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EXPLORING THE POTENTIAL OF HIGH-RESOLUTION SOIL MOISTURE INDICATORS FOR DECISION-MAKING IN REGIONAL OPERATIONAL WATER MANAGEMENT

Master thesis

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ABSTRACT

Water systems face an increasing pressure due to climate change and socio-economic developments. This emphasizes the need for rational and reliable information for decision-making in water management. In this MSc. study, soil moisture indicators are defined and validated to translate soil moisture data into information which can support decision-making in Dutch regional operational water management. Soil moisture is water in the pores between soil particles above the groundwater level. Although soil moisture is categorized as an Essential Climate Variable (ECV) by the European Space Agency, this variable is currently not applied for decision-making in water management, which is related to the lack of soil moisture data and perception of its importance in water management. The motivation for this study is the availability of new soil moisture data, for example from Sentinel-1 satellite data.

First, a theoretical framework is constructed to acquire insight in methods to bridge the science-policy gap. The outcomes are used to identify the information demand of water managers from the operational water management crisis team WOT (*Waterschap Operationeel Team*) of regional water authorities Vechtstromen and Drents Overijsselse Delta. The WOT is active among others in dry and wet periods and aims at mitigating the impact of extreme periods. The information demand of the water managers is identified by means of a survey, which contained two case studies concerning an extreme dry and an extreme wet case. The results of survey obtained insight in the following practical demands: insight in the storage capacity of the unsaturated zone, availability of water for crops, spatial information that distinguishes wet (or dry) and extreme wet (or dry) areas and specifications regarding the spatio-temporal resolution. These practical demands from water managers are merged with requirements that indicators should meet from a scientific perspective. These indicator requirements consist of data availability, accuracy, reliability, relevance, temporal and spatial resolution and translation (data into information). These requirements are used to develop indicators in this study and to select suitable indicators based available soil moisture indicators found in literature. To quantify the indicators, hydrological model data are used, because root zone and unsaturated zone soil moisture data cannot be retrieved by satellite measurements.

Three indicators comply with the requirements, namely the Storage Capacity Indicator (SCI), Soil Water Deficit Index (SWDI) and Soil Water Wetness Index (SWWI) of which the latter is developed in this study. The SWDI and SWWI classify the severity of dry and wet conditions respectively, whereas the SCI depicts the available storage of the soil. This SCI can be used in combination with precipitation forecasts to predict whether the precipitation amount can be stored in the soil. These indicators are validated by means of a workshop with employees of regional water autority Vechtstromen.

During the workshop, the participants considered the currently used information in operational water management accurate and easily interpretable. However, these information sources do not provide full insight in the water system. This means that water managers do not have all relevant information about the water system at their disposal yet. Therefore, they indicated earlier that there is a demand for more information. The participants stated that soil moisture data can offer new insights in the water system and can have a positive supporting value of the current insights. The soil moisture indicators that were used in this study were also valued positive with regard to the ease of use of the data, which means the application of indicators has potential in the translation of data into information. Therefore, soil moisture indicators may play a role in providing water managers new insights in the water system. As a side note, the usefulness of the soil moisture data and indicators in regional operational water management cannot be derived directly from the workshop, because they are not quantitatively applied in a case study to measure the impact of the indicators on decision-making.

To build upon the positive attitude of the participants of the workshop regarding soil moisture data and indicators, it is recommended to explore the integration of the data and indicators in operational water management. To enhance the water managers' understanding of the water system, a participative approach might be helpful. It is suggested to take four steps into account during this integration process. The first step involves the water managers gaining experience with the new soil moisture data and indicators. The second step focuses on the detection of trends and patterns in the soil moisture indicators to improve understanding in the water system. The third step concerns the water managers being allowed to adapt the classification structure of the indicators towards their perception in practice. After a positive result of the first three steps, the fourth step follows. This step comprises that soil moisture indicators might be part of a decision tool on which measures in the water system can be based.

SAMENVATTING

Watersystemen ondervinden een toenemende druk als gevolg van klimaatverandering en sociaal-economische ontwikkelingen. Om op verstandige wijze met deze toenemende druk om te kunnen gaan, neemt ook de noodzaak toe voor rationele en betrouwbare informatie voor het nemen van beslissingen in waterbeheer. In deze MSc. studie zijn bodemvochtindicatoren definieerd en gevalideerd om bodemvochtdata te vertalen in informatie die gebruikt kan worden als ondersteuning bij het nemen van beslissingen in regionaal operationeel waterbeheer in Nederland. Bodemvocht is het water in de poriën van bodemdeeltjes boven het grondwaterniveau. Ondanks dat de European Space Agency bodemvocht beschouwt als een essentiële klimaat variabele (ECV), wordt tot op heden deze variabele nog niet toegepast bij het nemen van beslissingen in waterbeheer, dit heeft te maken met het gebrek aan bodemvochtdata en de perceptie van het belang van deze data in waterbeheer. De motivatie voor deze studie is de beschikbaarheid van nieuwe bodemvochtdata, zoals Sentinel-1 satellietdata.

Om inzicht te verwerven in mogelijkheden om het kennishiaat tussen wetenschap en praktijk te dichten is een theoretisch raamwerk opgesteld. De verkregen uitkomsten zijn gebruikt om de informatiebehoefte van waterbeheerders in kaart te brengen. Deze waterbeheerders zijn onderdeel van het Waterschap Operationeel Team (WOT) van waterschap Vechtstromen en Drents Overijsselse Delta. Het WOT is actief tijdens afwijkende omstandigheden bijvoorbeeld in geval van extreem droge en natte situaties. Om inzicht te krijgen in de wensen vanuit de praktijk is een enquête opgesteld waarin twee case studies zijn voorgelegd. De twee case studies betreffen een extreem droge en een extreem natte situatie. Uit de enquête zijn de volgende praktische wensen voor indicatoren naar voren gekomen: inzicht in de grootte van de opslagcapaciteit van de onverzadigde zone, de mate van vochtbeschikbaarheid voor gewassen, de mogelijkheden om extreem droge of natte gebieden ruimtelijk te kunnen onderscheiden en specificaties omtrent de ruimtelijke en temporele resolutie. Deze praktische wensen zijn samengevoegd met een lijst van eisen waaraan de indicatoren moeten voldoen vanuit een wetenschappelijk perspectief. De eisen voor de indicatoren bestaan uit data beschikbaarheid, nauwkeurigheid, betrouwbaarheid, relevantie, ruimtelijke en temporele resolutie en vertaling (data in informatie). Deze eisen zijn in deze studie toegepast op indicatoren uit de literatuur en op indicatoren die voortkomen uit deze studie. Op basis hiervan zijn de meest geschikte indicatoren geselecteerd. Om de indicatoren te kwantificeren is gebruik gemaakt van hydrologisch model data, omdat gebleken is dat bodemvochtdata over de wortelzone en de onverzadigde zone niet kan worden verkregen op basis van satelliet metingen.

Drie indicatoren voldoen aan de indicatoreisen, te weten de Storage Capacity Indicator (SCI), Soil Water Deficit Index (SWDI) en Soil Water Wetness Index (SWWI). De eerste twee indicatoren komen uit de literatuur en de laatste is ontworpen in deze studie. De SWDI en SWWI classificeren respectievelijk de droogte en natheid van een gebied, terwijl de SCI de actueel beschikbare opslagcapaciteit van de bodem toont. De SCI kan worden toegepast in combinatie met neerslagvoorspellingen om te voorspellen of de bodem deze hoeveelheid neerslag kan opslaan. Deze drie indicatoren zijn gevalideerd middels een workshop met werknemers van waterschap Vechtstromen.

Tijdens de workshop hebben de deelnemers aangegeven dat de informatie die momenteel gebruikt wordt tijdens operationeel waterbeheer nauwkeurig en makkelijk te interpreteren is. Daartegenover staat dat deze gebruikte informatie niet volledig inzicht geeft in het watersysteem. Met als gevolg dat waterbeheerders nog niet alle relevante informatie over het watersysteem tot hun beschikking hebben. De deelnemers hebben in een eerder stadium al aangegeven dat voor het nemen van onderbouwde beslissingen meer informatie noodzakelijk is. Daarnaast gaven de deelnemers aan dat bodemvochtdata een ondersteunde rol zou kunnen bieden met betrekking tot het verkrijgen van nieuwe inzichten in het watersysteem. De in deze studie toegepaste bodemvochtindicatoren zijn volgens de deelnemers

duidelijk te interpreteren. Geconcludeerd zou kunnen worden dat het verder ontwikkelen en toepassen van bodemvochtindicatoren potentie heeft.

Om voort te borduren op de positieve houding van de deelnemers van de workshop betreffende de bodemvochtdata en -indicatoren, wordt aanbevolen om te onderzoeken hoe deze data en indicatoren kunnen worden geïntegreerd in operationeel waterbeheer. Om het inzicht van waterbeheerders in het watersysteem te verbeteren, kan een benadering geschikt zijn waarbij de praktijk en de wetenschap samen optrekken. Op dit moment lijken vieren stappen in dit integratieproces te kunnen worden beschouwd. Allereerst dienen de waterbeheerders ervaring op te doen en bekend te worden met de betekenis en bruikbaarheid van de nieuwe bodemvochtgegevens. Ten tweede kan worden gefocust op de ontdekken van trends en patronen in bodemvochtindicatoren om inzicht in het watersysteem te verbeteren. Ten derde moeten de waterbeheerders in staat worden gesteld om de interpretatiestructuur van de indicatoren aan te passen aan hun perceptie van de praktijk. Na een positieve uitkomst van de eerste drie stappen volgt de vierde stap. Deze stap behelst het implementeren van bodemvochtindicatoren in het beslissingsproces van waterbeheerders.

PREFACE

Before you lies my master thesis ‘Exploring the potential of high-resolution soil moisture indicators for decision-making in regional operational water management’. This thesis is the final product of the Master Civil Engineering & Management of the Faculty of Engineering Technology at the University of Twente.

I would like to use this preface to thank my graduation committee for their support and advice during the graduation period. Denie Augustijn and Michiel Pezij were very helpful to discuss issues and have provided me with new insights and feedback. I would also like to thank Sjon Monincx from regional water authority Vechtstromen for his help regarding the development of the survey and the organization of the workshop. Thanks to Robert de Lenne for his help with the development of the survey and the insight he gave me in the practices of water managers. Furthermore, I owe many thanks to the respondents of the survey and the participants of the workshop.

I hope you enjoy reading this thesis and I would like to express my hope that science and practice continue working together to explore the application of new data in practice.

Vincent de Heus
Enschede, January 23, 2019

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1 INTRODUCTION

1.1 Problem context

Water systems face increasing pressures due to climate change and socio-economic developments. These increasing pressures emphasizes the need for rational and reliable information during decision-making in water management. Soil moisture information might contribute to optimize regional operational water management, for example with regard to droughts and floods (Thoma, et al., 2008), optimal flow distribution or insight in the spatial variation of wet or dry areas. Soil moisture is water in the pores between soil particles above the groundwater level. Due to the lack of soil moisture observations, soil moisture information is currently not an applied variable in water management (STOWA, 2016c), whereas it is categorized as an Essential Climate Variable (ECV) by the European Space Agency (ESA, 2012).

The European Copernicus programme provides among others freely available Sentinel-1 surface soil moisture satellite data. OWAS1S (Optimizing Water Availability with Sentinel-1 Satellites) focuses on the integration of the Sentinel-1 soil moisture data in regional water management. This MSc. study is part of the OWAS1S project. The Sentinel-1 satellites provide one image each two to six days on a spatial resolution of 10 m by 10 meter (University of Twente, 2015).

One of the challenges in applying new data sources in decision-making is that these sources often fail to reach the decision-makers in a suitable way, while the new data source could be valuable in supporting decision-making. This gap between information provided by scientists and actual information used in practice is called the science-policy gap. Consequently, decision-makers are provided with information that still requires extended knowledge for interpretation (Horita et al., 2017). Indicators might play a role in the translation of soil moisture data into valuable information. Data does not have a detailed meaning of itself, whereas information is defined as data that is given a meaning when positioned into a context. The application of indicators could enhance the rationality of decision-making. These indicators are qualitative or quantitative parameters which offer spatio-temporal information and can be derived from soil moisture data.

Therefore, this study focuses on the application of soil moisture indicators and their usefulness in regional operational water management in the Twente region (eastern part of the Netherlands) as an example.

1.2 Research aim and questions

The research aim is:

> **Definition and validation of indicators derived from soil moisture data to support decision-making in Dutch regional operational water management.**

Regional operational water management is focused on decisions related to a temporal scale of hours to days. The definition of indicators is formulated as the selection of indicators from literature and development of indicators in this study based on practical and scientific demands. The validation of indicators is formulated as the usefulness of the defined indicators in regional operational water management. Usefulness is formulated as the added-value of soil moisture information with respect to currently used information in regional operational water management.

The main research question is:

How can soil moisture indicators support decision-making in Dutch regional operational water management?

Three sub-research questions are formulated:

1. Which information is demanded by Dutch regional operational water managers to support decision-making?

2. Which soil moisture indicators can be defined to support decision-making in Dutch regional operational water management?

3. To what extent are soil moisture indicators useful in Dutch regional operational water management?

1.3 Report outline

In Chapter 2 a theoretical framework illustrates requirements for indicators from a scientific perspective. Also, the gap between science and policy is analyzed, which is input for the methodology of research question 1. Furthermore, an overview of the available soil moisture indicators is given. Chapter 3 describes the methodology. Chapter 4 answers research question 1 and contains the information demand of water managers. This chapter ends with a list of indicator requirements based on science (Chapter 2) and practice. Chapter 5 involves the selection and development of indicators (research question 2) based on the indicator requirements. The validation of the defined indicators is discussed in Chapter 6 (research question 3). Chapter 7 contains the discussion and Chapter 8 consists of the conclusions and recommendations.

2 THEORETICAL FRAMEWORK

It is important to understand the information demand of water managers to effectively define soil moisture indicators for regional operational water management. Therefore, a theoretical framework is developed and applied to extract the information demand from water managers (§2.1). Furthermore, a theoretical framework is provided concerning requirements for indicators from a scientific perspective (§2.2). Additionally, an overview of the available soil moisture indicators is given (§2.3). In Chapter 5, these soil moisture indicators are subjected to a list of requirements, among others the aforementioned scientific requirements, in order to define the most suitable soil moisture indicators for this study.

2.1 Bridging the science-policy gap

Despite that scientific information enriches decision-making as it expands alternatives, clarifies choices and enables decision-makers to achieve better results (Dunn & Laing, 2017), the perspectives of scientists and decision-makers are different for various problems (Acreman, 2005). This is caused, among others, by the partial lack of cross-disciplinary interaction and the difference in mutual interests and values between them (Feldman & Ingram, 2009; Liua et al., 2008). Consequently, there is a gap between information offered by scientists and actual information used in practice: the so-called science-policy gap.

STOWA (2016b) adresses the science-policy gap as one of the main threats for the application of remote sensing products in operational water management. Although this study focuses on decision-making rather than policy-making, it can be stated that both elements are strongly related. Policy formulates a framework which is used to make decisions. This makes the science-policy gap an interesting phenomenon for this study. Four lessons that are learned from a literature review are described in order to bridge this gap.

Lesson 1 explains that specific information demands of water managers can be extracted by applying a specific problem that decision-makers face in a realistic context (Dunn & Laing, 2017; Cohen et al., 2016; Guo & Kildow, 2015). A specific information demand helps to deal with the data-rich-information-poor syndrome (Timmerman, 2015). This syndrome illustrates that scientists provide an overwhelming amount of information (data rich) towards the water managers, while it is not clear for the water manager which information to use (information poor) (Bradshaw, 2000). Therefore, the emphasis of information producers should shift from producing large amounts of data towards tailor-made information (STOWA, 2016b; Timmerman, 2015; Saeger, 2001).

Lesson 2 concerns the application of indicators to bridge the gap between science and practice. Indicators are seen as a media to bridge scientific work and policy needs (Hinkel, 2011), because of their ability to translate scientific information to a wide range of audiences (Saeger, 2001; Smeets & Weterings, 1999). Additionally, indicators are often linked to specific problems (Timmerman, 2015). The application of indicators enhances the rationality of decision-making by representing a state, change or trend over a time period.

Lesson 3 illustrates that information specified by water managers should be the real information needed. According to Timmerman et al. (2000), this discrepancy between information provided and information needed is a result of the respondent having difficulties in communication or interpreting the questions differently, for example due to application of unclear terms.

Lesson 4 describes that the strategy to collect information should provide the right information (Timmerman et al., 2000). This is a result of for example the information demand that does not fall within the scope of this study, such as a higher level of accuracy of precipitation data.

2.2 Scientific requirements

To provide a scientific base for defining soil moisture indicators, scientific requirements are derived from a literature study. These requirements are stated in Table 1. The requirement usefulness, indicated with the color green, is applied in research question 3 to assess the selected and developed indicators. The criteria column indicates the boundaries that a requirement should meet. The criteria that are indicated with the color red need to be derived from practical demands. The last column shows the distiction between scientific requirements related to the definition and input data of the indicator. The indicator definition requirements are applied to define the most suitable indicators, while the indicator data requirements are applied on the input data of the defined indicators.

TABLE 1: FRAMEWORK OF SCIENTIFIC REQUIREMENTS

Requirement	Description	Criteria	Input data or indicator
Availability[1]	Input data of indicators is available and can be used.[1]	The input data of the indicator should be available or can be derived from other data sources.	Indicator definition
Accuracy[2]	Degree of similarity of data with respect to ground truth.[2]	The indicator should use the most accurate available soil moisture data set that is analyzed.	Input data
Reliability[3]	Degree of consistency of data.[3]	The indicator should use the most reliable available soil moisture data set that is analyzed.	Input data
Relevance[3]	Relevance of indicator objective and information demand water managers (specification of quantity, quality, time and location).[3]	Criteria need to be derived from practical demands of water managers.	Indicator definition
Spatial resolution[4]	Provides data at regular spatial intervals.	Criteria need to be derived from practical demands of water managers.	Input data
Temporal resolution[5]	Provides updates at regular temporal intervals.	Criteria need to be derived from practical demands of water managers.	Input data
Translation[6]	Data is applied on a specific context.[6]	Indicator should translate data into information by scaling the actual data with extreme values (minimum or maximum), incorporating other variables to provide a specific context or with the help of a classification system.	Indicator definition
Usefulness[7]	Added-value of soil moisture information with respect to currently used information in regional operational water management.[7]	Indicator improves understanding of the water system.	-

2.3 Overview available soil moisture indicators

This section offers an overview of available soil moisture indicators based on a literature review. The available soil moisture indicators are listed below.

[1] Smith et al., 2007; Smith & Zhang, 2004
[2] van Voorn et al., 2016; Meul et al., 2009; Liua et al., 2008
[3] van Voorn et al., 2016; Lutter et al., 2011; Liua et al., 2008
[4] Holman et al., 2005
[5] Saeger, 2001
[6] Saeger, 2001
[7] Meul et al., 2009

Drought indicators: *assess the severity of a dry period.*

- **Soil Moisture Drought Severity** (SMDS): determines the severity of droughts based on long-term monthly soil moisture data series of at least 20 years (Qin et al., 2015).
- **Soil Moisture Anomaly** (SMA): assesses the start and duration of agricultural drought conditions. Based on actual soil moisture data and long-term average of the soil moisture level (EDO, 2018).
- **Drought Severity Index** (DSI): assesses the extension and magnitude of drought events by comparing the current soil moisture state to the normal state, which is derived from a probabilistic function based on soil moisture time series (Cammalleri et al., 2016).
- **Soil Moisture Deficit Index** (SMDI): monitors agricultural droughts by reflecting short-term dry conditions (Narasimhan & Srinivasan, 2005). The indicator uses daily and annual total soil moisture levels.
- **Soil Water Deficit Index** (SWDI): quantifies agricultural drought by classifying the crop water availability in the root zone (Martinez-Fernandez et al., 2015). The indicator uses soil moisture, field capacity and wilting point data.
- **Soil Moisture Deciles-based Drought Index** (SMDDI): measures the soil moisture deficiency attributed to rainfall and potential evaporation (Mpelasoka et al., 2008).
- **Soil Moisture Deficit** (SMD): estimates the amount of water in millimeters necessary to bring the soil moisture content back to field capacity (Andersson & Harding, 1991). The indicator uses precipitation and evapotranspiration data.
- **Soil Moisture Index** (SMI): monitors agricultural drought by using soil moisture, field capacity and wilting point data (Hunt et al., 2009). The classification structure of this index differs with the SWDI.
- **Soil Moisture Agricultural Drought Index** (SMADI): characterizes and detects short-term soil moisture drought conditions in order to improve crop growth (Sanchez et al., 2016). The index uses soil moisture, temperature and vegetation conditions.

Wetness indicators: *assess the severity of a wet period.*

- **Soil Wetness Index** (SWI^A): estimates the relative soil moisture availability (Mallick et al., 2009). This index uses land surface temperature.
- **Soil Wetness Index** (SWI^B): estimates the soil moisture availability (Wagner et al., 1999). It uses soil moisture data and a characteristic time scale based on the correlation between in-situ and satellite or model data as input values.

Wildfire indicator: *acquires insight in the probability of a wildfire as a result of a dry period.*

- **Keetch-Byram Drought Index** (KBDI): assesses the fire potential based on the soil moisture deficit (Keetch & Byram, 1968).

Vegetation indicators: *assess the impact of the available amount of water in the soil with respect to the crop water requirements.*

- **Temperature Vegetation Condition Index** (TVDI): derives the soil moisture status from temperature data (Patel et al., 2009).
- **Vegetation Drought Response Index** (VDRI): identifies regions that contain drought stressed vegetation (Otkin, et al., 2016). The index uses satellite data of vegetation conditions and land surface properties.

3 METHODOLOGY

The research questions require the application of various techniques. The methodology is described in this chapter. First, the research steps are schematized in Figure 1.

