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RESEARCH ARTICLE

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The water table: Its conceptual basis, its measurement and its usefulness as a hydrological variable

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Abstract

The water table, as used routinely by hydrologists in various disciplines, is seemingly a simple concept: it marks the top of the saturated zone in porous media. But closer inspection reveals that much of the theory and practice concerning the water table are less straightforward than is often assumed. We review departures from the classical definition of the water table and consider the following phenomena: perched and inverted water tables, gas bubbles within the "saturated" zone below the water table, and water tables in dual (and multiple) porosity media. We discuss some of the different methods used for measuring the position of the water table, their relative practicalities, and how to avoid measurement errors, such as those associated with hydrological instrument response times. We question whether the water table remains a useful concept, and conclude that it does, citing the examples of groundwater resource management and the water table's use as an indicator of soil aeration. In the concluding discussion, we identify the precautions that can be taken to ensure water tables are appropriately measured and interpreted.

KEYWORDS

classical water-table model, dual- and multi-porosity soils, perched water tables, quasi-saturation, water table, water-table measurement

1 | INTRODUCTION

As hydrologists, we all know what the water table is, don't we? It marks the top of the saturated zone in porous media (Fetter, 1994), but the soil or rock above it can also be saturated (Freeze & Cherry, 1979), while pockets of trapped gas may occur below it (Faybishenko, 1995). It is the surface within a porous medium where the water is at atmospheric pressure, and also a flux boundary (Youngs et al., 1989). It is easy to measure (Marshall & Holmes, 1988), except that sometimes it isn't (Bouma et al., 1980). It can be used as a predictor of soil biochemical processes (Baird et al., 2019; Kahlown et al., 2005; Laine et al., 2007), but these predictions are sometimes "noisy" and not consistent between different soil types. Perhaps the water table is not a simple thing after all. Given its ubiquity—"water table" and "watertable" have been mentioned in 1058 papers in *Hydrological Processes* since the journal's inception in 1986 (Google Scholar search on 19 July 2021)—it is surprising that there has been no detailed treatment of what we mean by "water table". This paper attempts to fill that gap and in so doing add to the short commentary by Holzer (2010). We start by considering problems with the classical definition of the water table. We then look at how the water table is measured and what the different measurement methods reveal about the hydrological functioning of a range of porous media. Finally, we reflect on its usefulness as a hydrological concept, and provide suggestions on the precautions that might be taken when collecting and analysing data on water-table dynamics in future studies.

FIGURE 1 Sandcastle with water-filled moat: A first (informal) study of the water table. (Photo: Andy Baird)

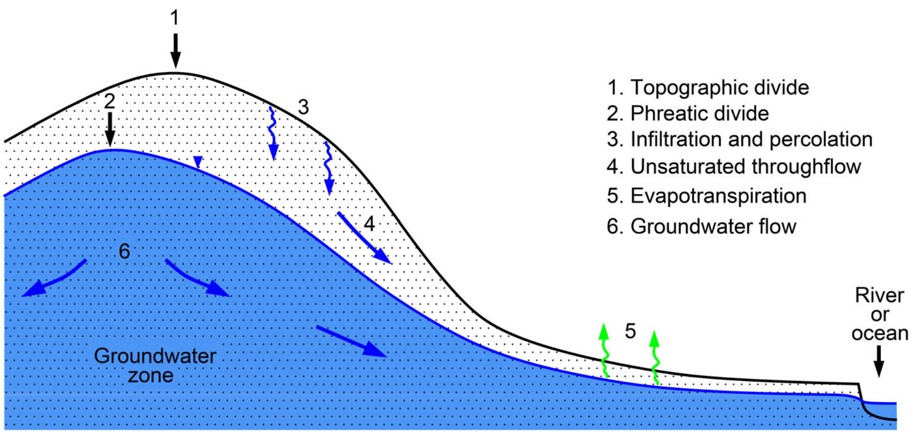

FIGURE 2 The topographic and the phreatic (water-table) divides between adjacent drainage basins. The inverted triangle is a widely used symbol for denoting the water table. The situation shown in the figure is idealized and may not apply to many real-world situations as we explain in Section 3.

We do not attempt to provide a synthesis of all that has been written on the water table; that would be a monumental, if not impossible, task. We do, however, assume that our own reading of the hydrological literature has provided a reasonably representative sample of what is written more widely on the water table, especially the water table as a concept. Nevertheless, it would be more accurate to describe this paper as an extended commentary rather than a review. Where appropriate we try to reference the foundational or early literature on the subject; our reference list therefore includes many old or middle-aged papers; more so than a typical paper in *Hydrological Processes*. Finally, our focus is somewhat biased towards soils, although we also consider water tables in the geological formations below soils. This emphasis reflects our backgrounds in soil hydrology (both authors) and applied hydrogeology (R. L.).

2 | THE WATER TABLE IN EVERYDAY HYDROLOGY

Without knowing it, many of us have our first encounter with the water table as children on the beach when we make a sandcastle surrounded by a moat. In digging the moat, we are making a type of ring well. Water flows into the moat until it is at the same level as the water table in the adjacent sand. Water may rise in the moat when the tide comes in, or the moat may become dry as the tide ebbs. When we ponder why these changes in the moat occur, we are, in effect, being hydrologists and hydrogeologists (Figure 1).

More formally, many of us are first introduced to the water table in secondary or even primary school in lessons on the hydrological cycle and drainage basins. Later at university we may also learn that the water table is sometimes used to delineate the boundaries of drainage basins, and that the water-table divide (or groundwater or phreatic divide) may not be the same as the topographic divide (or surface-water divide) (Price, 1996). Many text books give only a brief definition of the water table as the top of the groundwater zone, the latter being shown as a continuum within the drainage basin in Figure 2, such that water entering the zone will find its way to a river channel or the ocean, if it is not first lost to evaporation and transpiration which can happen when the water table is close to the ground surface (e.g., Arnell, 2002; Bras, 1990; Holden, 2005).

Beyond drainage basins and the hydrological landscapes within them, the water table is a "stock-in-trade" of many disciplines, including agronomy, hydrogeology and ecohydrology. Each of these examples is considered briefly below.

Crop yield is closely related to the hydrological status of the soil. If a soil is too dry or too wet the yields of many crops, most of which are mesophytes, are suppressed. Water-table position also affects crop yield indirectly through its impact on the workability and trafficability of the soil. In low-lying areas where water tables naturally occur near the ground surface, it is common for agricultural land to be drained with a combination of open ditches and buried (perforated) pipes or tiles. The literature on the relationship between crop-yield and water-table depth, and the causal mechanisms involved in the relationship, is enormous and spans many decades to the present (e.g., Benz et al., 1985; Evans et al., 1991; Wen et al., 2020; Williamson, 1968), and whole journals (e.g., *Agricultural Water Management* and *Journal of Irrigation and Drainage*) and books (e.g., Smedema & Rycroft, 1983) are dedicated to the subject. It is probably not an exaggeration to say that many agronomists are preoccupied with water-table management.

Hydrogeologists share this preoccupation, with the elevation, shape and behaviour of the water table usually being the first things to be considered, or measured, in most hydrogeological investigations. Groundwater—typically in geological formations below the soil zone—accounts for ~30% of all global freshwater (Shiklomanov & Sokolov, 1983, cit. Dingman, 1994), and in many places is the principal source of agricultural, industrial and domestic water supplies. For example, groundwater is abstracted at an aggregate rate of 7 million cubic metres per day in England and Wales, and locally in the south of England it fulfils in excess of 70% of the total supply (Jackson et al., 2015). Water-table elevation is a fundamental variable in relation to groundwater resource management because it defines the extent of the resource. At the small scale, the hydraulic properties of water-yielding rocks (aquifers) can be quantified through interpretation of water-table behaviour during borehole pumping tests (Kruseman & de Ridder, 1994), and groundwater recharge in response to rainfall events can be estimated through analysis of water-table response.

In ecohydrology—the study of the linkages between hydrological and ecological processes—water-table position relative to the ground surface is recognized as a key variable controlling vegetation composition in a range of environments. The component species of wetland plant assemblages, for example, often have physiological adaptations that allow them to exist under the varying levels of waterlogging associated with different water-table regimes, which in turn are reflected in differences in their competitive advantage or disadvantage with other species (Bannister, 1964; Wheeler, 1999). For example, many vascular wetland plants have connected pore space in cortical tissues, aerenchyma, which allows downwards diffusion of oxygen for root respiration (Jackson & Armstrong, 1999; Mitsch & Gosselink, 2000). Vegetation can also influence groundwater levels by affecting the rainfall receipt of the soil (interception losses) and via direct uptake of groundwater during transpiration (Benyon et al., 2006; Godwin, 1931).

Perhaps because of its ubiquity in the hydrological literature, and the fact that it is one of the most commonly-measured (and perhaps mis-measured – see Section 4) hydrological variables, we tend not to think too closely about the water table as a concept and what it really indicates about the hydrological status of the subsurface. Next, we consider classical soil water theory and then show how this applies strictly only to a small subset of circumstances.

