Trends in Austrian groundwater – Climate or human impact?

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ABSTRACT

Study region: Austria.
Study focus: Using publicly available data for the main components of the hydrological cycle we use standardization to calculate countrywide and regional averages of groundwater levels, stream stages and precipitation. These averages get analyzed for the occurrence of trends, compared with each other and the Austrian water use over time.

New hydrological insights for the region: It is shown that groundwater levels trend downwards until the 1980s, from whereon they recover. Precipitation follows this track, but the downward trend is much less severe. River stages lack data for the downward trending period, but follow the upward trend too. The trend in groundwater is a reverse of the trends observed in water use and we hypothesize that the discrepancy between average precipitation and average groundwater pre 1980s could be caused by the increasing water use in this period, especially since Austria’s water demands are mostly sourced from groundwater.

1. Introduction

Groundwater is an important resource for public, industrial, and agricultural water use, which is interlinked with other components of the hydrological cycle and thus replenished by infiltrating precipitation or surface waters. In some regions of the world groundwater resources are under stress, as the exploitation appears to be critically high relative to the rate of replenishment (Oki and Kanae, 2006). In Austria, renewable freshwater resources overall exceed by far water use, in particular, within the Alps. Yet, towards the pannonian climate zone in the eastern part of the country considerably lower precipitation and thus lower groundwater recharge prevails. In addition, the Alpine region is expected to be particularly affected by climate change and its impacts, as warming since the late 19th century was twice as high as the northern hemispheric and global average (Auer et al., 2007; Gobiet et al., 2014). As a result, groundwater resources may be temporarily stressed in some regions, e.g. under drought conditions, and future changes in climate, land use, and water management (e.g., as considered by Hohmann et al. (2018)) potentially can have adverse effects on both the replenishment and the exploitation of groundwater resources, thus aggravating water stress.

In order to improve our understanding how groundwater levels respond to changes in hydrometeorological variables, we have previously used standardized time series of groundwater levels, stream stages, and precipitation to compare the correlations of these variables in alpine and prealpine subregions of a river basin (Haas and Birk, 2017). This standardization of groundwater levels uses the Standardized Groundwater level Index (SGI; Bloomfield and Marchant (2013)) and allows averaging time series of groundwater levels from different observation wells.

Fig. 1 shows the average of the standardized groundwater levels calculated using the longest running time series available from

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the webportal of the Austrian hydrographic service (http://ehyd.gv.at (BMLFUW, 2016)). This country-wide SGI exhibits a distinct falling trend from 1960s onwards, which appears to turn into an increasing trend in the 1980s.

This finding poses a series of questions which we try to address in this paper: Are these trends just artifacts stemming from the low number of observation wells used for calculating the mean long term SGI or do they still hold when adding a larger number of wells into the dataset? How does a change in the number of wells in the dataset affect the validity of the found trends? Are these apparent countrywide trends also visible in all parts of the country or just a result of imbalances in the local distribution of observation wells? Are those trends a result of climatic conditions or do we see effects of groundwater exploitation, which is generally known to rise with GDP, until a certain point from whereon it tends to drop again (Jia et al., 2006)?

In order to contribute to an answer of these questions, we consider the representativeness of a single time series for a whole country, which is made up from different geographical and climatic regions by looking at local averages and by comparing the already mentioned groundwater (SGI) with precipitation (SPI; McKee et al. (1993)) and surface water (SRSI; Haas and Birk (2017)). Groundwater levels are impacted by precipitation and river stages which are linked to climate (change) and in the case of rivers various man-made changes for flood protection, power production and for the Danube the use as a major shipping route, which demand special consideration. The spatial distribution of the underlying time series and its change over time caused by the development of monitoring infrastructure over time is also possibly affecting the validity of the observed trends, so we compare datasets with a changing number of measurements with datasets where the number of measurements is fixed. Regarding the possible effects of water use, we try to give a short summary of Austria’s recent water use history.

To our knowledge, few studies have been conducted using a similar approach to ours or focusing on Austria. Livada and Assimakopoulous (2007) and Abdou and Thierry (2009) have used average SPIs but for Greece and the Sahel region respectively. Regarding Austria, Schöner et al. (2011) gives a detailed overview for the long term development for all components of the water cycle (e.g. also including temperature and glaciers) for Austria, including pre 1900 data and modeling approaches for the possible future development and adaption strategies aimed at policy makers. However, these authors did not compare the different components of the water cycle using standardization or did not consider averages of multiple time series as attempted here. Another groundwater issue which has also been considered by Schöner et al. (2011) is groundwater temperature, where Benz et al. (2018) provide a more recent overview.

2. Data and methods

2.1. Data

Most of the data used herein is sourced from the ehyd.gv.at website, which is the official public gateway to the Austrian precipitation, surface water and groundwater data (BMLFUW, 2016). For a more detailed discussion of the ehyd website, the interested reader is referred to Haas and Birk (2017) and the references therein. Further, for long term precipitation data, we use the ZAMG HISTALP dataset (http://zamg.ac.at/histalp/index.php, Auer et al. (2007)).

