Shallow groundwater level time series and a groundwater chemistry survey from a boreal headwater catchment, Krycklan, Sweden

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Abstract. ~~Groundwater~~Shallow groundwater can respond quickly to precipitation and is the main ~~contribution~~contributor to streamflow in most catchments in humid, temperate climates. Therefore, it is important to have high spatial and temporal resolution data on groundwater levels and groundwater chemistry to test spatially distributed hydrological models. However, currently, there are few datasets on groundwater levels with a high spatial and temporal resolution because of the large effort required to collect these data. To better understand shallow groundwater dynamics in a boreal headwater catchment, we installed a network of groundwater wells in two areas in the Krycklan catchment in Northern Sweden: a small headwater catchment (3.5 ha, 54 wells) and a hillslope (1 ha, 21 wells). The average ~~wells~~well depth was 274 cm (-range: 70 - 581 cm~~) and~~). We recorded the groundwater level variation at a 10-30 min interval between 18. July 2018 – 1. November 2020. Manual water level measurements (0 - 26 per well) during the ~~summer seasons in~~summers of 2018 and 2019 were used to confirm and re-calibrate the automatic water level ~~logger results.~~measurements. The groundwater level data for each well was carefully processed ~~and quality controlled,~~ using six data quality labels. The absolute and relative positions of the wells were measured with a high-precision GPS and terrestrial laser scanner (TLS) to determine differences in absolute groundwater levels and ~~thus~~calculate groundwater gradients. During the summer of 2019, all wells with sufficient water were sampled once and analyzed for electrical conductivity, pH, absorbance, anion and cation concentrations, as well as ~~δ18O and δ2H. This combined hydrometric and hydrochemical dataset can be useful to test models that simulate groundwater dynamics and to evaluate subsurface hydrological connectivity. We therefore made the data available on https://www.safedeposit.se/projects/82 (Erdbrügger et al., 2022).~~the stable isotopes of hydrogen and oxygen. The data are available at https://doi.org/10.5880/fidgeo.2022.020 (Erdbrügger et al., 2022). This combined hydrometric and hydrochemical dataset can be useful for testing models that simulate groundwater dynamics and evaluating metrics that describe subsurface hydrological connectivity.

1. Introduction

~~In most headwater catchments in temperate climates, streamflow is dominated by groundwater flow, even during rainfall or snowmelt events. In many areas, groundwater is also a major source of solutes~~In most headwater catchments in temperate climates, streamflow during rainfall or snowmelt events is dominated by shallow groundwater flow from unconfined aquifers in the soil or regolith, or groundwater perched above a less permeable layer. Shallow groundwater levels can increase quickly during rainfall or snowmelt events, and can vary considerably over distances of just several meters (van Meerveld et al., 2015; Moore and Thompson, 1996; Myrabø, 1997; Seibert et al., 2003; Tromp-van Meerveld and McDonnell, 2006).

Shallow groundwater is essential for streamflow and stream chemistry in headwater catchments. In many boreal ecosystems, shallow groundwater is also a major source of solutes to streamflow, such as nitrogen (Sponseller et al., 2016), dissolved organic carbon (Buffam et al., 2011; Ploum et al., 2020), or mercury (e.g., Eklöf et al., 2015; Munthe and Hultberg, 2004; Vidon, 2012). An accurate simulation of flow pathways and solute transport requires a good understanding of the groundwater flow directions, which depends on the difference in absolute groundwater levels. In temperate climates, shallow groundwater levels are assumed to be related to topography (Condon and Maxwell, 2015; Haitjema and Mitchell-Bruker, 2005; Tóth, 1962; Winter, 1999), but flow directions can change significantly over time and space. They tend to be more slope-parallel during wet periods with high groundwater levels and more stream-parallel during drier periods (e.g., Rodhe and Seibert, 2011; van Meerveld et al., 2015). The direction can even change from being directed towards the stream to away from the stream (Covino and McGlynn, 2007; Doering et al., 2007; Payn et al., 2009; Simpson and Meixner, 2013; Ward et al., 2013; Yu et al., 2013; Zimmer and McGlynn, 2017).

~~Shallow groundwater levels can increase quickly during rainfall or snowmelt events, and groundwater level dynamics can vary considerably over distances of just several meters (van Meerveld et al., 2015; Moore and Thompson, 1996; Myrabø, 1997; Seibert et al., 2003; Tromp-van Meerveld and McDonnell, 2006), thus~~ Thus, spatial and temporal resolution measurements of groundwater levels can help to improve our understanding of hydrological systems and their functioning. High-resolution groundwater data are also useful to better understand the relation between the depth to groundwater and vegetation (e.g., Bachmair et al., 2012), to test hydrological models (e.g., Jutebring Sterte, 2016) or methods to simulate groundwater levels at unmonitored sites or derived variables. For example, several approaches have been used to quantify hydrological connectivity based on groundwater level data and topography. Rinderer et al. (2019) estimated groundwater levels for unmonitored sites based on the relation between ~~the~~ relative groundwater levels and the topographic wetness index (TWI; Beven and Kirkby, 1979), and Jencso et al. (2009) estimated the duration of hillslope stream connectivity based on the upslope accumulated area. However, due to the lack of high-resolution groundwater level data in both space and time, these approaches have rarely been tested for multiple catchments.

Groundwater level data are often collected by regulatory or environmental management agencies, such
as the SverigeSveriges Geologiska Undersökning (SGU) in Sweden. Although these large datasets
include observations for many groundwater wells, they mainly contain data on groundwater levels in
major aquifers, reflecting the direct societal importance of these aquifers as a water resource. However,
theseThese datasets generally containhave no or only minimal data for shallow unconfined aquifers in
headwater catchments. Furthermore, the spacing of the wells is usually too wide to allow for the
calculation of the groundwater flow directions (but see Fan (2019) and Fan and Schaller (2009), who
used data from these types of datasets to determine the vertical component of groundwater flow across
the US).

Groundwater level data have been collected at a high spatial and temporal resolution infor a few research
catchments (Table 1).(see Table A 1 for an overview). For example, Jencso et al. (2009) continuously
measured groundwater levels in 84 wells across the 17.2 km^2 Tenderfoot Creek Experimental Forest in
Montana, USA, and Rinderer et al. (2014) measured water level dynamics indid so for 51 wells in the
20 ha Studibach catchment in Switzerland. A few other studies took manual measurements at many
wells (e.g., Moore and Thompson, 1996; Myrabø, 1997), or combined manual measurements with data
loggers (e.g., Bonanno et al. 2021). Other studies have collected high spatial resolution groundwater
data for individual hillslopes (for examples see Table 1).Table A 1).

One reason that so few high-spatial and temporal resolution groundwater level datasets exist is the high
cost (both time and money) to install and maintain a dense groundwater monitoring network (see also
Retike et al., 2022). Until a few decades ago, water level sensors with an integrated logger or options
for wireless data transmission were not readily available. This implied that automatic measurements in
multiple groundwater wells required either multiple data loggers, which were rather expensive, or that
sensors were connected to a single data logger by wires, which limited the maximum distancesdistance
between them or caused other problems (e.g., broken cables and an increased the risk of damage by
lightning). Sensors and data loggers were also more expensive then, so that where. Where multiple wells
were availablehad been drilled in a catchment, the groundwater level measurements were mainly often
done by hand, resulting in low temporal resolution data (e.g., Bishop et al., 2011; Seibert et al., 2011;
see also Table 1).(e.g., Bishop et al., 2011; Seibert et al., 2011; see also Table A1).

In addition to recent advances in data logging, there have also been advances in the development of
handheld (but powered) augers (e.g., Gabrielli and Mcdonnell, 2012), which makes it easier to install
multiple wells in a reasonable amount of time. At the same time, drillingDrilling rigs and drilling
services have become more readily available as well. This has made drilling in remote terrain more
practical and the installation ofinstalling a dense well network easier, though it is still costly and time-
consuming (see section 4.2). ToHowever, to calculate flow directions, the elevation of the wells and
their position also need to be known accurately (Rau et al., 2019). While this can be done with traditional
surveying methods, terrestrial LiDAR measurements have made it easier to determine the exact
positionsposition of groundwater wells in the landscape. In summary, recent technological advances in

data logging, drilling, and surveying, have made it easier to collect high-resolution groundwater- level data than was previously possible. However, there are still very few public datasets with high temporal and spatial resolution groundwater data due to the time and effort needed to collect, clean and publish the data (see also Retike et al., 2022).

110 Here, we present a unique dataset with two years of groundwater level data for 54 wells in a 3.5 ha headwater catchment and 20 wells in a 1 ha study area within the Krycklan catchment in Northern Sweden, where streamflow. Streamflow in this catchment is dominated by shallow groundwater flow (Laudon et al., 2013, 2021). The shallow aquifer in the study catchment consists primarily of till that is relatively uniform in its lateral extent. Long-term data for precipitation and streamflow make the two
115 years of groundwater measurements even more helpful for model testing purposes. In addition to the groundwater level data, we also present the results of a sampling campaign during the summer of 2019 to determine the spatial variability in groundwater chemistry. GroundwaterShallow groundwater chemistry can be highly spatially variable across headwater catchments (e.g., Kiewiet et al., 2019; Penna and van Meerveld, 2019) and are helpful to. Groundwater chemistry data help study groundwater flow
120 pathways and to validate hydrological models or nutrient- transport models (e.g., Kolbe et al., 2020). Please see Table 2In this manuscript, we describe the groundwater level and chemistry data (see also Table A 2 for a brief description of the two datasets, the files for each dataset, and the information contained in each file.).

125 Table 1: Selected catchment and hillslope scale studies with a large number of shallow groundwater level measurements and reported well densities (number of wells per hectare).

Reference	Catchment	Recording wells		Manual measurements	
#		#	#/ha	#	#/ha
Catchment studies					
Moore and Thompson (1996)	Malcolm Knapp Research Forest, Canada	-	-	59	15
Myrabø (1997)	Sæternbekken catchment, Norway	4		>100	0.01
Jencso et al. (2009)	Tenderfoot Creek Experimental Forest, Montana, USA	84	0.5	-	
Rodhe and Seibert (2011)	Östfora experimental catchment, Sweden	-		15	0.4
Rinderer et al. (2014)	Studibach catchment, Switzerland	51	2.6		
Bonanno et al. (2021)	Near the Weierbach experimental catchment, Luxembourg.	22	195	14	125
This study	Krycklan catchment (C6, area A), Sweden	54	15	-	
Hillslope studies					
Tromp van Meerveld and McDonnell (2006)	Panola Mountain Research Watershed trenched hillslope	29	29	135	135
Vidon and Smith, (2007), Vidon (2012)	Scott Starling Nature Sanctuary site/Riparian Zone	-		14	2.3
Haught and van Meerveld (2011)	Malcom Knapp Research Forest, Canada	18	819	-	
Bachmair, Weiler and Troch (2012)	Southern Germany	90	4.3	-	
This study	Krycklan catchment (S-transect, area B), Sweden	20	20	-	
Bishop et al. (2011), Seibert et al. (2011)	Gårdsjön Covered Catchment	3	4.8	34	54

Table 2: Name and short description of the datafiles included in the two datasets

Dataset	File names	Short description	Contents described in
1	Krycklan_gw_wells.csv	well position (x,y,z), height of correction factors, etc.	Table 4
1	Krycklan_gw_levels.csv	Groundwater levels from manual measurements and loggers, tube above ground, etc.	Table 5
1	TSL_registration_report_[A/B].rtf	TSL scan registration report	Section 3.3
2	Krycklan_gw_sampling.csv	Sampling information for groundwater chemistry	Table 7
2	Krycklan_gw_chemistry.csv	Chemistry data from groundwater sampling	Table 8
2	Field_protocol.csv	Field protocol for sampling of groundwater	Section 5
2	Lab_analysis_description.pdf	Information on the laboratory analyses	Section 5

2. Description of the Study Areas

130 The Krycklan catchment is located in Northern Sweden, about 60 km inland from Umea. The research catchment is used to collect long term data on hydrological, climatic, biogeochemical, and environmental variables (see Laudon *et al.* (2013) and Laudon et al. (2021)).The Krycklan research catchment (6790 ha) is located in Northern Sweden, about 60 km inland from Umeå (64°140N, 19°460E; Figure 1). The region has a cold temperate humid climate, with on average 167 days of persistent snow

135 cover (1981–2020 period)), but this duration has been declining in recent years (Laudon et al., 2021). The mean annual temperature (1981–2010) is 1.8° C; with a mean temperature in January of -9.5 °C and a mean temperature of 14.7 °C in July). The mean annual precipitation is 614 mm/y and the mean annual runoff is 311 mm/y (Laudon et al., 2013, 2021).

The landscape in Krycklan is influenced by the last glaciation, which formed a hilly landscape

140 withconsists of rock outcrops, moraine ridges,pine (Pinus sylvestris) and valleys that have thicker till depositsspruce (Picea abies) forest (87%), and fluvial deposits frommires (9%). The landscape is strongly influenced by the last glaciation 10,000 years ago, which left glacial tills up to ten meters deep overlying the Vindeln rivermetamorphic bedrock. The highest postglacial coastline crosses the study area at an elevation of approximately 257 m above mean sea level (amsl)(Laudon et al., 2021).

