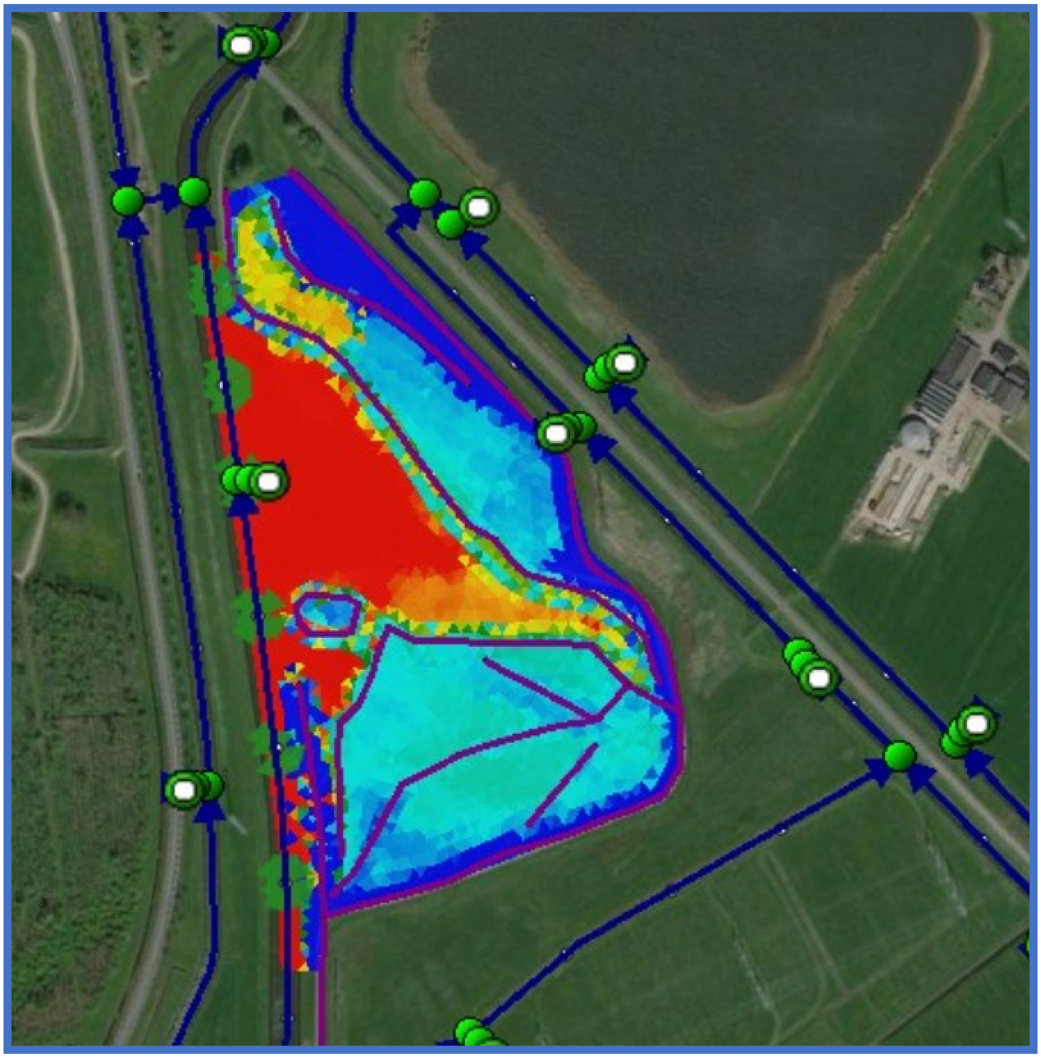
COMPARITIVE ASSESSMENT OF SOBEK2 AND D-HYDRO SUITE 1D2D FOR REGIONAL INUNDATION MODELLING



Thijs Lieverse
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University of Twente
MSc Thesis – Water Engineering and Management

Supervisors:
dr. Maarten Krol (University of Twente)
dr. Vasileios Kitsikoudis (University of Twente)
ir. Bas Agerbeek (Arcadis)
ir. Arjon Buijert (Arcadis)
ir. Stefan de Vries (Arcadis)

Summary

Hydrological and hydraulic modelling tools are critical for effective water management by water authorities in the Netherlands. Among others, models are used to perform a Water System Analysis (WSA), which entails assessing whether regional water hindrance norms are met. Historically, SOBEK2 has been applied for these purposes, generally employing a 1D schematization to represent hydraulic processes. However, recently D-HYDRO Suite 1D2D has been developed as the intended successor for SOBEK2, most notably improving 1D2D modelling functionality.