As of 2018, the ehyd website allows for access to 950 precipitation measurement time series (and thus corresponding to 950 measurement stations), 800 surface water level measurement time series and 3040 groundwater level measurement time series. Since we are interested in the long term development and since standardization needs a certain minimum length of record (see section 2.2), we chose only the stations that have data available from 1980 on, which results in a subset of 599 precipitation time series, 426 river level time series and 1017 groundwater level time series from all of Austria (see Fig. 2). Due to the development of the Austrian measurement network (see also Section 3.3), this number of stations is not static in time. While there are more measurements available for younger data (e.g. the 3040 groundwater levels mentioned above), this also means that for older time series, there are
less measurements available. A short overview of these numbers is given in Table 1 and a plot highlighting the development over time is shown in Fig. 3.

As shown in Fig. 2 groundwater observation wells tend to be clustered in the large valleys and the plains outside of the Alps, compared to a more uniform distribution of precipitation and river stages gauges. Though naturally, those also tend to show a lower density in the high and remote mountain regions. The regions with many groundwater observation wells are also the main settlement regions of Austria, as well as an Austrian province. The province of Tyrol is marked twice in the map, since it consists of two, unconnected regions.

While they are not spatially representative for the whole country, we deem them representative for the settled or used part of the country and we would estimate similar conditions in densely populated valleys such as the Inn or Enns valley for which there is no long term data available. The subset of the 24 oldest wells (see Fig. 2) shows a good distribution across the country, albeit with a bias towards the East and towards rural regions. However, since the largest population clusters are in the same regions as these oldest wells, and since they tend to be situated in large, unconsolidated aquifer bodies, we do deem them valid for an insight into the historical water levels across Austria. An introduction into the history of water use and monitoring in Austria is discussed in more detail in Section 3.3.

Table 1
Overview over the available and the used data. See also Fig. 3 for the development over time. As described in Section 2.1.1, time series with critical amounts of missing data get dismissed, whereas time series with small amounts of missing data get padded and are thus contained in the used data.

| Data Type      | Total Available | Available < 1980 | Critical Missing | Maximum Used | Small Missing | Oldest Data |
|----------------|-----------------|------------------|------------------|--------------|---------------|-------------|
| Groundwater    | 3040            | 1286             | 269              | 1017         | 216           | 1930        |
| Rivers         | 800             | 503              | 77               | 426          | 7             | 1921        |
| Precipitation  | 950             | 640              | 41               | 599          | 56            | 1971        |
| Precipitation* | 66              | 47               | 0                | 47           | 0             | 1900        |

* HISTALP precipitation dataset. This dataset also contains many locations outside of Austria which are not used herein and thus not included in the count of available data. Also some data dates back even further than 1900, which also are not used herein.
2.1.1. Erroneous data

Data from the HISTALP dataset is already homogenized and quality improved (see http://zamg.ac.at/histalp/about.php); thus we use this data as is. According to BMLFUW (2016), the ehyd dataset is also reviewed and error corrected. However, this includes flagging missing data in a time series as NaN. Since there can be considerable amounts of such missing data, we have multiple steps of checking a dataset. A time series is not used if there are more than 14 consecutive missing days (daily data) or if there are more than 3 consecutive missing months (monthly data) and if there are more than 10 % of the data missing throughout the time series (“critical missing” in Table 1). The numbers stated in the previous section thus already exclude these series with a large share of erroneous data. For time series below this threshold, the missing data gets filled with a linear interpolation between the last existing datapoints, which applies to 216 time series for groundwater, 7 time series for rivers and 56 time series for precipitation from ehyd (“small missing” in Table 1).

2.2. Standardization

In order to be able to compare different locations and different types of data, we are working with standardized time series. This allows for the comparison of – say precipitation in millimeters with groundwater levels in meters above sea level on the same scale. Further, this allows to calculate an average over a whole, standardized dataset, such as for example all Austrian precipitation measurements or all the groundwater observation wells in a certain province. While we already discard data with a large number of errors (see previous section), this averaging also reduces the effects of the interpolation fill over small amounts of missing data. For this standardization we use the standardized precipitation index, SPI (McKee et al., 1993) and the closely related standardized groundwater level index, SGI (Bloomfield and Marchant, 2013) and the standardized river stages index, SRSI (SGI applied to river stages, Haas and Birk (2017)).

As SGI and SRSI are build on the same approach as the SPI, they are expected to exhibit similar strengths and weaknesses. While the SPI has already been used for countrywide or regional averages (e.g. Livada and Assimakopoulos (2007) for Greece and Abdou and Thierry (2009) for the Sahel region), there are limitations for the needed lengths of time series and their suitability in comparing time series of different lengths.