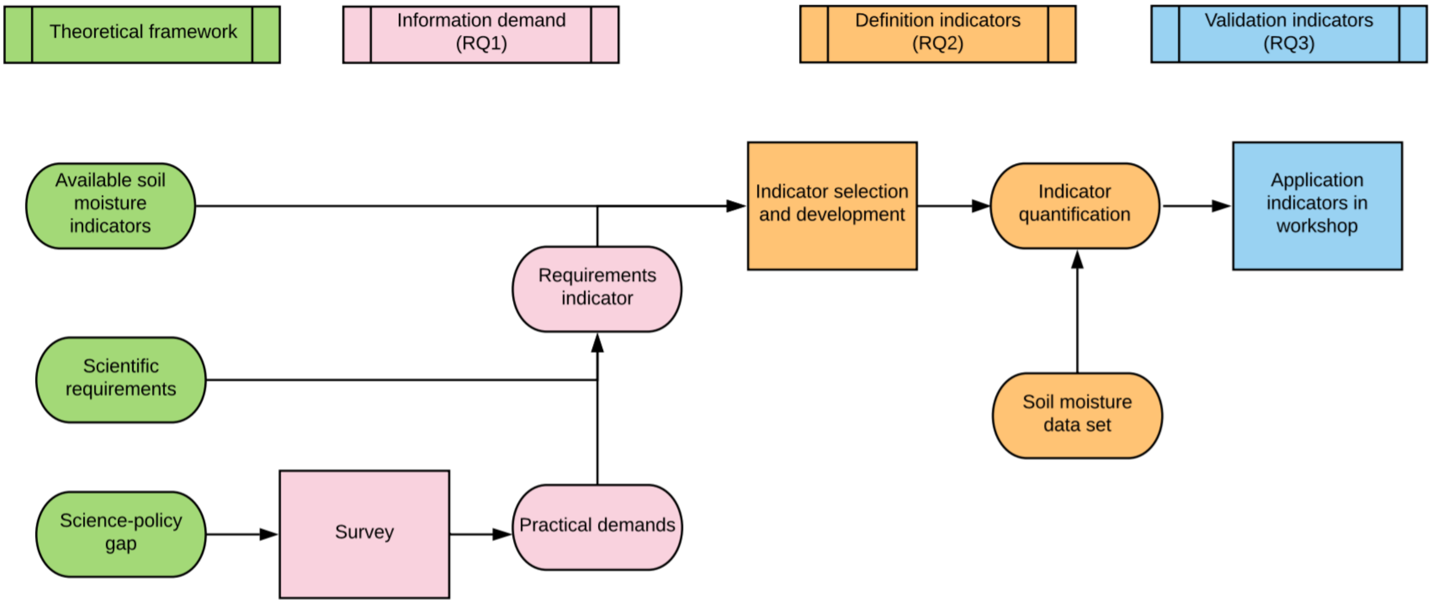

FIGURE 1: SCHEMATIZATION OF RESEARCH STEPS

The theoretical framework described in Chapter 2 helps to acquire insight in methods to bridge the science-policy gap. The framework is used to extract the information demand of water managers by means of a survey. The survey leads to a list of practical demands. This list is merged with requirements that indicators should meet from a scientific perspective (requirements indicator). Hence, research question 1 assesses the indicator requirements, which helps to effectively define soil moisture indicators for regional operational water management.

These indicator requirements are used to select the most suitable indicators based on the available soil moisture indicators from the theoretical framework and to develop indicators in this study. This list of suitable indicators is subjected to soil moisture model data to quantify the indicators. Hence, research question 2 provides a list of indicators that are suitable in regional operational water management based on research question 1.

These indicators are validated by means of a workshop, which focuses on the usefulness of the indicators for operational water management and may provide additional practical demands to improve the presentation of the indicators. Hence, research question 3 assesses to what extent the selected and developed indicators are useful for regional operational water management.

3.1 Research question 1: Information demand of water managers

This research question aims to provide a list of requirements that indicators have to comply with. These requirements are among others based on the practical information demand of water managers. The identification of the information demand is based on knowledge about the science-policy gap (§2.1).

A survey is a suitable method to collect the information demand of water managers (Van Tulder, 2012). The main advantages of a survey are efficiency (Mathers et al., 2007; Leong, 2006) and the incorporation of knowledge from experts from the field. The main objective of the survey is to identify the information demand of water managers (§2.1: science-policy gap: lesson 1).

3.1.1 Sample group survey

The survey target are the members of the operational water management crisis team WOT (*Waterschap Operationeel Team*) of regional water authorities Vechtstromen (20 persons) and Waterschap Drents Overijsselse Delta (20 persons), from this point on referred to as Vechtstromen and Drents Overijsselse Delta. The WOT is active among others in dry and wet periods and focuses on operational water management (Waterschap Vechtstromen, 2015). Their main objective is to mitigate the impact of extreme periods, while taking all possible effects of measures into account. The WOT members who are part of the survey are the water system advisors, water system specialists, water system policy advisors and the supervisor of water level managers (*peilbeheerders*). Other WOT members are for instance legal assistants, information managers (regulate information flows) and communication advisors. The WOT members have a relatively large degree of freedom in decision-making with respect to water level managers, because of their function and ability to operate during extreme conditions. The water level managers have to implement the measures of the WOT. Only with regard to regular activities, the water level managers have relatively more freedom. In general, the freedom of water level managers is restricted by fixed water levels that need to be maintained, for instance by adapting weir levels.

Seven water managers of Vechtstromen have completed the survey. Two water managers of Drents Overijsselse Delta responded. These two responses were used to verify the categories of the responses from the respondents of Vechtstromen. Due to the similarity of practices and the number of relevant measures and information sources, the deviation in responses was limited.

3.1.2 Development of survey

The survey focuses on a case study to acquire the information needed during decision-making in real-life events. Therefore, the survey contains two case-studies that are targeted at an extreme dry and an extreme wet situation (§2.1 science-policy gap: lesson 1). The application of case-studies in the survey should result in specific information about the daily practices of the water managers during extreme conditions. The first case concerns a dry situation, resulting from a lack of precipitation for four weeks. The drought contributes to reduced agricultural productivity. Furthermore, a prohibition for irrigation is instituted to emphasize the severity of the drought. The second case considers a wet situation, which concerns a heavy precipitation event after two weeks of constant rainfall. The extreme event also results in reduced agricultural productivity.

The survey content was discussed with an advisor of Vechtstromen before the survey was send to the WOT-teams (§2.1 science-policy gap: lesson 3). The discussion functioned as an evaluation tool for the survey, as it leads to clarifications of certain aspects, the application of right terms etc.

3.1.3 Analysis survey results

This section describes the motivation for incorporating the questions and analysis techniques for the responses, indicated per question with (i) and (ii) respectively. Open-ended questions are included to provide insight in the motivations of water managers (Dunn & Laing, 2017). The questions 2-7 are related to the case study, while questions 8-10 are general questions. The complete questionnaire can be found in Appendix A.

1 *What is your function within the regional water authority?*

i. To get an overview of the different functions of the respondents.

The questions 2-4 are related to the dry case.

2 A| *Which measures do you take to mitigate problems related to the decreasing availability of water?*

i. This question gives an overview of measures that mitigate the impact of a dry period. This question also helps the respondent to structure their response for question 2B.
ii. The qualitative answers are categorized to acquire an overview of the main categories that were mentioned. The different categories are derived from the responses. In case a response cannot be attributed to one of the categories, a new categories is derived from this response.

B| *Which information do you use to take these measures in operational water management?*

i. This question gives an overview of the currently used information sources in regional operational water management.
ii. This question concerns partial pre-coding of answers in order to help the respondent with specifying his answers of this relatively broad question (§2.1: science-policy gap: lesson 1). The pre-coding consists of categories derived from Pezij et al., 2019: measurement data, system knowledge, meteorological forecasts, experience, hydrological model output and legislation. The responses are analyzed similar to question 2A.

C| *Which additional information do you use when the dry conditions remain for a longer period (8 weeks instead of 4 weeks)?*

i. The objective of this question is to find out whether the information demand changes over time when the extreme conditions remain for a longer period. Together with question 2B, this question aims to obtain an overview of all information sources used during a dry period.
ii. The responses are analyzed similar to question 2A.

3 *Which information that is not yet used in regional operational water management do you demand to face problems related to drought? And for which purposes do you want to use this information?*

i. This question aims to find out what other information the water managers would like to have in the decision-making process.
ii. The responses are analyzed similar to question 2A. Parts of the demanded information may not fall within the scope of this study (§2.1: science-policy gap: lesson 4). Therefore, the underlying purpose of the demanded information allows us to think about other ways to achieve this purpose, for example by using other information sources.

4 *What is an acceptable time interval between the availability of new information flows to be able to support decisions during a dry period?*

i. This question provides insight in the demanded temporal resolution of information during dry periods.
ii. The outcomes are presented in a range of finest to coarsest demanded temporal resolution.

The questions 5-7 are related to the wet case. The objectives and analysis techniques of these questions are similar to questions 2-4.

5A *Which measures do you take to mitigate problems related to the wet situation?*

5B *Which information do you use to take the aforementioned measures in operational water management?*

5C *Which additional information do you use when the probability of negative consequences of the wet conditions increases?*

6 *Which information that is not yet used yet in regional operational water management do you demand to face problems in agriculture related to wetness? And for which purposes do you want to use this information?*

7 *What is an acceptable time interval between the availability of new information flows to be able to support decisions during a wet period?*

General questions:

8 *Rate the importance of the indicator categories*

i. This question aims to find out the importance of the soil moisture indicator categories (§2.3) for water managers (§2.1: science-policy gap: lesson 2). This helps to determine the type of indicators that needs to be defined.

ii. The Likert scale is used to scale the responses (Furnham & Boo, 2011). For each indicator category, the water manager specifies the level of importance on a four-fold scale (*very unimportant, unimportant, important, very important*). The neutral is excluded to enforce the water manager to formulate an opinion. For each indicator category, the variation in responses is reflected by the four-fold scale. The categories of this scale are translated to a rational sequence: very unimportant=1, unimportant=2, important=3, very important=4. The response rate is multiplied by this quantitative scale. The outcome of the multiplication provides insight in the degree of importance of the indicator category. An example is given in Table 2. The values between the brackets are part of the rational sequence. The other values indicate the number of responses for each category.

TABLE 2: ILLUSTRATION OF QUANTIFICATION OF IMPORTANCE INDICATOR CATEGORIES.

	Very unimportant (value = 1)	Unimportant (2)	Important (3)	Very important (4)
Category X	3 responses	2	4	1

The multiplication gives: (1*3 + 2*2 + 3*4 + 4*1) / (3+2+4+1) = 2.3 which is rounded down to 2, hence category X is valued unimportant (2). In the results, the number of responses of the most important category is indicated with a black dot, for instance ❷.

9 A| *Rate the importance of the scientific requirements*

i. This question enables the water managers to prioritize the importance of the scientific requirements that are derived in the theoretical framework (§2.2).

ii. The responses are analyzed similar to question 8. The requirement data availability is an important requirement to define indicators. This requirement is excluded, because it is a boundary condition to quantify the indicator which is not relevant to ask the water manager.

B| *Do you think that requirements are missing from the list in question 9a? If so, which ones?*

i. This question offers insight in additional specific practical demanded.

ii. These requirements are added to the list of practical demanded, if relevant with respect to this study.

C| *What should be the spatial resolution of information?*

i. This question provides insight in the demanded spatial resolution of information.

ii. The outcomes are presented in a range of finest to coarsest demanded spatial resolution.

10| *Model data might have been presented for you. Did you apply these data in your practices? And what purposes did these data serve? If not, why not?*

i. This question reflects the degree of acceptance of water managers regarding new data, using model data as an example. The responses may capture reasons why model data is not used, because the introduction of new data may show skepticism and problems with regard to the presentation.

ii. These pitfalls are used for the definition and presentation of the soil moisture indicators.

3.1.4 Indicator requirements

Based on the information demand of water managers, a list of practical demands can be derived. These practical demands function as criteria for the scientific requirements, as depicted in the theoretical framework. In case a practical demand does not match with a scientific requirement, the practical demand is added to the list of requirements.

3.2 Research question 2: Definition of indicators

This research question aims to define and quantify soil moisture indicators.

3.2.1 Definition of soil moisture indicators

To define the most suitable indicators, the indicator requirements are applied on available soil moisture indicators (§2.3) and on indicators that are developed in this study. The indicator requirements are divided into indicator definition requirements and indicator data requirements. The indicator definition requirements are *hard* requirements, because these are used to define the most suitable indicators. The indicator data requirements are applied on the input data of the defined indicators. These requirements are *soft* requirements, which means that indicators do not necessarily have to comply with these requirements. This is because these requirement may contain unfeasible scientific or practical demands. For example it is hard to asses when data is accurate and reliable, while it is even possible that data is reliable but not accurate. Additionally, practical demands like spatial resolution may be demanded on a too fine resolution. Therefore, the data requirements only guide the selection of the input data.

The definition of the indicators is guided by the focus on extreme dry and extreme wet conditions. Therefore, at least one indicator focusing on extreme dry conditions and one indicator focusing on extreme wet conditions should be selected or developed. The number of indicators should be limited considering the data-rich-information-poor syndrome (§2.1: science-policy gap: lesson 1). Additionally, Smith et al. (2004) mention that too many indicators leads to an inability to understand the system. Therefore, in this study a reasonable number of indicators is 2-4.

3.2.2 Soil moisture data set

The soil moisture data set is selected based on the indicator data requirements. First, the soil moisture data sets are briefly described. After that, the methods to derive the accuracy and reliability are explained.

3.2.2.1 Overview soil moisture data sets

This section describes three datasets: in-situ data, remote sensing data and hydrological model output.

In-situ: soil moisture measurements

The ITC faculty of the University of Twente installed twenty soil moisture monitoring stations in Twente to obtain a network, which continuously monitors soil moisture at various depths on a regional scale (50 by 40 km), see Figure 2. The main purpose of this network is to validate satellite soil moisture data, which also applies for this study. The data is available from 2008 till present. Since microwave remote-sensing instruments cannot observe the soil in forests or paved areas, the majority of the stations is installed in agricultural areas (Dente et al., 2011).

Remote sensing data

The Sentinel-1 satellites measure the radar backscatter with a spatial resolution of 10 m by 10 m and a temporal resolution of two to six days (University of Twente, 2015). Such radar signals typically provide data up to 5 cm soil depth. A change-detection algorithm is used to derive surface soil moisture estimations from the backscatter measurements of the Sentinel-1 satellites (Wagner et al., 1999). The output of this algorithm is used in this MSc. study. The data is available from 2014 till present.

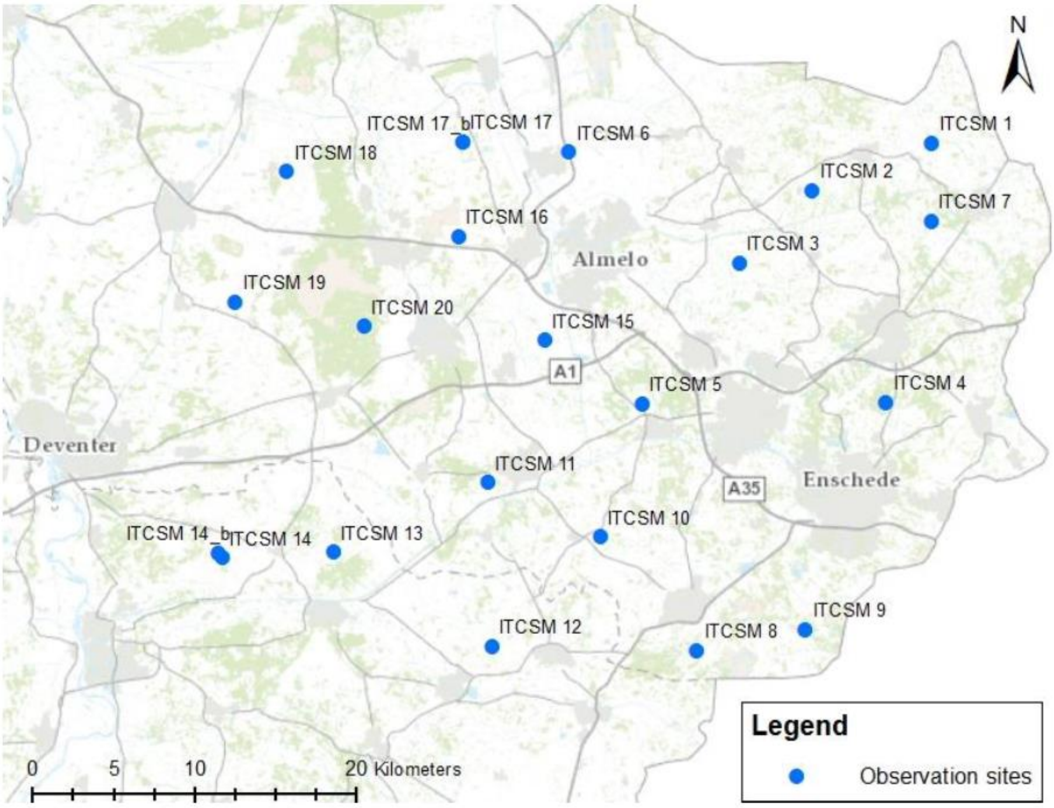

FIGURE 2: IN-SITU SOIL MOISTURE NETWORK IN TWENTE REGION (VAN GURP, 2016).

MIPWA data

The Netherlands Hydrological Instrument (NHI) is an integrated physically-based modelling framework for hydrological simulations on several spatial scales (De Lange, et al., 2014). A regional application of NHI (MIPWA: development of a Methodology for Interactive Planning for WAter management) is used in this study. This regional application has a temporal resolution of one day and is discretized on a grid with a spatial resolution of 250 m by 250 m. MIPWA is a groundwater modelling instrument that provides groundwater level estimates for the Northern regional water authorities of the Netherlands, among others Drents Overijsselse Delta and Vechtstromen (Berendrecht et al., 2017). The MIPWA data provide root zone soil moisture estimates up to 50 cm soil depth. The model is used to simulate the impact of policy measures and climate change (Berendrecht et al., 2017). MIPWA is included in this study, because the model is currently used in the study area for water management purposes by Vechtstromen.

Table 3 shows an overview of the soil moisture data sets and their properties used for the analysis in this study.

TABLE 3: OVERVIEW OF THE SOIL MOISTURE DATA SETS USED IN THIS STUDY

Data set	Variable	Temp. res.	Spatial resolution
In-situ	Soil moisture at various depths	Every 15 min	20 locations in Twente
Sentinel-1	Surface soil moisture	Every 2-6 days	10 m by 10 m
MIPWA	Root zone soil moisture	Daily	250 m by 250 m

3.2.2.2 Accuracy and reliability

The in-situ measurements are assumed as the ground truth, because of the high temporal resolution, direct physical contact with the variable of interest and the high level of accuracy (Dente et al., 2011; Peled et al., 2010; Sheffield et al., 2004). Therefore, the Sentinel-1 and MIPWA soil moisture data are compared with in-situ soil moisture data. However, due to the different representations of the Sentinel-1 (surface soil moisture) and MIPWA data (root zone), these data sets cannot directly be compared.

The accuracy and reliability are calculated for each of the twenty stations locations, which results in twenty values. These values are then averaged, resulting in the outcome of the accuracy of the Sentinel-1 and MIPWA data. The Sentinel-1 data are compared with the in-situ measurements at 5 centimeter depth, while the MIPWA data are compared with the weighted average of the in-situ data over the depths of 5, 10, 20 and 40 centimeter. For estimating the accuracy, the period of October 2014 till May 2017 was chosen, because the required data is available for Sentinel-1 and incorporate multiple years.

The accuracy of the soil moisture data sets is quantified by the Mean Absolute Error (MAE), Relative Volume Error (RVE) and correlation (r). The reliability is quantified by the Coefficient of Variation (CoV).

Mean Absolute Error

The Mean Absolute Error (MAE) represents the absolute average deviation of the Sentinel-1 and MIPWA soil moisture data compared to the in-situ measurements. A relatively small MAE represents a relatively large accuracy.

$$MAE = \frac{1}{N}\sum_{i=1}^{N} |\, \theta_{in-situ}(i) - \theta_{data\ set}(i)\, | \tag{1}$$

With:

N = number of days in time series

i = i^{th} day

$\theta_{in-situ}$ = soil moisture in-situ data

$\theta_{data\ set}$ = soil moisture Sentinel-1 or MIPWA data.

Relative Volume Error

The Relative Volume Error (RVE) determines the average bias of the soil moisture data. The result indicates whether the Sentinel-1 and MIPWA data generally under- or overestimates the in-situ measurements. The data set performs best when a value of zero is generated for the RVE (Booij & Krol, 2010).

$$RVE = 100 \sum \frac{[\theta_{data\ set}(i) - \theta_{in-situ}(i)]}{[\theta_{in-situ}(i)]} \tag{2}$$

Correlation

The correlation (r) indicates the similarity of two time series regarding the displacement, which is additional information with respect to the RVE. The correlation defines the degree of similarity between two datasets. The value of the correlation can vary between -1 and +1. A correlation value ranging between 0-1 implies a positive relation between the two datasets. A value around 0 corresponds to little or no relation.

$$r = \frac{\sum_{i=1}^{N}(\theta_{data\ set}(i) - \overline{\theta_{data\ set}}) \times (\theta_{in-situ}(i) - \overline{\theta_{in-situ}})}{\sqrt{\sum_{i=1}^{N}(\theta_{data\ set}(i) - \overline{\theta_{data\ set}})^2} \times \sqrt{\sum_{i=1}^{N}(\theta_{in-situ}(i) - \overline{\theta_{in-situ}})^2}} \tag{3}$$

$\bar{\theta}$ represents the average value of a monitoring station for N days.

Coefficient of Variation

The Coefficient of Variation (CoV) represents the ratio of the standard deviation with respect to the mean. The data set performs best when the variability of the MIPWA or Sentinel-1 data is close to the variability of the in-situ data. This means the variability characteristics are relatively similar.

$$CoV = \frac{\sqrt{\frac{\sum_{i=1}^{N}\left(\theta_{data\,set}(i) - \overline{\theta_{data\,set}}\right)^2}{N}}}{\overline{\theta_{data\,set}}} \times 100 \qquad (4)$$

3.2.3 Development of indicators

Besides the analysis of available soil moisture indicators derived from the literature review, indicators are developed in this study. The development of the indicators is guided by the practical demands of the water managers.

3.2.4 Application indicators in operational water management

The indicators are quantified based on the soil moisture data set. A first step to apply the indicators in operational water management is derived from the quantified indicators. The spatial and temporal resolution of the indicators depend on the outcome of the survey (research question 1).

3.3 Research question 3: Validation of indicators

Research question 3 describes the validation of the soil moisture indicators. This concerns the usefulness of the indicator information for application in regional operational water management. Additionally, the validation verifies the selection and development of the right indicators (information demand fulfilled).

A workshop is a suitable method to validate the application of the indicators, because it is helpful to explain and discuss the findings with the key stakeholders (here: water managers) to achieve their acceptance of the new product (Bertule & Vollmer, 2017; Tscherning et al., 2012). The objective of the workshop is to assess to what extent application of soil moisture data and indicators is useful in regional operational water management.

