



### Core Ideas

- The UN Sustainable Development Goals present a guiding principle for hydropedology.
- Hydropedology is potentially more effective than the separate disciplines.
- Pedologists should better support their observations with physical measurements.
- Measuring and interpreting bypass flow may be more effective than developing new theory.
- Existing soil databases can't provide a full picture of soil behavior in the field.

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# Hydropedology and the Societal Challenge of Realizing the 2015 United Nations Sustainable Development Goals

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The UN Sustainable Development Goals (SDGs) offer a major challenge for both society and the science community. Hydropedology, combining the expertise of soil physicists and pedologists, plays a key role in realizing goals focused on food, water, climate, and ecology, requiring interdisciplinary research. This update explores emerging trends and future work, focusing on examples of contributions by pedology to measuring and modeling in hydropedological studies. Many soil types create heterogeneous flow patterns that are difficult to characterize using current soil databases and physical flow models. The clear potential of hydropedology to produce better modeling results than those obtained from separate contributions by the two subdisciplines can, however, only be established by field validation of modeling results using different types of data and models. Overall soil input in interdisciplinary SDG-oriented research includes chemical and biological aspects that become more representative by considering hydropedological conditions.

Abbreviations: SDG, sustainable development goal.

Sustainable development has become a widely used concept after its introduction in the Brundtland report (World Commission of Environment and Development, 1987). The need to consider interrelated economic, social, and environmental aspects when dealing with societal issues is evident, but translating this rather abstract concept into operational criteria has been difficult, and difficult also for research. The acceptance, after much discussion, of 17 Sustainable Development Goals (SDGs) by the General Assembly of the United Nations in September 2015 (<https://sustainabledevelopment.un.org/sdgs>) provides a clear and useful focus, including for research, at a time when the research community is challenged by increasingly well-informed citizens and the policy arena both insisting that science should be more in tune with societal demands (e.g., Bouma, 2015). This update explores whether hydropedology can make more valuable contributions to achieving land-related SDGs than would be possible by separate actions in soil physics and pedology.

Considering hydropedology, a key question is whether the available data and procedures in soil physics and pedology are adequate to address future interdisciplinary demands focusing on the SDGs. If so, available databases and modeling software could provide the required information for agronomists, hydrologists, climatologists, and ecologists, and no more research would be needed. But this update argues that more hydropedological research is needed, if only because of a challenging statement by Vereecken et al. (2016):

*Despite being more than a century in use, Richards-based models are still not suitable for all soil types (particularly soils with high clay or organic matter contents) and there is still not an adequate physical theory linking all types of flow (Beven and Germann, 2013).*

This statement is correct when focusing on a comprehensive physical theory, covering macropore flow, fingering, unstable wetting fronts, swelling and shrinking, hydrophobicity, etc., but approaches based on pedological soil descriptions from soil survey have pragmatically and successfully been applied to characterize flow patterns in heterogeneous clay soils with macropores and in soils with distinct pedological soil horizons (discussed below). Also, soil surveys allow extrapolation of point data to areas of land, albeit in an empirical manner. This illustrates the potential of pedology, the primary focus of this update, to contribute to hydrogeology.

## Contributing to the Sustainable Development Goals

Of the 17 SDGs (Table 1), at least Goals 2, 6, 13, and 15 have a direct relation with soil water regimes, and a more indirect relation applies to Goals 7, 8, 11, and 12. This is a very positive and inspiring starting point for a discussion on the relevance of hydrogeology. Five general considerations apply:

1. Hydrogeology cannot by itself realize SDGs. Only interdisciplinary and transdisciplinary ecosystem research approaches can work, focusing on soil functions and ecosystem services that, in turn, can contribute to realizing SDGs (e.g., Dominati et al., 2010; Robinson et al., 2012; Keesstra et al., 2016).
2. Goals have to be realized! The SDGs are result oriented. Ending ..., ensuring ..., taking action ... . Glossy plans will not do the job. This, of course, applies to all sciences but should also be a guiding principle for hydrogeology.
3. Data, information, and knowledge are relevant in their function of contributing to the realization of the SDGs! They are not goals in themselves.
4. Many research projects already had, without stating so, a de facto focus on SDGs. Framing results of such studies in terms of the SDGs is needed to increase the external visibility of hydrogeological research. Bouma et al. (2015) illustrated this for six published case studies in the Netherlands and Italy with a hydrogeological character. They also showed that in three of the studies, results were obtained using existing methodologies that were inadequate in the remaining three studies, providing a rational justification for developing new research approaches.
5. The focus on 17 separate SDGs in UN publications may lead to neglecting their interrelationships, which are essential in a systems analysis of ecosystems focusing on several SDGs simultaneously.

## Developments within Soil Physics and Pedology

Effective inter- and transdisciplinary research is only possible when other disciplines and stakeholders show interest in the type of data, information, and knowledge that hydrogeology can contribute. What do we have to offer?

Soil physics has a good record in publishing a wide variety of methods to measure water, air, and temperature dynamics (e.g., Dane and Topp, 2002), and a recent review of important developments of in situ sensors and of modeling soil physical processes has indicated impressive advances (Vereecken et al., 2016). Many studies have been made characterizing flow in dual-porosity soils that contain macropores in a matrix with finer pores. Richards-based models cannot characterize such flow systems (e.g., Beven and Germann, 2013). Dual-porosity flow not only occurs in clay soils but also in lighter textured silt loam and silty clay loam soils

Table 1. The UN Sustainable Development Goals.

Goal	Description
1	End poverty in all its forms everywhere
2	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture
3	Ensure healthy lives and promote well-being for all at all ages
4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5	Achieve gender equality and empower all women and girls
6	Ensure availability and sustainable management of water and sanitation for all
7	Ensure access to affordable, reliable, sustainable, and modern energy for all
8	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all
9	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation
10	Reduce inequality within and among countries
11	Make cities and human settlements inclusive safe, resilient, and sustainable
12	Ensure sustainable consumption and production patterns
13	Take urgent action to combat climate change and its impacts
14	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development
15	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss
16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all, and build effective, accountable, and inclusive institutions at all levels
17	Strengthen the means of implementation and revitalize the global partnership for sustainable development

with stable macropores. Dual-porosity flow is important because it affects water availability for plant roots as water moves rapidly downward beyond the root zone, possibly carrying agrochemicals that may pollute ground- and surface water via drain flow. This important type of pollution cannot be explained by assuming homogeneous flow, so new approaches are being explored. (e.g., Šimůnek et al., 2003; Jarvis, 2007; Tiktak et al., 2012; Beven and Germann, 2013). Flow processes are complex, and volumetric estimates of the effective pore volumes involved are difficult because the volumes are small and macropore continuity determines the real flow patterns. Applying modern nuclear magnetic resonance spectroscopy and X-ray tomography techniques shows intriguing patterns of macropores but cannot address the continuity aspect either (Schjønning et al., 2013; Larsbo et al., 2014). Staining techniques may be more effective (e.g., Bouma and Dekker, 1978). In contrast, breakthrough curves demonstrate the effects of bypass flow, but this process is still difficult to express in terms of predictive parameters that can be validated by field measurements (e.g., Bouma and Anderson, 1977; Larsbo et al., 2014).

Pedology has sent three diverse signals. The first is soil classification that still receives attention (Soil Survey Staff, 2010; IUSS Working Group WRB, 2015). Empirical land evaluation and interpretation of soil maps—quite successful as part of soil mapping programs that have by now been completed in many countries—has not widely been followed by quantitative measurements of soil physical parameters and modeling techniques (e.g., Bouma et al., 2012), and this has increasingly limited its usefulness.