145 ~~The two study areas where the wells were installed are located in the core area of the Krycklan research catchment (Figure 1). One area is located in what is called sub-catchment 6 (110 ha) in other studies (e.g. Laudon et al., 2021). This is referred to study area A here.~~). The soils that developed in the till are podzols, except at the base of the slopes where organogenic soils have developed. The soil is thin close to the rock outcrops near the ridges and up to 10 m towards the streams. ~~The other area is located near~~

150 ~~what is called the S-transect in sub-catchment 2 (12 ha). This area is hereafter referred to as area B. The elevation of the study areas ranges from approximately 250-270 m amsl. The landscape consists primarily of pine (Pinus sylvestris) and spruce (Picea abies) forest (87%) and mires (9%). Both study areas are located within the zone that has been protected since 1922 and where forestry activities were limited. However, the area was subject to ditching around the beginning of 1900 (Laudon et al., 2013,~~

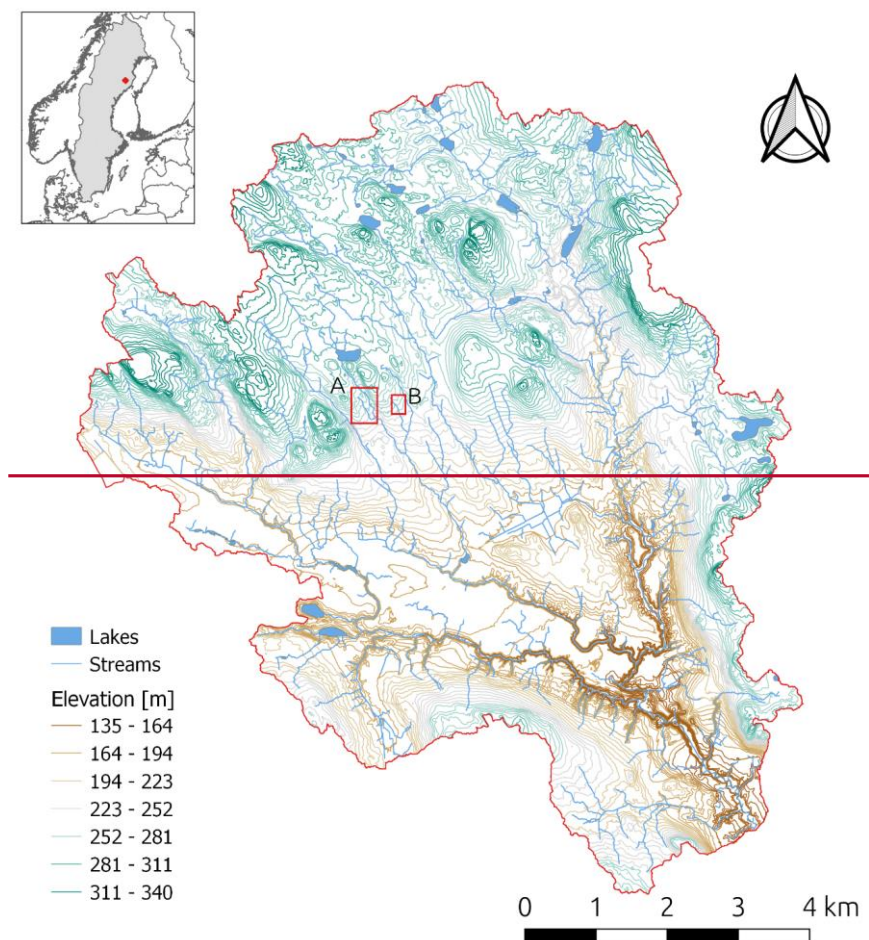
155 ~~2021). The soil in the study areas is comprised of till with occasional clusters of large boulders (see Ivarsson and Johnsson, 1988). The soil is very thin close to rock outcrops near the catchment ridges and up to 6 m towards the streams.~~ The saturated hydraulic conductivity of the soil declines rapidly with depth below the surface (at least for the upper meter of the soil (~~Ameli et al., 2021;~~ Bishop et al., 1990)). The shallow aquifers in the ~~study catchment consist mostly of~~ till ~~that is~~are relatively uniform in ~~its~~

160 lateral extent. The groundwater tables are generally shallow (< 6 m from the surface~~,~~ and in most locations < 2 m).~~~~ Shallow groundwater flow is the main source of streamflow (Ledesma et al., 2018; Lyon et al., 2012) and is driven by the topography (Leach et al., 2017; Ploum et al., 2020). About 15 m to 20 m below the water table, the water age increases by several decades (Kolbe et al. ~~(.,~~ 2020) ~~found that just below the water table, the water age suddenly seems to increase by several decades.~~. More

165 information on the soils, geomorphology, geology, and hydrology of the Krycklan catchment can be found in Laudon et al., (2013), Ivarsson and Johnson (1988) and Ivarsson (2007).

The wells described in this manuscript are located in two study areas in the core area of the Krycklan research catchment (Figure 1). One area is located in what is called sub-catchment 6 (110 ha) in other studies (e.g., Laudon et al., 2021). This is referred to as study area A here. The other area is located near

170 what is called the S-transect in sub-catchment 2 (12 ha). This area is, hereafter, referred to as area B. The elevation of the study areas ranges from approximately 250-270 m amsl. Both study areas are located within the zone that has been protected since 1922. Forestry activities have been limited in these areas, but the areas were subject to ditching at the beginning of the 1900s (Laudon et al., 2013, 2021). ~~A particular advantage of obtaining high density and high resolution groundwater data in the Krycklan~~

175 ~~catchment is the abundance of other data (e.g., precipitation, streamflow, vegetation, soil, etc.; Laudon et al., 2021, 2013), as well as atmospheric data from the Integrated Carbon Observatory System (ICOS) Svartberget station (ICOS, 2021), which is located close (<500 m) to the study areas.~~

A particular advantage of obtaining high spatial and temporal resolution groundwater data in the Krycklan catchment is the abundance of other hydrometric data (e.g., precipitation, streamflow since 1981), vegetation, and soil data (Laudon et al., 2021, 2013). This includes atmospheric data since 2011 from the Integrated Carbon Observatory System (ICOS) Svartberget station (ICOS, 2021), which is located close (<500 m) from the study areas. Long-term soil and groundwater chemistry data are available for 16 groundwater wells (2 m - 12 m) since 1989 (4 wells) and 2012 (16 wells) (Laudon et al., 2013).

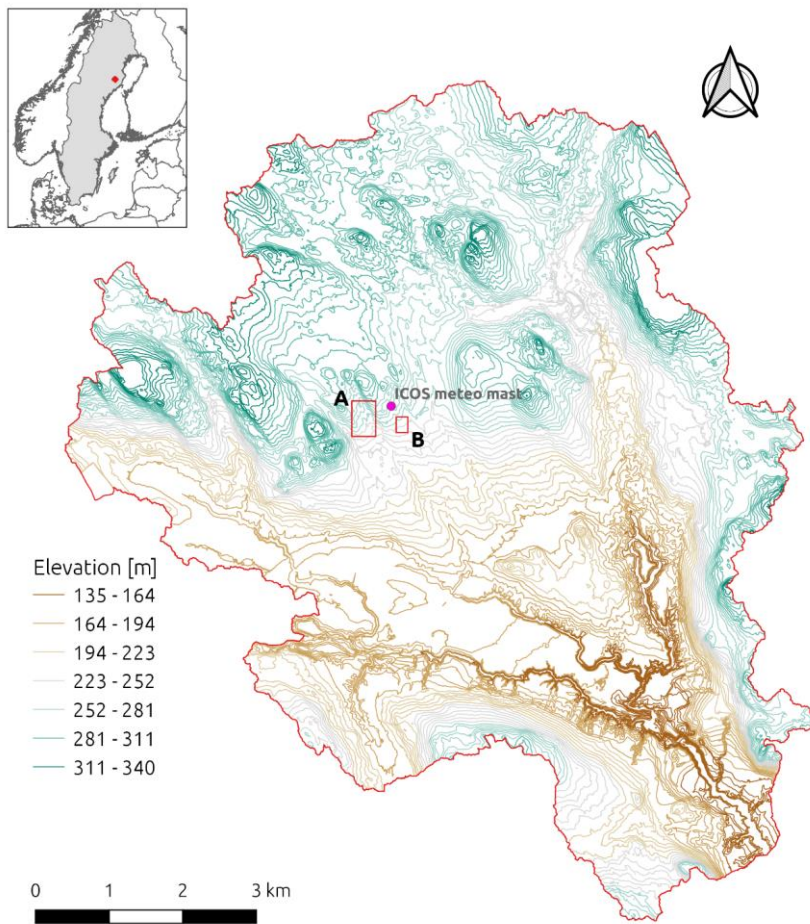



Figure 1: The Krycklan catchment and ~~and~~ the location of the two study areas (red squares, A (in C6) and B (~~s~~S-transect in C2)) with the networks of groundwater wells. **The location of the ICOS station is marked by a point (north of area B).** The inset shows the location in of the Krycklan catchment in Northern Sweden. See Figure 2 for a more detailed map of the study areas. **Datum: Swerref99 TM, EPSG 3006.**

3. Groundwater wells

3.1 Well network design

The locations for the wells were chosen based on the LiDAR-derived digital elevation model (DEM), with a closer well spacing in areas where we either expected very stable or very variable flow directions/gradients (Erdbrügger et al., 2021). To ~~determine~~allow determining groundwater gradients (i.e., flow directions), the wells were located in triangles of different sizes: 5 m, 10 m and 20 m (Figure 2). In the field, the planned positions of the wells were identified with a handheld GPS, and the help of elevation and vegetation maps. Not all wells could be installed as planned. For some locations, the

200   position had to be adjusted due to the presence of trees and big boulders. In addition, the access
       ~~required~~requirements for the drill rig (see section 3.2) meant that the location of some of the wells had
       to be moved. However, in most cases, the wells could be installed within 5 m of the pre-determined
       positions based on the DEM.

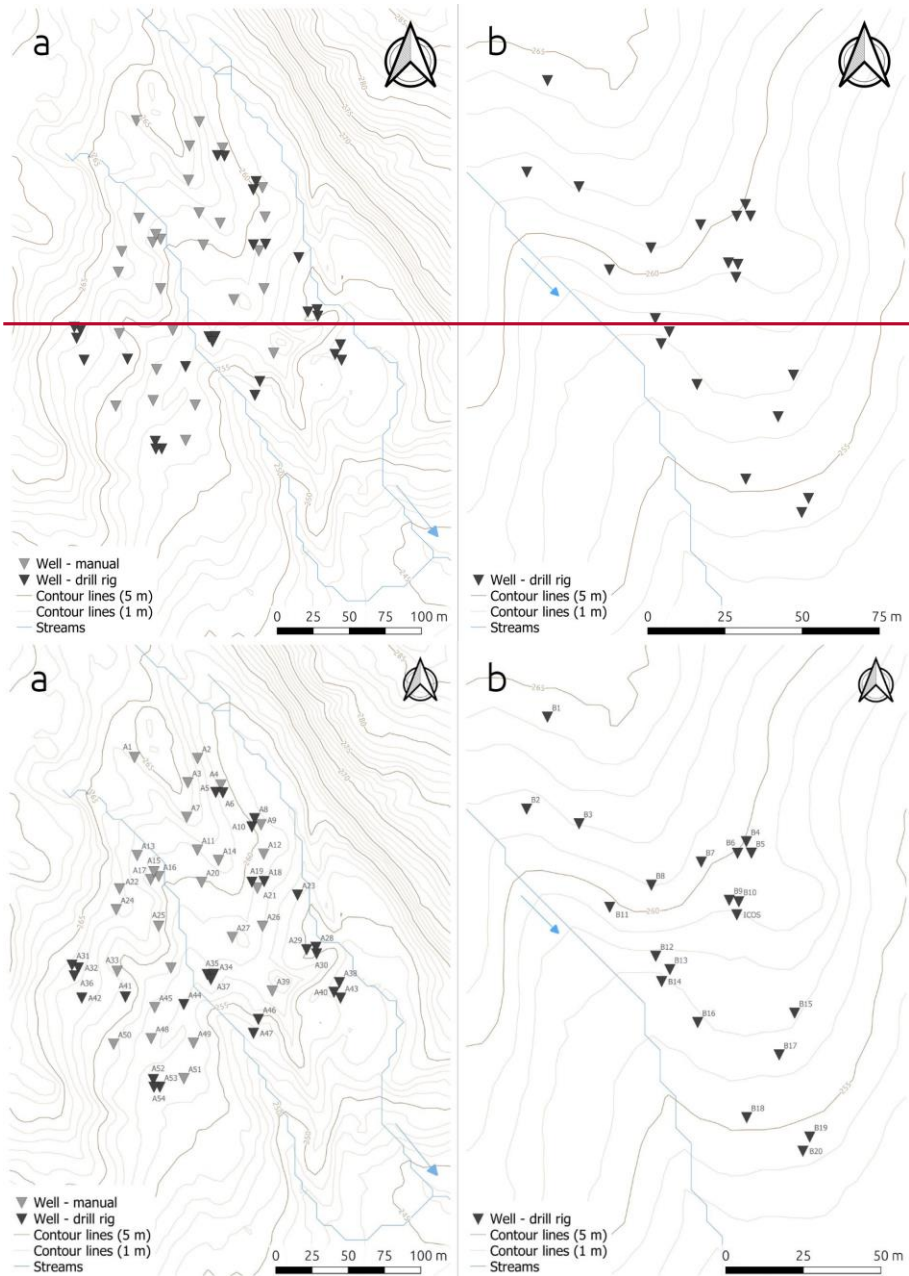



Figure 2: Maps of the two study areas (A (a) and B (b)) with the location of the 75 wells (triangles) that were either augured by hand (manual, in light gray) or installed by the drill rig (~~in black).~~dark gray). The letters next to each triangle indicate the name of the well. See Figure 1 for the location of the two study areas within the Krycklan catchment.

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3.2 Well installation

We installed 27 wells with a Cobra™ Petrol-Driven Drill and Breaker between May and October 2018 (all in area A) and 48 wells (27 in area A and 21 in area B) with a drill rig between February and March 2019 ~~(see~~(Figure 2 and Figure 3). The drill rig was ~~only~~ used in winter, when the ground was frozen and

215 covered by a thick snowpack, to minimize the impact of the heavy machinery on soil and vegetation. The wells consist of fully screened PVC pipes with an outer diameter of 5.0 cm and an inner diameter of 3.7 cm. A filter sock was placed over the entire screened length of the pipe to limit the entry of particles into the well.

The required well depths were estimated based on the "Depth to Water" index (Murphy et al., 2009)

220 ~~that~~which was calculated based on the DEM but ~~were~~was adjusted based on ~~local~~the groundwater ~~level observations~~levels observed during installation. Many of the wells needed to be deeper than suggested by the index. For the installations during winter, the required depths were based on the groundwater depths measured in the summer. We tried to install the wells at least one meter deeper than the lowest observed groundwater level in nearby wells~~, but in some cases, the~~. The target ~~depths~~depth could not be

225 reached in some cases due to boulders or other obstacles. ~~Some~~As a result, some wells were not sufficiently deep to measure the groundwater level during the driest periods. This was particularly the case for the wells located furthest away from surface water bodies. The average depth of the wells was 274 cm (standard deviation: 113 cm; range: 70 - 581 cm). The depth of the wells installed in summer (with Cobra) was generally less (average 193 cm; range: 57 cm – 386 cm) than for the wells installed in

230 winter with the drill rig (average: 316 cm; range 168 cm – 578 cm).