3.3.1 Sample group workshop

The workshop is conducted with five employees of Vechtstromen. In this workshop the results of the survey (see §3.1.3) are reflected in cooperation with WOT-members (see §3.1.1). Not only WOT members were present, also a geo-hydrologist, GIS specialist and senior water system advisors take part in the meeting.

3.3.2 Workshop development

The regional water authority aims to learn about the extreme dry summer of 2018 in the Netherlands. In the workshop, the usefulness of soil moisture data and indicators to improve insight in the water system is explored.

First, in-situ soil moisture data are presented to detect trends on point scale. The in-situ measurements are shown for the years 2015-2018 in order to create a reference or a context. These trends are compared with the current expertise and perception of the participants to gain insight in these different perspectives. The current expertise and perception of the participants is a qualitative representation of their knowledge derived from the currently used information. This comparison gives the participants a qualitative insight in the relationship between soil moisture and other hydrological variables. Then the soil moisture indicators are presented on a temporal (also 4 years) and spatial scale to find out the usefulness of the translation of soil moisture data into information for operational water management. Since the regional water authority wants to focus on the dry summer of 2018, the wetness, wildfire and vegetation indicators are not part of the evaluation.

The quantification of the usefulness of currently used information and soil moisture data and corresponding indicators offers insight in the attitude of the participants towards these different information sources. The usefulness is rated based on a set of criteria, which are, for their part, also rated with a qualitative score *very negative, negative, neutral, positive and very positive* (see the Likert scale in §3.1.3). By including the neutral, the water manager is enabled to objectively review the information sources.

The regional water authority aims to obtain an improved understanding of their water system. Therefore, the criteria are closely related to this aim and formulated as follows:

- **Supporting value:** confirmation of current insight into the water system, but data or indicator does not provide new insights.
- **New insights:** the data or indicator leads to improved insight in the water system.
- **Ease of use:** the data or indicator is easy and clear to interpret (Cherubini, et al., 2016; Shibl et al., 2013).

3.3.3 Analysis workshop results

This section contains an overview of the questions asked during the workshop. The complete questionnaire can be found in Appendix C. The responses on the Likert scale are processed similarly to the survey, see section 3.1.3.

1. A| *Assess to what extent the information that you currently use in operational water management (for example precipitation, groundwater levels and remote sensing evapotranspiration data) can support operational water management, give new insights in the water system, are easy to use or are accurate.*
   This question acquires insight in the attitude of the participants towards the currently used information. The outcome gives insight which criteria need to be improved. The criterion accuracy is added only here, because this gives insight in the level of trust of the participants in the used information.
   B| *Give a short explanation*
   This question enables water managers to qualitatively support question 1A.

2. A| *Assess to what extent spatial soil moisture data can support operational water management, give new insights in the water system or are easy to use.*
   This question offers insight in the attitude of the participants towards soil moisture data. The outcome is compared to the usefulness of the currently used information to observe changes with respect to the criteria.
   B| *Give a short explanation to voice your concerns*
   This question enables water managers to voice their concerns on (overseen) relevant issues (Bertule & Vollmer, 2017). These issues are practical demands that help to improve the presentation of soil moisture data and indicators.
   C| *Assess to what extent temporal soil moisture data can support operational water management, give new insights in the water system or are easy to use.*
   Similar to question 2A.
   D| *Give a short explanation to voice your concerns*
   Similar to question 2B.

3. *Assess to what extent the following soil moisture indicators can support operational water management, give new insights in the water system or are easy to use.*

This question provides insight in the attitude of the participants towards the soil moisture indicators. The outcome is compared to the usefulness of the soil moisture data to observe changes with respect to the evaluation of the translation of data into information by the participants.

A| Soil Water Deficit Index (Spatial)
B| *Give a short explanation to voice your concerns*
C| Soil Water Deficit Index (Temporal)
D| *Give a short explanation to voice your concerns*
E| Storage Capacity Indicator (Spatial)
F| *Give a short explanation to voice your concerns*
G| Storage Capacity Indicator (Temporal)
H| *Give a short explanation to voice your concerns*

4 INFORMATION DEMAND WATER MANAGERS

This chapter discusses the results of the survey from which a list of practical demands is derived. Subsequently, these demands are merged with the scientific requirements from the theoretical framework (§2.2). The chapter ends with a list of requirements from which indicators can be defined.

4.1 Information demand

This section contains an overview of the information demand of water managers of WOT in operational water management. The complete questionnaire and responses can be found in Appendix A.

4.1.1 Information demand: provided

This section mentions the currently used information of water managers to take measures during dry and wet conditions. The current information usage is related to questions 2 and 5 of the questionnaire, see section 3.1.3.

Problems related to the decreasing availability of water or wet conditions are mitigated by measures that focus on maintaining target water levels. During a wet period a mowing strategy is part of the available measures. The suitability of a measure depends on the water system characteristics.

In order to take these measures in operational water management, the following information sources are used during dry and wet periods. First, water managers use meteorological data and forecasts such as precipitation. Furthermore, measurement data that monitors variables as for instance groundwater and surface water levels is used by the water managers. Additionally, external advice from other organizations, such as consultation on distribution of water is incorporated. Moreover, hydrological model output is considered valuable to predict water levels and measure the impact of scenarios for instance. Finally, local field knowledge of the responsible water level manager is used. During a dry period, legislation in the form of the priority sequence plays a role. To mitigate the impact of a drought on society and economy, the priority sequence determines the distribution of water in the Netherlands for different functions (Rijkswaterstaat, 2011).

When the dry or wet conditions continue for a longer period the mentioned information sources are used on a finer temporal resolution. During a dry period such as the summer of 2018, meteorological forecasts regarding the duration of the drought and satellite evapotranspiration data are applied. The evapotranspiration data is acquired as part of a pilot, the data is currently not yet included in decision-making.

4.1.2 Information demand: not provided

This section involves information that is demanded but not yet used in operational water management (questions 3 and 6 of the questionnaire). Furthermore, the demanded temporal and spatial resolution and the importance of indicator categories and scientific requirements are mentioned (questions 4 and 7-10 of the questionnaire).

Information that is demanded to face problems related to drought or wetness but is not yet used in regional operational water management concerns insight in the crop water availability, the actual available soil moisture storage in the unsaturated zone, the relation between soil moisture levels and groundwater levels and the spatial distribution of dry areas during dry conditions. The unsaturated zone is the part of the soil between land surface and groundwater level. During wet circumstances, information regarding spatial variation of wet areas in combination with soil properties is demanded.

To support decision-making an acceptable time interval between the availability of new information flows should vary between every day and once a week during dry conditions. However, in case of wet conditions, the demanded resolution varies between one to four days. The spatial resolution is demanded at field scale (hectares) for both dry and wet conditions. Indicator categories related to wetness, drought and vegetation are considered important. The wildfire indicator is considered unimportant. Water managers mention this indicator might have added-value for other organizations like fire departments and security regions. Finally, the requirements reliability and accuracy are considered very important aspects of indicators and in general, the water managers are willing to use model data and do not mention any relevant reasons why not to.

4.2 Practical demands

The practical demands are:

1. An indicator has to focus on wet or dry situations, such as:
    a. Insight in available soil moisture storage in the unsaturated zone;
    b. Crop water availability;
    c. Spatial variation of wet (or dry) and extreme wet (or dry) areas.
2. Operational water management needs information every 1-7 days during dry conditions and 1-4 days during wet conditions.
3. Data should capture a resolution of 100 m by 100 m.

4.3 Indicator requirements

In this section, the practical demands and scientific requirements are merged into one list of requirements from which indicators are selected and developed. As stated in the theoretical framework (§2.2), the criteria for the requirements temporal and spatial resolution and relevance are derived from the practical demands of the water managers. These criteria are indicated with the color red.

TABLE 4: INDICATOR REQUIREMENTS

Requirement	Description	Criteria	Input data or indicator
Availability	Input data of indicators is available and can be used.	The input data of the indicator should be available or can be derived from other data sources.	Indicator definition
Accuracy	Degree of similarity of data with respect to ground truth.	The indicator should use the most accurate available soil moisture data set that is analyzed.	Input data
Reliability	Degree of consistency of data.	The indicator should use the most reliable available soil moisture data set that is analyzed.	Input data
Relevance	Relevance of objective indicator and information needs (specification of quantity, quality, time and location).	Indicator has to focus on wet or dry situations, such as insight in available soil moisture storage in the unsaturated zone, crop water availability or spatial variation of extreme wet (or dry) areas.	Indicator definition
Spatial resolution	Provides data at regular spatial intervals.	Data should capture a resolution of 100 m by 100 m.	Input data
Temporal resolution	Provides updates at regular temporal intervals.	Operational water management needs information every 1-7 days during dry periods and 1-4 days during wet periods.	Input data

Translation	Data is applied on a specific context	Indicator should translate data into information by scaling the actual data with extreme values (minimum or maximum), incorporating other variables to provide a specific context or with the help of a classification system.	Indicator definition

4.4 Conclusion

The information sources that are currently used by water managers of the WOT during dry and wet periods consist of meteorological data and forecasts, measurement data, hydrological model output, external advice and local field knowledge. When the dry or wet conditions continue for a longer period these information sources are used on a finer temporal resolution. During a dry period, meteorological forecasts regarding the duration of the drought and satellite evapotranspiration data are used. The evapotranspiration data is acquired as part of a pilot, the data is currently not yet included in decision-making.

To face problems related to drought or wetness, information is demanded that is not yet used in regional operational water management. This information concerns insight in the crop water availability, the actual available soil moisture storage in the unsaturated zone and the spatial variation of dry (or wet) areas during dry (or wet) conditions. The temporal resolution should vary between every day and once a week during dry conditions. During wet conditions, it should vary between one to four days. The spatial resolution should be at field scale (hectares) for both dry and wet conditions. Soil moisture indicator categories related to wetness, dryness and vegetation are considered important.

The indicator requirements consist of the practical demands merged with requirements that indicators should meet from a scientific perspective. These indicator requirements concern data availability, accuracy, reliability, relevance, temporal and spatial resolution and translation (data into information).

5 DEFINITION OF INDICATORS

In this chapter, the indicator definition requirements, which are derived in Chapter 4, are used to select the most suitable indicators based on available soil moisture indicators and indicators developed in this study (§5.1). Subsequently, the indicator data requirements are applied on the input data of the defined indicators (§5.2). Finally, the indicators are quantified and presented for application in water management (§5.3).

5.1 Definition of soil moisture indicators

Available soil moisture indicators derived from a literature review (§2.3) and indicators developed in this study are evaluated by the indicator definition requirements. Three indicators comply with the requirements, namely the Soil Water Wetness Index (focusing on extreme wet conditions), Soil Water Deficit Index (focusing on extreme dry conditions) and Storage Capacity Indicator. This number of defined indicators complies with the criterion of Smith et al. (2004) that too many indicators leads to an inability to comprehend the system. The indicators are described in the next paragraphs.

A significant number of soil moisture indicators do not meet the requirement data availability. These indicators need long-term soil moisture data to make predictions with regard to droughts, however these data were not available. Some of the indicators are not suitable, because they do not comply with the requirement translation. These indicators aim to estimate the soil moisture level instead of incorporating other variables or extreme values (minimum or maximum) to translate data into information. Furthermore, the soil moisture indicators that do not comply with the indicator definition requirements are mentioned in Appendix B.2.

5.1.1 Soil Water Deficit Index

The Soil Water Deficit Index (SWDI) quantifies agricultural drought by classifying the crop water availability in the root zone (Martinez-Fernandez et al., 2015). The application of the SWDI in scientific case studies is limited to a few case studies, see Table 5. In the majority of the cases, remote sensing Soil Moisture and Ocean Salinity (SMOS) data is used. This SMOS project is launched by the European Space Agency (ESA) in 2009.

TABLE 5: APPLICATION SOIL WATER DEFICIT INDEX IN SCIENTIFIC CASE STUDIES

Case study	Data set	Soil moisture	Spatial resolution
Martinez-Fernandez et al., 2016	SMOS	Surface soil moisture	15 km by 15 km
Martinez-Fernandez et al., 2015	In-situ soil moisture monitoring network in Spain (REMEDHUS)	At 5 cm depth (some sensors measure also at 25 and 50 cm depth)	Monitoring network covers area of 1300 km^2
Paredes-Trejo & Barbosa, 2017	SMOS	Surface soil moisture	27 km by 27 km
Pablos et al., 2017	SMOS	Surface soil moisture	1 km by 1 km

The SWDI can be calculated according to the following equation:

$$SWDI = \frac{\theta - \theta_{FC}}{\theta_{AWC}} \times 10 \quad (5a)$$

$$\theta_{AWC} = \theta_{FC} - \theta_{WP} \quad (5b)$$

With:
θ : Actual amount of soil moisture [m^3 m^{-3}]
θ_{FC} : Field Capacity [m^3 m^{-3}]
θ_{WP} : Wilting Point [m^3 m^{-3}]
θ_{AWC} : Available Water holding Capacity [m^3 m^{-3}]

Appendix B.3 gives more information about the meaning of the above mentioned variables. These variables and their relations are depicted in Figure 3.

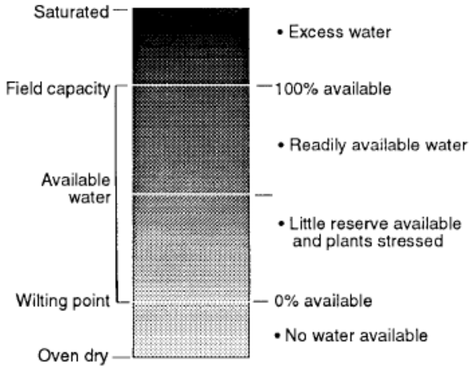

FIGURE 3: AVAILABLE WATER IN THE SOIL (WERNER, 2002).

In Table 6, the Soil Water Deficit Index is evaluated by the indicator definition requirements.

TABLE 6: VALIDITY SOIL WATER DEFICIT INDEX BASED ON INDICATOR DEFINITION REQUIREMENTS

Requirement	Verification	Input data or indicator
Availability	Yes, data regarding actual soil moisture level, field capacity and wilting point are available, see §5.2.	Indicator definition
Relevance	Yes, SWDI is able to show the spatial variation of dry and extreme dry areas. Additionally, the indicator classifies the crop water availability, which partly gives information about the vegetation conditions. This is part of the practical demands, see §4.2.	Indicator definition
Translation	Yes, the SWDI translates the soil moisture data into information with the help of a classification system, see §5.3.1.	Indicator definition

5.1.2 Soil Water Wetness Index

The Soil Water Wetness Index (SWWI) classifies the severity of wetness. The SWWI is derived from the Soil Wetness Index (SWI) and the Temperature Vegetation Condition Index (TVDI). These indices describe dry and wet conditions by using the minimum and maximum measured soil moisture or temperature value, see Appendix B.1. However, in this study a separate dry and wet indicator are demanded, because of the focus on extreme dry and extreme wet conditions. Figure 3 shows the wilting point, field capacity and saturation capacity are important soil moisture variables, therefore these variables are incorporated in the indicators. For the wet indicator, the lower limit is not the minimum measured soil moisture value, but the field capacity. As a result, the SWWI describes wet situations ($\Delta[\theta_{SAT.CAP} - \theta_{FC}]$) that are left out by the SWDI ($\Delta[\theta_{FC} - \theta_{WP}]$), which makes the indicators complementary. The SWWI can be calculated according to the following equation:

$$SWWI = \frac{\theta - \theta_{FC}}{\theta_{sat.\ cap} - \theta_{FC}} \times 10 \qquad (6)$$

With:
θ : Actual amount of soil moisture [m^3 m^{-3}]

θ_{FC} : Field Capacity [m³ m⁻³]
$\theta_{SAT.CAP}$: Saturation capacity [m^3 m^{-3}]

More information about the calculation method of the saturation capacity can be found in Appendix B.3. In Table 7, the Soil Water Wetness Index is evaluated by the indicator definition requirements.

TABLE 7: VALIDITY SOIL WATER WETNESS INDEX BASED ON INDICATOR DEFINITION REQUIREMENTS

Requirement	Verification	Input data or indicator
Availability	Yes, data regarding actual soil moisture level, field capacity and saturation capacity are available, see §5.2.	Indicator definition
Relevance	Yes, SWWI is able to depict the spatial variation of wet and extreme wet areas. This is part of the practical demands, see §4.2.	Indicator definition
Translation	Yes, the SWWI includes the field capacity and saturation capacity to provide a context for the actual soil moisture level. Additionally, a classification system is provided, see §5.3.2.	Indicator definition

5.1.3 Storage Capacity Indicator

The Storage Capacity Indicator (SCI) describes the actual available storage of the root zone. The indicator is derived from practice (Hydrologic, 2017) and from the Soil Moisture Deficit index (SMD) and the Soil Moisture Deciles-based Drought Index (SMDDI), which determine the soil moisture deficit with respect to the field capacity, see Appendix B.1. The SCI focuses on the soil moisture deficit with respect to the saturation capacity. The deficit can be used in combination with precipitation forecasts to predict whether the precipitation amount can be stored in the soil.
The SCI can be calculated according to the following equation:

$$\mathrm{SCI} = (\theta_{sat.\ cap} - \theta) \times d \tag{7a}$$

$$\theta_{sat,cap}[i] = \max(\theta[i])\ for\ all\ t \tag{7b}$$

With:

SCI : Actual available storage capacity[mm]
θ : Actual soil moisture level [m^3 m^{-3}]
$\theta_{sat.cap}$: Saturation Capacity [m^3 m^{-3}]
d : root zone depth [mm]
i : location
t : time

In Table 8, the SCI is evaluated by the indicator definition requirements.

TABLE 8: VALIDITY STORAGE CAPACITY INDICATOR BASED ON INDICATOR DEFINITION REQUIREMENTS

Requirement	Verification	Input data or indicator
Availability	Yes, data regarding actual soil moisture level, saturation capacity and root zone depth are available for model data, see §5.2.	Indicator definition
Relevance	Yes, the SCI depicts the available soil moisture storage in the soil. This is part of the practical demands, see §4.2.	Indicator definition
Translation	Yes, soil moisture data is translated into available storage of the soil to determine whether forecasted precipitation can be stored (incorporation of other variables).	Indicator definition

5.2 Input data of indicators

In this section, the most suitable soil moisture data set is determined. After that, the indicator input data requirements are applied on the input data of the defined indicators.

5.2.1 Soil moisture data set

The soil moisture data set is determined in this section. The accuracy and reliability are assessed for Sentinel-1 and MIPWA data for October 2014 till May 2017. Appendix B.4 contains additional information with regard to the calculations.

Based on Table 9, it can be stated that the Sentinel-1 data have little to no correlation with in-situ data. Additionally, the Sentinel-1 data underestimate the in-situ measurements. The RVE is partly reduced by overestimations, which leads to a smaller volume error. Furthermore, the Sentinel-1 data have a relatively large MAE when considering the range between the wilting point (0.05 m^3/m^3) and field capacity (0.30 m^3/m^3), which are average values for the Twente region.

TABLE 9: SPATIAL AVERAGE OF ACCURACY SENTINEL-1 AND MIPWA SOIL MOISTURE DATA

	MAE [m^3 m^{-3}]	RVE [%]	r
Sentinel-1	0.12	-15	0.2
MIPWA	0.08	-32	0.6

Based on Table 10, it can be stated that the variability characteristics of the Sentinel-1 data are relatively similar to the in-situ data at 5 cm depth. Furthermore, surface soil moisture (Sentinel-1) is more sensitive towards precipitation and evapotranspiration than soil moisture in the root zone (MIPWA), therefore surface soil moisture contains a larger temporal variation in the severity of drought or wetness. This explains the relatively high level of variability of the Sentinel-1 data compared to the MIPWA data.

TABLE 10: SPATIAL AVERAGE OF RELIABILITY SENTINEL-1 AND MIPWA SOIL MOISTURE DATA.

	Sentinel-1	In-situ at 5 cm depth	MIPWA	In-situ [weighted average]
CoV	41%	39%	22%	24%

Since the Sentinel-1 data only represents surface soil moisture, the MIPWA data set is more suitable to quantify the selected and developed indicators, because of its ability to represent root zone soil moisture.

5.2.2 BOFEK

The BOFEK2012 data set provides soil physical characteristics for soil units in the Netherlands (Wösten, et al., 2013). Based on these characteristics, the water retention curve of a soil profile is determined using the Van Genuchten (1980) model. The wilting point and field capacity are derived from this water retention curve. These variables have a spatial resolution of 25 m by 25 m and are considered constant over time.

5.2.3 Indicator data requirements

This section concerns the evaluation of the defined indicators by the indicator data requirements, see Table 11, Table 12 and Table 13. These data requirements are soft requirements which only guide the selection of the input data. The practical demand spatial resolution is not met by the MIPWA data set, because MIPWA has a spatial resolution of 250 by 250 meter instead of 100 m by 100 m.

TABLE 11: EVALUATION INPUT DATA SOIL WATER DEFICIT INDEX

Requirement	Verification	Input data or indicator
Accuracy	The level of accuracy and reliability of the soil moisture data set is subordinate to the practical reason that MIPWA soil moisture data represents root zone soil moisture, whereas Sentinel-1 soil moisture data only represents surface soil moisture.	Input data
Reliability		Input data
Temporal resolution	Yes, the temporal resolution of the soil moisture data is once a day, see §3.2.2. The field capacity and wilting point are considered constant over time.	Input data
Spatial resolution	No, the soil moisture data have a resolution of 250 m by 250 m (§3.2.2). The field capacity and wilting point have a resolution of 25 m by 25.	Input data

TABLE 12: EVALUATION INPUT DATA SOIL WATER WETNESS INDEX

Requirement	Verification	Input data or indicator
Accuracy	The level of accuracy and reliability of the soil moisture data set is subordinate to the practical reason that MIPWA soil moisture data represents root zone soil moisture, whereas Sentinel-1 soil moisture data only represents surface soil moisture.	Input data
Reliability		Input data
Temporal resolution	Yes, the temporal resolution of the soil moisture data is once a day, see §3.2.2. The field capacity and saturation capacity are assumed constant over time.	Input data
Spatial resolution	No, the soil moisture data have a resolution of 250 m by 250 m (see §3.2.2), which holds for the saturation capacity as well. The field capacity has a resolution of 25 m by 25 m.	Input data

TABLE 13: EVALUATION INPUT DATA STORAGE CAPACITY INDICATOR

Requirement	Verification	Input data or indicator
Accuracy	The level of accuracy and reliability of the soil moisture data set is subordinate to the practical reason that MIPWA soil moisture data represents root zone soil moisture, whereas Sentinel-1 soil moisture data only represents surface soil moisture.	Input data
Reliability		Input data
Temporal resolution	Yes, the temporal resolution of the soil moisture data is once a day, see §3.2.2. The saturation capacity is assumed constant over time.	Input data
Spatial resolution	No, the soil moisture data have a resolution of 250 m by 250 m (§3.2.2), which holds for the saturation capacity as well.	Input data

5.3 Application in water management

The selected and developed indicators are quantified in this section. The temporal components of the indicators are presented for hydrological model output for an arbitrary location with grassland. The spatial components are presented for an arbitrary wet or dry day, depending on the focus of the indicator.

