PhD Thesis

Groundwater response to extreme events: Drivers and thresholds

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Zusammenfasssung

Grundwasser ist in Österreich sowie in vielen weiteren Teilen der Welt eine wichtige, wenn nicht gar die wichtigste Ressource für die Wasserversorgung. Neben der offensichtlichen Nutzung als Trinkwasser spielt Grundwasser auch eine große Rolle in industriellen Prozessen und (außerhalb Österreichs/Mitteleuropas) in der landwirtschaftlichen Bewässerung. Neben inzwischen hinreichend bekannten Risiken für die Qualität (Altlasten und Unfälle) und die Quantität (Übernutzung) können sich durch den Klimawandel neue Gefährdungen ergeben.

Trotz seiner großen Wichtigkeit wird Grundwasser in Literatur zum Thema Klimawandel allerdings meist nur spärlich behandelt. Daher befasst sich diese Arbeit mit einigen Teilaspekten der Interaktion zwischen Klimawandel und Grundwasser.

Einerseits ist Österreich ein (Grund-)Wasserreiches Land und die Alpen generell werden in verschiedensten Kontexten gerne "Wasserturm" oder "Wasserschloss Europas" genannt. Andererseits zeigen die Alpen aber eine doppelt so hohe Erwärmung wie die restliche nördliche Hemisphäre und in Teilgebieten Österreichs wird aktuell schon mehr Grundwasser genutzt wie durch die natürliche Nachbildung geliefert wird. Neben dem intuitiv ersichtlichen Zusammenhang "mehr Wärme = mehr Trockenheit" ergeben sich aber auch Möglichkeiten für mehr Hochwässer, sei es durch Starkregenereignisse oder durch mehr Regen statts Schnee im Winter.

Um die Auswirkungen dieser Ereignisse auf das Grundwasser aufzuzeigen, sowie um die Langzeitentwicklung der Österreichischen Grundwasserstände zu zeigen und um sie mit Niederschlägen und Oberflächengewässern in Verbindung zu setzen, wurden in zwei Publikationen Untersuchungen an öffentlich zugänglichen Datensätzen durchgeführt.

In der ersten Publikation wurden die Auswirkungen von Extremereignissen (Dürre und Hochwasser) auf das Grundwasser in verschiedenen Gebieten entlang der Mur von den alpinen Gebieten der Obersteiermark bis zu den flachen Becken vor der Österreichisch-Slowenischen Grenze untersucht. Hierbei wurde gezeigt, dass sich die verschiedenen Regionen in ihren Reaktionen auf Extremereignisse ähneln. Die Frequenz der Ereignisse ist für den Niederschlag in allen Regionen ähnlich und zeigt eine Zunahme von Dürren. Das Grundwasser zeigt allerdings nur in dem außeralpinen Gebiet den gleichen Trend wie der Niederschlag, wohingegen die alpinen Gebiete abweichende Trends zeigen. Weiterhin wurde gezeigt, dass die vielen flussbaulichen Maßnahmen teils beträchtliche Auswirkungen auf das Grundwasser haben, insbesondere da in verhältnismäßig schmalen, alpinen Aquiferen der Fluss oft der bestimmende Faktor für das Verhalten des Grundwassers ist.

Die zweite Publikation befasst sich mit den großräumigen Entwicklungen der Grundwasserstände in ganz Österreich, bzw. den Entwicklungen in den einzelnen Bundesländern. Anhand von Mittelwerten aus allen erhältlichen Langzeitmessungen wird gezeigt, dass die Österreichischen Grundwasserstände bis in die 1980er Jahre fallende Trends zeigten, von da ab aber wieder ansteigen. Ein ähnlicher, aber schwächerer Trend zeigt

sich auch im Niederschlag. Für das Oberflächenwasser sind keine Daten für den frühen Zeitraum erhältlich, aber auch hier zeigt sich ein Anstieg in neuerer Zeit. Da allerdings die Trends im Grundwasser deutlich stärker sind als in Niederschlag und Oberflächengewässern, stellt sich die Frage was für diese Diskrepanz verantwortlich ist. Hierbei fällt auf das die Trends im Wasserverbrauch, steigend bis in die 80er Jahre, fallend danach, genau entgegengesetzt zu den Trends im Grundwasser entwickeln. Diese mögliche Kausalität kann zwar anhand der Datenlage nicht bewiesen werden, aber anhand von Beispielen wird gezeigt, dass eine menschliche Beeinflussung des Grundwassers zumindest plausibel ist.

Methodisch setzen beide Publikation stark auf den Einsatz von Standardisierungen. Hierbei werden Zeitreihen von (Grund-)Wasserständen oder Niederschlägen standardisiert, so dass ihre Absolutwerte in einen Wert der deren Abweichung vom Mittelwert angibt überführt werden. Dies ermöglicht eine Vergleichbarkeit von Messwerten verschiedenster Komponenten des Wasserkreislaufes sowie von Messwerten verschiedenster geographischer Lokalitäten.

Ein großes Problem vieler Publikationen ist die Tatsache dass die verwendeten Methoden oft nur sehr knapp und abstrakt geschildert werden, so dass eine Reproduzierung des Ergebnisses nur sehr schwer bis gar nicht möglich ist. Daher wurden die verwendeten Methoden in einer dritten Publikation detailliert ausgeführt und anwendungsorientiert erklärt. Kombiniert mit dem mit der Publikation mitgelieferten, ausführ- und änderbarem Pythoncode, stellt dies einen wichtigen Schritt zur reproduzierbaren und nachvollziehbaren, offenen Forschung dar.

Abstract

In Austria as well as in many other parts of the world, groundwater is an important, if not the most important, resource for water supply. Apart from the obvious use as drinking water, groundwater also plays a large role for industrial processes and for irrigation (outside of Austria/middle Europe). Besides the nowadays well known risks to water quality (contaminated sites and accidents) and quantity (overuse), climate change can foster new risks.

Even though groundwater is a very important topic, it is only sparsely discussed in literature covering climate change. Hence, this work is going to discuss some aspects of the interaction between climate change and groundwater.

On the one hand, Austria is a (ground)water rich country and the Alps in general are sometimes called the "water tower" of Europe. On the other hand, the Alps already show warming twice as high as the northern hemisphere and in some areas of Austria the current groundwater use is already higher than recharge. Besides the intuitively obvious connection between "more warmth = more dryness" there is also an opportunity for more floods, be it either due to torrential rain events or due to an increase in rainfall instead of snow in winter.

In order to show how such events affect groundwater and to show the long term development of Austrian groundwater levels, and their relation to surface water and precipitation, two publications have been written using publically available data.

The first publication focuses on the effects of extreme events (drought and flood) onto the groundwater. Various locations along the river Mur ranging from the alpine areas of upper Styria to the lowland basins close to the Austrian-Slovenian border have been assessed. It is shown that the different regions react similarly to extreme events. The frequency of events for precipitation is similar in all regions and shows an increase of droughts. Groundwater, however, only shows the same trend as precipitation in the non alpine regions, whereas the alpine areas show differing trends. Also it is shown that man made changes in the river can have considerable effects on groundwater, especially since the river tends to be the dominating factor in small, alpine aquifers.

The second publication focuses on the large scale development of groundwater levels for the entirety of Austria and in the various provinces of Austria. Using mean values from all available long-term measurements, it is shown that Austria had generally dropping groundwater levels towards the 1980s from whereon the trend reversed to rising levels. A similar but weaker trend is also visible for precipitation. Surface water is lacking data for the early period, but the rise for the recent period is also observable. The trend in groundwater is stronger than the trends observed in precipitation and surface water. This poses the question of the causation for this discrepancy in trends. It is observed that the trends in human water use, rising towards the 80s, falling afterwards, are an opposite fit for the trends observed in groundwater levels. This possible causation can

not be proved with the data available, but some examples show that such a human impact on groundwater is at least plausible.

Both publications make heavy use of standardization. This means that time series of (ground)water levels or precipitation amounts are standardized in such a way that their absolute values get translated into a number that indicates their deviation from the mean. This allows for a comparison of measurements of different components of the water cycle as well as the comparison of different geographical locations.

A big issue with many publications is that their methods are only described very briefly and in very abstract terms, making a reproduction of their results hard to impossible. In order to address this issue, a third publication provides a detailed and user oriented description of the methods used. This description is combined with executable and changeable python code, providing an important step towards reproducible, comprehensible and open science.

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1. Introduction

This work has been written in the context of a multi- or interdisciplinary doctoral program on the topic of climate change. As climate change potentially affects all aspects of our lives an approach with people from many different disciplines researching, discussing and learning together, allowed for an adequate coverage of this topic. This doctoral program covered for example the moral aspects of climate change (Mintz-Woo, 2018), emissions of greenhouse gasses from manure (Mohankumar Purath Erangu et al., 2017), the relationship between rain gauge network density and recorded rainfall intensity (Schroeer et al., 2018) and many other topics.

Climate change is linked closely to the term or concept of *global warming*. While the validity or use of the different terms is worth discussing (see e.g. Villar and Krosnick (2011) or Schuldt et al. (2011)), climate change tends to be closely associated with rising temperatures, both in the general public as well as in the Paris agreement to "keep [. . .] global temperature rise [in] this century well below 2 degrees Celsius above pre-industrial levels" (UNFCC, 2018). These associations with rising temperatures are of course connected to the topic of water, in scientific literature, media and public discussion. The most prominent connection probably is rising sea levels due to melting glaciers (seawater and frozen water), followed by droughts (rain water) and phenomena like waterways not suitable for navigation anymore (surface water) and water shortages (drinking water). Apart from the last point however, groundwater rarely gets mentioned in this context of climate change (see also section 1.3). On the face of it, this appears to make sense, since compared to the oceans, ice sheets and glaciers, groundwater makes up less than 1% of the worlds water resources and it's much harder to observe and access than for example precipitation. However, this comparatively small amount of the planets total water equals to about 20 to 30% of existing fresh water, or about 98% of fresh water, excluding glacial ice (Hölting and Coldewey, 2005; Fitts, 2002; Schwartz and Zhang, 2003).

This discrepancy of less than 1% of the total vs 98% of the usable fresh water, and the fact that water is not only the key element for human survival, but also for everything else that is living, as well as its key role in many technical and industrial processes give a special importance to groundwater, both in general and in the specific context of climate change.

Depending on the location, surface water or even desalinated seawater might be used as the sources for the majority of human water needs, but in most places groundwater is at least among the most important water sources, and always has been (see section 1.2). Besides the use as drinking water for human sustenance, groundwater also is used for agriculture and industry, with the latter two generally using more volume compared to drinking water.

Groundwater is directly linked to many parts of the hydrological cycle, so that changes in the above-ground components (i.e. changes in precipitation, linked to climate change) affect groundwater. Vice versa, changes in groundwater can affect the above ground components, mainly by affecting vegetation or groundwater fed river flow. Besides these natural effects on or of groundwater, groundwater can also be affected by direct, human actions, i.e. the extraction of water. In Austria in general, the rate of renewal of available freshwater is far higher than water use, but in many other countries or regions, this is not the case, with water use being far higher than the rate of renewal (Oki and Kanae, 2006). Besides such long-term and systemic issues, or non issues, in the case of Austria, drought conditions can also affect groundwater in countries or regions that otherwise would not suffer from water shortage.

According to Auer et al. (2007) and Gobiet et al. (2014), the alpine reach has been warming twice as much as the average of the northern hemisphere since the 19th century, so it is possible that some regions will experience more water shortages in the future. However, a warming climate not only makes an increase in droughts possible; there is also a possibility for an increase in floods (Seneviratne et al., 2006). Thus, in a future that is probably going to be affected by a larger amount of extreme events in the hydrological cycle, it is important to understand the interaction between the components of the hydrological cycle. In this context and as the relationship between climate change and groundwater is still underrepresented in the current science (see section 1.3), this work aims to provide insights into the interaction between climate change and groundwater.

