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Hydrology and Earth System Sciences
Discussions

Characterizing the spatiotemporal variability of groundwater levels of alluvial aquifers in different settings using drought indices

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Abstract. To improve the understanding how aquifers in different alluvial settings respond to extreme events in a changing environment, we analyze standardized time series of groundwater levels (Standardized Groundwater level Index - SGI), precipitation (Standardized Precipitation Index - SPI), and river stages of three subregions within the catchment of the river Mur (Austria). Using correlation matrices, differences and similarities between the subregions, ranging from the Alpine upstream part of the catchment to its shallow foreland basin, are identified and visualized.

The river is generally found to be a dominant factor, frequently affecting not only the wells closest to the river, but also more distant parts of the alluvial aquifer. As a result, human impacts on the river are transferred to the aquifer, thus affecting the behavior of groundwater levels. Hence, to avoid misinterpretation of groundwater levels in this type of setting, it is important to account for the river and human impacts on it.

While the river is a controlling factor in all of the subregions, an influence of precipitation is evident too. Except for deep wells found in an upstream Alpine basin, groundwater levels show the highest correlation with a precipitation accumulation period of six months (SPI6). The correlation in the foreland is generally higher than that in the Alpine subregions, thus corresponding to a trend from deeper wells in the Alpine parts of the catchment towards more shallow wells in the foreland.

Extreme events are found to affect the aquifer in different ways. As shown with the well known European 2003 drought and the local 2009 floods, correlations are reduced under flood conditions, but increased under drought. Thus, precipitation, groundwater levels and river stages tend to exhibit uniform behavior under drought conditions, whereas they may show irregular behavior during flood.

Splitting the time series into periods of 12 years reveals a tendency towards higher correlations in the most recent time period from 1999 to 2010. This time period also shows the highest number of events with SPI values below -2. The SGI values behave in a similar way only in the foreland aquifer, whereas the investigated Alpine aquifers exhibit a contrasting behavior with the highest number of low SGI events in the time before 1986. This is a result of overlying trends and suggests that the groundwater levels within these subregions are more strongly influenced by direct human impacts, e.g. on the river, than by changes in precipitation. Thus, direct human impacts must not be ignored when assessing climate change impacts on alluvial aquifers situated in populated valleys.

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1 Introduction

Climate change is expected to alter the hydrological cycle and thus the amount and timing of groundwater recharge, storage, and discharge. The future is likely characterized by more extreme hydrological events such as droughts and floods (Seneviratne et al., 2006). Predicting the impact of future climate change on groundwater resources therefore requires a sound understanding of the propagation of extreme events from the atmosphere to the groundwater.

One approach to understanding the variability of groundwater levels is the analysis of the aquifer responses to extreme events in the past (Eltahir and Yeh, 1999; Weider and Boutt, 2010). However, fluctuations of groundwater levels may not only be driven by hydrologic events. In particular, changes in land use or water management are known to be additional important factors (Stoll et al., 2011). Evaluating long-term trends or short-term fluctuations in groundwater level data, therefore, requires careful consideration of the factors potentially controlling the observed changes.

To be able to compare hydrologic extremes between different sites and different types of data various indices have been employed. For instance, the Standardized Precipitation Index SPI (McKee et al., 1993) has been used to identify and analyze the occurrence of extreme events in precipitation. Only recently a corresponding Standardized Groundwater level Index SGI (Bloomfield and Marchant, 2013) has been proposed. SGI values computed for observation wells in the UK (Bloomfield and Marchant, 2013) as well as in Germany and the Netherlands (Kumar et al., 2016) show significant correlation with SPI values. However, the maximum correlation and SPI accumulation period are found to differ between the sites. Thus, as noted by the authors of both studies, groundwater levels and SGI values are influenced by the local hydrogeological conditions.

This work aims to identify factors controlling SGI values of alluvial aquifers within a mountainous region and its foreland (Mur valley, Austria). In this type of setting, groundwater levels measured in the vicinity of rivers are expected to show correlations with the river stage. Going beyond earlier work, therefore, variations of standardized river stages are considered in addition to SPI and SGI. To decipher influences of the local as well as the regional hydrogeological setting correlations between the standardized hydrological time series within three subregions are evaluated and compared with each other. In addition, distinct drought and flood periods are analyzed separately, as groundwater levels are known to respond in different ways to floods and droughts (Eltahir and Yeh, 1999). Finally, the time series are split-up in several multi-year periods to identify potential long-term changes in the correlations between groundwater levels, precipitation, and river stages.

For this purpose, a novel approach employing correlation matrices is proposed. We visualize these subregions, showing how they differ from each other, how the different bodies of water are related to one another, how they respond to extreme events and how the dynamics in the systems changes over time. We use this approach to select single wells and discuss the limitations of this approach.

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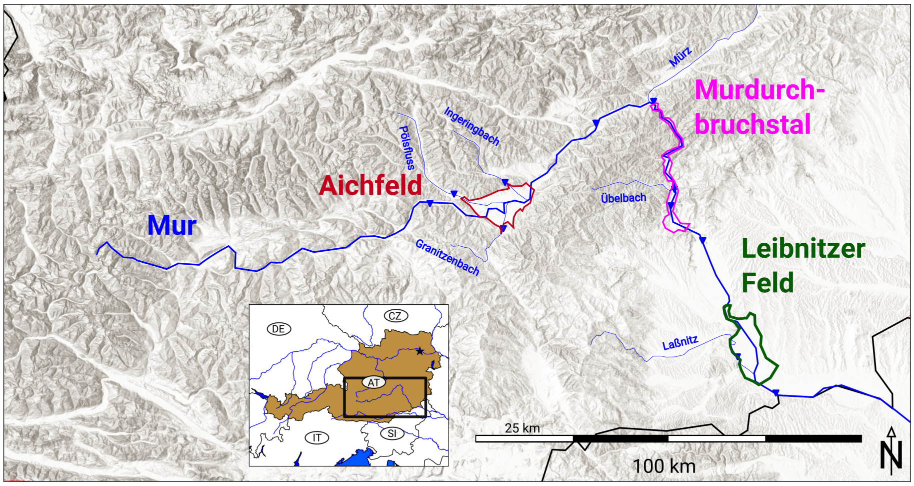

Figure 1. Map of the Austrian Mur catchment and its position within Austria, with the subregions studied in detail. See Appendix A for detailed maps of the subregions.

2 Method

2.1 Study areas

The catchment of the river Mur (Austria) ranges over 300 km from its Alpine source area at 2000 m asl to the Austrian-Slovenian border at 200 m asl (Figure 1). Three distinctive subregions, deemed to differ in their hydrological and hydrogeological situation, namely the Alpine Aichfeld region, a large and deep basin, the Murdurchbruchstal, a very narrow valley, with small and shallow aquifer bodies and the Leibnitzer Feld, a shallow, mostly river distant lowland aquifer in the Mediterranean/Pannonian climate border region, have been selected for closer investigation.

For these three subregions monthly groundwater levels as well as river stages and precipitation are available at a the ehyd.gv.at website (BMLFUW, 2016). According to the local government agency (personal communication), the data set started at private house wells, which used to be a common form of water supply in rural Austria. Thus, most of the monitoring wells are assumed to be influenced by human activities.

Detailed maps of the following subregions are available in Appendix A. Locations mentioned in the description are marked in said maps. The data sets mentioned are listed in detail in the supplementary material.

2.1.1 Aichfeld

The Aichfeld (also called Judenburg-Knittelfelder-Becken) is a large basin in the upper Mur valley. It covers an average elevation of about 650 m asl and an area of around 70 km^2. The basin itself is of Tertiary age and contains economic amounts of coal in depths of up to 1000 m bgl (Worsch, 1963). Those have been exploited starting in the 17th century and with industrial underground mining from approx. 1860 to 1978, in the town of Fohnsdorf, in the north-west of the basin (Scheucher, 2004).

Above its deep basin fill of Tertiary shales, marls and sandstones, it is filled with around 70 m of fluvio-glacial sediment - mostly gravels and sands, with significant clay layers only in some areas - in a terraced structure and surrounded by mountainous area of elevations between 1500 m asl and 2400 m asl.

Climatically, due to its basin structure, the region is prone to inversion climates with strong nightly cooling. For the climate station Zeltweg - in the center of the basin - ZAMG (2016) gives an average yearly temperature of 6.6 °C, an average yearly precipitation of 800 mm and an average 75 cm of snowfall (1971 - 2000).

The towns in the Aichfeld form an Alpine agglomeration with about 50000 inhabitants in the basin and about 80000 taking the surrounding catchment into account. Given this population and the associated settlement history and industry density, the area has a considerable infrastructure of groundwater wells, starting with the Knittelfeld drinking water supply from 1899 on (Gemeinde Knittelfeld, 2016), and considerable drainage activities during the days of active coal mining.

The data set for the Aichfeld consists of 20 groundwater monitoring wells (see supplementary material) covering the time span from 1975 to 2010. The surface elevations range from 693 to 619 m asl and the average depth of the wells below ground level is 13.5 m with a high standard deviation of 8.5 m, which can be explained by the existence of a second, deeper aquifer. A visual survey of aerial photography for the area shows that only 1 of the 20 wells is not in the close vicinity of farm, residential or industrial buildings, so direct human influence on most wells is likely. The river Mur in the Aichfeld region is only used by three small-scale run-of-the-river hydro power plants in its upstream part. So only 3 wells are situated in the vicinity of a stretch of the river that is deemed impounded. Consequently, the average distance from a well to an upstream power plant is 5.6 km, whereas the downstream distance - mostly to a power plant outside of the subregion - is 26 km.

Out of this data set of 20 wells, 3 wells were selected for closer investigation (see Table 1 and Figure 2).

2.1.2 Murdurchbruchstal

The Murdurchbruchstal is a narrow valley, where the Mur leaves the Mur-Mürz Furche and cuts through a mountain range, thus forming a mostly very narrow and steep valley until it reaches the lowlands south of Graz.

This subregion covers an area of around 41 km^2 and an elevation from approx. 480 m asl at the town of Bruck an der Mur at the beginning of the valley to approx. 368 m asl at the outskirts of the city of Graz at the end of the valley.

From the town of Bruck an der Mur at the beginning, the valley faces consist of metamorphic gneisses, amphibolites and shists of the Austroalpine crystalline basement. At the town of Mixnitz, roughly in the upper third of the subregion, this changes to the shales and mostly limestones of the Paleozoic of Graz, that is forming the Central Styrian Karst and the Graz Highlands (Wagner et al., 2011).

The valley itself is filled with various, mostly unconsolidated sediments. According to Zetinigg et al. (1966), these are mostly postglacial riverine gravels, some old glacial terraces at the margins of the valley, the alluvial fans of tributaries and weathered slope rock, all covered in part by clays. For the 2 km^2 location of Friesach in the lower part of the subregion, Zetinigg et al. (1966) lists thicknesses of 8 to 27 m for the central valley fill gravels.

