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Review of the methodologies used to derive groundwater characteristics for a specific area in The Netherlands

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A B S T R A C T

In this paper, we analyze the methods that are used in The Netherlands to upscale in-situ groundwater measurements in time and in space, and how the selected combinations of upscaling methods affect the resulting groundwater characteristic. In The Netherlands, a three-step approach is used to obtain groundwater characteristics for a specific area: (1) in-situ monitoring of the water table depth; (2) temporal upscaling; and (3) spatial interpolation and aggregation. The three-step approach is, however, not standardized, but a combination of the following methods is used: (i) four methods to measure/monitor the phreatic water table; (ii) four methods for temporal aggregation; and (iii) four methods for spatial interpolation and/or aggregation. Over the past sixty years, several combinations of these methods have been used. Our review shows that the use of these different combinations in the approach to measure and interpret water table depths has resulted in significant systematic differences in the corresponding groundwater characteristics and that there are many sources of potential error. Error in the in-situ measurement of the water table depth can be as high as 1 m. Errors in the temporal aggregation are in the range of 10 to 20 cm and for the spatial interpolation between 20 and 50 cm. We show that there has been no systematic assessment of how these errors influence the resulting groundwater characterization. Thus, we cannot answer the question of whether drought stress in The Netherlands is under- or overestimated. Based on these findings we give recommendations for a systematic approach to groundwater characterizations studies that can minimize the impact of errors.

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1. Introduction

In many parts of the world, (ground) water depths are intensively monitored. These water table depths vary in time and space and depend on the interactive pedological and hydrological processes and their properties in the (un)saturated zone (Lin, 2012). Because we cannot measure water table depths everywhere and all the time we use temporal and spatial interpolation and aggregation methods to characterize the fluctuating water table depths (e.g. Van Heesen, 1970; Finke et al., 2004; De Vos et al., 2010). All these methods have their pros and cons, which one is best depends very much on the objective(s) of the research and the availability of data. In The Netherlands, water depth classes are based on the mean highest (MHW) and mean lowest (MLW) water tables. The MHW and MLW are calculated from time series of dip-well records which have been collected on a national scale since the beginning of the 1950's (Van der Sluijs and De Gruijter, 1985). Using profile and field characteristics, the MHW and MLW of the observation points are extrapolated for larger areas. Relationships are derived making it possible to convert water table classes into duration classes of water table depth. The water table at the beginning of the growing season (MSW) can also be derived from the MHW and the MLW.

The spatial and temporal representation of the water table depth or its characteristics in an area depends on the accuracy of the basic data, i.e. the measured water table depth. Various monitoring methods are used, i.e. observation wells, piezometers, open boreholes, (De Ridder, 2006), thus it is important to realize that the measured water level is not necessarily equal to the position of the phreatic surface (e.g. Brassington, 1992; Chapuis, 2005, 2009; Elci et al., 2003; Paydar and Richardson, 2002; Van Duijvenbooden, 1981). Furthermore, soils and hydrological conditions are in general not homogeneous (Bjerg and Christensen, 1992), which influences the accuracy of the temporal and spatial upscaling. Numerous studies have described the natural uncertainties (e.g. barometric pressure) and errors made in the interpretation of groundwater level data (e.g. Saines, 1981; Church and Granato, 1996; Dalton et al., 2007) and in the temporal and spatial upscaling (e.g. Knotters, 2001; Stein, 1991), but how these measurement and methodological errors affect the final upscaling result is often lacking.

To analyze the effects and ultimate impact of these errors and uncertainties, we have used The Netherlands as a case study. However such errors are not unique to The Netherlands and we believe that the lessons learned from our analysis will be useful for many other countries or regions of the world. The Netherlands, a low-lying country in Western Europe (50° - 54° N and 3° - 8° E), consists of deltas and former flood plains of the rivers Rhine, Meuse and Schelde (Colenbrander, 1989; Overeem et al., 2001). The total territory, including inland lakes, estuaries and territorial waters, is 41,543 km2, of which 55% is agricultural, 12% is nature, 19% is open water and the remaining 14% is built-up area (CBS, 2014). The land consists mainly of alluvial deposits and about 25% of the country lies below mean sea level (MSL). The lowest point is some 7 m below MSL. In the absence of dunes and dikes, more than 65% of the country would be flooded at high sea and high river levels (Van de Ven, 1996). Average rainfall (851 mm/year) is substantially higher than the potential evaporation (559 mm/year) (KNMI, 2014), thus drainage is a fact of life as it is required to use the land: for the inhabitants, for agriculture and for nature.