Therefore work is presented for the location of Austria and on the questions of human effects on groundwater, both directly, by (drinking) water use and indirectly, by altering the course or regime of surface waters. This is done by assessing the effects of short term extreme events (i.e. droughts and floods) on groundwater in a variety of settings and by assessing the long term development of Austrian groundwater compared with precipitation and surface water.

1.1. Summary

Due to advances in hydrological monitoring tools and means, such as digital data loggers and more cost effective drilling methods as well as due to improvements in information technologies, hydrological and hydrogeological datasets are becoming both bigger and more accessible. However, while enabling new possibilities for research, this wealth of data also poses new challenges. Using classic tools such as spreadsheets or graphing software, handling large datasets with hundreds or even thousands of time series becomes tedious, error prone and hard to reproduce. Also, different types of data such as groundwater levels and precipitation amounts, make it difficult to compare those different types.

In order to overcome these challenges, Haas et al. (2018), see chapter 2, develops the means to apply existing standardization schemes to a large dataset of groundwater, surface water and precipitation time series, using reproducible and scalable python scripts.

This paper shows how standardized time series enable the comparison of different types

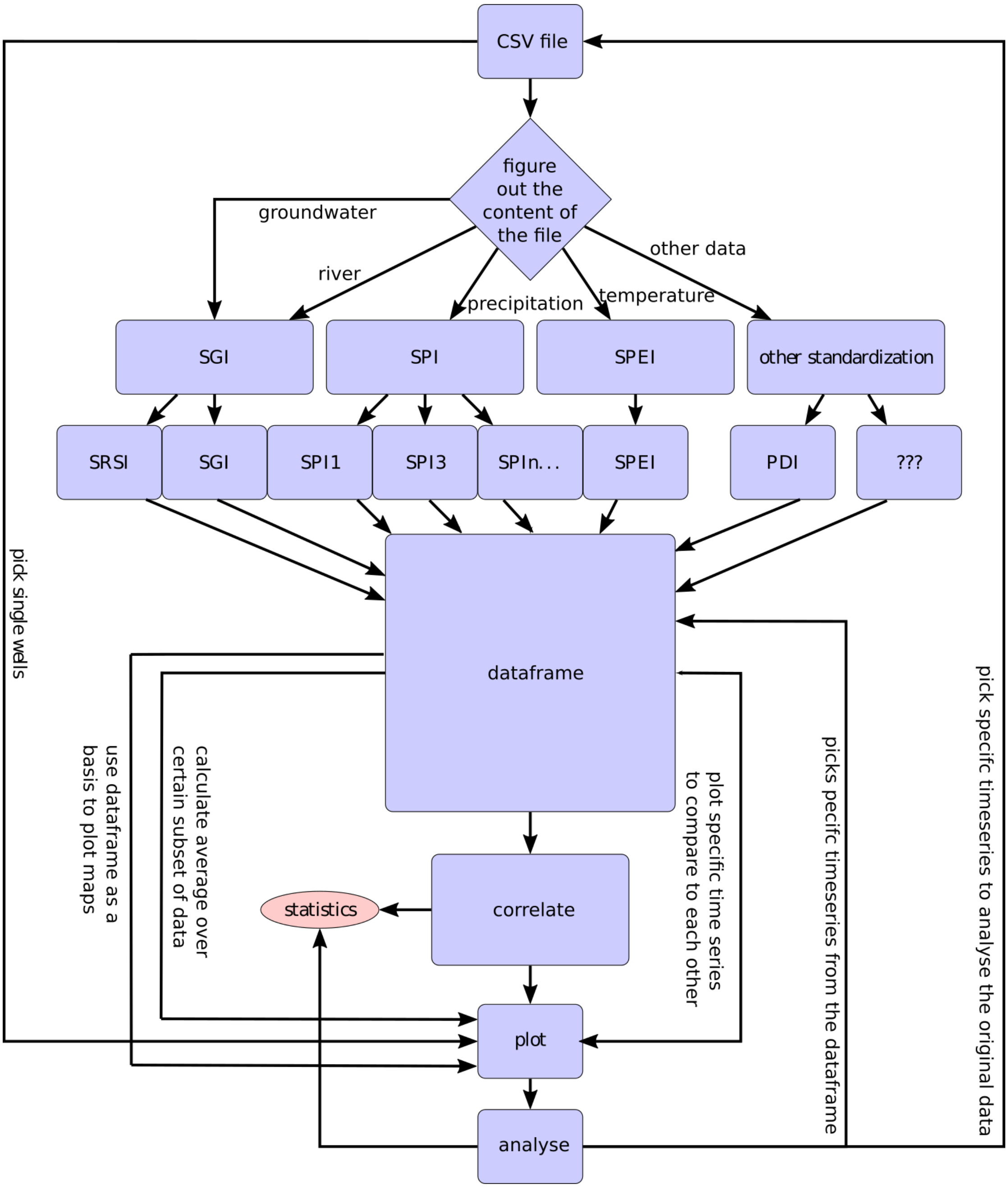

Figure 1.1.: Flowchart highlighting the workflow described in Haas et al. (2018)

of time series and how to use correlation matrices as a tool to screen large amounts of data (see figure 1.1). These correlation matrices of standardized time series allow a quick visualization of complex systems, so that wells, stream gauges, precipitation measurements or other time series that show a high correlation with each other, or vice versa, that correlate with no known components of the system, can be spotted. This can serve as a first step to identify drivers of a system, to classify data, to spot outliers or to compare different regions. When adding a temporal element, e.g. by splitting a long time series into yearly data, changes in the correlation patterns over time can be a first step towards new insights into data or regions. All these methods are not only described in a textual form, but are also shared with the paper as an executable python script, so that the results can be reproduced and can be easily adapted for other uses.

While Haas et al. (2018) focuses on the means, Haas and Birk (2017), see chapter 3, uses these means to study the hydrological behavior of the Styrian Mur catchment (see figure 1.2). Here, a wealth of groundwater, precipitation and river stage time series are compared and correlated in order to investigate three issues:

- How do the different geographical and hydro(geo)logical settings along the course of the river compare?
- How do the different regions react to floods and droughts and do we already see signs of a future where extreme events could become more more frequent (see also section 1.3)?
- What is the rivers influence on the aquifers and how does the human impact on the river, mainly run-of-river power plants, propagate to the groundwater?

It is shown that there can be different settings on the same river in close physical proximity. While all regions show a high correlation of river and groundwater levels there is also a strong influence of long-term precipitation, which is most noticeable in the shallow lowland aquifer. In contrast, the deep, inner alpine basin has a number of wells that are affected by neither the river, nor precipitation. While all regions show increased correlations of all wells under drought conditions, the correlations get reduced under flood conditions, showing that longer events like droughts will affect the whole aquifer, whereas short events like a flood will only have a limited or localized effect on groundwater (see figure 1.3). Looking at the temporal development of extreme events, we are already seeing an increase in precipitation droughts for the period after 1999 in all regions. Groundwater, however, only follows precipitations trend in the lowland basin, whereas the alpine aquifers differ, highlighting possible human impacts. Regarding human impacts, it is shown that changes of the river, as with the multiple, run-of-river power plants on the river Mur, also do affect the groundwater regime in their vicinity.

Following the detailed assessment of the comparatively small Mur region in Haas and Birk (2017), Haas and Birk (2019), see chapter 4, apply the methods from Haas et al. (2018) and an innovative trend analysis by Şen (2012) for a study of trends in groundwater, precipitation and river stages for the whole of Austria. Here, averages for the whole set of the official Austrian hydrological data (see also section 1.5.2) are used

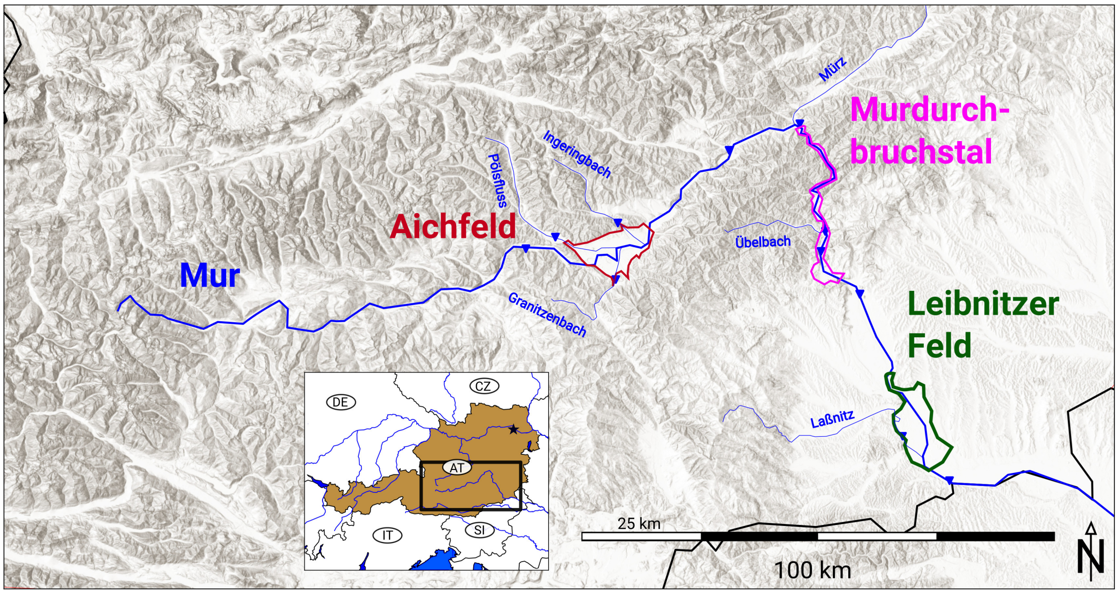

Figure 1.2.: Map of the regions along the river Mur which are discussed in detail in Haas and Birk (2017)

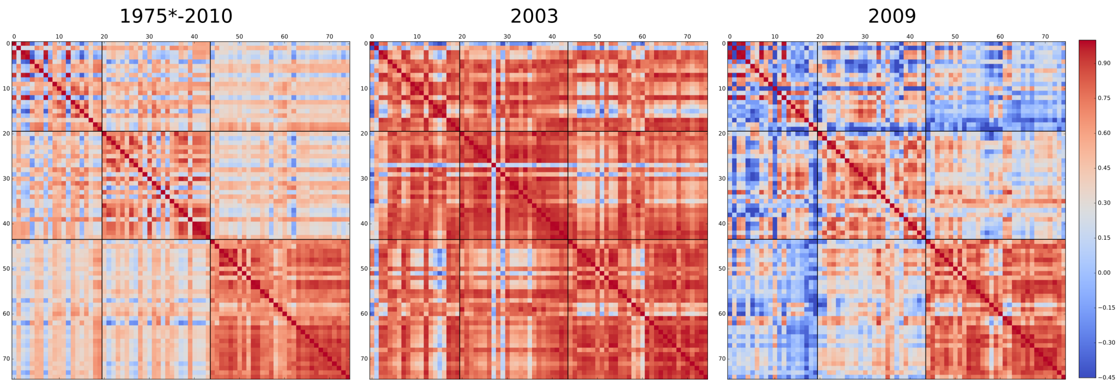

Figure 1.3.: Correlation matrix showing all groundwater level measuring wells used in Haas and Birk (2017). The different regions are the Aichfeld in the top left, the Murdurchbruchstal in the middle and the Leibnitzer Feld in the bottom right. The left matrix shows that the different regions are easily discernible from each other when assessing the whole available time period. The middle and the right matrices show the differing effects of a drought (2003) and flood (2009) year, where drought conditions tend to cause high correlations within a region and between regions. Under flood conditions, low to negative correlations prevail, especially in the alpine Aichfeld region. Image taken from Haas et al. (2018)

to analyze the long term development of the Austrian and the Austrian states averages of groundwater levels, river stages and precipitation amounts. Additionally, these long-term trends are compared with the development of Austrian water use (see also section 1.4).

