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Spatiotemporal dynamics of soil moisture and stream states based on qualitative methods

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1 | INTRODUCTION

Hydrology is a data-limited science. Measurements are needed at a high spatial and temporal resolution to understand the spatial and temporal variation in water storage and fluxes across a catchment, but continuous measurements are generally limited to a few sites due to the high costs of the equipment, installation and maintenance. Citizen science projects have developed qualitative methods to obtain information on hydrological variables. Although these methods are less precise and accurate than traditional methods, they can also be used in research or student projects. We used the instrument-free qualitative approaches from a citizen science project (CrowdWater, 2023) to study the spatial and temporal variation in surface soil moisture and the flow conditions in a subcatchment of the Krycklan Catchment in northern Sweden during two summer seasons (May–October of 2018 and 2019). The animations of these qualitative (visual and tactile) data highlight their extraordinary information content and their usefulness to study the spatial and temporal variation in moisture conditions across a catchment.

2 | STUDY AREA

The study area is located in the Krycklan catchment, in Northern Sweden. The soil moisture observations were made in a 20 ha area in what is known as subcatchment C6 (64°15′16″ N, 19°45′52″ E). The stream state observations were made in a 9 ha area of this subcatchment. The elevation of the subcatchment ranges from 245 to 294 m above sea level. A lake feeds the permanent main stream. Inflows and outflows of this stream are monitored at two gauging stations (named C5 and C6, respectively). The average annual temperature at the study site is 1.8°C and the average annual precipitation is ~620 mm. The vegetation consists mainly of pine forests and peatlands. For more information on the catchment, we refer to Laudon et al. (2021, 2013).

3 | SOIL MOISTURE

Soil moisture measurements provide information on catchment water storage, and are valuable for understanding hydrological connectivity or to predict the catchment's responses to precipitation (Ali & Roy, 2010; McNamara et al., 2005; Western et al., 2005, 2004, 2001). Soil moisture measurements, and especially information on the location of saturated areas, can also be used for model calibration and validation (Beven & Kirkby, 1979; Blazkova et al., 2002; Glaser et al., 2016; Güntner et al., 2004). However, the spatial variation in soil moisture is generally high and influenced by factors such as soil type (i.e., soil hydraulic properties, e.g., Jarecke et al., 2021), vegetation cover (due to its effect on evapotranspiration), and topography (due to the lateral redistribution of moisture) (Grayson & Western, 1998; Western et al., 2004).

Soil moisture is typically measured with indirect methods that measure the dielectric or electrical resistance of the soil, or by destructive gravimetric methods (e.g., Walker et al., 2004). Soil saturation can be assessed with the ‘squishy boot’-method (e.g., Ambroise et al., 1996; Latron & Gallart, 2007). Rinderer et al. (2012) extended this approach to seven qualitative moisture classes, which are now used in the CrowdWater project (Seibert et al., 2019; Table 1). We evaluated the surface soil moisture conditions across the study area using these seven classes.

TABLE 1 Soil moisture classification scheme used in this study (after Rinderer et al., 2012). Note that we did not actually sit on the soil to determine how quickly the trousers would get wet but rather assessed the soil moisture states visually and tactile.