The height of the top of the wells above the ground (i.e., the stick-up) was measured ~~several times~~ after installation, ~~as well as~~on three occasions in 2018 and two occasions in 2019. A marker on the pipe ensured that ~~the~~this height was always measured on the same side of the pipe. ~~These measurements of the stick-up were used to determine water level below to the ground surface from the absolute levels.~~

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Table 3: Estimated costs for installing the well network

What	Notes	Cost
Well installation with machinery	February-March 2019, drilling company in charge of 52 wells with depths ranging from 2 – 5 m (including installation of fully screened PVC pipes)	~15 500 EUR (~300 EUR per well)
Well installation manually	Summer season 2018, 3 student interns for 3 months (half-time) with Cobra	(~ 5 800 EUR for a new cobra not including well installation equipment, payment of staff depends on local wages)
Water level loggers	Depending on cable length. In total 75 wells equipped Odyssey capacitance water level loggers (Dataflow Systems Ltd, 2021)	~210 EUR per logger
PVC pipe and filter sock	Fully screened PVC groundwater tubes, filter sock, etc.	~10-20 EUR per well

Figure 3: ((a) and (b)) Well installation in winter 2019, picture of an installed well (with ~ 35 cm of pipe above ground), and ((c), (d)) closely positioned wells that form triangles (length of pipe above ground appr. 50 cm in panel (c) and 110 cm in panel (d)). The gray caps were placed over the loggers for protection. The aluminum poles with the red paint next to the wells were used to determine the location of the wells when snow covered the ground.

3.31.1   Well geo-referencing

The position of the wells was determined with a high-precision GPS after installation. All wells were scanned with a terrestrial laser scanner (Trimble TX8) in May 2019 to more accurately determine their vertically and horizontally position relative to each other. About 68 single scans (39 in area A and 29 in area B) were done at a distance of about 20 m. The scan resolution at 30 m from the scanner was one point every 11.3 mm (Drive and Trimble Inc., 2017). The generated point clouds were combined into one large point cloud following the procedure proposed by the Ljungberget Remote Sensing Laboratory at the Swedish University of Agricultural Sciences (Bohlin and Nyström, 2019). The wells were manually identified in the combined point cloud, and the upper end of the tube was taken as the reference point (Figure 4). The relative positions of the wells are given in the Krycklan_gw_wells.csv file. The registration reports are given in the TLS_registration_area[A/B].rtf-files); the full scan data are available via the Krycklan database (Lindgren, 2021).

260 ~~The positions of the well tops were exported as an ESRI shape file. We then used a similarity transformation (only rotations and x and y offsets, no scaling) to georeference the well positions (x and y coordinates only). As orientation points for the similarity transformation, we used the locations of four wells measured in the field with the high precision GPS. Since the scan was already level in the horizontal direction (using the TLS internal leveling), we adjusted the z-offset by the GPS z-position of one of the wells to obtain a general offset for all wells. The procedure was carried out separately for the two study areas (A, B) (Table 3).~~

265 ~~**Figure 4: Example of the point clouds for manually identified wells. The well (on the right and in the foreground on the left), filter sock, and the aluminum pole (in the middle, top cut off) marking the well and surrounding vegetation are clearly visible in the point cloud.**~~

270 ~~We used the elevation of the well top (i.e., top of the PVC pipe) to determine the water level (see sections 4.2 and 4.3).~~ The position of the well tops may have shifted slightly over the measurement period due to freezing and thawing of the ground. Soil heave in the Krycklan catchment can be several centimeters over the frost season (Bergsten et al., 2001). We, however, assume that this effect was minor for the wells (and thus the well tops) because the pipes reached well below the average freeze/thaw line, which is located at -19 cm in the Krycklan catchment (Panneer Selvam et al., 2016). Thus, although the relation

275 of the tube top to the soil surface may have changed slightly over time due to soil heave, as well as trampling, we assume that the relation of the well tops to each other remained the same.

Table 1: Estimated costs for installing the well network

What	Notes	Cost
Well installation with machinery	February-March 2019, drilling company in charge of 52 wells with depths ranging from 2 – 5 m (including installation of fully screened PVC pipes)	~15 500 EUR (~300 EUR per well)
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PVC pipe and filter sock	Fully screened PVC groundwater tubes, filter sock, etc.	~10-20 EUR per well
Water level loggers	Depending on cable length. In total 75 wells equipped Odyssey capacitance water level loggers (Dataflow Systems Ltd, 2021)	~ 210 EUR per logger
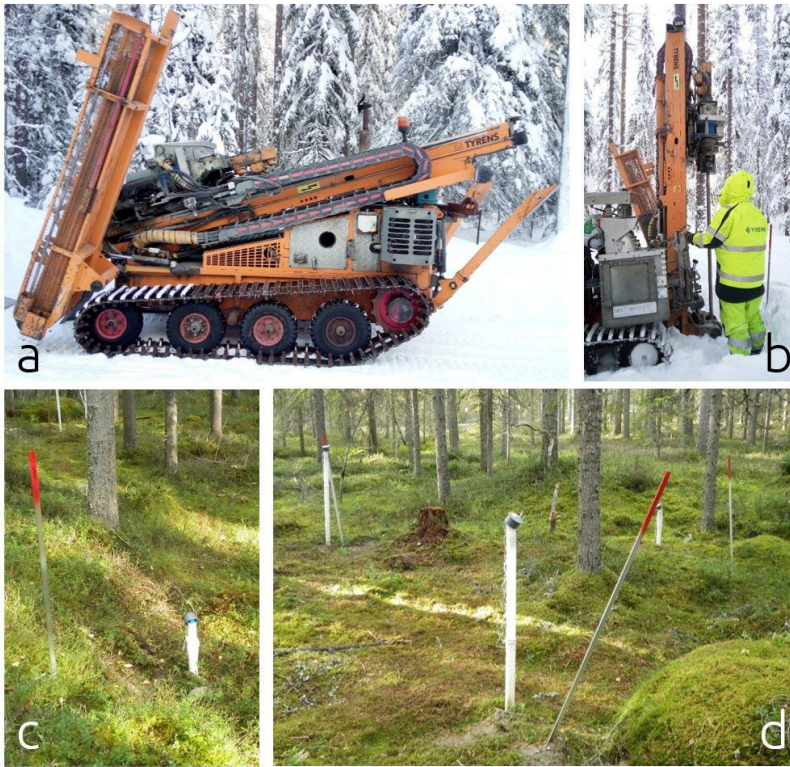
Figure 3: (a) and (b) Well installation in winter 2019, and (c) and (d) pictures of closely positioned wells that form triangles (length of pipe above ground ~ 50 cm in panel (c) and 110 cm in panel (d)). The gray caps were placed over the loggers for protection. The aluminum poles with the red paint next to the wells were used to determine the location of the wells when snow covered the ground.

3.3 Well geo-referencing

After installation, the position of the wells was determined with a high-precision GPS. All wells were scanned with a terrestrial laser scanner (Trimble TX8) in May 2019 to more accurately determine their vertical and horizontal position relative to each other. About 68 single scans (39 in area A and 29 in area B) were done at a distance of about 20 m. The scan resolution at 30 m from the scanner was one point every 11.3 mm (Drive and Trimble Inc., 2017). The generated point clouds were combined into one large point cloud following the procedure proposed by the Ljungberget Remote Sensing Laboratory at the Swedish University of Agricultural Sciences (Bohlin and Nyström, 2019). The wells were manually identified in the combined point cloud, and the upper end of the tube was taken as the reference point (Figure 4). The relative positions of the wells are given in the Krycklan_gw_wells.csv file. The registration reports are given in the 2022-020_Erdbruegger-et-al_TLS_registration_area[A/B].rtf files; the complete scan data are available via the Krycklan database (Lindgren, 2021).

The positions of the well tops were exported as an ESRI shape-file. We then used a similarity transformation (only rotations and x and y offsets, no scaling) to georeference the well positions (x and y coordinates only). As orientation points for the similarity transformation, we used the locations of four wells measured in the field with the high-precision GPS. Since the scan was already level in the horizontal direction (using the TLS internal leveling), we adjusted the z-offset by the GPS z-position of one of the wells to obtain a general offset for all wells. The procedure was carried out separately for the two study areas (A, B) (Table 3).

Figure 4: Example of the point clouds for manually identified wells. The well (on the right and in the foreground on the left), filter sock, and the aluminum pole (in the middle, top cut off) marking the well and surrounding vegetation are clearly visible in the point cloud.

4. Dataset 1: Groundwater levels

4.1 Dataset structure

The groundwater level dataset (Dataset 1) consists of two files. One file (2022-020_Erdbruegger-et-al_Krycklan_gw_wells.csv) provides a description of each well (Table 4) and the other file (2022-020_Erdbruegger-et-al_Krycklan_gw_wells.csv) provides the time series of the actual measurements and the calculated water level in meters above mean sea level (m amsl) for each well (Table 5). See and for the structure of these datafiles, respectively. The measurements and data processing steps to obtain the time series of the groundwater levels are described in the following sections.

Table 4. Structure of the groundwater well location data file (Krycklan_gw_wells.csv) and description of the column names

Column name	Full title	Description
Well	Well_name	Name of well
Well_field	Well field name	Name of the well used in the field originally

X	X-Coordinate	X coordinate [m] as extracted from TLS
		Datum: EPSG:3006 - SWEREF99 TM
Y	Y-Coordinate	Y coordinate [m] as extracted from TLS
		Datum: EPSG:3006 - SWEREF99 TM
Z_abs	Z tube top	Absolute elevation of pipe top above mean sea level extracted from TLS [m amsl]
Depth	Well depth	Depth of the well below the ground surface at the time of installation [m]
intercept	Recalibration offset	Recalibration offset calculated based on the linear regression between the manually measured water levels and the logger derived data, used to correct the logger measurements (only applied correction values)

Table 5 Structure of the groundwater level data file (Krycklan_gw_levels.csv) and description of the column names

Column name	Full title	Description [unit]
Well	Well_name	Name of well
datetime	Date and time	Date and time (CET) of the measurement Format: DD/MM/YYYY hh:mm:ss (no energy saving time)
tube	Length of the pipe above ground	Length of the PVC pipe above the ground [cm] as measured during field season (i.e., stick-up). Values are assumed to remain constant between measurements.
mnl_level	Manual water level	Groundwater level [m amsl], calculated by subtracting the manually measured distance between the water level and the top of the pipe (man_level) from the from the absolute elevation (Z_abs)
Log_level_uncorr	Water level below top of well (uncorrected)	Water level from logger [cm from the top of the tube], calculated based on the logger length and string length (if logger was suspended inside the well). Note that this is the level before the re-calibration with manually measured water levels
Log_level_corr	Absolute water level (corrected)	Water level after correction and subtraction from the absolute elevation (Z_abs) [m amsl]
Class	Data classification	Data point flagging as valid, outlier, recovery, etc. (see Table 6)
Class_mnl	Manual Data classification	Manual data point flagging based on field observations (valid, outlier)

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4.2 Manual water level measurements

The distance between the top of the well and the water level (*man_level*) was manually measured at a weekly to a bi-weekly interval in July, September and October 2018 and between May and September 2019. On average, the depth to the water level could be manually measured 14 times (range: 0-26). For the shallow (< 1 m) groundwater levels, we usually used a bubbler to measure the distance between the top of the well and the water level. ForWhen the water level was deeper wells, we used either a water level plopper ("kluk lod" in Swedish) or an acoustic water level sounder. because the bubbler did not work as well for these conditions. For more detailed information on these manual measurements, see Appendix A.

330

335 The distance to the water level was noted directly in a spreadsheet and on paper for cross-referencing after the fieldwork. These data were screened visually and checked for plausibility. Data points that deviated strongly from the expected range were double-checked based on field notes, meteorological data, and data from nearby wells. Data entries outside the expected range that could not be ~~verified~~confirmed by any other source were classified as outliers. In total, five manual measurements

340 that deviated more than 1 m from the expected value were excluded and are assumed to have been entered incorrectly in the datasheets.

4.3 Continuous water level measurements

4.3.1 Initial logger calibration, installation and maintenance

For the continuous water level measurements, we installed capacitance water level loggers (Dataflow

345 Systems PTY Limited, Christchurch, New Zealand) in 74 wells. The length of the cable of the water level loggers was based on the depth of the well and the ~~estimated~~expected changes in water level. Although we used loggers with different housing lengths and cable lengths, they all function similarly (see Appendix A). The resolution of the sensors is 0.8 mm (Dataflow Systems Ltd, 2021).

All loggers were calibrated according to the instructions provided by the supplier (Dataflow Systems

350 PTY Limited, 2012) prior to field installation. In short, two points (at 20 cm and 140 cm from the lower end of the weight at the end of the cable; see Figure A 1) were marked and the logger was suspended in a sealed PVC pipe filled with water from one of the groundwater wells so that ~~it~~the water reached exactly the mark on the cable. For each position, the raw measurement values were noted after an acclimatization phase of about half a minute or until the values had stabilized. This two-point linear calibration was used

355 to convert the raw sensor values to distances (in cm) above the bottom of the sensor.

The loggers were set to record at a 10 min interval, except in the first measurement week when it was 15 min, and in winter 2018/2019 when it was set to 30 min to avoid filling the memory (and overwriting the data) during the winter period. The data were downloaded three or four times during the field season (May to October). Loggers that did not record any data or only recorded data for part of the ~~time~~period

360 were inspected and usually reinstalled the same day or the following day.

~~For the manual water level measurements, we~~We had to take the loggers out of the wells for the manual water level measurements. We tried to time this so that it would not coincide with the measurements (i.e., we aimed to do this within the 10 min interval between measurements). ~~The~~When the data were being downloaded, the loggers were inspected visually for any disturbances, such as biofilm or dirt on

365 the cable, kinks, or obstructions, and were cleaned when necessary. ~~We~~At this time, we also measured and adjusted the logger string lengths if the groundwater level had fallen, or was expected to fall, below the deepest point of the sensor, or if it was expected to rise above the logger body during snowmelt.

The groundwater level (*Log_level_uncorr*) in cm below the top of the well was calculated by subtracting the water level measured by the logger (in cm from the bottom of the logger weight) from the sum of

370 the length of the logger body, cable and weight length, and string length (see Figure A 1). These water

level time series were inspected manually for incongruences. For five wells, the string length information was accidentally not recorded for all ~~time~~ periods (after adjustments due to very high or very low water levels in the well~~)~~), so ~~that~~ the groundwater level below the top of the well could not be calculated; these data points were marked (*Offset* flag, see section 4.4~~)~~), and can only be used to investigate groundwater level dynamics but not the actual level.

