7 Nitrogen flux modelling in Slovenia based on GROWA results

Reporting on the implementation of Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources (Directive 91/676/EEC, 1991) requests an assessment of developments in water quality. Up to recently the assessment in Slovenia was based on trend analysis of monitored nitrate concentration from country-wide groundwater and surface water monitoring networks (Matoz et al., 2012).

Since a couple of years the evaluation of data from the national monitoring networks is supported in many countries by nitrogen flux model analyses at a national or river basin scale (e.g. SWAT: Gassmann et al., 2010; STONE: Wolf et al., 2005; HYPE: Arheimer et al., 2012). In Germany the most common nitrogen flux models applied on the level of river basins and Federal States include MONERIS (Behrendt et al., 1999) and GROWA – DENUZ / WEKU (Kuhr et al., 2013; Kunkel et al., 2010; Wendland et al., 2009b).

The model system GROWA – DENUZ / WEKU has just been introduced in Slovenia for the determination of the diffuse nitrogen inputs into groundwater and surface water (Andjelov et al., 2014). For this purpose the agricultural nitrogen balance surpluses derived by the Agricultural Institute of Slovenia (Sušin & Verbič, 2015) were coupled with the model system GROWA – DENUZ / WEKU.

The here presented GROWA-SI model results on runoff components (direct runoff and groundwater recharge) assessed in a spatial resolution of 100 m x 100 m for the entire territory of Slovenia are essential for defining the regional dominant input pathways for diffuse nitrogen inputs into river systems (see Figure 7-11).

Regions where low BFI values predominate, charachterize the regions where most of the percolation water reaches the surface waters via direct runoff, i.e. without reaching the aquifer. In contrast, regions where high BFI values dominate charachterize the regions where most of the percolation water infiltrates into the aquifers as groundwater recharge. In all these areas of high BFI groundwater runoff is the dominant nitrate transport pathway. Accordingly, all groundwater bodies displaying high portions of karst porosity and/or intergranular porosity indicate the regions, in which high nitrate inputs into the aquifer may occur. Management strategies to protect groundwater from high diffuse nitrate inputs should directly be implemented in these regions. GROWA results on the ratio direct runoff / groundwater recharge indicate such regions from the outset.

The percolation water rates from the GROWA model are essential to determine nitrate concentration in the leachate. The leachate rate is defined as the difference between total runoff and surface runoff. Fig. 7-11 shows the leachate rates for the time period 1971-2000 calculated with the GROWA-SI model. A considerable variation occurs within the country, which refers to the heterogeneity of the prevailing site conditions. The regional differentiation shows a significant decrease from the parts of the Alps and Dinaric macro regions to the sub-continental Pannonian macro region. The central parts show a wide range of leachate rates between 400 and 1,200 mm/a. Low leachate rates can be found in the Pannonian macro region below 300 mm/a, with low peaks <150 mm/a in the north east of the country. High values above 900 mm/a are modelled for the alpine regions in the northern and especially northwestern parts of Slovenia.