No climate data is available in the Murdurchbruchstal itself, but ZAMG (2016) provides information for the station in Bruck an der Mur at the beginning of the valley, where an eastern Alpine valley climate with low winds prevails. The average yearly temperature is 8.1 °C, the average yearly precipitation is 795 mm, with an average of 73 cm of snowfall (1971 - 2000).

The settlements in the area are mostly small, though with considerable industries (quarries, paper production) in some locations and a chain of 8 run-of-the-river hydro power plants over a valley length of approx. 30 km, turning large parts of the river into storage area for said power plants. Further, there is a large water plant for the city of Graz in the vicinity of the town of Friesach, where extraction of drinking water is conducted since 1977 as well as infiltration of river water from 1980-1982 on (ÖVGW, 2016).

The data set for the Murdurchbruchstal consists of 24 groundwater monitoring wells (see supplementary material) covering the time span from 1980 to 2010. The surface elevations range from 413 to 374 m asl and the average depth of the wells below ground level is 10.7 m with a standard deviation of 4.3 m. Due to their vicinity to buildings, 16 of the 24 well are considered likely to be directly human influenced. With the 8 large hydro power plants in the subregion, 4 wells are situated in the vicinity of a stretch of river that is impounded, with an additional 10 wells where an influence is considered likely. The average distance from a well to an upstream power plant is 2.4 km and the average distance to a downstream one is 3.2 km.

Out of this data set of 24 wells, 3 wells were picked for closer investigation (see Table 1 and Figure 2).

2.1.3 Leibnitzer Feld

The Leibnitzer Feld is a large and topographically relatively flat lowland basin of the river Mur, named after its central town. Important rivers besides the Mur are the Laßnitz and the Sulm in the western part of the basin. Besides the town of Leibnitz, the area is mostly used for agriculture.

This subregion covers an area of around 100 km^2 and an elevation from approx. 302 m asl at the town of Mellach at the southern tip of the subregion and approx. 258 m asl at the town of Ehrenhausen at the northern tip of the subregion.

The region is underlain by the Neogene Styrian Basin which consists of various layers of sea, lake and river sediments, which are in turn underlain by the continuation of the Paleozoic of Graz. Apart from the Leitha limestones at the town of Wildon at the northern border of the region, all of the Tertiary sediments are very soft, so they have been mostly eroded and replaced with a series of quaternary gravels, sands and clays in a terraced form (Fabiani, 1971). The mentioned limestones at Wildon are narrowing the aquifer and are thus a natural barrier against inflow from upstream, whereas the southern border is well connected to its downstream regions.

The thicknesses of the groundwater bearing gravels in the vicinity of the river Mur is between 4 and 6 m in the north-east of the region and 3 to 5 m in the south-east with coverages of fluvial gravels, sands and clays of only 0 to 3 m, whereas the higher terraces can have aquifer thicknesses of 3 to 6 m with 3 to 10 m of coverage (Fabiani, 1971).

According to ZAMG (2016), the town of Leibnitz has an average yearly temperature of 8.8 °C, an average yearly precipitation of 908 mm and 49 cm of snowfall (1971 - 2000).

The data set for the Leibnitzer Feld includes 31 groundwater monitoring wells (see supplementary material) covering a time span from 1975 to 2010. The surface elevations range from 298 to 259 m asl and the average depth of the wells below ground level is 6.4 m with a standard deviation of 2.9 m. Due to their vicinity to buildings, there are only 3 wells where a direct human influence is considered unlikely.

Since the Mur in the Leibnitzer Feld region is also heavily used for power production with 5 run-of-the-river power plants, 9 wells are located in areas where the Mur is clearly impounded, with another 11 wells where this is considered likely, and 8 wells where it is not clearly visible, leaving only 3 wells situated in parts of the area where the river is not impounded. Due to the large extent of the region and the size of the hydro power plants, the average distance from a well to an upstream power plant is 3.2 km and the distance to a downstream power plant is 3.2 km.

Out of this data set of 31 wells, 2 wells were picked for closer investigation (see Table 1 and Figure 2).

2.2 Drought indices

Monthly time series were obtained for the subregions from ehyd.gv.at (BMLFUW, 2016). Single time series have been used for groundwater monitoring wells and river stage measurements, whereas the precipitation is averaged over the subregion. Short gaps (only relevant for 1 to 4 wells per subregion) have been padded with the previous water level.

Due to the different start and end dates of the single time series, the raw data has been cut to periods offering both the most wells for the subregion in question and the longest possible time period.

To be able to compare both different types of data and different subregions the data was standardized using the Standardized Precipitation Index (SPI, McKee et al. (1993)), the Standardized Groundwater Index (SGI, Bloomfield and Marchant (2013)) and the SGI applied on river stages (SRSI).

2.2.1 SPI

For precipitation, the SPI, developed by McKee et al. (1993) is used. This allows for both a standardization of data and the computation of average standardized precipitation, where McKee et al. (1993) suggest periods of 3, 6, 12, 24 or 48 months, which "represent arbitrary but typical time scales for precipitation deficits to affect the five types of usable water sources".

For the standardization, the data set gets split-up into time series for each month, which is then fitted to the gamma distribution to relate the respective months to each other instead of months from different seasons.

While there is some criticism of the gamma distribution (see e.g. Guttman (1999)), it is generally a widely used and recommended index (see e.g. Svoboda et al. (2012)).

2.2.2 SGI

For the groundwater, the relatively new Standardized Groundwater Index, SGI proposed by Bloomfield and Marchant (2013) has been used. The SGI is based on the SPI, but whereas the SPI uses a fixed transformation of the raw data by fitting it on a gamma distribution, the SGI uses a non-parametric normal scores transform on the raw data, taking into account the different possible distributions of groundwater time series.

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Table 1. Wells selected for closer investigation or specifically mentioned in the text. The "HZB" (from Hydrographisches Zentralbüro) refers to their identifier at the ehyd.gv.at website. The "Identifier" is a short code used in this paper to identify the wells in the various plots. "Influence" lists factors that might affect the behavior of the groundwater shown in the well.

Subregion	HZB	Location	Identifier	Influence
Aichfeld	314807	Aichdorf	AAn	Well located in a deeper aquifer body, only well in the data set that is not located close to human settlements or activities, deepest well in the data set
Aichfeld	315077	Raßnitz	ARf	Well deviating from the average behavior in the subregion in the 2009 flood year (see Section 3.2 and Figure 3)
Aichfeld	314922	Apfelberg	AAr	Well closest to the river Mur, very high correlation with river and neighboring wells
Aichfeld	211128	Pölsfluß	APr	Mid sized tributary stream, deemed mostly natural
Aichfeld	211185	Mur Leoben	AMr	River Mur, gauge downstream of the subregion
Murdurchbruchstal	325506	Friesach-St.Stefan	MFd	Well deviating from the average behavior in the subregion in the 2003 drought year (see Section 3.2 and Figure 3), located next to the Friesach water plant
Murdurchbruchstal	325142	Deutsch Feistritz	MDp	Well located close to a power plant, no likely direct human impact besides this
Murdurchbruchstal	325191	Kleinstübing	MKr	Well without obvious human influence, close to the river
Murdurchbruchstal	328674	Judendorf-Strassengel	MJc	Well located central in the highly correlated "cluster" in Figure 2
Murdurchbruchstal	211649	Übelbach	MUr	Mid sized tributary stream, deemed mostly natural
Murdurchbruchstal	211292	Mur Bruck	MMr	River Mur, gauge upstream of the subregion
Leibnitzer Feld	311514	Untergralla	LUr	Well located closest to the river Mur, no directly visible human influence
Leibnitzer Feld	311001	Joess	LJc	Well highly correlated to most of the other wells and the SPI, direct human influence likely, close to river Laßnitz
Leibnitzer Feld	211466	Mur Spielfeld	LMr	River Mur, gauge downstream of the subregion
Leibnitzer Feld	211441	Laßnitz	LLr	Mid sized tributary stream, deemed mostly natural

Similar to the SPI, the data set gets split-up into time series for each month (e.g. January 1982, January 1983, January 1984, etc. ; February 1982, February 1983, February 1984, etc.) to relate the respective months to each other instead of months from different seasons.

Unlike the SPI, the SGI is not accumulated over specific time periods due to the continuous nature of the underlying groundwater level (Bloomfield and Marchant, 2013).

2.2.3 SRSI

To characterize and monitor hydrological drought, streamflow indices were previously employed (e.g., Vicente-Serrano et al. (2012); Lorenzo-Lacruz et al. (2013); Barker et al. (2016)). As we are interested in the impact of rivers on groundwater level fluctuations, it is straightforward to consider river stages instead of streamflow.

In order to be able to compare river stages with precipitation and groundwater, we used the SGI on river water levels. Due to its self fitting nature, it can also be used with river water levels, which have a probability distribution different from many groundwater times series.

In order to fit with the naming convention of the other indices, we propose to name this index the SRSI - Standardized River Stages Index.

2.3 Correlation matrix

For each possible combination of standardized wells (SGI), standardized precipitation (SPI) or standardized river stages (SRSI) a Pearson Correlation coefficient was calculated. In order to facilitate the comparison of standardized groundwater levels, river stages, and precipitation within the individual subregions, the correlations between the indices have been plotted within a matrix, showing all the groundwater monitoring wells, all the river stages and SPI1, 3, 6, 9 and 12 for each subregion, similar to the matrices applied in Stoll et al. (2011) and Loon and Laaha (2015).

According to Vekerdy and Meijerink (1998), correlations between daily river stages and groundwater levels in distances similar to those relevant for this paper are mostly below 30 days. Likewise, Bloomfield and Marchant (2013) as well as Kumar et al. (2016) found with few exceptions the highest correlation between SGI and SPI associated with a time lag of zero months. As this is particularly expected in shallow alluvial aquifers, only Pearson Correlation coefficients without a time lag are considered here.

The Pearson correlation coefficients where color coded according to their value and plotted in a matrix with a mirror symmetry going through an axis from the top left to the bottom right. The sorting of the single data points is done in such a way that the main block of the matrix shows the correlations of the groundwater wells with each other, followed by their correlations with the 1 to 12 month SPI, followed by their correlations with the rivers in the subregion. The SGIs are sorted from left to right starting with the well that is the furthest away from the Mur in the subregion on its left riverbank with the distance to the river getting smaller until the closest well to the river on its left side is reached, from whereon the SGIs are starting to increase their distance to the river on its right side, ending the SGI block of the matrix on its right side with the well that is the furthest away from the river on its right riverbank.