Using a large and changing dataset in order to built averages and to analyze trends is rarely done, but it is shown that for this case, the approach is very likely to be valid. It is shown (see figure 1.4) that groundwater levels tend to show a falling trend towards the 1980s, followed by an apparent recovery. These trends are also shown in precipitation data, albeit less strong. River levels, while lacking data for the early period, also follow the upwards trend from the 1980s on. As was already shown in Haas and Birk (2017), rivers can have considerable impacts on groundwater, especially when human impacts, such as the construction of a power plant, force changes on them. Looking at the data for the whole country, it becomes apparent that there are multiple and ongoing human impacts on most of Austrias water courses, which makes it hard to judge their impacts on the long term groundwater trends. But as the downwards trend in groundwater is much stronger than in precipitation, and human water use is shown to have increased towards the 1980s, which in Austria is sourced almost exclusively from groundwater (see also section 1.4), it is hypothesized that this discrepancy could be explained by said human use. Looking at the example of the vegetable growing region "Marchfeld", it is shown that it is possible for humans to cause a drop in water levels and subsequently "repair" them, but for the rest of Austria, further work would be necessary.

In summary, these three papers are tied together by three overarching topics:

- The use of standardization of data to make different locations comparable and using the python programming language to address the issue of reproducibility.

- The location Austria, starting with a focus on a small area (the Mur catchment, local to Graz), followed by widening the focus to the whole of Austria.

- The connection of groundwater to the other components of the water cycle, to human influences and to climate change.

What could only be addressed very briefly in the papers, is the connection between human and urban development and groundwater exploitation and monitoring. While these subjects would be apt for a whole dissertation in itself, this introduction tries to give a more detailed overview on these important constraints.

Another issue that is only touched upon briefly in the method sections of the three papers (most notably Haas et al. (2018), see chapter 2), but is a very important part of this work, is the use of python scripts in order to make the methods used more understandable and reproducible. This issue is discussed in more detail in section 1.5 and extended with the example of a python script for building and running a modflow model (see Appendix).

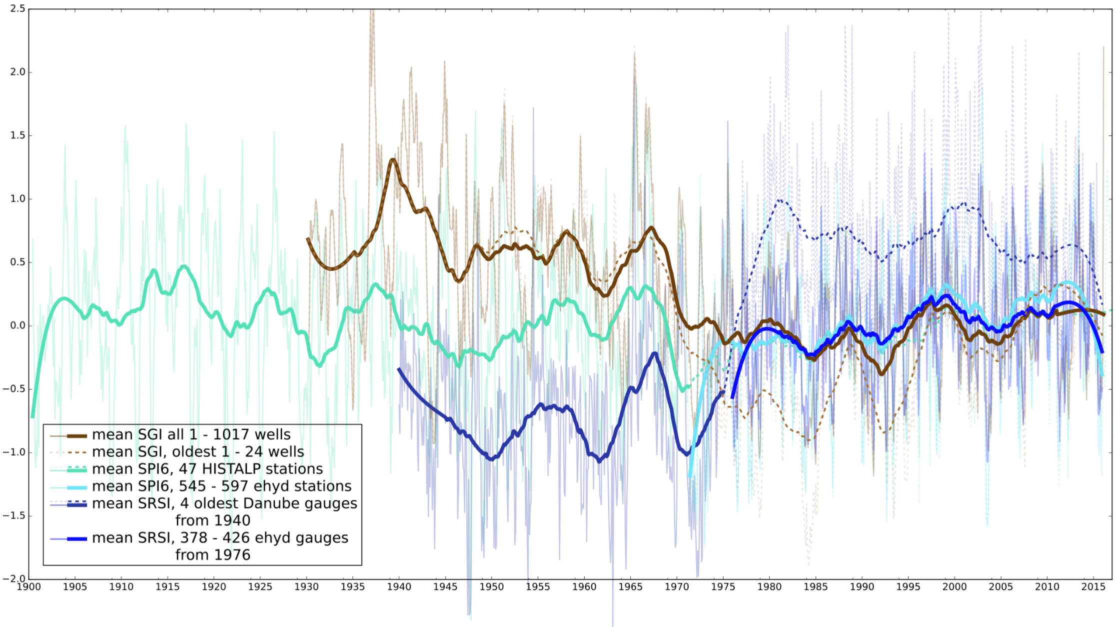

Figure 1.4.: Figure from Haas and Birk (2019) showing the trends in the countrywide mean standardized groundwater levels (SGI), precipitation (SPI6) and surface water (SRSI, all thin lines) and their 10 year Savitzky-Golay filtered means (thick lines). Note the discrepancy between groundwater and precipitation before 1980.

1.2. Human and groundwater

As the overarching subject of this work, climate change, is intrinsically linked to human activities and actions, a very brief look into humans relation to water, and more specifically, groundwater is warranted.

Since water is the most important substance to sustain life, the use of it as drinking water from surface water, rainfall or even thaw and groundwater, mainly in the form of springs, certainly predates the written record and even the modern homo sapiens. Besides sustenance, historically, or even pre-historically, man has always been affected by surface and atmospheric water, e.g. by river floods or with rainfed agriculture. Thus the first records that could be seen as the beginnings of the predecessors of meteorology and hydrology are found around 3500 BC in ancient Egypt, in the form of recordings of the Nile and attempts at damming and flood control (Biswas, 1970; Frisinger, 2018). Groundwater wells only get mentioned in the bible at Abrahamian times (around 2000 BC, Fetter (2004)) but records of engineering feats comparable to the mentioned damming in ancient Egypt are only documented with the Qanats in Armenia around 700 BC (Biswas, 1970; Fetter, 2004).

In more modern times, many aspects of surface hydrology have been mastered leading up to the industrial revolution at the turning point from the 18th to the 19th century, shown for example in the extensive networks of shipping canals built already in its beginning phase. Not only have canals been built in the form of the well known British canal system, but also in Austria, exemplified by the Wiener Neustädter canal, originally supposed to supply the capital with coal (Slezak et al., 1989).

But it probably took until Snow's (1855) discovery of the spreading mode of cholera to generally realize a surface-groundwater connection, followed by 1856 where Henry Darcys key paper marks the beginning of modern hydrogeology (Darcy, 1856; Simmons, 2008). Still, even with its longer history, "hydrology [. . .] remained a science filled with empiricism, qualitative descriptions, and little overall understanding of ongoing processes [until the 1930s]" (Bras, 1999), so it is assumed that early hydrogeology faced similar issues.

Their different visibility – everyone can readily observe rainfall or the water level in a river whereas groundwater is mostly invisible without the help of sophisticated tools or large amounts of labor – probably also plays a role in the understanding and recording of the different components of the water cycle. Thus "groundwater" still is a concept that is very alien to much of the general public (Reinfried, 2006; Reinfried et al., 2012), as well as to highly educated people from other disciplines, as has been shown to the author in many seminars in the course of this interdisciplinary doctoral program.

This time lag in the understanding and thus observation of groundwater, compared to surface water or precipitation still shows in the data used herein: Records for the above ground precipitation and surface water tend to have a much longer availability than records of subterranean groundwater. For the case of Austria, the long-term data is tied to the development of the Austrian water supply (see Section 1.4) but even in more recent data and more recent reports, this discrepancy in the record is still visible.

1.3. Climate change and groundwater

As explained in the previous section, there generally is a discrepancy in the records between groundwater and surface water or precipitation data. Further, not only does groundwater rarely feature in the public debate unless specific circumstances require it (e.g. the cases of the 2011-2017 California drought or the European record summer of 2018), it also is covered rather sparsely in the main reports by the Intergovernmental Panel on Climate Change (IPCC). See for example Masson-Delmotte et al. (2018), the "Summary for Policymakers", where "water" gets mentioned 15 times, but never as "groundwater". Similarly, the chapter 3 on the impacts on natural and human systems (Hoegh-Guldberg et al., 2018) only deals with groundwater in a small subsection. Still, the IPCC reports, as well as the similar report of the Austrian Panel on Climate Change (APCC), can serve as a good and thorough introduction into the topic. Thus, a short overview is given in the following paragraphs.

While Masson-Delmotte et al. (2018) states that there is "high confidence" for increasing air temperatures under the 1.5 or 2°C scenarios, heavy precipitation and drought increases are only projected with "medium confidence". Subsequently, groundwater is covered only very briefly in Hoegh-Guldberg et al. (2018), "owing to a lack of appropriate observation wells and an overall small number of studies (Jiménez Cisneros et al., 2014)", a fact that remains the same after the 4 years between the 2014 5th assessment report and 2018 special report on a 1.5°C warming. A further factor making attribution of climate change effects on groundwater rather difficult, is the various additional influences on groundwater such as land use change or abstraction, which appear to wield more influence on groundwater levels, compared to climate change. However, Jiménez Cisneros et al. (2014) state that it is unknown how much climate change already affects the rate of groundwater extraction.

While not explicitly listed as factors that will affect groundwater, both Jiménez Cisneros et al. (2014) and Hoegh-Guldberg et al. (2018) list various effects of climate change and climate change mitigation or adaption that have a large potential for groundwater effects. For example, the emission pathways modeled for Masson-Delmotte et al. (2018) to reach the 1.5°C target do include means of CO_2 removal, which range from *simple* afforestation to Bioenergy with Carbon Capture and Storage (BECCS), all of which affecting land use and thus potentially groundwater, either indirectly due to changes in vegetation or directly by expansion of groundwater irrigated agriculture for energy crops. Regarding the latter, Jiménez Cisneros et al. (2014) state that agricultural droughts have already become more common in some regions and that water demand from (general) agriculture is projected to exceed the supply in various regions. While it is likely that this additional demand will affect surface water, as surface water remains the main water supply for many regions, there is also a potential for large portions of this additional demand being filled from groundwater.

Other issues that are not explicitly listed as groundwater related in Jiménez Cisneros et al. (2014) but can be, are the changes in snow cover and timing as well as shrinking glaciers. Here, changes (amounts and timing) in river discharge, have the potential to affect the groundwater in catchments with a good groundwater-surface water connection (see also section 1.4.2 and the paper in chapter 3). These changes in river flow also have impacts on the mode of operation of damns for storage and power production, which in turn might inflict other changes on the downstream river and its connected aquifers.

For an overview on the general situation in Austria and following the model of the IPCC reports, Austria has published an APCC report (APCC, 2014a). This report concludes that Austria has already experienced a higher temperature increase than the global average which is expected to continue. Precipitation trends are shifting towards more precipitation in the winter and less precipitation in the summer and a reduction in snow cover and glacier volume is also expected (APCC, 2014b). While it has to be noted that there are considerable uncertainties when using climate models for regional forecasts, all the main findings are considered likely (Ahrens et al., 2014).

Most relevant for the focus of this work, Nachtnebel et al. (2014) list the impacts of climate change on the Austrian hydrosphere: While Austria as a whole uses only a small portion of the available water, there are areas in the north east and south east of the country that already have a yearly precipitation that barely covers the yearly evaporation. Here, groundwater sourced irrigation is already in operation, and it is expected that irrigation schemes will increase in importance and volume. Regarding floods, their increasing occurrence in the last decades is deemed to be within the natural variability, but an impact of climate change cannot be ruled out. These floods have the potential to influence groundwater recharge, a fact highlighted by some irrigated areas in the eastern part of the country, where intense rainfall and floods are deemed to be the cause of rising groundwater levels.

Besides the issues that are stated as explicitly groundwater related in Nachtnebel et al. (2014), there are also many expected or possible changes in a variety of fields, that have the potential to influence groundwater quantity or quality in Austria. Following, a short selection of these issues is given.

