Rasterised Water Demands: Methodology for Their Assessment and Possible Applications

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Abstract In this paper a methodology for the calculation of grid cell spatially distributed water demands—for the stakeholders domestic, municipal, industrial and agricultural (without rainfed or irrigated crop production) water use—is presented. As case study the Kitzbühel region in the Austrian Alps, encompassing 20 municipalities, was chosen. Austria is one of few countries within the European Union that provides data of the population and housing census of 2001 in a raster format, with resolutions 125, 250, 500, 1,000 and 2,500 m. From these available data, population and employment raster data were used for the analysis. Based upon the latter and a calibrated related rate of water use (litre per unit per time interval), rasterised yearly and winter water demands were calculated. These rasters represent the alpine character of the study area and are independent of political borders. They can be used in hydraulics related studies, a wide range of water resources management studies and for landscape and urban planning studies. The limiting factor and scale for all applicable studies is the resolution and availability of accurate population and water use data. This fine-resolution water demand dataset can only be generated with the high resolution census data and (reasonably) accurate water use data via survey and expert input. Therefore the scale of studies where the proposed methodology is applicable is limited to a local and regional scale, up to national borders where the detailed population and housing census of 2001 is available as raster data.

Keywords Raster · Grid · Spatially distributed · Population census ·
Water demand · Europe

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1 Introduction

Water demand rasters have been used in different studies like (Alcamo et al. 2003, 2007; Craswell et al. 2007; Döll et al. 2003; Durga Rao 2005; Meigh et al. 1999; Perveen and James 2010; Vörösmarty et al. 2000; Vorosmarty et al. 2010). These rasters were computed using (1) population data and in some cases socio-economic data and (2) per capita consumption rates. However, the measure of detail of these rasters is not very high. (Alcamo et al. 2007) e.g. used demographic and socio-economic data to downscale country-scale estimates of domestic and industrial water to a 0.5° grid (about 55 km at the equator) on a global level. They then re-aggregated these values to the river basin scale for water stress calculations. (Meigh et al. 1999) calculated similarly a global population water demand raster with a 0.5° grid resolution. Urban and rural populations were treated separately since the water consumption rates are considerably different. (Vörösmarty et al. 2000) calculated domestic and industrial water demands globally with a 0.5° grid resolution by means of population and per capita use statistics. The geography of contemporary urban and rural population was developed from a 1-km data set. Country-level water withdrawal statistics were used to estimate contemporary water demands.

With rasterised data becoming more available—on the one hand resulting from census data and on the other hand provided by modelling of for example light emission data (Briggs et al. 2007)—the computation of water demand rasters will be possible in more areas of the world and at higher resolutions. Some institutions provide gridded population data on the web, like the gridded population of the world (CIESIN 2005). The latter is available in a 1 km resolution, with a differentiation between urban and rural population. In other words, by means of this dataset and data on per capita consumption rates, water demands can be regionalised to a resolution of 1 km. However, the rate of accuracy of such regionalisation depends on available data. When e.g. per capita consumption rates are only obtained from national estimates of domestic and industrial use (withdrawal and/or consumption), the resulting regionalised water demand raster will not contain much detailed information.

This paper presents a methodology for the calculation of a very detailed water demand geographical grid, which is made possible by the availability of a raster geodataset of the population and housing census of 2001 for different European countries (Statistics Austria 2008). Different water demand stakeholders can be computed separately on a grid cell basis into one total water demand raster owing to the latter geodataset. To obtain such a grid, the number of units of this detailed population and housing census raster are multiplied with a rate of water use (litre per unit per time interval) for the different stakeholders. These water use rates are obtained from literature and calibrated with operating data from the water supply undertakings in the study area.

The water demand raster includes following stakeholders: domestic water demand, municipal water demand, industrial water demand and agricultural water demand. In this study the latter relates to agricultural activities which are generally water fed by the public municipal water supply system, i.e. (1) persons employed in the agricultural sector and (2) water consumption of livestock. Rainfed (green water) and irrigated (blue water) crop production are major water demand stakeholders (Falkenmark and Lannerstad 2007; Rockström et al. 2009; Vanham 2010; Wichelns 2010), but they are not included within the water demand raster. Water demand

rasters for both rainfed and irrigated crops based upon agricultural fields have been calculated in numerous studies, e.g. (Siebert and Döll 2010).

Within this paper the methodology to calculate such a grid is described. Possible applications for the generated water demand raster are also discussed further in Section 4.2. They include hydraulics related studies, water resources management and landscape and urban planning studies. It has to be stressed that this approach is only applicable in countries where such detailed information is available.

The detailed population and housing census of 2001 raster (Statistics Austria 2008) is available in the resolutions 125, 250, 500, 1,000 and 2,500 m. The cost to purchase this dataset is dependent on the resolution. The methodology can be used for all resolutions. Dependent on the purpose and the budget of a (research) project any resolution can be chosen. The next population and housing census is set for 2011 and will provide for updated data.

2 Case Study Description

The study area—the greater Kitzbühel region—encompasses 20 municipalities in the Austrian Province of Tyrol (Fig. 1), the largest part of them with a rural character. Only Kitzbühel and Sankt Johann have a more urban character. The part of the valley between Kirchdorf and Kitzbühel has a larger concentration on industry and small trade as compared with the remaining study area.

Each municipality has its own water supply organisation. More specifically, 25 major water supply undertakings serve 86% of the principal residence population (Table 1). Apart from these larger municipal undertakings, a high number of small
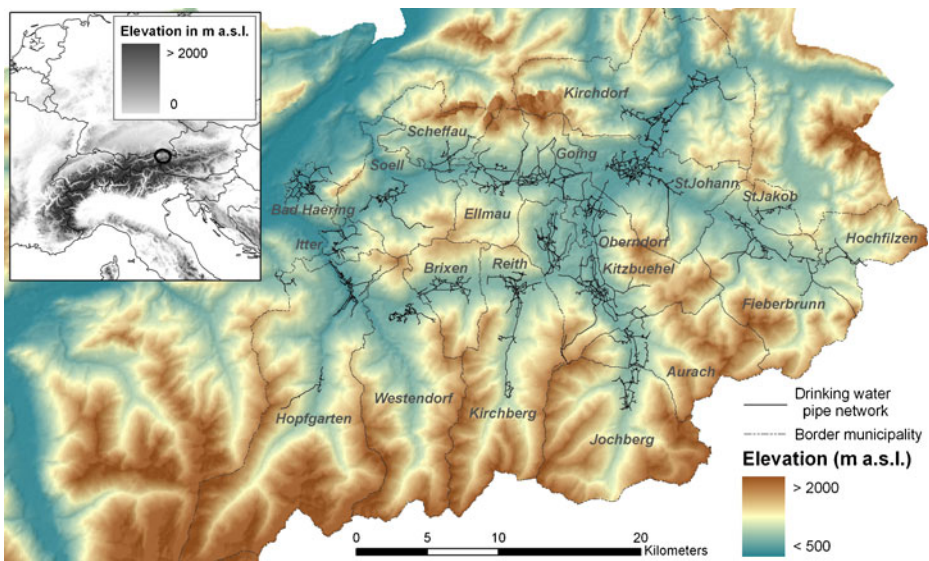
Fig. 1 Location of the 20 municipalities with their principal drinking water distribution networks of the study area within the Austrian Province of Tyrol