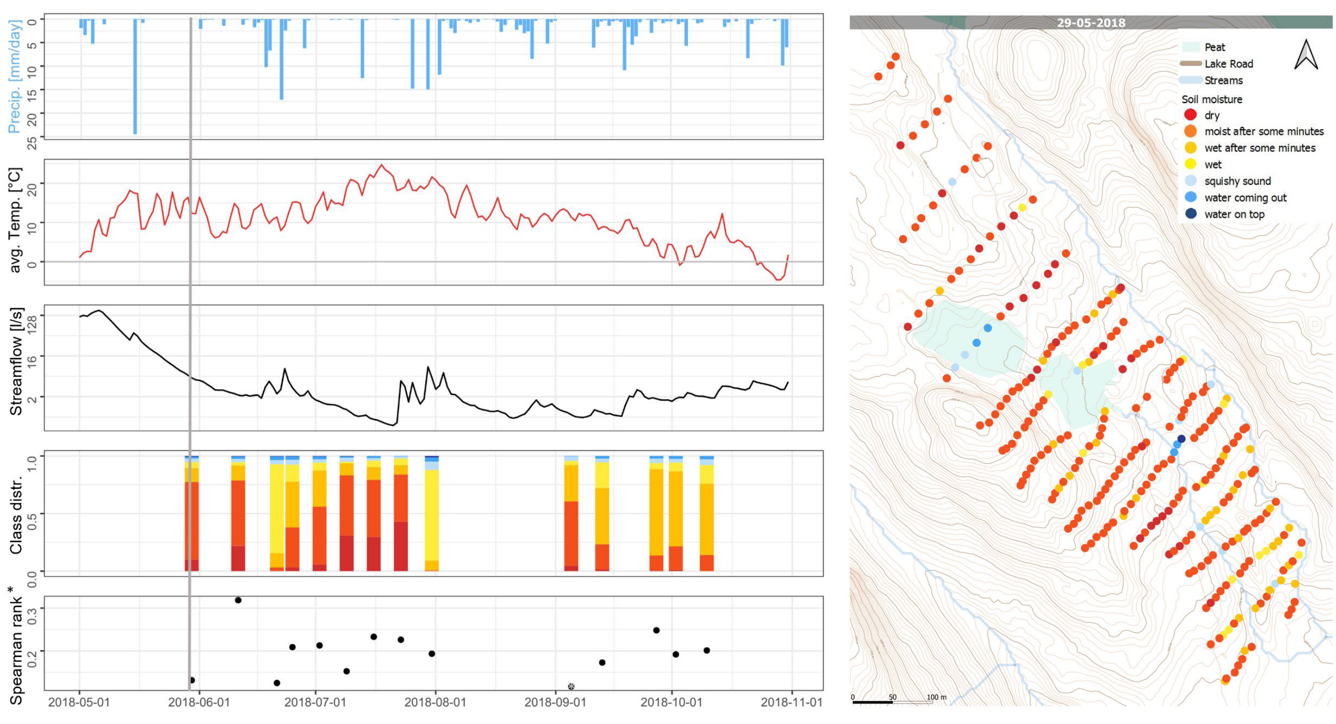
Class	Qualitative indicator criteria
1	The trousers of a person sitting on the ground would stay **dry**
2	The trousers of a person sitting on the ground would get **moist after some minutes**
3	The trousers of a person sitting on the ground would **wet after some minutes**
4	The trousers of a person sitting on the ground would **wet immediately**
5	**Squelchy noise** can be heard when stepping on the ground, but no water is visible
6	**Water squeezes** out of the topsoil when stepping on it
7	**Water** can be seen on the soil surface

We established transects 40 m apart, with points marked every 10 m in the lower part of the study area. In the upper part, the distance between the transects was 80 m and the points on the transects were located 20 m apart. This spacing and number of locations allowed one person to observe the soil moisture conditions at all 277 points within half a day. The moisture conditions were assessed for each point 14 times during each summer season.

Even though the qualitative method relies on a subjective classification of the moisture conditions, the agreement between people who assess soil moisture this way is high (Rinderer et al., 2012). To improve the consistency of the ratings further, all 'measurements' on a particular survey day were taken by the same person. The four observers that assessed the soil moisture conditions during a summer season were instructed at the start of the season to create a shared understanding of the classes.