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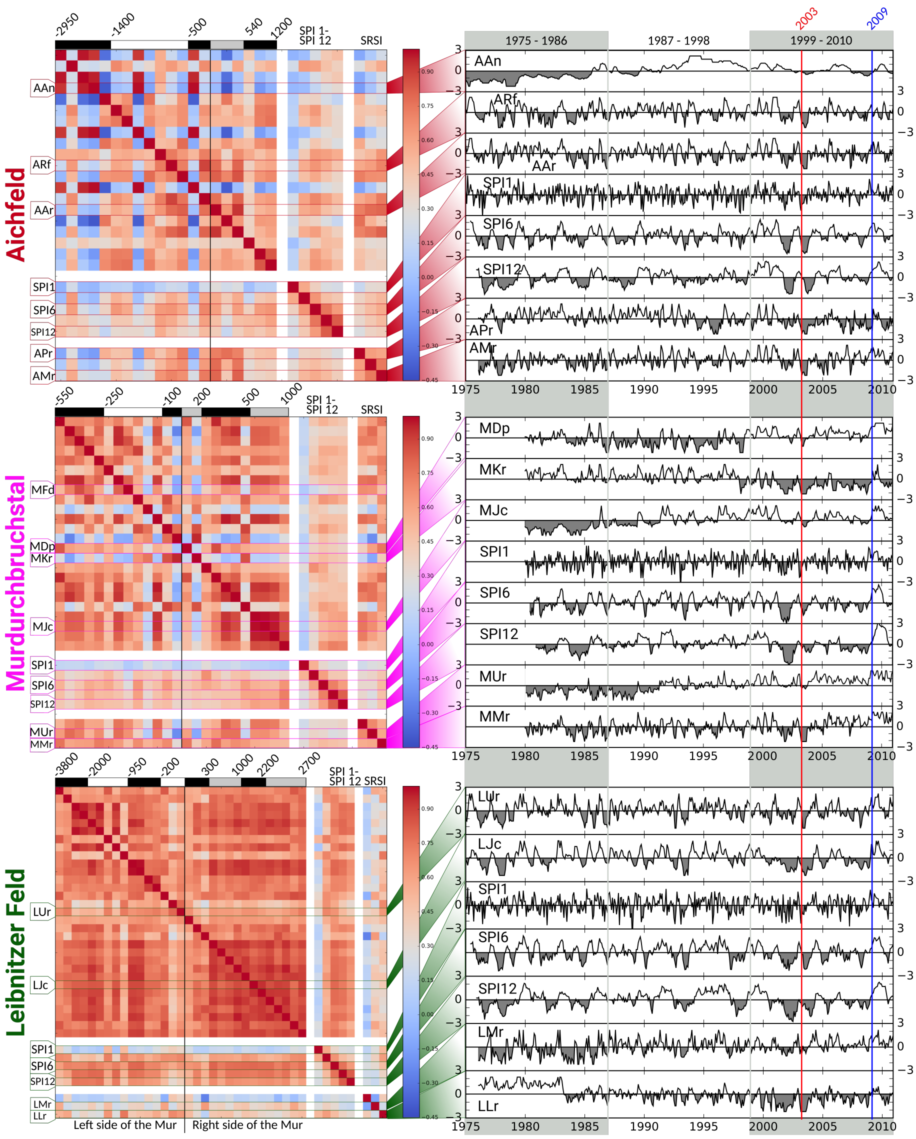

Figure 2. Matrix visualization of the correlations within the three subregions (left side) with selected standardized wells, SPI periods and river stages (right side). Each box reflects a color coded Pearson correlation coefficient for one well (or SPI accumulation period, river stage gauging station) with another well (or SPI accumulation period, river stage gauging station). See table 1 and the markers on the left for a description of the wells and river stages. The markers on top of the matrices are the distances of the wells from the river Mur (negative numbers: left side; positive numbers: right side) in meters. Also shown are the time periods used in Section 3.3 and Figure 4 and the years 2003 and 2009, used in Section 3.2 and Figure 3.

Table 2. Average Pearson correlation coefficients for all wells of a subregion with each other (SGI with SGI), all wells with single rivers and precipitation averaging periods (SGI with SRSI 1, ..., SPI1, ...) and the average correlation coefficient for all rivers of a subregion with the precipitation averaging periods (SRSI with SPI1, ...).

	SGI with								
Location	SGI	SRSI 1	SRSI 2	SRSI 3	SPI1	SPI3	SPI6	SPI9	SPI12
		Pöls	Mur up	Mur down					
Aichfeld shallow	0.59	0.55	0.5	0.52	0.15	0.47	0.57	0.47	0.38
Aichfeld deep	0.96	-0.13	0.04	0.24	-0.04	0.005	0.19	0.32	0.38
		Mur down	Übelbach	Mur up					
Murdurchbruchstal	0.55	0.55	0.5	0.6	0.16	0.41	0.51	0.49	0.47
		Mur up	Mur down	Laßnitz					
Leibnitzer Feld	0.73	0.16	0.38	0.44	0.21	0.58	0.72	0.68	0.61

	SRSI with				
Location	SPI1	SPI3	SPI6	SPI9	SPI12
Aichfeld shallow	0.27	0.45	0.48	0.42	0.34
Aichfeld deep	0.27	0.45	0.48	0.42	0.34
Murdurchbruchstal	0.26	0.38	0.39	0.35	0.37
Leibnitzer Feld	0.31	0.41	0.36	0.26	0.24

3 Results

3.1 Observations within the subregions

3.1.1 Aichfeld

In the Aichfeld subregion two patterns emerge (Figure 2):

A large area in the plot shows wells that are highly to very highly correlated with each other and with the rivers in the subregion. These wells are the wells situated closest to the river Mur on both riverbanks. Most wells outside of the core of this region show a similar behavior, resulting in an average Pearson correlation coefficient of all of these wells with each other of 0.59. These wells show a low correlation with the SPI1 and moderate to high correlations with the longer SPI averaging periods, as expected from the previous literature (Bloomfield and Marchant, 2013; Kumar et al., 2016). The average Pearson correlation coefficient of all of these wells with SPI1 is 0.15, which raises to a maximum with SPI6 of 0.57 and decreases to 0.38 with SPI12. The average correlation of the SGI with the rivers in the subregion is similar for all rivers, with an average correlation for all rivers of 0.52 (see also Table 2).

The second feature of the region are 5 wells that show a very low to negative correlation with all other wells, SPIs and rivers in the subregion, but are extremely highly correlated with each other, with an average Pearson correlation coefficient of wells with wells of 0.96. Those wells reach an end depth significantly deeper (avg. 24.9 m bgl) than that of the other wells in the data set (avg. 9.7 m bgl), so it is reasonable to assume that they show a different, deeper aquifer system. This is also in accordance with Worsch (1963), who mentions that earlier wells of a similar depth for the military airfield at this location encountered a conglomerate layer and Stadlbauer and Lorbeer (2000) who mention a significant groundwater inflow in this area. The wells from the deeper aquifer also show a clear increase in correlation with an increase in the length of the SPI averaging periods, starting with an average correlation of the wells with the SPI1 of -0.04, reaching a maximum correlation of 0.38 with the SPI12, which is significantly lower than the correlations seen in the shallow wells. The average correlations of the deeper wells with the rivers range from -0.13 with the local Pöls to 0.24 with the downstream Mur.

The rivers are correlated well with each other, indicating a similar flow regime in the upstream and downstream Mur, as well as in the tributary Pöls, but the correlations with the precipitation are low to moderate, ranging form an average of 0.27 with SPI1 to 0.48 with SPI6.

For further investigations, one of the wells from the shallow, highly correlated wells and one well from the deeper aquifer have been picked (see also Table 1).

Well AAr, highly correlated with most other shallow wells and closest to the river Mur, shows frequent changes between wet and dry conditions of different lengths and magnitudes just as the highly correlated AMr Mur gauge downstream of the subregion. Generally, this fast changing well shows only moderate correlation with precipitation no matter the averaging period. However, large events such as the 2002 and 2003 double drought are clearly visible.

Well ASf, situated in the deeper aquifer system and furthest away from the river Mur, shows a much slower oscillation of the water levels, overlain by a long-term trend from wet conditions into dry ones and then possibly back into wet. Apart from significant events, such as the double wet event in 1985 and 1986 and the double drought in 2002 and 2003, no similarities with the shallow wells, the precipitation or the rivers are obvious.

3.1.2 Murdurchbruchstal

In this subregion, the matrix visualization shows a picture significantly different from the upstream Aichfeld (see Figure 2). As expected in a narrow valley with small aquifers, there is a high correlation between groundwater and river levels.

A cluster of highly correlated wells is situated at the furthermost distances to the river on its right bank, which are all - except for one well - situated in the town Gratwein-Straßengel and are also highly correlated with the single well in the neighboring town of Gratkorn on the opposite side of the Mur.

This cluster and the majority of the wells in the subregion show high to very high correlations with the rivers. The average correlation for the groundwater with the rivers is the highest for the upstream Mur gauge with a Pearson correlation coefficient of 0.6 and the lowest for the local tributary Übelbach with 0.5. Correlations with the precipitation are generally lowest with the SPI1 with an average of 0.16 and have the highest correlations with the SPI6 and 9 with average Pearson correlation coefficients of 0.51 and 0.49 respectively.

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Surprisingly, some of the wells closest to the Mur on both sides of the river are not very well correlated with each other and are also not among the wells with highest correlations with the rivers.

The matrix view shows three clear outliers (well 4th closest and well closest to the Mur on its left bank and second closest on its right), which are correlated very low or negative with the rest of the wells, but high to very high with each other. The pair of Mur-close wells is situated in the same stretch of the river Mur opposite each other. These wells are also the only wells that are negatively correlated with the rivers in the system.

For further investigations, one of the wells from the cluster, the well closest to the river Mur and one well from the outliers also very close to the river Mur have been picked (see also Table 1).

Well MJc is located centrally in the highly correlated cluster of wells and shows a trend from mostly dry conditions to wetter conditions, which matches the observation of the local tributary Übelbach (MUr). The SPIs for the subregion show no such trends, however the SPI6 and 9 show large dry events in the period from 1980 - 1992, as well as the 2003 drought and 2009 flood. Some large events, such as the 2003 drought and 2009 flood are also noticeable in well MJc albeit not too significantly due to the underlying trend from dry conditions to wetter conditions.

Well MKr is located closest to the river Mur, yet it shows no high correlation with it. We observe wet conditions until 1999 and dry conditions thereafter. Large events are also visible in this time series, albeit damped or amplified by the change in conditions around 1999. Well MDp is located very close to well MKr and shows an opposite change from dominant dry conditions until 1999 to wet conditions afterwards.

The rivers are very highly correlated with each other, but only show some minor correlations with the 3 and 6 month SPI with average correlation coefficients of 0.38 and 0.39.

3.1.3 Leibnitzer Feld

In the Leibnitzer Feld, the situation is different again (see Figure 2). Besides the fact that this region has a much higher amount of groundwater wells, the matrix visualization is very different from the previous two subregions.

Apart from a zone of differing wells on both benches of the river and some moderately correlated wells on the left side, high to very high correlations of most wells with each other prevail, resulting in an average Pearson correlation coefficient of 0.73.

