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A Decision Support Model for Assessing the Water Regulation and Purification Potential of Agricultural Soils Across Europe

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Water regulation and purification (WR) function is defined as "the capacity of the soil to remove harmful compounds and the capacity of the soil to receive, store and conduct water for subsequent use and to prevent droughts, flooding and erosion." It is a crucial function that society expects agricultural soils to deliver, contributing to quality water supply for human needs and in particular for ensuring food security. The complexity of processes involved and the intricate tradeoff with other necessary soil functions requires decision support tools for best management of WR function. However, the effects of farm and soil management practices on the delivery of the WR function has not been fully addressed by decision support tools for farmers. This work aimed to develop a decision support model for the management of the WR function performed by agricultural soils. The specific objectives of this paper were (i) to construct a qualitative decision support model to assess the water regulation and purification capacity of agricultural soils at field level, to (ii) conduct sensitivity analysis of the model; and (iii) to validate the model with independent empirical data. The developed decision support model for WR is a hierarchical qualitative model with 5 levels and has 27 basic attributes describing the soil (S), environment (E), and management (M) attributes of the field site to be assessed. The WR model is composed of 3 sub-models concerning (1) soil water storage, (2) P and sediment loss in runoff, and (3) N leaching in percolating water. The WR decision support model was validated using a representative dataset of 94 field sites from across Europe and had an overall accuracy of 75% when compared to the empirically derived values across these sites. This highly accurate, reliable, and useful decision support model for assessing the capacity of agricultural soils to perform the WR function can be used by farmers and advisors help manage and protect their soil resources for the future. This model has also been incorporated into the Soil Navigator decision support tool which provides simultaneous assessment of the WR function and other important soil functions for agriculture.

Keywords: soil functions, water quality, water regulation, water purification, decision support tool, food security, climate change

INTRODUCTION

Clean, accessible water for all is crucial for guaranteeing food security thereby establishing a close link between two of the most important UN Sustainable Development Goals (SDGs): SDG6 on ensuring clean water and sanitation and SDG2 on zero hunger (United Nations, 2015). Agriculture is the dominant user of water (Peragón et al., 2018), which is a most critical resource in the sustainable development of agriculture (Chartzoulakis and Bertaki, 2015). Climate change is driving more frequent weather extremes, which represents a particular challenge for agricultural systems (FAO and WWC, 2015). While the specific shifts ascribed to climate change are difficult to predict, and will vary depending on region (Olesen et al., 2011) it is agreed that overall effects will be generally negative on agriculture (Beck, 2013). The role of soil in regulating water has been highlighted in mitigating the consequences of climatic change on agricultural productivity (FAO, 2011), with an emphasis on soil water retention capacity. Despite these challenges and scientific evidence, policies do not consider that soil is the link between food security and water security (Hatfield et al., 2017), and do not recognize the importance of understanding the corresponding soil functions related to primary productivity (Sandén et al., 2018) and water purification and regulation (WR) (Wall et al., 2018).

The regulatory effect of soil on water flows, whether in storage, as runoff or drainage, has clear implications for primary productivity and consequently food security. Water regulation by soils is increasingly relevant in a context of climate change, where a decrease or increase in rainfall is expected depending on the region, and an increment of extreme climatic events is probable worldwide (Putnam and Broecker, 2017). In addition to water regulation, the interaction of soil with contaminants and nutrients in water solution circulating through the soil has clear implications for the environment, the quality of water for human consumption, and in the provision of healthy food (Delgado and Scalenghe, 2008; Keesstra et al., 2012). Even though soil is a natural filter, modern agriculture is a major contributor to water pollution and is considered the major source of nitrate and phosphate in water (OECD, 2001). In this way, this critical resource required for sustainable agriculture is often undermined by the system that is considered to need it the most. Equally, the loss of soil sediments must also be taken into account when considering the WR function as soil erosion processes, typically occurring during intense rainfall events, affect both water quality and water availability.

Overall the WR function can be defined as "the capacity of the soil to remove harmful compounds and the capacity of the soil to receive, store, and conduct water for subsequent use and to prevent of droughts, flooding, and erosion" (Schröder et al., 2016a; Wall et al., 2018). In the agricultural context, the water processes involved mainly include water storage, flooding, runoff/erosion (sediment and nutrient loss), percolation/drainage (nutrient leaching). Water storage is the ability of soils to hold water that can be stored for subsequent use after excess water has drained by gravity, the so called soil water holding capacity [European Commission (EC), 2014]. Flooding events have increased in recent years, with serious economic and social consequences and are likely to increase due to climate change (Mitchell et al., 2006; Rahmstorf and Coumou, 2011). The extent that soil contributes to flood protection relies on the volume of rainfall that can be temporarily stored [European Commission (EC), 2014]. Although erosion, transport, and deposition of fine sediments are natural hydro-geomorphic processes, excessive transfers can have serious negative environmental and economic consequences (Sherriff et al., 2015). In tandem with water regulation, water is naturally purified as it percolates through the soil, which is important for reducing pollution in receiving water bodies and to limit the risk of water as a vector in the spread of plant, animal, and human diseases (Wall et al., 2018). Water purification is a complex process of adsorption and, or, precipitation processes of potentially harmful compounds through retention in the solid phase or through nutrient transformations, including biologically mediated processes (Schulte et al., 2018). At the local scale, the relationship between soil properties and water regulation and purification relies on soil physical properties, texture, and structure, that combined affect water retention and hydraulic conductivity in the soil (drainage). The mineralogy, chemical and biological properties are those that essentially affect the capacity of the soil to fix dissolved chemical elements and compounds in the water flowing through of soil, including contaminants (Delgado and Gómez, 2016). For example, the effects of organic matter and pH can increase the retention of water and contaminants in the soil and can increase the biological diversity along with the capacity for recycling nutrients (Schröder et al., 2016a).