This study describes the comparative assessment of a (1D) SOBEK2 and a D-HYDRO Suite 1D2D model in the context of the WSA, with the intent of obtaining insights in how the new tool compares to the current standard and potential consequences of this tool for current best practices. The Soestwetering catchment in the west of Overijssel, the Netherlands, was used as a realistic and representative case study.

An Assessment Framework was developed to assess model suitability for the WSA, consisting of model performance, usability and applicability criteria. The SOBEK2 and D-HYDRO models are similar in model performance for the chosen case. Simulated 2D flow dynamics seem to be realistic, although they had little effect on model performance. However, various issues, including several related to the used beta version of D-HYDRO Suite 1D2D (0.9.7.51931), prevent effective use at the moment. In addition, 1D2D modelling does not seem superior to 1D modelling for a WSA, among others because the current 1D approach is sufficiently accurate and more practical. Two exceptions to this are when overland flow processes are relevant for overall model performance, or when detailed inundation insights are desired. When 1D2D modelling would be applied in a WSA context, it may be preferable to opt for a simple 2D schematization at the locations of interest, sacrificing model accuracy and mesh optimization for a faster schematization process.

It was concluded that the used beta version of D-HYDRO Suite 1D2D (0.9.7.51931) is not suitable for the WSA, most notably due to several (yet) unsupported features and long computation times. That being said, experts agree on the expectation that most of these issues will be resolved before the official release version of D-HYDRO, which would likely make it more suitable than SOBEK2 for the WSA in the future.

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Many thanks to all,
Thijs Lieverse

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1 Introduction

Effective management of water systems requires insights in relevant processes and how they behave under various conditions. As such insights are critical to maintain water safety, water authorities in the Netherlands employ a wide variety of hydrological and hydraulic modelling tools to obtain an understanding of their water systems. These models can be used for many different goals, such as determining how a flood may develop after a dike breach, analyzing the effect of a specific intervention or predicting which areas may be at risk in the future due to climate change.

For water authorities, an important application of hydrological and hydraulic models is to evaluate whether a water system meets the water hindrance norms (developed after the ''Nationaal Bestuursakkoord Water'', 2003). Specifically, this evaluation concerns inundation caused by high water levels in surface water. A standardized guideline for this process has been developed by Stichting Toegepast Onderzoek Water (STOWA, 2011): the Water System Review (WSR), presenting a framework for the Water System Analysis (WSA) used to determine bottleneck locations, as well as discuss best-practices.

Continuous developments on hydrological and hydraulic modelling may be a reason for water authorities to reevaluate the WSR approach and determine whether current practices can be improved upon. Examples of relevant model innovations include the subgrid method enabling computationally efficient 2D analyses, developments in 1D2D hydrodynamic modelling tools which combine the strengths of 1D and 2D modelling, or new possibilities for 2D mesh configurations. Additionally, the steady increase in computational capacity could both reduce uncertainty (e.g. through a probabilistic approach) or allow new local processes such as overland flow to be investigated through a higher resolution of the 2D mesh. As such, novel insights and innovations may enable water authorities to perform their tasks more efficiently and effectively.

In the Netherlands, the standard tool used to perform the WSA is SOBEK2, a hydrological and hydraulic modelling tool developed by Deltares, allowing users to simulate entire water systems in an efficient and effective manner. D-HYDRO Suite 1D2D (internationally known as Delft3D Flexible Mesh Suite 1D2D), also developed by Deltares, is established as the successor to SOBEK2. Among others, it offers a variety of new features, most notably on 2D modelling, such as efficient 1D2D coupling and flexible mesh options, Potentially, D-HYDRO Suite 1D2D may offer significant advantages over SOBEK2, enabling water authorities to obtain new insights during the WSA.

In this study, the current standard modelling tool (1D) SOBEK2 is compared with a beta version of the newly developed D-HYDRO Suite 1D2D (version 0.9.7.51931) in a realistic case study, aiming to comparatively assess them in the context of the WSA, as well as investigate the new possibilities offered by 1D2D modelling in the context of the WSA.