However, (second signal) pedological research has successfully focused on spatial soil variability, applying geostatistics and digital soil mapping, the latter assembling soil characteristics in grid cells of various dimensions needed for interdisciplinary modeling of ecosystem processes (e.g., McBratney et al., 2011; Arrouays et al., 2014; Hengl et al., 2014). For 1- by 1-km grids (recently extended to 250- by 250-m grids), covering the entire world, eight soil characteristics (soil organic C, pH, texture, bulk density, cation exchange capacity, coarse fragments, soil organic C stock, and depth to bedrock) were defined for six soil depths (Hengl et al., 2014). Also, dominant soil classification units were registered, and this is important for communication (Soil Survey Staff, 2010; IUSS Working Group WRB, 2015). This was a clear and timely response to the urgent quest for soil data by hydrologists, climatologists, and ecologists. There is a risk, however, that these soil characteristics will start to have a life of their own with no relationship to particular soil types (often soil series) occurring in characteristic landscapes (Sanchez et al., 2009). Folberth et al. (2016) also demonstrated the importance of using soil types to communicate the role that soils can play in climate change mitigation.

Of the soil characteristics mentioned, texture, soil organic C, and bulk density are widely used in pedotransfer functions (Bouma, 1989; Vereecken et al., 1992), deriving relationships with hydraulic

transport characteristics such as hydraulic conductivity and moisture retention (e.g., Vereecken et al., 2016). When used in models assuming homogeneity, this can produce poor results and create the false impression that measurement and consideration of particular flow conditions at sites being considered would not be necessary anymore. This is particularly relevant when the pedotransfer functions used are derived from a different set of soils than the ones being investigated.

Concurrently, (third signal) innovative soil physical measurements and modeling, inspired by pedology, were presented to answer pressing societal problems that needed an effective reaction, addressing several SDGs. These studies related to grassland management of clay soils, water regimes in natural areas, agricultural development vs. nature preservation, precision agriculture, the effects of climate change on maize (*Zea mays* L.) production and irrigation needs, and the effects of soil excavations on regional water regimes (e.g., Bouma et al., 2015; Bouma and Wösten, 2016). These studies illustrated the use of pedological expertise in refining the physical characterizations of soils, thereby illustrating the relevance of hydropedology.

The contributions of pedology to hydropedology consist of three types: (i) protocols for linking soil structure descriptions prepared during soil surveys to hydrological soil characteristics; (ii) defining flow systems based on soil morphological characterizations; and (iii) the use of soil maps to allow spatial expressions. Of course, pedology has a much wider scope, covering soil survey techniques, spatial variability, landscape evaluation, and biological, chemical, and mineralogical soil formation processes.

The role of pedology in hydropedology is discussed next in the context of addressing the SDGs in future research by analyzing measuring, monitoring, and modeling.

## 💧 Measuring and Monitoring

Six examples, illustrating the use of pedological data to improve soil physical field measurements, are briefly discussed:

1. Anderson and Bouma (1973) and Lauren et al. (1987) showed that any saturated hydraulic conductivity ( $K_{\text{sat}}$ ) could be measured in a structured silt loam soil by varying the height and volume of the samples. Using small cores resulted in a very high variability of measurements. The standard research response of reducing variability by increasing the number of samples did not work here: data scattering remained. Variability could be explained by macropore continuity patterns and resulted in defining critical elementary volumes for soil samples as a function of the observed soil structure, described by standard procedures in soil survey. The  $K_{\text{sat}}$  values for a heavy clay soil could be calculated by applying such a macropore-continuity model (Bouma et al., 1979), showing that “saturated” flow was governed by small, 30- $\mu\text{m}$ -wide “necks” in the flow system,

occupying very small volumes that cannot be characterized by insensitive physical bulk density or porosity measurements.