3 | DEFINING THE WATER TABLE

3.1 | Popular definitions

As noted in Section 2, the water table is widely reported as the upper surface of the groundwater zone or the upper level of saturation in the subsurface. Some texts are more precise, and identify the water table as the free surface within a porous medium; that is, the position within a soil or geological formation where the pore water pressure is equal to atmospheric pressure (Dingman, 1984; Domenico & Schwartz, 1990; Hubbert, 1940). Generally, the latter definition is preferred because it avoids confusion over the capillary fringe, a zone of saturation above the water table in which water is held at sub-atmospheric pressures (Holzer (2010); see Section 3.2). Below, we consider the concept of the water table in simple, homogenous, porous media; we call this the "classical case". We follow by looking at (i) more realistic and complicated scenarios where the subsurface is heterogeneous, (ii) situations where the porous medium *below* the water table is unsaturated, and (iii) dual- and multi- porosity media where water-filled macropore networks may juxtapose an unsaturated matrix. Finally, we briefly consider situations where rapid water-table fluctuations may occur.

3.2 | The classical case

In a simple homogenous and isotropic porous medium, such as a medium-grained sand, the water table is readily defined as shown in Figure 3. In the figure, conditions are assumed to be hydrostatic, and complications such as water flow through the soil profile after rainfall are ignored. Below the water table, all pores in the sand are water-filled (Figure 3b). Above it is a capillary fringe, where again all or most pores are water-filled, water being held in these pores by capillary forces against gravity at less than atmospheric pressure. A saturated capillary fringe may not be present in coarser-grained soils or sediments, because, as well as smaller pores, these soils contain larger, non-capillary, pores in which water cannot be held at sub-atmospheric pressures. Above the capillary fringe, water content decreases with height. In the hydrostatic case shown in Figure 3, changes in pore-water pressure (shown as the pressure head in Figure 3c) follow a 1:1 line, with negative values (sub-atmospheric pressures) above the water table and positive values below it. Elevation head also follows a 1:1 line, with positive values above the water table, which is treated as the datum. The total or hydraulic head ($H_T = H_e + H_p$) is constant with height at a value of 0.

Conditions above a flat water table can also be highly dynamic. Vertical downwards flow to the water table may occur after rainfall, while vertical upwards flow may occur in response to evaporation from the ground surface. These situations are not considered here but would result in moisture and head profiles different from those shown in Figure 3 (for more detail, see Wellings & Bell, 1982; Dingman, 1994; Marshall & Holmes, 1988).

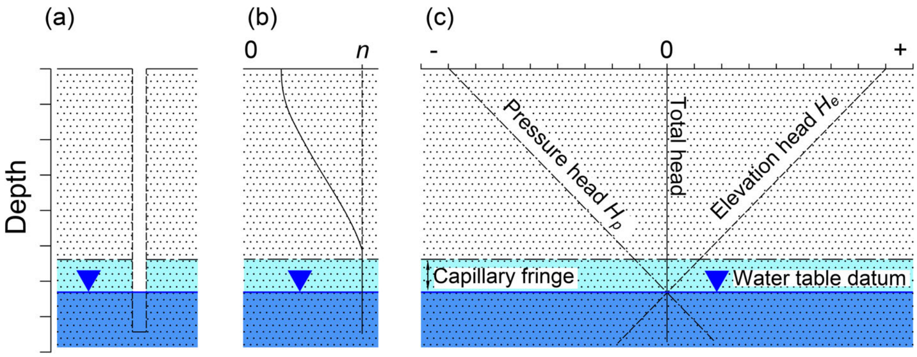

FIGURE 3 The water table in an idealized porous medium or classical soil. (a) Well (see Section 4.2) showing the position of the water table, below a saturated capillary fringe. (b,c) Soil water content and soil-water energy status vertically above and below the water table. *N* denotes (total) porosity. Based on original figures in Price (1996) and Freeze and Cherry (1979).

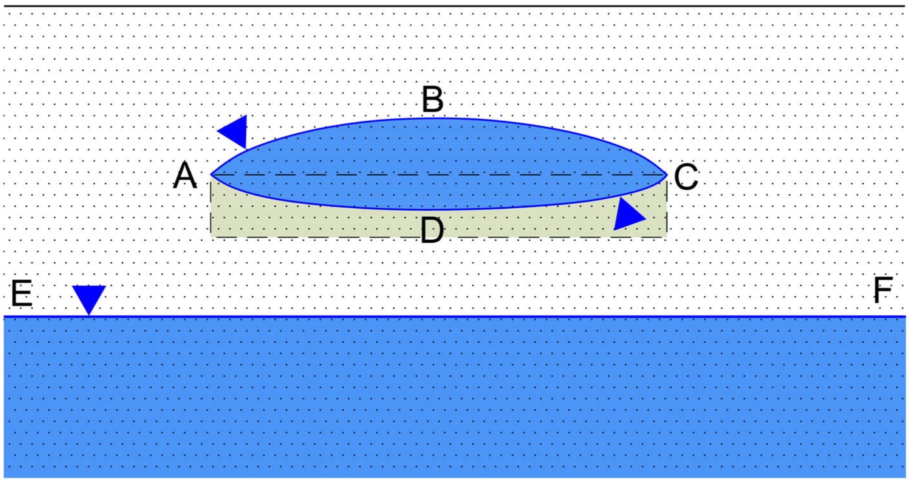

FIGURE 4 Three water tables in one porous medium. Perched water table: (A-B-C); inverted water table: (A-D-C); and "true" (Freeze & Cherry, 1979) water table: (E-F). Based on an original diagram in Freeze and Cherry (1979). The grey shading shows the silt layer set within the sandy soil. For simplicity, capillary fringes are not shown.

3.3 | Departures from the classical case 1: Perched and inverted water tables

The situation depicted in Figure 3 assumes a simple continuum. Everywhere below the water table is saturated, everywhere above the capillary fringe is below saturation, and the vertical head distribution shown in Figure 3c applies to all points laterally across the medium. We may introduce a complication to this situation and imagine a low-permeability silt or clay layer is present within the sand, as shown in Figure 4.

The silt impedes downward-flowing water (after rainfall, for example). Water "ponds" on the layer forming a saturated lens. The wetting front moving downwards through the silt forms an inverted water table, while above the surface of the silt, a perched water table develops. In the sand below the silt layer, a lower water table is also present, denoted E-F. Freeze and Cherry (1979) call this lower water table the "true water table", although A-B-C and A-D-C both meet the common criteria of a water table noted in Section 3.1. Ignoring (for simplicity) any capillary fringes, surface A-B-C is the top of a saturated zone and also the surface at which water is under atmospheric pressure. A-D-C is also at atmospheric pressure but is the bottom of the local saturated zone.

In our commercial (consultancy) experience, perched water tables are often wrongly inferred where steep vertical hydraulic gradients occur, even though there is full vertical hydraulic continuity in the system; that is, the system is saturated throughout. Although there are also large differences in hydraulic head between the perched and "true" water tables in Figure 4, the two are separated by unsaturated ground, and therefore not in direct saturated hydraulic contact (Hiscock, 2005).

The situation shown in Figure 4 is necessarily hydrodynamic and because of this would not, in reality, be as simple as depicted: as long as there is a groundwater lens associated with the silt layer, water will drain through and from the edges of the layer. In consequence, we might expect E-F to bulge upwards in various locations below the lens. Water flowing through the lens may also be subject to "fingering" (Beven, 2018).

Figure 4 depicts a very simple heterogeneous soil. Many parts of the subsurface have a much more complicated structure than shown in the figure, and it is possible that such structures, in turn, lead to greater complexity in water tables than so far considered. However, the effect of heterogeneity will depend in part on the scales at which it operates (Baveye & Laba, 2015). If, for example, most of the variability occurs over small scales—perhaps within volumes of the order of several dm^3 (litres)—then the system may not behave much differently from the idealized continuum shown in Figure 3.

To illustrate this second point, consider a soil in which hydraulic conductivity (permeability) (*K*) ($L\ T^{-1}$) measured using soil samples of the volume noted above (several dm^3), varies by two orders of magnitude within a hillslope. If the variation in *K* at the scale of the measurement volume is mostly random along and across the hillslope, the system will tend to "even itself out". Water flowing downslope will be impeded by a low-*K* "parcel" of soil. However, because the low-*K* parcel is small, and because it is likely to adjoin parcels with a much higher *K*, water can find an alternative route downslope. The same is true in the vertical. The parcels of low-*K* soil are too small to allow a situation to develop such as that depicted in Figure 4. Percolating water impeded by the low-*K* parcels flows easily to the side of them and continues downwards; perched water tables do not develop above the parcels. Therefore, in terms of both the flow field and the water table, this situation of small-scale and random variability of *K* is probably well described by a model in which a single "effective" *K* value is assumed to apply to all of the soil, in which a single continuous water table, like that shown in Figure 2, also prevails. This model of random, small-scale, heterogeneity is called an "equivalent homogeneous hillslope" (Binley et al., 1989) (see also "functional homogeneity", e.g., Basu et al. (2010)).