A further aspect of climate change is its possible influence on the relief and the geosphere. While Glade et al. (2014) conclude that it is not possible to make forecasts with high certainties, long to mid-term phenomena such as changing land cover or changes in glaciation, or changes to the extent or frequency of events such as debris flows or forest fires can possibly be affected by climate change. While not discussed in detail, this topic also contains many issues that could affect (ground)water, for example, a debris flow induced lake and a flood, following the bursting of such a lake, or the need for firefighting water due to forest fires. Regarding groundwater quality, possible nitrate leaching under forests due to increases in extreme precipitation events (Lexer et al., 2014) is among the possible effects of climate change on groundwater.

Water supply and distribution tends to be on the receiving end of climate induced changes but it is also an emitter of greenhouse gasses (GHGs). While it is not a noteable contributor of GHG emissions in Austria, a short view into it is warranted.

As stated in Eitzinger et al. (2014), drinking water supply itself has "no relevant GHG emissions" but its tail end, waste water transport and cleaning do have. While the APCC report does not show any data, the various equipment used in the distribution of drinking and waste water (mainly the pumps) do need power and thus cause GHG emissions. As power use is seen mainly a cost issue, maintenance and replacement tends to favor lower power solutions. However, no sufficient data is available for the situation in Austria. Reductions of sewage plant GHG emissions at the current techniques are contrary to their primary goal, the (biological) removal of organic matter from waste water.

Regarding needed adaption measures, Eitzinger et al. (2014) list a few means on how water supply could cope with possible changes. While generally, there is no expected shortage in available freshwater for Austria, various factors are expected to affect groundwater supply. E.g. increased water use due to temperature increases (e.g. private swimming pools or irrigation of house gardens) combined with climate induced reductions in groundwater recharge and the impact on water quality by extreme events, such as extreme precipitation induced flooding of wells are seen as the main factors. As these are likely to be local issues, interconnections between local and regional water suppliers are suggested as mitigation.

Another water and climate related issue is power production. Besides the potential for a loss of cooling capacity for power plants due to warmer surface water, hydro power can also be an emitter of GHGs. As is generally known (e.g St. Louis et al., 2000) reservoirs potentially emit climate gasses. While Eitzinger et al. (2014) recognize this, no data for the Austrian situation is known, but according to Austrias topography and climate, very few reservoir emissions are expected. Increasing temperatures do, however, have the potential to increase emissions from Austrian reservoirs.

Increases in, or prolongation of, periods of low water levels in rivers do affect the water supply threefold: Besides the general lower water availability, water quality tends to be lower due to lower dilution of pollutants and sewage plants tend to have issues in discharging their cleaned water, which, while cleaned, does have a lower oxygen concentration and thus needs water available for dilution in its receiving water.

Due to changes in sediment transport, there is potential for changes in the clogging layer in riverbeds, which could affect the rivers connection to the aquifer, which might change the observations discussed in the paper shown in chapter 3.

Finally, a factor of special interest for Austria is the production and distribution of artificial snow on large portions of the countries many skiing resorts. While definite data is hard to come by, literature (e.g. Haßlacher, 2006; Teich et al., 2007; APCC, 2014b) indicates that the percentage of ski piste area with artificial snow cover in Austria is above 50% and rising, combined with a general rising area of ski pistes. Very recently this issue caused considerable controversy after a report by Schwaiger et al. (2017) found a general positive climate effect of artificial snow pistes and almost immediately received a public, critical reply by Kaser et al. (2017), resulting in a very thorough press coverage of the issue. While this specific discussion appears not directly connected to (ground)water use, it can serve as an example of the general importance of artificial snow production in Austria. However, while water use for snow production does not show up in national statistics (e.g. BMLFUW, 2007), water availability can limit snow production capacity (APCC, 2014b). Locally water demand for artificial snow production can be equal to two thirds of public base water demand (Vanham et al., 2008), which in turn can affect local groundwater conditions by various factors. While at first sight, this water use appears to be a negative effect, the need for considerable storage and distribution infrastructure could also be part of a sensible and beneficial water management, see for example Gurung et al. (2018).

1.4. History of Austrian water use

Austrias past, current and future water use can be split into three separate but closely linked use cases: The use of water for drinking, for transport and for power production. For the case of Austria, the first one does appear to be a clear groundwater issue, whereas the other two appear to only affect surface water. However due to the close interaction between river and groundwater, (human) impacts on surface water do also affect groundwater, as shown in Haas and Birk (2017) and Haas and Birk (2019), see chapters 3 and 4.

Hence, the scope of this work also demands an overview of the latter two cases. Thus, the following sections attempt to give a brief overview over Austrias relationship with its water bodies and a short outlook into its future.

1.4.1. Groundwater

When addressing the history of groundwater, one must focus on the history of drinking water supply. While medieval water supply would be an interesting topic, the modern period is more apt for this work. While groundwater use from hand dug wells certainly goes back to medieval times and beyond, a more systematic approach is tied to our modern forms of water supply. In the case of Austria however, we have the special case that most of the population is - and has been - centered in the large valleys and lowlands and in and around the capital, Vienna. This population pattern is reflected in the density and location of the Austrian groundwater measuring wells (see figure 1.5) and gives special importance to the city of Vienna, which has a very specific form of water supply.

Vienna, which is by far the most populous city in Austria, housing around 20% of the countries population (1,888,776 people of 8,822,267 in total, Statistik Austria, 2018d), a special position within Austria that was even more distinctive at the beginning of the 20th century (2,083,630 people of 6,614,000 in total = 32%, Stadt Wien, 2000; Statistik Austria 2018a). Most of these about 2 million people moved to Vienna within the 19th century, at the beginning of which Vienna only had about 250,000 inhabitants, or about 8% of the countries population (Stadt Wien, 2000; Statistik Austria, 2018a).

Hence, around 1800, Vienna was supplied mostly from groundwater wells and a few small pipelines for important buildings. Since those wells were mostly located at the grounds of the houses they were supposed to supply, they also tended to be very close to the houses cesspits, resulting in bad water quality. Besides supply not being able to keep up with the growing city, this situation also led to various outbreaks of the Cholera, resulting in about 22,000 deaths from 1830 to 1873 (Csendes and Opll, 2006).

In order to alleviate this situation, it was realized that a large and future proof solution was needed which resulted in the planning and construction of the "Kaiser-Franz-Josef-Hochquellenleitung" (nowadays called "erste Wiener Hochquellenwasserleitung", approx.

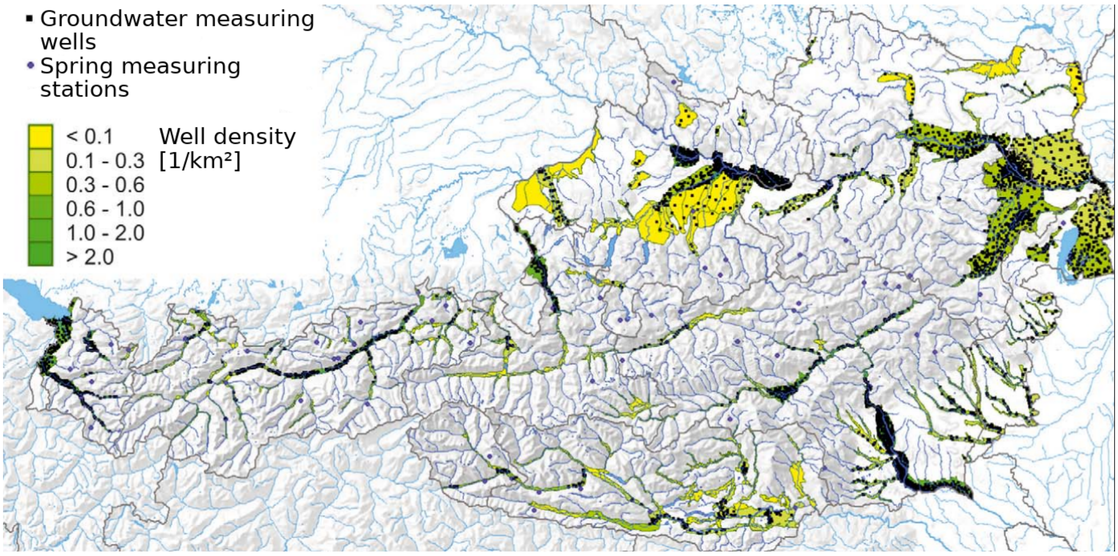

Figure 1.5.: Distribution of the Austrian groundwater measurement stations of the BMFLUW. Translated from Nachtnebel et al. (2014), CC BY-NC 3.0, https://creativecommons.org/licenses/by-nc/3.0/

"first Vienna Mountain Spring Pipeline"), which was put into operation in 1873 (Stadt Wien, 1901; Csendes and Opll, 2006). As the name implies, this first mountain spring pipeline supplied the city with high quality spring water from the karst mountain ranges of Lower Austria and Styria.

In general, this new mountain spring pipeline was considered a great success, especially from a hygienic standpoint and led to the decommission of the previous water supply systems. However, the availability of large amounts of high quality water led to an unforeseen increase in demand, which combined with unforeseen decreases in supply in the cold winter months forced the city to again seek improved water supply (Stadt Wien, 1901, 1910). This led the city to build some auxiliary groundwater supply plants, but most importantly, to the construction of the "II. Kaiser-Franz-Josef-Hochquellenleitung" (nowadays called "zweite Wiener Hochquellenwasserleitung", approx. "second Vienna Mountain Spring Pipeline"), which was put into operation in 1910 (Stadt Wien, 1910). Again, this pipeline supplied the city with spring water from a karst mountain range in Styria, over 100 km away from the city of Vienna.

While there have been various upgrades and extensions, these two mountain spring pipelines are still the backbone of the Vienna water supply, able to cover 100% of the cities drinking water demands under normal conditions (Stadt Wien, 2018). This puts Vienna into a special position. Unlike comparable cities such as Berlin which is exclusively supplied by groundwater (bwb.de, 2018), Viennas dependence on external water supply also externalizes its impact on the natural (groundwater) conditions. Hence it appears likely that the groundwater in the city of Vienna and its vicinity only shows moderate human impacts. However, Csendes and Opll (2006) note that in the period of rising water use after the second world war the mountain spring pipelines capacities have been significantly exceeded, causing further extensions of the pipelines and periods where groundwater from the Viennese vicinity was supplemented. Combined with the fact that there were still about 700 private groundwater wells in use after the second world war (mostly for industry) and that this number increased to about 2000, the picture becomes less clear.

For Austrias other big cities, a quick overview is much harder to obtain than for Vienna. Due to their much smaller sizes, epochal and thus widely known infrastructure means such as the mountain spring pipeline(s) have not been needed. While Austria's second biggest city, Graz, has a history of groundwater exploitation ranging back to 1872 (holding-graz.at, 2018), it was an order of magnitude smaller than Vienna at the beginning of the 20th century (Statistik Austria, 2018c). Still, Graz is among the localities where the longest running groundwater level time series are available.

Other long running time series are various, mostly rural, locations, which have historically been supplied mostly by house wells, and still can have considerable uses of them, up to 30% (Schönbäck et al., 2003; Flamm, 2010), see the paper shown in chapter 4.

This short excursion shall also serve to highlight two issues that can become relevant again with a changing, future climate: While Austria as a whole is expected to keep its status as a water rich country, some areas are likely to face troubles in their water supply, or already have issue in dry summers (Nachtnebel et al., 2014). Not unlike the situation and solution of Vienna in the past, this can be solved by piping in the water from water rich locations. And while it is a generally recognized phenomenon that the water use per head is dropping (see also in the paper shown in chapter 4), there are possibilities that a rising temperature will change this (see e.g. Neunteufel and Richard, 2012). But much more importantly, the current trend of growing cities is expected to continue, not unlike the situation in Vienna at the turn of the 19th to the 20th century, where water use also increased with the population, which might cause a revival of issues long deemed solved (Stadt Wien, 1901; Csendes and Opll, 2006; Örok, 2014; Magistrat Graz, 2015).