2. The occurrence of macropores can also have an effect on the measurement of pressure heads with tensiometers. Bouma et al. (1982) used tensiometers with large and small cups and registered brief saturation with the large cups, which intersected macropores, while the small cups registered only unsaturated conditions within the peds. Pedology distinguishes a large number of subsoil horizons that often have quite different properties compared with over- and underlying horizons. This will strongly affect flow patterns, including subsurface lateral flow at the regional level.
3. In many subsoils of glacial-till-derived soils, heterogeneous conditions arise from dense peds while areas adjacent to cracks have a sandy texture due to the preferential flow of water and leaching for long periods. In pedology this is referred to as “tonguing of the albic horizon into the argillic” (Sauer et al., 2009) (Fig. 1). Sampling the two areas separately results in two distinct populations of  $K_{\text{sat}}$  data, while random placement of an infiltrometer results in enormous “spatial variability” that cannot be handled by statistical methods (Bouma et al., 1989).
4. Cemented by Fe and Al, compact spodic horizons in sandy soils were supposed to be impermeable, and this had implications for ecological management of some natural areas in the Netherlands. But permeabilities had never been measured because core samples could not be taken. By using the column method (Booltink and Bouma, 2002a), carving out a column and plastering the sidewalls with plaster of paris, it turned out that the  $K_{\text{sat}}$  was significant, and this observation changed management practices in the area (Dekker et al., 1984).
5. Measuring water-table levels in structured soils may offer problems when sand-based techniques are used because of preferential flow along macropores, producing a wide variety of “free” water levels in boreholes at different depths below the surface. The use of tightly placed piezometers rather than open boreholes was recommended and this resulted in a clear record

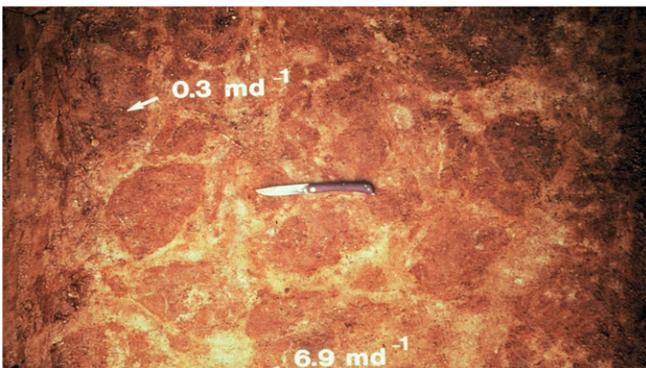


Fig. 1. Horizontal cross-section at the 40-cm depth in a Glossaquic Hapludalf formed in a boulder clay, where clay has been leached in areas around cracks (gray colored) that separate dense prismatic soil peds (brown). Vertical saturated hydraulic conductivity measurements in the peds were significantly different from measurements in the sandy leached areas, as indicated, causing preferential movement of water into the sandy subsoil (after Bouma et al., 1989).

of water-table levels (Bouma et al., 1980). The idealized picture of flat water tables needs correction, including in teaching, and hydrogeology can contribute to more realistic representations.

6. Water movement sometimes leaves characteristic patterns of Fe and Mn precipitates when reduction and mobilization during local saturation is followed by local oxidation and immobilization. These flow patterns of water in soil can be characterized in unique ways that cannot be identified with physical monitoring methods (e.g., Bouma, 1983).

These ad hoc examples show that soil morphological observations can result in modifying existing soil physical measurement and monitoring methods. More examples could be generated from other soils, but pedologists have failed to see that just a description of soil morphological phenomena followed by empirical statements as to their effects is not enough to satisfy modern demands for soil data and that engaging soil physicists in quantifying the physical implications of such observations is needed to satisfy the potential of soil morphology. At the same time, soil physicists have felt uncomfortable when confronted with complex field soils and pedological terminology, inhibiting their active involvement. Introducing hydrogeology as a means to stimulate interaction between the two groups of scientists has therefore been valuable and also quite successful (Vogel et al., 2013; Lin et al., 2015). Overall, much emphasis is on innovative field measurements, while pedological input appears to be somewhat limited, with notable exceptions (e.g., van Tol et al., 2013).