The WR function is just one of five major soil functions that society expects agricultural soils to deliver but, due to complex interactions, has implications for the delivery of all other soil functions (Schulte et al., 2015). The interactions between the WR function and other soil functions go beyond the primary productivity function. For example the capacity of soils to deliver WR has been highlighted as a relevant function in mitigating the consequences of climatic change on agricultural productivity. Increased focus has been put on soil water retention capacity. Soils with high plant available water capacity are assumed to have lower response of water-limited yield to rainfall changes and its productivity would be less affected by rainfall decrease compared with soils with low available water capacity (Wang et al., 2017). While there is a well-known synergy between carbon (C) storage and primary productivity (Lal, 2004), often such synergies between functions are ignored, and in particular, how primary productivity can be improved or sustained when other functions of the soil are enhanced or optimized. There is an urgent need to better understand water functioning including the interactions with other functions, to safeguard water resources. Implicit is the critical need to optimize soil management to ensure the future sustainability of soils and the multiple functions they perform.

The knowledge base about soil and the management consequences has often been limited to a few soil functions typically primary productivity and nutrient cycling. Research on how agricultural management affects soil functions has traditionally focused on conservation agriculture, especially on the tillage method, while there are few studies that contemplate the set of soil functions necessary to guarantee the ecosystem services that society demands (Stavi et al., 2016; Ghaley et al., 2018). The focus of environmental studies, has typically considered soil as "the ultimate object of pollution," and research on soil water interactions are often framed in the context of diffuse land pollution and the role of agricultural land, underpinned by soil, as a source of pollutants. These issues have been researched extensively, and represent important considerations for defining management needs. The widely discussed example of water contamination in agricultural landscapes is by losses of nutrients, in particular nitrogen (N) and phosphorus (P) from the soil (FAO and WWC, 2015). This problem has led to national and European water agendas {e.g., EU Water Framework Directives (2000/60/EC) [European Commission (EC), 2000] and Nitrates Directive (91/676/EEC) [European Commission (EC), 1991]}. However, the dynamics of contaminants in the soil have rarely been considered within the context of a potential positive effect in maintaining water quality. More than its role as a source of contaminants, soil can be considered a pollutant sink that preserves water quality. Although this may represent a research gap, the literature does provide understanding of the key drivers of the WR function and the attributes of relevance for conceptualizing a decision support model for improving WR. Sustainable agriculture for guaranteeing food security should rely on practices targeted to preserve and enhance the five main soil functions. However, WR involves a set of complex processes acting at different scales where a crucial issue is the connectivity between soil and waterbodies. In addition, the intricate trade-offs between functions should be also taken into account. Management practices may also alter the intrinsic capability of soils to retain nutrients. For example, lime or organic amendments can alter the retention capacity of many pollutants in soil. The management focus has been put on crop production, but the potential impacts of livestock production systems also require attention. This highlights the need for a wider approach for water regulation and purification that considers all aspects of farming system design and analysis.

An extensive review by Vereecken et al. (2016), highlighted that there is limited availability of models for predicting the wide set of soil processes affecting soil functions under changing climate scenarios. Decision support approaches to water management are necessary to mitigate the negative consequences of climate change. The consequences of farm and soil management practices on the delivery of the WR function has not been fully addressed by decision support tools for farmers. These issues and knowledge gaps reveal the need for integrating efforts to enhance the WR function of soils which cannot be isolated from the other functions. Scale specific knowledge based decision-making targeted at farm, local, regional, and societal challenges is required. This paper discusses the development of a decision support model for the management of the WR function performed by agricultural soils. This is in conjunction with work on four other soil functions investigated in the H2020 LANDMARK project (Debeljak et al., 2019; Sandén et al., 2019; Van de Broek et al., 2019; van Leeuwen et al., 2019). This tool provides the user with qualitative information regarding the capacity of an agricultural soil to perform the water regulation and purification function. In addition, the aim of this tool is to increase awareness among model users about the multi-functionality of agricultural soils, and the existence of important trade-offs between the performances of these soil functions as a consequence of the applied management. The models for the five soil functions have been brought together to assess the trade-offs between different soil functions for a given set of management practices across Europe (Debeljak et al., 2019). The specific objectives of this paper were (i) to construct a qualitative decision support model to assess the water regulation and purification capacity of agricultural soils at field level, to (ii) conduct sensitivity analysis of the model; and (iii) to validate the model with independent empirical data.