1.4.2. Surface water

Though human use of (ground)water for settlements is an important factor for the history of the Austrian groundwater, rivers do play an equally important role for it. While historically, some of the auxiliary supply systems from the early days of the Vienna water supply mentioned in the previous section did tap surface water, mostly from the Danube, nowadays this use does not play a role anymore. There are some cases where groundwater plants draw water infiltrating from a river or operating with artificial aquifer recharge (see e.g. Tischendorf et al., 2008) but unlike many other countries with up to 90% of drinking water sourced directly from surface sources, surface or river water directly plays virtually no role in Austrian drinking water supply (BMLFUW, 2007).

However, in many stretches of Austria, a basins main river has a very good connection to the groundwater, making it the dominating factor in the areas groundwater dynamics (see chapter 3). Thus, changes in a rivers waterlevel, course or *behavior* will reflect in the groundwater. Naturally, many of the rivers in an alpine, water rich country such as Austria should be very dynamic braided or meandering rivers, resulting in an ever changing riverine landscape, as described for example in Hohensinner and Jungwirth (2016) for the Danube close to Vienna. As described therein, in the past, changes in the river also affected the groundwater *landscape* below the surface. Not only did these changes affect groundwater and the topography of the rivers plains, but they also brought with it many administrative and property rights issues and the erosion of infrastructure (Jungwirth et al., 2014). Another, important issue is the rivers role as the source of floodings and thus often death and destruction (Rohr, 2005). Besides these issues, the Danube also has a long history as an important shipping route since medieval times and earlier, for which changes in the rivers course caused issues in navigation.

Thus, the Danube and other rivers have a long history of straightenings, regulations and other alterations, which changed their courses and characteristics. Human activities as early as during medieval times, such as settlements and forest clearances in the flood plains (Jungwirth et al., 2014), certainly did alter the conditions in the floodplain and the river, but "[t]here are hardly any studies on floods in Late Medieval, Early Modern and Modern Austria, except some case studies" (Rohr, 2005), so making any statements about possible artificial changes is beyond the scope of this work. Though Rohr (2005) indicates that technical means of flood protection in the medieval times were limited to placing statues of the protection saint John of Nepomuk along the rivers course.

For more recent times, there are records available for changes due to the use of the Danube as a shipping route, even as early as during Habsburgian times, e.g. the blasting of rapids at what is now Persenbeug in 1777 (Weithmann, 2012), or for alterations for flood control, such as the *regulation* of the Danube at Vienna, which got kickstarted by the the large spring flood in 1862 (Csendes and Opll, 2006). These regulations and modification of the river, however, are not without issues. Besides the ecological impacts of a channelized river, which shall not be the subject of this work, it also leads to changes in the rivers waterlevel. For example natural erosion and the beginning of the Danube "regulation" caused changes in the rivers waterlevel and thus negative measurements, which lead to a recalibration of the gauging stations in 1854 (Hohensinner and Jungwirth, 2016). As shown in the paper in chapter 4, the long term data used herein for the Danube shows a similar behavior, which cannot readily be explained or tied to a known event.

For the special case of the river Danube, the already mentioned role as an important shipping route demands some special, albeit very brief, attention. Following various smaller operations powered by other means, the founding of the *Donaudampfschifffahrts-gesellschaft* (DDSG) in 1829 turned it into a very important waterway and subsequently, the DDSG was the largest inland shipping company of the world at the end of the 19th century and in part continues to operate until this day (Dosch, 2009). This use as a shipping route caused the Danube to be "improved" over time with the removal of underwater obstacles and the deepening and straightening of the shipping lane. Contemporary literature (e.g. Wessely, 1950) lists various spots that need to be "improved" or regulated, since "the upper Danubes [...] incomplete regulations causes capacity limits between 5 - 10 mil tons per year", showing a belief in progress and technical solutions also reflected in projections on the Rhine-Main-Danube Canal (e.g. Kastner, 1973). While these projections proved to be exaggerated and the Rhine-Main-Danube Canal has seen many delays and issues, a current freight rate of 9.6 mil tons (Statistik Austria, 2018b) still makes the Austrian Danube an essential part of the Austrian (transport) economy.

Finally, the Austrian Danube's role as "central European electric power bastion" (Sinclair, 1964) demands some attention. Due to the Austrian topography, the 356 km of the Danube's course in Austria with a height difference of aprox. 160 m, have the same energy potential as do the 1900 km of its lower reach (Veichtlbauer, 2008), which means that there is a considerable history of power plant construction in Austria. First plans to tap this immense energy potential have been made as early as 1909, but due to the technical and financial challenges arising from shipping and sediment load, it took until 1938 for construction of the first run of river powerplant at Ybbs-Persenbeug to start and, due to the second world war, until 1959 to finish it, so that the Jochenstein plant upstream at the German-Austrian border started its operation earlier, in 1956 (Veichtlbauer, 2008; VERBUND AG, 2018). Following these first plants at Ybbs-Persenbeug and Jochenstein, more where brought online in 1964, 1969, 1975, 1976, 1980, 1982, 1985, and 1999 (see also figure 7 in the paper in chapter 4) with drop heights between 8.6 and 15.3 m (mean 11.2 m, total 112.4 m, approx. 73% of total height drop of the Austrian Danube) (VERBUND AG, 2018).

This intense construction activity over time and the following changes and use of the river do have a considerable effect on the Danubes waterlevel, not only in the direct vicinity of the site, but also in considerable up and downstream distances. These effects are twofold: First, there is a waterlevel before and after the construction of the power plant, adding an element of nonstationarity to the waterlevels' development over time and second the behavior of the the rivers' waterlevel changes from a natural one, driven by seasons and rainfall, to a technical one, driven by the demands of power production and flood protection. Besides those large effects on the river itself, there can also be considerable effects on the groundwater, as highlighted by an example on the river Mur in the paper shown in chapter 3.

While the Danube has been highlighted herein, and the river Mur is discussed in Haas and Birk (2017) (see chapter 3), these rivers are of course not the only waterbodies in Austria which have an intense human use for power production. Besides the already mentioned Danube plants and the Mur plants discussed in the paper in chapter 3, Austria's largest operator, Verbund AG, lists 10 further plants at the river Drau, 16 at the river Enns, 5 at the river Inn, 9 at the river Salzach and over 20 on further rivers and streams (VERBUND AG, 2019). Compared to this one, large power provider, the "Verein Kleinwasserkraft", the industry body of the small scale water power providers, lists almost 4000 small scale water power plants (up to 10 MW), distributed all over the country (Verein Kleinwasserkraft, 2019). This kind of small water power plants can reach even the most remote parts of the country, for example by supplying some of the mountaineering huts of the Austrian and German alpine clubs (see e.g. ÖAV, 2019; DAV, 2019).

Another type of hydro power plant that are also affecting the remote parts of the country are storage and pumped storage power plants, for which the large operator Verbund AG lists 15 storage and 6 pumped storage power plants (VERBUND AG, 2019). While many of the alpine valleys that have been flooded by the reservoirs are likely to have had no considerable aquifer body, the reservoirs operation imprints a human footprint not only onto its downstream catchment, but also often onto different catchments that have been tapped to fill the reservoir. Further, the reservoirs do not only affect a limited downstream area. According to Kling et al. (2012) their effects can often be recorded as far as in Danube gauges, which in turn means that they also have the potential to affect large swathes of aquifer.

A rising power demand, for example due to increasing use of *green* electric cars, combined with a general push to reduce GHG emissions, is likely to result in an extension of the worldwide and Austrian hydro power inventory (Zarfl et al., 2015). According to Fuchs et al. (2013), 35,300 GWh/a of the total Austrian hydro power potential of 75,000 GWh/a are already tapped (as of 2012) and about 18,000 (13,000) GWh/a are technically and economically (and environmentally) feasible for a future extension of the Austrian water power inventory. Besides run of river power plants, (pumped) storage power plants will likely be a very important feature of the future, intermittent, power landscape (see e.g. Gurung et al., 2016). Some of these future power demands could be covered by *unconventional* water power plants, such as drinking water power plants or by also using storage ponds for artificial snow production for power production which are deemed to have no additional environmental impacts (Tauber and Mader, 2013; Gurung et al., 2018), but it is likely that there will be new projects that will affect as of yet unaffected streams or stretches of river and thus the connected groundwater bodies.

As has been shown by the 2018 drought in much of Europe, low water levels in large rivers such as the Rhine can affect shipping, and thus many parts of the economy. As indicated by many press reports, 2018 has resulted in an overall 0.2% drop in German economic output, raises in fuel prices, reduction of production at large chemical and steel plants (see e.g. FAZ, 2019; Bloomberg, 2018). While this appears not directly groundwater related, this raises the possibility of a renewed push for river regulations in order to be able to keep operating under drought conditions, which as previously explained will affect the groundwater bodies in the vicinities of the large streams.

In summary, a large part of Austrias groundwater bodies are affected by human use of surface water, ranging from very small operations, such as remote small hydro power plants to very large operations such as the Danube, whose whole course is being used, and thus changed, for shipping and power production. These human uses are ongoing since the 19th century, and it is likely that we are going to see more and different uses in the future.

1.5. Methods

The methodology of all three papers is tied together by two common threads: The use of standardization to make different time series comparable and the use of the python programming language in order to do so. Besides the short overview over the methods used, this section will also delve into on the *big picture* of using (and publishing) reproducible computer code.

1.5.1. Standardization

All three papers make use of standardization of data by employing, or in the case of the SRSI, adapting, existing drought indices, suited to a particular component of the water cycle. Mishra and Singh (2010) give an overview over the various concepts as well as the various indices, "each with its own strengths and weaknesses". Additionally, Svoboda and Fuchs (2016) "cover some of the most commonly used drought indicators/indices that are being applied across drought-prone regions".

These indices include, but are not limited to, widely used *standards* such as the Palmer Drought Severity Index (PDSI, Palmer, 1965), the Standardized Precipitation Index (SPI, McKee et al., 1993) and the more recent Standardized Evapotranspiration Precipitation Index (SPEI, Vicente-Serrano et al., 2010), the Standardized Groundwater Index (SGI, Bloomfield and Marchant, 2013), as well as more specific indices, such as for example the Crop Moisture Index (CMI, Palmer, 1968), Surface Water Supply Index (SWSI, Shafer and Dezman, 1982) or the Soybean Drought Index (SDI, Meyer and Hubbard, 1995).

As the name implies, drought indices mostly do serve to quantify the severity of a drought. Since drought is not only related to a raw meteorological observation such as current precipitation, but also to its relation to the areas average, those raw values can only be used for their respective location. For example a total of 20 mm of rainfall in June could easily be considered a meteorological drought in Graz (average rainfall for June: 118 mm, ZAMG (2019)), whereas for Granada in Spain, the same 20 mm would be considered very wet (average rainfall for June: 11 mm, AEMET (2019)).

Drought indices take these statistical properties of the, in this case precipitation, time series into account and allow for the calculation of a single, location independent number, which can be assigned to certain levels. McKee et al. (1993) for example assigns SPI values from 0 to -0.99 to a mild drought, -1 to -1.49 to a moderate drought, -1.5 to -1.99 to a severe drought and values below -2 to an extreme drought.

However, these indices do not only work for droughts, they also allow to classify wet or flood conditions, on the positive side of their scale. In the case of the related indices SPI, SGI, SRSI and SPEI which are used herein, they offer the additional benefit of working on the same scale (-3 to $+3$), so they make different components of the water cycle comparable. As with the precipitation example above, the raw information about a river stage of 200cm and a groundwater level of 345.7 m a.s.l. makes it impossible to judge their meaning without knowing the local context. However, stating a SRSI of -1.5 for the river and an SGI of -2 for the groundwater not only makes them easily comparable but also allows for a ready assessment of drought conditions in those two bodies of water.