5.3.1 Soil Water Deficit Index

The classification structure of the index is shown in Table 14. The classes enable water managers to apply thresholds which indicate when to intervene. Appendix B.3 explains the classification structure in more detail.

TABLE 14: DROUGHT CATEGORIES SWDI (MARTINEZ-FERNANDEZ ET AL., 2015)

SWDI value	Drought category
> 0	No drought ($\theta > \theta_{FC}$)
0 to -2	Mild
-2 to -5	Moderate
-5 to -8	Serious
-8 to -10	Severe
< -10	Extreme ($\theta < \theta_{WP}$)

The spatial distribution of the Soil Water Deficit Index is shown in Figure 4. The spatial distribution enables to identify extreme dry locations for the actual soil moisture level. Based on these locations, water managers can take measures to mitigate the impact of the dryness, for example to distribute water differently. Furthermore, a spatio-temporal presentation enables to depict areas that are prone to drought, for example in relation to soil properties, elevation and land-use.

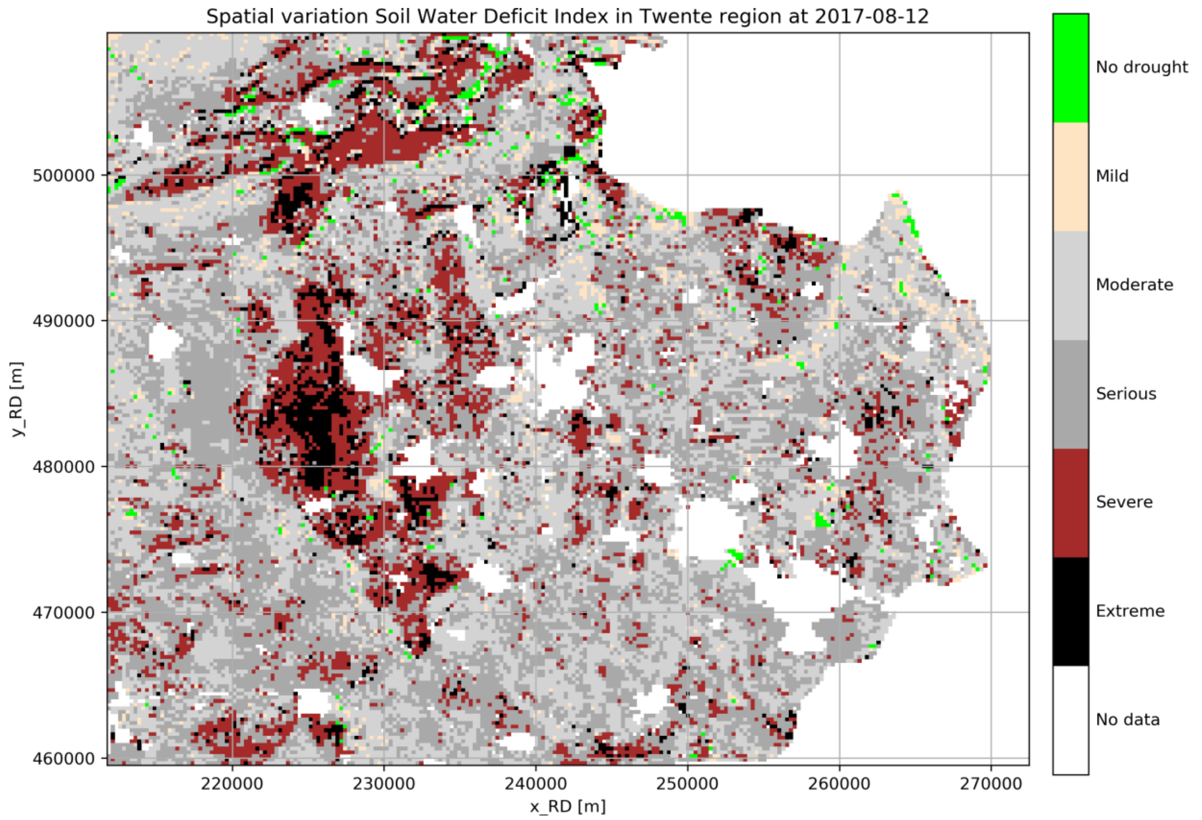

FIGURE 4: SPATIAL VARIATION SWDI IN TWENTE REGION AT 2017-08-12.

The temporal variation of the Soil Water Deficit Index is presented in Figure 5. The temporal variation enables to identify trends. In case the SWDI is larger than 0 (No drought), the water manager might consider to implement the SWWI.

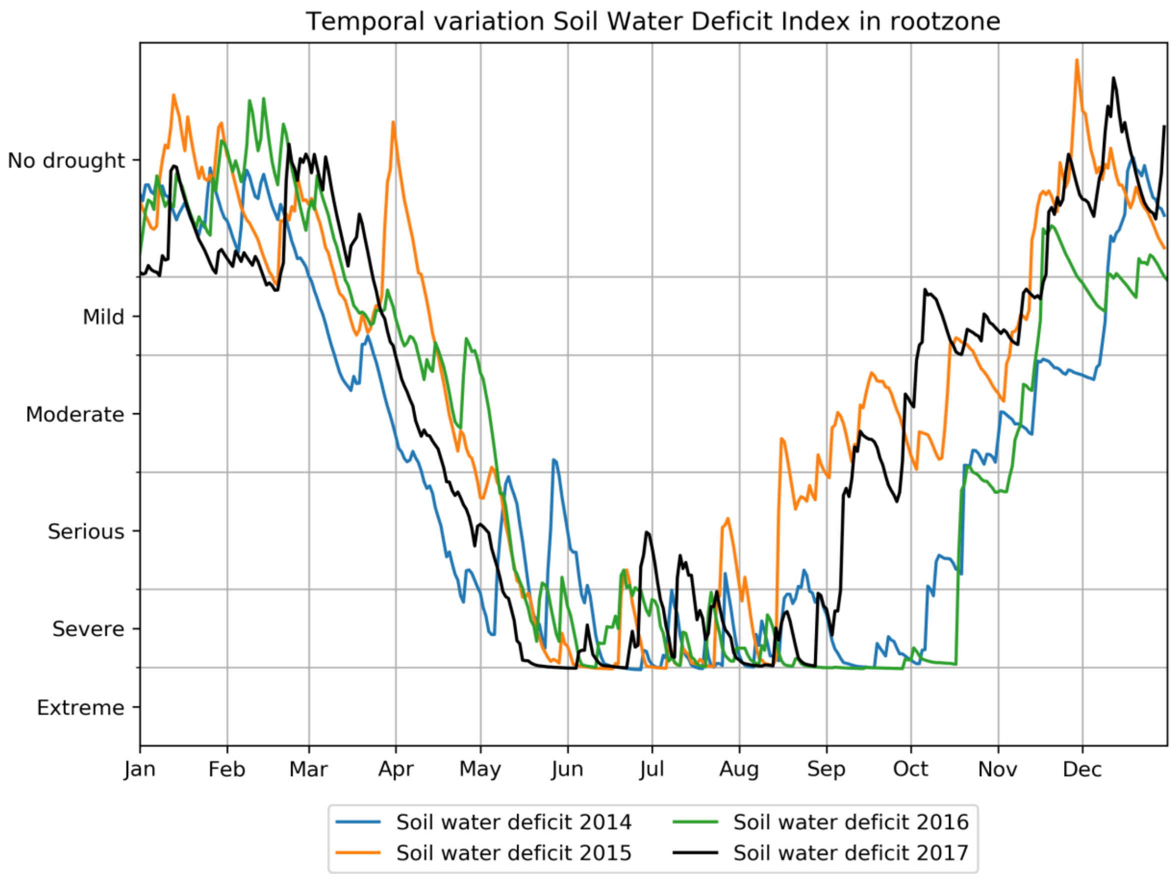

FIGURE 5: TEMPORAL VARIATION SWDI IN ROOTZONE BASED ON MIPWA DATA

The SWDI is presented for four-years, as an example, to enable water managers to make a comparison between the years, which provides a context for the classes. This context can be used to state a norm of acceptability, for example severe dryness is acceptable, but extreme dryness needs to be prevented. The water managers' perception of the actual severity of drought can be used to improve the classification system. The four-year time series is analyzed in order to make a first step for application of the indicator in operational water management. The analysis is related to hydrological model data for a specific location in the Twente region and therefore, the results cannot be directly extrapolated to the complete Twente region.

During the summer, the severity of the drought is mitigated by precipitation. These precipitation events result in replenishment of soil moisture, which prevents further desiccation of the soil. As a result, the soil moisture levels remain larger than the wilting point for most of the time. This means that for the presented years, water should nearly always be available for crops to grow. Although the available amount is limited which may result in reduced agricultural yield, this does not necessarily lead to dying crops. This theoretical statement can be compared with perception in practice.

Soil moisture is sensitive to precipitation. Soil moisture can significantly increase depending on the amount of precipitation, for instance large precipitation events in May 2014 and March 2015 have impact for a longer period than smaller events. The short term impact is related to the outflow of water, for example evapotranspiration or infiltration to groundwater. Soil moisture is less sensitive in a dry period, because this process proceeds slower compared to precipitation.

The temporal variation of the SWDI for a specific year can be compared with precipitation data to monitor the impact of a precipitation event on the severity of the drought, for instance precipitation of 20 mm/h during a severe drought results in a moderate drought. This comparison also enables to assess the impact of the groundwater level on the soil moisture level, for example when the soil moisture level increases while the precipitation is zero.

5.3.2 Soil Water Wetness Index

The classification structure of the SWWI is described in Table 15. The categories enable water managers to apply thresholds which indicate when to intervene. Appendix B.3 explains the classification structure in more detail.

TABLE 15: WETNESS CLASSIFICATION SWWI

SWWI	Wetness level
< 0	No wetness ($\theta < \theta_{FC}$)
0 – 5	Moderate
5 – 8	Severe
8 – 10	Extreme (close to saturation)

Figure 6 shows the spatial distribution of wetness in the Twente region, which enables to identify extreme wet locations for the actual soil moisture level. Based on these locations, water managers can take measures to mitigate the impact of the wetness, for example to distribute water differently over the area. Furthermore, a spatio-temporal presentation enables to depict areas that are prone to wetness, for example in relation to soil properties, elevation and land-use.

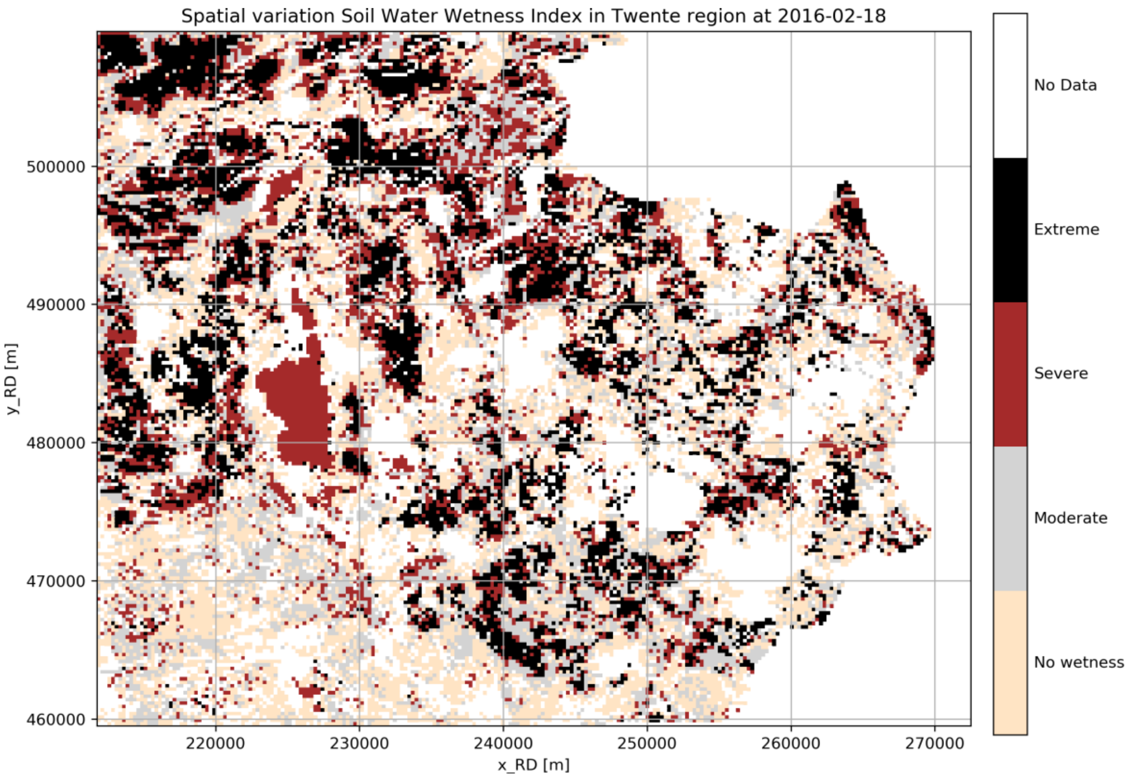

FIGURE 6: SPATIAL VARIATION SWWI IN TWENTE REGION AT 2016-02-18

The temporal variation of the Soil Water Wetness Index is presented in Figure 7. The temporal variation enables to identify trends. In case the SWWI is dropping below 0 (No wetness), the water manager might consider to implement the SWDI.

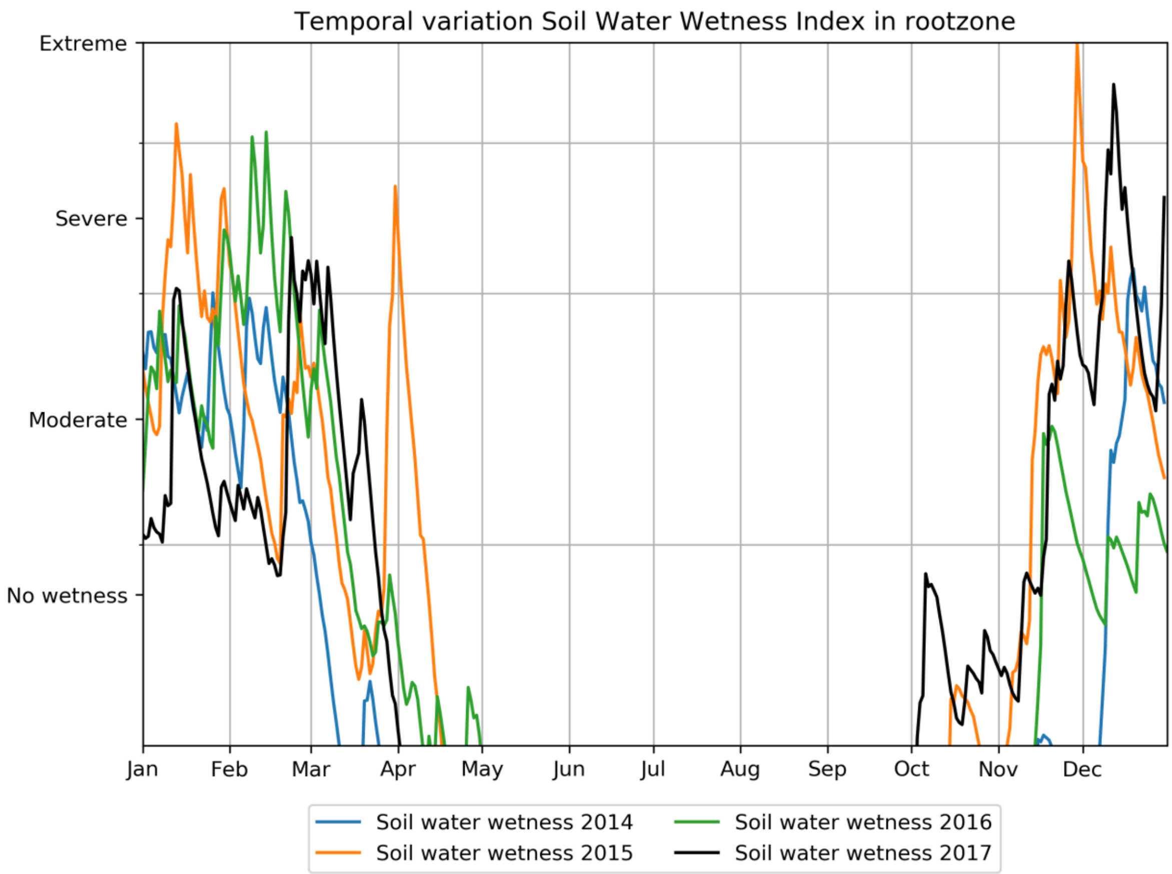

FIGURE 7: TEMPORAL VARIATION SWWI IN ROOTZONE BASED ON MIPWA DATA

The SWWI is presented for four-years, as an example, to enable water managers to make a comparison between the years, which provides a context for the classes. This context can be used to state a norm of acceptability, for example, during the winter, severe wetness is acceptable but extreme wetness needs to be prevented. The perception of the water managers of the actual severity of wetness can be used to improve the classification system. The four-year time series is analyzed in order to make a first step for application of the indicator in operational water management. The analysis is related to hydrological model data for a specific location in the Twente region and therefore, the results cannot be directly extrapolated to the complete Twente region.

The SWWI is relevant for water managers when the soil moisture level is larger than the field capacity. This is the case between roughly mid-November till mid-April. From March, the desiccation trend starts which results in lower soil moisture. The variability of the data is larger during a wet period than during a dry period, due to the sensitivity of soil moisture to precipitation, since relatively many precipitation events take place during a wet period. Large precipitation events near the end of the wet period, for example end of March 2015, delay the desiccation process.

When the dry period in the summer ends relatively early, it does not necessarily result in an extremely wet period afterwards. This mainly depends on the intensity and duration of the precipitation events. In 2017, the dry period ended early, however the number of precipitation events was not large, which did not result in an extremely wet period. In 2015, the dry period also ended relatively early. In this year, the maximum soil moisture level was reached due to the relatively large number of precipitation events and their intensity. The tangent of desiccation and wetness trends are more or less similar for the four-years.

5.3.3 Storage Capacity Indicator

For application with regard to dryness, the difference between the available storage and the saturation capacity depicts to what extent the drought can increase. Additionally, it shows the amount of water in millimeters necessary to bring the actual soil moisture content back to the saturation capacity.

For application with regard to wetness, the SCI can be compared with precipitation forecasts to gain insight whether these precipitation amounts can be stored in the soil. This information can be used in operational water management to distribute water differently. However, the impact of the infiltration capacity is not incorporated, which means that the available storage capacity cannot optimally be used, due to for example initial conditions of soil wetness, soil compaction or soil type (Ziyaee & Roshani, 2012).

The spatial variability of the available storage capacity is presented in Figure 8. The SCI shows discrepancies with the spatial distribution of the SWWI for the *Sallandse Heuvelrug* (see arrow in Figure 8). The available storage capacity for the grassland is relatively low, whereas the forest has a relatively large available storage capacity. This might be related to the MIPWA model data that considers the root zone depth of grassland significantly smaller compared to forest. Due to a smaller root zone depth the maximum storage capacity of the soil under the grassland is also smaller for the model, which results in smaller saturation capacity for grassland. This small saturation capacity leads to limited values of the available storage capacity.

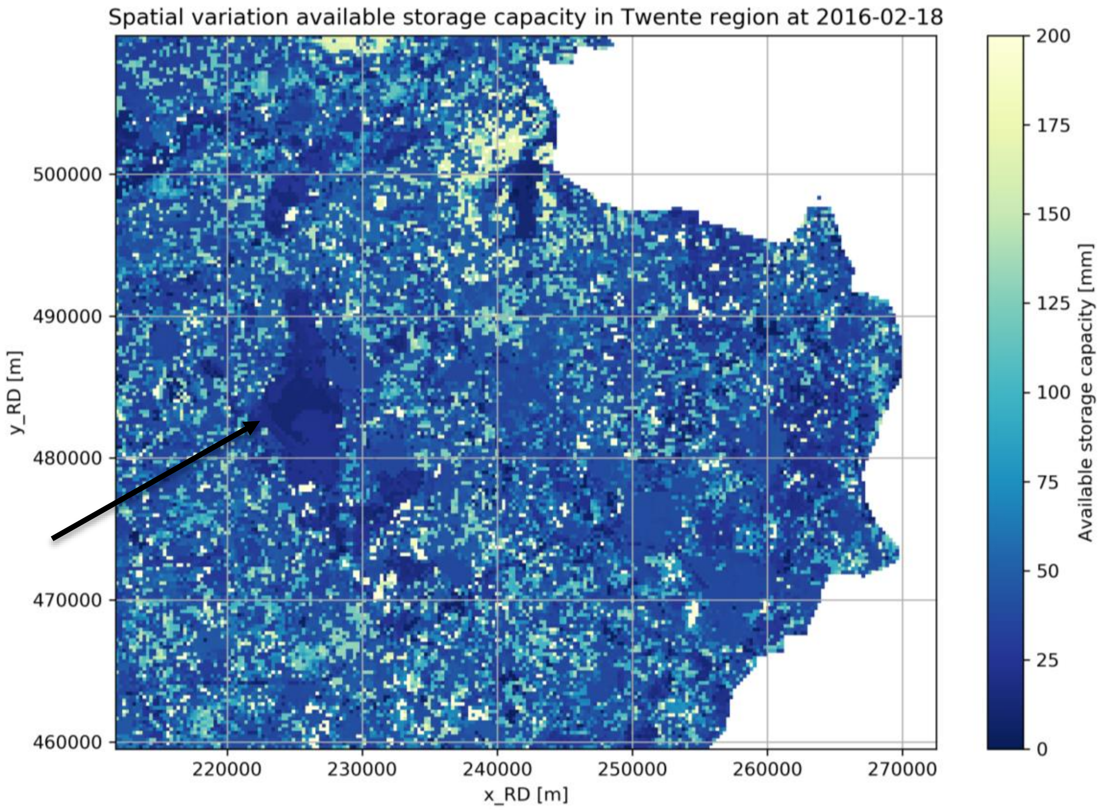

FIGURE 8: SPATIAL VARIATION SCI IN TWENTE REGION BASED ON ROOT ZONE MIPWA DATA.