The SPI is a widely used and recommended index (see e.g. Svoboda et al. (2012)). However, it is know to have certain weaknesses. Apart from McKee et al. (1993)’s original demand for at least 30 years of data, Wu et al. (2005) also highlight the need for long time series, “because the SPI is a probability-related index, the longer the length of record the more confidence there is in the stability of the underlying statistics”, which is echoed by similar reservations in Svoboda et al. (2012). Hence, we are only using long (30+ years) time series for the analysis presented herein in order to lessen possible negative effects from too short time series.

Besides these demands for a certain minimum length, different lengths of time series can also cause different standardized values for a certain event “due to differences in the shape and scale parameters of the fitted gamma (or other) distribution for different length records” (Bloomfield and Marchant, 2013). Wu et al. (2005) show that this can possibly cause large discrepancies for a single event standardized with a 13 month SPI when using approximately 30 years compared to 100 years of data, but in most cases the discrepancies are minor.

Monthly SGI values are frequently found to correlate with the SPI accumulated over periods of several months. For data from the Mur valley, which is part of the data set explored herein, Haas and Birk (2017) found the highest correlation with SGI for an SPI accumulation period of six months (SPI6). Although the accumulation period yielding the highest SGI-SPI correlation varies...
2.3. Trend analysis

Besides visual identification from plots, methods such as the Mann–Kendall test (Mann, 1945; Kendall, 1975) or regression analysis are generally used to identify trends in time series. However, these methods require various assumptions or data preprocessing which might invalidate their results (Şen, 2012; Şen, 2017). In order to avoid these shortcomings, Şen (2012), with further details in Şen (2017), proposed an “innovative trend analysis methodology” that plots two sorted halves of the time series against each other on a Cartesian coordinate system.

As shown in Fig. 4, this results in an increasing trend (light gray line) plotting in the upper left part of the plot (light gray stars), whereas a decreasing trend would plot in the lower right (not shown). For comparison, a trendless time series (black line) plots on a 45° straight line (black dots). If various phenomena are found in the time series, as often the case in hydrologic observations, a Şen plot can serve to highlight these. For instance, Fig. 4 shows a synthetic time series (gray dashed line) where the low values increase, whereas the high values decrease, which could be, for example, a river discharge showing a trend towards more extremes. While the trends in the examples in Fig. 4 are quite obvious, this method can robustly analyze real, noisy data, where underlying trends are not as apparent. Further, when applied to datasets split in time, it can serve to highlight differences in behavior over time. In this paper, we use this approach to explore the differences before and after 1980.

Further, this method also allows to test these trends for significance, as explained in Şen (2017). However, it has to be noted that this significance test uses a single slope for the whole time series in question. For many hydrological time series as described herein, a purely linear trend might not be the best interpretation of a trend, as highlighted by the increasing and decreasing time series in Fig. 4, for which the method looses the information about two opposing trends in the series in an average slope, which in this case is also insignificant. Due to this, the simple significances quoted in the figures have to be interpreted with caution.

Besides this quantitative method, we also use smoothed plots of the country or province means to help with visual trend or tipping point identification. For this, we use the Savitzky–Golay filter (Savitzky and Golay, 1964; The SciPy Community, 2018), with a window size of 10 years (plus one month due to technical reasons). In order to be able to smooth over the full time series, the used method defaults to fitting a degree polyorder polynomial to the ends of the time series (The SciPy Community, 2018), which results in the noticeably rising or falling ends of the smoothed series. Since this method cannot fore- or backcast, the first and last 5 years of the smoothed time series do have to be interpreted with caution.

![Fig. 4. Three synthetic time series of twelve data points with added random noise showing no trend (black), a clear increasing trend (light gray) and increasing and decreasing components (gray dashed) (left) and their Şen plots (right). A trendless time series (black dots) plots on a 45° straight line in the Şen plot; an increasing time series (light gray stars) plots above the 45° line; increases in high values combined with decreases in low values (gray X), however, plot above and below this line. Following the approach by Şen (2017), only the increasing series shows a significant trend at the 0.05 level, with its slope of 0.47 being outside of the ± 0.013 confidence limits for a no-trend hypothesis. As expected, the trendless series shows no significant trend (slope of 0.002 is still inside the confidence limits for the no-trend hypothesis). However, while the gray dashed line with its rising and falling components clearly shows those two trends in the Şen plot, this information gets lost when a slope and significance is calculated. Here, the two components even out into a small, falling trend with a slope of −0.003, which falls within the expectedly very high confidence limits of ± 0.05 and thus gets flagged as an insignificant trend. Thus while we also provide information about these significances of the trends, we generally refer to the visual features of the Şen plots, when discussing trends in this paper.](image-url)
3. Results and discussion

3.1. Standardization of time series of different lengths

As mentioned in Section 2.2, the standardization methods employed herein show certain weaknesses. In order to see whether our dataset suffers from these issues, we have taken the 24 oldest wells in the dataset (approximately 95 to 65 years of data) and standardized them twice, once for their whole period, and once cut to a 35 year period from 1980 on. As can be seen in Fig. 5, the mean SGI values for this set of wells between 1980 and 2015 do differ, however the differences are minor. Thus, we deem it suitable to use the full period for the SGI (and other indices) in the following sections, albeit with the caveat that the changing number of wells in the early time periods can affect their meaningfulness.