However, if the soil contains distinct structures—if *K* is spatially auto-correlated—then this equivalent homogeneous simplification no longer applies, as shown theoretically in a modelling study by Binley et al. (1989), and for a real drainage basin by Ali et al. (2011). In the latter study the authors made multiple water-table measurements from a network of 94 wells in an area of 5.1 ha, and found that water-table depths below the ground surface depended on patterns of heterogeneity in a low-*K* soil horizon. Pronounced, spatially-structured heterogeneity of soil hydraulic properties is common in some soils such as fragipans, and extensive perched water tables may occur in these (McDaniel et al., 2008). Perched water tables may be monitored by shallow wells ("dipwells" – see Section 4.2) with bases that terminate at the low-permeability lens or soil horizon above which the perched water table is found (McDaniel et al., 2008).

3.4 | Departures from the classical case 2: Air encapsulation and biogenic gas bubbles below the water table

In Figures 3 and 4 the zone below the water table is shown as saturated, as is the lens between the perched and inverted water table. Even when the water table is defined as the plane or surface at which water is at atmospheric pressure, it is usually assumed that conditions below it are saturated (e.g., Fetter, 1994). In reality, soils are probably rarely saturated below the water table (Peck, 1960). Faybishenko (1995) makes a distinction between what is commonly called the unsaturated zone above the water table (or above the capillary fringe) and unsaturated conditions below the water table, for which he uses the term "quasi-saturated". Quasi-saturation may occur through the entrapment or encapsulation of soil air or may be caused by the generation of decay gases in situ.

Water percolating into a soil during and after rainfall tends to "flood" through larger pores, which saturate and fill, thereby blocking the escape of air from smaller pores connected to the larger pores (Bond & Collis-George, 1981; Peck, 1969; Philip, 1957). Air encapsulation has also been reported in laboratory studies in columns of soil that have been wetted slowly from their base to raise the water table to the soil surface. For example, Beckwith and Baird (2001) and Baird et al. (2004) found that samples of bog peat contained a trapped volumetric gas content of between 1% and 13% after they had been wetted in this way, while for columns of sand Marinas et al. (2013) report values of between 8% and 16%. The difficulty of achieving full saturation even with slow upwards wetting in laboratory settings suggests that field soils must be rarely, if ever, saturated below the water table (see also Norum & Luthin, 1968; Peck, 1960).

The generation and build-up of bubbles containing a mixture of mostly methane (CH_4) and carbon dioxide (CO_2) produced from the decay of soil organic matter can also lead to considerable undersaturation below the water table. Bubbles of decay gases forming in situ have been reported widely in organic soils (Beckwith & Baird, 2001; Comas et al., 2005; Kellner et al., 2005; Mustasaar & Comas, 2017; Strack et al., 2005), and volumetric gas contents as high as 20%–25% have been recorded in these studies. It seems organic soils have a threshold volumetric gas bubble content beyond which there is little or no further net accumulation of bubbles. If more bubbles are produced, these new bubbles, or pockets of existing bubbles, will escape to the water table in a process known as ebullition (Rosenberry et al., 2006; Tokida et al., 2005). The threshold, however, is fuzzy and seems to depend on soil (peat) type (Kellner et al., 2006; Ramirez et al., 2015).

As biogenic gas bubbles form and enlarge they will displace water and cause the water table to rise. More generally, any gas trapped below the water table, biogenic or not, will give rise to fluctuations in water-table height with changes in atmospheric pressure. Gas is approximately 10 000 times more compressible than water, and compression and expansion of bubbles with rises and falls in atmospheric pressure will cause the water table, in turn, to fall and rise. In a laboratory experiment on a sand column, with a water table ~160 cm above the base of the column and a trapped gas content below the water table of 6%, Peck (1960) found a sensitivity between water table height (*h*, m) and atmospheric pressure (*P*, hPa)—expressed as d*h*/d*P*—of ~0.0005 m hPa^{-1}. This ratio is also called the barometric efficiency (Price, 1996) when the same units are used for *P* as for *h* (0.0005 m hPa^{-1} is 0.05 when both *h* and *P* are given in units of cm or m of water). Peck (1960) developed an equilibrium model based on changes in gas volume due to changes in pressure (the Ideal Gas Law) and solubility (Henry's Law) to estimate the barometric efficiency. Norum and Luthin (1968) accounted for the same effects in a dynamic model based on the Richards equation and found a significantly greater sensitivity: a barometric efficiency two to three times that reported by Peck. The sensitivity of water tables to changes in atmospheric pressure is not insignificant and will depend on trapped gas content, which can be much higher than measured and assumed in Peck's (1960) or Norum and Luthin's (1968) work (e.g., more than 20% in some peats – see above this section). It will also depend on the thickness of the quasi-saturated zone and the pore-size distribution above the water table and may be of the order of a few cm or more during the passage of a low-pressure weather system after a period of anti-cyclonic weather.

Water tables may show higher-frequency variations than those associated with the passage of synoptic-scale weather systems. Diurnal fluctuations have been interpreted as a response to evapotranspiration, and methods have been developed to estimate evapotranspiration rates from these cyclical changes (for relatively recent examples, see Loheide II, 2008; Wang et al., 2014). However, as noted by Peck (1960), such high-frequency variations may be caused by a range of mechanisms, and the degree to which water tables vary in response to fluctuations in atmospheric pressure must be known before such variations can be attributed and related with any accuracy to other factors. Cyclical variations in atmospheric pressure can be diurnal, as can occur with local weather systems that develop and decay in response to solar heating, and both diurnal and semi-diurnal as is the case with atmospheric tides (McMillan et al., 2019). Because water has to flow through the soil to accommodate changes in the volume of trapped gasses there may be a lag between changes in atmospheric pressure and water tables (Norum & Luthin, 1968). Depending on the length of this lag, it is possible for water-table changes to seemingly lead pressure changes, and such complications can make the interpretation of water-table fluctuations and their causes more difficult. Changes in atmospheric pressure may also cause falls in water tables by inducing ebullition and loss of trapped bubbles to the zone above the water table. Both rises and falls in atmospheric pressure can destabilize gas pockets within a soil (Kellner et al., 2006; Tokida et al., 2005).

One important consequence of the classical assumption of saturation below the water table is that the hydraulic conductivity K_{sat} in this zone is taken as being constant in time, an assumption made in the great majority of groundwater models. In practice, K is likely to be lower than the saturated value because trapped gas bubbles act as embolisms in the soil pores, blocking water flow. Therefore, below the water table it is more appropriate to think of $K(\omega)$, where ω denotes the volumetric fraction of trapped gas bubbles, given by $\theta_{sat} - \theta_{qsat}$, with θ denoting volumetric water content and *qsat* quasi saturation (Faybishenko, 1995; Marinas et al., 2013). The difference between K_{sat} and $K(\omega)$ can be substantial. For example, Beckwith and Baird (2001) found that K_{sat} was five to eight times greater than $K(\omega)$ in a peat soil in which biogenic gas bubbles accumulated, while for encapsulated air in loamy soils Faybishenko (1995) showed that K_{sat} could be up to two orders of magnitude greater than $K(\omega)$.

As well as being less than K_{sat}, $K(\omega)$ will typically vary over time as the trapped gas content changes. For example, trapped air may go into solution over periods of hours to days (Bond & Collis-George, 1981; Faybishenko, 1995), while biogenic gas bubbles may grow (as decay proceeds) or be lost through ebullition (see above, this section) over periods of hours to weeks (Baird et al., 2004; Comas et al., 2011; Goodrich et al., 2011; Stanley et al., 2019; Strack et al., 2005; Tokida et al., 2007). Thus $K(\omega)$ measured in situ on one occasion may not be suitable for modelling groundwater flows on another occasion if there is a change in ω. The error involved in using the wrong K could be considerable – flows modelled using Darcy's Law may be several factors or more (see above) too high or low. Clearly, unless it is known that the trapped gas content is unchanging (very unlikely) or conditions are always saturated (also unlikely), in situ measurements of K below the water table should not be regarded as being a constant in time.

$K(\omega)$ can be expected to differ from $K(\theta)$, the latter referring to the hydraulic conductivity in the zone above the water table. The difference is explained by the size and location of unsaturated pores above and below the water table. As water drains from the zone above the water table, it tends to do so in the order of largest pores first and then progressively smaller pores, meaning that K-θ relationships are often well defined (van Genuchten, 1980). Below the water table, entrapped gas may be present across a wide range of pore sizes, and its location in the pore space may vary in time as bubbles move through the soil and coalesce, or dissolve and shrink, or form at different micro-sites.