SPI

As mentioned previously, the Standardized Precipitation Index - SPI (McKee et al., 1993) is a widely used index that only needs precipitation data as an input. In order to turn the raw precipitation (in millimeters) into its SPI value, which is essentially a count of how many standard deviations a precipitation event deviates from the mean, the data gets split up into monthly data first, so that the severity of a drought gets judged in comparison to the month it occurs in. I.e. for the example of a precipitation of 20 mm in Graz in June, these 20 mm do get compared to the mean precipitation for the month of June, instead of the mean of the whole dataset, or the mean of the year it occurs in. Besides offering an SPI for a single month, the SPI also tends to be used with various averaging periods, taking into account the fact that precipitation deficits tend to matter not only on a monthly scale but often on longer time scales, such as for example 3 months, 6 months or a full year.

However, it has to be noted that the SPI as used herein assumes a gamma distributed rainfall pattern. According to various authors (e.g. Guttman, 1999; Blain and Meschiatti, 2015) a gamma distribution might not be the most fitting distribution for rainfall patterns in certain regions, indicating that the SPI could need some further input besides raw precipitation data.

SGI

Based on the same principles as the SPI, the Standardized Groundwater Index - SGI (Bloomfield and Marchant, 2013) is a more recent index that turns raw groundwater levels into an SGI value, a count of how many standard deviations a given water level deviates from its monthly mean. Unlike the SPI, which assumes a gamma distribution, and is criticized for this, the SGI uses a non-parametric normal scores transform, which can accommodate the many different probability distributions that might occur in groundwater level data. Another difference to the SPI is that the SGI generally is not used for data averaged over certain periods, since groundwater by its very nature is already a signal that has been accumulated over a long time scale.

SRSI

Since the SGI works independent of the underlying probability distribution of the data it can also be applied to river stages in order to provide a standardized value for those. In order to fit with the naming convention of the other indices, Haas and Birk (2017) has introduced the name Standardized River Stages Index - SRSI for the SGI applied to river stages.

SPEI

The Standardized Precipitation Evaporation Index - SPEI (Vicente-Serrano et al., 2010) works similar as the SPI and SGI, but takes into account two types of raw data: Precipitation data and temperature data. These get used to calculate the potential evapotranspiration and how it differs from the precipitation, "respresent[ing] a simple climatic water balance" (Vicente-Serrano et al., 2010), which in turn gets standardized to the same scale as the SPI and SGI.

1.5.2. Data Sources

All three papers mostly use data from `https://ehyd.gv.at`, the official platform for the government operated Austrian groundwater, precipitation and surface water measurement stations. While this data is freely available in the widely used csv file format, the ehyd platform is not yet suited for the automated download and analysis of large amounts of data. Thus, various workarounds around the limitations of the ehyd platform had to be devised. Additionally, the license for the data prohibits re-sharing of the data. While it can be assumed that there will always be a way to access official data, these two points are a hindrance to easy reproducibility and shareability of the work shown herein. The issues of reproducibility and accessibility are discussed in detail in the following sections 1.5.3 and 1.5.5.

Besides the ehyd data, the long term precipitation data from ZAMG HISTALP dataset (http://zamg.ac.at/histalp/index.php, Auer et al. (2007)) was used for Haas and Birk (2019), see chapter 4.

1.5.3. Reproducibility and tools used

In an analysis of "the duke cancer scandal" where a high profile cancer research paper could not be repeated, Fienen and Bakker (2016) argue that a similar incident could also happen in hydrology. In both fields, large datasets undergo various steps of preprocessing, analysis and interpretation mostly done through various graphical user interfaces, so they "can[not] be repeated without going through the same sequence of mouse clicks, menu selections, and entries made in boxes [and] repeating all these steps is tedious, prone to errors, and does not include documentation of interpretations made" (Fienen and Bakker, 2016). Further, these steps tend to be only sparsely described in the resulting publication, which is only focused on the obtained results. A suggested solution for this is to document the work done, which however is often not feasible with GUI software, hence, the use of scripting languages such as R and python is encouraged.

Unlike *classic* and low level languages such as for example Fortran or C, modern high level languages like python are comparatively easy to learn (see e.g. Millman and Aivazis, 2011; Pérez and Granger, 2007; Oliphant, 2007). Like python, other, similar languages like for example the already mentioned R, MATLAB and GNU Octave/Scilab as well as julia offer similar ease of learning, but python was chosen for various reasons.

Python is a widely used general purpose language, as of 2018 being the third popular language in the TIOBE index (TIOBE software BV, 2018), a fact certainly helped by the availability of a multitude of extension packages, making it suitable for use in fields as diverse as game development or smartphone application development (a complete overview can be found at Python Software Foundation (2018)).

Besides this general uses and usability, python is also widely used in the scientific community. Naturally, there is also a considerable amount of of packages available to help with various aspects of *scientific computing*, ranging from general and widely used base packages such as numpy (van der Walt et al., 2011), pandas (McKinney, 2010) and matplotlib (Hunter, 2007) to fields as diverse such as Biology (see e.g. Cock et al., 2009) or Astronomy (see e.g. Robitaille et al., 2013). Also hydrology and hydrogeology are among the fields python is already used (see e.g. Bakker, 2014) and the flopy module allows to set-up, run and automate modflow models in a python environment (Langevin, 2013; Bakker et al., 2013; Bakker, 2014; Bakker et al., 2016).

Looking into a possible future, sharing scientific papers not in the classic, static *paper* form, but rather in an interactive form is a possibility worth considering. While there are still issues to be discussed - most notably, making sure that old papers remain readable and runable - interactive notebooks where executable code and its interpreted results are embedded into a text document are worth mentioning. While there are now multiple languages that can be presented and shared in such a form, jupyter notebooks (formerly ipython notebooks), using the python language are the most popular (Project Jupyter, 2019; Somers, 2018).

While python of course does have weaknesses (e.g. lack of speed being often the issue that's first mentioned), for most uses the benefits do outweigh the weaknesses.

1.5.4. Example for a reproducible MODFLOW model

Generally, hydrogeologic models tend to be discussed and published only as results, lacking a way for an interested researcher to reproduce it. Even when the model files are available, they tend to be large, sparsely documented and often tailored to the GUI used, that often requires considerable financial and timely investment to obtain and master. While python and flopy do of course also require time to familiarize oneself with them, they are free and open source software. The jupyter notebook provided in the appendix, shows a very simple example of a modflow model, using the python package flopy. As discussed in the previous section, this jupyter notebook, if shared in an executable form and not as a printed paper or pdf, would be immediately runable as is. So a reader would not only be presented with the discussion of the result of the provided model, but he or she could also execute the provided model to ratify the provided results and make changes to the scenario to directly use the model to test their own ideas or observations.

The model in the appendix is a 2D model, showing how the flood induced waterlevel in an aquifer will get affected by zones of different conductivity or different aquifer bottom geometries. In order to highlight the differences between these three scenarios, it runs the same (aside from the modifications that are to be investigated) model 3 times and then plots those three results into one figure, which is produced for every time step in the model and then turned into an animated movie. While all of this is certainly possible with a conventional, GUI based modeling software, it requires much more undocumented *click work* and sharing a reproducible example is much harder. Going from this easy example to a more realistic scenario, the work needed to share a GUI based model grows considerably, whereas the flopy based model still only requires the same amount of files and information.

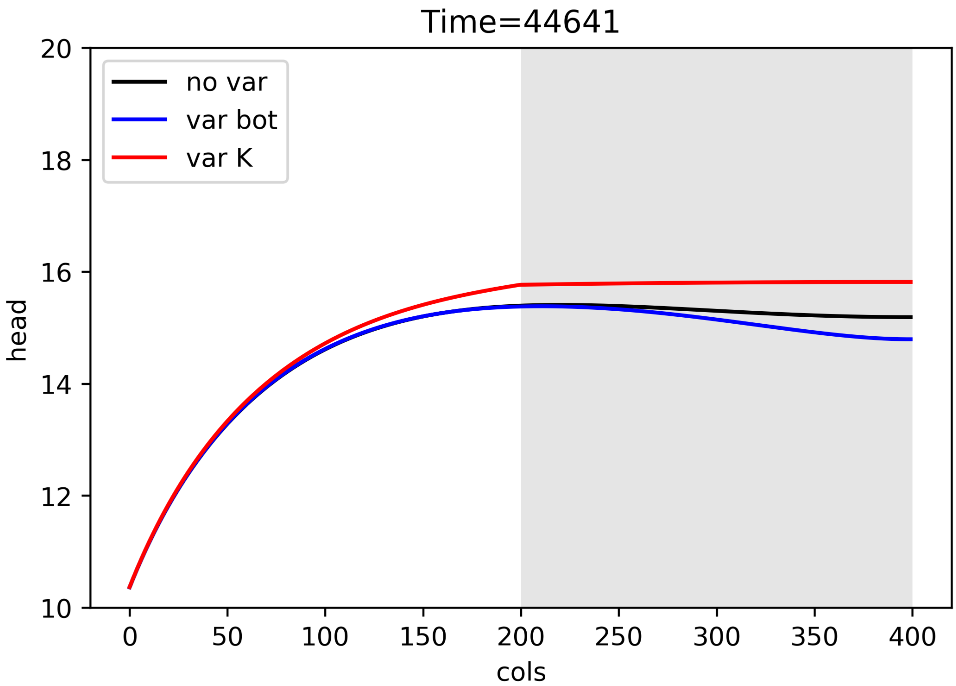

Figure 1.6.: Waterlevel in the model aquifer, approx. 12 hours after a 20m flood passed through the river at its left hand side, highlighting the differences in groundwater level in an uniform aquifer (black line), an aquifer with a higher conductivity in its right half (red line) and an aquifer with a ramp like bottom in its right half (blue line).

Model output

One way to show the results of a model run, would be to plot the waterlevel at a certain time as a contour map for a 3D model, or as a crosssection in a 2D case, as shown in figure 1.6. Conventionally, figure 1.6 would be discussed in a textual form and this approach can (and should) also be repeated in a jupyter notebook. While it is valid for an author to select certain scenarios or times to prove a point, it often can be very helpful for a reader to see more times or scenarios, in order to understand or verify some findings. With a conventional paper, this can quickly use a lot of space, but even then, there is likely only a selection of scenarios shown, that have been picked by the author.

With a jupyter notebook, it is possible to prepare a model in such a way, that much more output can be produced, if so desired by the reader, and care can be taken that key assumptions by the author can be changed.

1.5.5. Data accessibility

Another part of being able to reproduce a paper's results, is the ability to access the data used. While probably not fitting with today's data protection standards (it contains the full names and addresses of the deceased), Snow (1855) shows an early example of shipping the data with the paper. In assessing the spread and possible causes of the cholera epidemic, he not only describes his cases in a textual form, he also lists the full amount of used data in the appendix. However, for most modern data, measured in Gigabytes or even Terrabytes, instead of pages, such an approach is not feasible. For modern data, immutable data archives are probably the way forward. However, licensing and property issues are often not yet solved. For example in the three papers that make up the majority of this work, public data is used. While this data is openly accessible, and can be used by everyone, it is (as of this writing) only accessible in a less than ideal way, by only being available on the ehyd.gv.at website through a GUI, instead of having an API for bulk downloads. Also, the website stipulates that one is not allowed to (re)share data downloaded from it, so for now, sharing the data used was not possible. However, assuming that the Austrian government will keep the data openly available and will keep the same scheme of data catalogization in use, a description as used in Haas and Birk (2017) should enable an interested reader to obtain the data:

"The “HZB” numbers and names given in the Supplement should enable the reader to use the ehyd website described in Sect. 2.1 to obtain the data set used herein. Due to the ongoing efforts towards open data and the fact that the ehyd website is government operated and the data shown therein is government sourced, we are confident that this data source will persist or that a future successor system for ehyd will enable open access to the same data. Alternatively, the responsible government agency should be able to provide the data listed in the Supplement upon request."