MATERIALS AND METHODS

Model Description

The WR function model has been developed based on the rationale that it should make a reliable assessment of the water regulation function of agricultural soils based on data that is readily available. A standard modeling procedure was applied to obtain a reliable decision support model. It consists first of model development, verification, sensitivity analysis, and calibration in an iterative way, followed by validation (Jørgensen and Fath, 2011). The model was built using multi-criteria decision analyses, using the DEX (Decision Expert) integrative methodology for qualitative decision modeling (Bohanec and Rajkovic, 1990; Bohanec et al., 2013; Bohanec, 2017) to structure the current knowledge of water interactions in soil to construct the multi-attribute decision model (Greco et al., 2016). Domain experts (soil and water scientists) helped design the theoretical scenarios used to structure the model to inform expected outcomes. The principles of this methodology follow intuitive human decision-making, where the main decision problem (water regulation and purification) is broken down into smaller, less complex sub-problems (in our case, water storage, nutrient, and sediment loss in water runoff and nutrient leaching with percolating water). This breakdown is represented in the form of a hierarchy, where the main concept, water regulation and purification, was at the top of the hierarchy and was related to lower-level attributes on which it depends. These attributes represent the characteristics of the system, which are environmental variables, soil properties, and management practices. The attributes on the lowest level of the hierarchy are the basic attributes. The intermediate attributes are obtained using integration rules, which also determine how the attributes are combined into the final water regulation function.

Initially a list of 48 soil (S), environment (E), and management (M) attributes were identified, as being important for WR function, through a combination of literature analysis and expert judgement. Their qualitative values (high, medium, low) were obtained using decision rules defining accurate thresholds that reflected the statistical and expert distribution of the measured values. The thresholds of the dependent WR function variable were defined in the context of a selected crop based on the differences in yields between different crops. Decision rules (also referred to as integration rules) are a tabular representation (integration table) of a mapping from lower-level attributes to higher-level ones. The qualitative modeling approach of the DEX methodology helps formalize the input values into discrete (finite) scales. Our case unifies the scales along all basic attributes in a set of three categorical values: "Low," "Medium," and "High." Exceptions are attributes that play binary roles, represented with value scales consisting of two values: "Yes" and "No." Calibration was conducted to find the best agreement between the computed and observed data by modifying the integration rules.

Sensitivity Analysis

Sensitivity analysis was conducted to reduce model complexity by distinguishing between those input attributes whose values have a significant impact on model behavior, and those attributes whose values have low or no impact. Weightings define the contribution of a corresponding attribute to the final evaluation. The total weight of the top-most attribute in the model was 100%, whereas the weight of the basic or intermediate attributes could be between 0 and 99%. We performed sensitivity analysis to assess the extent to which the model results were influenced by changes in S, E, and M. This was done separately for three components of the overall WR model: (1) water storage, (2) water runoff leading to P and sediment loss, and (3) water percolation leading to N leaching. The model sensitivity was assessed by gradually changing different S, E, and M attributes which are expected to change the final outcomes of these WR model components.

Model Testing and Validation using European Soil Quality Monitoring Sites

The decision support model for WR was finally validated using a representative dataset of 94 sites from across Europe (Creamer et al., 2019, **Figure 1**). This factual test showed how well the model output performs and fits empirically derived data. An assessment of the accuracy of the model was made by simulating the WR function and its components in agricultural soils across the 94 LANDMARK soil quality monitoring sites in Europe. These 94 sites were chosen because they facilitate the assessment of a range of different S, E, and M across Europe where appropriate water response variables were measured directly *in-situ* at each site. The aim of this evaluation was to test if the model is able to correctly predict the WR function. The dataset used in this study is composed of attributes underlying a soil's capacity to regulate and purify water within agricultural ecosystem boundaries, i.e., water regulation. These attributes included soil properties (S), environmental aspects (E), and management options (M) (**Table 1**), in line with some of the attributes recommended by van Leeuwen et al. (2017). Soil and management data were collected for the 94 sites, using a designed questionnaire to capture the relevant management attributes as categorical output data (Creamer et al., 2019) for observing changes in soil quality across Europe. This dataset covered a broad spectrum of climatic, soil, and agricultural conditions at all 94 sites, including five climatic zones (Atlantic, Alpine S, Continental, Mediterranean N, and Pannonia) and two