The phenomenon of quasi-saturation will also affect the rate with which the water table rises and falls in response to recharge and water losses. The effect of gas bubbles on such water-table dynamics can be considered in terms of the specific yield (s), which may be defined as the amount of water released from (or taken up by) a soil, sediment, or rock formation when a unit fall, or rise, of the water table occurs (Youngs et al., 1989):

$$s = {}^{V_w}\!/_{A\Delta h} \tag{1}$$

where V_w is the volume of water (L^3) that drains from a column of soil or rock when the water table falls by Δh (L), and A (L^2) is the cross-sectional area of the soil (rock) column. In situations with a rising water table, V_w is the amount of water that has to be added to the soil to cause the water table to rise by Δh. Specific yield is a key parameter in models of water-table dynamics in which the unsaturated zone is not explicitly modelled, such as the simple, but widely used, Boussinesq equation (McWhorter & Sunada, 1977), and models based on the full version of Darcy's Law such as Modflow (or MODFLOW) (Harbaugh, 2005).

In addition to causing water-table fluctuations in response to changes in atmospheric pressure, trapped gas will affect s and water-table dynamics in two ways. First, if trapped bubbles reside in pores that would normally drain or fill during the fall or rise of the water table, s will have a lower value and the water table will be more dynamic. Secondly, because the amount of trapped gas may vary over time, the response of the water table to a given gain or loss of water will also vary (Nachabe, 2002). For example, a water-table may rise by 10 cm in response to 1 cm of rainfall on one occasion, but only 7 cm on another, the difference being due to the amount of air that was encapsulated as rainwater percolated downwards to the water table. Variations in the amount of encapsulated gas may be related to rainfall intensity: higher-intensity rainfall may trap more air than lower-intensity rainfall (Fayer & Hillel, 1986a, 1986b). The volumetric gas content below the water table following rainfall can also be highly variable in time (see above)), again giving variations in s, so that the degree to which the water table drops in response to a given loss of water from the profile on one occasion may be different from that on another occasion. We can therefore think of *s* not only varying with position in the soil profile (*z*) but with time (*t*): *s*(*z*, *t*). However, the extent to which variations in trapped gas have an effect on *s*, and the scales over which it does so, is, to our knowledge, unknown for many soil types.

3.5 | Departures from the classical case 3: Dual (and multiple) porosity soils and aquifers

In some types of soil and rock formation there may be discontinuities in the size distribution of the pores. An example is swelling/shrinking clays where the soil, especially after dry periods, consists mostly of (i) very small pores in what is often called the soil "matrix" (Beven & Germann, 1982) and (ii) a network of cracks. Even in non-cracking clay soils, the soil may have a blocky structure where large peds (soil aggregates) of matrix are separated by planar voids. The cracks and voids may be orders of magnitude wider than the pores within the matrix but occupy only a small relative volume in the soil (perhaps just a few percent).

Strong bi-modality or discontinuities in the pore-size distribution may give rise to complicated patterns of water flow and water-table dynamics. In an early study Bouma et al. (1980) investigated water tables in a clay soil with angular blocky peds. To monitor the water table, they installed, in replicate, a vertical array of tensiometers (see Section 4.3) to a depth of 100 cm, and also a series of unlined auger holes to depths up to 50 cm in an area of just 0.5 m × 1 m. Water levels in the shallow holes were spatially very variable (by more than 20 cm, with some holes remaining dry) and mostly above the position of the interpolated zero pressure head (H_p) (see Section 3.1) obtained from the tensiometers (see also Section 4.3). Bouma et al. (1980) interpreted these results as arising from a partly discontinuous network of voids between the peds, as shown in their conceptual model reproduced in part in Figure 5. Some shallow auger holes (such as shown to the left in Figure 5) intercepted percolating water from relatively high in the soil profile (upper 20 cm) which flowed into them and then drained slowly from the base of the hole which, unlike the upper part of the hole, was not connected to the network of structural voids. Other auger holes were connected along their lengths to the void network, and filled and drained readily as water levels in the voids rose and fell (see the auger hole to the right in Figure 5). Bouma et al. (1980) noted that, because of the low density and small relative volume of the inter-ped voids, the chances of a tensiometer cup intersecting them was low. In other words, the tensiometers measured pore-water pressures in the peds only and indicated the presence of a water table only when the ped had wetted up in response to rainfall.

Bouma et al. (1980) took a narrow view of what constitutes a water table. They suggested that the free water surface in the voids does not qualify because pore-water pressures in the surrounding soil were often below zero (sub-atmospheric); the peds were not saturated. They state: "classical flow theory does not allow for the simultaneous presence of saturated and unsaturated soil at the same

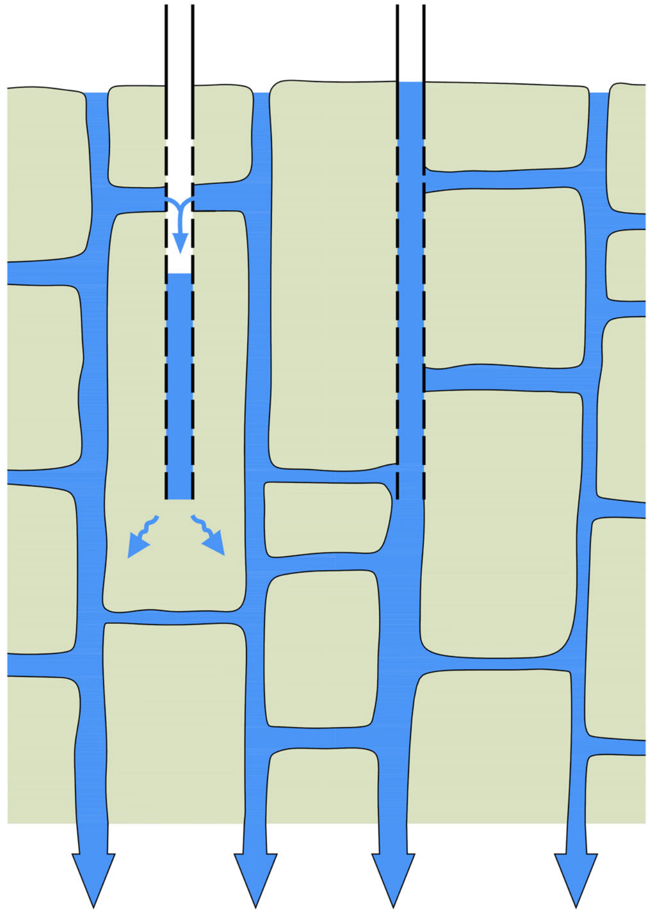

FIGURE 5 Part of the conceptual model of blocky clay soils proposed by Bouma et al. (1980) (redrawn, with modifications). The structural voids have been exaggerated in size. Flow through the voids will follow a complex pattern depending on the 3-D connectivity of the network. See text for further explanation.

depth". Their definition requires the free surface to be laterally extensive and would even exclude perched water tables such as that shown in Figure 4 if the silt lens was limited in extent (perhaps less than a metre or two in length). Other authors have taken a broader view on the matter. Armstrong (1983), for example, noted that water levels in the cracks and voids in structured clay soils should be regarded as real water tables and are physically and biologically meaningful. Nevertheless, because of the high spatial variability of water levels in these soils, he suggested that the water table in structured clay soils should be considered in probabilistic terms, using the mean and spread (standard error) of a set of measurements rather than a single value.

The size of the inter-ped voids in dual-porosity soils may vary over time. For example, in winter the matrix is hydrated and expands to its maximum volume, closing or sealing cracks that may have formed in summer. Variations in the specific volume of the inter-ped voids can in turn lead to variations in water-table behaviour. Baird (1995) recorded water tables in a cracking clay soil adjacent to a drainage ditch and found that water tables following rain fell more rapidly in autumn than in winter. He attributed the difference to two possibilities. First, the more rapid autumn response could be due to crack flow which is reduced in winter by swelling of the clay matrix as the soil wets up fully. Alternatively, if the clay matrix has not reached saturation in the autumn, the fall of the water table may have been due to flow from the voids and cracks into the matrix as well as flow through the crack network to the drainage ditch. Of course, the two possibilities are not mutually exclusive.

The structural voids in the soil studied by Bouma et al. (1980) are a type of macropore. Definitions vary, but macropores are usually considered to be larger pores in the soil in which capillary forces are absent or small (for a review, see Beven & Germann, 1982). As well as cracks due to shrinkage, macropores may be formed by plant roots, faunal activity (e.g., earthworm burrows), or by within-soil erosional processes (Beven & Germann, 1982; Beven & Germann, 2013; McCoy et al., 1994). Water flow within macropore networks in general—not just in cracks and structural voids—is often much more rapid than that in the surrounding matrix. Therefore, as with the soil studied by Bouma et al. (1980), the matrix will be by-passed during downwards percolation following rainfall, with local areas of saturation developing in the vicinity of macropores, potentially leading to a complex spatial pattern of water tables. Beven and Germann (1982) have argued that the classical treatment of a soil as a continuum in which "equilibrium" flow occurs (sensu Jarvis, 2007) is unsuited to the complexity of real (field) soils in which networks of macropores are common. Despite a now long history of macropore research, Beven and Germann (2013) suggest that much more empirical work is needed on how macropores affect the movement and distribution of water in soil profiles.