4.3.2 Logger level data correction (re-calibration)

When analyzing the data, it became apparent that there was a systematic offset between the logger data (*Log_level_uncorr*) and the manual measurements (*man_level*) (Figure 5 (a) and (c)), with the logger-based water levels being systematically higher (i.e., closer to the surface) than the manual measurements. In some cases, they were above the surface, although we only observed flooding for two of the wells (i.e., only for these two wells did we expect the water levels to rise above the ground surface at some point in the year). We deemed the manual measurements ~~to be~~ more reliable and assumed that the shift was due to a systematic error in the initial calibration of the loggers or calculation of the ~~logger~~logged water levels. We can exclude pipe length (which would have been an individual error for each well) and string length (the shift also appears for loggers that were not attached to strings) as the source of the systematic error and, therefore, assume that the shift was due to a systematic offset in the calibration of the loggers before field deployment.

We corrected the logger data in a two-step process based on the assumption that we only needed to correct the vertical shift in the logger data. We first determined the linear regression between the manual measurements and logger data, ~~with~~using a slope of ~~1~~one. We then defined points more than 5 cm from ~~our~~this initial linear regression as outliers ~~to account for potential~~caused by errors in the manual water level measurements. After excluding these outliers, we determined ~~the~~a new linear regression between the manual measurements and logger-derived water level data, again with a slope of ~~1~~one, and calculated the offset (see two examples of the correction in Figure 5). The mean value for this correction (i.e., *intercept*) was -9.91 cm (standard deviation: 6.74 cm; range: -28.1 - -0.05 cm). We then used ~~the~~this offset (*intercept*) to correct the logger data. Thus, effectively, we lowered the logger data to match the manual water level measurements. This fixed the issues with the water levels rising above the surface for all wells for which this was not observed. ~~The correction (*intercept*) was only calculated for the wells for which there were at least two valid manual water level measurements (i.e., two points that were not considered outliers after the first step).~~ The data were not corrected for 18 of the 74 wells ~~with loggers~~ because there were ~~insufficient~~less than two valid manual water level measurements to calculate the correction (i.e., *intercept*).

The final absolute groundwater level (*Log_level_corr*; in m asl) was ~~then~~ calculated by adding the correction factor (*intercept*) to the uncorrected logger level (*log_level_uncor*) and the elevation of the well top (*Z_abs*): *Log_level_corr = Z_abs – (Log_level_uncorr+intercept)*.
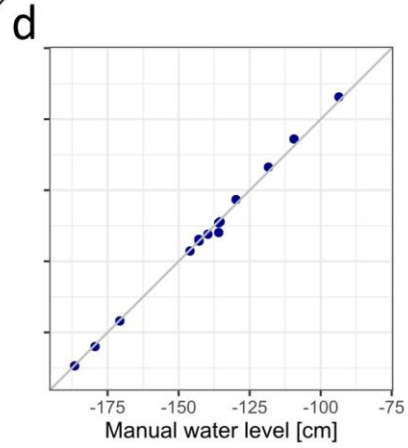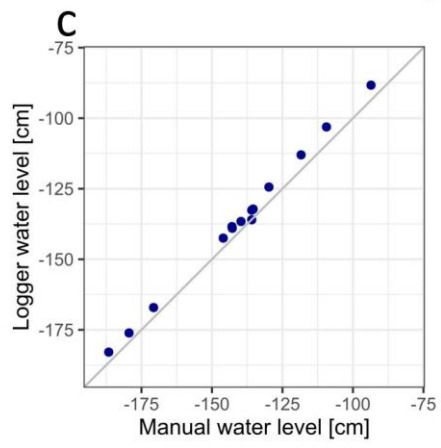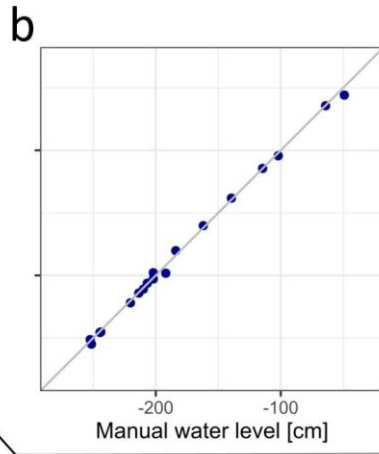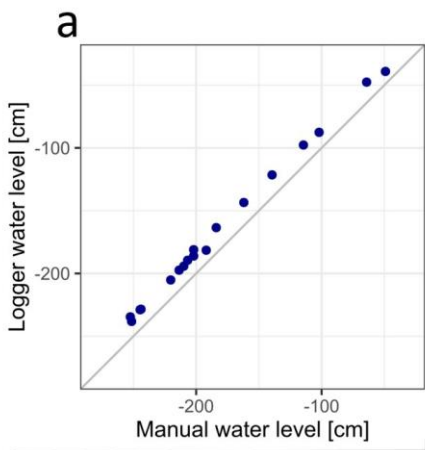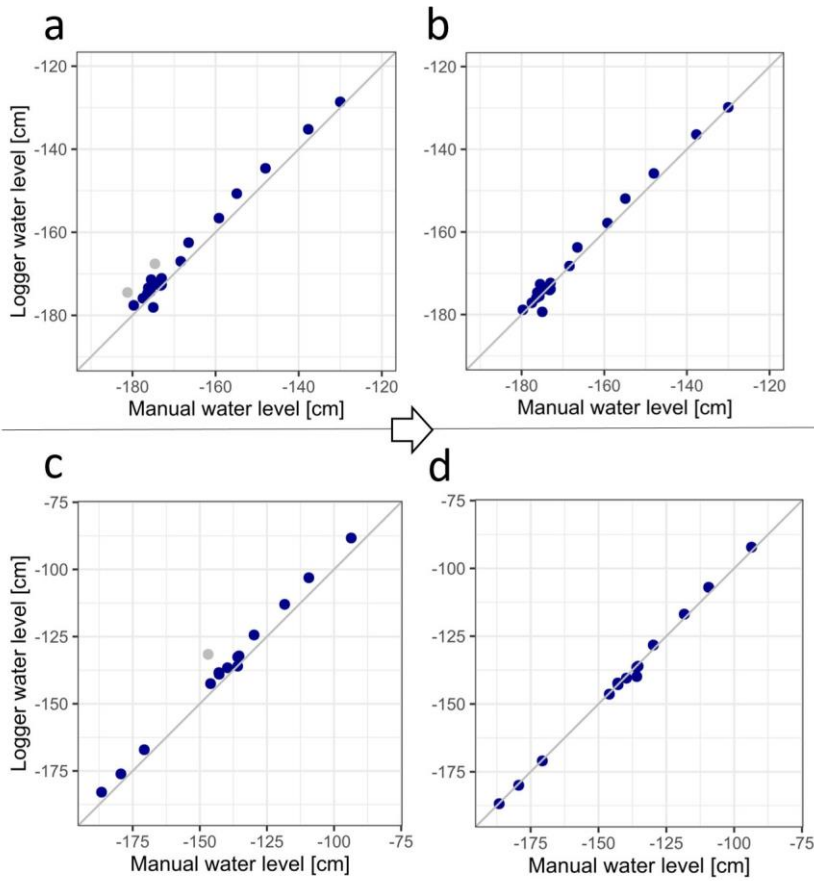
Figure 5: Relation between the manual and logger water level measurements in cm below the top of the well before ((a) and (c)) and after ((b) and (d)) recalibration of the logger for well ~~A12~~A7 ((a) and (b)) and well B18 ((c) and (d)). Manual measurements which were identified as outliers are marked in gray (in (a) and (c)). The correction factor (i.e., intercept) was -~~16.8~~1.2 cm for well ~~A12~~A7 and - 3.9 cm for well B18.

4.4 Data Flagging

~~Observed outliers~~Outliers or discontinuities in the water level time series were classified into six different categories (~~Table 6~~Table A 5;

Figure 6). ~~The~~This flagging allowed us to keep all data points in the record ~~and~~so that they could be re-~~evaluate the classification~~evaluated if necessary.

420 ~~Table 6: Classification of data points~~

~~Class~~	~~Description~~
~~Valid~~	~~No known or apparent reason to indicate that the measurement is not valid. This is the default classification for all data points~~
~~Outlier~~	~~Known outliers (during pumping) and unknown outliers (>10 cm drop in ≤10 min)~~
~~Recovery~~	~~Recovery of water levels after pumping (0-12 h after re-introduction of the logger into the well)~~
~~Censored~~	~~Uncertain values due to low water levels (< 5 cm above logger bottom) or water in lower well ends (lower 5 cm of unscreened pipe)~~
~~Strange~~	~~Snowmelt curve with sudden breaks (probably related to a rapid decrease in the electrical conductivity of the water)~~
~~Offset~~	~~String length or tube length were unknown. The relative changes in water level are correct but the absolute level could not be calculated.~~

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Figure 6: Example of a groundwater time series (well A12, May 2019) affected by two pumping events, with identification of the outliers (black) during the time that the logger was outside the well (while the pumping took place) and the recovery period (green). Water levels below the threshold of 5 cm above the logger end are classified as censored (red).

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To download the loggers, take manual water level measurements, or purge the wells for cleaning and sampling (see description of Dataset 2), the loggers were taken out of the wells. This usually took a short time, and therefore, the loggers were not stopped. Most of the measurements taken during these periods were significantly lower than ~~the measurements~~those taken before or afterwards and are ~~therefore~~consequently classified as *outlier*s. To find these outliers, we used a filter based on the changes in the water levels. Assuming that groundwater levels generally do not drop abruptly (i.e., the recession is smooth), we used a threshold value of a ~~>~~more than 10 cm drop in groundwater level within 10 min to find outliers~~, which~~. These outliers were then manually investigated to ensure correct identification. Data points collected after the re-introduction of the logger into the well after well purging were classified as *recovery* to mark the time of recovery of the water level within the well. To be ~~certain~~sure that equilibrium had been reached, all data points within 12 hours after the re-insertion of the logger to the well were classified as recovery. Where the recovery time appeared to exceed the 12-hour time span, we extended the classification to 24 hours after re-introduction of the logger.

When the groundwater level was close to the weight at the end of the sensor cable, the recorded data often showed sudden jumps, suggesting a low accuracy of the measurements. To eliminate this problem and the problem of standing water in the very bottom of the well (which was not screened), we classified all points that were less than 5 cm above the logger end as *censored*.

For five wells ~~five~~ of the 74 wells (A21, A9, A4, B1, and B6), we observed a continuous drop in the water level between 21.04.2019 and 30.04.2019 (see examples in Figure 7). ~~This was the peak snowmelt period for which we~~We expect the groundwater level to rise, rather than drop~~.~~ for this peak snowmelt period. The start of the drop in the water level differed for the wells, but it ended suddenly for all five wells on 30.04.2019, when the loggers were removed from the wells to download the data. After the re-introduction of the loggers in the wells, the measured water levels were several centimeters higher than before. The logger string or tube lengths were not adjusted during this period and the sudden change in the recorded water level can ~~therefore~~ not be related to errors in these measurements. The wells for which this strange behavior was observed were not located in one region or characterized by a particular topographic position either. These were all located close to other groundwater wells (within ~ 5 m), for which we did not observe such a change. ~~The~~Therefore, the data from these wells during this period are ~~therefore~~ flagged as *strange*.

Because the recorded time series after the re-introduction of the loggers to the well seems to agree with the water levels observed in the days before the sudden drop, we expect that the lowering of Electrical Conductivity (EC) of the water in the wells due to the infiltration of low EC meltwater caused this change. Odyssey water level logger recordings can be sensitive to a large change in EC (Larson and Runyan, 2009). Most probably, the removal of the logger from the well and its re-introduction stirred the water inside the wells and led to ~~a~~the mixing of the snow meltwater and older groundwater. The alternative explanation of a film (biological or other) on the cables does not correspond with our field

notes. Only in two cases was a film observed on the sensor cables, but for these sensors, the logged values seem to be normal during this period.

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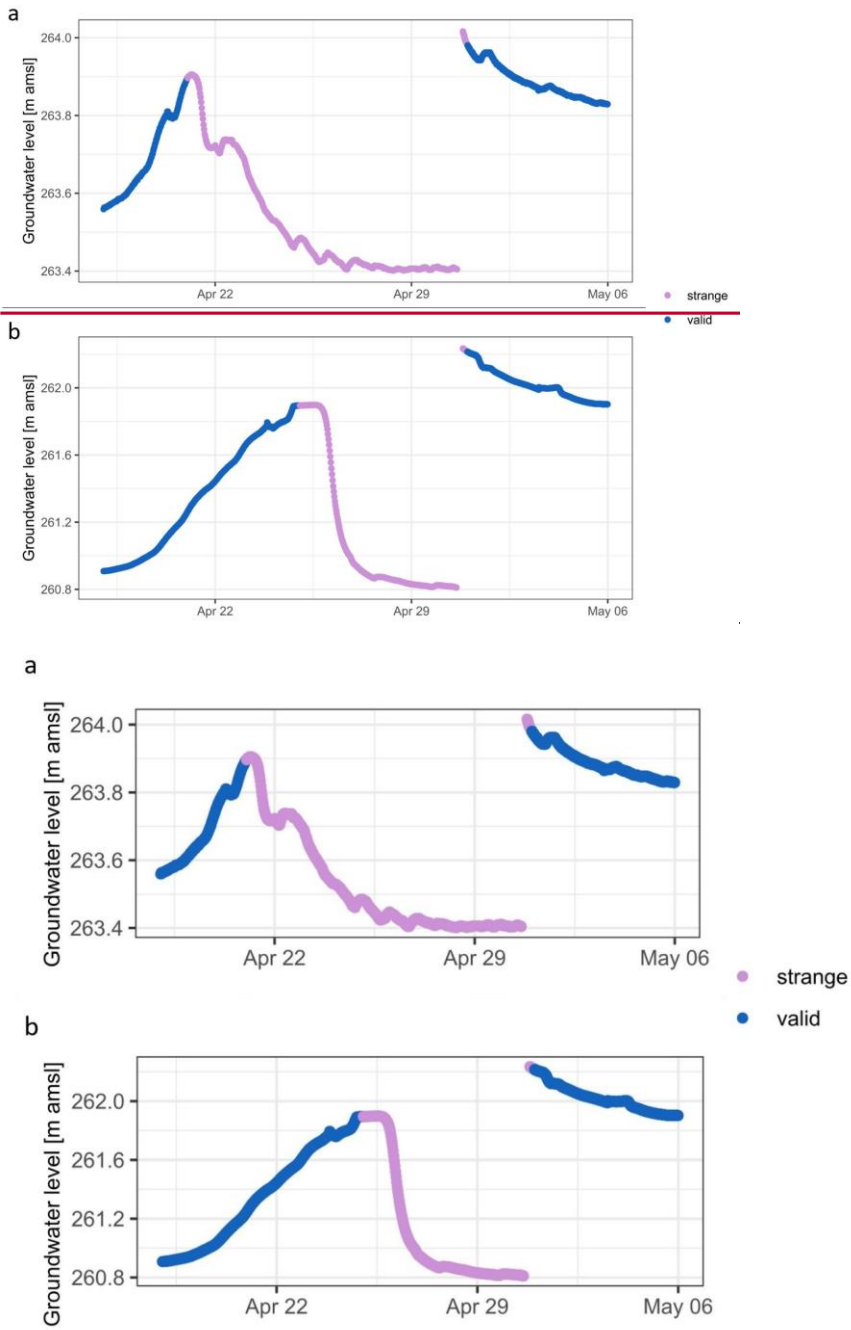
Figure 7: Examples of strange drops in the measured water level during the 2019 spring melt period for two wells (well A4 (a) and well A21 (b)).