Table 1 Basic data from the EU-census of 2001 for the 20 municipalities of the project area

Municipality	Principal residence	Secondary residence	Persons employed[a] (without agriculture)	Persons employed in agriculture[a,b]	Yearly overnight stays[c]	Livestock units[c]	Major water supply undertaking[c]	Connection % principal residence[c,d]
Aurach	1,203	392	338	165	70,773	974	1	88
Brixen	2,574	673	679	346	251,173	1,351	1	93
Fieberbrunn	4,180	498	1,606	421	422,983	1,796	2	87
Going	1,730	293	590	204	306,132	913	1	96
Hochfilzen	1,109	129	503	96	48,620	675	1	83
Hopfgarten	5,266	1,196	1,649	871	337,044	3,424	3	69
Itter	1,060	96	499	135	74,202	733	1	93
Jochberg	1,540	606	361	153	63,938	736	1	84
Kirchberg	4,958	1,760	1,711	464	861,551	2,045	1	91
Kirchdorf	3,490	756	1,295	327	334,221	1,661	1	89
Kitzbuehel	8,571	4,084	6,009	274	767,259	1,484	1	96
Oberndorf	1,944	529	637	163	190,349	1,320	2	97
Reith	1,595	810	356	146	114,056	953	1	91
St.Jakob	635	149	119	80	82,591	379	1	100
St.Johann	7,959	1,363	5,131	366	517,857	2,871	1	91
Westendorf	3,454	1,692	922	453	418,244	2,305	2	43
Bad Haering	2,265	118	711	96	149,975	463	1	100
Ellmau	2,524	1,035	997	209	662,712	918	1	92
Scheffau	1,211	362	432	174	246,248	612	1	77
Soell	3,364	346	1,080	455	449,624	2,109	1	75
total	60,632	16,887	25,625	5,598	6,369,552	27,722	25	86

[a] Persons employed: self-employed and salaried employees

[b] Persons employed in agriculture: from agricultural census of 1999

[c] Data not originating from the 2001-census

[d] Connection % principal residence: of the major water supply undertakings

water co-operatives serve about 10% of the inhabitants. Cross-connections between the different supply systems are very rare, as they were not really necessary up to present due to the abundant availability of water resources of good quality. Due to this comfortable situation on the one hand, and the physical mountain barrier between different valleys on the other hand, alpine water supply systems developed into small structured, decentralised systems during the past century.

Population statistics are given for the greater Kitzbühel region for 2001, as in this year an EU-wide population census was conducted, for which raster data are available for the Austrian member state (Statistics Austria 2008; Wonka 2006). Tourism is by far the largest industry, with a total number of overnight stays of 6.4 million in 2001, of which more than half during the winter months December to March (Vanham et al. 2008). The 25 water supply undertakings serve the population through a water distribution network (without house connections) with a length (the sum of pipe lengths in all systems combined) of 556.7 km (Fig. 1). There is no irrigation in the region and rainfed crop production is of minor importance. Basically the only agricultural activity is livestock production. Water for technical snowmaking is taken from streams and springs (Vanham et al. 2009b). In very seldom cases small amounts of water for snowmaking are taken from the public drinking water system; however this is neglected within this study. As technical snowmaking requires large amounts of water, the cost for using water from the public system is too high.

3 Methodology: Calculation of Rasterised Water Demands

3.1 Introduction: The Basics of the Methodology

To obtain a water demand grid for a certain period of time, the number of units of the detailed population and housing census raster of the year 2001 (Statistics Austria 2008) are multiplied with a rate of water use for the different stakeholders. The time interval can range from yearly, to seasonal, monthly, weekly, and daily up to hourly, as water demands tend to fluctuate during these different intervals. This is due to both fluctuations in water use rates as in the number of water demand stakeholder units. Water use rates can be obtained from literature and calibrated with operating data from the water supply undertakings.

Within a certain water supply service area both spatial and temporal water demand fluctuations exist. Different population densities within a water supply service area result in spatial differences in domestic water demands (Fig. 2). The rate of water use for population e.g. can spatially differ between rural and urban areas, or within urban areas according to socio-economic factors (e.g. high income and low income areas in a city). The rate of water use also differs temporarily, e.g. during summer water demands can be higher due to garden watering or the water rate is higher during daytime than during night time. Also the number of units in population can temporarily fluctuate, e.g. the number of population of secondary residence will be higher during holiday seasons in a touristic region as during the rest of the year. These aspects will be discussed in detail in the following sections.

The water demand raster in this paper represents following stakeholders:

- Domestic water demand or household demand
- Municipal and industrial water demand without tourism (overnight stays)
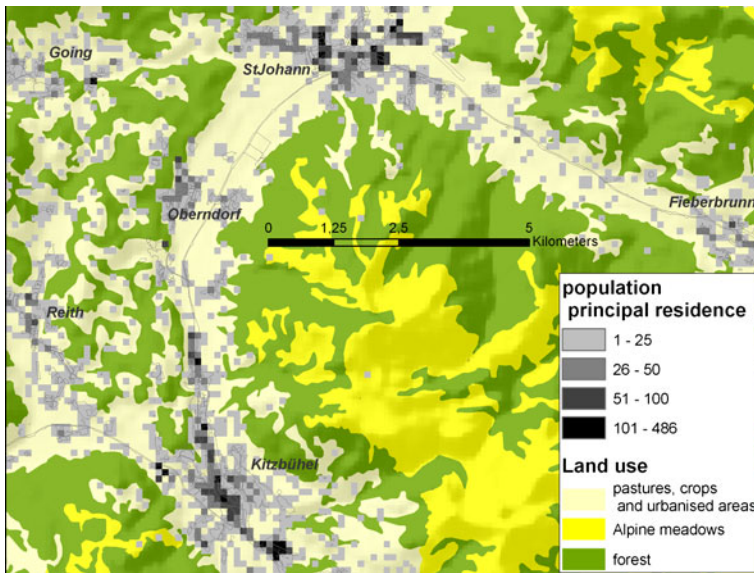
Fig. 2 Population of principal residence raster (people per grid cell, resolution 125 m) for the area Kitzbühel–Sankt Johann

- Municipal water demand restricted to tourism (overnight stays)
- Agricultural water demand (without rainfed and irrigated crop production)

The water demand Q within a grid cell for a certain time interval can be calculated as

$$Q = POPp*q_{POPp} + POPs*q_{POPs} + EMPL*q_{EMPL} + TOUR*q_{TOUR}$$
$$+ LU*q_{LU} + AGR*q_{AGR} \qquad (1)$$

with POPp and POPs defined as the number of population of principal respectively secondary residence within the grid cell, and q_{POPp} and q_{POPs} the rate of water use for population of principal respectively secondary residence within the grid cell. The term EMPL*q_{EMPL} represents the water demand for all employment activities (industries, small trade, schools, hospitals, administration, …) within the grid cell, with EMPL defined as the number of employed personnel and q_{EMPL} its rate of water use. The term TOUR*q_{TOUR} represents the water demand for tourist overnight stays within the grid cell, with TOUR defined as the number of overnight stays and q_{TOUR} its rate of water use. The term LU*q_{LU} represents the water demand for livestock within the grid cell, with LU defined as the number of livestock and q_{LU} its rate of water use. The term AGR*q_{AGR} represents the water demand for the employment activity agriculture within the grid cell, with AGR defined as the number of persons employed in agriculture and q_{AGR} its rate of water use.