A similar situation to that in the clay soils studied by Bouma et al. (1980) exists at a much larger scale in some geological formations, notably limestones. For example, in the Chalk aquifer of north-western Europe the vast majority of mobile water and groundwater flow is hosted by the fracture and fissure network, yet this network only represents between 1% and 2% of the bulk volume of the aquifer (Downing et al., 1993). Limestone aquifers are usually considered as dual-porosity, and often triple-porosity, systems (Boak & Johnson, 2007). At the smallest scale is matrix porosity, comprising inter-crystalline and inter-granular pores of small diameter (50–500 μm). At the intermediate scale are fractures that have experienced little or no dissolutional enlargement and have typical widths less than 1 mm. The largest scale is represented by fractures which have been dissolutionally enlarged to some degree, with apertures ranging from several millimeters to meters (i.e., caves).

The marked heterogeneity in limestone aquifers, in both porosity and permeability, inevitably leads to complex groundwater systems with, for example, epikarst (saturated, often highly permeable limestone close to the ground surface, perched on less permeable unsaturated limestone [Williams, 2008]) and stepped water tables. A study similar to that of Bouma et al. (1980), but at a larger scale in a limestone aquifer, would reveal this complexity and its broad similarity to the clay soils discussed above. However, the water table in limestone aquifers is frequently monitored using deep boreholes perforated along their length which tend to intercept the network of dissolutionally-enlarged fractures, therefore allowing monitoring of the lowest, functional (in the sense of water resource management) water table.

3.6 | Rapid fluctuations of the water table in classical soils

Differences in water-table response between autumn and winter (Baird, 1995) (Section 3.5) and variations in water tables with changes in atmospheric pressure over diurnal and sub-diurnal timescales (Norum & Luthin, 1968; Peck, 1960) (Section 3.4) may be regarded as "unusual". However, other types of unusual behaviour have been reported. Perhaps the most notable are instances of apparently disproportionate rises of the water table in response to rainfall (Gillham, 1984); that is, the situation when a small amount of rainfall, say 0.3 cm, leads to a very large water-table response, say 30 cm. This phenomenon—widely called the reverse(d) Wieringermeer effect (Gillham, 1984)—is readily explained by the presence of a thick capillary fringe above the water table that reaches the ground surface (Cloke et al., 2006; Gillham, 1984). Only a small depth of water is needed to convert this zone of tension saturation to one of positive pore-water pressures, causing the water table to rise to the ground surface. Groundwater "ridging" associated with rapid water-table rise has been invoked to explain a range of other hydrological phenomena, including the appearance of old water in river discharge waters shortly after the onset of rainfall (Abdul & Gillham, 1994). McDonnell and Buttle (1998) and Cloke et al. (2006) suggest the phenomenon is unlikely to be widespread, and probably only applies to well-sorted sands that conform with the requirements of the classical model shown in Figure 3. However, sandy soils can extend over large areas and be of regional importance (Jaber et al., 2006). Substantial and rapid water-table rise may also be caused by the over-pressuring of air trapped below an advancing wetting front following rainfall or irrigation, a process called the Lisse effect (Weeks, 2002; Waswa and Lorentz (2016).

4 | MEASURING THE POSITION OF THE WATER TABLE

4.1 | A measurement-dependent concept?

Unusually in the hydrological literature, Marshall and Holmes (1988) (see also Hubbert, 1940) define the water table in terms of how it is measured:

> "In the field the water table lies at that depth in an auger hole where free water just begins to flow in. It is accurately indicated by the static level of the water in the hole when the depth of water is vanishingly small, a curious requirement that guards against hydraulic head gradients with a vertical component".

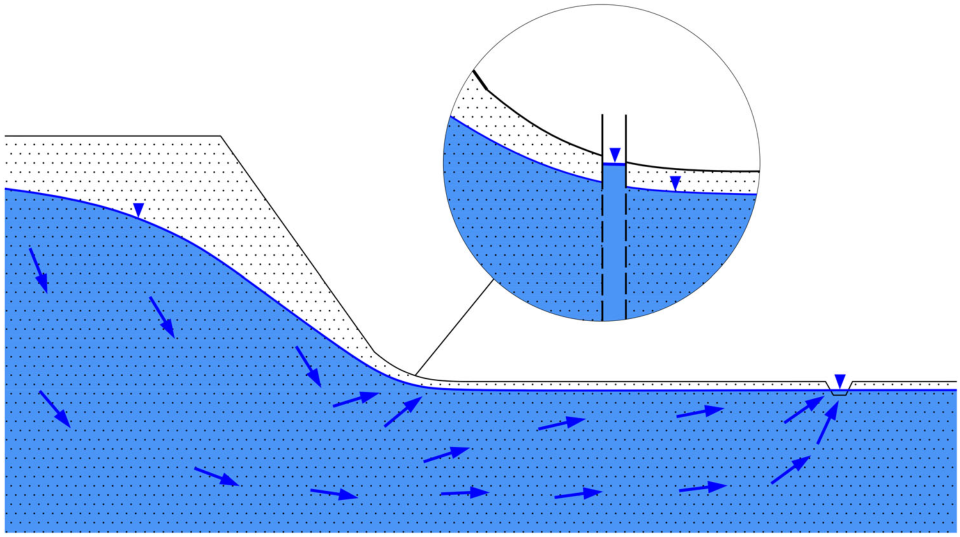

FIGURE 6 The water table and patterns of groundwater flow in a floodplain soil and adjoining hillslope. Upwards flow of water at the hillslope-floodplain boundary leads to errors in measurements of the water table when using a dipwell that extends a substantial distance below the water table (see inset and text for further information).

This definition is identical to one of the two given in Section 3.1 above: namely, that the water table represents the level in the soil at which water is under atmospheric pressure. In practice, it would be difficult to follow the advice of Marshall and Holmes (1988). Their method would require deepening an auger hole as the water table dropped and excavating a series of shorter holes as the water table rose. An observer would have to be in the field constantly, and a site might soon be riddled with holes. Nevertheless, the strict requirement set out by Marshall and Holmes (1988) is useful to bear in mind as a standard against which more practical measurement methods might be compared.

Advice on measuring water tables in hydrological textbooks rarely amounts to more than a short description similar to that given by Smedema and Rycroft (1983):

> "Its [the water table's] location may be found by sinking a borehole into the groundwater body. Water from the surrounding soil will flow into the hole and fill it to the watertable [*sic*] level…For regular watertable depth measurements the borehole may be fitted with a perforated pipe in order to give the hole a degree of permanence". [text in square brackets added]

Smedema and Rycroft (1983) is a standard textbook on how to manage water-table levels in agricultural land through land drainage. The principal focus of the book is water tables. So, it is surprising that such a terse description of water-table measurement is given. However, in our experience, many field hydrologists regard water-table measurement as a simple procedure, and it is common to find a similar absence of detail in papers in which water-table data are presented. Few method descriptions go beyond the following (written here as instructions): auger a hole that extends at least several 10s of cm below the expected level of the water table in the soil; line the hole with a perforated plastic tube; measure the water level in the tube to obtain the water table. While such an instrument may provide useful data, it is possible that it gives readings that are substantially different from the level of the free-water surface outside the tube. In practice, accurate measurement of the water table is not simple, as we discuss below.

4.2 | Auger holes/dipwells

Consider a floodplain as shown in Figure 6 comprising a moderately-permeable soil. Away from the boundary with the hillslope and away from the immediate vicinity of the river, the floodplain water table slopes gently. In this zone the method outlined by Smedema and Rycroft (1983) (see above) would probably yield an accurate water-table measurement. An auger hole 3.5 cm diameter is drilled to a depth of 150 cm, the latter chosen to ensure the base of the hole is always at least 10–20 cm below the expected water-table level. The hole is lined with a plastic tube that has been drilled with holes throughout its length. Auger holes lined for the purpose of measuring water tables are often called dipwells. After installation, water will flow into the dipwell until the water level in the well equals that in the surrounding floodplain soil. In this case only a short period of time is required for equilibration (perhaps a few minutes) because of the moderate permeability of the soil and the small internal volume of the dipwell. Close to the river and close to the hillslope boundary, the same type of dipwell may not provide reliable readings. For example, at the boundary between the hillslope and the floodplain, water from the hillslope may flow partly upwards into the floodplain soil as shown in Figure 6. In such a situation the water level in the dipwell may be higher than in the surrounding soil (Figure 6).