For the SRSI with its two regime shifts (see Fig. 10), the second of which also coincides with a large increase in the number of gauging stations, the difference between the time series of different lengths however is strong. Thus we only use a shortened time series for most of the discussion of river levels.

The precipitation time series available to us all (HISTALP data) or mostly (ehyd data) have the same length, so they are not strongly affected by these possible issues.

3.2. Development over time

3.2.1. Groundwater

3.2.1.1. Countrywide. Fig. 6 shows the mean SGI for all of Austria as well as the mean SGI smoothed with a 121 month

![Fig. 5. mean SGI for the 24 wells in the dataset with the longest time series available, once standardized with the whole time available and once cut to ≥ 1980. As can be seen, there are slight differences in the 1980–2016 period, but the overall result is not changed, even though the time series have largely different lengths.](image)

![Fig. 6. Mean SGIs for the whole of Austria (dotted lines) and their 10 year Savitzky-Golay smoothed means (solid lines). The long time series are 1–2 wells before 1947 and then increase to 24 until 1950. See Fig. 3 for the timely development of all of the wells and Fig. 2 for the locations of the wells.](image)
Savitzky–Golay filter. As already discussed in the introduction, the SGI appears to be falling until the mid 80s and shows a rising trend following that, which appears to fit well with the trends in water use and the fact that most of the Austrian water is sourced from groundwater.

Since this long dataset possibly contains some artifacts due to the changing number of time series and their differing lengths, the declining trend towards the 1980s has to be interpreted with caution (see also Section 3.1).

In order to test our dataset for such possible effects, we have split the dataset into various subsets for a trend analysis with Sen plots. As shown in Fig. 7 the falling trend before 1980 differs considerably, depending on the subset of data. Ignoring the very high SGI period before 1950 obviously reduces the falling trend, as does using a subset of data with a vastly changing number of wells. The rise from 1980 on however is much more stable since there is neither a possibility for a large change in the number of wells, nor is there a possibility to compare time periods of differing lengths. Different periods used for the standardization of data do affect the trend too, but only in a minor way.

These trends shown in Fig. 7 are partly different from the trends observed by Schöner et al. (2011) who analyzed the 1956–2006 and 1976–2006 periods. Using yearly data and counting the number of time series showing a trend, they found that for the short period 24% of measurements show a significant falling trend, whereas only 10% show a rising one. The long time period on the other hand, has 42% of time series that show a falling trend. The latter is consistent with the visual assessment of the SGI values in Fig. 6, suggesting a decreasing trend from 1956 to 2006, and with our finding of a decrease before 1980 that is more pronounced than the subsequent increase. In contrast, the low number of wells showing an increasing trend from 1976 to 2006 appears to be different from our finding of an increasing trend after 1980. Yet, a direct comparison of these results is difficult, as the approach employed by Schöner et al. (2011) differs in several aspects from the one used here (groundwater levels of individual wells vs. average of standardized values; different time periods and numbers of time series; different handling of errors and gaps in the data; etc.).

3.2.1.2. Provinces. As Fig. 2 shows, the groundwater observation wells that cover a long enough time frame for standardization are mostly situated close to Austria’s major population centers in its lowlands, with a strong bias towards the northeast. Yet, Fig. 8 shows that the falling trend towards 1980 and the reversal afterwards as discussed in the previous section also holds true for province mean SGIs, albeit the rises after 1980 are less prominent or might even not be rises for some provinces. While we have shown (see Section 3.1) that the artifacts from a changing number of data points are likely minor, this is still something to be considered. A Sen trend analysis (see Fig. 9) reveals that the rise and fall for the oldest wells are very consistent and affect all three provinces in this subset, apart from some extreme values in Styria. The falling trend before 1980 for the whole dataset also appears to show in almost all provinces besides Salzburg and the mid-low values for Upper Austria. However, this subset of the data shows a large variation in the number of wells (0–220) and length of available data (5–50 years), highlighted by the case of Salzburg, where the apparent clear rise is only due to < 28 wells for the 5 year period of 1975–1979. Using the stable dataset from 1980 on, the rising trend that appears to be small but consistent for all but the medium values in Fig. 7 splits into provinces that show mostly a rising trend (Lower Austria, Vienna, Vorarlberg, Burgenland, Upper Austria), mostly a falling trend (Carinthia) and differing or no trends (Styria, Salzburg), where the rising provinces make up the largest number of wells and thus dominate the countrywide average.