In more detail Eq. 1 represents the different stakeholders as follows:

- *Domestic water demand or household demand*, based upon the census raster data population of principal and secondary residence. The first two terms ($POP_p*q_{POP_p} + POP_s*q_{POP_s}$) within Eq. 1 represent this water demand stakeholder.

- *Municipal and industrial water demand without tourism (overnight stays)*. The municipal water demand normally represents the water requirements of the commercial sector (shops, department stores, hotels, . . .) and for the services sector (hospitals, offices, schools and others). The services for tourism are thus normally included. The calculation of the total municipal and industrial water demand is based upon the census raster data number of persons employed in the different sectors (industries, small trade, schools, hospitals, administration, . . .). A differentiation between on the one hand the commercial sector and the services sector and on the other hand industry is very complicated within the list of ÖNACE-classes (Austrian 1 version of NACE, a pan-European classification of economic activities in the EU)—as described in the following section—used in the paper to differentiate amongst people employed in different classes. Therefore the paper identifies municipal and industrial water demands together. Within the commercial sector tourism in the form of overnight stays is calculated separately. The third term ($EMPL*q_{EMPL}$) within Eq. 1 represent these water demand stakeholders.

- *Municipal water demand restricted to tourism (overnight stays)*, based upon the census raster data tourist overnight stays. The fourth term ($TOUR*q_{TOUR}$) within Eq. 1 represents this water demand stakeholder.

- *Agricultural water demand (without rainfed and irrigated crop production)*. In this study this demand relates to agricultural activities that are generally water fed by the public municipal water supply system. The calculation is based upon the census raster data persons employed in the agricultural sector and livestock units (LUs). The fifth term ($LU*q_{LU}$) and sixth term ($AGR*q_{AGR}$) within Eq. 1 represent this water demand stakeholder.

3.2 Population and Housing Census Raster Data

Census data are definitely the best available baseline data on population. Across most of the world, census data provide routinely available information on population numbers and composition, at least on a decennial basis. CIESIN for example provides gridded population data of the world cost-free and easily available on the web (CIESIN 2005). However, despite the improvements made in census procedures over recent decades, the availability of detailed population data on the raster level is often limited. Continuous effort on obtaining detailed raster information through modelling e.g. Briggs et al. (2007) is made.

For the most recent EU population and housing census of 2001 (the next one will be in 2011), some member state countries (Austria, Denmark, Estonia, Finland, The Netherlands and Sweden) and associated states (Norway and Switzerland) provide census data on a raster level. However, the methods to ensure statistical confidentiality and therefore the resolution of the available data generally differ

between these countries (Szibalski 2007). For example, in Switzerland census data are offered already in a 100-m grid. Austria uses a lower threshold of 125 m. In Finland and Norway, the threshold is 250 m. Estonia publishes grid maps with a minimum resolution of 500 m. Sweden modifies data in order to make single persons unrecognizable. In Switzerland raster cells with low population values are only made available in a classified way (for examples 1–3) and in Austria some data are not given when a raster cell contains only one element. In all these cases a disadvantage has to be taken into account, as the sum of raster values can differ from the absolute value (Kaminger and Meyer 2007).

Table 2 provides an overview of raster data available in Austria for the 2001 census (Statistics Austria 2008) which were used in this analysis. For the calculation of the water demand, following raster data were used: population principal and secondary residence (POPp and POPs in Eq. 1), the number of workplaces and the number of persons employed (EMPL in Eq. 1) within the OENACE-codes C to O. The number of persons employed in the OENACE codes A (agriculture, hunting and forestry; AGR in Eq. 1, i.e. the number of persons employed in agriculture, without hunting and forestry) and B (fishing) were not available as raster data as they were not accounted for in the 2001 census. The number of persons employed in agriculture was collected in a 1999 agricultural census in Austria (Statistics Austria 2008), and is not available in raster format. The 1999 data were here regarded as equal for 2001. Sector growth statistics were not used because this sector is relatively small as water demand stakeholder compared to the other sectors.

3.3 Water Demand Raster

In order to include the spatial variation in water demand, the population and housing census raster of the year 2001 (Statistics Austria 2008) was used. In order to show temporal variations in water demand, a spatially distributed annual water demand raster and winter water demand raster were calculated. For the case study area (Vanham et al. 2008) defined winter as the period from December to March, the season with the highest water demands. The authors indicate that Alpine regions are particularly affected by seasonal variations in water demand and water availability.

Prior to the analysis, operating data (in this case annual sold water volumes) of the 25 drinking water supply systems were collected by means of a questionnaire. Maps of the water pipe distribution network were obtained from the water supply undertakings and implemented in a GIS.

Table 2 2001-census raster data available from Statistics Austria (former Austrian Central Statistical Office) used in this study (Statistics Austria 2008) (X = available)

| Raster resolution	125 m	250 m	500 m	1,000 m	2,500 m
Population principal residence	X	X	X	X	X
Population secondary residence	X	X	X	X	X
Persons employed (without agriculture)	X	X	X	X	X
Workplaces	X	X	X	X	X
Persons employed (without agriculture) within the OENACE-codes (the Austrian version of NACE) C to O.		X	X	X	X

As first step in the analysis, the service zones of the water supply undertakings need to be defined. A clear delineation of these zones is necessary to assess the rate of water use (Eq. 1) of the different water demand stakeholders, using operating data. The borders of these zones were defined within GIS (1) primarily by means of the water pipe distribution network (Fig. 1) and (2) supportively—as house connections were not available—by means of different raster layers of the population and housing census as well as local expertise of the water supply undertakings. An example of this procedure is displayed in Fig. 3 for the service areas of Sankt Johann and Oberndorf. The figure shows the water distribution network (without house connections) of these two service areas, which are both served by springs and groundwater wells. Apart from the population rasters in resolution 125 m, the service areas were also delineated using the raster "persons employed" in resolution 125 m. The so called Tyrolean "Water Book"—a register containing all water rights—and local expertise showed that the wood manufacturer "Egger" has its own groundwater well. Therefore the company with its 837 employees does not fall within the service zones of either Sankt Johann or Oberndorf. As data on house connections were not available, it was not certain whether this company is connected to the public supply system or not. In Eq. 1 this company represents a separate grid cell (EMPL = 837 employees) with its own water use rate (q_{EMPL}).