The injunction of Marshall and Holmes (1988) to avoid a hole that extends too far below the water table now becomes apparent. The flow situation at the hillslope-floodplain edge is one in which the auger hole provides a high-permeability conduit to upwards flow. Because the auger hole extends several 10 s of cm below the water table, water will seep into its base and discharge through its walls higher up. In acting as a conduit in this way, the well may have a water level several cm higher than in the surrounding soil where greater frictional resistance leads to more substantial head losses and a lower water-table height. To our knowledge, this problem was first discussed by L. A. Richards (1954).

More recently in the hydrogeological literature the same problem has received attention for the case of measuring water tables in the drawdown "cone" surrounding a pumped well. Rushton and Howard (1982) found that water levels in an observation well located in the cone were substantially below the true water table. A component of the groundwater flow in the vicinity of the observation well was vertically downwards and the well-acted as a short-circuit for this vertical component. To obtain more reliable estimates of water tables, Rushton and Howard (1982) recommended using a stack of piezometers with "intakes" spaced at regular depth intervals. Piezometers measure the pressure head at different depths in an aquifer. In their simplest form they comprise a plain pipe with a perforated section at its lower end: the "screen" or intake. Water can flow into or out of the piezometer until the pressure of the water inside the pipe at the depth of the intake is equal to the water pressure in the pores of the soil or rock formation outside the intake.

Figure 7 shows how the readings from multiple piezometers in a vertical stack can provide reliable water-table estimates. If the water table is within the range of the intake of one of the piezometers, the water level in the piezometer will coincide exactly with the water table (as with the uppermost piezometer in Figure 7), provided response-time errors are minimal (see below this section and Section 4.3). If the water table is between the intakes of two piezometers, it can be obtained from the water level in the lower piezometer. Because the intake of the lower piezometer is below the water table, it may record a pressure head below (the case in Figure 7) or above (where groundwater flow is vertically upwards, e.g., the hillslope-floodplain boundary in Figure 6) the water table, but the error should be small if short piezometer intakes are used and the vertical gaps between intakes are also small. An alternative is to plot the elevations of the piezometer intakes (*y* axis) against the corresponding pressure heads (*x* axis). The resulting curve is extrapolated to a pressure head of zero to obtain the water-table elevation (Richards, 1954).

The situation shown in Figure 6 is somewhat idealized, and soils in real floodplains may have a complicated structure and may even host more than one water table, as noted above in Section 3.3 (see Figure 4). To judge whether such complications occur, it is wise to undertake a stratigraphic survey of the soil or aquifer being investigated.

Water levels in dipwells may show an attenuated and lagged response to water-table fluctuations. This damped response may arise for several reasons. Flow into and out of the well may be impeded because there are too few perforations in the lining tube or because the soil around the edge of the hole was smeared during augering, causing a reduction in its hydraulic conductivity (Butler Jr, 2020). The volume of water required to flow into or out of a dipwell per unit

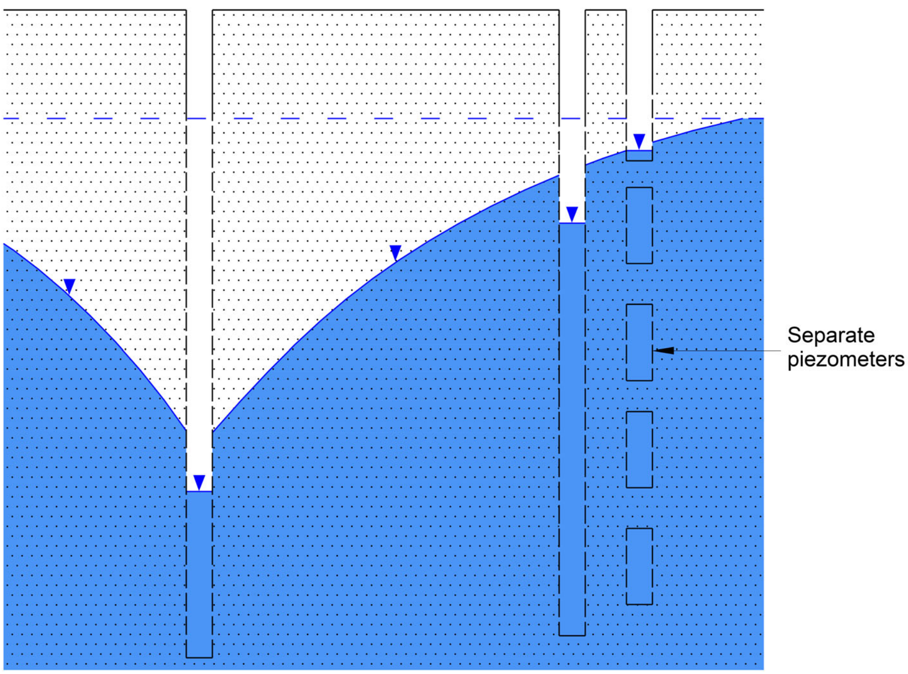

FIGURE 7 The flow situation considered by Rushton and Howard (1982). The pumped well is shown to the left and the observation well to the right. Heads decrease vertically as well as horizontally in the vicinity of the pumped well; that is, flow to the well is radial in cross-section, with a pronounced downwards component. This means that the observation well will act as a short-circuit for flow in the aquifer causing its water level to be lower than the actual water table. A more accurate estimate of the position of the water table can be obtained using a nest of standpipe piezometers, shown to the right of the observation well. The first piezometer is fully shown as a standpipe terminating in an intake. The intakes of the remaining piezometers are also shown. Note that, although a vertical stack of intakes is shown, each piezometer in the nest would be displaced horizontally from its neighbours. See text for further details.

change in water table will also affect instrument response time. A doubling in well diameter will lead to a fourfold increase in the amount of water required to register a change in water-table level. This increase is offset in part by the increase in area of lining tube in contact with the soil for water to flow across. However, the change in response time is not related simply to the ratio of a well's volume to its contact area with the soil, because changes in area also cause changes in the geometry of flow around the well and, therefore, of rates of flow into or out of it (Butler Jr, 2020).

Response times will improve (will shorten) as the depth of penetration of the well below the water table increases because this controls the surface area of the well available for water exchange with the surrounding soil. However, as noted above, a well that extends too far below the water table may be prone to considerable errors in settings in which vertical flow is important.

Finally, we note that, in our experience, dipwells are often mistakenly called piezometers, and single piezometers are sometimes assumed to give water-table level, which they do only in special circumstances as noted above (Figure 7).

4.3 | Vertical arrays of tensiometers or piezometers

As noted in Sections 3.5 and 4.2, an alternative to dipwells is a vertical stack or array of tensiometers or piezometers (i.e., tensiometer cups or piezometer intakes are placed at regular depth increments through the soil profile). Tensiometers fitted with pressure transducers can often be set up to provide measurements of H_p (see Figure 3) both above (negative H_p values) and below (positive H_p values) the water table. In the latter case the tensiometer is more properly called a hydraulic piezometer (see Hanschke & Baird, 2001). The position of the water table is obtained by interpolating between the tensiometer with the lowest positive reading and the one above it, which should have the smallest negative reading (i.e., the least negative). In rare cases H_p will equal zero, indicating that the water table is at the position of the tensiometer's cup. The procedure for estimating water tables from a vertical stack of open or standpipe piezometers is discussed above in relation to the flow situation shown in Figure 7. Although requiring more equipment and introducing uncertainty associated with using interpolation to obtain the water-table depth, stacks of tensiometers or piezometers avoid the problems of short-circuiting flow identified above (Sections 3.5 and 4.2). As with dipwells, tensiometers and piezometers take a finite time to respond to changes in H_p. Nevertheless, tensiometers (hydraulic piezometers) will typically have much faster response times than standpipe piezometers and will generally provide reliable H_p estimates (Hanschke & Baird, 2001): ignoring flexing of the instrument casing and the compressibility of water, the only water exchange required is that related to the movement of the membrane within the transducer unit. In contrast, the errors associated with standpipe piezometers may be substantial because of the much larger changes in water volume required to register a change in head (Hanschke & Baird, 2001).

4.4 | Soil moisture content profile

The volumetric water content of the soil may be measured in the vertical. For example, a stack of time-domain reflectometry (TDR) (Dalton, 1992), capacitance (Gardner et al., 1998) or other probes (such as neutron probes – see Or et al., 2012) could be used to measure moisture variations down the soil profile. If the porosity or saturated volumetric water content through the soil profile is also known, then it may be assumed that the water table is indicated by the uppermost of those probes registering saturation. A problem with this approach is that it is often impractical to measure porosity for the depth of each probe. A more serious problem is that conditions below the water table may be unsaturated (see Section 3.4), and there is no way of knowing from moisture probes alone what level of saturation represents the water table. Finally, if there is an appreciable capillary fringe, this method will suggest the water table is higher than it actually is, unless the thickness of the fringe can be estimated, which in itself can be difficult.