## Modeling Bypass Flow and Internal Catchments in Hydrogeology

Macropore continuity up to the soil surface is critical for bypass flow to occur. Pragmatic procedures have therefore been based on the measurement of bypass flow in the top 20 cm of soil, as a function of soil structure, soil moisture content, and water application rates, which can be related to the natural intensities of heavy and very heavy showers. The measurement method is quick and cheap (Booltink and Bouma, 2002b). A simple algorithm has been applied assuming that the flow of water into macropores at the soil surface occurs only when the application rate of water exceeds the infiltration rate. Downward water movement into the unsaturated soil matrix is assumed to follow Richards-type flow, while water that moves rapidly downward along vertical faces of the peds in the cracks represents “bypass flow” that can be collected (Booltink and Bouma, 2002b). Field measurements have confirmed that this simplified modeling approach can successfully predict water regimes in soils with macropores (Bouma, 1989; Bouma et al., 1982, 1983; Bouma and Wösten, 2016).

A basic question can be raised at this point in time as to what represents an effective approach to characterize macropore flow. While certainly the development of theory needs to be continued, the measurement of bypass flow, as discussed, could be a pragmatic starting point, focusing on threshold values in the system.

What are critical soil structures, water application rates, and soil moisture contents in any given type of soil with macropores? An important aspect is also the permanency of macropores. Worm channels don't close when clayey soils swell, but cracks do. Again, a threshold is reached when swelling soil closes the cracks. Illitic Luvisol clays in the Netherlands don't reach this state, but montmorillonitic Vertisol clays do (Bouma and Loveday, 1988; Bouma and Wösten, 2016). Infiltration rates are then reduced to zero. Defining thresholds can include testing of management measurements to control bypass flow, for instance by creating loose soil structures at the surface and reducing application rates when irrigating. Effects can be documented rapidly with bypass-flow measurement. This may represent an effective way to address the concerns of environmental quality regulators and requires, in addition, measurements of the quality of ground- and surface waters and drain outflow.

Of practical interest is the phenomenon of an "internal catchment," the accumulation of free water at the bottom of discontinuous macropores, be it animal channels or cracks (Van Stiphout et al., 1987; Tiktak et al., 2012). This water is freely available to plant roots that often follow vertical ped faces or worm channels downward to great depth, and the process thus forms an effective form of subsurface irrigation because evaporation at the soil surface is avoided. A field feature of some clay soils is the often abrupt increase in soil moisture content at a given depth due to the formation of horizontal cracks on drying of the soil. This stops upward fluxes of water from the groundwater, if present. Bouma and Wösten (2016) used a staining test to estimate the air-filled horizontal crack area as a function of the moisture content. In this way, they could define a separate hydraulic conductivity curve describing upward unsaturated flow, providing a typical example of soil morphological input into a soil physical flow analysis.

Detailed modeling of these bypass and accumulation processes is difficult because of complex macropore continuity patterns, but a distinction between "available" water, defined since the 1930s as being present between certain pressure heads, and "accessible" water is relevant (e.g., Droogers et al., 1997). The concept of the "root zone" in simulation models implicitly assumes that water within that zone is "accessible" by roots as a function of the pressure head of the soil water, which defines its "availability." Inaccessibility not only applies to clay soils with large peds that cannot be penetrated by roots but also to compacted soil horizons in other soils, a still largely unexplored area of research.

Finally, soil physicists should be aware of the fact that many non-soil-scientists and -pedologists interpret the widely used term "available water" to represent water that is available for plants in a given soil in a given year. Of course, it is not because the latter is determined by rainfall and evapotranspiration, the associated soil retention processes, and possible upward unsaturated flow from the groundwater, which can be measured and simulated (e.g.,

Vereecken et al., 2016; Bonfante and Bouma, 2015). This should be pointed out more clearly to users of soil information.

The recently much increased possibilities to validate model runs by applying remote and proximal sensing techniques (e.g., Vereecken et al., 2016; Viscarra Rossel and Bouma, 2016) are crucial to substantiate claims by pedologists that their input to hydropedology would improve simulation of soil-water processes in field soils. Comparing simulation runs using different types of soil data for a given area, including a base level where soil data are either omitted or highly simplified, is needed to provide a basis for comparison and evaluation. A recent and alarming study in the Machakos and Makueni counties in Kenya, Africa, by Hendriks et al. (2016) showed that soil data derived from six different databases yielded significantly different predictions of maize yields. Lack of field validation data, however, did not allow a conclusion as to which soil data were most representative for the area. Validation of simulation results for actual conditions using remote or proximal sensors to assess the reactions of crops or natural vegetation is therefore essential to justify the use of a given model and certain types of soil data. Such validation is essential to allow studies on future climate change where validation is obviously not possible.