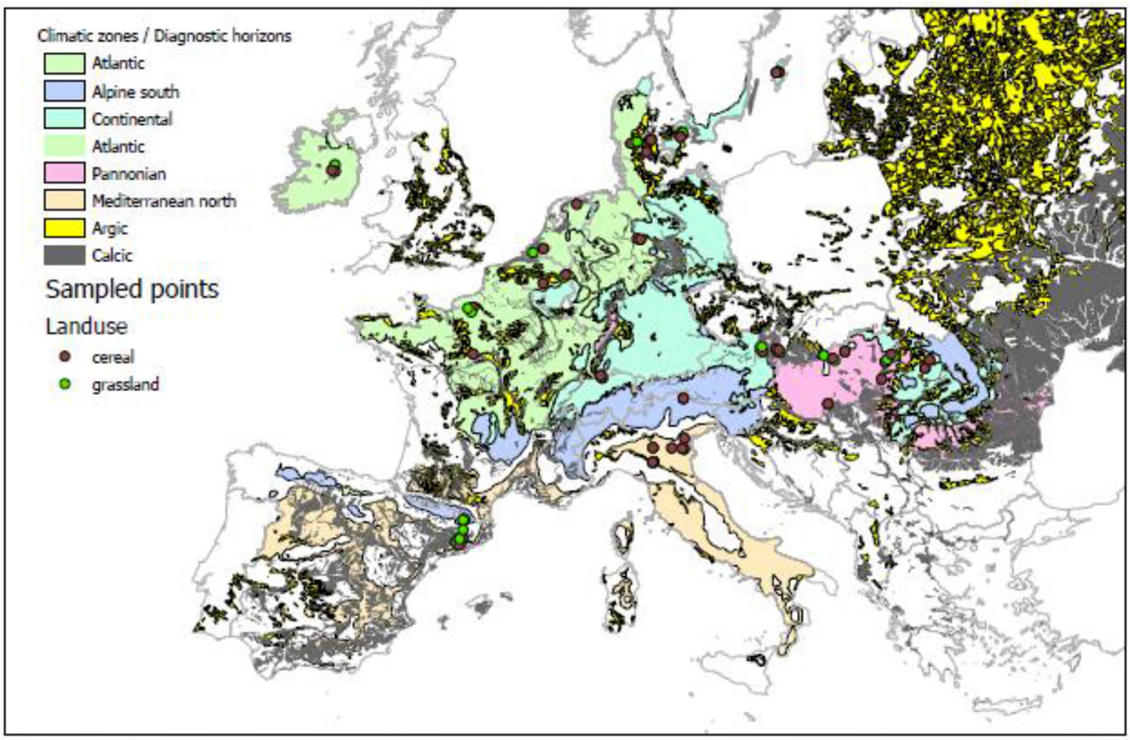

FIGURE 1 | Map showing the 94 soil monitoring points across Europe, including land use and climatic zone.

TABLE 1 | Thresholds used to categorize input attributes into "low," "medium," and "high," or "yes" or "no."

S, E, or M	Model input attribute	Units		Categories: threshold values[#]	
Environment					
E	Precipitation—annual	mm	High: >750	Medium: 500–750	Low: <500
E	Precipitation—wet season	mm	High: >750	Medium: 500–750	Low: <500
E	Precipitation—cropping season	mm	High: >750	Medium: 500–750	Low: <500
Soil					
S	Clay content	%	High: >40	Medium: 20–40	Low: <20
S	Soil drainage class	(WRB*)	High: well	Medium: moderately	Low: poorly
S	Water table depth	m	High: >2	Medium: 1–2	Low:<1
S	Bulk density	g cm^{-3}	High: >1.5	Medium: 1.35–1.5	Low:<1.35
S	Organic matter	%	High: >10	Medium: 3–10	Low: <3
S	pH[$]		High: >7.1	Medium: 5.5–7.1	Low: <5.5
S	Soil test P[$]	mg kg^{-1}	High: >120	Medium: 50–120	Low: <50
S	Soil crusting	Yes/no		Yes/no	
Management					
M	Artificial drainage	Yes/no		Yes/no	
M	Carbon input	Yes/no		Yes/no	
M	Stocking rate	LU ha^{-1} years^{-1}	High: >2	Medium: 1–2	Low:<1
M	Organic manure N input	kg ha^{-1} years^{-1}	High: sludge	Medium: liquids frac.	Low: pig, cattle
M	Mineral N fertilizer N input	kg ha^{-1} years^{-1}	High: >200	Medium: 50–200	Low:<50
M	Organic manure P input	Manure type	High: solid frac.	Medium: compost	Low: pig, cattle,
M	Mineral P fertilizer input	kg ha^{-1} years^{-1}	High: >25	Medium: 10–25	Low: <10
M	Crop type (water use)	Various crop types	High: e.g., maize	Medium: e.g., grass	Low: e.g., squash
M	Plant rooting depth	m	High: >2	Medium: 0.4–2	Low: <0.4
M	Cover cropping	Yes/no		Yes/no	
M	Crop residue management	Yes/no		Yes/no	
M	Irrigation rate	mm h^{-1}	High: <6	Medium: 6–12	Low: >12
M	Irrigation frequency	Days	High: >20	Medium: 10–20	Low: <10
M	Irrigation type	Type	High: drip	Medium: sprinkler	Low: furrow

**WRB, world reference base soil drainage class descriptions. [#]Threshold values provided based on the Atlantic central region, different threshold values are specified for different regions. [$]Different soil tests are used in different countries and will have different thresholds. Input attributes should reflect the current practices for the past 5 years, while temperature and precipitation inputs should be based on regional or local long term climatic data (e.g., 30-year average).*

land-use types; permanent grassland (under grass for 5 years or more) and cereal based rotation farm system (**Figure 1**). The model validation was conducted using a set of rules and defined as follows: an estimation of the WR soil function was considered accurate if the estimated value by the WR sub-model was equal to (received the same "Low, Medium or High" classification) the measured variable or observed characteristic collected on site or in the associated questionnaire. Otherwise, the estimation was considered to be incorrect. This process was conducted for each of the WR sub-models (1) water storage, (2) water runoff leading to P and sediment loss and for (3) water percolation leading to N leaching, where appropriate discrete variables were available for each. For example, for the water transport aspects of each model we used (1) soil moisture content, (2) water infiltration rate, (3) modeled drainage using RETC (van Genuchten et al., 1991). Finally the ratio between correct estimations and total estimations was taken as an accuracy measure for model performance.