In this chapter, firstly the study background is discussed in (1.2), providing context on the relevant practical and scientific developments, separated in a literature review, introduction of both modelling tools and elaboration on the WSA. In (1.3), the knowledge gap for the study is introduced, after which the research questions (1.4) and scope (1.5) will be presented.

1.1 Background

In this paragraph, the context for the study will be elaborated on. Firstly, a literature review will discuss the history and current state-of-the-art of hydraulic 1D(2D) modelling, after which SOBEK2 and D-HYDRO Suite 1D2D will be introduced along with their conceptual differences. Finally, the practical context for application relevant to this study (Water System Review) will be discussed.

1.1.1 Literature review

Hydrodynamic tools have been used extensively in (flood) inundation modelling, and can be separated in three categories: 1D, 2D and 3D modelling (Teng et al, 2017). Appropriate model tools may differ based on the desired insights of the model application, relevant processes in the water system and practical considerations such as data availability and computational capacity.

To this day, 1D models are effectively used to simulate main waterways and water systems, where they often are sufficiently accurate and easy to implement (Deltares, 2018). This is especially true when the desired insights are more general to (e.g. water level at this location). However, when insight is preferred in complex processes, such as inundation patterns in cities or overland flow, 2D models are required, as 1D models do not provide an accurate representation of reality, especially at more local levels (Afshari et al, 2018). 3D modelling is often only applied when specific processes which can only be effectively simulated in 3D are relevant (Teng et al, 2017).

1D models simplify the characteristics of the water system while accounting for the most relevant hydraulic processes. Typically, they only accurately account for processes in (simple) water channels, such as rivers or sewer systems (Teng et al, 2017). When processes outside of simple environment become relevant, such as when considering flow over floodplains, 2D models are necessary to accurately account for spatial variations in bed levels and roughness (Fleischmann et al, 2020). 3D models have enabled new studies to account for complex hydraulic mechanisms, such as turbulence or sediment transport patterns of the Sand Engine pilot in the Netherlands (Luijendijk et al, 2017). Especially when flow in the vertical plane is relevant (e.g. when simulating waves crashing on a coast), 3D models are necessary for accurate results.

Practical considerations also play a role in model suitability, especially. Although 2D models have greatly risen in popularity, the method remains data- and computationally intensive and therefore generally difficult to apply to large areas (Pasquier et al, 2019). In many situations, the time and effort to develop a 2D model and obtain sufficient data may not be warranted over a simple 1D model (Kitsikoudis et al, 2020; Jowett and Duncan, 2011). 3D models also require significant spatial data, while also having a higher computational demand compared to 2D models (Teng et al, 2017).

One of the most significant developments has been the emergence of 1D2D models, which combine the calculation speed and simplicity of 1D with the insights of 2D (Teng et al, 2017). A good example of this is connecting a 1D breach model with a 2D floodplain model to obtain insight in the consequences of a dike breach (Vanderkimpen and Peeters, 2008). Currently

1D2D models are a popular choice for many flood inundation simulations (Teng et al, 2017; Nazari et al, 2016).

Various themes can be identified on the state of the art of 1D2D hydrodynamic modelling focused on flood and inundation studies, with the most relevant for this study being [1] 2D mesh properties, [2] comparative and suitability studies for 1D2D and [3] best practices related to model performance.

2D mesh properties can have a significant impact on the model performance and accuracy. Several studies have investigated and compared the effect of the different properties between mesh types. Among others, these have showcased the added value unstructured meshes can have, especially when combining specific cell shapes depending on the location (Lai, 2010; Bomers et al, 2019). Unstructured or flexible meshes can be built around spatial attributes, such as a riverbend or a dike, which can allow them to provide a more realistic representation, where a higher resolution would be required for structured grids to achieve the same representativeness. However, structured meshes can still be preferable over unstructured meshes, as they were found to be efficient in calculation, and depending on the context, can yield similar results and are easier to implement (Bern and Plassman, 2000). Furthermore, studies have highlighted the importance of careful mesh generation as the influence of the grid design can affect the results to a similar extent as physical factors such as friction (Voullième et al, 2012). Mesh resolution is at least as important as other calibration parameters, which requires a trade-off between model accuracy and calculation time (Hardy et al, 1998). Numerical friction, viscosity and bathymetry accuracy are therefore relevant factors to account for when designing the mesh (Bomers et al, 2019). Best-practices suggested by literature include analyzing various mesh resolutions (Hardy et al, 1998), accounting for spatial characteristics in mesh building (Marsh et al, 2018) and aligning grids based on topography and the dominant flow direction (Bomers et al, 2019; Betsholtz and Nordlöf, 2017). With respect to computational demand of meshes, adaptive grid refinement techniques could be applied to both structured and unstructured meshes to reduce computation time but maintain sufficient quality in areas of interest (Wackers et al, 2012).