Nevertheless high correlations of groundwater with precipitation can be observed in almost all wells, with the highest correlations found with the 6 and 9 month SPI, with average correlation coefficients of 0.72 and 0.68 respectively. Unlike the other subregions, the correlations of the groundwater with the rivers are generally low to negative even for the wells very close to the Mur. The lowest average correlation is seen with the upstream Mur with an average of 0.16 and the highest with the local river Laßnitz with 0.44.

It should be noted that part of this can be explained by the fact that the Leibnitzer Feld is also a region, where the Mur is heavily used for power production, so the river levels and their fluctuations are not natural. Due to the different times the dams have been built, it is also likely that significant changes in the river regime have occurred during the life time of the data set. In addition, both gauging stations for the Mur used for this subregion are outside of the subregion and outside of the area of influence of the power plants in the subregion, so they likely show a behavior different from that of the river Mur within this subregion.

For further investigations, one of the wells from the highly correlated group and one well close to the river have been picked (see also Table 1).

Well LJc, which is highly correlated to most wells in the subregion, shows frequent changes between dry and wet conditions. Compared with the SPI1 or the rivers LMr and LLr, it shows a smooth signal visually similar to the highly correlated SPI6. Large events such as the two droughts between 1976 and 1979 are also similar to the river Mur (LMr) or river Laßnitz (LLr) in the case of the 2002 and 2003 droughts.

Well LUr, situated right next to the river Mur, shows only moderate correlations with most wells in the subregion. Just as well LJc, it shows frequent changes between dry and wet conditions. The correlation is highest with the SPI3 (not shown in Figure 2), but despite a slightly lower correlation the SPI6 shows a good visual fit with well LUr too. Large events such as the 1976 - 1979 and 2002 - 2003 droughts are visually similar to the river time series LMr and LLr, but apart from that, the rivers show a behavior different from that of the nearby wells.

The mentioned discrepancies in the water levels of the river Mur are also visible in the correlations of the three river gauging stations with each other. Here, unlike in the other regions, generally very low correlations are seen not only when comparing the Mur with the Laßnitz - which is expected due to their different catchments - but also when comparing the two Mur stations, which would be expected to show a similar signal, if they where behaving naturally. Only the local tributary Laßnitz shows a moderate correlation with the 1 to 3 months SPI. For the average correlations with the rivers, the highest value is seen for the SPI3 with a Pearson correlation coefficient of 0.41.

3.2 Selected flood and drought years

Figure 3 shows the correlation matrices for the standardized time series for the well known European drought year 2003 (see for example Beniston and Diaz (2004); van der Schrier et al. (2007); García-Herrera et al. (2010) and Nobilis and Godina (2006) and BMLFUW(2006) for Austria) and the local (see BMLFUW(2011) for Austria and Hornich (2009); Schatzl (2009); Stromberger et al. (2009) and Ruch et al. (2010) for the Mur region) flood year 2009.

In the 2003 drought year, the Mur catchment saw only 80% of the 1961 - 90 average precipitation, 64% of discharge at the Mur in Leoben (between the Aichfeld and Murdurchbruchstal), 59% of discharge at the Mur in Spielfeld (downstream of the Leibnitzer Feld), compared with the 1991 - 2000 average and a general reduction in groundwater levels (BMLFUW, 2006). In the 2009 flood year, the Mur catchment saw 123% of the 1961 - 90 average precipitation, 128% of discharge at the Mur in Leoben, 135% of discharge at the Mur in Spielfeld, compared with the 1991 - 2000 average and a general increase in groundwater levels (BMLFUW, 2011).

Compared with the correlations over the total time period (see Figure 2), it is noticeable that the drought year generally shows higher correlations between the groundwater wells with each other, the wells and the precipitation, the wells and the rivers and between rivers and precipitation.

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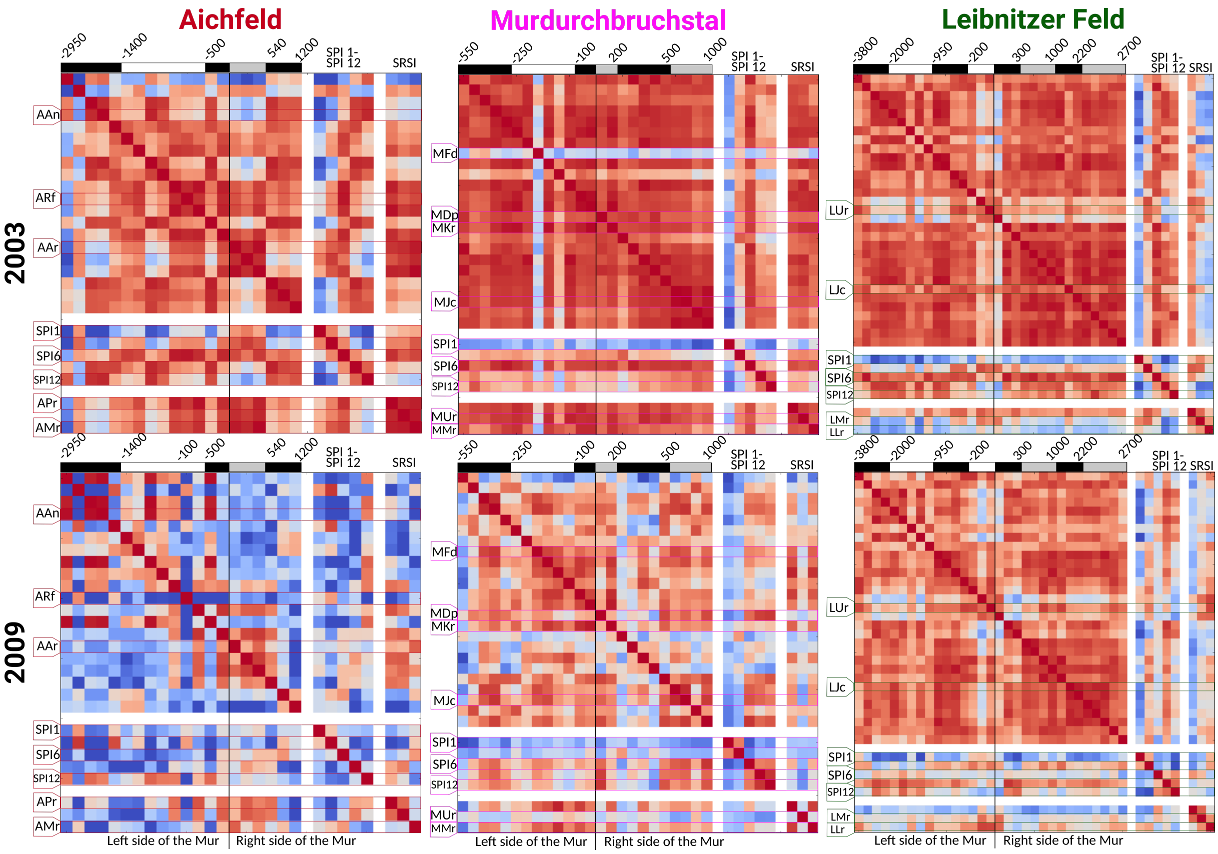

Figure 3. Correlation matrices for the three subregions, showing the effects of the drought year 2003 and the flood year 2009. Legend for the colors and description of the distances: see Figure 2

The flood year shows lower correlations than the drought year, however compared with the total time period, the difference is not as visible as with the drought year, since with the exception of the Aichfeld high correlations generally still prevail.

The strongest difference between flood and drought is visible in the Aichfeld, where negative correlation prevails under flood conditions, going even lower than the -0.45 threshold chosen for the color scheme in the figures.

Another noticeable phenomenon is that certain wells can deviate significantly from their average behavior and the general trends for a given time span. For example well MFd in the Murdurchbruchstal and well ARf in the Aichfeld are among the highly correlated wells in their respective subregions for the complete time period (see Figure 2) but show low correlations under flood conditions (well ARf, 2009, Figure 3) or drought conditions (well MFd, 2003, Figure 3). Well MFd shows less wet conditions in spring and is less affected by the 2003 summer drought than most other wells in the subregion. Well ARf shows a drier spring and winter than most other wells in the subregion during the wet year 2009.

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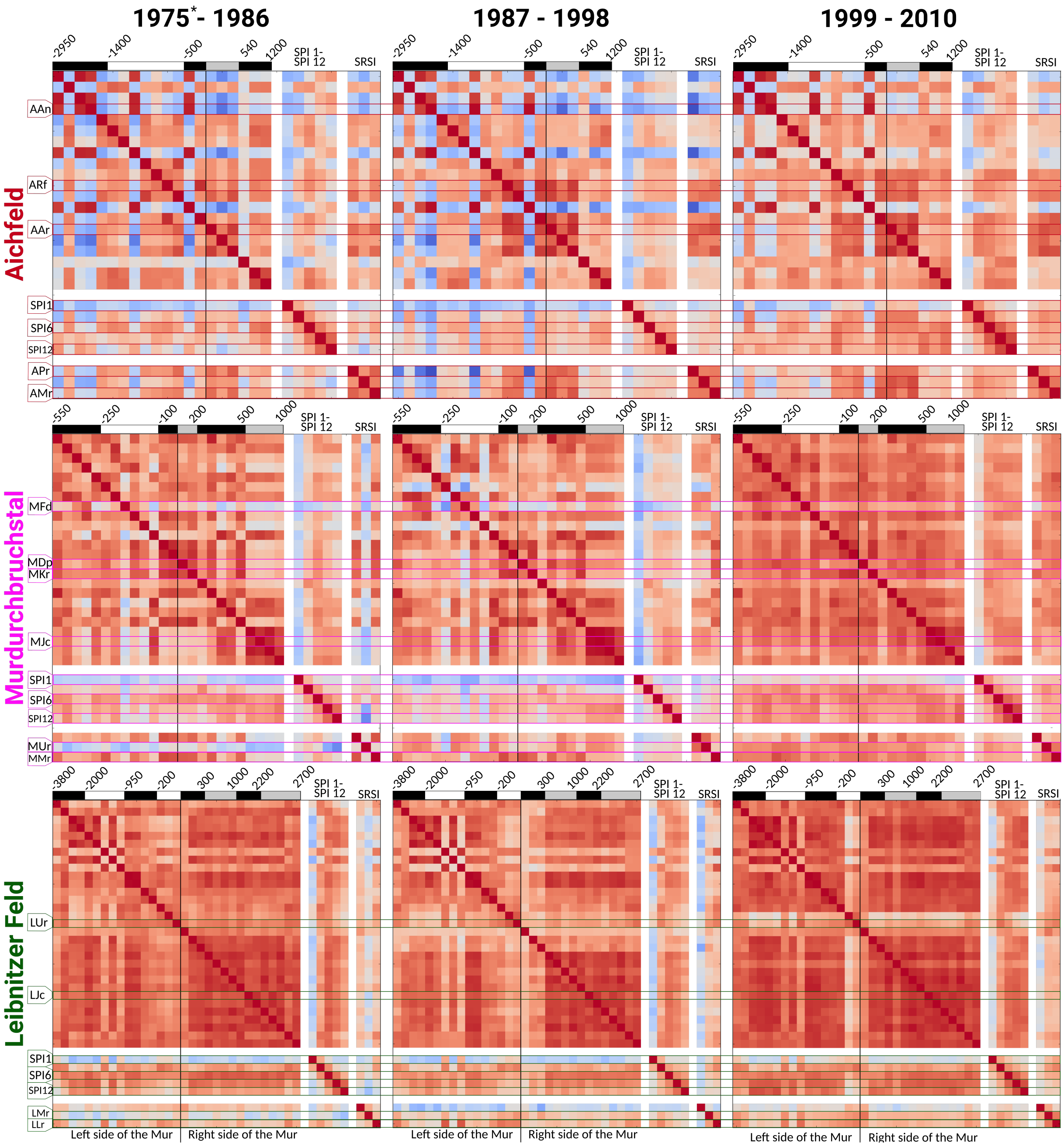