1.6. Conclusions and Outlook

As stated at the beginning of this introduction, this work aims to provide insights into the still underrepresented interaction between climate change and groundwater. In order to do so, and with a focus on Austria, work is presented on the effects of the already changing regime of floods and droughts and on indirect climate effects, namely human alterations of surface waters and human use of groundwater as water supply. Besides this, a further focus is on making different regions and types of data comparable and on making results reproducible.

This has been supplemented in this work with a closer look at humans use of, and impact on, groundwater and rivers as well as an introduction into reproducible and shareable groundwater models with flopy.

1.6.1. Scientific findings

Extreme events which are expected to increase under climate change have a particular effect on groundwater. While floods tend to be short term and localized, droughts are long term events that affect large regions. Thus, flood conditions tend to force differing behaviors onto an aquifer body, whereas a drought tends to cause groundwater levels, surface water levels and precipitation to fall in unison. Haas and Birk (2017) shows an increase of drought events for this millennium in precipitation for all of the Styrian Mur catchment and an increase of drought events in groundwater for the lowland parts of the catchment. However, on average, this appears to be partly offset by a similar increase in flood events for the same time span. Looking at the whole of the province of Styria, or even the whole of Austria (Haas and Birk, 2019), there even appears to be a general increasing trend in all parts of the water cycle from the 1980s, as opposed to generally falling trends before this. Besides possible effects of climate change, this also points towards the link between the human use of groundwater and groundwater levels. As shown in Haas and Birk (2019), the change from a generally falling trend towards a rising one falls into the 1980s, a period in time where human water use changed from an increasing trend towards a decreasing one, offering a simple explanation for a country such as Austria which sources its water predominantly from groundwater.

However, since surface water and precipitation show similar trajectories, a causal link with water use is not that clear. Furthermore, the complicated history of Austria's groundwater use, as shown in some more detail in section 1.4, also leaves some questions. And finally, future water use under climate change is a topic that warrants closer scrutiny.

Additionally, Haas and Birk (2017), see chapter 3, takes a closer look at the catchment of the river Mur, in the greater vicinity of Graz, delving into river-groundwater interaction and thus human impacts and the concept of non-stationarity. It is shown that a river used for power production, such as the river Mur can introduce a strong, human signal onto its connected groundwater bodies, adding an element of non-stationarity to groundwater levels. While not relevant for the river Mur, Austrias large stream, the Danube has a considerable history of shipping use (see section 1.4.2), which adds another human dimension to its levels, possibly affecting very large stretches of Austrian groundwater.

Thus, the work described herein opens many avenues for further work. Besides striving and encouraging to publish open and reproducible science, the timely development of groundwater levels and human impacts on groundwater are areas that warrant closer attention.

The impact of climate change on groundwater is still underrepresented in climate research (as highlighted in section 1.3) and offers many fields for new work. Especially the apparent increases shown in Haas and Birk (2019) and the tendency towards more extreme events (Haas and Birk, 2017) warrant closer attention. While both cases highlight strong correlations and offer plausible explanations, they have not yet proven causations.

Besides a direct impact of climate (change) on groundwater, indirect impacts by changes in human use are posing many questions: How will the desired switch to green energy and thus more hydro power affect rivers and thus the many groundwater bodies connected to rivers? Will water savings continue or will increasing temperatures cause an increase in water use? Will Austria be able to simply *outsource* the water supply for dry areas to wetter areas of the country? How will a trend towards urbanisation affect water use and water supply?

1.6.2. Methodology

As shown in Haas and Birk (2019), see chapter 4, standardization of data allows for a ready comparison of different types of data from differing locations. While the timely development of the dataset holds some pitfalls, the findings of said paper are found to be statistically valid. The approach of averaging a large number of data for a region, combined with the "innovative trend analysis method" of Şen (2012) provides a novel insight into the development of Austrias groundwater bodies, river levels and precipitation amounts. This paper does not only contain a usual methods section with a short verbal description of the means used and references to the publications of these means, it also cites Haas et al. (2018) which not only contains a more thorough description of the methods but also executable python code which serves as the base of most of the analysis done in Haas and Birk (2019).

As described in section 1.5 of this introduction, sharing not only a description of your methods but the executable code for those methods offers multiple benefits and is thus a coming topic not only in hydrogeology but in many other branches of science. While there is not yet a ready standard for this similar to the *classic* scientific article which is published and shared as a physical piece of paper or a standardized pdf file, it is still an approach worth following and forcing. Additionally, the sharing, or rather - lack thereof, of the data used still leaves plenty of room for improvements.

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2. Paper 2

This chapter is published as *Haas, J.C. , Switanek, M. and Birk, S. Analysis of hydrological data with correlation matrices: technical implementation and possible applications* in *Environmental Earth Sciences, 77:310, 2018; doi:10.1007/s12665-018-7469-4doi* under the open-access Creative Commons Attribution 4.0 license.

Abstract

Changing political frameworks in addition to novel and more cost-effective means to investigate the subsurface have led to an increase in the availability of hydrological data. This wealth of data, however, poses new challenges in effectively making use of it. Traditional tools such as spreadsheets or proprietary datalogger software often do not scale easily with a larger amount of available datasets, requiring considerable user interaction. Also, comparing different locations and types of data can be difficult and tedious. Thus, a python script is presented that enables the user to quickly visualize and compare different types of data such as for example groundwater levels or precipitation amounts. This is done by first standardizing the data using different drought indices and, subsequently, visualization of correlation matrices or plots of data on maps. This approach can be used for data quality control (identifying erroneous data, classifying data into different types), data comparison (comparing different types of data, such as groundwater and precipitation; comparing different locations) and to visualize and analyze the development of hydrological data and their correlation patterns over time. Prospects and limitations of the approach are illustrated and discussed using various example applications.

3. Paper 1

This chapter is published as *Haas, J. C. & Birk, S. Characterizing the spatiotemporal variability of groundwater levels of alluvial aquifers in different settings using drought indices* in *Hydrology and Earth System Sciences, 21, 2421-2448, 2017; doi:10.5194/hess-21-2421-2017* under the open-access Creative Commons Attribution 3.0 License.

Abstract

To improve the understanding of 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.

Generally, river stages exhibit the highest correlations with groundwater levels, 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. Similarly, correlations are found to be weaker in years with little snow as compared with those with much snow. This is in agreement with typical aquifer response times over 1 month, suggesting that short events such as floods will not affect much of the aquifer, whereas a long-term event such as a drought or snow-rich winter will.

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.

4. Paper 3

This chapter is published as *Haas, J.C. and Birk, S. Trends in Austrian groundwater – Climate or human impact?* in *Journal of Hydrology: Regional Studies, 22, 100597; doi:10.1016/j.ejrh.2019.100597* and is published under the open access Creative Commons Attribution 4.0 license.

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 Austrias water demands are mostly sourced from groundwater.

A. Jupyter notebook for a modflow model

Example for a jupyter notebook that runs a simple flopy modflow model

How to run this example

In order to run this example, one needs python (3.7) with the numpy, matplotlib and flopy packages as well the jupyter package. As of this writing, the suggested way to obtain python is via the open source anaconda distribution: [https://www.anaconda.com/distribution/#download-section (https://www.anaconda.com/distribution/#download-section)](https://www.anaconda.com/distribution/#download-section).

A full explanation for jupyter notebooks is provided at [https://jupyter-notebook.readthedocs.io/en/stable/index.html (https://jupyter-notebook.readthedocs.io/en/stable/index.html)](https://jupyter-notebook.readthedocs.io/en/stable/index.html). The shortest possible tutorial is to produce a new notebook from the notebook dashboard and to copy the code cells (the grey boxes starting with `In [some number]`) into code cells. Care has to be taken that the indentation survives this copying and pasting. If not, the indentation has to be added by hand, as the python language uses whitespace as a way to structure the program. Following this, the cells can simply be executed by pressing `shift + Enter` in them, in the sequence they occur.

The markdown cells, such as this one, serve as explanation of the code cells.

As mentioned in the *Reproducibility and tools used* section, there is not yet an accepted standard to share executable code with a scientific paper, but jupyter notebooks appear to be a promising solution. However, since a printed, or pdf, document as in this case, cannot contain interactive code, it is shared as a printout from a jupyter notebook, adding the inconvinience of having to copy and paste the code cells (see above).

Model description

The following example is based on the flopy projects tutorial, found at [http://modflowpy.github.io/flopydoc/ (http://modflowpy.github.io/flopydoc/)](http://modflowpy.github.io/flopydoc/). It shows in a 2D model how the flood induced waterlevel in an aquifer will get affected by zones of different conductivity or different aquifer bottom geometries. In order to highlight the differences between these three scenarios, it runs the same (aside from the modifications that are to be investigated) model 3 times and then plots those three results into one figure, which is produced for every time step in the model and then turned into an animated movie. while all of this is certainly possible with a conventional, GUI based modeling software, it requires much more undocumented *click work* and sharing a reproducible example is much harder. Going from this easy example to a more realistic scenario, the work needed to share a GUI based model grows considerably, whereas the flopy based model still only requires the same amount of files and information.

The examples and documentation for flopy mostly use the original modflow variable names, such as `ibound` , `strt` , `perlen` , `nstp` and so on, so the brevity stemming from Modflows Fortran core still survives, which for readers familiar with modflow is an asset, so this nomenclature will mostly be kept. However, for example for an introductory class, one could easily name those variables in more verbose terms, such as for example `head_type` , `starting_head` , `period_length` , `number_of_timesteps` and so on and then simply reassign them (e.g. `strt = starting_head`) where needed, thus introducing modflows naming convention in a slow way, as demonstrated with a few variables in the following code.

While this section cannot serve as an introduction to python, pythons inherent readability should make it possible to follow along. Also, context and descriptions are given between the code parts, something that can also be done when supplying the code in pure text files with the help of comments.

In [2]:
```
import flopy.modflow as fpm  # imports the module
# everything after the "#" character is a comment
# for longer comments, multiple lines are possible
import numpy as np
import matplotlib.pyplot as plt
import flopy.utils.binaryfile as bf
```

As demonstrated, comments can follow after some code, in the same line, or have a line on their own. In this case, most of what would be longer comments is described here in the text, between the parts of the code, whereas short explanations are given as inline comments in the code blocks. The part above serves to highlight the *comment concept* and lists the modules that need to be imported. Following that, the model gets setup:

In [3]:
```
Lx = 100. # model dimenstions
Ly = 10.
ztop = 20.
zbot = 0.
nlay = int(1)
nrow = 1
ncol = 400
cell_x = Lx / ncol  # delr, using own shorthand
cell_y = Ly / nrow  # delc
delv = (ztop - zbot) / nlay
botm = np.linspace(ztop, zbot, nlay + 1)
hk = 1e-3   # [m/s]
vka = 1.
laytyp = 1  # 1 = convertible/unconfined
```

For someone familiar with modflow, most variables should be known; the lesser known ones have been changed or commented to make them easier to understand. It quickly becomes apparent that these few lines allow for a very quick change of the fundamental model parameters, such as the models extent, number of cells or the hydraulic conductivity.

In [4]:
```
ibound = np.ones((nlay, nrow, ncol), dtype=np.int32)
ibound[:, :, -1] = 0
```

These two lines set the models ibound to 1, for variable head and afterwards, the last number in the array gets replaced with -1, setting this cell, the right end of the model, to a no flow boundary.

In [5]:
```
strt = 10. * np.ones((nlay, nrow, ncol), dtype=np.float32)
```

Here, the starting head is set to 10, by filling an array for the model with ones and then multiplying by 10.