The number of units for the water demand stakeholders principal and secondary residence, persons employed (without agriculture) and persons employed in industrial zones are available as raster data. Annual and winter water demands for these stakeholders are assumed to be constant—which is a simplification—, thus expressing
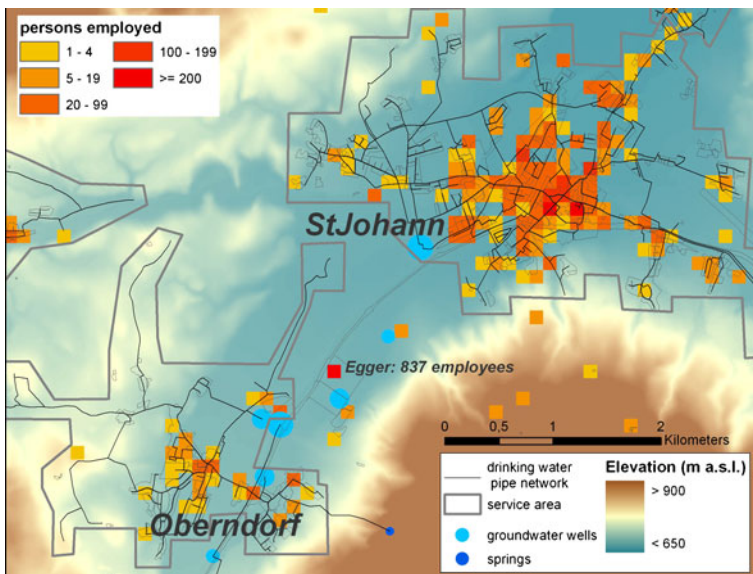

Fig. 3 Raster of the total number of people employed (resolution 125 m) in the different OENACE-classes within and around the service areas of Sankt Johann and Oberndorf. The company Egger, belonging to the subgroup "manufacturing of wood and wood products" within OENACE class D, has own groundwater wells and is not connected to the public supply system of Oberndorf
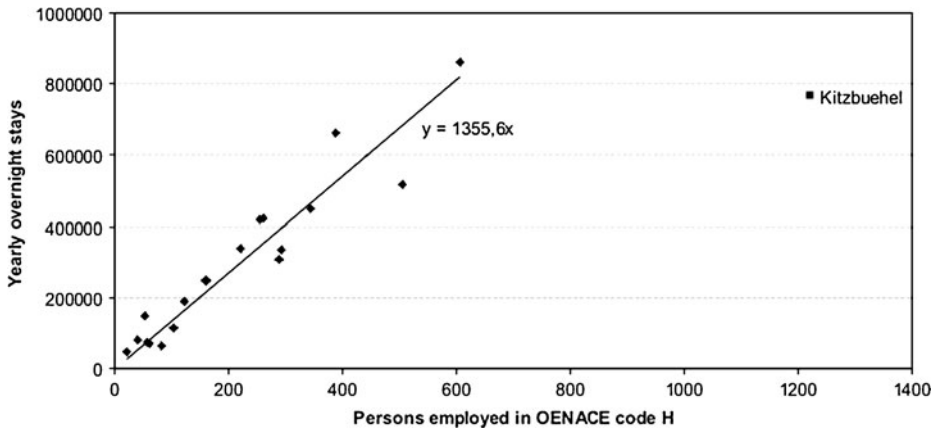
Fig. 4 Relationship between persons employed in OENACE code H (hotels and restaurants) and number of yearly overnight stays in the 20 municipalities of the study area in 2001

a base water demand. A differentiation between base and seasonal water demand has also been used by numerous authors e.g. Vanham et al. (2008) and Zhou et al. (2002). For the remaining water demand stakeholders overnight stays (tourism) and agriculture (persons employed in agriculture and livestock units) unit data are only available at the municipality level.

In order to rasterise the water demand for overnight stays, it is assumed that the number of persons employed in the OENACE code H (hotels and restaurants)—available as a 250 m raster (Table 2)—relates linear to the number of overnight stays. Amongst all municipalities except Kitzbühel a significant linear relationship (Pearson correlation 0.953, $p < 0.1$) between persons employed in OENACE code H (hotels and restaurants) and number of yearly overnight stays is observed (Fig. 4). The high number of employees for Kitzbühel could be explained by a higher amount
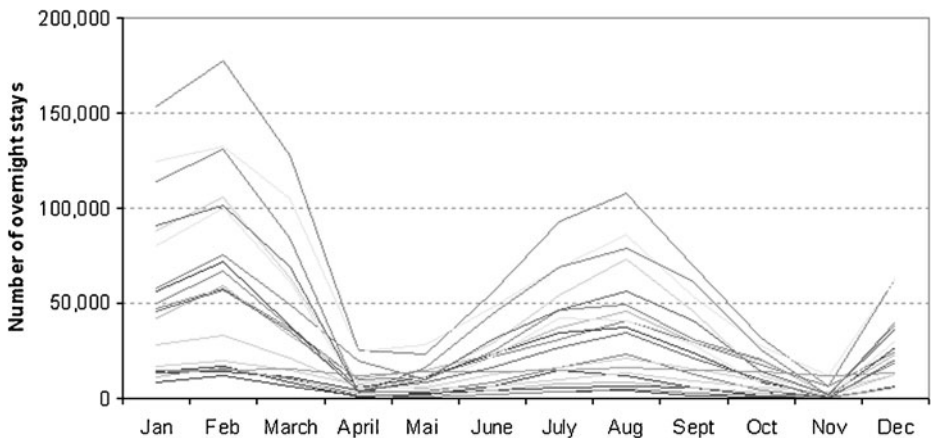

Fig. 5 Monthly overnight stays in the 20 municipalities of the case study area during the year 2006

Livestock	Livestock unit (LU)
Cows (female cattle from 2 years old on)	1.0 LU
Other cattle	0.6 LU
Horses	1.0 LU
Pigs	0.3 LU
Scheep and goats	7 units per LU
Chickens and other fowl	250 units per LU (0.004 LU)

Table 3 Livestock units (LU) for animals of different species or categories kept for agricultural purposes within the project area

of high class hotels in a municipality with a glamorous reputation. As the number of overnight stays (Table 1) is also available on a monthly basis, this seasonal water demand can be projected to the winter period. Of all overnight stays 54% occur in the winter months from December to March. A monthly distribution of overnight stays is shown in Fig. 5.

In order to rasterise the water demand for agriculture, a differentiation between persons employed in agriculture and livestock units is made. The Livestock unit (LU) is a unit used to compare or aggregate numbers of animals of different species or categories across geographical regions (FAO 2003). It is a standardized animal unit obtained by multiplying the total number of animals with a conversion factor that takes into account "feed requirements" for the animal. However, there are different
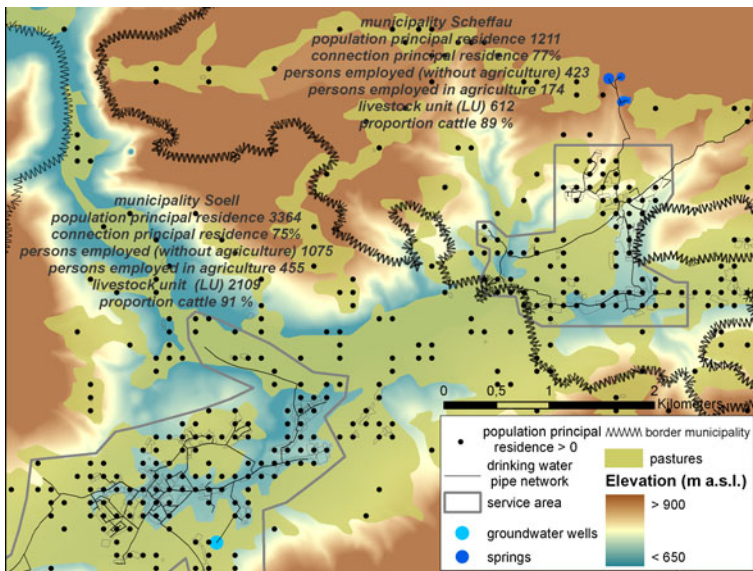
Fig. 6 Raster (resolution 125 m) of the population principal residence within and around the service areas of the municipalities Söll and Scheffau. In order to spatially distribute the water demand for agriculture (calculated for both livestock units LU and the number of people employed in agriculture), the total water demand is distributed over the cells of the raster population principal residence located in the land use zone "pastures". This procedure is used as raster data on agricultural animals and persons employed in agriculture are not available