Geophysical methods such as ground-penetrating radar (GPR) can also be used to indicate changes in water content in soil profiles and have the advantage that they can provide continuous data over large areas (Bristow et al., 2000). However, they have the same drawbacks noted above in that they do not measure the water table directly. When compared with dipwell data, GRP-derived water tables may be in error by as much as 10–20 cm. Doolittle et al. (2006) provide a useful review of the use of GPR for measuring water tables and note that the method is best applied to coarse soils where the contrast in water content above and below the water table is large, unlike in fine soils which may have a thick capillary fringe.

4.5 | Hydrological instrument response time and the observer effect

The problem of hydrological instrument response time has already been noted above in the discussions of dipwells, piezometers, and tensiometers, but deserves a brief additional mention here. Excepting methods such a GPR, many hydrological instruments disrupt the system they are designed to measure (the well-known "observer effect"). For example, augering a hole for a dipwell or digging a hole for the insertion of moisture probes will alter a soil's structure and the way in which water moves through and is stored in the soil. Similarly, trampling by the observer around an equipment installation may change the structure of the soil surface, in turn affecting infiltration and evaporation, and therefore the supply and loss of water to and from the water table. These sources of error are often fairly obvious, and many hydrologists take care to reduce the impacts of them. In our experience, response-time errors associated with hydrological instruments are less often appreciated or accounted for.

An analogy can be drawn here with thermometers. Most thermometers measure their own temperature, and those with a lower thermal mass are more responsive to changes in ambient temperatures. Similarly, dipwells, piezometers and tensiometers will generally be more accurate if only small amounts of water have to flow to or from the instrument to register a change in water-table level or pressure head. It is possible to model the response of a range of hydrological instruments used for water-table monitoring. Towner (1980) develops and presents the theory of tensiometer response time, while Hvorslev's (1951) analysis can be used to simulate the response time of piezometers and dipwells (e.g., Hanschke & Baird, 2001). The response time of an instrument may be distinguished from the response time of the hydrological system being measured. Problems may arise when the former exceeds the latter, because it indicates the hydrological behaviour in the real system is not being recorded fully by the instrument. However, high-frequency information from the real system may not be needed. For example, a researcher interested in obtaining monthly average water-table depths may not need a dipwell that has a response time of less than, say, 4 h, whereas someone interested in the response of water tables to short-lived rainstorms would find such an instrument unsatisfactory.

The response time of an instrument can be estimated directly. If it is known that a soil is in a hydrostatic condition and that the water level in a well is in equilibrium with the water table, the well level can be lowered by bailing and the time it takes to recover recorded. The response time will depend on the properties of the instrument and the soil around it (Hanschke & Baird, 2001; Hvorslev, 1951), but even with a rapidly-responding instrument some features of system behaviour may be difficult or impossible to measure such as rapid water table rise (see Section 3.6).

4.6 | Water-table height and water-table depth

As we discuss in Section 5, water tables may be measured for a variety of reasons. The height of the water table relative to a (fixed) datum is often referred to as the water-table elevation. The slope of the water table relative to a datum indicates the general direction in which groundwater will flow, and, as such, is a useful hydraulic variable. The water table itself can also be used as a datum when considering vertical water flows through the soil profile.

The position of the water table relative to the ground surface—that is, water-table depth (WTD)—has also proved useful as an indicator of soil aeration and biochemical conditions pertaining in the soil (see Section 5.2), but there seems to be some confusion over how this depth should be expressed. Many authors use positive values to indicate the depth of the water table below the surface, while others use negative values. The confusion arises because the direction of the vertical axis is not properly considered. A depth is a positive value below a surface (the vertical axis is positive downwards – depth increases downwards). For example, we might say “the soil auger was inserted to a depth of 20 cm”; we would not say it was inserted to a depth of −20 cm. The same convention should apply to water-table depths. A negative WTD is either meaningless or implies a water level (no longer a water table) above the ground surface.

5 | IS THE WATER TABLE A USEFUL CONCEPT AND A USEFUL VARIABLE?

5.1 | All water-table measurements are wrong…

Box and Draper (1987) famously noted that “… all models are wrong; the practical question is how wrong do they have to be to not be useful”. We might extend this aphorism to hydrological measurements and specifically the water table. From Section 3 it is clear that the water table is not a simple concept. For this reason and for the more practical reasons given in Section 4, neither is it an easy variable to quantify. It is likely that a majority of studies in which water-table data are presented have not considered in sufficient detail the accuracy with which it can be determined. Nevertheless, in many cases it remains an indispensable metric—it is most definitely “useful”—while in other situations we might wish to consider alternative hydrological variables, or at least improve how we measure the water table and take more care in how we interpret our measurements. The usefulness of the water table as a concept is considered further below.

5.2 | The water table as a groundwater resource indicator and as a proxy for soil saturation (aeration), redox status and water availability

As noted in Section 2, the water table is used by hydrogeologists to quantify and understand groundwater resources. Measurements and analysis of the natural behaviour of the water table in response to spatial and temporal variations in, for example, recharge (Crosbie et al., 2019; Healy & Cook, 2002), aquifer hydraulic properties, and groundwater discharge (Lewis et al., 1993), can provide sophisticated insights into the functioning of a groundwater system. Likewise, measurement and analysis of water-table behaviour in response to artificial perturbations—for example, during a borehole pumping test—provides site-specific information on aquifer hydraulic properties. The real-time monitoring of the water table is often used in groundwater resource management, including management of both groundwater drought and flooding. The overall importance of the water table to hydrogeologists is perhaps best illustrated by the fact that the usefulness of groundwater models is almost always judged through their capacity to simulate various aspects of historical water-table behaviour, such as absolute elevation, annual fluctuation, and the shape of water-table hydrograph recession limbs. Considerable effort also goes into understanding the dynamics of groundwater replenishment (recharge) by studying the lag-times of water-table responses to both single rainfall events and seasonal meteorological cycles (for an example relating to the Chalk aquifer in England, see Taylor et al., 2012).

Relationships between WTD and many other variables have been found, including soil greenhouse gas emissions (Evans et al., 2021), plant rooting depth (Fan et al., 2017), primary productivity and crop yield (Weltzin et al., 2000; see Section 2), and the species composition of wetland vegetation (Wheeler, 1999). These relationships exist because the water table is a proxy for degree of waterlogging and soil

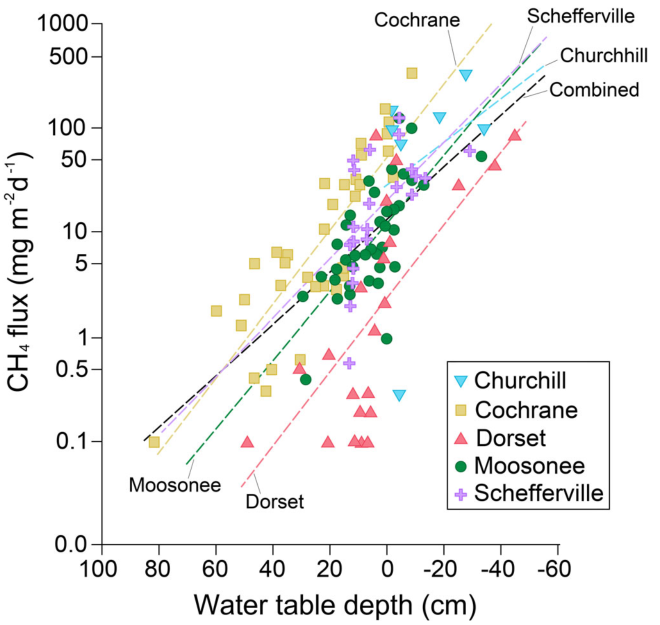

FIGURE 8 The relationship between growing season average CH_4 flux (log scale) and average water-table depth from research sites in Canada (a negative water-table depth represents surface ponding). Re-drawn from an original figure in Moore and Roulet (1993).

redox status (Blodau, 2002), and also water availability (Allred et al., 2003), and it is these that are the true explanatory variables. The water table is used, however, because it is perceived as a simple variable and easy and inexpensive to measure. Perhaps not surprisingly, there is often considerable scatter in the relationships involving the water table. An example is the non-linear (exponential) dependency of seasonal methane (CH_4) emissions from wetland soils on average WTD as shown in Figure 8 from Moore and Roulet (1993) (see also recent studies such as Tiemeyer et al. (2016)). The scatter shown in Figure 8 may arise for at least three reasons:

(i) CH_4 emissions depend on more than just one factor and cannot be represented fully as a bi-variate relationship. For example, in addition to anoxia, rates of methanogenesis (archaeal CH_4 production) depend on substrate supply, while both methanogenesis and methanotrophy (bacterial CH_4 consumption) are affected by other variables such as the chemical status of soil water, soil temperature (Laine et al., 2007), and vegetation type (Green & Baird, 2012; Ström et al., 2005).

(ii) The water table's usefulness as an indicator of soil redox status varies between soils. In some soils, a fall of the water table may be marked by only a small change in saturation level and redox because the soil supports a thick capillary fringe. In other soils, there may be substantial changes in redox in the zone through which the water table has fallen because the soil has a much higher specific yield (see Equation (1)).