RESULTS

Structure of the Decision Support Model for Water Regulation

The developed decision support model for primary productivity is structured in a hierarchical way to take into consideration soil (S), environment (E), crop (C), and management (M) attributes (**Figure 2**). It comprises 5 levels and has 27 basic attributes (**Table 1**). The top of the hierarchy represents the capacity of the soil to deliver the overall WR. In the 2nd tier the model sub-functions, water storage, P and sediment loss in runoff and N leaching in percolating water are shown. The intermediate levels represent attributes that integrate the

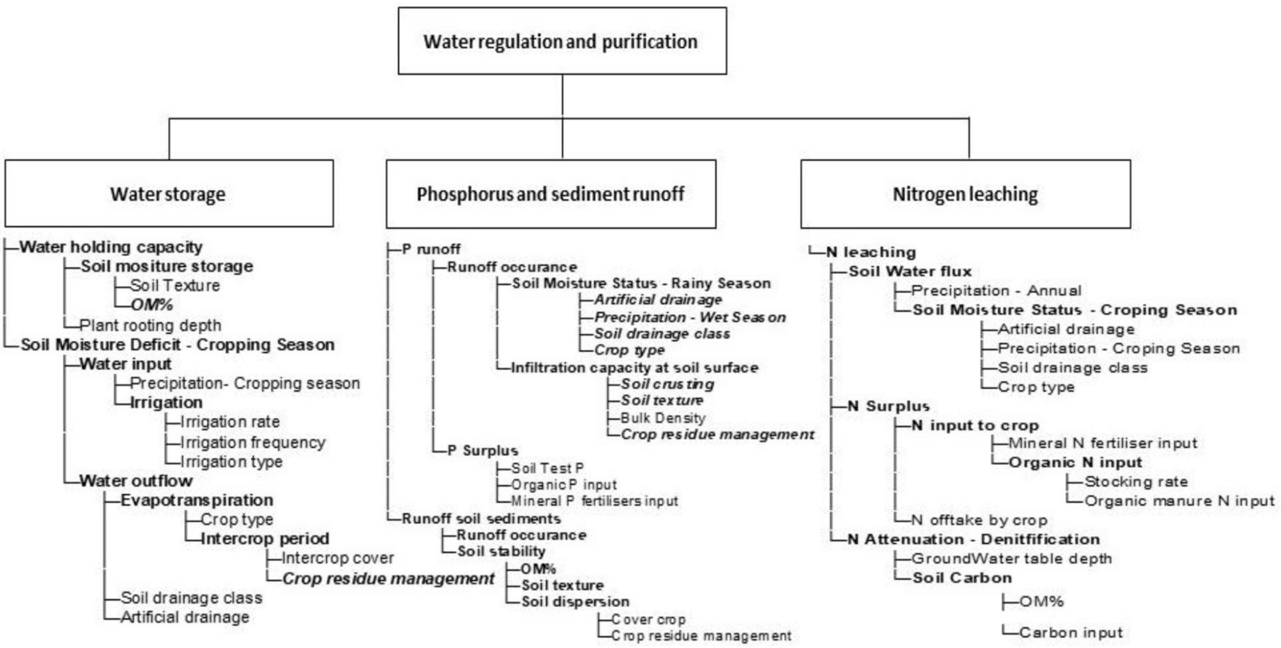

FIGURE 2 | The decision support model for water regulation and purification (WR) that is built up from basic attributes via aggregated attributes to the ultimate soil function, water regulation and purification.

lower level attributes and finally the basic input attributes are shown. These S × E × M interactions determine whether the capacity of a soil to regulate and purify water is "Low," "Medium," or "High." The soil attributes consist of physical (e.g., texture, bulk density, drainage class etc.) and chemical (e.g., macro-elements including phosphorus) attributes as well as attributes known to influence the biological activity, specifically relevant are N mineralization and denitrification processes in soils (soil organic matter, soil pH). The environment attributes relate mainly to precipitation during different key periods of the year, including the main cropping season when crop water demand is highest, or the period with the highest rainfall leading to increased risk of P runoff and soil erosion potential. Management attributes include: irrigation or artificial drainage if needed, nutrient N and P management, crop residue and organic amendment management, and live-stocking rate. The crop management attributes link crop types to demand for water use and to cover cropping which enhance water infiltration and protect the soil aggregates from rainfall impact and erosion. Each attribute in the decision support model can have one out of three (or two) values (e.g., "High," "Medium," "Low," or "yes," "no"). Subsequently, values of a similar nature are assigned to the overarching process of each possible combination of two or three underlying attributes, until the ultimate function water regulation (at the top) is reached.

Water Storage

The water storage sub-model simulates the current water storage potential of the soil by integrating the attributes influencing soil moisture [soil moisture deficit (SMD)] and the capacity of the soil to retain and store the water inputted [water holding capacity (WHC)] which can be re-supplied for crop growth (**Figure 2**). Soil moisture deficit relates to the current balance of water inputs through precipitation and, or, irrigation vs. water outputs through evapotranspiration and, or drainage. The water holding capacity is related to the texture and organic matter level of the soil and considered to the extent of the plant rooting depth. The integration rules that determine the capacity of the soil to store and supply water for use during the main cropping season were chosen so that increasing WHC and decreasing SMD leads to increasing water storage. Where a soil has high WHC and water inputs exceed water outputs filling this capacity (low SMD) this receives a high water storage capacity. Where a soil has lower WHC and, or, less than sufficient water inputs during the crop growing season to sustain crop growth it receives a medium or low value.