In [6]:
```
nper = 3  # Number of model stress periods
day = 24*60*60
perlen = [1, 10*60*60, 10*day]  # An array of the stress period lengths.
nstp = [1, 10, 100] # Number of time steps in each stress period
steady = [True, False, False]
varhead = [10, 20, 10]
```

After the information about the starting heads, the information about the times are set up. In this case, the model runs for three stress periods, the first being steady-state and the rest being transient. In this case, the model runs in meters and seconds (note the value for the hydraulic conductivity in cell 3, but for hydrogeologic problems, days are a more useful time unit. Hence, I set up the `day` variable in cel 6, highlighting the ability to use mathematical operations in defining variables. Finally, the variable head gets set up.

Up to this point, every operation was a standard python operation. The modflow variable names have only been used for consistency with general modflow nomenclature. The `ibound` variable from cell 4 for example is just an ordinary numpy array filled with ones and a single zero `[[[1 1 1 ... 1 1 1 0]]]` , whose only connection to modflow is its name. In order to turn this basic information about the model, into the input files needed to run modflow, flopy needs to be used. As per the import in cell 2, functions from the flopy package start with `fpm.` followed by a shorthand for the modflow file they are supposed to write.

Since this short model shall highlight the ease of comparing different model runs with each other, all of the model setup is packaged inside a function, starting with the `def` in the following cell and containing all the indented code therein.

In [7]:
```
def build_n_run(modelname, K, bottom):
        mf = fpm.Modflow(modelname, exe_name='mf2005')
        dis = fpm.ModflowDis(mf, nlay, nrow, ncol, itmuni=1,
                            delr=cell_x, delc=cell_y,
                            top=ztop, botm=bottom,
                            nper=nper, perlen=perlen,
                            nstp=nstp, steady=steady)
        bas = fpm.ModflowBas(mf, ibound=ibound, strt=strt)
        lpf = fpm.ModflowLpf(mf, hk=K, vka=vka, laytyp=laytyp)
        pcg = fpm.ModflowPcg(mf)
        head = varhead[0]
        boundary_cond0 = hk * (head - zbot) * cell_y
        bound_sp1 = [0, 0, 0, head, boundary_cond0]
        head = varhead[1]
        boundary_cond1 = hk * (head - zbot) * cell_y
        bound_sp2 = [0, 0, 0, head, boundary_cond1]
        head = varhead[2]
        boundary_cond2 = hk * (head - zbot) * cell_y
        bound_sp3 = [0, 0, 0, head, boundary_cond2]
        stress_period_data = {0: bound_sp1, 1: bound_sp2, 2: bound_sp3}
        ghb = fpm.ModflowGhb(mf, stress_period_data=stress_period_data)
        # Output control
        stress_period_data_OC = {}
        for kper in range(nper):
            for kstp in range(nstp[kper]):
                stress_period_data_OC[(kper, kstp)] = ['save head',
                                                    'save drawdown',
                                                    'save budget',
                                                    'print head',
                                                    'print budget']
        save_head_every = 1
        oc = fpm.ModflowOc(mf, stress_period_data=stress_period_data_OC,
                        compact=True)
        # Write the model input files
        mf.write_input()
        # Run the model
        success, mfoutput = mf.run_model(silent=True, pause=False)
```

The above code only prepares the model, by telling what variables are to be used for the various used modflow packages, but no files are written yet. In order to run the function, we need to call it and hand over the variables defined in at the beginning, as done in the following code cell.

In [8]:
```
K = hk
bottom = botm[1:]
modelname = 'no_variables'
build_n_run(modelname, K, bottom)
# Create the headfile
headobj_novar = bf.HeadFile(modelname+'.hds')
```

These five lines just take about 144 ms to run on an ordinary desktop computer, but produce around 1.7 MB of modflow input and output files, for the model with a spatially constant conductivity and a straight aquifer bottom.

In order to be able to compare the effects of different conditions, two more model runs are needed, easily enabled by the packing of the whole model setup into a convenient function. In the following few lines, the variables that are to be changed are set up.

In [9]:
```
#set a variable bottom
leftbot = np.zeros(int(ncol/2))
rightbot = np.linspace(0, int(ztop/2), int(ncol/2))
varbot_list = np.concatenate((leftbot, rightbot), axis=0)
varbot = [[[varbot_list]]]
modelname_bot = 'ramp_bot'
#set a variable K
leftK = np.ones(int(ncol/2))*hk
rightK = np.ones(int(ncol/2))*hk*10
varK = np.concatenate((leftK, rightK), axis=0)
varK = [[[varK]]]
modelname_K = 'right_high_K'
```

After this short setup, it just takes a few lines and very little time to run the model 2 more times, with changed parameters.

In [10]:
```
build_n_run(modelname_bot, hk, varbot)
headobj_bot = bf.HeadFile(modelname_bot+'.hds')
bot_reg = botm[1:]
build_n_run(modelname_K, varK, bot_reg)
headobj_K = bf.HeadFile(modelname_K+'.hds')
```

All in all, this is less than 100 lines of code that results in a well documented modflow model, run for three times under different conditions, that can easily be changed for additional runs.

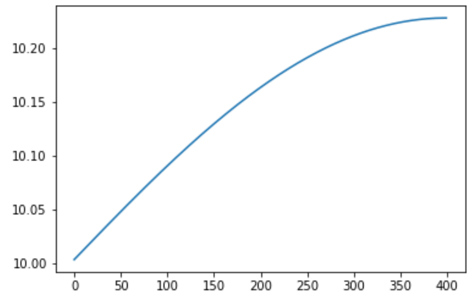
Additionally, it can make sense to provide not only a result for such a model, but also the information about how this result and its interpretation came to be, which is done in the following section.

Model output

One way to show the results of a model run, would be to plot the waterlevel at a certain time as a contour map for a 3D model, or as a crosssection in a 2D case, as shown below. This would be done by extracting the heads for a certain time from the head file (`head_novar = headobj_novar.get_data(totim=252001)`), flattening the resulting array in order to be able to plot it (`head_novar = np.squeeze(head_novar)`) and replacing the `-999` head for the dry last cell with a more fitting number (`head_novar[-1] = head_novar[-2]`) and then plotting it (`plt.plot(head_novar)`):

In [11]:
```
head_novar = headobj_novar.get_data(totim=252001)
head_novar = np.squeeze(head_novar)
head_novar[-1] = head_novar[-2]
plt.plot(head_novar)
```

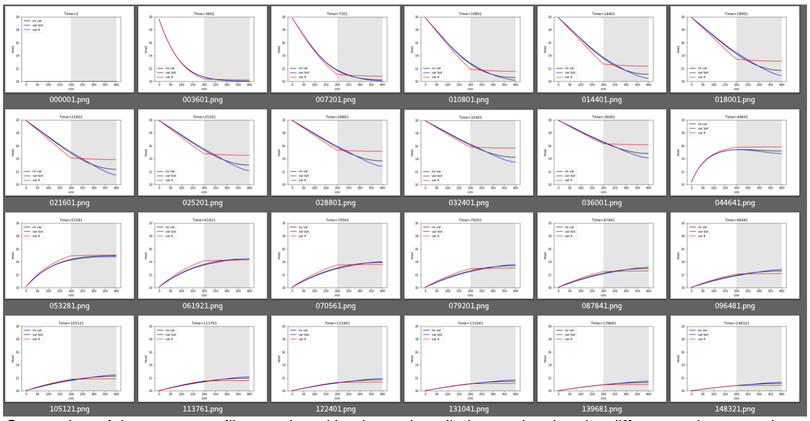
Out[11]: [<matplotlib.lines.Line2D at 0x7f768edfb320>]



However, instead of picking single times manually, for each model and then comparing them, using python enables one not only to automate the model runs, but one can also easily automate the printing. The following code extracts the timesteps from the results and plots a png file with all three head in one figure for every single time step in the model.

In [12]:
```
times = headobj_K.get_times()
for time in times:
    printtime = int(time)
    head_bot = headobj_bot.get_data(totim=time)
    head_K = headobj_K.get_data(totim=time)
    head_novar = headobj_novar.get_data(totim=time)
    h_sq_bot = np.squeeze(head_bot)
    h_sq_K = np.squeeze(head_K)
    h_sq_novar = np.squeeze(head_novar)
    h_sq_bot[-1] = h_sq_bot[-2] # last cell becomes -999 which mangles the plot
    h_sq_K[-1] = h_sq_K[-2]
    h_sq_novar[-1] = h_sq_novar[-2]
    plt.plot(h_sq_novar, color='k', label='no var')
    plt.plot(h_sq_bot, color='b', label='var bot')
    plt.plot(h_sq_K, color='r', label='var K')
    plt.xlabel('cols')
    plt.ylabel('head')
    plt.ylim((10,20))
    ttl = 'Time={0}'.format(printtime)
    plt.title(ttl)
    plt.legend()
    plt.axvspan((ncol/2),(ncol), facecolor='k', alpha=0.1)
    plt.plot((varbot_list), color='m', linestyle='dashed')
    figure = plt.gcf #get the current figure
    figure.figsize=(19,12)
    filename = '{0:06d}.png'.format(printtime)
    plt.savefig(filename, dpi=400)
    plt.close()
```

Unlike the running of the model itself, printing hundreds to thousands (depending on the number of time steps) of png files can be rather slow, but in some circumstances, having an archive of heads for every possible time step can still be very handy.



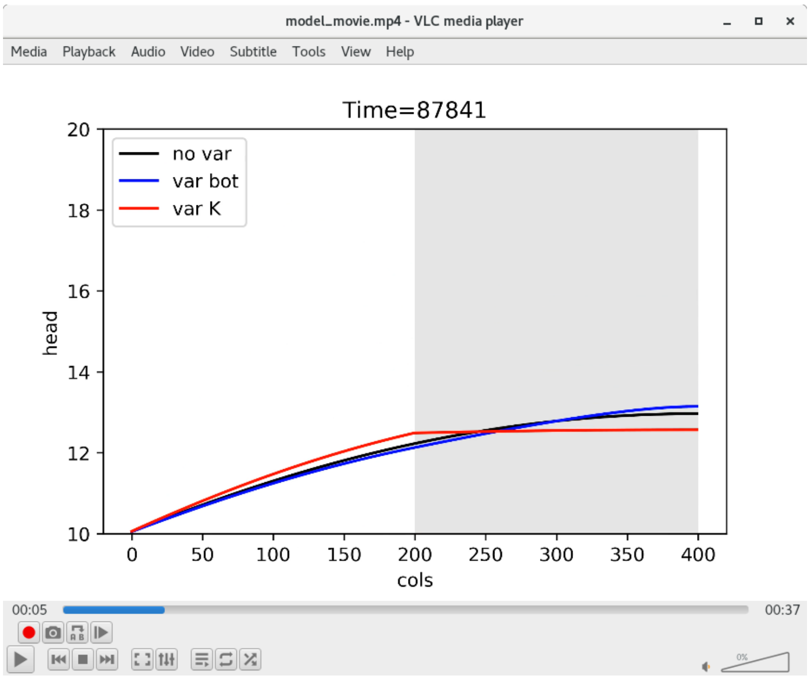
Screenshot of the many png files produced by the code cell above, showing the differences between the three scenarios at each time step.

For example, one could easily use the `ffmpeg` program (see [https://ffmpeg.org/ (https://ffmpeg.org/)](https://ffmpeg.org/)) to turn this series of files into an animated movie, by running `ffmpeg  -framerate 3 -pattern_type glob -i '*.png' -vcodec libx264 -r 24 -pix_fmt yuv420p -tune animation model_movie.mp4` . This, of course, could also be done from within python, by importing the os module first `import os` and putting the external ffmpeg call into a python function `cmd = "ffmpeg  -r 3 ... "` and running it in the python script `os.system(cmd)` , or probably by using one of the various python modules meant for animations or movies.

In [15]:
```
cmd = "ffmpeg  -framerate 3 -pattern_type glob -i '*.png' -vcodec libx264 -r 24
```

In [16]:
```
import os
os.system(cmd)
```

Out[16]: 0



Screenshot of the approx. 0.5MB animation produced by the above code