Other phenomena visible in Fig. 9 are that all provinces besides Salzburg show an increase in positive extremes and that the provinces that show the most decreases (albeit only for low values in the case of Styria) are situated in the south of the country.
3.2.2. Rivers

3.2.2.1. Countrywide. Due to its intensive use and importance, the Danube is the most measured river in the dataset, with 15 out of the 426 gauging stations being on the Danube (followed by the Mur and the Traun with 9 each, the rest being made up from various smaller rivers and streams). Thus, the longest running gauging stations are all along the river Danube. As can be seen in Fig. 10, these stations show a long period of negative SRSIs, which includes a first distinct change to higher but still slightly negative values around 1940 followed by a second regime shift between 1970 and 1980. Hohensinner and Jungwirth (2016) mentions a similar phenomenon for the beginning of the 19th century, where natural erosion and the beginning of the Danube “regulation” caused changes in the river’s water level, which led to a recalibration of the gauging stations in 1854. We do not know the cause for the shifts observed herein, but suspect that the second shift is related to the adaptions of the Danube for its role as a shipping route and for power production, since the lowest values become noticeably less and the increase falls in the period with most intense power plant building (VERBUND AG, 2018). These power plants use approximately 73% of the Danubes height drop of approximately 160 m over Austria's 356 km of the stream (VERBUND AG, 2018), making the Danube a "central European electric power bastion" (Sinclair, 1964).

Besides power plants directly on the river Danube, there are multiple power plants in its tributaries, including various large reservoirs in the Alps. Their operation also changes the behavior of their downstream river, which then propagates through the system, so that it even is still noticeable at the Vienna gauge (Kling et al., 2012). From 1976 onward, the Danube represents only 15 of 426 gauging stations in the data set. There have been four run of river power plants under construction on the Danube since 1976. Likewise, there have been or still are underway a multitude of mid-sized, small and even micro water power projects on many of the Austrian streams, rivers and creeks, which are all featured in the data. While the effects of these human impacts hamper any interpretation of the time series with regard to climate impacts on river flow, one might suspect that the changing stream stages have impacts on the variability and trends of groundwater levels of the corresponding alluvial aquifers. For the period after 1976 (i.e. after the second regime shift) there is a general rising trend of the river water levels as indicated by the lower right inset of Fig. 10.

3.2.2.2. Provinces. As the old gauging stations are only found along the river Danube and the interpretation of the data from these stations is complicated by regime shifts before 1976, we focus on the data from 1976 on for further analysis. Compared to the groundwater observation wells, the river gauging stations have a much better spatial coverage and tend to be more uniformly distributed across Austria (see Fig. 2).

As shown in Fig. 12 all of the provinces show a rising trend, besides Carinthia where the mid-lower values are trending downwards and Styria and the river Danube, where some low extreme values trend downwards. The rise is most prominent in Lower Austria and in the upper values for the Burgenland. Also noticeable are increases in the lowest values for Tyrol and Vienna, as well as in the highest for Vienna, the Danube and Upper Austria.

When assessing Fig. 11 the most notable features of the dataset are the maximum for Tyrol around the year 2000 and Burgenlands maximum around 1997, the minima at 2003/04 and the rise towards 2010, as well as the heavy impacts of the 2002 floods and 2003 drought on all province wide averages (apart from Tyrol for 2003).

3.2.3. Precipitation

3.2.3.1. Countrywide. The data available from ehyd only starts in the early 1970s, and it takes until approx. 1980 for the number of measurements in the dataset to stabilize. Thus, we supplement our analysis of precipitation with the long term data from HISTALP (Auer et al., 2007), which only varies between 44 and 47 measurement stations, (thus avoiding artifacts from a changing dataset) and is available for times going back even earlier than 1900. Due to this smaller number of measurements, the regional coverage is not as...
The countrywide SPI6 appears to show a decreasing trend, followed by a rising trend (Fig. 13), which is confirmed by the Sen plot (Fig. 14). Even though there are visible differences between the ehyd and the HISTALP data in Fig. 13, which are likely caused by their different geographical distribution, the rise after 1980 is confirmed by Fig. 14. Due to the nature of precipitation, we deem these identified trends to represent the natural variability in precipitation and thus climate.

The 2002 floods and 2003 drought is very visible in the countrywide average, with both showing some of the highest and lowest values for the datasets.

3.2.3.2. Provinces. The rise and fall in the countrywide average HISTALP data shown in the previous section are not as clearly visible...
in the smoothed plot for the Austrian provinces, whereas the rising trend after 1980 is clearly visible in the province level ehyd data (Fig. 15). The Şen plots (Fig. 16) however do confirm that the pre and post 1980 trends are also a feature of most of the HISTALP data.