Figure 4. Correlation matrices for the three subregions split into three time periods. Note that the first period for the Murdurchbruchstal is from 1980 - 1986 due to lack of data before 1980. Legend for the colors and description of the distances: see Figure 2

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3.3 Development over time

Figure 4 shows the development of the three subregions when split-up into time periods of 12 years. It should be noted that the Murdurchbruchstal only got a significant number of groundwater wells after 1980, so the first time period differs for this region, and is only 7 years long, from 1980 to 1986.

In the Aichfeld, there is no noticeable trend over time. From the first to the second period, we see an increase in correlations in a cluster of wells around the river and thus an increase of correlation of those wells with the river. In the last period, the correlations generally decrease apart from the deeper wells, where we see a slight increase in correlations with the other wells.

The Murdurchbruchstal shows similar behavior in the first and second period, with some slightly different clusters. In the first period, the upstream and downstream Mur gauges are highly correlated with each other. In the last period, we see higher correlations of all wells with each other, the precipitation and the rivers, with only the one month SPI and the downstream Mur gauge showing some low correlations.

The Leibnitzer Feld also shows a slight decrease in correlations in the middle period, followed by a significant increase in the last time period. Compared with the complete time period shown in Figure 2, the Leibnitzer Feld shows higher correlations of groundwater with the rivers for the shorter time periods, but wells close to the river show a comparably lower correlation.

These developments are mostly related to changes in the subregions (such as the construction of power plants), which is discussed in detail in Section 4.4.

4 Discussion

4.1 Spatial variability

As already shown in Section 3.1, a large number of groundwater wells in each subregion is highly correlated with each other. Some of those wells are also in close vicinity to each other (e.g. the cluster of highly correlated wells in the Murdurchbruchstal subregion, all located in the town Gratwein-Straßengel), to the river Mur (e.g. most of the shallow wells in the Aichfeld subregion) or located in a similar geologic setting (e.g. the deep wells in the Aichfeld subregion or almost all the shallow wells in the Leibnitzer Feld subregion).

As a result of the different behavior of the groundwater wells in the different subregions, the correlations of groundwater wells with the precipitation also differs between the subregions (see Table 2). While the SPI1 still shows similar, low correlations (averages of 0.1, 0.16 and 0.21 for Aichfeld, Murdurchbruchstal and Leibnitz Feld), the longer SPI averaging periods show a different behavior in the subregions. Hence, we are only discussing the higher averaging periods, except for parts of the Aichfeld.

Since there are 2 distinct aquifer bodies in the Aichfeld, the groundwater data was split-up into a shallow (average depth of the wells: 9.7 m) and a deep (average depth of the wells: 24.9 m) part. The deep wells are only lowly correlated with precipitation, with a minimum for the SPI1 of -0.04 and a maximum of 0.38 for the SPI12. The average SPI-SGI correlations for the shallow wells range from 0.38 for the SPI12, to a maximum of 0.57 for the SPI6.

In the Murdurchbruchstal, where all of the wells have similar depths (average: 10.7 m), the correlations between groundwater and precipitation range from a minimum of 0.41 for the SPI3 to a maximum of 0.51 for the SPI6.

The wells in the Leibnitzer Feld also have similar depths (average: 6.4 m). Here, the average correlations between groundwater and precipitation range from 0.58 for the SPI3 to 0.72 for the SPI6.

All subregions (or the shallow part of the subregion in the case of the Aichfeld) have the highest correlation with the precipitation with an SPI averaging period of 6 months. Only the deep part of the Aichfeld has its maximum correlation with the 12 month SPI, which fits the findings of Kumar et al. (2016) who found that deeper wells correlate better with longer SPI averaging periods.

The SPI6 - SGI correlations follow the average depths of the wells, with the highest correlation found in the most shallow Leibnitzer Feld, and the lowest correlation found in the deep part of the Aichfeld, a pattern that is also repeated for all other averaging periods. The shallow part of the Aichfeld and the Murdurchbruchstal have very similar average depths (9.7 and 10.7 m, compared to 24.9 and 6.4 for Aichfeld deep and Leibnitzer Feld), so that they show similar correlations, ranging between those of the deep wells in the Aichfeld and the Leibnitzer Feld.

In all regions, there is a low correlation between river stages and precipitation, with an average correlation coefficient for SPI with SRSI ranging from 0.47 in the Aichfeld to 0.37 in the Leibnitzer Feld (see also Table 2), with the highest correlations between river and precipitation generally found for the 3 and 6 month SPI. This indicates that the rivers can transport a precipitation signal from a region upstream of the subregion in question, which can have a different precipitation signal from the local precipitation. Also, this upstream signal can in itself be a “collection” of many different regional precipitation patterns. This suggests that the correlation with the 3 and 6 month SPI results from the influence of the large, general “climate” in the region.

Another factor affecting the rivers are the numerous run-of-the-river power plants, which alter the natural course and timing of the rivers and remove their natural short-term precipitation signal. For the Aichfeld, where there are only 5 small-scale power plants in its upstream part, this does not affect the river Mur too much, shown by the high average correlation of the river gauging stations with each other of 0.65. A similar value of 0.61 is observed in the Murdurchbruchstal, even though there are 8 hydro power plants in the subregion. In the Leibnitzer Feld however, the combination of 5 power plants, and the fact that the gauge stations are located outside of the subregion results in an average correlation of the river gauging stations with each other of only 0.17.

Thus in small systems such as the Aichfeld and the Murdurchbruchstal - and to some amount probably also the Leibnitzer Feld -, the river and the groundwater will be closely related to each other. At high water levels, the river feeds the groundwater, thus superpositioning its signal onto the groundwater, whereas the groundwater provides the river baseflow in low water conditions, thus giving the river a groundwater signal at low water levels.

In summary, the most obvious differences between the subregions are the low correlation of the river gauges with the groundwater in the Leibnitzer Feld, described in detail in Section 3.1.3, and the differences between groundwater-precipitation correlations, where Aichfeld and Murdurchbruchstal show generally low to moderate correlations, and the Leibnitzer Feld shows generally high to very high correlations, following the depths of the aquifers in the subregions.

4.2 Selected flood and drought years

As shown in Figure 3 and Section 3.2, the drought and flood years of 2003 and 2009 show a very different behavior in the regions investigated herein. Generally, we see an increase in correlations under drought conditions and a decrease under flood conditions. The average Pearson correlation coefficient over the whole matrix under drought conditions is 0.56 for the Aichfeld, 0.7 for the Murdurchbruchstal and 0.64 for the Leibnitzer Feld, compared with 0.12 for the Aichfeld, 0.42 for the Murdurchbruchstal and 0.56 for the Leibnitzer Feld under flood conditions. With the exception of the low correlation between the SPI1 and the SGI under both conditions, these changes in correlation affect most aspects of the system. As shown in Figure 3, when comparing 2003 with 2009 we see a decrease in correlation of groundwater wells with each other, of groundwater wells with precipitation, of groundwater wells with rivers (except for the inconclusive picture in the Leibnitzer Feld) and of rivers with precipitation.

In order to interpret these differences, it is important to look at the differences in the underlying drought and flood. As shown in Section 3.2, the 2003 drought was a long term and large-scale event, affecting all of Europe for most of the year (e.g. Beniston and Diaz (2004); Nobilis and Godina (2006); van der Schrier et al. (2007); García-Herrera et al. (2010) and BMLFUW(2006)). The 2009 flood on the other hand, was a more small-scale event, split-up into multiple flood peaks (e.g. Hornich (2009); Schatzl (2009); Stromberger et al. (2009); Ruch et al. (2010) and BMLFUW(2011))

The 2003 deficit of only 59% of discharge at the Mur gauge in Spielfeld (BMLFUW, 2006) was the result of long term and country wide dry conditions, whereas the 2009 excess discharge of 135% in Spielfeld (BMLFUW, 2011) is the result of multiple flood events, often very localized in the small tributaries to the Mur (Schatzl, 2009; Hornich, 2009), partly also resulting in considerable, localized overbank flow.

While the 2003 drought showed a slow decrease in water levels in the aquifer and the rivers, the 2009 flood showed fast increases in water levels, which in case of the rivers get transported downstream to an area that might not be affected by a localized precipitation maximum.

The phenomena discussed above match the findings of Eltahir and Yeh (1999), who stated that droughts have a much more "persistent signature on groundwater hydrology , in comparison to [...] floods". They suggest that floods - increases in groundwater levels - can dissipate very quickly by groundwater runoff, whereas there is no dissipation mechanism available for low groundwater levels. Following this interpretation, Eltahir and Yeh (1999) argue that this explains the asymmetry of the water levels response to a flood or drought event and suggest that this mechanism deserves further investigation. We argue that this asymmetry is not only seen in a single hydrograph, but also in the whole area, resulting in the different pictures shown in Figure 3, where only the SPI1 shows similar correlations under flood and drought conditions.

Looking at the parts of the aquifers not influenced by rivers, an increase in precipitation will increase infiltration and thus simply increase the water levels, keeping the general flow direction and thus correlations between neighboring wells intact, shown by the areas of high correlations in Figure 3.

However, looking at the parts of the aquifer close to the rivers - which includes many wells that are close to small creeks and streams that are not considered for the general discussion in this paper - a multitude of possible phenomena is seen. As a direct pathway, bedload during floods can erode the clogging layer in the river bed, and thus provide a significant short-time improvement in infiltration (Schubert, 2002). Sophocleous (1991) shows that river floods can transport pressure pulses in highly conducting channels, as described in Zetinigg et al. (1966). A similar phenomenon, is shown by Vekerdy and Meijerink (1998) following floods through the aquifer for distances of over 2 km. Doble et al. (2012) describes wells at similar distances that show a strong and fast reaction to a river flood within 1.5 to 6 days, both with inundation and without. In a further paper, Doble et al. (2014) argue that "overbank flood recharge is not an insignificant volume". As discussed in Workman and Serrano (1999), flood events - with overbank flow - can make up significant parts of the recharge in river-close parts of an aquifer.