Phosphorus and Soil Sediment Loss in Water Runoff

The water runoff sub-model evaluates the extent to which a soil generates water runoff, implying (i) phosphorus (P) losses and (ii) sediment losses in water runoff (**Figure 2**). This soil sub-function is assessed based on the following integration rules; a soil with water inputs surplus to its water storage, water use by crops or water drainage capacity (i.e., surface water inputs > outputs) thereby generates water runoff. In this model the interaction of environment, specifically precipitation, across different soils leads to different levels of water runoff potential where situations

TABLE 2 | Integration rules used to classify the water regulation and purification (WR) soil function as "low," "medium," or "high" based on the determined capacity to store water and regulate P and sediment runoff and mitigate against N leaching.

Water regulation and purification (WR) function	Water storage	P and sediment loss (water runoff)	N leaching (water drainage)
Weighting	33%	33%	33%
Low	Low	*	*
Low	*	High	*
Low	*	*	High
Medium	Medium	Medium	≥Medium
Medium	Medium	≥Medium	Medium
Medium	≥Medium	Medium	Medium
High	≥Medium	Low	Low
High	High	≥Medium	Low
High	High	Low	≥Medium

of precipitation > water infiltration resulting in increased water runoff. Where soils are compacted (high bulk density), are prone to capping, or have impeded drainage there is increased potential for soil runoff to occur. However, management practices that increase water infiltration, such as cover cropping, crop residue returns or artificial drainage of the soil, were associated with a reduction in water runoff generation.

The water runoff sub-model also captures the main concerns related to water runoff being its potential to transport P or soil sediments (erosion) from agricultural soils (FAO, 2019). These concerns were considered by integrating both source and transport factors into the water runoff sub-model. The P source relates to the levels of soil and P input sources (legacy soil test P and P fertilizer (chemical fertilizer and organic manures) inputs and live-stocking rate) vs. the levels of P outputs (crop P offtake, P outputs related to stocking rate in milk and meat). Where P inputs > outputs, if the soil test P is also high, the P source factor favors P loss and the P runoff receives a high value and *vice-versa.* It is noted that the model is not designed to make predictions of the P concentration in runoff water from the soil. Similarly the stability of soil aggregates in relation to its effect on sediment transport in water runoff is considered. The integration rules consider the effects of soil texture and soil organic matter on aggregate stability which are key soil attributes regulating soil dispersibility (Chenu et al., 2000).

Nitrogen Leaching With Percolating Water

The water percolation sub-model evaluates the capacity of the soil to transmit water as drainage and includes the potential for nitrogen (N) leaching to occur (**Figure 2**). As with the water runoff, this sub-model is broken down into its transport and source components. In relation to transport, the water percolation sub-model is based on integrating the attributes influencing available soil water [soil moisture deficit (SMD)] and the capacity to transmit water through the soil (influenced by soil drainage class or artificial drainage) (**Figure 1**). Under the integration rules a soil with low SMD and high water infiltration and drainage potential will receive a high water percolation value.

The water percolation sub-model also captures N leaching potential as one of the main water purification concerns related to water percolation (FAO, 2019). To capture the N leaching source factor levels of N input sources [soil N and fertilizer N (chemical fertilizer and organic manures), live-stocking rate] vs. the levels of N outputs (crop N offtake and N outputs related to stocking rate in milk and meat). Where N inputs > outputs the N source factor favors N loss and N leaching receives a high value and *vice-versa.* It is noted that the model is not designed to make predictions of the N concentration in drainage water from the soil.

The Water Regulation and Purification (WR) Soil Function

The final WR soil function is determined based on the combination of the water storage, P and sediment loss in water runoff and N leaching with percolating water. The integration rules that define the magnitude of the WR function are shown in **Table 2**. For example, a medium value for water storage and a high value P in runoff and high value for N leaching led to a low overall WR value.

Sensitivity Analysis

The variability of importance of each attribute within the model on the WR function is shown in **Table 3**. The three WR sub-models (2nd hierarchy tier) were set to contribute equally (expressed as global normalized weights of 33% each) to the overall WR function for the sensitivity analysis. This means that the inner variability of these structures contributes equally to the variability of the outcome. Examining the lower level of the hierarchy reveals that the water inflow (precipitation and irrigation), as well as inherent soil properties on water flux (soil texture, organic matter, and drainage class, and soil capping/slaking), nutrient management (mineral and organic N and P fertilization) and presence of livestock greatly influence the variability of the WR function. In contrast, the least important individual attributes involve crop type, including cover crops, irrigation method and frequency, and soil pH whereby, in general, soil physical and environment attributes dominate somewhat over management practices.

Model Validation

Finally model validation and performance evaluation of the WR decision support model was performed after completing the sensitivity analysis of attributes contained in the model. The performance of the final decision support model, was expressed by its accuracy in correctly classifying the level of WR function provision compared to the empirically derived and observed values at each of the 94 field sites, which were also classified as either Low, Medium, and High (**Table 4**). We examined model performance for each of the WR sub-models separately as well as the overall WR function, based on the model prediction for each of the 94 sites categorized as either "Low," "Medium," and "High." Overall the WR decision support model correctly classified 74.5% of cases, and incorrectly classified 10.6% of sites by 2 levels (**Table 4**). Across the WR function sub-models the

TABLE 3 | Importance of attributes and sub-models in the water regulation and purification (WR) model.