5. Dataset 2: Groundwater ~~Chemistry~~chemistry

5.1 Dataset structure

In the summer of 2019, a groundwater sampling campaign was undertaken to obtain spatially distributed information on groundwater chemistry. The resulting groundwater chemistry dataset (Dataset 2) consists of four files. One file (Krycklan_sampling.csv) provides a description of each sample (Table 2) and another one (Krycklan_chemistry.csv) the laboratory results for each sample ~~(Table 8).~~(see Table A 6 for a description of its structure). The third file contains the field protocol (Field_protocol.csv), and the fourth file (Lab_analysis_description.pdf) provides additional details on the laboratory analyses. The sampling and data analyses are described in more detail in the following sections.

Table 2: Description of groundwater sampling data (file: 2022-020_Erdbruegger-et-al_Krycklan_sampling.csv)

Column name	Full title	Description [unit]
Well	Well name	Name of the sampled well
sample	Upper [1] or lower [2] sample within well	Upper (first [1]) or lower (second [2]) sample from well. If only one sample was taken, it was also noted as upper (first [1]) sample
Depth	Depth of sample	Sample depth (midpoint of the sample range, 40 cm)depth,) in absolute elevation [m amsl]
date	Date of sample	Date the sample was taken [DD/MM/YYYY]
sample_num	Sample number	Sample number assigned for SLU laboratory analysis
wl	Water level	Water level measured manually directly before sample extraction [m amsl], corresponds to mnl_level in Dataset 1.
quality	Sample quality	First impression in field of sample quality (turbidity/suspended sediment, air intrusion in sampling tube, etc.) [g] = Good, [d] = Doubtful (possible influence of aeration on the sample), [b] = Bad (influence on of sediment or aeration on the water sample)

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Table 8: Description of groundwater chemistry data (file: Krycklan_chemistry.csv), see Lab_analysis_description.pdf -file for more information on the laboratory analysis.

Column name	Full title or description	[units]
sample_num	Sample number assigned for SLU laboratory analysis	Sample number assigned for SLU laboratory analysis
d18O	$\delta^{18}O$	[‰ relative to VSMOW]
d2H	δ^2H	[‰ relative to VSMOW]
EC	Electrical conductivity EC	[µS/cm]
pH	pH	[-]
EC_field	Electrical conductivity measured in the field	µS/cm]
pH_field	pH measured in the field	[-]
absorb_254	Absorbance at 254 nm	[A/cm]
absorb_365	Absorbance at 365 nm	[A/cm]
absorb_420	Absorbance at 420 nm	[A/cm]
absorb_436	Absorbance at 436 nm	[A/cm]
Flu	Fluoride	[mg/L]
Cl	Chloride	[mg/L]
SSO4	Sulfate SO_4	[mg/L]
PPO4	Phosphate PO_4	[µg/L]
NNH4	Ammonium NH_4	[µg/L]
NNO3	Nitrate NO_3	[µg/L]
Na	Sodium	[mg/L]
NH4	Ammonium	[mg/L]
K	Potassium	[mg/L]
Mg	Magnesium	[mg/L]
Ca	Calcium	[mg/L]

5.2 Well purging prior to sampling

490 To ensure that the water samples were representative of the local groundwater, we did two rounds of purging with a peristaltic pump (see Figure A 2) between the middle and the end of May 2019. The loggers were removed for the duration of the pumping. We measured the depth to the water table prior to purging. During each round, the wells were either pumped dry or a volume of at least three times the

well volume (see Appendix B) was pumped out to ensure full replacement of the well water with "fresh" groundwater. The pumping also removed the sediment and other particles from the wells.

5.35.2   Sampling

The groundwater sampling was done between July 19th and 31st, 2019. Total precipitation during thisthe sampling period in July was relatively low (28.16 mm in total, max. daily precipitation 13.49 mm). The sampling procedure and field protocol used for the campaign followed the Svartberget research station and Swedish University of Agricultural Sciences (SLU) standard procedure for groundwater sampling (see also the Field_protocol.csv file).2022-020_Erdbruegger-et-al_Field_protocol.csv-file). To ensure that the water samples were representative of the local groundwater, we did two rounds of purging with a peristaltic pump (see Figure A 2) between the middle (shortly after peak snowmelt) and the end of May 2019 (when groundwater levels were generally lower than for the first round). During both rounds, the wells were either pumped dry or at least three times the well volume (see Appendix B) was pumped out to ensure full replacement of the well water with "fresh" groundwater. The pumping also removed the sediment and other particles from the wells.

A custom-made straddle packer system with inflatable rubber tubes (see Appendix B, Figure A 3) allowed us to isolate a specific part of the well and sample water from a roughly 25 cm long interval. We aimed to obtain two samples per well: one sample just below the groundwater table (which would correspond to the uppermost portion of the groundwater at the respective location) and another sample from the deepest part of the well. Because many wells were shallow and groundwater levels were low at the end of July, there was insufficient water for two samples for many wells. In these cases, we took only one water sample from the deepest point of the well.

Prior to taking the actual sample, the tubes were flushed with ~2 L of well water to reduce cross-contamination of samples and the sample bottles were rinsed three times to avoid contamination. All bottles were filled to the top, without air bubbles. The pumping was done slowly (regulated manually)Additionally, we measured the electrical conductivity (EC) and pH in the field with a pH/Cond 3320 sensor (Xylem Analytics Germany GmbH). The pumping was done slowly to not draw water from above, allow for recharge, and avoid excessive aeration of the samples. However, in some cases, the recharge of the wells was so slow that even the lowest pumping rate was too high, and the water level in the well dropped, or the well was pumped dry and aeration of the samples took place. When aeration occurred, it was noted in the sampling protocol as a qualitative indication that sample quality might be doubtful (d) or even bad (b) (see Table 2: quality; Sample quality). Prior to taking the actual sample, the tubes were flushed with ~2 L of well water to reduce cross-contamination of samples. The sample bottles were rinsed three times before filling them to the top, without air bubbles. Additionally, we measured

the electrical conductivity (EC) and pH in the field with a pH/Cond 3320 sensor (Xylem Analytics Germany GmbH).

5.45.3   Lab analyses

530   The samples were analyzed for: EC, pH, absorbance at 254 nm, 365 nm, 420 nm, and 436 nm, anion (F, Cl, S-SO$_4$) concentrations, nutrient (P-PO$_4$, N-NH$_4$, N-NO$_3$) concentrations, and stable isotopes (δ^{18}O and δ^2H) in the laboratory of SLU, Sweden. The cation (Na, NH$_4$, K, Mg, Ca) concentrations were analyzed at the Hydrogeological Laboratory of the TU Bergakademie Freiberg, Germany. A detailed description of the lab procedures is given in the file: 2022-020_Erdbruegger-et-535   al_Lab_analysis_description.docx.

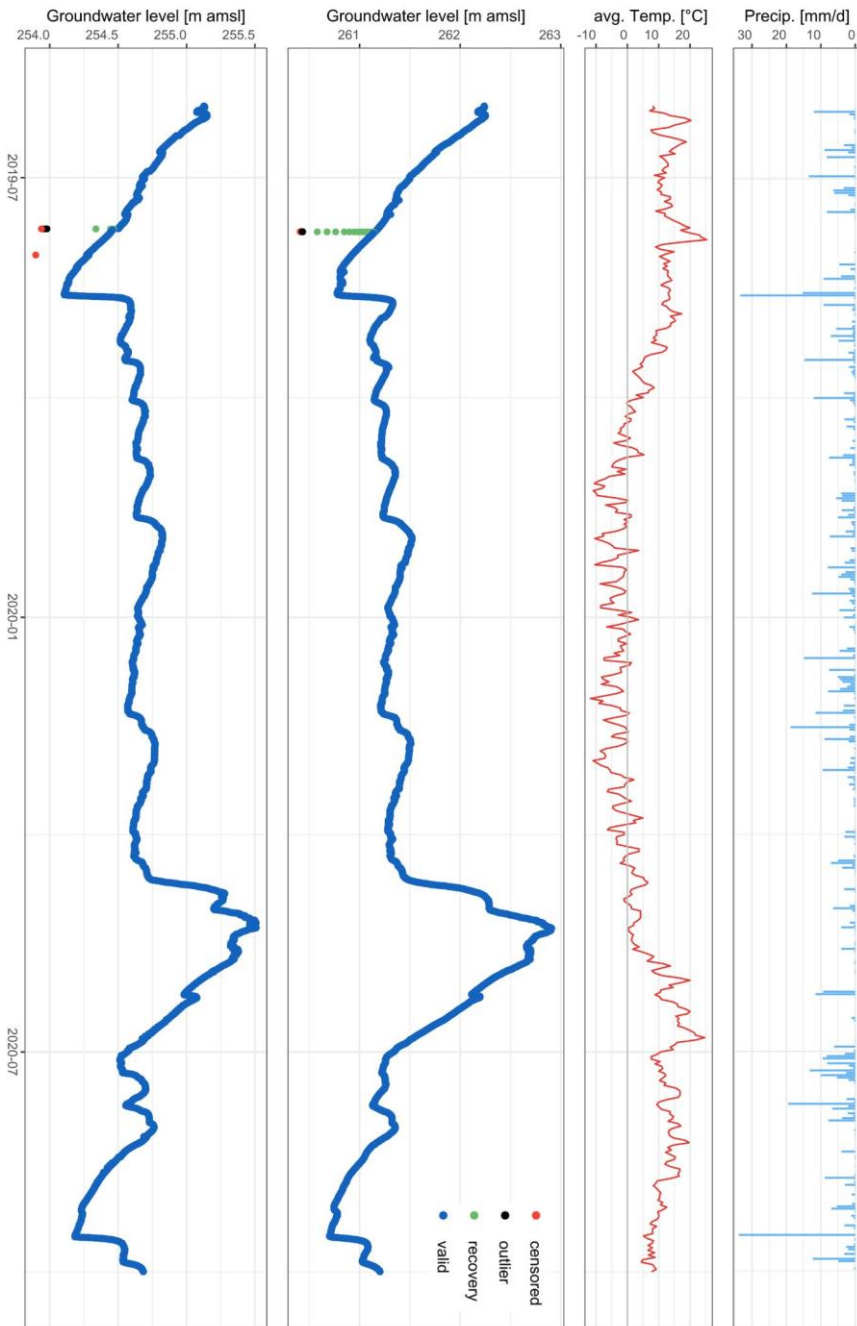
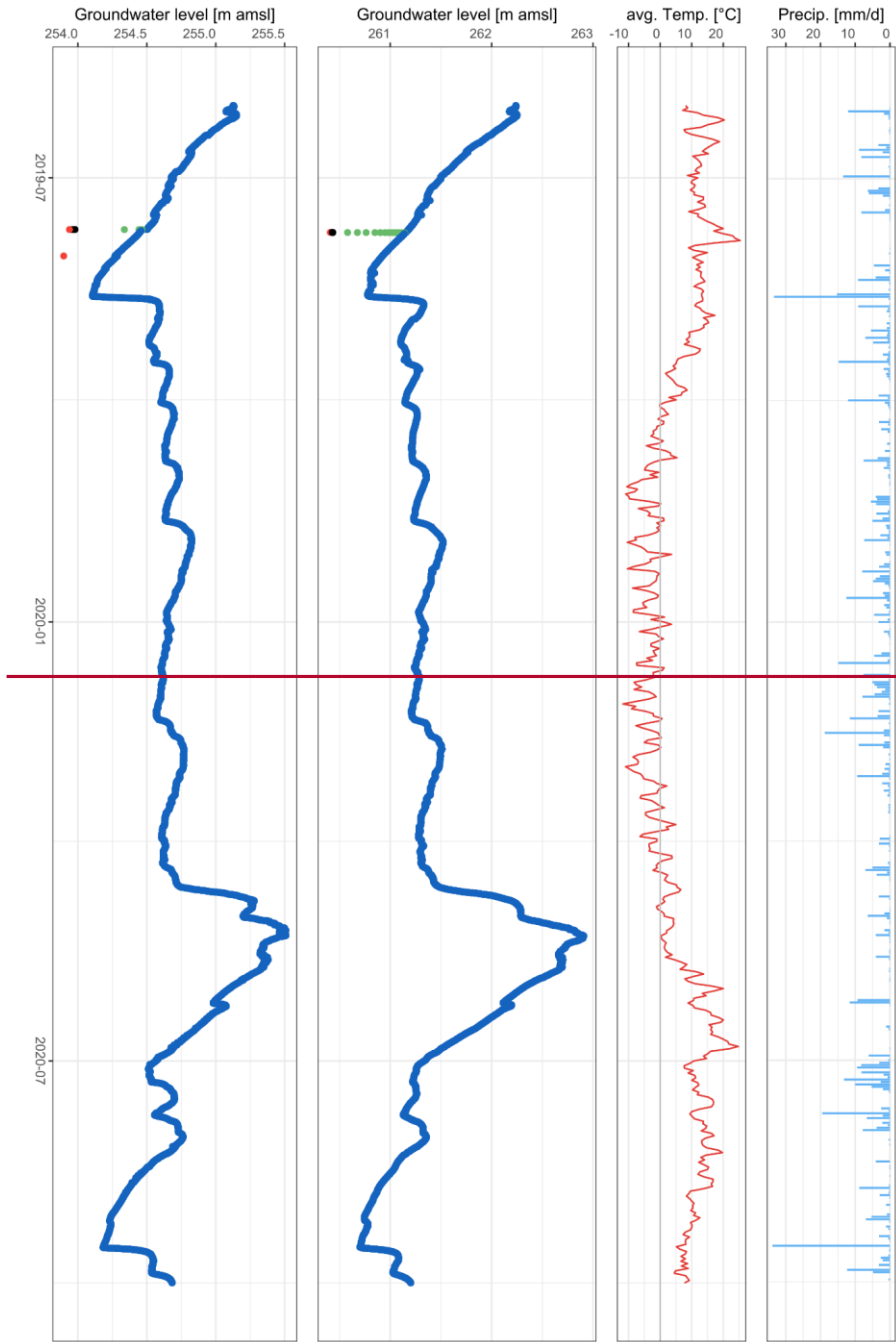
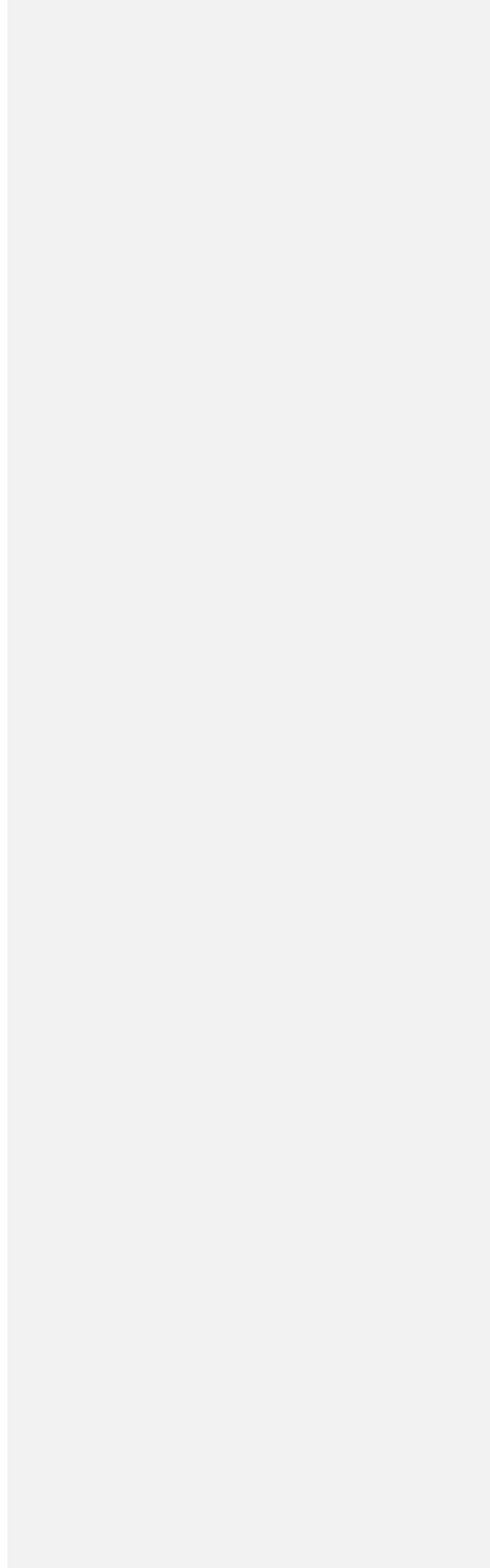