LU conversion keys—depending on the type of use a conversion key is defined for (BMLFUW 2006). Generally, for water demand purposes, a categorisation according to animal species and age class is used. By definition, a cow of age 2 years and more is 1 LU (Table 3) (Mutschmann and Stimmelmayr 2007). Of the 27,722 LU units in the different municipalities in the study area (Table 1), about 90% is made up by cattle. In alpine regions cattle are generally driven up to pastures at high altitudes in summer, where they drink from local springs or streams. In winter they reside in barns in the valley, which are partly connected to the public water supply system. This cyclical, seasonal movement of livestock, called transhumance grazing (Omer et al. 2006), distributes yearly water demand equally over winter (December to March) and the months of April, May, October and November. It is assumed that during the remaining summer months cattle reside on alpine pastures, which are then generally free of snow. Both persons employed in agriculture and LU are restricted to the agricultural land in the valleys as defined by the land utilization or zoning plan of the area. The agricultural water demand is regionalized to a raster dataset both in and outside of the water supply service zones according to the population of principal residence within the agricultural land. The total agricultural water demand within the service area is estimated. This is of course a simplification. Figure 6 displays this procedure for the municipalities Söll and Scheffau. The agricultural water demand is here distributed over the cells of the raster population principal residence which are located in the CORINE land use class "pastures".

The rate of water use for each stakeholder (Eq. 1 and Table 4) which is calibrated with operating data is based upon literature values (DVGW 1995; Hoch 2007; Mutschmann and Stimmelmayr 2007; Trifunović 2006) and local expertise. A differentiation between rural municipalities and the urbanized municipalities Kitzbühel and Sankt Johann is made. Oberndorf and Kirchdorf have relative large industrial areas due to their location on the axis Kitzbühel–Sankt Johann, which results in different rates of water use. In addition, large water demand stakeholders like hospitals or industries that use water for cooling were identified based upon their number of employees per work place (Table 2) and OENACE code. They were then incorporated in the rasterised water demand analysis by means of information

Table 4 Rate of water use for the different water demand stakeholders in the project area

	Rural municipalities	Oberndorf	Kirchdorf	Urban municipalities: Kitzbühel, Sankt Johann
	L per unit per day	L per unit per day	L per unit per day	L per unit per day
Principal residence	120	120	120	150
Secondary residence	25	25	25	70
Overnight stays	250	250	250	250
Persons employed (without agriculture)	70	70	150	150
Persons employed in industrial zones	70	300	150	300
Persons employed in agriculture	40	40	40	40
Livestock units (LU)	50	50	50	50

acquired from the "Water Book". However, often such water demand stakeholders are not connected to the public water supply, and obtain water from private wells. Within Eq. 1, they were treated as separate demand stakeholders ($EMPL*q_{EMPL}$). For the other raster cells outside the service zones, identical water use rates q_{POPp}, q_{POPs}, q_{TOUR}, q_{EMPL} and q_{AGR} are assumed within the same municipality.
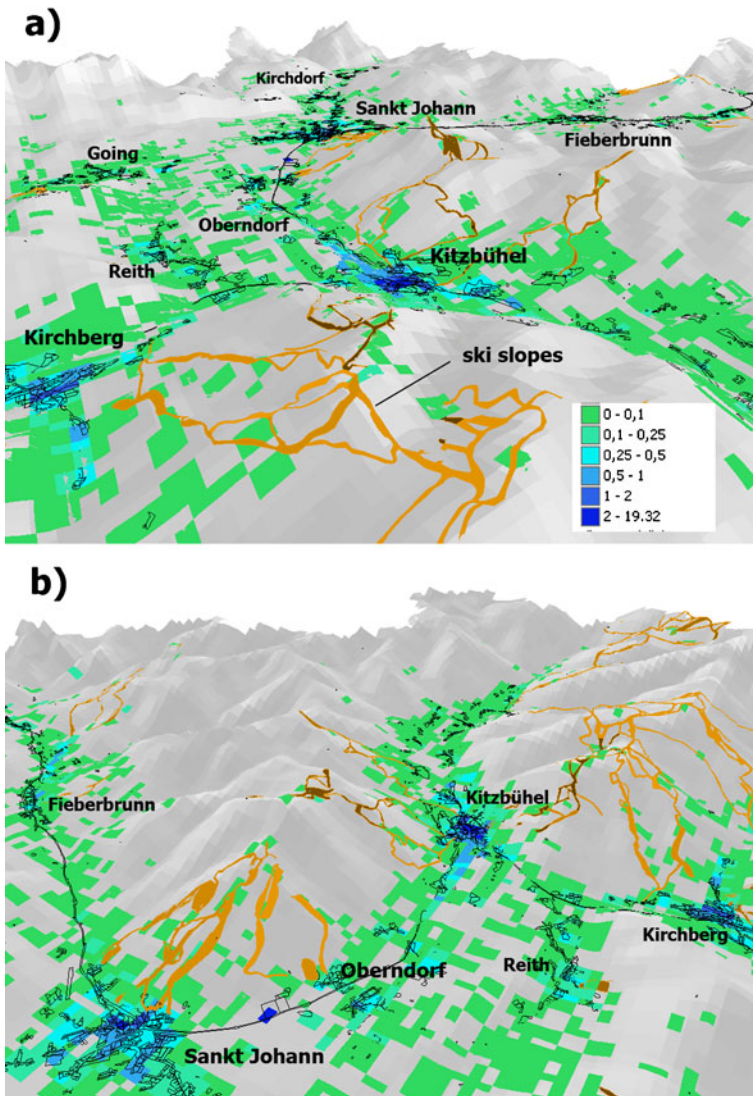
Fig. 7 Calculated yearly water demand (in litre per second) for the north eastern part of the case study area in raster resolution 250 m, with **a** three-dimensional view to the north and **b** three-dimensional view to the south. Water demands are clearly concentrated in the valleys. Apart from snowmaking water demands on the mountains are very little. Ski slopes are represented in orange

4 Results and Discussion

4.1 Calculated Spatially Distributed Water Demands

As a result the raster datasets yearly and winter water demand were calculated for the different raster cell resolutions 250, 500, 1,000 and 2,500 m. Within this specific analysis the methodology was applied for the finest resolution and the results then aggregated to the coarser resolutions.

As an example the calculated yearly water demand (in litre per second) with resolution 250 m for the north eastern part of the case study (Fig. 7) area shows that water demands are clearly concentrated in the valleys. Water demands are the highest in town centres and for certain large buildings or complexes (industry, hotels, hospitals, ...). On the mountains water demands are very small, as the terrain is too rough and steep for permanent settlements as well as too dangerous due to avalanches, torrents and landslides. Mountain huts represent water demands for their permanent or temporary residents and overnight stays. Snowmaking represents a large water demand in the mountains, but is not taken into account in this study.