The mechanisms described above can result in two phenomena besides the still existing baseflow: a pressure pulse propagating through the aquifer or a real and rapid infiltration, both being oriented against the usually dominating flow towards the river, and a potential for local backwaters where the inflow from the river and the baseflow towards the river meet.

This results in similar changes in all of the aquifer under normal and drought conditions, resulting in high correlations, whereas flood conditions can cause differing changes in the aquifer, resulting in low correlations.

4.3 Development over time

As shown in Figure 4 and Section 3.3, the Murdurchbruchstal and Leibnitzer Feld subregions show an increase of correlations with time within the aquifer and between the aquifer and the rivers and the precipitation. In contrast, the Aichfeld shows no clear trend over time.

Compared with the increased correlations under drought conditions (Sections 3.2 and 4.2), one simply could assume that the split-up time series show a development towards dryer conditions, which is in line with the general assumption of an already warming and drying climate for Austria (Kromp-Kolb et al., 2014). However, looking at the underlying means (see Figures 5, 6 and 7) and counting the extreme events, a different picture manifests itself.

While the average standardized precipitation in all regions remains more or less stable, there are some noticeable changes in groundwater and river stages. As shown in Figure 5, the Aichfeld shows a clear decrease in groundwater levels only for the beginning of the first period and the time before that, whereas the Murdurchbruchstal (see Figure 6) shows an increase in groundwater and river water levels in all time periods. Contrary to those two regions, the Leibnitzer Feld, shown in Figure 7, shows an incoherent signal.

When analyzing the occurrence of extreme events (SGI, SPI and SRSI below/above -2/+2), we observe the following:

For values below -2, the SPI1 has the largest count in 1987 - 1998 in the Aichfeld and the Murdurchbruchstal and in 1987 - 1998 and 1999 - 2010 in the Leibnitzer Feld. This only is reflected in the groundwater in the Leibnitzer Feld, where the largest count of below -2 events is seen in the 1999 - 2010 SGI.

The SGI does not follow this pattern for the Aichfeld and the Murdurchbruchstal, where the highest count is observed in the 1975 (1980) - 1986 period, medium count is observed in 1999 - 2010 and lowest count is observed in 1987 - 1998. As shown in Sections 3.1 and 4.1, the SPI6 is highest correlated to the groundwater. For this SPI averaging period, the highest count of below -2 events is observed in the 1999 - 2010 period in all subregions.

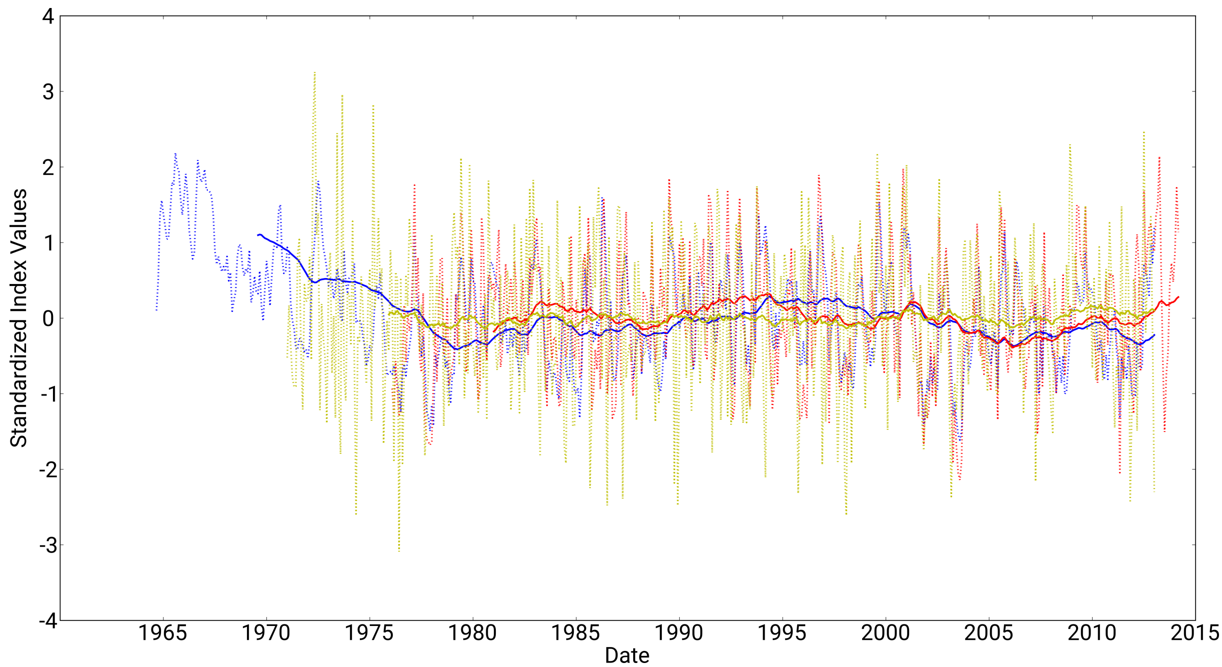

Figure 5. Average values (dotted lines) for the SGI (blue), SPI (yellow) and SRSI (red) and their 5 year running means (solid lines) for the Aichfeld subregion. Note that a larger number of wells with different start and end dates has been used, compared with Figures 2, 4 and 3

Only the Leibnitzer Feld shows the highest number of below -2 events in the same (1999 - 2010) period in the SGI, the SPI1 and SPI6, which is another indicator for the dominant role of precipitation in this subregion.

The most extreme values below -2.5 only occur in SPI, most prominently in the Murdurchbruchstal, where we are observing an increase from 0 in the 1980 - 1986 period to 2 events (one each in SPI1 and SPI3) in 1987 - 1998 to 17 (SPI6: 3; SPI9:6; SPI12:8) in 1999 - 2010. The other subregions show smaller counts, with most of the below -2.5 events being observed in the higher SPI averaging periods and the 1999 - 2010 period.

The SRSI behaves inconclusive. For the Aichfeld it shows the same pattern of events with values below/above -2/+2 as the SPI6, indicating a delayed precipitation controlled river system. In the Murdurchbruchstal, it follows the same pattern as the groundwater, which fits the interpretation of the rivers being the driver of the groundwater dynamics.

The SRSI pattern of the Murdurchbruchstal (highest counts of negative events in 1975/1980 - 1986, lowest in 1987 - 1998) is also seen in the Leibnitzer Feld, but here it fits neither the behavior of the SPI nor that of the SGI. This is in accordance with our other observations that the river in this subregion is intensively human influenced and that both, the upstream and the downstream gauging station are outside of the subregion.

For extreme flood values above +2.5, it is again only the SPI where those occur, but with a lower count of only 1 in SPI1 and SPI3 each in the Aichfeld in the 1975 - 1986 period and 11 (SPI6: 1; SPI9: 4; SPI12: 6) in the Murdurchbruchstal in the 1999 - 2010 period.

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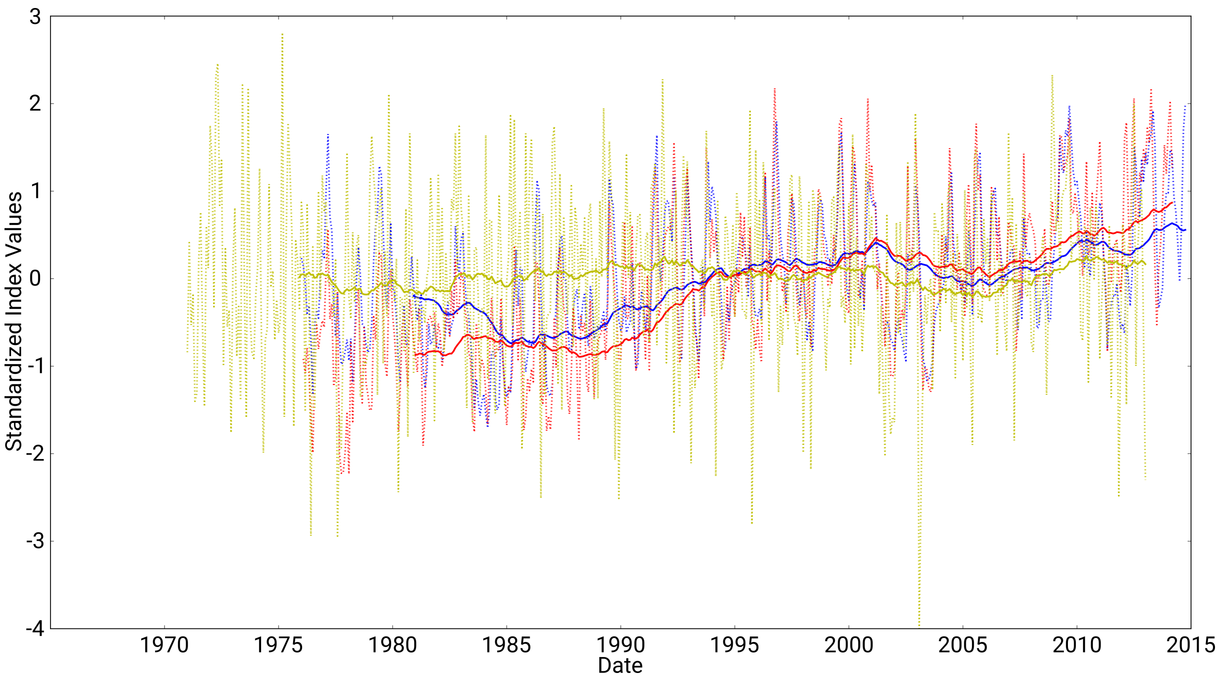

Figure 6. Average values (dotted lines) for the SGI (blue), SPI (yellow) and SRSI (red) and their 5 year running means (solid lines) for the Murdurchbruchstal subregion. Note that a larger number of wells with different start and end dates has been used, compared with Figures 2, 4 and 3

SPI1 and SPI6 values above +2 show the same patterns as SPI1 and SPI6 values below -2, with the largest counts mostly occurring in the 1999 - 2010 period. In contrast SGI above +2 shows the 1975 - 1986 period as the wettest in the Aichfeld and the Leibnitzer Feld. Only in the Murdurchbruchstal, the highest count of +2 SGI events occurs in the time period from 1999 - 2010.

The SRSI also shows inconsistent patterns for positive events, where only the Murdurchbruchstal has the same behavior in the +2 SRSI as it does in the +2 SGI, confirming again the influence of the river on the groundwater.