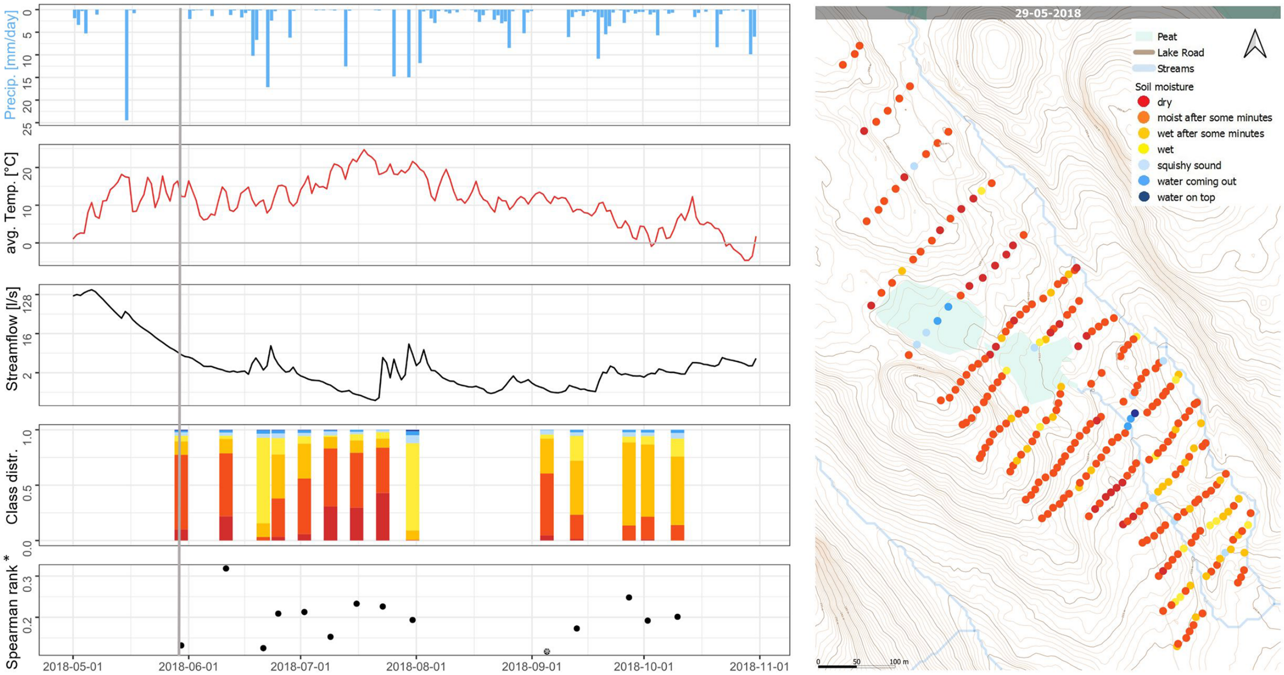
The high water-holding capacity of the moss may make the ground appear much wetter than it is, particularly after a rainfall event, leading to an overestimation of the moisture conditions. To minimize this influence, the soil moisture conditions were assessed 2 or more days after precipitation events. This means that all measurements were taken after some drying and drainage of excess water, and that none of the surveys cover the wettest conditions. Similarly, early mornings were avoided to allow dew to dry off before we assessed the moisture conditions.

The maps of the soil moisture conditions show that despite the considerable temporal variation in soil moisture, the soil moisture patterns are highly persistent (Figure 1, Video 1, 3:20–4:03 min). The peatland area in the middle of the catchment remained wet, even during the driest conditions in August 2019. The correlation with the topographic wetness index (TWI; Beven & Kirkby, 1979) based on the 5 m resolution Digital Elevation Model of Norstedt (2017), was



*p-value < 0.05, except for 2018-09-05 (marked gray)

FIGURE 1 Screenshot showing the soil moisture results: the left panel shows the time series of the daily precipitation (top), average air temperature (second from top), stream flow at the outlet of the subcatchment (C6 gauge; middle), the distribution of the soil moisture classes (second from bottom) and the Spearman rank correlation between the soil moisture classes and the topographic wetness index (TWI). The panel on the right shows the map of the subcatchment with the classification of the soil moisture points for 29 May 2018 (indicated by the grey line on the left-hand panel).