Figure 8: Precipitation (first plot, blue bars), temperature (daily average, second plot, red line) and classified groundwater levels for two wells (A12 third plot, B18 fourth plot) between June 2019 and September 2020. See ~~Table 6~~Table A 5 for further information on the classification of the data points ~~and Figure 6 for the legend.~~

540

6. Example results

6.1 Groundwater level data

Figure 8 shows the groundwater level time series for two selected wells (A12 and B18) and highlights
the quick response to ~~the~~ snowmelt ~~period~~ and rainfall events. Thanks to the relatively high resolution
of the groundwater data, the immediate response of groundwater levels to specific rainfall events is
clear. Interesting dynamics like daily groundwater level variations due to snowmelt, with peak water
levels occurring during the early evening ~~(~~(see examples in Figure 9 (a)) and due to evapotranspiration
with groundwater levels dropping during the day and stabilizing at night ~~(~~(see examples Figure 9 (b))
can also be observed for ~~many~~most wells (cf. Kirchner et al., 2020).

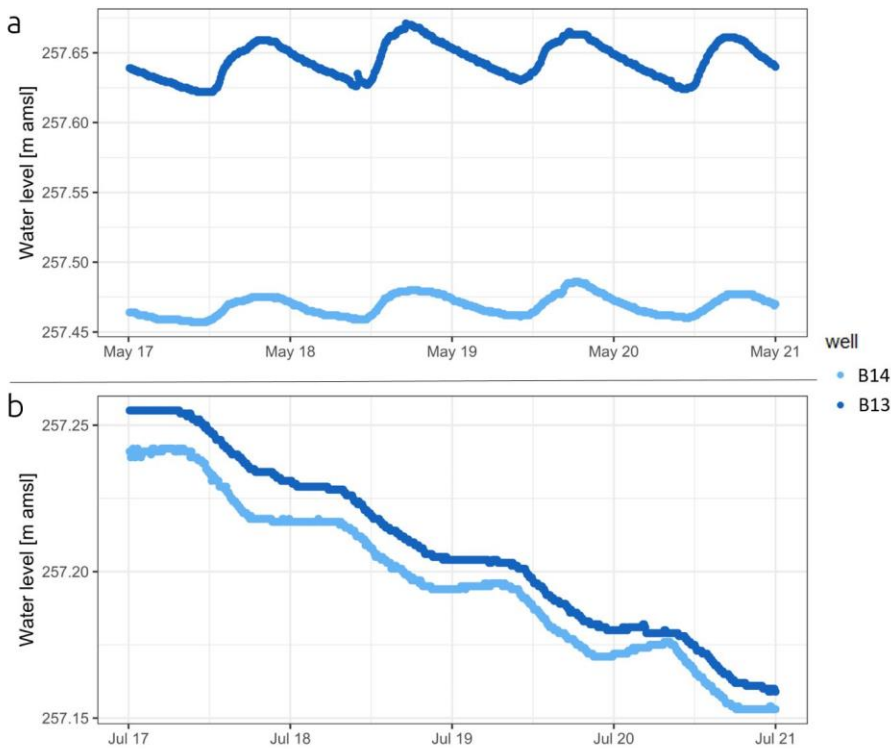
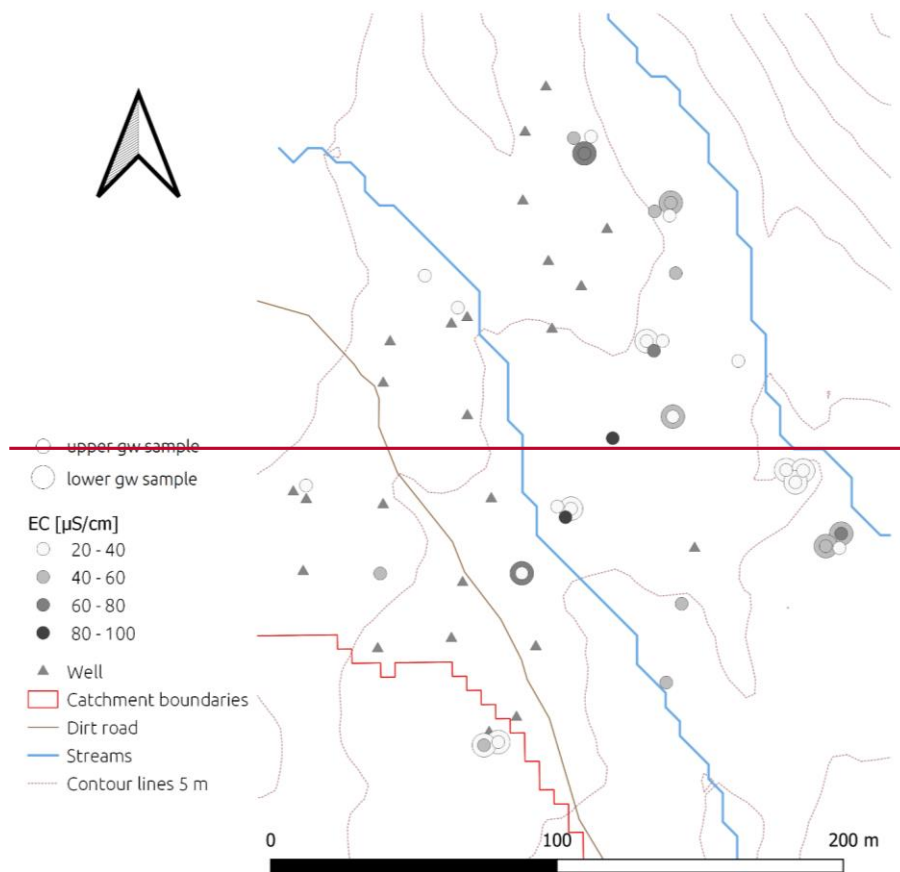
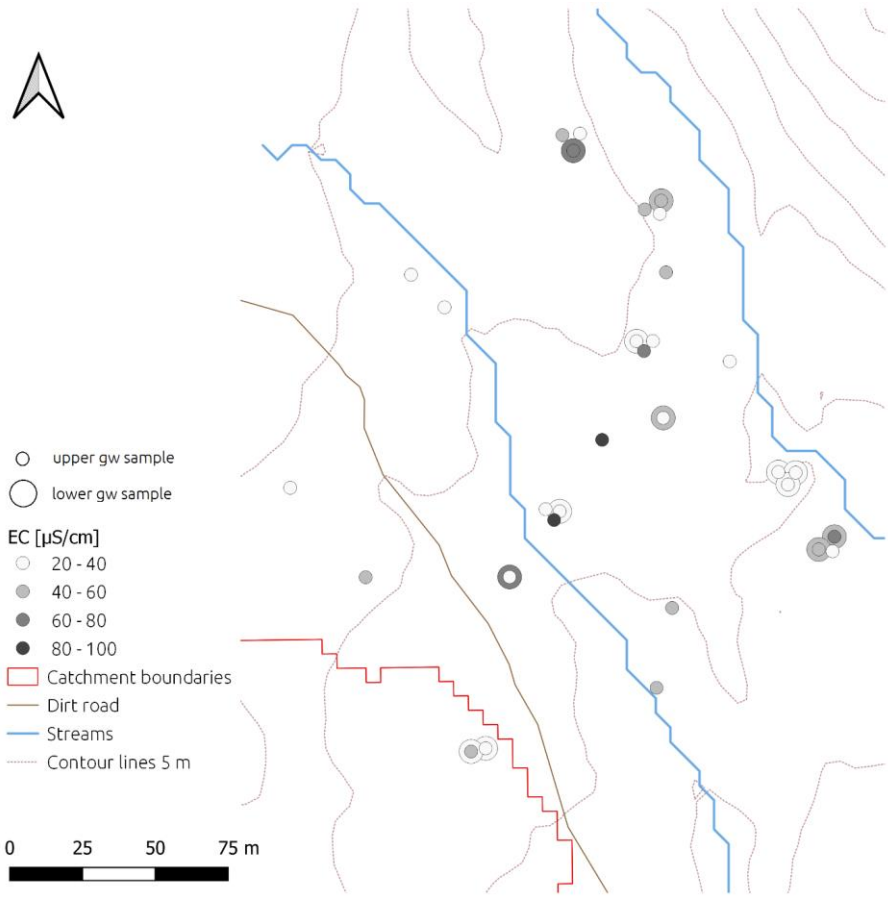



Figure 9: Example time series of diurnal ~~variation~~variations in groundwater ~~level~~levels for two wells during the late snow melt period in May 2020 (a) and the summer (July 2020) when diurnal variations are caused by evapotranspiration (b).

555

6.2 Groundwater ~~Chemistry~~chemistry

~~The concentrations of the anions, cations, and nutrients in the groundwater are comparable to those reported from other measurements in the Krycklan catchment, but the spatial variation in the concentrations was very spread (cf. Kiewiet et al., 2020), with the coefficient of variation ranging from 2.5 % (for $\delta^{18}O$) to 238.8 % (for F) (see examples Figure 10 and Figure 11). In general, the concentrations for the deep groundwater samples differed from those of the shallow groundwater samples (e.g., Figure 10), but the differences were not statistically significant. The isotopic composition of the groundwater was also variable, with the $\delta^{2}H$, for example, varying by 1.25 ‰ for the shallow groundwater samples (Figure 11).~~

The concentrations of the anions, cations, and nutrients in the groundwater are comparable to those reported from other measurements in the Krycklan catchment (e.g., Kolbe et al., 2020; Laudon et al., 2013, 2021), but the spatial variation in the concentrations was large (cf. Kiewiet et al., 2020), with the coefficient of variation ranging from 2.5% (for $\delta^{18}O$) to 239% (for F) (see examples Figure 10 and Figure

570 11). The concentrations for the lower groundwater samples differed from those of the upper groundwater samples for most locations (e.g., Figure 10), but no clear trends could be identified. The isotopic composition of the groundwater was also variable, with the δ^2H, for example, varying by 12.5‰ for the groundwater samples taken near the groundwater table (Figure 11).