This different patterns follow our previous interpretation of river dominated upstream subregions and a precipitation dominated Leibnitzer Feld. It thus appears that the influence of precipitation is sufficient to cause a similar behavior in groundwater levels within the shallow aquifer of the Leibnitzer Feld, while it is overruled by direct human impacts in the upstream part of the catchment. When looking at detailed time series (e.g. well MJc or river gauge MUr in Figure 2), it becomes obvious that many events above the +/-2 threshold are not flood or drought events, but result from an overlying trend or are the result of direct human activities. The only exception from this is the SPI since there is no direct human influence on precipitation. This poses the question of the feasibility of the indices, which is going to be discussed in the following section.

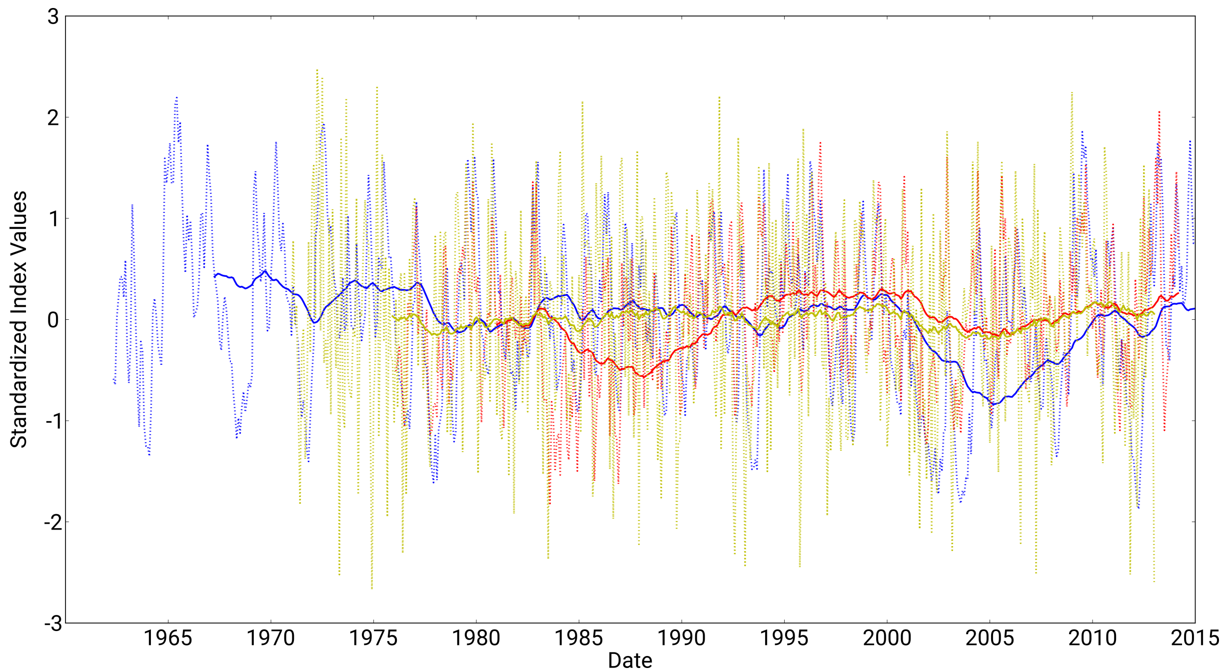

Figure 7. Average values (dotted lines) for the SGI (blue), SPI (yellow) and SRSI (red) and their 5 year running means (solid lines) for the Leibnitzer Feld subregion. Note that a larger number of wells with different start and end dates has been used, compared with Figures 2, 4 and 3

4.4 Feasibility of the indices and synthesis

As already discussed in Section 2.2, SPI and - to a smaller amount - SGI have seen considerable use. However, the shallow aspect of most of our region presents a challenge to the SGI - or similar indices such as the SRSI: While the general consensus in hydro(geo)logy seems to be the assumption of stationarity (Milly et al., 2008; Koutsoyiannis, 2010, 2011), some of the time series singled out in this investigation show a different behavior. Besides the looming threat of climate change, as for example mentioned by Milly et al. (2008), various events that cause a deviation from a stationary trajectory (see also Section 3.3 and Section 4.3) can be observed. As shown in Figure 2, the wells MDp, MKr and MJc and the river gauges MUr and LLr exhibit a split pattern, where at a certain point in time, the standardized values change from a wet(dry) dominated to a dry(wet) dominated regime.

For some of the time series in question the culprit can be easily found. In the case of MDp and MKr, it is the construction of the power plant “Friesach” in 1998 with a pondage of approx. 7 m upstream and a decrease in tailwater of approx. 1 m (VERBUND AG, 2016a). Well MDp is situated approx. 200 m upstream of the weir, and thus shows “dry” conditions before the construction and “wet” ones afterward. MKr is just located 1.1 km downstream of MDp and 1 km downstream of the weir, and thus shows “wet” conditions before the construction and “dry” ones afterward.

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Other time series also seem to be linked to a certain event, such as the case with MJc and MUr, where a change from a wet to a dry regime happens around 1990. However, in this case, both points are situated 9 km apart from each other, and none of the power plants that could affect them have been built at the time in question.

It is interesting to note that those time series discussed above are visually very similar to the synthetic time series discussed in Koutsoyiannis (2011). The effect of apparent stationarity when "zooming in" can also be seen in Sections 3.3 and 4.3, where it becomes apparent that the split-up time series are generally showing higher correlations than the full time series, since only comparably smaller parts of the time periods are affected by a large change.

A quantification and counting of extreme events for the full time, as attempted in Section 4.3, is thus problematic. Calling e.g. an index value of -1 to -1.49 "moderate drought" (McKee et al., 1993) can be misleading when assessing a nonstationary time series, such as well MDp (Figure 2). Here the first approx. 18 years would be interpreted as a period of multiple and persistent moderate to severe droughts, followed by a period of multiple and persistent moderate to severe floods. What the time series really shows is an aquifer in equilibrium with its surroundings before and after the construction of a run-of-the-river power plant and the associated change in groundwater level. To enable a quantification of the negative (and positive) events, the time series in question could be split-up at the time of the change, standardized independently and put back together. However, this requires knowledge of the nature and the timing of the underlying events, which in our case was not always available.

For systems understanding and correlation however, these jumps in time series are not an issue. As shown with wells MDp and MKr, the construction of a run-of-the-river power plant does not only change the water levels of the river in question, it also does affect the groundwater up- and downstream of it. With our matrix-view (Figure 2), it can be shown that this change did not only affect the two wells singled out, but also at least one other well downstream in the case of MKr, where the first "blue outlier" above it is situated directly across the Mur from MKr. The second one however is upstream of MKr and its power plant, but in a similar downstream distance from another power plant (VERBUND AG, 2016b). With well MDp, there are at least two other wells upstream that show very high correlations with MDp.

This shows that large events or human induced changes in the river, such as the construction of a run-of-the-river power plant can not only affect its direct vicinity, but also large portions of the surroundings. This is a further important factor besides other human induced changes, such as change in land use (surface sealing, afforestation, deforestation etc.) and pumping activities as for example mentioned by Stoll et al. (2011). In small, and heavily human impacted systems, such as in the Mur valley described herein, those human induced changes can be among the most important influences, rendering the concept of "natural conditions" almost impossible in shallows wells. Short-term disruptions on the other hand (as demonstrated by well MFd in the Murdurchbruchstal in 2003), do not affect the long term correlations.

5 Conclusions

Three subregions of the Austrian Mur catchment were analyzed. Long-term time series (1975/1980 - 2010) of 75 groundwater monitoring wells, 9 river gauging stations and 3 regional average precipitation time series have been standardized and correlated

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in order to gain insight into the controlling factors for groundwater in alluvial aquifers, the effects of extreme events, the impacts of human activities and the development over time.

It was shown that the correlation matrix approach enables a quick visualization and comparison of different locations and time spans and that standardized indices, such as the SPI, the SGI and the SRSI (SGI applied to river levels), allow for a thorough comparison of groundwater wells, rivers and precipitation.

With the help of these tools, it was shown that subregions in a catchment can show very different behavior, stemming from their different climatic and geologic conditions as well as human impacts. In general, in small subregions and shallow alluvial aquifers as shown here, the river is always a dominant driver in the system. As a consequence, (human) impacts on the river (e.g. construction of a run-of-the-river power plant) propagate into the aquifer system. When assessing shallow groundwater basins in a densely populated area, human impacts must be taken into account. Without this context, many phenomena observed in the system can easily be misinterpreted.

The correlation of groundwater levels with precipitation is more significant in the foreland than in the upstream, Alpine part of the catchment. This corresponds to a tendency towards more shallow water tables in the foreland, and the existence of a second, deeper aquifer in the upstream basin. The shallow wells are highest correlated with the SPI6, whereas the deep wells have the highest correlation with the SPI12. This highest precipitation - groundwater correlation of the deep wells is still considerably lower than the highest correlation of the shallow wells. Besides being only lowly correlated with precipitation, the deep wells also appear to be unaffected by river stage fluctuations.

Extreme events, exemplified by the 2003 drought and the 2009 floods, significantly impact the correlations between the standardized time series, but differ in their effects. Drought shows a tendency towards higher correlations and thus uniform behavior of precipitation, surface water and groundwater, whereas flood results in lower correlations and thus irregular behavior.

When assessing the development over time, the most recent time period from 1999 to 2010 shows significant changes and a trend towards higher correlations. This corresponds to an increase of the number of negative events in precipitation in all subregions and in the groundwater of the foreland subregion. The investigated Alpine aquifers, however, exhibit a contrasting behavior with the highest number of negative events in the time before 1986. This suggests that the groundwater levels within these subregions are more strongly influenced by direct human impacts, e.g. on the river, than by changes in precipitation. Thus, direct human impacts must not be ignored when assessing climate change impacts on alluvial aquifers situated in populated valleys. Accounting for human impacts within such assessments remains a challenging task that requires further investigation into the nature of the various impacts and the mechanisms of their propagation through the hydrological system. Further work could address different types of aquifers, including larger aquifer bodies or aquifers in different climate zones.