*p-value < 0.05, except for 2018-09-05 (marked gray)

VIDEO 1 Spatiotemporal dynamics of soil moisture and stream states based on qualitative methods. Video content can be viewed at https://onlinelibrary.wiley.com/doi/10.1002/hyp.15141

higher when soil moisture conditions were overall moist and low for most other surveys. However, the correlations were weak for all surveys (Spearman rank correlation r_s: 0.11–0.32, $p < 0.05$ except for the lowest value, which was not significant).

4 | STREAM MAPPING

Temporary (i.e., non-perennial) streams dry periodically and include intermittent or ephemeral streams. Although temporary headwater streams are extensive, they are poorly monitored and often missing from maps (Bishop et al., 2008; DeBell et al., 2015; Spence & Hedstrom, 2021; van Meerveld et al., 2020). Stream intermittency can be caused by both natural and human factors (Acuña et al., 2014; Meinzer, 1923). For temporary headwater streams in the boreal region, snowmelt in spring and intense rainfall events during the growing season are the most critical drivers of flow (Ågren et al., 2015; Kuglerová et al., 2014; Spence & Woo, 2003). The flowing stream network can expand in an upstream direction, from the stream heads downwards, or by expanding disconnected sections or puddles (Bhamjee & Lindsay, 2011). Surface flow in a temporary stream reach occurs when the inflows to the stream reach (e.g., from upstream or local sources) are larger than downstream drainage through the streambed (Godsey & Kirchner, 2014).

We determined the full extent of the stream network at approximately the time of the snowmelt peak, which should be the time of the most extended stream network (Ågren et al., 2015). We installed stakes at 49 points in the streams. At 21 of these points, we marked

TABLE 2 Stream state classification used in this study. Note that we combined the subclasses for standing water for the visualization. We estimated the surface velocity of the water by observing the movement of bubbles, leaves, and so forth.

Class		Description	
D		Dry	
W		Wet	
S	a	Standing water	Isolated pools
	b		Connected pools
	1		Ponding water (<2 cm deep)
	2		Standing water (>3 cm deep)
WT		Weakly trickling (<1 m per minute)	
T		Trickling (1–2 m per minute)	
WF		Weakly flowing (2–5 m per minute)	
F		Flowing (>5 m per minute)	

transects of 2 to 11 points perpendicularly across the stream, spaced every 1 m (147 points in total) to capture the entire width of the (often undefined) streambed.

Typically, the stream network extent is documented by walking along the streams and classifying the stream state as either flowing or not flowing (e.g., Bhamjee & Lindsay, 2011; Hinrich Kaplan et al., 2019) or as dry or wet (e.g., Jensen et al., 2017; Turner & Richter, 2011). Because there are important ecological flow states in between these two end points (Gallart et al., 2012), we used the classification with seven states (Table 2). The classification of the stream state