In contrary to the SWDI and the SWWI the temporal component of SCI, see Figure 9, is not able to detect trends or to compare between years. This is a result of the root zone depth, which highly fluctuates throughout the year for model data. Since this depth affects the calculated available storage capacity of the soil, the temporal component can only be depicted for periods when the root zone depth does not vary significantly over time.

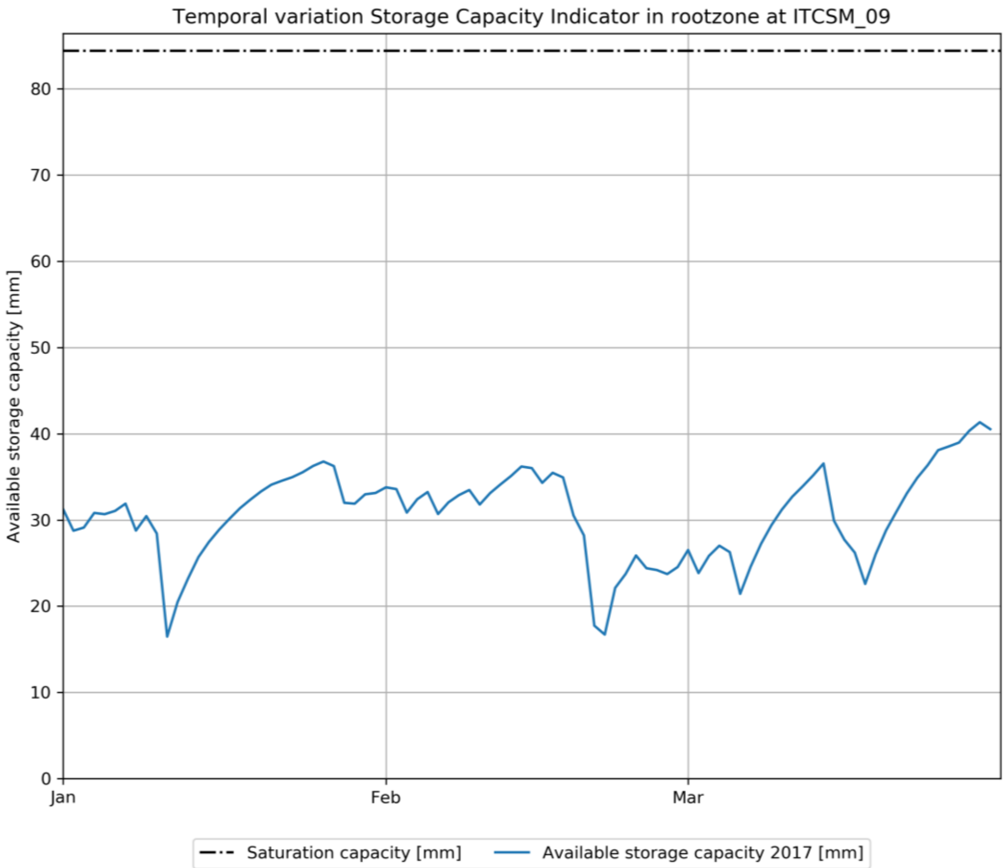

FIGURE 9: TEMPORAL VARIATION SCI FOR ITC STATION 9 BASED ON MIPWA DATA

5.4 Conclusion

The indicator requirements, derived in Chapter 4, are used to select and develop the most suitable indicators. Three soil moisture indicators comply with the indicator requirements, see Table 16 on the next page. The indicator requirements are divided in indicator definition requirements and indicator data requirements. The first consist of data availability, relevance and translation (data into information). These requirements are used to define the most suitable indicators. The second concern accuracy, reliability and temporal and spatial resolution. These requirements are applied on the input data of the defined indicators.

The definition of indicators is done on the available soil moisture indicators found in literature and indicators that are developed in this study. The defined indicators are quantified using the MIPWA data set, which is considered the most suitable compared to the Sentinel-1 soil moisture data. The MIPWA data set does not comply with the demanded spatial resolution.

TABLE 16: FORMULATION OF DEFINED INDICATORS

Indicator	Description	Formula	Parameters
Soil Water Deficit Index (SWDI)	Quantifies the crop water availability based on soil moisture data. Indicator is relevant when $\theta < \theta_{FC}$	$SWDI = \frac{\theta - \theta_{FC}}{\theta_{AWC}} \times 10$ $\theta_{AWC} = \theta_{FC} - \theta_{WP}$	- θ : Actual soil moisture level - θ_{FC} : Field Capacity - θ_{WP} : Wilting Point - θ_{AWC} : Available Water holding Capacity
Soil Water Wetness Index (SWWI)	Depicts the wetness in the root zone based on soil moisture data. Indicator is relevant when $\theta > \theta_{FC}$	$SWWI = \frac{\theta - \theta_{FC}}{\theta_{sat.\ cap} - \theta_{FC}} \times 10$	- θ: Actual soil moisture level - θ_{FC} : Field Capacity - $\theta_{sat.\ cap}$: Saturation Capacity
Storage Capacity Indicator (SCI)	Describes the actual available storage of the soil in the root zone based on soil moisture data.	$SCI = (\theta_{sat.\ cap} - \theta) \times d$ $\theta_{sat,cap}[i] = \max(\theta[i])\ for\ all\ t$	- θ: Actual soil moisture level - $\theta_{sat.\ cap}$: Saturation Capacity - d: depth root zone - i: spatial location - t: time

6 VALIDATION OF INDICATORS

This chapter contains the validation of the indicators defined in Chapter 5. First, the results of the questionnaire, used to determine the usefulness of the currently used information, are discussed. Subsequently, the results of the questionnaire related to the soil moisture data and indicators are explained. Finally, practical demands from the participants to improve the presentation of the data and indicators are discussed. The questionnaire can be found in Appendix C.

6.1 Currently used information

The currently used information in operational water management, that is discussed in section 4.1, was considered accurate and easily interpretable by the participants in the questionnaire. However, these sources do not provide full insight in the water system, see Table 17.

TABLE 17: USEFULNESS CURRENTLY USED INFORMATION. ❷ INDICATES MEAN CATEGORY

Criteria	Very negative	Negative	Neutral	Positive	Very positive
Supporting-value		1	❷	2	
New insights		1	❷	2	
Ease of use			2	❸	
Accuracy			2	❸	

In order to improve insight in their water system, Vechtstromen has been exploring the added-value of new remote sensing data. The participants of the workshop meet on a monthly base to discuss findings of remote sensing actual evapotranspiration data. With regard to these data, two questions are interesting for the regional water authority. The first question relates to the accuracy and underlying methodology (model or algorithm) of the remote sensing data and the possibilities to validate the data. The second question involves the ease of use and application of the data in water management. The latter is related to the research questions of this study.

One of the participants of the workshop declared that most of the currently used information is related to meteorological data and ground and surface water measurements, but the information demand also expands towards insight in the soil physical processes that affect the storage capacity in the water system. During dry periods, storage of water in the soil is needed to mitigate the impact of the drought. During wet periods, storage of water is needed to discharge peak volumes in a controlled manner over time. Currently, water runs off quickly due to for example drainage and ditches, which means that the ability of the soil to store water is not exploited to its full extent. An improved insight in the physical processes that affect the storage capacity helps to optimize management of the water system.

6.2 Soil moisture data

This section contains the results of the questionnaire and practical demands of the participants to improve the presentation of the soil moisture data.

6.2.1 Usefulness soil moisture data

The participants indicated that temporal and spatial soil moisture data can provide new insights in the water system and can have a positive supporting value, see Table 18 and Table 19. The ease of use of the data is classified as neutral.

During the workshop, the participants recognized characteristics from changes in the soil moisture level, for example due to precipitation events in 2018. Additionally, wet springs were recognized. This might have increased trust in reliability and supporting-value of the data by the participants.

TABLE 18: USEFULNESS TEMPORAL SOIL MOISTURE DATA

Criteria	Very negative	Negative	Neutral	Positive	Very positive
Supporting-value			1	❹	
New insights				❹	1
Ease of use			❸	2	

TABLE 19: USEFULNESS SPATIAL SOIL MOISTURE DATA

Criteria	Very negative	Negative	Neutral	Positive	Very positive
Supporting-value			1	❹	
New insights				❺	
Ease of use			❸	2	

According to the participants, groundwater data is currently used as a drought indicator. The groundwater levels recover slowly after the dry summer of 2018, which leads to concerns about the availability of water for the growing season of 2019. In general, the participants noticed that a drought is percepted differently based on soil moisture data compared to groundwater data. This different perception of the severity of the drought is a result of the sensitivity of soil moisture regarding precipitation. This might have had a positive impact on the valuation of the criterion new insights in the water system. Based on the different perception, one of the participants suggested the soil moisture data has potential to function as a prediction tool on which measures in the water system can be based, due to its sensitivity to precipitation.

6.2.2 Practical demands soil moisture data

One of the participants mentioned that soil moisture data can be useful, when combined with soil moisture indicators. The soil moisture data are considered difficult to interpret, which can lead to non-uniform decision-making.

In addition, the participants indicated that specific relations between hydrological variables need to be clarified to acquire insight in the concept of soil moisture and its role in hydrology. This holds for the relation between soil moisture data and meteorological data (temperature, cloudiness, precipitation and evapotranspiration). Additionally, as mentioned in the information demand (§4.1), insight in the relation between soil moisture levels and groundwater levels is demanded.

6.3 Soil moisture indicators

This section contains the results of the questionnaire and practical demands of the participants to improve the presentation of the soil moisture indicators. The Soil Water Wetness Index is not part of the evaluation, because the regional water authority wants to focus on the dry summer of 2018.

6.3.1 Usefulness soil moisture indicators

The participants classified the soil moisture indicators positive with regard to supporting value, new insights and ease of use, see Table 20, Table 21, Table 22 and Table 23. The participants have a more positive attitude towards the ease of use of the soil moisture indicators compared to soil moisture data. Hence, the application of indicators has potential in the translation of data into information.

According to the participants, the Soil Water Deficit Index might be useful to depict the soil moisture deficit, is easy to understand and provides new insights in the water system.

TABLE 20: USEFULNESS SPATIAL SOIL WATER DEFICIT INDEX, ALSO SEE FIGURE 4.

Criteria	Very negative	Negative	Neutral	Positive	Very positive
Supporting-value				❹	1
New insights				❹	1
Ease of use				❺	

TABLE 21: USEFULNESS TEMPORAL SOIL WATER DEFICIT INDEX, ALSO SEE FIGURE 5.

Criteria	Very negative	Negative	Neutral	Positive	Very positive
Supporting-value				❺	
New insights				❺	
Ease of use			1	❹	

The participants mentioned that the SCI is valuable with regard to available storage capacity and the relation between precipitation and quick runoff.

TABLE 22: USEFULNESS SPATIAL STORAGE CAPACITY INDICATOR, ALSO SEE FIGURE 8.

Criteria	Very negative	Negative	Neutral	Positive	Very positive
Supporting-value				❹	1
New insights				❹	1
Ease of use				❸	2

TABLE 23: USEFULNESS TEMPORAL STORAGE CAPACITY INDICATOR, ALSO SEE FIGURE 9.

Criteria	Very negative	Negative	Neutral	Positive	Very positive
Supporting-value				❺	
New insights				❺	
Ease of use			1	❹	

The participants stated that a spatial presentation of the soil moisture indicators is preferred over a temporal presentation, because the representativeness of these trends is bounded by local conditions such as soil type or land-use. As a result, the trends cannot directly be extrapolated to a larger area without adapting them to the specific local conditions. Furthermore, a spatial representation acquires insight in local differences or patterns and locations to intervene, which enhances more effective decision-making.

6.3.2 Practical demands soil moisture indicators

The participants voiced their concerns over the soil moisture indicators and brought up practical demands to improve the indicators. These concerns and demands related to the Soil Water Deficit Index and the Storage Capacity Indicator are presented in this section.

Soil Water Deficit Index

According to one of the participants, the interpretation of the class names needs to be explained in more detail, because the exact meaning of each term can be interpreted differently. The temporal indicator could be improved by taking into account the duration of a certain class, for example four severely dry weeks might have a significantly larger impact on the crop growth than one extremely dry week.

Storage Capacity Indicator

This indicator emphasizes the need for insight in the relation between groundwater level and available storage capacity. This relation determines to what extent the complete soil profile is actually filled when the SCI depicts that the available storage is zero. For application in dry periods, the field capacity can be incorporated to depict the amount of millimeters water needed to bring the soil moisture content back to field capacity (optimum growing condition for crops). The interpretation of the available storage capacity needs to be explained in more detail.

6.4 Conclusion

The currently used information in operational water management was considered accurate and easily interpretable by the participants. However, these sources do not provide full insight in the water system, which means that water managers do not have all relevant information about the water system at their disposal yet. Therefore, they indicated that there is a demand for more information, which resulted in the acquisition of evapotranspiration data. However, these data face difficulties regarding reliability and interpretation.

The participants noticed that a drought is classified differently based on soil moisture data compared to groundwater data. Both data sources offer a different perception in the severity of a drought. This different perception is a result of the sensitivity of soil moisture regarding precipitation. The participants indicated that soil moisture data can provide new insights in the water system and can have a positive supporting value. Moreover, the soil moisture indicators that were used in this study were also valued positive with regard to the ease of use of the data, which means the application of indicators has potential in the translation of data into information. Therefore, soil moisture indicators may play a role in providing new insights in the water system. As a side note, the usefulness of the soil moisture data and indicators in regional operational water management cannot be derived directly from the workshop, because the soil moisture data and indicators are not quantitatively applied in a case study to measure the impact of the indicators in decision-making.

The participants mentioned five practical demands regarding the indicators. First, a spatial presentation of the soil moisture indicators is preferred over the temporal presentation. This is because the first acquires insight in local differences or patterns and locations to intervene, which enhances more effective decision-making. Second, the interpretation of the class names of the indicators needs to be adapted for practical use, because the exact meaning of each term can be interpreted differently. Third, the concept of soil moisture and its role in hydrology. This holds for both the relation between soil moisture data and meteorological data and the relation between soil moisture levels and groundwater levels. Fourth, the temporal component of the SWDI could be improved by taking into account the duration of a certain class. Finally, the field capacity can be incorporated in the SCI to depict the amount of water needed to bring the soil moisture content back to the optimum growing condition for crops.

7 DISCUSSION

The aim of this study was to define and validate indicators derived from soil moisture data to support decision-making in Dutch regional operational water management. This chapter provides the implications of the results and addresses the shortcomings.

Methodology

The framework based on scientific requirements and practical demands aimed to support the definition of indicators. A disadvantage of this framework was the restriction to these scientific requirements and demands from practice, whereas input of the author also could play a role in the definition of indicators. For example, two drought indicators from the literature review were not selected due to practical reasons, such as the complexity of calculation and the usage of relatively unknown variables compared to the variables of the SWDI. However, this type of practical reasons was not part of the framework. Another example, the water managers demanded insight in the unsaturated zone, while the infiltration rate and the intensity and duration of precipitation also determine which part of the unsaturated zone is of interest for the water manager. In case of flash precipitation, water managers might prefer insight in surface soil moisture and the infiltration rate to determine the quick runoff. When precipitation has a longer duration, the storage capacity of the entire unsaturated zone might be more relevant. Furthermore, it was relatively difficult to assess when the input data was accurate and reliable. Since the included data sets could not be compared because they measured different phenomenon (surface versus root zone soil moisture), it was not possible to select the soil moisture data with the relatively highest level of accuracy and reliability. Additionally, scientific requirements were often focused on the input data or were not relevant in this study, for example cost-effectiveness or modest data requirements. Consequently, the framework served as a guideline in the definition process of the indicators rather than a set of *hard* requirements that the indicators had to meet.

The method for determining the level of accuracy did not provide insight in differences between the accuracy for extremely wet or dry conditions. The Sentinel-1 and MIPWA data underestimate the in-situ measurements. This leads to an overestimation of the impact of a dry period and an underestimation of the impact of a wet period, see also Appendix B.4.

The survey aimed to identify the information demand of the water managers. The outcome of the survey aligned with the expectations to focus on wet and dry situations. Additionally, the survey showed that soil moisture data is demanded and provided more specific applications of the soil moisture data, for example crop water availability and spatial variation of extreme wet and dry areas. As a result, the survey functioned as a tool to involve stakeholders, confirm expectations and gain insight in practices of water managers. In the questionnaire of the survey, a bias was introduced by removing the neutral in the Likert scale for the valuation of the scientific requirements and indicator categories. The water managers were obliged to value these requirements and categories unimportant or important, hence enforcing them to formulate their opinion, while they may have a neutral opinion. Therefore, in the questionnaire of the workshop, the neutral was included. To extract a specific information demand of the water managers, one question was pre-coded with the information types of Pezij et al. (2019). This publication identified measurement data, system knowledge, meteorological forecasts, experience, hydrological model (output) and legislation as the six information types used by water managers. The categories measurement data, hydrological model output and legislation were mentioned by the WOT-members. The categories system knowledge and experience were not mentioned, although system knowledge is partly covered by knowledge of field workers. The category meteorological forecasts was converted into data and forecasts, because insight in the actual precipitation was also demanded. Furthermore, the category external advice was added, which might be a result of the WOT-members being active during extreme dry and extreme wet conditions. Whereas the water level managers, which were part of the sample group of Pezij et al., 2019, are active during regular conditions, when advice and consultation are less important than during extreme conditions. Significantly more external advice sources are applied during dry conditions compared to wet conditions. This might be a result of the timing of the survey during the extreme dry summer of 2018, when these sources might have been used. Since a wet period has not occurred in the past months, external advice sources have not been used recently. It is therefore possible that (some of) these sources did not come to mind when the participants were asked for this. The application of a realistic case study may refine the information demand, for example the temporal resolution, and might also show additional information demand that was not mentioned here.

The survey was distributed among Vechtstromen and Drents Overijsselse Delta, whereas the validation of indicators only took place at Vechtstromen. As a consequence, the outcome of the workshop cannot directly be extrapolated to other regional water authorities like Drents Overijsselse Delta. Furthermore, not all participants of the workshop are part of WOT of Vechtstromen and the number of participants was relatively low. The outcome of the workshop, therefore, showed a certain level of interest in soil moisture indicators within Vechtstromen, which is not specifically related to the WOT. The respondents of the survey and the participants of the workshop had an open mind with regard to the new soil moisture data source. Often, new methods or data are perceived with a negative attitude (Guo & Kildow, 2015). This open attitude might be explained by the extremely dry summer of 2018. The attitude of WOT members of other regional water authorities can be different, which may affect their assessment of soil moisture data and indicators. Furthermore, the information demand of WOT members from other regional water authorities may be shifted due to differences in the characteristics of the water system.

The results of the questionnaire of the workshop show that the soil moisture data and indicators are valued more positive than the currently used information sources. This does not necessarily mean that the soil moisture data and indicators are more valuable than the currently used information, but this might be related to the formulation of the questionnaire. In the questionnaire, the participants had to value whether the current information sources support current insights and provide new insights in the water system. Additionally, they could voice their concerns about the currently used information. Since it is difficult to obtain new insights while using the same information, the question rather evaluates the completeness of the current information sources regarding insight in the water system. Therefore, a direct comparison between the valuation of the current information and the valuation of the soil moisture data and indicators cannot be made based on these outcomes.

Remote sensing

The currently used information in operational water management does not provide full insight in the water system for the participants. Therefore, they indicated that there is a demand for more information, which resulted in the acquisition of evapotranspiration data. However, these evapotranspiration data face difficulties regarding reliability and interpretation. According to the responses of the water managers in the survey, the evapotranspiration data is demanded information for the assessment of crop water availability. This underlying objective of the evapotranspiration data might be even more directly derived from the soil moisture data. The actual evapotranspiration rates are among others related to the available soil moisture level in the soil profile (Seneviratne, et al., 2010). This is because the soil moisture level determines the maximum rate at which water can be extracted from the soil by plants (Vogt & Niemeyer, 1998; Wood, 1997).

Similar to the evapotranspiration data, the remote sensing soil moisture data have shortcomings, in this case with regard to accuracy and temporal resolution. For application in operational water management, the data should become available quickly after measuring in order to have sufficient time to implement the data in decision-making. Furthermore, the Sentinel-1 satellite observes surface soil moisture, similar to other remote sensing satellites that measure soil moisture (Ford et al., 2014). Surface soil moisture, however, only partly indicates the crop water availability, because water can be available in deeper layers for crops. Therefore, hydrological model data, that provides root zone soil moisture data, is taken as proxy in this study. The application of the model data has impact on the information provided by the indicators. Surface soil moisture is more sensitive towards precipitation and evapotranspiration than soil moisture in the root zone, therefore surface soil moisture contains a larger temporal variation in the severity of drought or wetness.

Soil moisture indicators

The level of accuracy of the MIPWA data affects the uncertainty of the information provided by the indicator. An example: assume field capacity is 0.30 m^3/m^3 (average over Twente region), wilting point is 0.05 m^3/m^3 (also average) and actual soil moisture level is 0.15 m^3/m^3, when applying these values for the SWDI, this leads to a serious drought classification. When the Mean Average Error is taken into account, the classification of the SWDI shifts between moderate and severe, which is a relatively large deviation. This affects the robustness of decision-making. Furthermore, the uncertainty in the field capacity and wilting point affects the accuracy of the indicator. These variables are used in the Soil Water Deficit Index and the Soil Water Wetness Index and are derived from application of the Van Genuchten (1980) model on the BOFEK2012 data set. BOFEK2012 provides theoretical values for soil properties, which may not capture local soil variability, for example due to local spatial variation in soil compaction. Local soil variability also affects the saturation capacity, which is used in the SCI and SWWI. The saturation capacity is derived from a four-year time series and assumed constant over time. However, this variable depends on the measured maximum soil moisture level. In case this level is exceeded, the saturation capacity should be adapted to this new value. Therefore, the actual saturation capacity is not a constant value.

The SCI is more relevant when the available storage in the unsaturated zone is provided rather than in the root zone depth. This is mentioned by the water managers in the questionnaire and by the participants of the workshop. The available storage in the unsaturated zone offers insight in the storage of the complete soil profile (ignoring non-permeable layers), whereas the root zone depth only partly covers the soil profile.

The SWWI is not included in the workshop, however the structure of this indicator is relatively similar to the SWDI. Therefore, some of the practical demands of the water managers to improve the SWDI might be extrapolated to the SWWI. Furthermore, the classification system of the SWWI is not derived from literature, which emphasizes need for the adaption of this system by water managers based on their perception in practice.