<table>
<tr><th>Attribute</th><th>Normalized weight</th><th>Attribute</th><th>Normalized weight</th><th>Attribute</th><th>Normalized weight</th></tr>
<tr><td>Water storage</td><td>33</td><td>P and sediment loss (water runoff)</td><td>33</td><td>N leaching (water percolation)</td><td>33</td></tr>
<tr><td>| ⊢Water holding capacity</td><td>17</td><td>| ⊢P runoff</td><td>17</td><td>⊢N leaching</td><td>33</td></tr>
<tr><td>| | ⊢Soil moisture storage</td><td>8</td><td>| | ⊢Runoff occurrence</td><td>14</td><td>⊢Soil water flux</td><td>9</td></tr>
<tr><td>| | | ⊢Soil texture</td><td>4</td><td>| | | ⊢Soil moisture status—wet season</td><td>7</td><td>| ⊢Precipitation—annual</td><td>4</td></tr>
<tr><td>| | | ⊢OM%</td><td>4</td><td>| | | | ⊢Artificial drainage</td><td>1</td><td>| ⊢Soil moisture status—crop season</td><td>4</td></tr>
<tr><td>| | ⊢Plant rooting depth</td><td>8</td><td>| | | | ⊢Precipitation—wet season</td><td>3</td><td>| ⊢Artificial drainage</td><td>1</td></tr>
<tr><td>| ⊢Soil moisture deficit</td><td>17</td><td>| | | | ⊢Soil drainage class</td><td>1</td><td>| ⊢Precipitation—crop season</td><td>1</td></tr>
<tr><td>| ⊢Water input</td><td>8</td><td>| | | | ⊢Crop type</td><td>1</td><td>| ⊢Soil drainage class</td><td>1</td></tr>
<tr><td>| | ⊢Precipitation—crop season</td><td>6</td><td>| | | ⊢Infiltration capacity</td><td>7</td><td>| ⊢Crop type</td><td>1</td></tr>
<tr><td>| | ⊢Irrigation</td><td>3</td><td>| | | ⊢Soil crusting</td><td>2</td><td>⊢N Surplus</td><td>15</td></tr>
<tr><td>| | ⊢Irrigation rate</td><td>1</td><td>| | | ⊢Soil texture</td><td>2</td><td>| ⊢N input to crop</td><td>7</td></tr>
<tr><td>| | ⊢Irrigation frequency</td><td>1</td><td>| | | ⊢Bulk density</td><td>1</td><td>| | ⊢Mineral N fertilizer input</td><td>4</td></tr>
<tr><td>| | ⊢Irrigation type</td><td>1</td><td>| | | ⊢Crop residue management</td><td>2</td><td>| | ⊢Organic N input</td><td>4</td></tr>
<tr><td>| ⊢Water outflow</td><td>8</td><td>| | ⊢P surplus</td><td>3</td><td>| | ⊢Stocking rate</td><td>2</td></tr>
<tr><td>| ⊢Evapotranspiration</td><td>3</td><td>| | ⊢Soil test P</td><td>1</td><td>| | ⊢Organic manure N input</td><td>2</td></tr>
<tr><td>| | ⊢Crop type</td><td>2</td><td>| | ⊢Organic P input</td><td>1</td><td>| ⊢N offtake by crop</td><td>7</td></tr>
<tr><td>| | ⊢Intercrop period</td><td>1</td><td>| | ⊢Mineral P fertilizers input</td><td>1</td><td>⊢N attenuation—denitrification</td><td>10</td></tr>
<tr><td>| | ⊢Intercrop cover</td><td>1</td><td>| ⊢Runoff soil sediments</td><td>17</td><td>⊢Water table depth</td><td>6</td></tr>
<tr><td>| | ⊢Crop residue management</td><td>1</td><td>| ⊢Runoff occurrence</td><td>12</td><td>⊢Soil carbon</td><td>4</td></tr>
<tr><td>| ⊢Soil drainage class</td><td>2</td><td>| | ⊢Soil moisture status—wet season</td><td>6</td><td>⊢OM%</td><td>3</td></tr>
<tr><td>| ⊢Artificial drainage</td><td>3</td><td>| | | ⊢Artificial drainage</td><td>1</td><td>⊢Carbon input</td><td>1</td></tr>
<tr><td></td><td></td><td>| | | ⊢Precipitation—wet season</td><td>3</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| | | ⊢Soil drainage class</td><td>1</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| | | ⊢Crop type</td><td>1</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| | ⊢Infiltration capacity at soil surface</td><td>6</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| | ⊢Soil crusting</td><td>1</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| | ⊢Soil texture</td><td>1</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| | ⊢Cover crop</td><td>2</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| | ⊢Crop residue management</td><td>2</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| ⊢Soil stability</td><td>5</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| ⊢OM%</td><td>2</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| ⊢Soil texture</td><td>1</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| | ⊢Soil texture</td><td>1</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| ⊢Soil dispersion</td><td>2</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| ⊢Cover crop</td><td>1</td><td></td><td></td></tr>
<tr><td></td><td></td><td>| ⊢Crop residue management</td><td>1</td><td></td><td></td></tr>
</table>

Importance is expressed in percentage representing the contribution (ratio) of attribute's variability in outcome's variability. Hence, sub-models, water storage, phosphorus and sediment runoff and nitrogen leaching contribute 33% each to the overall WR function value.