Comparing ehyd with HISTALP, the most obvious feature is the differing post 1980 trend in the province of Burgenland, where HISTALP shows a strongly falling trend, opposed to a mostly rising trend in ehyd. In order to interpret this finding, it has to be mentioned that HISTALP only has one measurement station in Burgenland, compared to ehyds 49, so this single station is likely not to be deemed representative for the whole province.

3.3. Comparison of different components of the water cycle

As is generally known, the different components of the hydrological cycle are interlinked with each other. When observing the features discussed in the previous sections, first similarities can be easily observed. Besides the original hypothesis that the fall and rise in groundwater level might be related to water use, one can also observe a similarity to the behavior observed in precipitation or surface water. Some more local features such as for example the SGI and SRSI behavior in the Burgenland between approximately 1995 and 2010 (see Figs. 8 and 11) also appear related.

When comparing the countrywide averages, the highest correlations with groundwater and river stages that have been identified for the SPI6 in Haas and Birk (2017) still hold.
Fig. 17 shows two main features: A discrepancy in their values and trends for the SGI, SPI6 and SRSI before 1980, but similarities between various events. From 1980 on, the dataset (except the long SRSI) shows stark similarities, both in level, long term trends and events.

In general, Fig. 17 after 1980 appears to show an expected behavior of the hydrologic cycle: Precipitation tends to show the most extreme reactions to drought and flood events, whereas surface water and groundwater react in a more dampened fashion. However, groundwater appears to be more affected by smaller negative events which tend to accumulate into larger drought periods, when looking at the smoothed curves (e.g. around 1992/93), especially so when looking at the 24 oldest wells only.

As precipitation and its natural variations are the source of the hydrologic cycle, one would assume that the other components follow it, which is however not the case for the pre 1980 trends. Here, groundwater shows a falling trend and surface water shows no distinct trend but with increasing peaks, followed by a regime shift, whereas the falling trend towards 1980 in precipitation is only clearly visible in the Şen plot (see Fig. 14), when setting 1980 as an inflection point. The high variability of the unsmoothed early SRSI, the oldest SGI as well as the HISTALP SPI6 are likely caused by the comparatively low numbers of measurements contained in these datasets. Regarding the SRSI, as discussed in Section 3.2.2, we do not know the cause of the instationarity, so we are not
discussing this data further.

The discrepancy between precipitation and groundwater before 1980 leaves a possibility for water use having caused the decreasing trend in groundwater. This possibility is supported by assessing the smoothed curve for the 24 oldest wells in the dataset, which show a longer decreasing period and are reaching a lower minimum. These oldest wells are mostly situated in a rural environment (14 wells), of which 8 are situated in the Marchfeld Region. 3 of the wells are clearly in an urban area, whereas the remaining 7 wells are in the outskirts of larger cities, showing vicinities with mixed residential, industrial and agricultural use.

This distribution highlights the history of Austrian water use and thus the development of the measuring network. As described in Section 2.1, groundwater monitoring tends to focus on the large aquifers where Austria’s population, industry and agriculture also clusters. Historically, many rural communities and households relied on house wells and while this practice became less common with the rise of public water supply, it still is used in many parts of Austria. Thus, many (former) house wells got integrated into the official measurement network.

It is safe to assume that most, if not all, of the 24 oldest wells were in use as local water supply at least in the early period of the data but their purpose then got superseded by central water supply, so that they turned into monitoring only wells. Data cited in Schönback et al. (2003) supports this, showing a countrywide decrease in households supplied by house wells from 13.3% in 1980 to 11.9% in 1998, albeit with large local differences (Vienna: 0.3%, Upper Austria (2 wells) 24.8% and Lower Austria (16 wells) 15.6%). Of these 16 wells in Lower Austria, 8 are situated in the Marchfeld region and another 8 in the Tullnerfeld, both regions where Schönback et al. (2003) lists the highest percentages of single suppliers with over 30%, supported by a statement in Flamm (2010) who considers the Marchfeld population to be predominantly supplied by house wells.

Further, the observation that groundwater tends to accumulate droughts for the period after 1980 fits the observations by Stoll et al. (2011), who explain similar observations by soil water depletion due to precipitation deficits and higher temperatures combined with increased water demand leading to groundwater drawdowns on top of naturally low groundwater levels during such periods. Again, this feature is most visible in the oldest wells which are likely situated in an aquifer with a long history of exploitation. Thus, a detailed look into the Austrian water use is warranted.

As is commonly known, water usage used to rise until the 1980s/90s, from whereon it dropped due to the rise of environmentalism, technological advances and a move towards a higher share in economic output of the tertiary sector (Jia et al., 2006), which would fit the observed groundwater levels. This pattern should affect all three big water users: Agriculture, industry and domestic use. Worldwide, agriculture is the main water user, however in Austria irrigated agriculture is a niche application (5% of the Austrian water use [BMLFUW, 2007]), though of regional importance in the Marchfeld region and estimated to be rising in importance with a changing climate.