Outlook

To build upon the positive attitude of the participants of the workshop with regard to the soil moisture indicators, the integration of the indicators to support decision-making in Dutch regional operational water management might be explored. A participative approach might be helpful, because it incorporates local knowledge and expertise of water managers (Basco-Carrera et al., 2017) and enhances the water managers' understanding of the water system and its dynamics under various conditions (Voinov & Bousquet, 2010). It is suggested to take four steps into account during this integration process. The first step involves the water managers acquiring experience and becoming familiar with the new soil moisture data and indicators, for example specific and realistic case studies allow the water managers to inspect the added-value of the soil moisture data and indicators in order to find out whether decisions would have been made different. Another way for the water managers to become familiar with the soil moisture data is to define its relationship with other hydrological variables, as suggested by the participants of the workshop. The second step focuses on the detection of trends and patterns in the soil moisture indicators to improve understanding in the water system. To effectively use the soil moisture indicators, a first step is made in section 5.3. In addition, a spatio-temporal analysis might detect areas that are prone to drought or wetness. For example, these areas can be determined visually, however machine learning could be useful to recognize patterns in the data of the soil moisture indicators for these specific areas, for instance in relation with other (hydrological) variables. More effective measures might be taken based on these patterns, for instance to mitigate or even prevent the impact of the dryness or wetness. Since machine learning is a relatively new technique, validation in the field is considered necessary (Safdar et al., 2018). Additionally, the machine learning system needs to be trained with (a huge amount of) historical data regarding wet events and droughts (Navarro-Hellín et al., 2016), which might not be available yet. Furthermore, these historical data can be used to develop the soil moisture indicators that require long-term data series, see Appendix B, which may be useful to make predictions regarding the soil moisture state. The third step concerns the water managers being able to review assumptions of the indicators (Refsgaard, et al., 2004). The experience and tacit knowledge of the water managers regarding the soil moisture indicators (derived from the first two steps) should allow them to adapt the classification structure of the indicators towards their perception in practice. These classes can be used by the water manager as threshold valves for decision-making. After a positive result of the first three steps, the fourth step follows. This step describes that soil moisture indicators might be part of a decision tool on which measures in the water system can be based. This is derived from a suggestion of one of the participants of the workshop. For instance, the process of decision-making in operational water management should be divided into decision steps with relevant information requirements (Fountas et al., 2006), for example from decision triggers (when is the situation problematic) and decision context (identification of problem) to development of measures (how to solve the problem) and implementation of measures (Failing et al., 2007). Based on the decision-making process, the role for soil moisture indicators can be assessed in this process and implemented in a form of a Decision Support System (DSS). This kind of systems can support the decisions of water managers based on the currently used information, soil moisture indicators and the threshold valves for decision-making (step 2).

8 CONCLUSIONS AND RECOMMENDATIONS

The aim of this study was to define and validate indicators derived from soil moisture data to support decision-making in Dutch regional operational water management. This chapter contains the conclusions of this study and presents recommendations for future research.

To define indicators that support decision-making in regional operational water management, the information demand is identified from the operational water management crisis team WOT (*Waterschap Operationeel Team*) of regional water authorities Vechtstromen and Drents Overijsselse Delta. The WOT is active among others in dry and wet periods and aims at mitigating the impact of extreme periods. The information sources that are currently used by water managers of the WOT during dry and wet periods consist of meteorological data and forecasts, measurement data, hydrological model output, external advice and local field knowledge. To face problems related to drought or wetness, information is demanded that is not yet used in regional operational water management. This information concerns insight in the availability of water for crops, the actual available soil moisture storage in the unsaturated zone and the spatial variation of dry (or wet) areas during dry (or wet) conditions. The temporal resolution should vary between every day and once a week during dry conditions. During wet conditions, it should vary between one to four days. The spatial resolution should be at field scale (hectares) for both dry and wet conditions. Soil moisture indicator categories related to wetness, dryness and vegetation are considered important. These practical demands are merged with requirements that indicators should meet from a scientific perspective. These indicator requirements concern data availability, accuracy, reliability, relevance, temporal and spatial resolution and translation (data into information).

The indicator requirements are used to define the most suitable indicators that might support decision-making in operational water management. Three soil moisture indicators comply with the indicator requirements, see Table 24. The indicator requirements are divided in indicator definition requirements and indicator data requirements. The first consist of data availability, relevance and translation (data into information). These requirements are used to select and develop the most suitable indicators. The second concern accuracy, reliability and temporal and spatial resolution. These requirements are applied on the input data of the selected and developed indicators. The defined indicators are developed in this study and selected from available soil moisture indicators found in literature. The indicators are quantified using MIPWA soil moisture data. MIPWA is a groundwater modelling instrument that also provides root zone soil moisture estimates up to 50 cm soil depth for the Northern regional water authorities of the Netherlands. Although the MIPWA data set does not comply with the demanded spatial resolution, this soil moisture data set is considered the most suitable compared to the Sentinel-1 satellite soil moisture data.

TABLE 24: FORMULATION OF DEFINED INDICATORS

Indicator	Description	Formula	Parameters
Soil Water Deficit Index (SWDI)	Quantifies the crop water availability based on soil moisture data. Indicator is relevant when $\theta < \theta_{FC}$	$SWDI = \frac{\theta - \theta_{FC}}{\theta_{AWC}} \times 10$ $\theta_{AWC} = \theta_{FC} - \theta_{WP}$	- θ: Actual soil moisture level - θ_{FC} : Field Capacity - θ_{WP} : Wilting Point - θ_{AWC}: Available Water holding Capacity

Soil Water Wetness Index (SWWI)	Depicts the wetness in the root zone based on soil moisture data. Indicator is relevant when $\theta > \theta_{FC}$	$SWWI = \frac{\theta - \theta_{FC}}{\theta_{sat.\ cap} - \theta_{FC}} \times 10$	- θ: Actual soil moisture level - θ_{FC} : Field Capacity - $\theta_{sat.\ cap}$: Saturation Capacity
Storage Capacity Indicator (SCI)	Describes the actual available storage of the soil in the root zone based on soil moisture data.	$SCI = (\theta_{sat.\ cap} - \theta) \times d$ $\theta_{sat,cap}[i] = \max(\theta[i])\ for\ all\ t$	- θ: Actual soil moisture level - $\theta_{sat.\ cap}$: Saturation Capacity - d: depth root zone - i: spatial location - t: time

During a workshop with five employees of regional water authority Vechtstromen, the selected and developed indicators are validated. The soil moisture indicators were applied on the extreme dry summer of 2018 in the Netherlands. The participants of the workshop considered the currently used information in operational water management accurate and easily interpretable. However, these sources do not provide full insight in the water system, which means that water managers do not have all relevant information about the water system at their disposal yet. The participants indicated that soil moisture indicators can support current insights and provide new insights in the water system. The indicators were also valued positive with regard to the ease of use of the data, which means the application of indicators has potential in the translation of data into information. Therefore, soil moisture indicators may play a role in providing new insights in the water system. As a side note, the usefulness of the soil moisture data and indicators in regional operational water management cannot be derived directly from the workshop, because the soil moisture data and indicators are not quantitatively applied in a case study to measure the impact of the indicators in decision-making.

The first recommendation involves the integration of soil moisture data and indicators in operational water management in order to build upon the positive attitude of the participants of the workshop with regard to the data and indicators. To enhance the water managers' understanding of the water system, a participative approach might be helpful (Basco-Carrera et al., 2017). It is suggested to take four steps into account during this integration process. The first step involves the water managers gaining experience and becoming familiar with the new soil moisture data and indicators. This can be realized three-fold. First, specific time periods should be quantitatively evaluated with the new data (Carmona et al., 2013), for example the extreme dry summer of 2018 or a wet winter period. This enables the water managers to inspect the added-value of the soil moisture data for a specific and realistic case study in order to find out whether decisions would have been made different. Secondly, similar to the current role of evapotranspiration data by Vechtstromen, the soil moisture indicators can be used as a pilot during regular practices or extreme events to gain experience with the indicators, to analyze which parts of the presentation need to be improved and to determine their impact on decisions. Thirdly, the water managers can become familiar with the soil moisture data by defining its relationship with both meteorological data (temperature, cloudiness, precipitation and evapotranspiration) and groundwater levels, as suggested by the participants of the workshop. Additionally, it is recommended to define the relation between soil moisture data and elevation, soil properties and land-use to acquire insight in the spatial distribution of extreme wet and dry areas. The second step focuses on the detection of trends and patterns in the soil moisture indicators to improve understanding in the water system. A spatio-temporal analysis might detect areas that are prone to drought or wetness. Although these areas might be determined visually, machine learning could be useful to recognize patterns in the soil moisture indicators for these specific areas, for instance in relation with other (hydrological) variables. More effective measures might be taken based on these patterns, for instance to mitigate or even prevent the impact of the dryness or wetness. The third step describes that, based on their experience and tacit knowledge regarding the soil moisture indicators (derived from the first two steps), the water managers should be allowed to adapt the classification structure of the indicators towards their perception in practice. An example to adapt this structure is to add an interpretation memo for each class and change the colors and the range of the classes. These classes can be used by the water manager as threshold valves for decision-making. After a positive result of the first three steps, the fourth step follows. This step comprises that soil moisture indicators might be part of a decision tool on which measures in the water system can be based. Based on the decision-making process in water management, the role for soil moisture indicators can be assessed in this process and implemented in a form of a Decision Support System (DSS). This kind of systems can support the decisions of water managers based on the currently used information, soil moisture indicators and the threshold valves for decision-making (step 2).

Furthermore, it is recommended to implement the practical demands derived from the workshop. First, the temporal component of the SWDI could be improved by considering the duration of a certain class. Second, a spatial presentation of the soil moisture indicators is preferred over the temporal presentation by the participants. This is because the first acquires insight in local differences or patterns and locations to intervene, which enhances more effective decision-making. Third, the SCI needs to be adapted to wet and dry periods. For wet situations, the available storage capacity and saturation capacity are of importance. For dry situations, the available storage capacity and the field capacity are more relevant, because this enables to estimate the amount of millimeters water needed to bring the soil moisture content back to the optimum growing condition for crops. Additionally, data regarding the infiltration rate is needed to acquire insight in the quick runoff. Finally, insight in the soil physical processes that affect the storage capacity in the water system is demanded, for example soil compaction due to dryness.

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APPENDICES

A. SURVEY

A.1 Questionnaire

The content of the survey is shown in this section.

Inleiding

De enquête heeft als doel een inschatting te maken van de informatiebehoefte op het gebied van bodemvocht van waterbeheerders voor het dagelijks waterbeheer. Om deze inschatting zo nauwkeurig mogelijk te maken, is gekozen om u twee probleemsituaties voor te leggen. Probleemsituatie 1 heeft betrekking op een droge situatie en probleemsituatie 2 heeft betrekking op een natte situatie. Aan de hand van elke probleemsituatie wordt u een aantal vragen gesteld.

Informatie over bodemvocht (water tussen maaiveld en grondwaterspiegel), afgeleid van bijvoorbeeld satellietdata, kan door middel van het toepassen van indicatoren worden gebruikt. Indicatoren kunnen bijvoorbeeld plaatselijke droogte of (potentiële) wateroverlast aanduiden. De indicatoren zijn onderverdeeld in een aantal categorieën:

a. Droogte-indicatoren: inschatten van droogte. Aan de hand van deze indicatoren kunnen bijvoorbeeld beslissingen worden genomen om de gevolgen van de droogte te verzachten.
b. Overstromingsindicatoren: richten zich op de vullingsgraad van de bodem (de hoeveelheid water die de grond kan opnemen).
c. Natuurbrand indicatoren: geven de kans op een natuurbrand, bijvoorbeeld een bermbrand, als gevolg van een droge periode.
d. Vegetatieindicatoren: laten de effecten van de beschikbare hoeveelheid water in de bodem op de gewassen en vegetatie zien en vice versa.

VRAAG 1

1. Wat is uw functie binnen het waterschap en hoelang bekleedt u deze functie?

De volgende vragen hebben betrekking op onderstaande tekst (*Zo droog als nu was het bijna nooit*). Lees deze tekst alvorens vragen 2-4 te beantwoorden.

Probleemsituatie 1 – Extreem droge situatie

Zo droog als nu was het bijna nooit

Nederland wordt geplaagd door een historische droogte. De afwezigheid van neerslag in combinatie met de grote gewasverdamping zorgt voor de droogte. De verdamping wordt aangewakkerd door veel zon, zeer lage luchtvochtigheid en relatief veel wind. Eén van de risico's van de droogte is een verlaagde productie in de landbouw.

De droogte, die nu al vier weken aanhoudt, veroorzaakt problemen voor de landbouw, meldt Boerderij.nl.
Aardappelteler Kees-Jan van den Burg vreest voor zijn oogst: "De aardappelen staan nu al een week of twee stil qua groei en zouden nu al twee keer zo groot moeten zijn." Hij zegt dat de productie in de landbouw slechts op 80% ligt van de normale productie rond deze tijd. Immers, door de droogte produceren gewassen minder en tegelijkertijd mogen boeren van het waterschap hun gewassen niet meer besproeien met water uit sloten, beken en kanalen.
Van den Burg bezit vier lappen grond van 100 bij 500 meter, elk omringd door sloten.

2. A| Welke maatregel(en) zou u nemen om de problematiek van de afnemende watervoorraad, waar de aardappelteler last van heeft, op te lossen?

   B| Van welke informatie maakt u in het dagelijks waterbeheer gebruik om maatregelen te kunnen nemen voor de aardappelteler bij deze droge periode?
   Denk bijvoorbeeld aan veldmetingen, meteorologische voorspellingen, uw eigen ervaring, wetgeving, kennis van uw beheersgebied of uitkomsten van hydrologische modellen.

   C| Maakt u gebruik van andere, extra informatie naarmate de beschreven droge periode langer duurt dan de genoemde vier weken, bijvoorbeeld acht weken? Zo ja, van welke informatie maakt u dan gebruik?

3. Welke informatie gebruikt u in het dagelijks waterbeheer nog niet, maar zou u graag erbij willen hebben om de genoemde droogteproblematiek het hoofd te bieden? En voor welke doeleinden wilt u deze informatie gaan gebruiken?

4. Wat is een acceptabel tijdsinterval tussen de beschikbaarheid van nieuwe informatie en het moment waarop beslissingen tijdens de genoemde droge periode voldoende goed gebaseerd kunnen worden?

De volgende vragen hebben betrekking op onderstaande tekst (*Zware regenbuien veroorzaken wateroverlast in noorden en oosten van Nederland)*. Lees deze tekst alvorens vragen 5-7 te beantwoorden.

Probleemsituatie 2 – Extreem natte situatie

Zware regenbuien veroorzaken wateroverlast in grote delen van Nederland

Grote delen van het land hebben ***zondag*** hinder ondervonden van wateroverlast door zware buien die over het gebied trokken.

Na de afgelopen twee weken waarin het voortdurend regende, kwam zondagmiddag in 3 uur tijd een hoop regen naar beneden. Volgens de Waterschappen is er plaatselijk 20 millimeter regen gevallen; ongeveer een derde van wat normaal in de hele maand mei valt.

Op een aantal plekken kwam landbouwgrond onder water te staan. Bij een van deze lappen grond is als gevolg hiervan 10% van de productie verloren gegaan. De lap grond heeft een omvang van 200 bij 500 meter en is omringt door sloten.

5. A| Welke maatregel(en) kunt u nemen om de wateroverlast voor de landbouwer te verzachten?

   B| Van welke informatie maakt u in het dagelijks waterbeheer gebruik om maatregelen te kunnen nemen voor de landbouwer bij deze wateroverlast?
   Denk bijvoorbeeld aan veldmetingen, meteorologische voorspellingen, uw eigen ervaring, wetgeving, kennis van uw beheersgebied of uitkomsten van hydrologische modellen.

   C| Maakt u gebruik van andere, extra informatie indien de kans op wateroverlast dreigt toe te nemen? Zo ja, van welke informatie maakt u dan gebruik?

6. Welke informatie gebruikt u in het dagelijks waterbeheer nog niet, maar zou u graag erbij willen hebben om wateroverlast in de landbouw het hoofd te bieden? En voor welke doeleinden wilt u deze informatie gaan gebruiken?

7. Wat is een acceptabel tijdsinterval tussen de beschikbaarheid van nieuwe informatie waarop beslissingen met betrekking tot wateroverlast in de landbouw voldoende goed gebaseerd kunnen worden?

Algemene vragen

Nu volgen nog enkele vragen met betrekking tot de beide probleemsituaties.

8. Stel de probleemsituaties zoals beschreven in probleemsituaties 1 en 2 treden op in uw gebied. Geef uw interesse weer voor de volgende indicatoren (reeds genoemd in de inleiding). In de tabel kruist u aan of u de indicator zeer onbelangrijk of onbelangrijk of belangrijk of zeer belangrijk vindt.

Indicatoren	Zeer onbelangrijk	Onbelangrijk	Belangrijk	Zeer belangrijk
Droogte				
Overstroming				
Wildvuur				
Inklinking land				
Vegetatie (tijdens natte situatie)				
Vegetatie (tijdens droge periode)				

9.

A|

Bovenstaande indicatoren dienen aan een aantal toetsingscriteria te voldoen om ervoor te zorgen dat de toegevoegde waarde voldoende gewaarborgd is.

Stel de problematiek, zoals beschreven in probleemsituaties 1 en 2 treedt op in uw beheersgebied. In de tabel kruist u aan of u het criterium zeer onbelangrijk of onbelangrijk of belangrijk of zeer belangrijk vindt. De criteria worden hieronder kort toegelicht.

Criteria:

- **Betrouwbaarheid:** indicator geeft gelijke uitkomsten als omstandigheden niet veranderen.
- **Nauwkeurigheid:** indicator is in lijn met metingen in het veld.
- **Updates:** nieuwe informatie is tijdig beschikbaar in een regulier interval.
- **Relevantie:** informatie die indicator geeft stemt overeen met uw informatiebehoefte.

Criterium	Zeer onbelangrijk	Onbelangrijk	Belangrijk	Zeer belangrijk
Betrouwbaarheid				
Nauwkeurigheid				
Updates				
Relevantie				

B| Bent u van mening dat criteria missen in de lijst van vraag 9a, zo ja welke?

C| Wat is uw voorkeur voor de ruimtelijke schaal waarin u de informatie ontvangt?

10. Mogelijk is u wel eens eerder modeldata gerelateerd aan waterbeheer voorgelegd. Heeft u deze uitkomsten toen toegepast tijdens uw werkzaamheden? En wat voor doeleinden dienden deze uitkomsten? Zo nee, wat weerhield u van toepassing?

Tot slot, zou ik u mogen benaderen voor een follow-up interview waarin ik u naar aanleiding van de enquête enkele dieptevragen zou kunnen stellen? Zo ja, wilt u dan ook uw e-mail adres (of andere contactgegevens) noteren s.v.p.

En zou ik u mogen uitnodigen voor een workshop waarin de toegevoegde waarde van de indicatoren wordt getoetst bij het maken van dagelijkse beslissingen?

Einde van de vragenlijst - Bedankt voor uw medewerking
##

A.2 Results of questionnaire

2A/5A| *Which measures do you take to mitigate problems related to the decreasing availability of water (dry) or related to the wet situation (wet)?*

During dry periods, the achievement of target water levels might be limited by the priority sequence (*verdringingsreeks).*

Dry	Wet
Maintenance of target water levels: - Increase surface water level to counterpressure the groundwater levels by using inflowing discharge (if possible) or using inlet sluices; - New techniques: application of *smart* water management, for example weirs that distribute water to areas that are most in need.	**Maintenance target water levels** - Lower the water levels by lowering the weirs; - Use maximum capacity of drainage pumps; - Discharge of excess water by surrounding ditches; - New techniques: the application of *smart* weirs that distribute water to areas with a relatively large storage capacity.
Legislation: - Prohibition of groundwater abstraction; **Longer term measurements:** storage of water in an earlier stage.	**Mowing strategy**: mowing water courses few days ahead of rainfall event.

2B/5B| *Which information do you use to take the aforementioned measures in operational water management?*

Dry	Wet
Meteorological data and forecasts: - Precipitation, actual and predicted precipitation deficit, - Limited use of actual and predicted evapotranspiration deficit; - Application of precipitation data for drought indicator (Standardized Precipitation Index)	**Meteorological data and forecasts:** mainly precipitation (amount, intensity, location, uncertainty, predictions), evapotranspiration.

Measurement data: - Groundwater levels; - Surface water levels (discharge and water level); - Discharge (inflow near inlets and waste water treatment plants); - Pressure head	**Measurement data**: - Groundwater levels; - Surface water levels (discharge and water level); - Discharge (inflow near inlets and waste water treatment plants; - Pressure head
External advice: *Informatiebeeld Watersysteem* (provided by Information Center Water). This center provides insight in the state of the water system.	**External advice:** *Informatiebeeld Watersysteem* (provided by Information Center Water).
Hydrological model - Flood Early Warning System (FEWS) and SOBEK model to predict water levels; - Predict precipitation and discharge	**Hydrological model** - Flood Early Warning System (FEWS) and SOBEK model to predict water levels; - Impact roughness vegetation in water courses on water level; - Predict precipitation and discharge
Local field knowledge: - Knowledge of responsible water manager or senior employees.	**Local field knowledge:** - Knowledge of responsible water manager, visual assessment of the situation.
Legislation: priority sequence	

2C| DRY: *Which additional information do you use when the dry conditions remain for a longer period (8 weeks instead of 4 weeks)?*
5C| WET: *Which additional information do you use when the probability of negative consequences of the wet conditions increases?*

Dry	Wet
External advice: related to the severity of the drought (actual water shortage) rather than duration. - Nationwide information: provided by Ministry of Infrastructure and Water Management (*Rijkswaterstaat*); - RDO Noord and RDO Twenthekanalen: Regional Drought Consultation for the Northern area in the Netherlands and Twente region; - Information from the water management center of the Netherlands: *Landelijke Coördinatiecommissie Waterverdeling (LCW);* - Information from province	**External advice:** - Nationwide information: provided by Ministry of Infrastructure and Water Management (*Rijkswaterstaat*)
Frequency of normal information flows increases.	**Frequency** of normal information flows increases.

Measurement data: - Satellite evapotranspiration data
Meteorological forecasts: - Duration of the drought (long term).

The water management center monitors discharges of rivers on regional and national level and is part of Rijkswaterstaat.