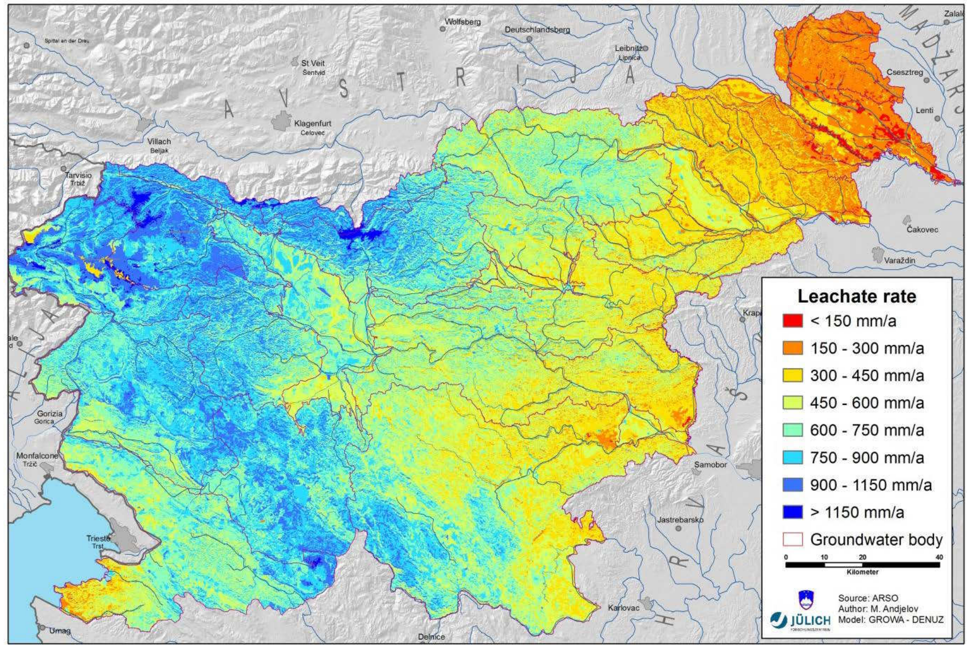

Figure 7-11: Calculated mean total leachate rate in Slovenia for the period 1971-2000.

The leachate dilutes the displacable N-quantity in the soil. Modelled nitrate concentrations in the leachate therefore exhibit significant differences, which depend not only on the the displacable N-quantity in the soil, but also on the leachate rate. Thus, the dilution of the same displacable N-quantity in the soil is 10 times higher in regions where leachate rate is about 1,500 mm/a, compared to regions where the leachate rate is in the range of 150 mm/a.

The final report in which the procedure and the most important results of implemeting the GROWA – DENUZ / WEKU model system in Slovenia is in preparation and will be published in 2016 (Andjelov et al., 2016). The GROWA – DENUZ / WEKU model system results will directly support the implementation of the EU – Nitrate Directive and EU – Water Framework Directive in Slovenia, e.g. as a framework for planning of regionally adapted and hence effective nitrogen reduction measures.

8 Conclusions and outlook

The main objective of the project, the implementation of GROWA model for the quantification of groundwater recharge in Slovenia has been successfully achieved. Research work carried out has shown that the GROWA model concept could be transferred to Slovenia with complicated physio-geography at the intersection of four European macro regions: The Alps, Dinaric Alps, Mediterranean and The Pannonian.

Model results for thirty years period show that on average Slovenia is a country rich in groundwater resources, but at the same time the uniform and consistent derived groundwater recharge map for the whole country reveals a big regional variability of groundwater recharge. There is also a big inter-annual variability as documented by the GROWA-SI model runs for single years. This regional and temporal variability poses a challenge to the water management.

Groundwater recharge modelling is a big step forward for water resources management in Slovenia, as the so called static and dynamic groundwater reserves determined in previous studies could be replaced by nationwide approach which takes the renewable groundwater quantities into account in high spatial resolution and on a multi-annual time scale as well as for single years. The GROWA-SI model results of the here presented study are the starting point to derive these time and area variable groundwater quantities.

To arrive to the groundwater recharge other major components of the water balance have to be calculated: real evapotranspiration, total runoff and direct runoff. These GROWA-SI model products have still to be recognised by the users and get a wider use by planners, industrial associations, manufacturers and decision makers.

As shown by some analyses already performed, the model results have also a big potential for simulating climate change impacts on water resources in Slovenia in the coming decades.

The good cooperation between Forschungszentrum Jülich and Slovenian Environment Agency in successfully transferring GROWA model to Slovenian hydrologic practice already initiated further steps in the joint research projects.

The GROWA - DENUZ / WEKU systems of models for modelling nitrogen input into groundwater and surface waters is in the final phase of introducing into Slovenian practice, while in the just recently started joint research project on mGROWA model transfer to Slovenia the partners will work together on developing new module in the model system. It is expected that mGROWA results for water balance components on daily time scale will expand use of water balance to new sectors in water management in Slovenia.

In the future it is envisioned to jointly develop a soil erosion model for Slovenian site conditions that will enable the expansion of nitrogen flux modelling to sediment and phosphate flux modelling.

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