N leaching model correctly classified 96.8% of cases correctly followed by the model for P and sediment runoff loss which correctly classified 93.6% of cases with the water storage model classifying 70.2% of cases correctly. However, these three WR sub-models showed very few incorrect classifications at 2 levels of difference (0, 2.1, and 0%, respectively). This indicates that

TABLE 4 | No of sites classified as either low (L), medium (M), or high (H) and model performance compared to empirically derived water regulation and purification (WR) function assessments across the 94 European soil quality monitoring sites.

Water function	Water regulation and purification (WR) function	Water storage	P and sediment loss (water runoff)	N leaching (water percolation)
Classification: # sites	L:37, M:13, H:44	L:38, M:33, H:23	L:89, M:3, H:2	L:91, M:3, H:0
Correctly classified	74.5%	70.2%	93.6%	96.8%
Incorrectly classified 1 and 2 levels*	23.5%	29.8%	6.4%	3.2%
Incorrectly classified = 2 levels*	10.6%	0%	2.1%	0%

Incorrectly classified at Level 1 is a single level difference between the model classification and empirically derived classification (e.g., low vs. medium or medium vs. high and vice-versa). At Level 2 is two levels of difference between classifications (e.g., low vs. high and vice-versa).

that differences in model input attributes values were pushing them across attribute thresholds potentially leading to partially incorrect categorization in one or more of the sub-models at 1 level of difference from the empirically derived classification.

DISCUSSION

The H2020-LANDMARK project has provided a set of outcomes in relation to key indicators and management strategies for water purification and regulation (Wall et al., 2018). As identified, the water function is governed by a complex interaction of soil (S), environment (E), and management (M) interactions that may drive synergies or trade-offs with other soil functions. Schröder et al. (2016b) apply this S × E × M expression to all five soil functions, indicating that soil functions are never uniquely determined by only one of these factors. Attributes of the soil (S) exhibit variation in sensitivity to change associated with management; some attributes exhibiting static characteristics such as texture while others are more dynamic such as bulk density, soil organic matter etc. In turn, environmental (E) factors such as temperature and precipitation will affect S and M requirements. Implicit in the fact that interactions occur as a continuum such that an S property may contribute significantly to the water function in one environment but may be far less relevant in another environment. As a result, countless combinations exist which means that M requires a targeted approach to support the water function. The decision support model for the assessment of the WR function in agricultural soils was based on capturing water movement through and over soils i.e., the water regulation component of the soil function, and also considered the nutrient solutes, specifically N and P, that aquatic environments are more sensitive toward, i.e., the water purification component of the soil function. This model does not currently consider other potential water pollutants e.g., pesticides, that soil may also play a role in retaining or purifying from water.

The LANDMARK project has developed this WR function decision model in conjunction with similar models for the other four soil functions: primary productivity (Sandén et al., 2019), soil biodiversity and habitat provision (van Leeuwen et al., 2019), climate regulation (Van de Broek et al., 2019) and nutrient recycling (Schröder et al., 2016a). The water model shares a number of attributes with the other models, including precipitation (all models), irrigation and artificial drainage (biodiversity, nutrient cycling and climate regulation) and groundwater table depth (biodiversity, nutrient cycling and primary productivity). Together these soil function models assess the current capacity of soils based on the range of S, E, and M scenarios that exist across agricultural soils in Europe. These models allow stakeholders, by changing the M factor, to better understand the trade-offs and synergies between the different soil functions. This has been a basis for the LANDMARK project to develop the Soil Navigator decision support tool (DST), which can be used by farmers and farm advisory personnel at local scales to assess the current capacity of soils to deliver the five soil functions and select beneficial management practices for soil function optimization depending on demands and priorities (Debeljak et al., 2019). Such a DST that integrates all five soil functions will be a valuable complement to existing stand-alone tools covering only nutrient management or water management.

CONCLUSIONS

To date, soil is not the main subject of any regulatory framework in EU but there must be increased coherence in existing policies to protect soil functioning including water regulation and purification. The WR function of soils has been highlighted in terms of meeting relevant societal challenges including maintaining food security and mitigating the consequences of climate change. The protection and enhancement of this critical soil function requires a holistic approach that also considers other functions. Here we developed a WR decision support model which can be used by farmers and farm advisors to enhance the delivery of the WR function at farm and field levels. This tool should provide a reliable qualitative estimate for the current capacity of soil to regulate water storage, to mitigate P and sediment losses in water runoff and to minimize N leaching with water percolating below the root zone. A sensitivity analysis of the model input attributes helped to identify those of most relevance in the model, followed by model validation using a soil quality monitoring empirical data-set where soil, weather and management data and water related response variables were measured *in-situ* across the main geo-climatic regions in Europe. This approach resulted in an accurate, reliable, and useful decision support model for the assessment of the WR soil function at the field level. This WR model can be used to help inform choices related to farm management practices toward enhancing the WR function provision of agricultural soils. This model has also been used to underpin the Soil Navigator developed by the LANDMARK H2020 project, together with four other soil function models.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

This article resulted from cooperation with soil functions' task groups in the LANDMARK H2020 project. DW, MD, AT, CB, LO'S, and AD contributed to the development of the water regulation and purification decision models discussed in this paper. DW, MD, and VK conducted the sensitivity analysis and optimization of the models while VK, RC, and DW organized the validation data and conducted the validation exercises. All authors contributed to writing of this paper, contributed to the article, and approved the submitted version.

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