Industrial use however is responsible for 56% of Austrian water use, which makes it the most important use case for Austria (BMLFUW, 2007). Unfortunately, the data availability for these water uses is very low (Steurer, 1992; Wriedt et al., 2009) so a comparison of water use with water level is not possible. However, Wriedt et al. (2009) (for agriculture) and Fritsch et al. (2011) (proxy data from German industry) make it at least plausible that water use could follow the expected pattern.

The second most important and most documented water use (39% of total) for Austria is domestic (and small business) use, which is sourced almost completely from groundwater, with a 50/50 split between wells and tapped springs. Published data for Austria is rather rare, but due to the cultural similarities, we deem it reasonable to use (West)German data, where Fritsch et al. (2011)’s estimate for 2011 compares favorable to the one from Neunteufel and Richard (2012) for Austria and sets the peak water use between 1980 and 1990. However, it has to be noted that other sources show higher differences (e.g. Karger and Hoffmann...
Fig. 15. Mean SPI6s for the Austrian provinces (dashed lines) with their 10 year Savitzky–Golay filtered averages (thick lines) for each province over time for the HISTALP dataset (top) and the ehyd dataset (bottom). Please note that the provinces all have different numbers of stations in the ehyd dataset, ranging from a maximum of 161 for Lower Austria to 13 for Vienna, with the numbers increasing from 1971 to 1982. Please see the supplement for a detailed plot on this timely development.

Fig. 16. Şen plots for the Austrian provinces for the HISTALP data before and after 1980 (left and middle) and for the ehyd data after 1980 (right). The falling trend before 1980 is strongest in Burgenland (only one measurement station), whereas Upper Austria shows a rising trend, as do the positive SPIs in Vorarlberg. Extreme events tend to deviate from their provinces average behavior. The rise after 1980 is less pronounced in the smaller and spatially different HISTALP dataset, most prominent in Burgenland (only one measurement in HISTALP vs. 49 in ehyd) and the negative values in Lower Austria. All trends except for < 1980 Salzburg in the HISTALP dataset are significant at the 0.05 level.
As highlighted, there is high uncertainty in the sheer numbers of water use, but since the root cause for the reduction in domestic use goes back to the oil crisis in 1973 (Roth et al., 2013), it is reasonable to assume that a rise–(stagnation)–reduction trend opposite to the groundwater level trend holds. This (inverse) correlation of groundwater levels and groundwater use does not necessarily proof a causation though. Yet, for the Marchfeld region, where 8 of the 24 oldest wells of the data set analyzed here are situated, the human impact on groundwater levels (and water quality) is well known and understood. The Marchfeld is the countries most important vegetable growing region (BMNT, 2018) and one of the regions where (as of 2000) house wells still are the backbone of the water supply (Schönbäck et al., 2003; Flamm, 2010). The region has a long history of groundwater-fed irrigation and water scarcity (see e.g. Kozlowski (1965)), which lead to a drop in groundwater levels of 2.5 m from 1945 to 1995 combined with high concentrations of fertilizer sourced nitrate in the groundwater (Ernegger et al., 1998). These issues led to the planning and construction of the Marchfeldkanal in various steps between 1983 and 2004, with the flooding of the canal taking place in 1992 (Betriebsgesellschaft Marchfeldkanal, 2018; Ernegger et al., 1998; Neudorfer and Weyermayer, 2007), whose main purpose is to provide water for groundwater recharge facilities in the central Marchfeld. As a consequence, the groundwater levels in this region have risen again during the last decades.

Regarding future changes in water use, besides economic incentives for further industrial water use reduction, Roth et al. (2013) (for Germany) states that the technical means in appliances are very small, but Neunteufel and Richard (2012) expects ongoing water savings due to replacement of old appliances for Austria for another 20–40 years. However both authors state that changing uses and settlement structures have potential not only for further reductions but also for increases. For the medium term, Neunteufel and Richard (2012) expects a further water use reduction in Austria, mainly still due to technical means, which already does include a rise in the water use for house gardens and due to the dissemination of private swimming pools. Up to 2100, no further technical reductions are expected, so a further rise of outdoor water use will result in an increase in the total use.

If the connection between water use and groundwater level holds, decreasing groundwater levels thus could be expected again. That this is possible, is shown by the above Marchfeld, where this link has been closely investigated. In the Marchfeld, this was rectified by technical means. While such technical means are plausible for many other Austrian locations, the potential for decreasing groundwater levels deserves to be investigated in more detail, especially considering that Austrias water supply is vastly depending on groundwater use.

4. Future work

As described in Section 3.3, the development of the Austrian measurement network is linked to the history and locations of the Austrian water use, leading to the issue that only that what is used, is also measured. Thus, a thorough history of the development of this network and how it is linked to the development of water use and exploitation would be a welcome addition to the body of scientific literature.