575 **Figure 10. Map of the electric conductivity (EC) of** ~~shallow and deep groundwater in the study area A (C6 catchment). Values for shalow~~the **groundwater samples** ~~are indicated with a~~ taken near the water table (**small circle**; upper gw sample) **and** ~~values for deep groundwater with~~ the bottom of the well (**larger circle.** ~~Thus where~~; lower gw sample) for the wells in study area A (also know as the C6 catchment). Where **two circles are shown, the outer circle represents the** ~~deep~~ groundwater sample taken from the bottom of the well **and the inner circle the** ~~shallow~~ groundwater near the water table**.**

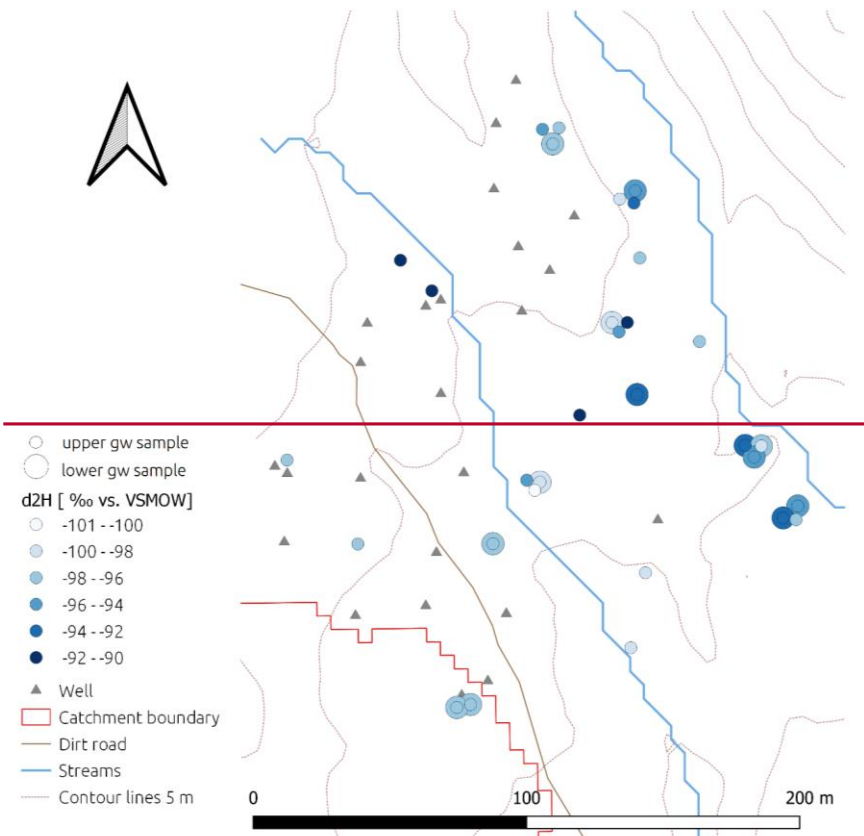
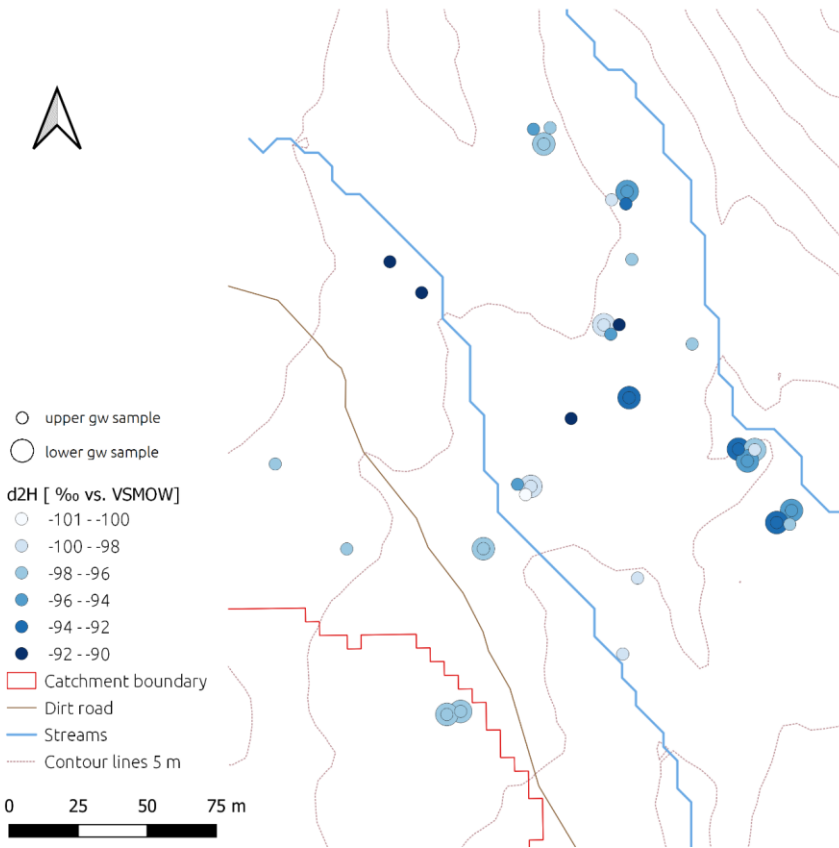



Figure 11: Map of δ^2**H of** ~~shallow and deep groundwater in study area A (the C6 catchment). Values for shalow~~**the groundwater samples** ~~are indicated with a~~ **taken near the water table (small circle**~~; upper gw sample)~~ **and** ~~values for deep groundwater with~~ **the** **bottom of the well (larger circle**~~. Thus where~~**; lower gw sample) for the wells in study area A (also know as the C6 catchment). Where** **two circles are shown, the outer circle represents the** ~~deep~~ **groundwater** **sample taken from the bottom of the well** **and the inner circle the** ~~shallow~~ **groundwater** **near the water table**.

7. Concluding remarks

The datasets presented in this paper can be used to investigate the spatial and temporal dynamics of shallow groundwater and to test hydrological models or upscaling approaches. The datasets also allow comparing groundwater level dynamics and groundwater chemistry. These data can be used in other studies in the Krycklan catchment to ~~better~~ understand better its hydrological functioning or geochemical or ecological processes. ~~The wells are still in place and accessible, thus, there is the possibility for continued groundwater level measurements, as well as repeated water sampling.~~ The highly instrumented sites within the Krycklan catchment provide unique opportunities to study groundwater dynamics and ~~thepotential~~ the potential findings are relevant for other boreal catchments.

The wells are still in place and accessible. Thus, there is the possibility for continued groundwater level measurements and repeated sampling.

8. Data Availability

600 Dataset 1 and 2 can both be accessed and downloaded via https://www.safedeposit.se/projects/82 (Erdbrügger et al., 2022). The zip-compressed folder (Krycklan_Groundwater_levels_sampling.zip) includes all the files listed in Table 2

Dataset 1 and 2 can both be accessed and downloaded via https://doi.org/10.5880/fidgeo.2022.020 (Erdbrügger et al., 2022). The zip-compressed folder (2022-020_Erdbruegger-et-
605 al_Krycklan_Groundwater_levels_sampling.zip) includes all the files listed in . A brief description of the data and information on licensing and the format of the tabular data is available from 2022-020_Erdbruegger-et-al_data-description.pdf (available separately and within the zip-folder).

9. Author contribution

610 JE, IvM, JS and KB designed the experiments, JE led the installation of the wells, field measurements, recording of the water levels, and sampling. JE prepared the manuscript and data files with contributions from all co-authors.

10. Competing interests

The authors declare that they have no conflict of interest

615 ## 11. Acknowledgements

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Appendix A: Additional information on the water level measurements

Table A 1: Selected catchment and hillslope scale studies with a large number of shallow groundwater level measurements and reported well densities (number of wells per hectare).

Catchment	Recording wells		Manual measurements		Reference
	#	#/ha	#	#/ha	
Catchment studies					
Malcolm Knapp Research Forest, Canada	-	-	59	15	Moore and Thompson (1996)
Sæternbekken catchment, Norway	4		>100	0.01	Myrabø (1997)
Tenderfoot Creek Experimental Forest, Montana, USA	84	0.5	-		Jencso et al. (2009)
Östfora experimental catchment, Sweden	-		15	0.4	Rodhe and Seibert (2011)
Studibach catchment, Switzerland	51	2.6			Rinderer et al. (2014)
Near the Weierbach experimental catchment, Luxembourg.	22	195	14	125	Bonanno et al. (2021)
Krycklan catchment (C6, area A), Sweden	54	15	-		This study
Hillslope studies					
Panola Mountain Research Watershed trenched hillslope	29	29	135	135	Tromp-van Meerveld and McDonnell (2006)
Scott Starling Nature Sanctuary site/Riparian Zone	-		14	2.3	Vidon and Smith, (2007), Vidon (2012)
Malcom Knapp Research Forest, Canada	18	819	-		Haught and van Meerveld (2011)
Southern Germany	90	4.3	-		Bachmair, Weiler and Troch (2012)
Krycklan catchment (S-transect, area B), Sweden	20	20	-		This study
Gårdsjön Covered Catchment	3	4.8	34	54	Bishop et al. (2011), Seibert et al. (2011)

Table A 2: Name and short description of the datafiles included in the two datasets

Dataset	File names	Short description	Contents described in
1	2022-020_Erdbruegger-et-al_Krycklan_gw_wells.csv	well position (x,y,z), height of correction factors, etc.	
1	2022-020_Erdbruegger-et-al_Krycklan_gw_levels.csv	Groundwater levels from manual measurements and loggers, tube above ground, etc.	
1	2022-020_Erdbruegger-et-al_TSL_registration_report_[A/B].rtf	TSL scan registration report	Section 3.3
2	2022-020_Erdbruegger-et-al_Krycklan_gw_sampling.csv	Sampling information for groundwater chemistry	Table 2
2	2022-020_Erdbruegger-et-al_Krycklan_gw_chemistry.csv	Chemistry data from groundwater sampling	
2	2022-020_Erdbruegger-et-al_Field_protocol.csv	Field protocol for sampling of groundwater	Section 5
2	2022-020_Erdbruegger-et-al_Lab_analysis_description.pdf	Information on the laboratory analyses	Section 5

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Appendix B

Table A 3: Structure of the groundwater well location data file (2022-020_Erdbruegger-et-al_Krycklan_gw_wells.csv) and description of the column names

Column name	Full title	Description
Well	Well_name	Name of well
Well_field	Well field name	Name of the well used in the field originally
X	X-Coordinate	X coordinate [m] as extracted from TLS Datum: EPSG:3006 - SWEREF99 TM
Y	Y-Coordinate	Y coordinate [m] as extracted from TLS Datum: EPSG:3006 - SWEREF99 TM
Z_abs	Z-tube top	Absolute elevation of pipe top above mean sea level extracted from TLS [m amsl]
Depth	Well depth	Depth of the well below the ground surface at the time of installation [m]
intercept	Recalibration offset	Recalibration offset calculated based on the linear regression between the manually measured water levels and the logger derived data, used to correct the logger measurements (only applied correction values)

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Table A 4: Structure of the groundwater level data file (2022-020_Erdbruegger-et-al_Krycklan_gw_levels.csv) and description of the column names

Column name	Full title	Description [unit]
Well	Well_name	Name of well
datetime	Date and time	Date and time (CET) of the measurement Format: DD/MM/YYYY hh:mm:ss (no energy saving time)
tube	Length of the pipe above ground	Length of the PVC pipe above the ground [cm] as measured during field season (i.e., stick-up). Values are assumed to remain constant between measurements.
mnl_level	Manual water level	Groundwater level [m amsl], calculated by subtracting the manually measured distance between the water level and the top of the pipe (man_level) from the from the absolute elevation (Z_abs)
Log_level_uncorr	Water level below top of well (uncorrected)	Water level from logger [cm from the top of the tube], calculated based on the logger length and string length (if logger was suspended inside the well). Note that

		this is the level before the re-calibration with manually measured water levels
Log_level_corr	Absolute water level (corrected)	Water level after correction and subtraction from the absolute elevation (Z_abs) [m amsl]
Class	Data classification	Data point flagging as valid, outlier, recovery, etc. (see)
Class_mnl	Manual Data classification	Manual data point flagging based on field observations (valid, outlier)

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815 **Appendix C**

Table A 5: Classification of logged data points

Class	Description
Valid	No known or apparent reason to indicate that the measurement is not valid. This is the default classification for all data points
Outlier	Known outliers (during pumping) and unknown outliers (>10 cm drop in ≤10 min)
Recovery	Recovery of water levels after pumping (0-12 h after re-introduction of the logger into the well)
Censored	Uncertain values due to low water levels (< 5 cm above logger bottom) or water in lower well ends (lower 5 cm of unscreened pipe)
Strange	Snowmelt curve with sudden breaks (probably related to a rapid decrease in the electrical conductivity of the water)
Offset	String length or tube length were unknown. The relative changes in water level are correct but the absolute level could not be calculated.

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Appendix D

Table A 6: Description of groundwater chemistry data (file: 2022-020_Erdbruegger-et-al_Krycklan_chemistry.csv), see Lab_analysis_description.pdf - file for more information on the laboratory analysis.

Column name	Full title or description	[units]
sample_num	Sample number assigned for SLU laboratory analysis	Sample number assigned for SLU laboratory analysis
d18O	$\delta^{18}O$	[‰ relative to VSMOW]
d2H	δ^2H	[‰ relative to VSMOW]
EC	Electrical conductivity EC	[μS/cm]
pH	pH	[-]
EC_field	Electrical conductivity measured in the field	μS/cm]
pH_field	pH measured in the field	[-]
absorb_254	Absorbance at 254 nm	[A/cm]
absorb_365	Absorbance at 365 nm	[A/cm]
absorb_420	Absorbance at 420 nm	[A/cm]
absorb_436	Absorbance at 436 nm	[A/cm]
Flu	Fluoride	[mg/L]
Cl	Chloride	[mg/L]
SSO4	Sulfate-SO_4	[mg/L]
PPO4	Phosphate-PO_4	[μg/L]
NNH4	Ammonium-NH_4	[μg/L]
NNO3	Nitrate-NO_3	[μg/L]
Na	Sodium	[mg/L]
NH4	Ammonium	[mg/L]
K	Potassium	[mg/L]
Mg	Magnesium	[mg/L]
Ca	Calcium	[mg/L]

825   **E.1 Manual water level measurements**

We used three different methods to measure the depth between the top of the well and the water level: a bubbler, a water level plopper ("kluk lod"), and an acoustic water level sounder. The so-called "bubbler" consists of a rigid tube connected to flexible tubing. In our case, we used a 1 m long metal tube with a ~ 5mm diameter connected to flexible rubber tubing. The metal tube was inserted into the

830   well and air was blown into the flexible tube. The water level in the well was determined based on the change in the sounds once the metal tube reached the water surface (i.e., as soon as one could hear a "bubbling" noise). This method worked best for shallow groundwater levels since the sound was difficult to discern when the water level was deeper (as well as in noisy circumstances (e.g., strong winds)). Because the water can be blown out of the well when blowing too strongly, leading to a slightly

835   deeper groundwater level, we carefully approached the groundwater surface from above and provided only moderate pressure.

A water-level plopper consists of a small metal cylinder attached to the tip of a measuring tape. It is lowered into a well and produces a "plopping" sound when the cylinder hits the water surface. When the water level was deep (>3 m), the sound was sometimes not audible. Also, for shallow groundwater

840   levels, it often took several tries and "plop" sounds to determine the exact depth to the water level with the measuring tape because it required enough momentum for the cylinder to produce a sufficiently distinguishable sound.

The electronic water level meter or (acoustic) water level sounder emits a sound upon contact with water. In addition, a light switches on. The sensor at the tip of the tape or meter has an open electrical circuit

845   closed when it is in contact with water because of the much lower electric resistivity of water than air. Because the groundwater in the Krycklan area has a relatively low electric conductivity (mean EC from the surveys 48.6 µS/cm), the electronic water level meter sometimes failed and indicated the water surface only after being submerged for about half a meter. The problem was solved after purging the wells or stirring the water in the wells. The low EC in some wells may have originated from the

850   snowmelt water that did not drain or mix much with the other groundwater in the well.