## From Point Observations to Area Representations

A basic problem of soil science is the invisible character of its object of study. Augerings, pits, and road cuts are needed for exposure. Of course, different soil types (often soil series in Soil Survey Staff, 2010) correspond with certain landscape features, and this allows extrapolation from a limited number of point observations to areas of land, a procedure that forms the foundation of soil survey. Traditionally, mapping units on soil maps are named after a given soil type observed in a pit within that unit that is considered by the soil surveyor to be representative for that unit. This ignores spatial variability but can be useful to demonstrate the importance of soil moisture regimes affecting SDGs. For example, Bonfante and Bouma (2015) reported results for the Destra Sele area in southern Italy (22,000 ha), considering potential productivity of 11 maize hybrids for different irrigation scenarios and projected climate conditions in 2050. The results were helpful in identifying risks and opportunities when considering future land use in the area. It turned out that plant breeders and irrigation engineers were pleasantly surprised to receive this unexpected information from soil scientists because their experience with the profession had been rather less inspiring, as it seemed to focus on complex and abstract terminology and theories, creating a lack of affinity! This study also showed that three SDGs were served in the context of a comprehensive systems analysis (covering food: no. 2; water: no. 6; and climate: no. 13). The SWAP simulation model used in that study was validated in many other studies in comparable areas, which can justify its use for predicting the effects of climate change.

Soil maps are useful as a basis for simulation modeling on a regional level. Concern about spatial soil variability has been a major driver for soil research applying geostatistics during the last decades. But few, if any, studies have extended this work to define ranges for the results of agronomic, hydrological, or climate modeling. Bouma et al. (2011) discussed the hydrogeological aspects of modeling watersheds, defining Hydrological Response Units, and presenting three case studies where simulations were made with the 3D-SWAT model. These case studies again covered several SDGs. Reference is made to that publication, showing that soil maps can provide relevant data for regional hydrological simulation models and for regional policy studies on land use around the Aral Sea, the Middle East and North Africa, and in Kenya (Droogers and Bouma, 2014).

## Future Challenges

At least two major challenges may be distinguished. First, cooperation between pedologists and soil physicists has been discussed here in the context of hydrogeology. However, the soil science discipline covers, of course, many other subdisciplines. The presentation of soil science to colleague scientists in other disciplines is now often rather fragmented, focusing too often on subdisciplines. It might be more effective to systematically follow a logical sequence, starting with pedology defining the physical constitution of any given soil, followed by water regimes, expressed by hydrogeology, that determine the physical conditions for chemical and biological processes. Soil information becomes more attractive when chemical and biological studies also relate to hydrogeological conditions in the field. Presenting soil science expertise in this sequential manner to stakeholders and policymakers would do justice to the diversity of soil behaviors and would counteract simplified pedotransfer procedures.

Second, the availability of soil characteristics for worldwide grid cells of 1000 by 1000 m, and now even of 250 by 250 m (<http://soilgrids.org>) represents an excellent reaction from the soil science community to questions by agronomic, climatological, and ecological modelers, and such data are quite useful. However, the limited number of soil characteristics in the databases cannot completely represent dynamic hydrogeological soil behavior in a landscape context when used in models based on assumed soil homogeneity because they don't allow expressions for the heterogeneous soil properties discussed here. Consideration of soil types, as defined by soil classification systems, which, in fact, function as "class pedotransfer functions" (Bouma, 1989) continues to be important. Each soil type has "a story to tell!"

In the end, however, only field validation of modeling experiments can indicate which data and models are most suitable for hydrogeological applications in the context of SDG-related studies.

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