After the Second World War, agriculture intensified and more intensive drainage was required, resulting in deeper water tables, increased drainage rates and more drought stress in dry periods (Ritzema and Stuyt, 2015). This process was further intensified by an increase in groundwater abstraction and land consolidation practices employed to reduce the problems of fragmentation of land holdings (Van den Noort, 1987). These land consolidation activities were often combined with improvement of the water management and road infrastructure (Prak, 2002; Stańczuk-Gałwiaczek et al., 2018). It is estimated that the resulting average drop of the water table in agricultural areas has been in the range of 20 to 40 cm (Kremers and van Geer, 2000; Van der Sluijs and van Heesen, 1989). The drops of the water table in agricultural areas also resulted in deeper water tables in the neighboring nature areas (Martens et al., 2013; Van Tol et al., 1998). The water table in many areas is now significantly lower than the target values set by the Ministry of Transport, Public Works and Water Management (1999), not only in the man-made polders but also in the higher sandy areas in the east and south of The Netherlands. To counteract the adverse effects that these deeper water tables have on the environment, in particular nature reserves, the government has initiated policies to reverse the trend. However, in order to make informed decisions, policy makers and practitioners need reliable information on groundwater levels (Lijzen et al., 2014; De Lange et al., 2014).

In this research we contribute to the emerging interdisciplinary science of hydropedology by presenting an integrated, iterative methods for improved understanding of methodologies to derive groundwater characteristics for multiple scales. Hydropedology is an intertwined branch of soil science and hydrology that encompasses multiscale basic and applied research of interactive pedological and hydrological processes and their properties in the unsaturated zone (Lin et al., 2005). The objectives of our research were to analyze (i) the methods used to measure and upscale groundwater level information in both time and space and (ii) how the selected combinations of these methods affect the resulting groundwater characterization. For this analysis we reviewed all projects assessing the characteristics of seasonal fluctuation in groundwater behavior conducted by the Dutch Soil Survey Institute and its successors over the last 25 years. These projects have been documented in more than 170 reports and papers (Ritzema et al., 2012). One test/aspect of our results will be to see if we can answer the question of whether drought stress in The Netherlands (as determined by groundwater levels) is under- or overestimated.

After a brief discussion of the various definitions used for groundwater and groundwater characteristics, this paper presents:

- How different measurement methods and measuring depths lead to discrepancies or errors in the measured or estimated water table depth;
- How different temporal aggregation techniques lead to discrepancies or errors in the estimated characteristics of the seasonal fluctuation of water table depths;
- How different spatial interpolation and aggregation techniques lead to discrepancies or errors in the estimated spatial characteristics of the seasonal fluctuation of water table depths;
- The extent or impact that errors in these methods and techniques may have on the accuracy of the steps and ultimate determination of groundwater characteristic.

We conclude with a recommendation for a systematic approach that can minimize the effects of uncertainties and interpretation errors to provide the most consistent and robust estimate of groundwater characteristics for a specific area.

2. Definitions of groundwater and groundwater characteristics

In The Netherlands, several definitions of the hydrological parameters to define the position of the water table are used simultaneously, i.e. water table depth, groundwater level, phreatic level, phreatic surface, etc. This data is stored in "*Aquo-standard*", the data base of standardized concepts and definitions for data storage, exchange and processing for the Dutch water sector (http://www.aquo.nl/aquo-standaard). Water table depth is relative to the ground surface, whereas the other parameters are relative to a reference level. There are also various methods to measure the groundwater level, e.g. a groundwater observation well, piezometer, borehole, etc. All these definitions and methods are used interchangeably with the result that it is often not