3/6| *Which information that is yet not used yet in regional operational water management, do you demand to face problems related to drought or wetness? And for which purposes do you want to use this information?*

Parts of the satellite data can also be added to measurement data. The satellite data was specifically added, because of the desire of water managers to use these data. The category model data is defined as measuring the relations between variables and the impact of variables and scenarios on the status of the water system.

Dry	Wet
Model data: - Relation between groundwater and root zone; - Relation between groundwater and surface water; - Improved insight in the variables of the water balance; - Losses due to drought: in case water is stored and large rainfall event takes place versus in case water is not stored and drought spell takes place.	**Model data:** - Improved accuracy of predictive models; - Losses due to wet spell: in case water is not drained and large rainfall event takes place versus in case water is pumped and rainfall event does not take place.
Satellite data: - Evapotranspiration data: crop water availability; - To distinguish dry and extremely dry areas; - To measure impact water inflow.	**Satellite data:** - To indicate inundations; - To distinguish wet and extremely wet areas (also based on soil properties); - To measure impact water inflow.
Measurement data: - Real-time groundwater monitoring data; - Storage capacity in unsaturated zone.	**Measurement data:** - Storage capacity in unsaturated zone to assess quick runoff.
	Meteorological forecasts: - Spatial distribution of precipitation; - Early warning of flash precipitation (time, precise location and intensity).
	Mowing strategy: frequency, moments and vegetation type in water course

7| *What is an acceptable time interval between the availability of new information flows to be able to support decisions during a wet period?*

DRY: The demanded temporal resolution varies between one day and once a week. It depends on the actual situation, because droughts develop slowly. Therefore, information does not necessarily have to be real-time, because decisions can be made based on trend analysis. In case of changes, for instance precipitation forecasts, a finer temporal resolution is demanded to support decisions.

WET: The demanded temporal resolution varies between two to four days. Additionally, real-time information was mentioned, however this does not necessarily indicate a specific time interval (enables to continuously adapt to the situation to minimize impact of event). Furthermore, it was stated that the information regarding predictions becomes more accurate when the interval is shorter. Therefore, initial signs (days) and almost certain information (one day) were distinguished. Moreover, information that is available five days before the events enables to optimize mowing strategies and inform relevant people.

8| *Rate the importance of the indicator categories*

Table 25 shows importance of the indicator categories rated by the water managers. One water manager did not answer this question.

TABLE 25: IMPORTANCE OF INDICATOR CATEGORIES. THE BLACK DOTS INDICATE THE MOST IMPORTANT VALUATION.

Indicators	Very unimportant	Unimportant	Important	Very important
Drought			2	❻
Wetness			1	❼
Wildfire	1	❸	4	
Vegetation (during wet period)		2	❻	
Vegetation (during dry period)	1	1	❺	1

9A| *Rate the importance of the scientific requirements*

Table 26 depicts the water managers indicated the described scientific requirements are (very) important. One water manager did not answer this question.

TABLE 26: IMPORTANCE OF SCIENTIFIC REQUIREMENTS. THE BLACK DOTS INDICATE THE MOST IMPORTANT VALUATION.

Criterion	Very unimportant	Unimportant	Important	Very important
Reliability			1	❼
Accuracy			❹	❹
Updates			❼	1
Relevance		1	❸	4

9B| *Do you think that requirements are missing from the list in question 9a? If so, which ones?*
No relevant criteria were mentioned.

9C| *What should be the spatial resolution of information?*
The information flows should be able to provide detailed information on field scale. In addition, the spatial resolution depends on the conditions of the water system. During a wet period, local information is demanded, whereas during a dry period information on a less fine scale is already sufficient.

10| *Model data might have been presented for you. Did you use these data in your practices? And what purposes did these data serve? If not, why not?*
The water managers are willing to use model data and do not mention any relevant reasons why not to.

B. DEFINITION OF INDICATORS

B.1 Helpful soil moisture indicators

This section describes the indicators from which the SWWI and SCI are derived.

Soil Wetness Index (SWI[A]):

$$SWI = \frac{T_{s-max} - T_s}{T_{s-max} - T_{s-min}} \tag{8}$$

With:

T_s = land surface temperature [℃]
T_{s-min} = minimum land surface temperature [℃]
T_{s-max} = maximum land surface temperature [℃]

Temperature Vegetation Condition Index (TVDI):

$$TVDI = \frac{T_s - T_{s-min}}{T_{s-max} - T_{s-min}} \tag{9}$$

With:

T_s = observed surface temperature [℃]
T_{s-min} = minimum surface temperature [℃]
T_{s-max} = maximum surface temperature [℃]

Soil Moisture Deficit (SMD): estimates the amount of water necessary to bring the soil moisture content back to field capacity.

$$SMD_t = SMD_{t-1} - P + ET_\alpha + D \tag{10}$$

With:

SMD_{t-1} = Soil Moisture Deficit at time step t-1 [mm]
P = rainfall [mm d^{-1}]
ET_α = actual evapotranspiration [mm d^{-1}]
D = drain of water by percolation or runoff [mm d^{-1}]

Soil Moisture Deciles-based Drought Index (SMDDI): estimates the amount of water necessary to bring the soil moisture content back to field capacity.

$$SS = ST - ET_\alpha + P \tag{11}$$

With:

SS = current soil moisture storage [mm]
ST = soil moisture at previous state [mm]
ET_α = actual evapotranspiration [mm d^{-1}]
P = rainfall [mm d^{-1}]

B.2 Invalid soil moisture indicators

This section contains the soil moisture indicators that do not meet the indicator definition requirements.

B.2.1 Availability of data

The following indicators did not comply with the indicator requirements, because these indicators need a soil moisture time series of at least 20 years (Qin et al., 2015).

Soil Moisture Drought Severity (SMDS): determines the severity of droughts based on long-term monthly soil moisture data series of at least 20 years (Qin et al., 015). The SMDS ranges between 0-1. When the SMDS increases, the drought becomes more severe. Due to the lack of availability of such time series, this index fails on availability of data.

$$P = \frac{m}{n+1} \times 100\% \qquad (12a)$$

$$SMDS = 1 - P \qquad (12b)$$

With:

P = soil moisture percentile [-]
m = rank number of soil moisture value from time series [-]
n = sample size of time series [-]

Soil Moisture Anomaly (SMA): assesses the start and duration of agricultural drought conditions (EDO, 2018).

$$A_t = \frac{X_t - \bar{X}}{\delta} \qquad (13)$$

With:

A_t = anomaly of soil moisture value [m^3 m^{-3}]
X_t = soil moisture value at time t [m^3 m^{-3}]
X = long-term average of soil moisture [m^3 m^{-3}]
δ = standard deviation long-term soil moisture values [m^3 m^{-3}]

Drought Severity Index (DSI): assesses the extension and magnitude of drought events by comparing the current soil moisture state to the normal state, which is derived from a probabilistic function based on soil moisture time series (Cammalleri et al., 2016). To obtain insight in the precise method and equations, we refer to the publication of Cammalleri et al. (2016).

Soil Moisture Deficit Index (SMDI): monitors agricultural drought by reflecting short-term dry conditions important for local agricultural applications (Narasimhan & Srinivasan, 2005).

If $SW_{i,j} = MSW_j$:

$$SD_{i,j} = \frac{SW_{i,j} - MSW_j}{MSW_j - \min(SW_j)} \times 100 \qquad (14a)$$

If SWi,j > MSW_j :

$$SD_{i,j} = \frac{SW_{i,j} - MSW_j}{\max(SW_j) - MSW_j} \times 100 \qquad (14b)$$

$$SMDI_j = 0.5 \times SMDI_{j-1} + \frac{SD_j}{50} \qquad (14c)$$

With:

i = period [e.g. 1990-2010]
j = year [1-52 weeks]

SW = mean weekly soil water availability in soil profile [mm]
MSW = long-term median of total available soil moisture during period *i* for week *j*
min(SW) = long-term minimum of total available soil moisture during period *i* for week *j*
max(SW)= long-term maximum of total available soil moisture during period *i* for week *j*
SD_j = soil water deficit at time step j [%]
$SMDI_{j-1}$ = SMDI at time step j-1

B.2.2 Translation

Indices that did not comply with the requirement translation:

Soil Moisture Index (SMI): the outcome of the SMI can be compared with the three key values -5 (extreme dry situation), 0.0 (separator of stress versus non-stress situations) and +5 (wet situation).

$$SMI = -5 + 10\frac{\theta - \theta_{WP}}{\theta_{FC} - \theta_{WP}} \quad (15)$$

With:
Θ = actual soil moisture content [m^3 m^{-3}]
Θ_{FC} = field capacity [m^3 m^{-3}]
Θ_{WP} = wilting point [m^3 m^{-3}]

The SMI uses the same parameters as the SWDI, however the SWDI classifies all outcomes instead of providing only key values.

Soil Wetness Index (SWI^B): only estimates the amount of soil moisture, but do not provide a context for this value, for example comparing it with the maximum soil moisture value (saturation capacity) like the SWI^A and SWWI do.

$$SWI = \frac{\sum_i m_s(t_i)\exp\left[\frac{-(t-t_i)}{T}\right]}{\sum_i \exp\left[\frac{-(t-t_i)}{T}\right]} \; for\; t_i < t \quad (16)$$

With:
M_s = surface soil moisture estimate [m^3 m^{-3}]
t_i = time
T = characteristic time scale determined by calculating the correlation between satellite or model data and ground observations

B.2.3 Relevance

There were also indices that fail on the relevance requirement:

Keetch-Byram Drought Index (KBDI): the index calculates the Soil Moisture Deficit to assess the fire potential. According to the results of the survey, the water managers indicated this wild fire indicator is not relevant to support their practices.

B.2.4 Practical reasons

The following indices were not selected due to practical reasons regarding this study.

Vegetation Drought Response Index (VDRI): this drought index was not selected because of the relatively complex calculation process compared to the SWDI. Additionally, the SWDI incorporates the variables field capacity and wilting point, which are familiar for water managers. To obtain insight in the precise method and equations, we refer to the publication of Brown et al., (2008).

Soil Moisture Agricultural Drought Index (SMADI): this drought index was not selected because of the relatively complex calculation process compared to the SWDI. Additionally, the SWDI incorporates the variables field capacity and wilting point, which are known by water managers. The outcomes of the index are classified.

$$SMCI_n = \frac{\theta_{max} - \theta_n}{\theta_{max} - \theta_{min}} \qquad (17a)$$

$$MTCI_n = \frac{LST_n - LST_{min}}{LST_{max} - LST_{min}} \qquad (17b)$$

$$VCI_n = \frac{NDVI_n - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \qquad (17c)$$

$$SMADI_n = SMCI_n \times \frac{MTCI_n}{VCI_{n+1}} \qquad (17d)$$

With:
$SMADI_n$ = slope of MTCI and VCI multiplied by SMCI [-]
$SMCI_n$ = normalized surface soil moisture (Soil Moisture Condition Index) [-]
$MTCI_n$ = normalized temperature (Temperature Condition Index) [-]
VCI_n = normalized vegetation (Vegetation Condition Index) [-]

B.3 Classification structure and variables of defined indicators

This section describes the classification structure and variables of the defined indicators.

B.3.1 Soil Water Wetness Index

Saturation capacity

The saturation capacity was determined with the Maximum-Value composite method. This method takes the largest soil moisture value for each pixel for the available time series (2014-2017). The Maximum-Value composite method was suitable, as during the period 2014 – 2017, it is highly probable the soil has been completely saturated due to heavy or long-lasting rainfall.

Classification

The classification structure of the SWWI was derived from the SWDI (Martinez-Fernandez et al., 2015) to provide unambiguous classes and comparison between dry and wet situations. The *serious* class was removed, because the saturation capacity is the upper limit, there is no need to insert a category describing values larger than the saturation capacity (as these are non-existent). Furthermore, the *mild* and *moderate* class were merged into *moderate*, because the range between field capacity and saturation capacity is smaller than wilting point and field capacity. This may not lead to overstating the spatial variation.

B.3.2 Soil Water Deficit Index

In this section, the variables and classification structure of the SWDI are evaluated.

Field Capacity and Wilting Point

The Field Capacity (FC) is the water content the soil can hold in its capillaries against gravity. After a rainfall event or irrigation, water starts to drain into the soil (due to gravity), after one or two days the water content remains at a constant value. This constant value is the FC. It is affected by many factors, such as soil structure, previous soil water history, presence of impeding layers and groundwater table. In reality, the FC is not the upper limit of the available water holding capacity (AWC), because the excess of water that flows by during rapid drainage also partly supplies water for the plants (Grewal et al., 1990). The Wilting Point (WP) is the minimum amount of water that is required in order to prevent plants to wilt. When the soil moisture content falls below WP, plants will not be able to extract water from the soil pores and thus plants will wilt (Savage et al., 1996; Grewal et al., 1990). The AWC is the maximum amount of water that is actually available to plants. It is the difference between FC and WP.

Classification

The boundaries of the SWDI were shaped by the FC (maximum) and the WP (minimum). Therefore, the indicator is too a less extent suitable to assess the wetness of a specific area, because soil moisture values larger than the FC are not divided in classes.

The underlying theory of the value and classes of the SWDI is related to the readily available soil water (RAW) concept provided by the Food and Agriculture Organization (FAO) that assesses the crop water requirements (Allen, et al., 1998). The p-factor indicates the fraction of AWC that can be depleted before soil moisture stress takes place. A value of 0.5 for the p-factor is commonly used (Ceppi, et al., 2014), however the p-factor varies between 0.2 and 0.8 for 45 different crops (Allen, et al., 1998). The SWDI couples the p-factor with a classification system to reflect the soil moisture stress. For example, the p-factor of 0.2 reflects the SWDI of -2 (close to FC). This is explained with the following equation:

$$p_{factor} \times \theta_{AWC} = \theta - \theta_{FC} \tag{18}$$

Allen et al. (1998) state that 50% of the investigated crops have a p-factor below 0.5. This justifies the division of the ‘severe drought’ category (0.5 – 1.0) into two categories. This results in more equally divided classes, as the minimum p-factor and maximum p-factor then both have a specific class (0.2 – 0.5 and 0.5 – 0.8). The additional class is labelled as ‘serious’ for 0.5 – 0.8 and remains ‘severe’ for 0.8 – 1.0. For crops with a relatively low p-factor, this provides insight in the severity of the drought when the depletion of the soil moisture level continues.

The classes of the SWDI are based on general values of crop water requirements and not on the climate of a particular area. Therefore, it is not necessary to convert the classes into Dutch conditions.

B.4 Soil moisture data sets

This section visualizes the results of the accuracy and reliability.

B.4.1 Accuracy

Sentinel-1

In Figure 10 the Sentinel-1 and in-situ (at 5 cm depth) soil moisture data is depicted for the period October 2014 till May 2017. Due to the inability of Sentinel-1 satellites to measure soil moisture near forest or bush, stations 1 and 20 are left out. Additionally, data of stations 4, 9, 17 and 19 is unavailable.

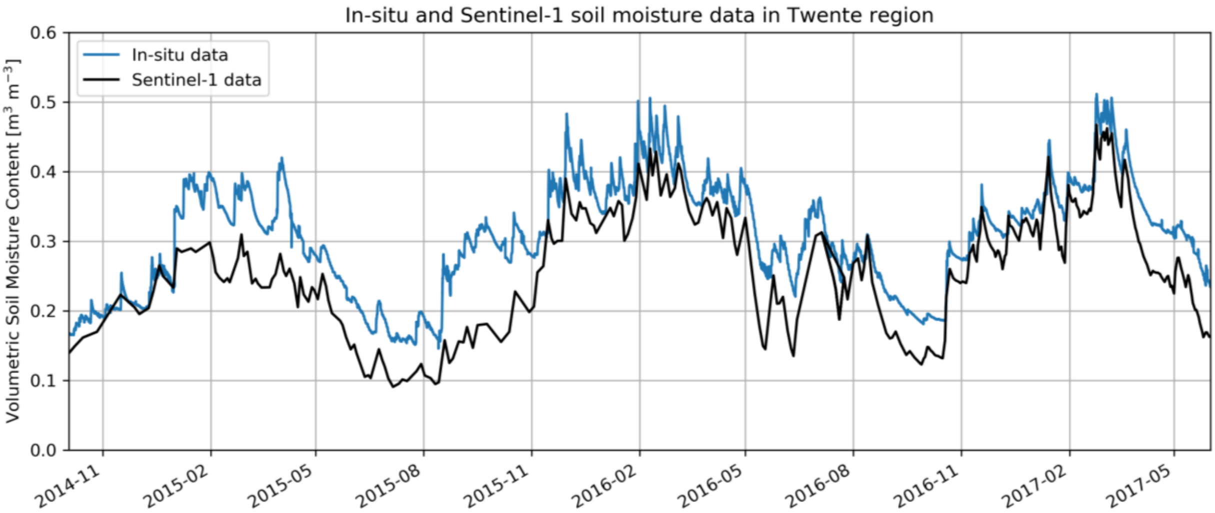

FIGURE 10: IN-SITU (AT 5 CM DEPTH) AND SENTINEL-1 SOIL MOISTURE DATA IN TWENTE REGION.

Figure 11 shows the accuracy of Sentinel-1 data for each of the twenty stations.

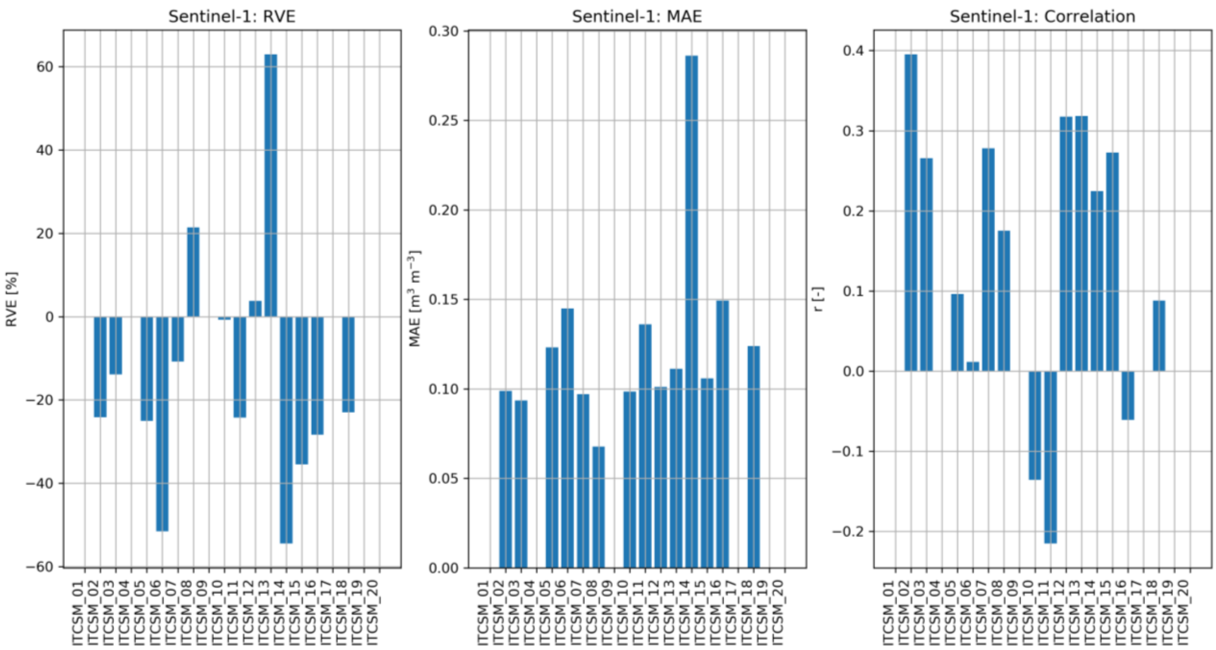

FIGURE 11: ACCURACY OF SENTINEL-1 AT THE TWENTY STATIONS

MIPWA

Figure 12 depicts the MIPWA and in-situ (weighted average over depth) soil moisture data for the period October 2014 till May 2017. Due to the lack of in-situ data of the deeper layers, stations 3, 4 and 16 are left out.

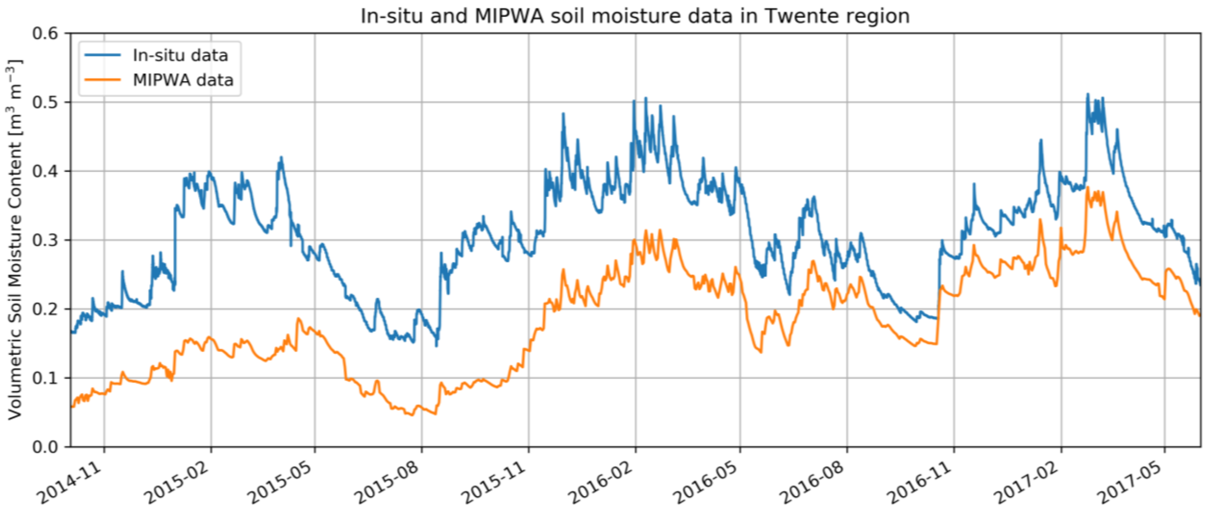

FIGURE 12: IN-SITU (AVERAGED OVER DEPTH) AND MIPWA SOIL MOISTURE DATA IN TWENTE REGION

Figure 13 shows the accuracy of the MIPWA data for each of the twenty stations.