The representation of the alpine character of this calculated water demand raster however is dependent on the raster resolution. Figures 7 and 8 show that for a spatial resolution of 250 m water demand cells are concentrated in the valleys. However,
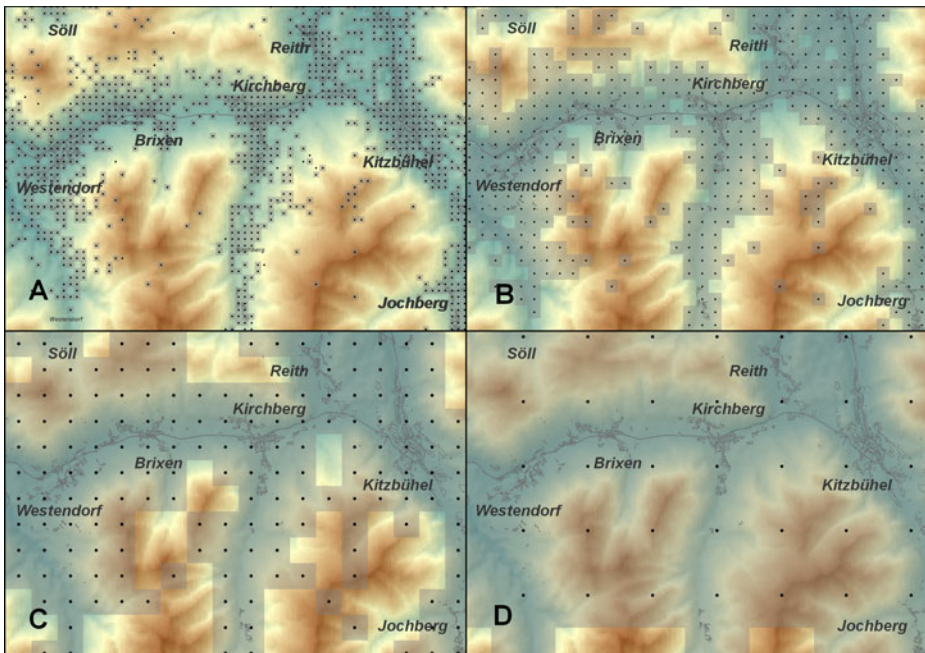

Fig. 8 Water demand raster cells in the centre of the case study in different resolutions: **a** 250, **b** 500, **c** 1,000 and **d** 2,500 m

with decreasing cell resolutions (Fig. 8) the representation of the alpine character of the study area tends to disappear. This is particularly true for a resolution of 2,500 m.

Figure 9 shows the total calculated winter water demand (litre per second) for the different water demand stakeholders within the public water supply service areas for each municipality, as well as the water demand for the study area not connected to one of the 25 major water supply undertakings. Within the service zones of the rural municipalities the major water demand stakeholders are the persons of principal residence and tourism (overnight stays). For the two municipalities with a more urban character—Kitzbühel and Sankt Johann—also the persons employed represent a large water demand. Outside of the 25 large water supply zones, agriculture also represents a major water demand stakeholder.

Figure 10 shows the percentage of the winter water demand for both persons employed and overnight stays to the total winter water demand within central and northern Kitzbühel. High percentages of the water demand for persons employed can be seen within the northern commercial and industrial zone of the city, as well as in the city centre where many shops and administration are located. High percentage water demands for overnight stays are observed within the city centre—where many hotels and guest houses are located—as well as in several locations at the outskirts of the city as for example in large accommodation zones (Fig. 10a).

As an example of the temporal fluctuation in water demand the resulting yearly and winter water demand (litre per second) for the town centre of Kirchberg is shown in Fig. 11. This municipality has the highest amount of overnight stays in the study area Table 1, and the difference in rasterised water demand is considerable. The yearly water demand within the total public water supply service zone is 16.5 l/s, the winter water demand 21.6 l/s.
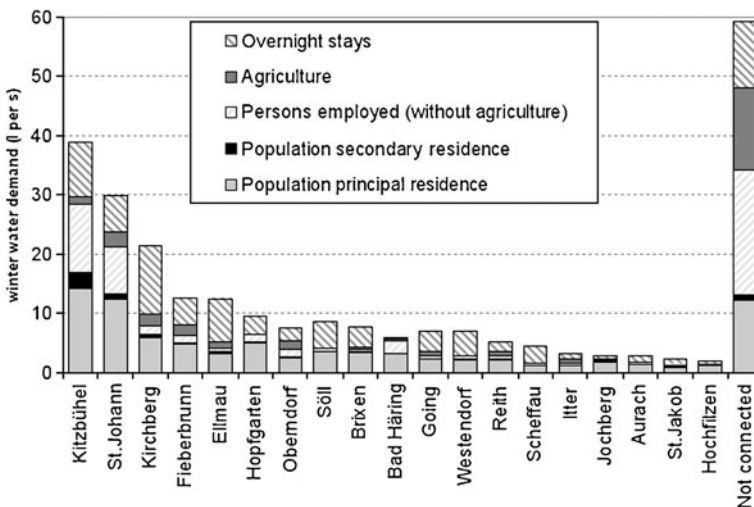
Fig. 9 Total calculated winter water demand (litre per second) for the different water demand stakeholders connected to the 25 major water supply undertakings for each municipality. Also the water demand for the stakeholders not connected to one of these major undertakings within the project area is shown
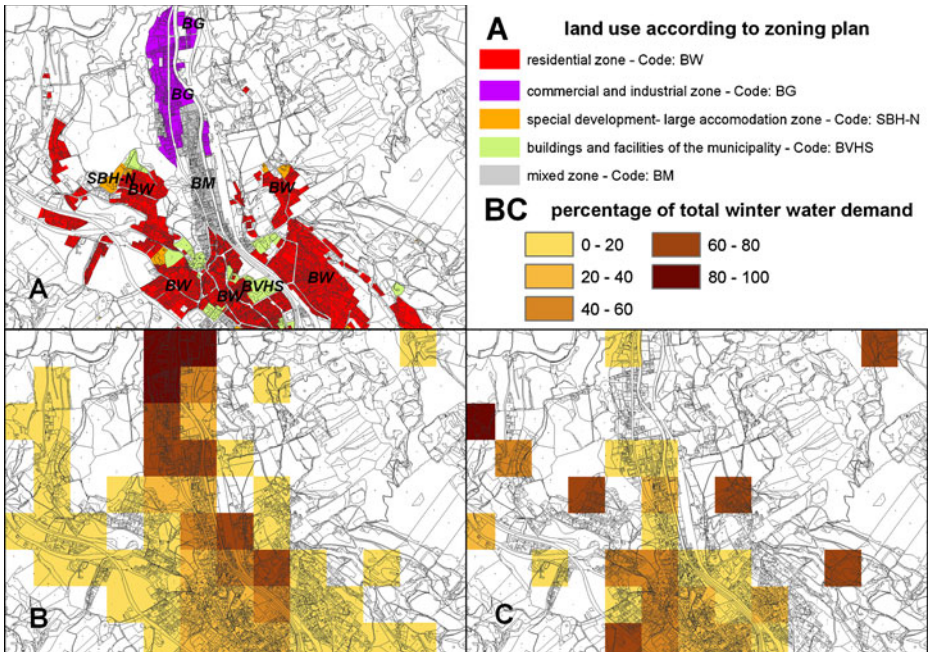
Fig. 10 Centre and northern part of the city of Kitzbühel, with **a** selected land use classes according to the zoning plan, and the percentage of the winter water demand for **b** persons employed and **c** overnight stays (tourism) to the total winter water demand

4.2 Possible Applications

Rasterised water demands can be used within the scope of hydraulics, water resources management and landscape and urban planning related studies.