In recent times, there has been a push to monitor more areas of the country (compare for example the current distribution of
measurement wells at ehyd.gv.at with the long term wells shown in Fig. 2), but the observation wells still tend to follow the population centers. Thus, this poses the question what happens in the unmonitored aquifers. While often of limited extend, Austria's reliance on a large percentage of spring water from such aquifers lends particular importance to these, often alpine and hardrock, aquifers.

While we do show that trends exist and offer possible explanations for those trends, we cannot yet offer a statistically sound proof whether these explanations are true or false. A starting point for such a proof could be the assessment of a single location with a good monitoring well infrastructure, where extraction rates of a local water plant are available, combined with information about population growth, industrial development and agricultural practices and development. This would allow for such a location to assess how much of an aquifer is affected by extraction activities, possibly resulting in a sound understanding of how many wells are representative for the human factor and for how many are showing background natural fluctuations.

5. Conclusions

It is shown that groundwater levels show an almost countrywide falling trend until the 1980s, followed by a rising trend that affects the majority of Austria. While the rising groundwater levels after 1980 run in parallel with climatic bounds (precipitation and in its extension, surface water) there is a large discrepancy between precipitation (and possibly surface water) and groundwater in the time before the 1980s.

The estimated water use runs contrary to the measured groundwater levels, raising the possibility that water use affected groundwater levels. While there is no full data available for Austria's country wide water use, we have shown via literature review that a rise-and-fall opposite the groundwater level trends for Austria's total water use is plausible.

The countrywide falling groundwater levels before the 1980s appear to be quite strong, whereas the rising trend afterwards is less distinct. While the dataset before 1980 contains a vastly changing number of wells, this number after 1980 is mostly constant. However, a fixed subset of the 24 oldest wells shows an even stronger falling trend for most of the water levels. The falling trends before 1980 are much more robust when assessing province levels, but again might be affected by artifacts from a changing number of wells. However, the small long term data set with a fixed number of wells shows these trends to be robust for the oldest wells in the dataset. After 1980, some province wide groundwater levels also show falling or partly falling trends, most notably in the southern province of Carinthia or the southeastern province Styria, whereas the other provinces do mostly show the rising trend observed in the countrywide average. This rising trend appears most robust when assessing only the oldest 24 wells. While we deem the oldest wells representative for the insights shown herein, it has to be noted that almost all of the groundwater measurements herein come from the large basins and valleys that are the primary settlement, industry and agricultural regions of Austria. Thus, the conclusions drawn from this study are representative for the populated and thus anthropogenically affected part of the country. The hard rock aquifers of the alpine peaks and ranges, as well as the small valley fill aquifers of unsettled or sparsely populated valleys might still show natural conditions, but since the monitoring of nature without any economic interest is a rather new phenomenon, we do not have sufficient data to enable a full assessment of these regions.

For surface waters there is a rising trend in the countrywide average from 1976 on, which has a high similarity with precipitation trends and natural variations. On a province level, the rising trend is robust, apart for some exceptions for again the southern province of Carinthia and the river Danube. For the Danube, we have shown that there is a long history of hydraulic constructions for flood protection and shipping, as well as the construction of numerous power plants, using now over 70% of its height drop. Similar developments (minus the use as shipping route) have happened for many other Austrian rivers and streams, thus adding a human dimension to the surface water signal. These human interventions are now embedded into the nature of most streams and thus suspected to propagate into connected groundwater bodies.

For precipitation, we have analyzed the HISTALP dataset and the data available from ehyd, with only HISTALP offering time series before 1971. Thus, the trend analysis before 1980 is only done on the comparatively small HISTALP dataset. Here we see a falling trend in the countrywide average. This is followed by a clear, countrywide rising trend from 1980 on in both datasets. The rising trend before 1980 is valid for most of the country, but the northern and western provinces of Upper Austria and Vorarlberg differ. The rising trend after 1980 shows in most provinces, except for Burgenland and the lower extremes of most provinces in the HISTALP dataset. This dataset however only contains very few measurements on a province level. Unlike groundwater and surface water, we assume that there are no direct human impacts on the precipitation amounts, so these trends and variations are seen as the natural background for the regions.

While standardizing, comparing and averaging time series of different lengths and locations has some weaknesses, we have shown that those are likely to be minor in our case and are further decreased by using datasets that are close to stable in their numbers for most analysis.

In summary, the country of Austria shows clear trends in countrywide, average standardized groundwater levels, river stages and precipitation. Even though Austria has a diverse and differing geography, these observed trends hold for almost all regional subsets. However, since most measurement follows human use, large parts of the country (mainly the alpine regions in groundwater) are still missing from (long term) measurement.

While we have not proven a causal link between these long term trends and the water use, the example of the Marchfeld region shows that human induced lowering of groundwater levels has happened in Austria. While this appears to have been “fixed” by technical means, projections of future increases in water use and a changing climate warrant more attention to this topic.
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