Appendix A: Maps

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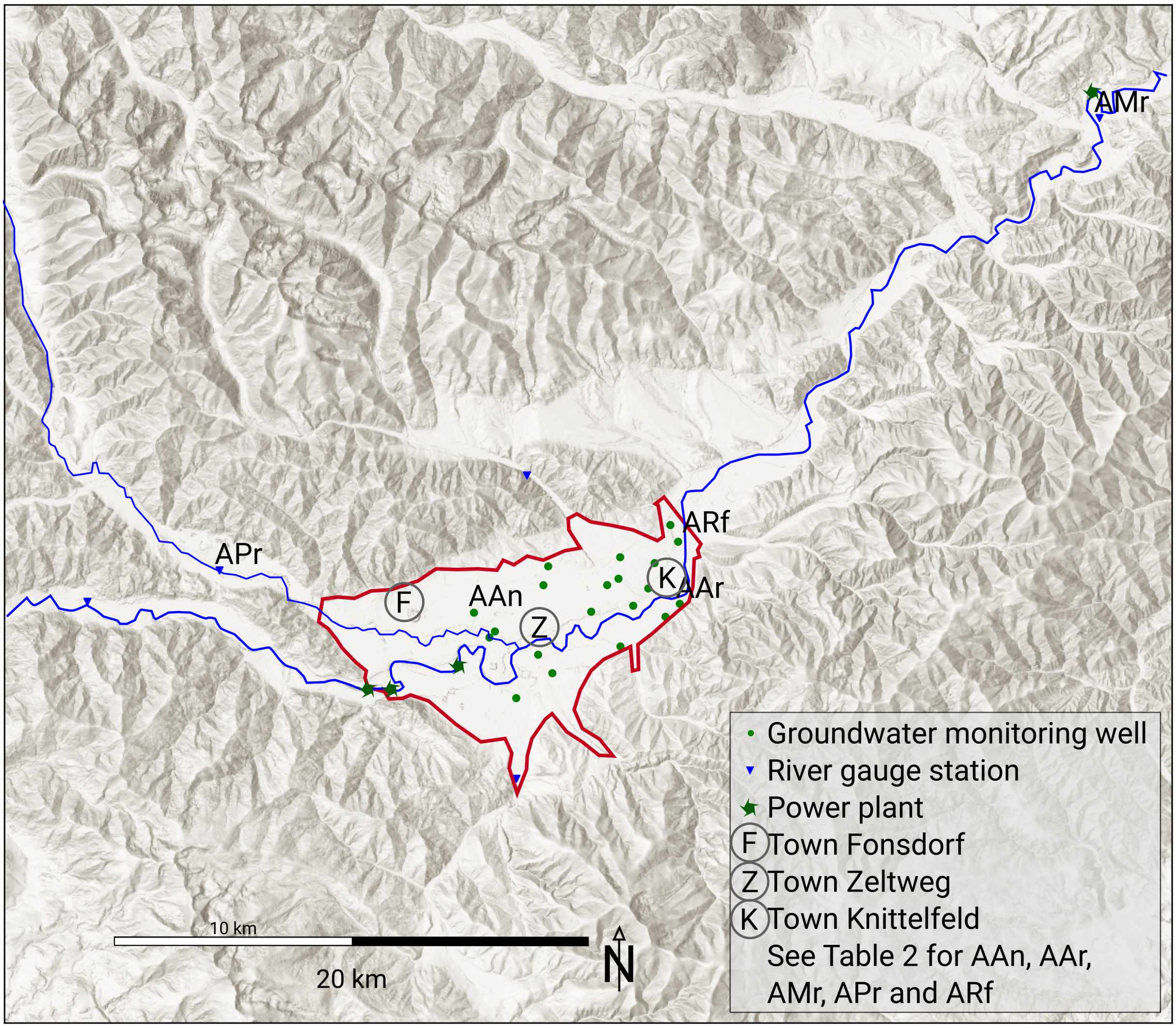

Figure 8. Detailed map for the Aichfeld subregion

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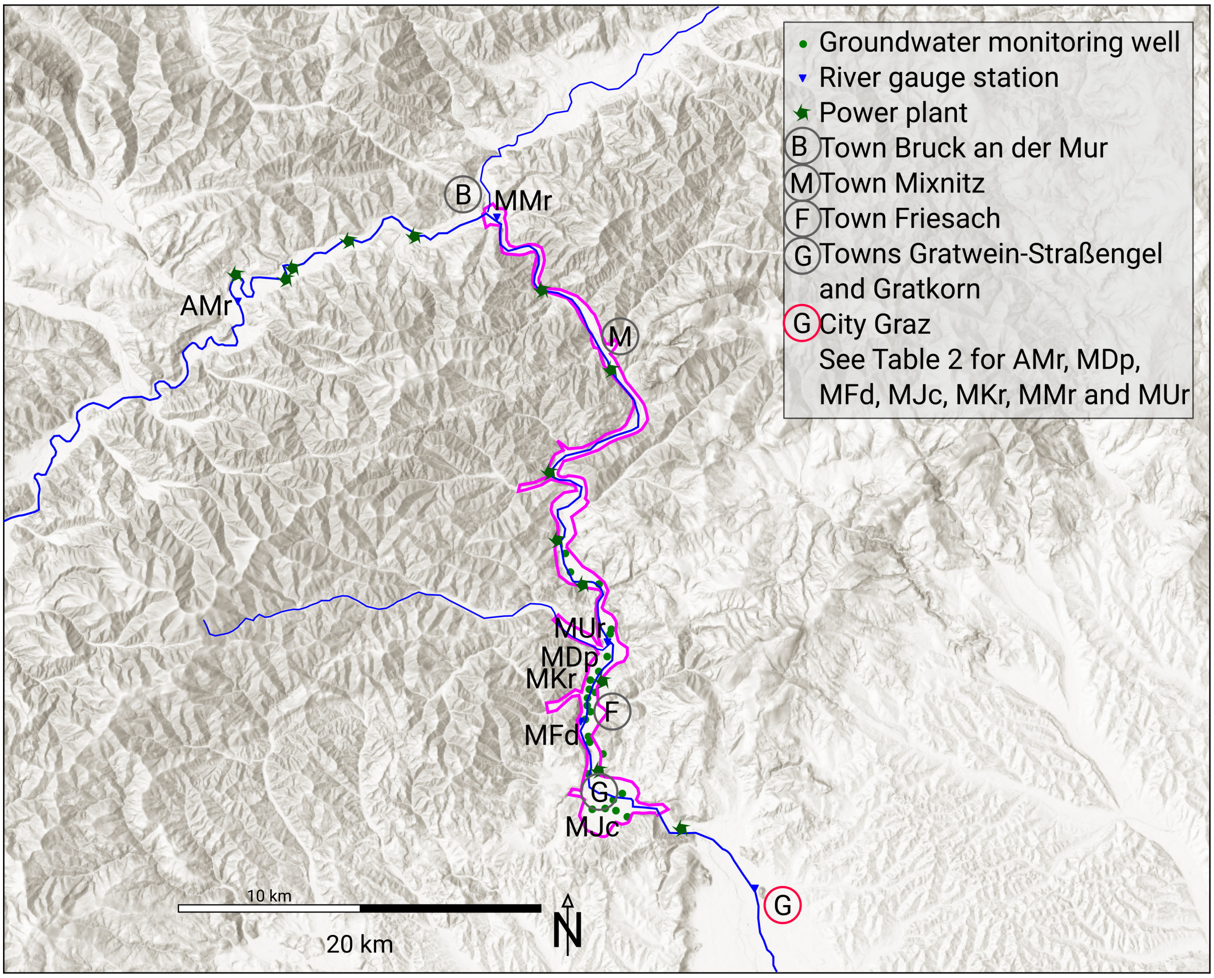

Figure 9. Detailed map for the Murdurchbruchstal subregion

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Background maps for Figure 1 and Appendix A: ESRI World shaded relief

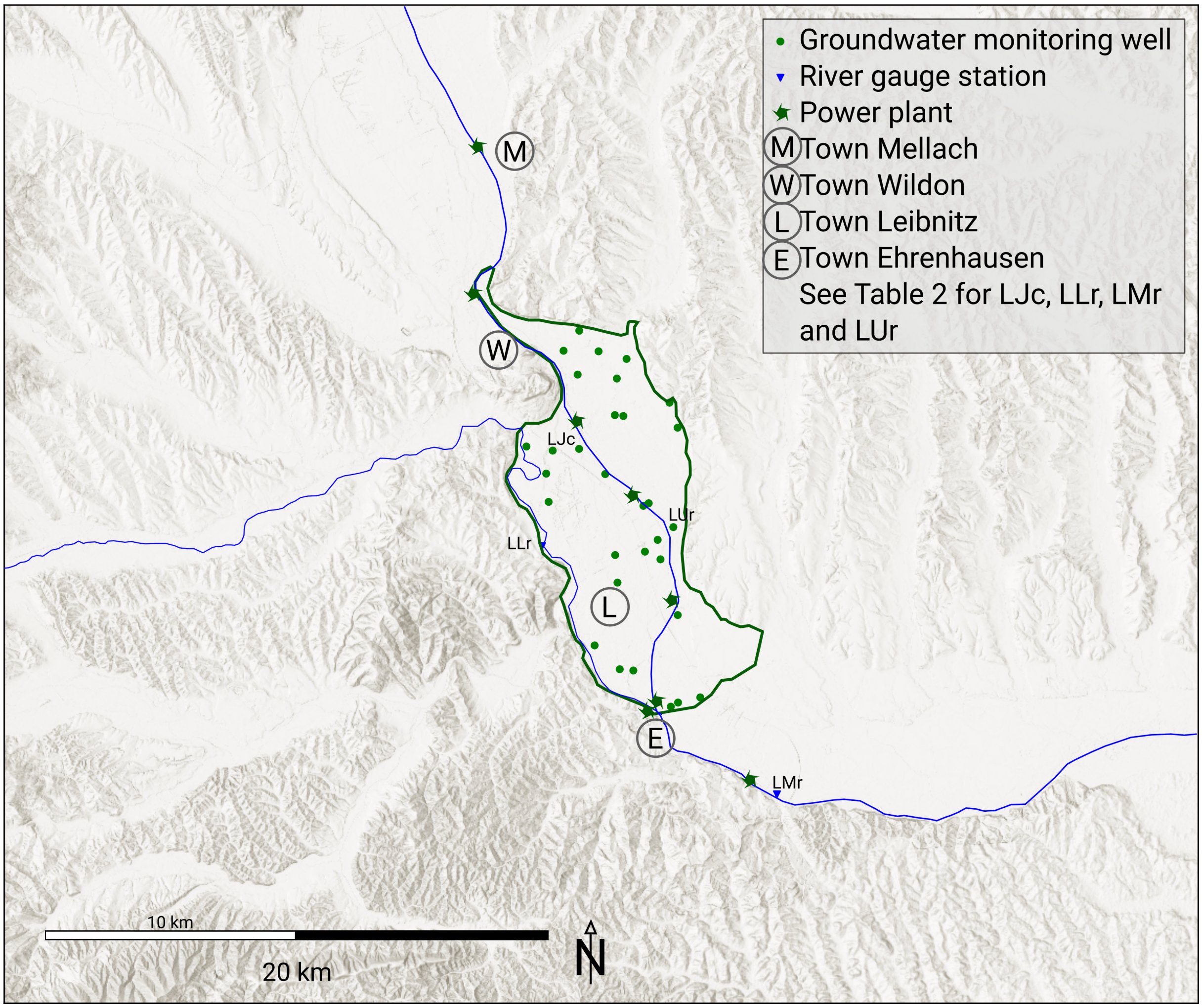

Figure 10. Detailed map for the Leibnitzer Feld subregion

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