A̶E.2 Continuous water level measurements

We used Odyssey water level loggers for the continuous water level measurements. These capacitance sensors are based on the difference in the dielectric constants of water and air. The weight at the end of a cable serves as one capacitance plate, and the cable as the second. A change in the area of the second

855   capacitance plate (i.e., the cable in contact with the water) results in a change in the signal. For more information on capacitance sensors, see Larson and Runyan (2009); Dataflow Systems PTY Limited (2012); Guaraglia and Pousa (2014)). We deployed two generations of the same type of loggers, which differ in their dimensions (Figure A 1 (a) and (c)). The new logger bodies (from 2019) are larger and do not fit completely into the well pipes (see Figure A 1 (b) and (Figure A 1 (d)).

860   The water used for the calibration was taken from a groundwater well to account for local water chemistry (as this has been shown to be a potential error source by Larson and Runyan (2009)) and thus to minimize errors in the calibration. Other error sources identified by Larson and Runyan (2009), like the potential for a biofilm to build up on cable and counterweight of the loggers, were minimized by cleaning the cables and weights with a cloth during logger read-outs. The building of films varied

865   strongly between wells but did not appear to have an identifiable impact in the data of the water levels and therefore we did not correct for this.

    Since the loggers do not show the remaining battery power, it is relatively difficult to predict when they run out of power. Although a rough estimate says the batteries last for about 18 months, this time can vary considerably with environmental factors and is much shorter during low temperatures. This resulted

870   in incomplete time series for some wells (see Table A 7 in Appendix C).
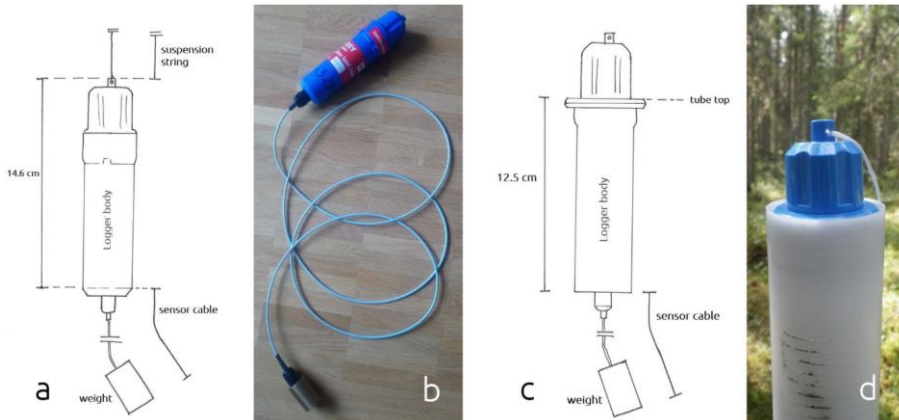
Figure A 1: Odyssey water level sensors and the respective measures of the logger body and cable lengths for the 2012 Odyssey water level sensor ((a) and (b)) and the 2019 Odyssey water level sensor (c), and the 2019 sensor installed in a
875   **well tube (d). Note, drawing is not to scale.**

Appendix ~~B~~F: Well purging and groundwater sampling

The well purging and subsequent sampling was done using two peristaltic pumps (see Figure A 2). The volume of water that needed to be pumped from the well during purging was calculated based on the volume of water inside the well, and multiplied by a factor of three to ensure the recharge of fresh groundwater:

$$V_{pump} = 3 * \left(\pi * \left(\frac{d_{well}}{2} \right)^2 \right) * (L_{well} - d_{gw})$$

Where the V_{pump} is the volume to be pumped, d_{well} is the inner well diameter (3.7 cm in our wells), L_{well} is the well depth (from tube top), and d_{gw} is the depth from the well top to the water level.

In some cases, recharge into the well was very slow, and in these cases, we would stop the purging when the well ran dry (i.e., before V_{pump} was reached). All wells (with water in them) were purged twice within the space of two weeks. After the second purging round (31. May 2019) and before the sampling campaign started (01. July 2019), precipitation was 68.4 mm.
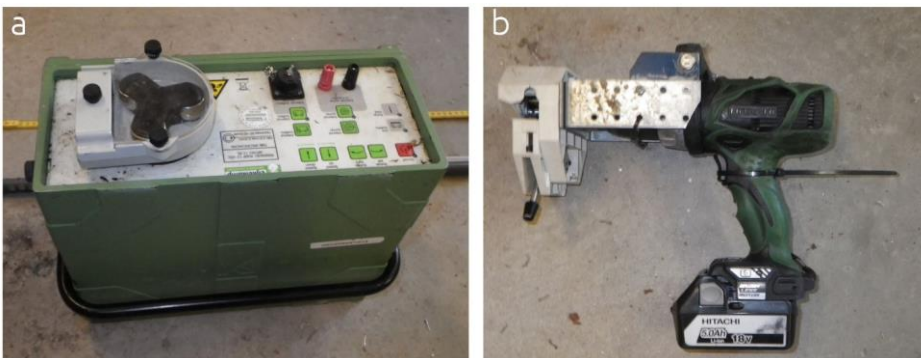
Figure A 2: Photo of peristaltic pump (a) and peristaltic pump mounted on a drill (b) used for purging the wells

For the groundwater sampling, we used a custom-made packer system (Figure A 3) that could seal off the access to water below and above the part where the sample would be taken. This allowed for sampling at discrete depths. Markers on the tube of the packer system allowed the determination of the sample depth. The packer was designed to sample up to a depth of 6 m. Since the sample opening is

located above the lowest end of the packer, a minimum water level of 40 cm inside the well was necessary to take a sample with the packer system.

Figure A 3: Photo of the custom-made straddle packer system with two inflatable parts to isolate specific depths in the wells and to pump water from specific depth (a) and the upper part and tubing system (pumping tube and t wo air tubes to inflate the flexibles tube parts) of the packer system (b). The yellow arrows in (a) indicate inflatable packer system parts to seal off the water above and below the selected sample depth.

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Appendix G: Logger and manual water level summary

Table A 7: Summary of the recorded water level data per well and the manual measurements for each well. The summary statistics (mean, median, minimum and maximum) were only calculated over the valid data points. Note that for some wells (e.g., A45 and A50) the number of valid data points is very small because the well was dry for most of the study period or the data were flagged as censored data. *non-valid data points and manual outlier include dry well values

well	Logger data — Valid data points	Non-valid data points*	level in [m amsl] mean	median	min	max	Manual measurements — Number of measurements	Number of valid	Number of outliers*	level in [m amsl] mean	median	min	max
A1	0	97353					0	0	0				
A2	97145	258	264.18	264.16	263.61	265.07	26	5	21	264.40	264.48	263.76	264.75
A3	90299	231	261.45	261.30	260.70	262.98	18	16	2	261.47	261.31	260.83	262.72
A4	96838	677	263.35	263.41	262.20	264.20	25	10	15	262.99	262.88	262.59	263.77
A5	67179	11803	264.93	264.87	264.40	265.65	17	4	13	265.09	265.08	264.88	265.33
A6	78746	234	263.47	263.43	262.04	264.29	17	13	4	263.51	263.52	263.02	263.88
A7	71683	8653	265.85	265.79	265.64	266.45	25	23	2	265.79	265.75	265.63	266.21
A8	72037	6947	262.10	261.94	261.50	263.21	17	7	10	262.06	262.03	261.90	262.32
A9	97084	440	261.76	261.70	260.60	263.03	25	16	9	261.58	261.47	261.26	262.81
A10	47317	29229	262.24	262.01	261.80	263.50	11	3	8	262.34	262.36	262.11	262.54
A11	97040	723	264.22	264.22	263.87	264.66	23	18	5	264.16	264.18	263.90	264.45
A12	97027	486	261.20	261.19	260.39	262.32	25	7	18	260.59	260.60	260.44	260.80
A13	70774	237	265.25	265.27	264.64	265.41	20	19	1	265.22	265.25	264.97	265.32
A14	2953	86887	264.37	264.37	264.23	264.67	2	2	0	264.26	264.26	264.19	264.33
A15	97055	416	264.21	264.22	264.23	264.48	26	23	3	264.23	264.24	264.08	264.32
A16	97242	187	264.11	264.14	263.51	264.34	26	16	10	264.14	264.14	263.99	264.25
A17	57718	32496	264.22	264.17	264.00	264.65	12	12	0	264.19	264.14	263.98	264.52
A18	72977	230	261.05	260.92	260.30	262.36	11	1	10	260.94	260.94	260.94	260.94

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well	Logger data						Manual measurements					
	Valid data points	Non-valid data points *	level in [m amsl]				Number of valid measurements	Number of outliers *	level in [m amsl]			
			mean	median	min	max			mean	median	min	max
A19	78843	150	261.50	261.40	260.63	262.71	10	7	261.47	261.34	260.78	262.56
A20	86289	3549	263.56	263.60	263.02	263.74	15	1	263.53	263.55	263.16	263.65
A21	95942	1526	261.84	261.93	260.45	262.25	16	9	261.79	261.72	261.42	262.13
A22	275	78914	265.46	265.47	265.23	265.65	1	0	265.22	265.22	265.22	265.22
A23	51623	230	259.39	259.35	259.02	259.96	16	1	259.37	259.29	259.09	259.81
A24	0	71921					4	0	265.75	265.75	265.75	265.76
A25	240	114128	264.00	263.99	263.98	264.20	2	0	263.95	263.95	263.95	263.96
A26	91847	5562					0	6				
A27	97238	271	261.03	261.08	259.44	261.63	18	7	260.95	260.94	260.42	261.50
A28	79115	161	257.58	257.51	257.17	258.29	16	1	257.56	257.44	257.22	258.15
A29	60092	154	258.31	258.25	257.92	258.88	17	0	258.29	258.21	257.98	258.75
A30	66847	150	258.13	258.16	257.57	258.50	5	3	258.06	258.11	257.71	258.39
A31	75478	0	263.19	263.21	262.41	263.94	9	1	263.08	263.05	263.00	263.23
A32	75405	78	263.42	263.40	262.56	264.13	14	1	263.36	263.34	263.18	263.61
A33	264	66577	263.31	263.28	263.08	263.61	0	0				
A34	58548	1669	261.01	261.02	260.12	261.33	11	6	260.98	260.96	260.92	261.15
A35	73967	5323	261.01	261.04	260.29	261.40	13	4	261.03	261.01	260.95	261.15
A36	14769	16537	277.77	278.17	262.77	278.63	0	0				
A37	79058	235	260.73	260.79	259.85	261.27	14	3	260.76	260.78	259.98	261.01
A38	74321	153	257.16	257.15	255.57	257.35	15	0	257.14	257.12	256.95	257.26
A39	0	97756					0	0				
A40	79124	160	257.01	256.92	255.91	257.50	15	2	257.05	256.95	256.68	257.43
A41	30199	45368	261.40	261.21	260.76	262.86	9	9	260.35	260.35	260.35	260.35
A42	75399	74	261.52	261.38	261.15	263.12	0	9				

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Table with two main sections: **Logger data** and **Manual measurements**. Level values in [m amsl].

well	Valid data points	Non-valid data points *	mean	median	min	max	Number of valid measurements	Number of outliers *	mean	median	min	max
A43	79132	154	257.12	257.06	256.20	257.85	11	6	257.16	257.05	256.96	257.64
A44	65520	19891	259.35	259.04	258.56	261.67	8	10	259.12	258.86	258.46	260.42
A45	16346	71051	260.87	261.01	259.99	261.29	2	10	260.56	260.56	259.98	261.14
A46	79061	228	257.07	257.03	256.55	257.81	11	5	257.05	256.92	256.75	257.58
A47	79068	227	256.68	256.67	255.61	257.02	2	15	256.66	256.66	256.59	256.74
A48	23935	99650	260.96	261.03	259.68	261.89	4	9	261.18	261.22	260.53	261.76
A49	2960	94487	258.55	258.55	258.46	258.64	0	0				
A50	23010	48967	261.07	260.89	260.89	262.23	0	5				
A51	32573	64715	257.09	257.08	256.38	258.04	4	4	256.58	256.56	256.45	256.76
A53	68316	7243	257.08	256.76	256.42	259.28	9	1	257.04	256.83	256.47	258.62
A54	56619	18909	257.37	256.98	256.58	259.23	8	6	257.47	257.33	256.50	258.82
B1	75616	6502	263.88	263.81	263.04	265.20	13	2	263.79	263.83	263.47	264.15
B2	66356	5438	261.87	262.07	260.92	262.30	0	11				
B3	71507	286	261.53	261.43	261.01	262.43	11	0	261.51	261.47	261.03	261.98
B4	75555	6570	259.39	259.27	258.65	260.56	13	2	259.28	259.28	258.68	260.17
B5	65675	16455	258.45	258.28	258.02	259.66	7	8	258.18	258.15	257.92	258.38
B6	56558	23909	258.77	258.59	258.41	259.95	4	11	258.50	258.40	258.35	258.84
B7	63063	6419	259.25	259.14	258.44	260.44	3	0	258.79	258.83	258.62	258.92
B8	68540	156	259.53	259.43	258.72	260.78	9	0	259.25	259.35	258.99	259.48
B9	75628	76	257.76	257.61	257.10	259.13	12	3	257.70	257.61	257.13	258.58
B10	12001	63102	258.80	258.78	258.19	259.40	1	8	257.57	257.57	257.57	257.57
B11	75621	6595	259.39	259.35	258.71	260.58	15	0	259.33	259.35	258.89	259.72
B12	74599	7516	257.51	257.47	257.00	258.45	5	10	257.32	257.47	257.00	257.62
B13	75622	6496	257.26	257.25	256.78	258.35	4	11	257.34	257.34	257.18	257.49

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well	Logger data						Manual measurements					
	Valid data points	Non-valid data points *	level in [m amsl]				Number of valid measurements	Number of outliers *	level in [m amsl]			
			mean	median	min	max			mean	median	min	max
B14	68391	7308	257.24	257.25	255.94	257.54	15	0				
B15	23385	52314	256.40	256.26	255.97	257.28	0	15				
B16	75618	80	256.85	256.83	255.83	257.30	10	5	256.70	256.78	256.30	256.98
B17	67719	7982	255.54	255.38	255.14	256.68	8	7	255.45	255.37	255.18	255.90
B18	75624	78	254.71	254.67	254.11	255.51	14	1	254.59	254.62	254.13	255.06
B19	69087	6614	253.68	253.53	253.23	254.28	11	4	253.60	253.49	253.15	254.18
B20	40737	816	253.53	253.41	252.85	254.50	13	0	253.36	253.37	252.82	254.02