In hydraulics related studies these rasters can be very useful for the transposition of cell water demand values to respective pipe sections of a water distribution network. An example of this application can be found in Möderl et al. (2008a, b). The authors test the vulnerability of the water pipe distribution network of several municipalities of the same case study area of this paper. Therefore they use the methodology described in this paper to generate a 125 m water demand raster (they transpose the values of the 250 m raster to a 125 m raster), and relate cell values to the respective pipe sections of the network located in the cell. A cell resolution of 125 m is required for this analysis. They also combine Alpine natural hazard maps with these vulnerability maps to generate risk maps, identifying low to high risk areas. With these results landscape and urban planning can be optimised with respect to natural hazards and its (potential) effect on the water supply systems of a certain region.

These rasters are also extremely valuable for water resources management studies, like e.g. water availability-water scarcity studies. Such detailed analyses can be made within a catchment or river basin on a local or regional level with the restriction that the case study area is located within the borders of a country (or different countries) that offer(s) the detailed census data set. Studies on transnational
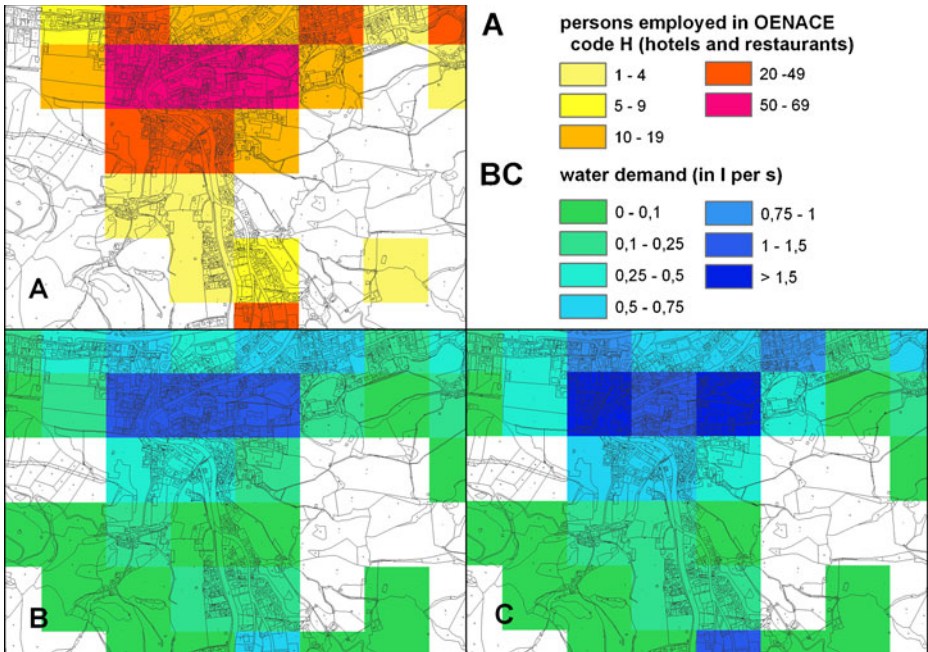
Fig. 11 Town centre of Kirchberg, with **a** the persons employed in OENACE code H; and the calculated yearly (**b**) and winter (**c**) water demand (litre per second) in raster resolution 250 m

catchments can be carried out for Switzerland and Austria or for Sweden, Norway and Finland, as all these countries offer the detailed census of 2001 raster dataset. Therefore it could apply to studies like Barthel et al. (2010). Integrated water resources management is conducted on the watershed or basin level. By means of the water demand rasters, original water demand data on the political entity level (e.g. country, state, district, municipality, ...) can thus be transposed to catchment, basin, subbasin, ... level. Water demand data are generally available for political entities. For the Kitzbühel case study area a spatially distributed hydrological model (Vanham et al. 2009a, b; Vanham and Rauch 2009) is available in a resolution of 250 m. By means of this model and the generated water demand rasters detailed water balance (water availability-water demand) analyses can be made on the basin or subbasin level independent of political entities. For the case study area—typical for Alpine regions—municipality borders often coincide with basin or subbasin borders. However, in many regions of the world this is not the case. When agricultural water demand rasters representing rainfed (green water) and irrigated (blue water) crop water requirements are combined with the demand raster described in this paper, total water demand rasters are achieved. Also additional stakeholders can be incorporated, like a water demand raster for snowmaking.

Such detailed water demand rasters can also be useful in landscape and urban planning studies, e.g. in city planning to produce more thorough and accurate means of assessing city development.

This methodology describes how spatially distributed water demand rasters for a certain time step can be generated. In practice, consumption varies seasonally,

monthly, daily, and hourly. Seasonal or monthly variations are prominent in alpine countries like Austria (Vanham et al. 2008) or countries with wet and dry seasons like India (Durga Rao 2005; Rai 2011; Vanham et al. 2011) or Pakistan (Laghari et al. 2011). Evaluating the reliability of a water distribution system (example of hydraulics related applications) can include different scenarios, like meeting the average day conditions, or meeting an hourly peak demand, both in fulfilling water demands and satisfying pressure requirements. The presented methodology is applicable for generating water demand rasters for these different time steps. As an example for monthly variations in water demand (water demand TOUR*q_{TOUR} in Eq. 1) the monthly overnight stays in the different municipalities are shown in Fig. 11. Temporal fluctuations in overnight stays also occur during shorter time steps (weekly, daily), e.g. during Christmas holidays. In this paper summer water demands were kept constant although these tend to increase due to garden sprinkling and increased use of the shower e.g. in tropical countries. This increased demand can however be implemented within the term POPp*q_{POPp} + POPs*q_{POPs} in Eq. 1.

Spatial refinements can also be implemented in the methodology. Different areas within the water undertaking service zone can be related to different water use rates for the same water demand stakeholder. For example for the stakeholder population different rates can be used for areas in the centre of the city and in residential areas of the city (where generally water use rates are higher). The only constraint is that the total water demand has to be equal to the measured water demand by the water supply undertaking. Therefore the rate of water use for each stakeholder (Eq. 1 and Table 4) had to be calibrated by means of these operating data. The water rates were first estimated based upon literature values (DVGW 1995; Hoch 2007; Mutschmann and Stimmelmayr 2007; Trifunović 2006) and local expertise. Then they were calibrated based upon the operating data. This is off course a simplification as every spatial and temporal variation cannot be accounted for. In this paper calibration occurred according to service data without water losses (the water sold to the customer was given in the questionnaire). A raster can also be generated including water losses, when the total water loss value is known as well as the state of the distribution network.

5 Conclusion

This paper presents a methodology to calculate a spatially distributed water demand raster for a certain time step. Domestic, municipal, industrial and agricultural (without rainfed and irrigated crop water requirements) water demands are represented in this raster. As case study area the Kitzbühel region—encompassing 20 municipalities—in the Austrian Alps was chosen. To calculate such a raster the number of units of a detailed population and housing census raster available in different resolutions (Statistics Austria 2008) are multiplied with a rate of water use for the different stakeholders (Eq. 1). The different demand stakeholders are represented by population of principal and secondary residence, tourist overnight stays, employment activities (industries, small trade, schools, hospitals, administration, . . .) and agriculture.