(iii) Perhaps most problematically, differences in the CH_4-water-table relationship between sites may, in part, be due to differences in water-table measurement methods. For example, the response time of dipwells may vary substantially between sites, which in turn will affect the estimates of seasonal-average water-table depth and the CH_4-water-table relationship.

In terms of its scatter, Figure 8 appears to be fairly typical of the relationships observed between other environmental variables and the water table. And, in those other relationships, similar points to those made above seem to apply. For example, in the case of wetland vegetation, Wheeler (1999) notes that there are several reasons why it may be difficult to relate species composition to water table behaviour. These include:

(i) The complexity of the behaviour of the water table in wetlands and the difficulty of identifying which aspects of water-table behaviour are most important in affecting plant distributions; it is possible that the most important metric of water-table behaviour varies according to plant species and the hydrological setting of the wetland.

(ii) In some circumstances, the likelihood that soil moisture content may be more meaningful to plant growth than water-table depth. This point has also been made in the case of *Sphagnum* mosses by Thompson and Waddington (2008), who note that the near-surface moisture content of Sphagna is often not accurately indicated by water-table position, or when it is, the relationship is not stable over time. They propose instead using a different hydrological variable—the soil water suction or pressure head—as a more reliable indicator of water availability to the growing tips of the mosses (capitula).

(iii) As with the example above of CH_4 emissions from wetlands, other variables may modify relationships between plants and water tables.

Given these problems, is it naïve to expect simple relationships to exist with the water table? There is not a simple answer to this question, but in many cases we suspect it will be "no, it's not naïve". There is considerable merit in looking for simple bivariate relationships between environmental variables, before resorting to more complicated ones if necessary. Simple relationships are often easier to apply and therefore more useful than more complicated ones (although simplicity is not always a guarantee of being closer to the truth, cf., Ball, 2016). Also, if artefactual reasons for scatter can be estimated or removed (such as the problems of using different water-table measurement methods – see above), the remaining scatter can be more easily interpreted in terms of other causal variables. And, even if a multi-variate model is needed, the water table will often remain as a key explanatory variable. It is also worth noting that strong relationships have been found with water-table depth alone. Evans et al. (2021), for example, found relationships between greenhouse-gas emissions and water-table depth that have far less scatter than shown in Figure 8. Although their dataset came from many study sites, this reduction in scatter may, in part, be explained by water tables being measured in similar ways across the sites. Finally, while we may wish to use other variables to indicate soil aeration status and greenhouse gas exchanges between soils and the atmosphere, the water table is still often easier to measure than these, notwithstanding the problems highlighted in Section 4 (for the case of redox, see Fiedler et al., 2007).

5.3 | The water table in other (lesser known) settings

Novel uses of the water table continue to be found. An example perhaps not known to many hydro(geo)logists concerns the analysis of testate amoebae sub-fossils in peat cores to reconstruct past hydrological conditions in peatlands (Amesbury et al., 2016; Booth et al., 2010). Testate amoebae are single-celled organisms that live in freshwater environments including soils and the surface of peatlands. Species assemblages vary according to the wetness of the soil or peat, allowing the establishment of relationships—transfer functions—between testate community composition and water-table position. In peatlands, the tests from dead testate amoebae become incorporated into the peat as the peat deposit thickens, and cores of peat taken from a peatland may contain a record of variations in testate amoebae populations spanning many thousands of years. The age of the peat down the core can be dated using ^{14}C and other techniques to establish an age-depth profile. Samples of peat down-core can then be analysed for their sub-fossil testate amoebae remains to reconstruct past community composition and, therefore, past hydrological conditions. Peatland water tables respond to processes internal to the peatland but also to changes in climate and human management such as drainage (Swindles et al., 2012; University of Leeds Peat Club, Bacon et al., 2017). Therefore, through their relationship with water tables, testate amoebae can be used to reconstruct past environmental conditions.

Figure 1 may seem like a somewhat light-hearted or even trivial example of a groundwater system. However, water-table dynamics and associated groundwater flows in beaches have been studied for many decades, with a noticeable upsurge in interest from the 1990s onwards because of the importance of water-table position in the beach to: the interstitial and macro-fauna (Horn, 2002), coastal groundwater quality, including contaminant transport from agricultural, urban, and industrial areas (Xin et al., 2010), and sediment movement (beach accretion and erosion) (Horn, 2002, 2006). Water tables are probably more dynamic in beaches than in almost any other porous medium, because of their response to wave, swash and tidal cycles (Li et al., 1997; Horn, 2006; Bakhtyar et al., 2011). They can fluctuate by several dm over timescales of minutes to hours and show characteristic periodic behaviour according to the properties of the beach sediment (particle size and sorting) and the beach's geomorphological and hydrogeological setting (Baird et al., 1998; Li et al., 1997; Raubenheimer et al., 1999). One interesting feature of coastal groundwater systems is that the mean water-table position is higher than mean sea-water level; this overheight or "superelevation" arises from the properties of the groundwater system, the shape of the beach, and the hydraulic properties of its sediment (Baird et al., 1998; Horn, 2006; Raubenheimer et al., 1999).

The coastal groundwater system has been called the "subterranean estuary" (Luijendijk et al., 2020; Robinson et al., 2007) and includes freshwater discharge to the oceans as well the highly dynamic re-circulating flow of mostly salt water discussed above. Nevertheless, at the global scale fresh groundwater discharge to oceans is a tiny fraction of that from rivers (probably less than 1%), although it can be locally important for coastal nutrient dynamics in some estuaries, salt marshes and coral reefs (Luijendijk et al., 2020).

It is clear in both peatland palaeo-ecological studies and coastal science that the water table is highly useful as a concept and a measurable variable. However, although there is appreciation within these fields of the limitations of what the water-table can indicate (e.g., University of Leeds Peat Club, Bacon et al., 2017), and also of the need to account for errors in measurement (Baird & Horn, 1996), more work on addressing these limitations is required.

6 | CHALLENGES AND CONCLUDING REMARKS

Where does the foregoing discussion leave us? Reassuringly, we can be confident there is such a thing as the water table—it is not a chimera—but neither is it something that is always simply defined or easily measured. We hope we have shown that care needs to be taken when using water-table data in a study. If we are to make sound interpretations of how a soil, sediment, or geological formation functions hydrologically based on the position and behaviour of its water table(s), we recommend the following steps or checks, posed here as questions:

(i) Is the system being studied hydrologically simple, complicated or somewhere in-between? Before installing equipment to measure the position of the water table, it is very worthwhile undertaking a stratigraphic survey, even if only a basic one, to check whether the soil has structured heterogeneity or properties that may give rise to perched or multiple water tables and other hydrological discontinuities. Such a stratigraphic survey, in combination with other information such as the wider topographical and geological setting, can be used to construct a conceptual model of how a site functions hydrologically, and the model can be used to guide placement of water table measuring equipment.

(ii) What is the hydrological response time of the system? This is not a question that can be answered properly without measuring water-table position and behaviour, so it may seem nonsensical to have it in the checklist. However, from the conceptual model, which may also be based on an understanding of basic soil properties (e.g., hydraulic conductivity, inferred from grain size, and the presence of macropores), it's possible to come to a tentative estimate of response time and which parts of the system are likely to be most hydrologically dynamic and therefore need denser monitoring.

(iii) How is the water table best measured in the system being studied? In other words, it is important to install water-table monitoring equipment that is suitable to the environment and the purposes of the study. Unfortunately, in our experience it is common to see water-table wells that have been poorly designed and installed, such that we would have little confidence in the measurements obtained from them. The problem seems to be the assumption by some workers that the water table is easily measured, and the mistaken conclusion that, because the water level can be seen going up and down in a well in response to rainfall and dry weather, the well is functioning properly. It should go without saying that unreliable data will lead to a mistaken interpretation of how a site behaves hydrologically.

If these three questions can be addressed satisfactorily, and account is also taken of what the water table actually shows in a particular porous medium (e.g., aeration above and below the water table will depend on soil, sediment or rock type), then a more refined model of how the system functions hydrologically will be obtained.

From our sampling of the hydrological literature, surprisingly little appears to have been written on the water table as a concept, yet its conceptual basis is related to whether we think of soils and other porous media as being complex structures where there are discontinuities in pore-water pressure and hydraulic gradients between different domains or pore networks. Beven and Germann (2013) contend that such non-equilibrium or non-continuum conditions are typical in soils, but whether this also means soils commonly have multiple water tables within a profile is unclear. We simply do not have the data. Similar uncertainty applies to many geological formations. We can, however, be confident that the simple classical model (Figure 3) probably does not apply very often, except in soils that have been greatly simplified by human activity (e.g., some agricultural soils) and some sandy soils. We can also conclude that the concept of the water table is useful, but greater attention to what the water table means across a range of settings and how it is best measured will help avoid the many pitfalls of misinterpretation.

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