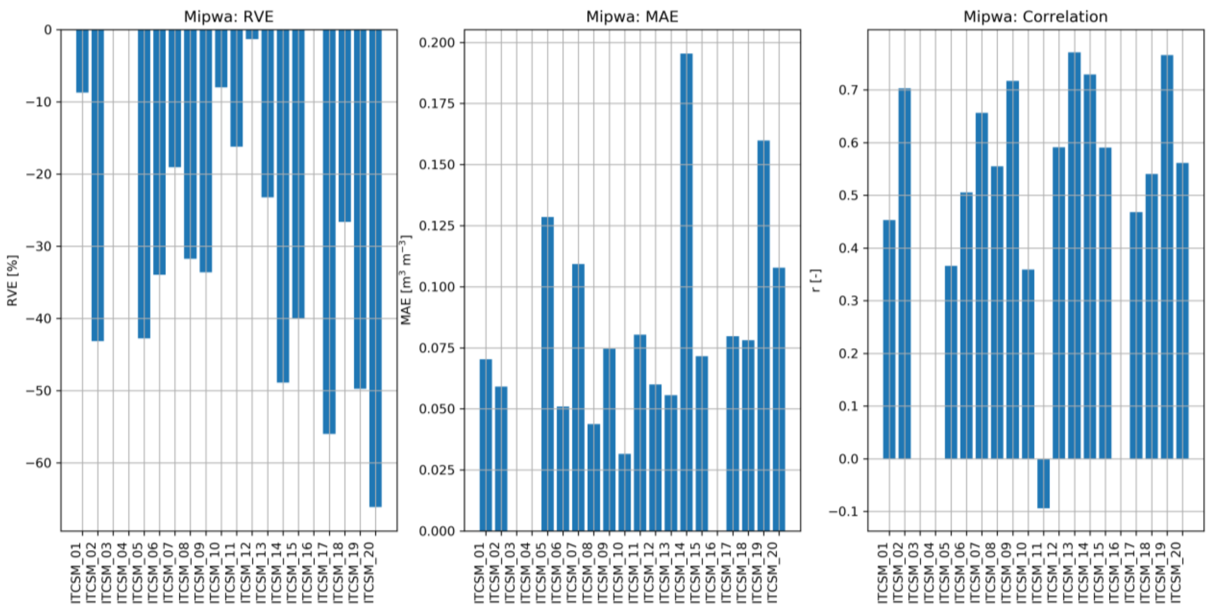

FIGURE 13: ACCURACY OF MIPWA AT THE TWENTY STATIONS

B.4.2 Reliability

The variability of the Sentinel-1 and MIPWA data is illustrated for each of the twenty ITC soil moisture network stations. Figure 14 illustrates the Coefficient of Variation of the Sentinel-1 and in-situ data at 5 cm depth. The Coefficient of Variation of the MIPWA and the weighted average of the in-situ data is shown in Figure 15.

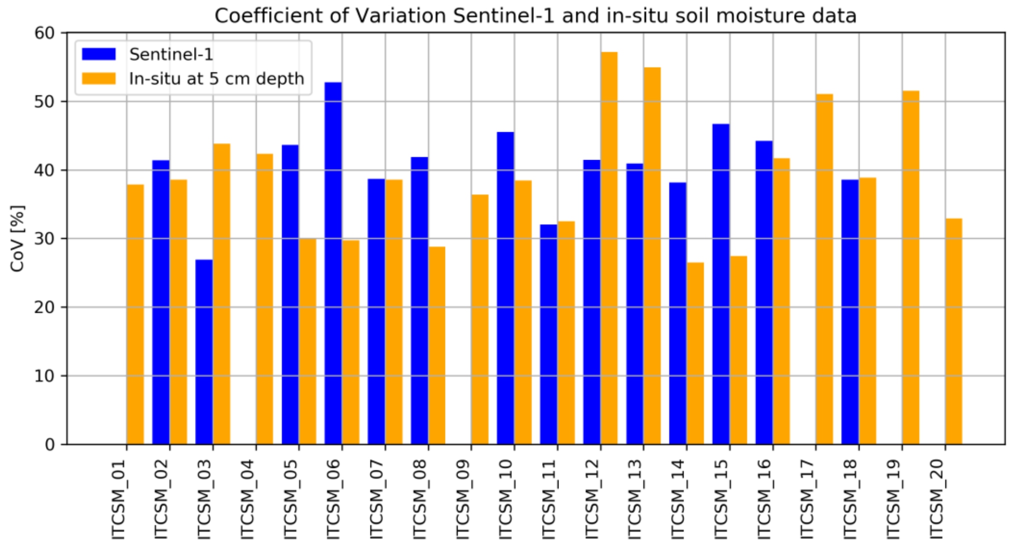

FIGURE 14: COEFFICIENT OF VARIATION FOR SENTINEL-1 DATA

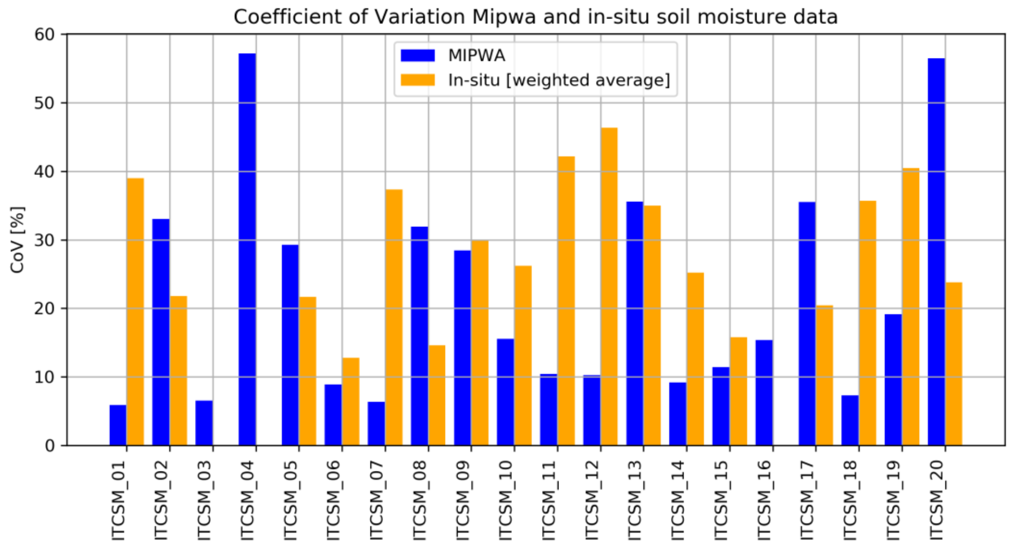

FIGURE 15: COEFFICIENT OF VARIATION FOR MIPWA DATA

Based on these results, there is no clear relationship detected between the accuracy and reliability of Sentinel-1 and MIPWA with respect to land-use and soil properties.

C. VALIDATION INDICATORS

Invulformulier werksessie 4 december 2018

Dit invulformulier heeft als doel te analyseren in welke mate bodemvochtdata en -indicatoren waterbeheerders nieuw inzicht kan geven in het watersysteem. Hiervoor worden een aantal vragen gesteld waarin onder andere de volgende criteria worden gehanteerd:

- **Ondersteuning**: bevestiging van huidig inzicht in water systeem, maar geen nieuwe inzichten.
- **Nieuwe inzichten**: data of indicator leiden tot een verbeterd inzicht in water systeem.
- **Interpretatie**: de weergave van de data of indicator is duidelijk te interpreteren.

Geef voor elk criterium aan of u dit zeer negatief, negatief, neutraal, positief of zeer positief beschouwd.

1. Huidige data

Beoordeel in de onderstaande tabel de huidige databronnen die u gebruikt (bijvoorbeed neerslag, grondwater maar ook remote sensing verdampingsdata).

Criteria	Zeer negatief	Negatief	Neutraal	Positief	Zeer positief
Ondersteuning					
Nieuwe inzichten					
Interpretatie					
Nauwkeurigheid					

Ruimte voor een korte toelichting:

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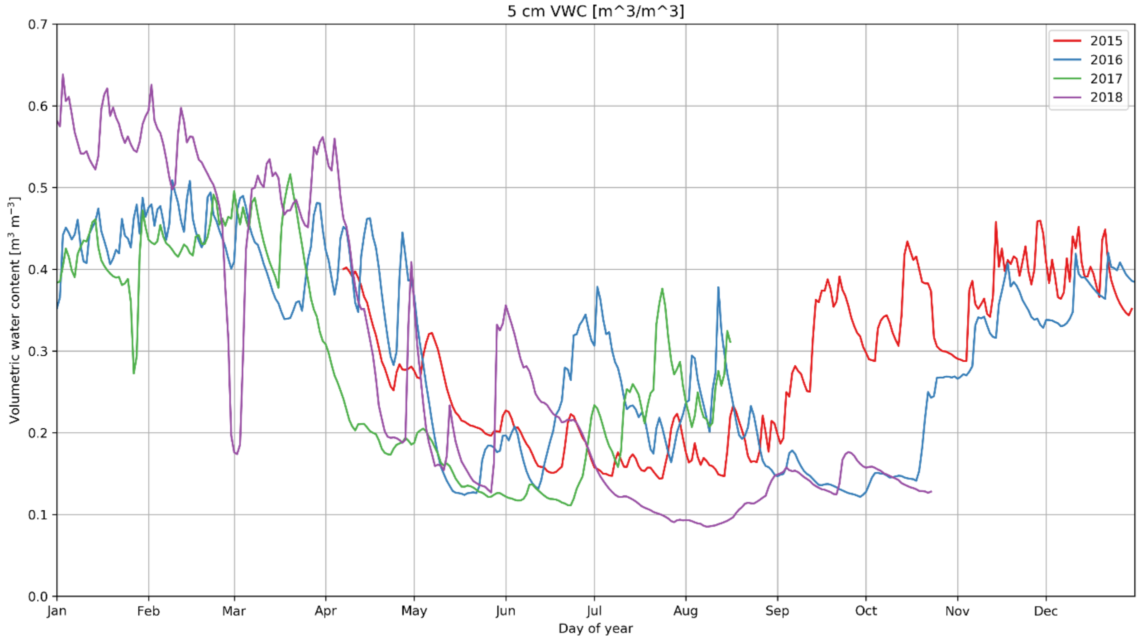
2. Bodemvochtdata

Geef aan in welke mate bodemvochtdata (temporeel en ruimtelijk) uw werkzaamheden kan ondersteunen, nieuwe inzichten brengt en duidelijk te interpreteren is. Per criteria geeft u aan of dit zeer negatief, negatief, neutraal, positief of zeer positief is.

(1/2) Onbewerkte bodemvochtdata (trend)

Criteria	Zeer negatief	Negatief	Neutraal	Positief	Zeer positief
Ondersteuning					
Nieuwe inzichten					
Interpretatie					
Nauwkeurigheid					



Ruimte voor een korte toelichting:

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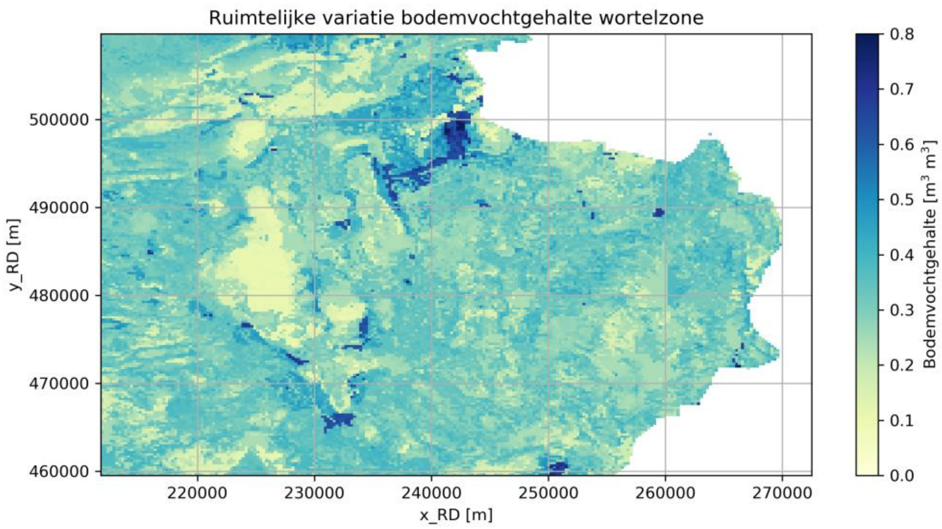
(2/2) Onbewerkte bodemvochtdata (ruimtelijk)

Criteria	Zeer negatief	Negatief	Neutraal	Positief	Zeer positief
Ondersteuning					
Nieuwe inzichten					
Interpretatie					
Nauwkeurigheid					



Ruimte voor een korte toelichting:

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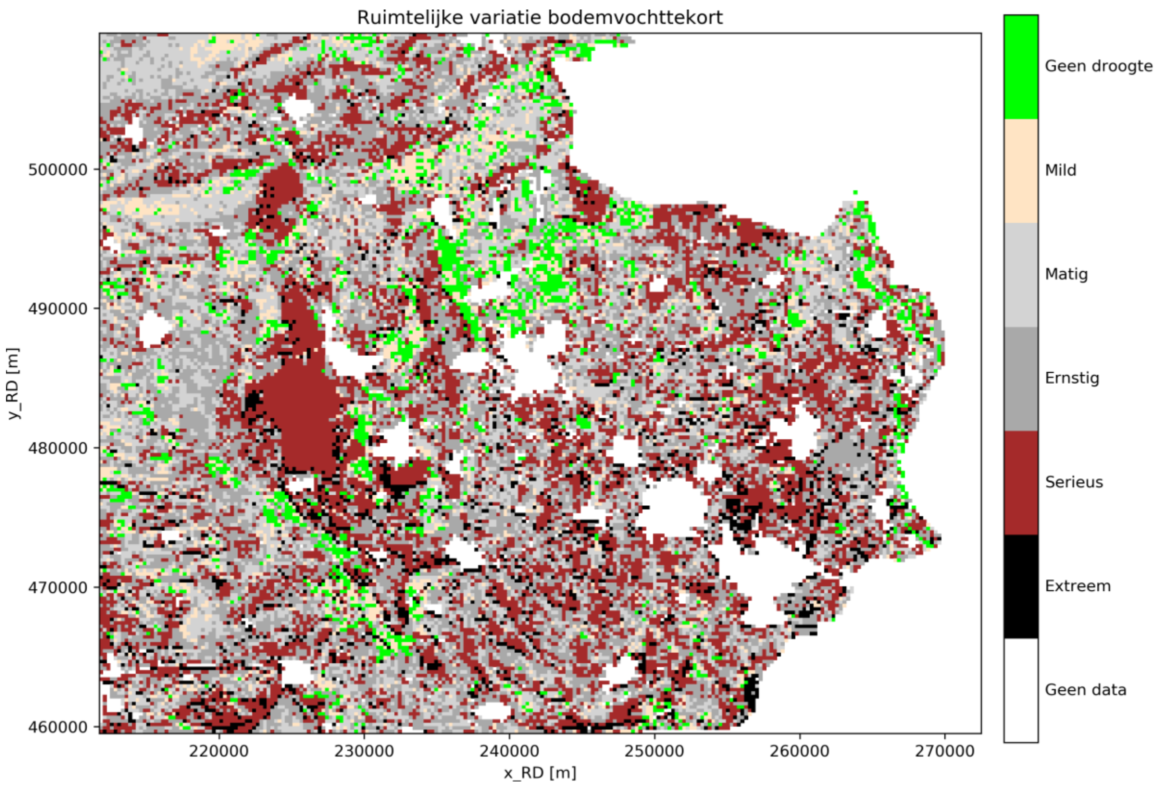
3. Bodemvocht indicatoren

Geef voor de volgende indicatoren aan in welke mate de indicator uw werkzaamheden kan ondersteunen, nieuwe inzichten brengt en of de indicator duidelijk te interpreteren is. Per criteria geeft u aan of dit zeer negatief, negatief, neutraal, positief of zeer positief is. De indicatoren staan vermeld op de volgende paginas.

(1/4) Bodemvochtwatertekort indicator (ruimtelijk)

Criteria	Zeer negatief	Negatief	Neutraal	Positief	Zeer positief
Ondersteuning					
Nieuwe inzichten					
Interpretatie					
Nauwkeurigheid					



Ruimte voor een korte toelichting:

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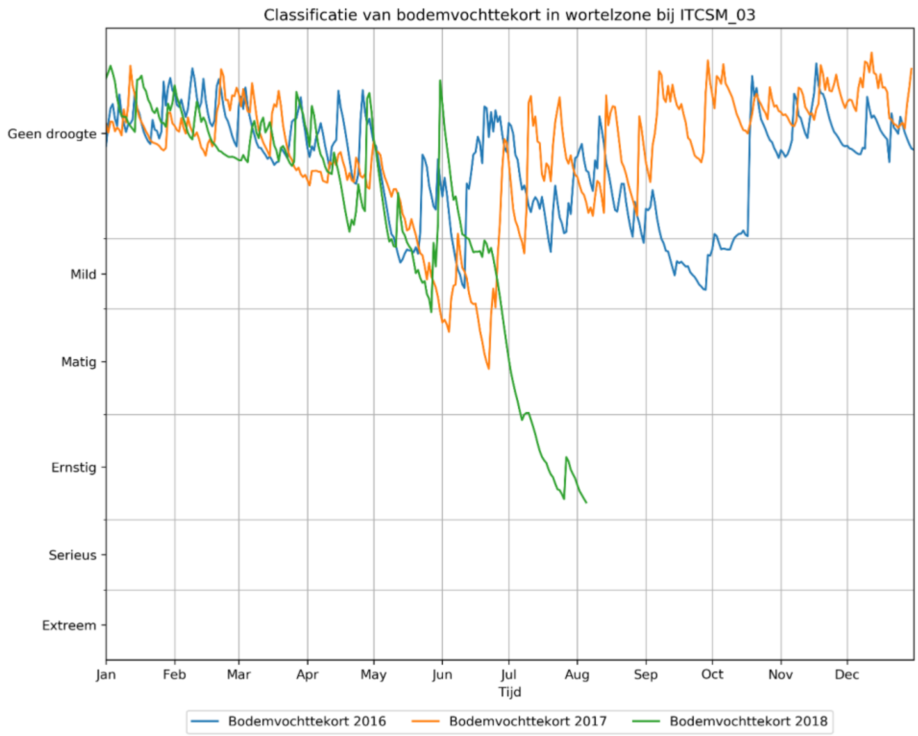
(2/4) Bodemvochtwater tekort indicator (trend)

Criteria	Zeer negatief	Negatief	Neutraal	Positief	Zeer positief
Ondersteuning					
Nieuwe inzichten					
Interpretatie					
Nauwkeurigheid					



Ruimte voor een korte toelichting:

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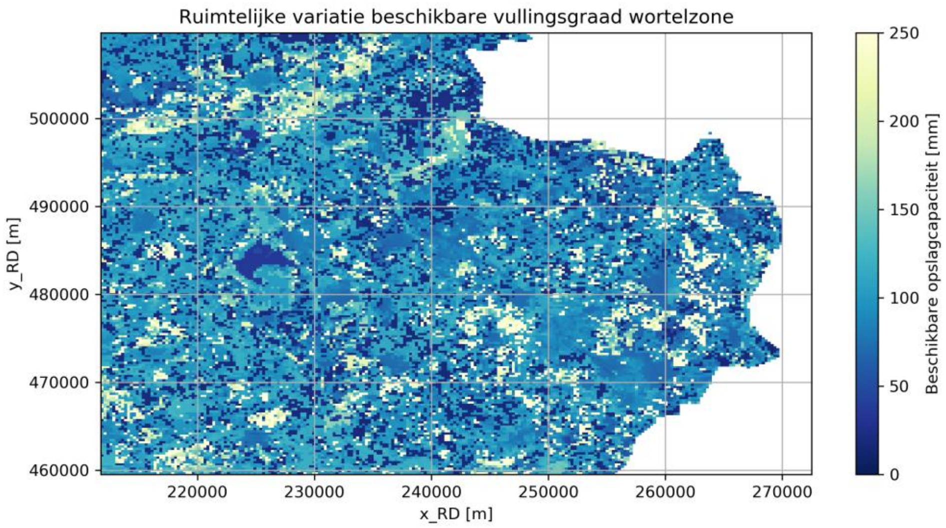
(3/4) Vullingsgraad (ruimtelijk)

Criteria	Zeer negatief	Negatief	Neutraal	Positief	Zeer positief
Ondersteuning					
Nieuwe inzichten					
Interpretatie					
Nauwkeurigheid					



Ruimte voor een korte toelichting:

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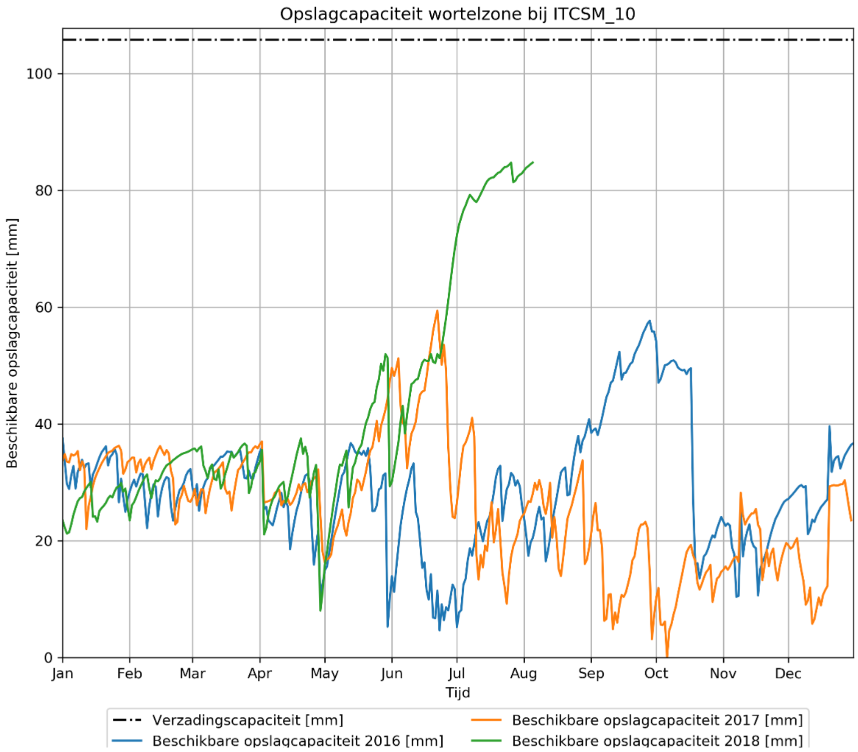
(4/4) Vullingsgraad (trend)

Criteria	Zeer negatief	Negatief	Neutraal	Positief	Zeer positief
Ondersteuning					
Nieuwe inzichten					
Interpretatie					
Nauwkeurigheid					



Ruimte voor een korte toelichting:

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