Yearly and winter water demand rasters in the resolutions 250, 500, 1,000 and 2,500 m were generated. Apart from detailed spatially distributed information, this

methodology can also be used for different time steps (yearly, seasonal, monthly, weekly, daily, hourly).

Water demand rasters can be used in hydraulics related studies e.g. Möderl et al. (2008a, b), a wide range of water resources management studies e.g. water availability-water scarcity studies and for landscape and urban planning studies. A large advantage is that they are independent of political entities like countries or municipalities. They provide the possibility to re-aggregated water demands on political entity levels to the river basin scale. A limitation to generate a detailed water demand raster is of course the availability of a detailed population census raster data set as well as information on water use rates. For the next population and housing census in 2011 this dataset will be provided by 11 European countries. The Geostat project (www.efgs.info) aims at representing census data in a standardised European population grid. Data availability could increase in future in many countries, making the proposed methodology applicable for a wider geographic range.

References

Alcamo J, Döll P, Henrichs T, Kaspar F, Lehner B, Rösch T, Siebert S (2003) Development and testing of the WaterGAP 2 global model of water use and availability. Hydrol Sci J 48:317–338

Alcamo J, Flörke M, Marker M (2007) Future long-term changes in global water resources driven by socio-economic and climatic change. Hydrol Sci J 52:247–275

Barthel R, Janisch S, Nickel D, Trifkovic A, Hörhan T (2010) Using the multiactor-approach in glowa-danube to simulate decisions for the water supply sector under conditions of global climate change. Water Resour Manag 24(2):239–275

BMLFUW (2006) Definitions of agriculture and forestry, environment and water management, Bundesminsterium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Abteilung II 5. BMLFUW, Wien, p 73

Briggs DJ, Gulliver J, Fecht D, Vienneau DM (2007) Dasymetric modelling of small-area population distribution using land cover and light emissions data. Remote Sens Environ 108(4):451–466

CIESIN (2005) Gridded population of the world version 3 (GPWv3). Socioeconomic Data and Applications Center (SEDAC), Columbia University, Palisades, NY

Craswell E, Bonnell M, Bossio D, Demuth S, Giesen N, Islam MS, Oki T, Kanae S, Hanasaki N, Agata Y, Yoshimura K (2007) A grid-based assessment of global water scarcity including virtual water trading: integrated assessment of water resources and global change. Springer, Dordrecht, pp 19–33

Döll P, Kaspar F, Lehner B (2003) A global hydrological model for deriving water availability indicators: model tuning and validation. J Hydrol 270(1–2):105–134

Durga Rao KHV (2005) Multi-criteria spatial decision analysis for forecasting urban water requirements: a case study of Dehradun City, India. Landscape Urban Plan 71:163–174

DVGW (1995) Arbeitsblatt W 410—Wasserbedarfszahlen, Deutsche Vereinigung des Gas—und Wasserfaches

Falkenmark M, Lannerstad M (2007) Consumptive water use to feed humanity—curing a blind spot. Hydrol Earth Syst Sci 9:15–28

FAO (2003) Compendium of agricultural—environmental indicators. Statistics Analysis Service, Statistics Division, Food and Agriculture Organization of the United Nations, Rome, p 35

Hoch W (2007) Bedarfsgerechte Planung—Anpassung der Planungsgrößen auf den Wasserbedarf. GWF-Wasser/Abwasser 148(13):22–28

Kaminger I, Meyer W (2007) Neue Raster-orientierte Statistik in Europa. In: 19. Angewandte geoinformatik (AGIT)-symposium. Strobl, Blaschke, Griesebner, Salzburg, pp 303–308

Laghari AN, Vanham D, Rauch W (2011) The Indus Basin in the framework of current and future water resources management. Hydrol Earth Syst Sci Discuss 8:1–26

Meigh JR, McKenzie AA, Sene KJ (1999) A grid-based approach to water scarcity estimates for Eastern and Southern Africa. Water Resour Manag 13:85–115

Möderl M, De Toffol S, Vanham D, Fleischhacker E, Rauch W (2008a) Abschätzung des Risikos von Naturgefahren für Wasserversorgungssysteme auf Basis der Systemvulnerabilität. Österreichische Wasser- und Abfallwirtschaft 9–10:149–155. doi:10.1007/s00506-008-0018-8

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

Mutschmann J, Stimmelmayr F (2007) Taschenbuch der Wasserversorgung. Vieweg, Braunschweig, p 926

Omer RM, Hester AJ, Gordon IJ, Swaine MD, Raffique SM (2006) Seasonal changes in pasture biomass, production and offtake under the transhumance system in northern Pakistan. J Arid Environ 67(4):641–660

Perveen S, James L (2010) Multiscale effects on spatial variability metrics in global water resources data. Water Resour Manag 24(9):1903–1924

Rai S (2011) Water management for a megacity: national capital territory of Delhi. Water Resour Manag. doi:10.1007/s11269-011-9807-0

Rockström J, Falkenmark M, Karlberg L, Hoff H, Rost S, Gerten D (2009) Future water availability for global food production: the potential of green water for increasing resilience to global change. Water Resour Res 45:W00A12

Siebert S, Döll P (2010) Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. J Hydrol 384:198–217

Statistics Austria (2008) www.statistik.at

Szibalski M (2007) Grid data in official statistics of Europe—a survey about the storage, analysis and publication of census data and business statistics (in German). Wirtschaft und Statistik 2:137–143

Trifunović N (2006) Introduction to urban water distribution. In: UNESCO-IHE lecture note series. Taylor & Francis, London, p 509

Vanham D (2010) Feeding the world: the importance of green water in water resources management. In: Proceedings of the 5th IWA YWPC, Sydney, 5–7 July 2010

Vanham D, Rauch W (2009) Retreating snowpacks under climate change: implications for water resources management in the Austrian Alps. In: Improving integrated surface and groundwater resources management in a vulnerable and changing world, IAHS Publication 330, pp 231–238

Vanham D, Fleischhacker E, Rauch W (2008) Technical note: seasonality in alpine water resources management—a regional assessment. Hydrol Earth Syst Sci 12(1):91–100

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

Vanham D, Fleischhacker E, Rauch W (2009b) Impact of snowmaking on alpine water resources management under present and climate change conditions. Water Sci Technol 59(9):1793–1801

Vanham D, Weingartner R, Rauch W (2011) The Cauvery river basin in Southern India: Major challenges and possible solutions in the 21st century. Water Sci Technol. doi:10.2166/wst.2011.554

Vorosmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Liermann CR, Davies PM (2010) Global threats to human water security and river biodiversity. Nature 467(7315):555–561

Vörösmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global water resources: vulnerability from climate change and population growth. Science 289:284–288

Wichelns D (2010) Virtual water: a helpful perspective, but not a sufficient policy criterion. Water Resour Manag 24(10):2203–2219

Wonka E (2006) Regionalstatistik in Österreich—Von der Tabelle zu räumlicher Analyse und Visualisierung. In: Strobl J (ed) Salzburger geografische Arbeiten. Fachbereich Geographie und Geologie der Universität Salzburg, Salzburg, p 168

Zhou SL, McMahon TA, Walton A, Lewis J (2002) Forecasting operational demand for an urban water supply zone. J Hydrol 259(1–4):189–202