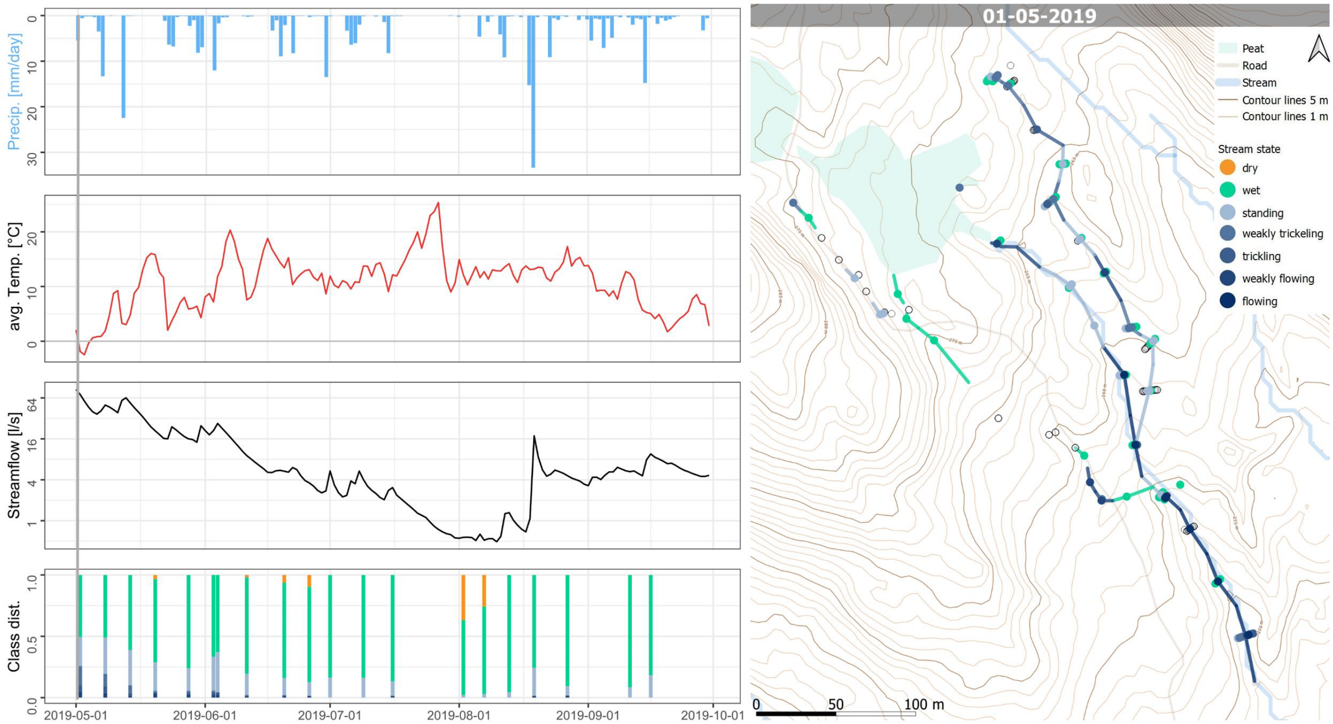


FIGURE 2 Screenshot showing the stream mapping results. The panels on the left show the time series of the daily precipitation (top), average air temperature (second from top), streamflow at the outlet (C6 gauge; second from bottom), and the distribution of stream state classes (bottom). The map on the right shows the classification of stream observation points for 01 May 2019 as indicated by the grey line on the left panel. The state observed at a point (as indicated with a circle) is attributed to half of the segment above and below the point (as indicated by the coloured segments). Note that for the locations where there were multiple observations (i.e., along the transects), we plotted the wettest observed state. Also note that this map shows a smaller part of the catchment than Figure 1.

with more than two categories also allows for more nuance than a two-state classification. The classification was developed specifically for the conditions encountered in the research catchment, based on a combination of classifications used by other researchers (CrowdWater, 2023; Gassmann, 2018). Although temporary stream observations are fairly reliable (Scheller et al., 2024), the four observers that assessed the stream states during a summer season were instructed at the start of the season to create a shared understanding of the classes.

The animation of the temporary stream observations demonstrates that a large portion (50%) of the network was active (classified as either standing, trickling or flowing) during the snowmelt period in May 2019 (see Figure 2), and that for each survey there were some sections that were not active (i.e., did not have water; dry or wet streambed). During the drier periods in the summer of 2018 (July and the end of August) and 2019 (August), the stream network dried out, and less than 3% of the total network was active.

5 | CONCLUDING WORDS

The animations of the soil moisture and stream state observations highlight the usefulness of the qualitative (visual or tactile 'measurement') approaches that are used in citizen science projects to obtain helpful information on catchment wetness conditions. We, therefore, recommend these approaches for student projects or other projects for which there is only a small budget or a lack of equipment. The data can be used to understand the factors that affect soil moisture conditions or the spatial patterns of streamflow (e.g., to test the effects of topography or vegetation on the spatial variability in soil moisture or flowing stream network extent). Together with meteorological data and streamflow data, these data are also useful to test spatially explicit hydrological models. The visualization of the data in animated graphs is very useful to quickly see and understand the dynamic changes between repeated measurements and to interpret the observed patterns and dynamics.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Safedeposit at https://www.safedeposit.se/projects/82.

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