1D2D models have been studied extensively in literature, both compared against each other and against 1D, as well as showcasing their applicability in various case studies. In general, 1D2D models can be more easily applied than 2D models, provide similar model performance, and have a lower computational demand (Teng et al, 2017). For a large-scale application in a river basin, it was concluded that 1D and 2D are both capable of representing main water channel dynamics, but for complex wetlands and floodplains, 2D is essential (Fleischmann et al, 2020). Historically, 1D2D models were generally a combination of 1D grids with structured 2D grids (Vanderkimpen and Peeters, 2008), but more recently, coupling with flexible meshes is also used, improving accuracy and calculation time when applied correctly (Bakhtyar et al, 2020). 2D and 1D2D models can lead to a more detailed representation of inundation patterns (Bakhtyar et al, 2020; Sarchani et al, 2020), especially when high-resolution spatial data is available (Erpicum et al, 2014) or when environments are more complex, such as urban areas (Fan et al, 2017). As such, a 1D2D model may be preferable over a 1D one when (relevant) flow occurs over spatially complex areas or insight is desired on inundation extent and patterns.

1D2D models may be preferable over 2D models when parts of the model can be represented in 1D, especially if these parts are not relevant for the model purposes.

However, studies discuss the dependency of (1D)2D models on accurate spatial information and data, with model results being sensitive to inaccuracies or low spatial resolution, indicating the necessity of suitable spatial data for flood and inundation studies (Papaioannou et al, 2015; Sarchani et al, 2020). On top of that, 1D2D models can be affected by incorrect 1D2D coupling, which may significantly affect model results (Betsholtz and Nordlöf, 2017). Furthermore, studies note that when complexity of the water system is relatively low, 1D models can still perform similar or better than (1D)2D models, among others due to issues mesh properties create for calibration or lack of high-resolution spatial data (Horrit and Bates, 2002; Dimitriadis et al, 2016). Even when there is complexity, depending on the study context and scope, 1D models may still perform adequately for flooding simulations (Pinho et al, 2015).

Finally, because of the aforementioned dependency of 2D models on high-resolution spatial data and sensitivity to mesh properties, uncertainty plays an even more important role in 2D flood modelling (Willis et al, 2019). For (1D)2D studies, relevant recurring sources of uncertainty are the mesh properties (Bomers et al, 2019; Voullième et al, 2012) and friction (Dimitriadis et al, 2016). Preferably, uncertainty is identified, quantified and properly communicated (Teng et al, 2017).

1.1.2 Model tools

In the Netherlands, a popular modelling tool for water systems is SOBEK2 developed by Deltares, which enables the user to both simulate hydrological processes through the ''Rainfall-Runoff'' module (RR) and hydraulic processes through the ''Channel-Flow'' module (CF). In practice, the CF module is ofen applied in 1D, where both modules are sequentially (or offline) coupled. Although this is more computationally efficient, it prevents CF processes (e.g. high water levels or inundation) to influence RR processes (e.g. groundwater levels). Simultaneous runs do enable this physical interaction (Deltares, 2019). It should also be noted that (1D)2D modelling is possible through the SOBEK 2DFLOW (Overland Flow) module, although this is much less commonly used than 1D modelling (Arcadis, personal contact).

SOBEK2 computes the water flow by solving the shallow water equations (also ''De Saint Venant'') for unsteady flow, assuming [1] one-dimensional flow (uniform across a cross-section), [2] hydrostatic pressure, [3] effects of friction and turbulence can be computed similarly to resistance laws in steady flow and [4] small average channel bed slope (Cunge et al, 1980; Deltares, 2019). More specifically for CF, the 1D continuity equation (quantity) and 1D momentum equation (dynamics) are solved.

1D Continuity Equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

Where A is the total flow and storage area (m²) and Q is the discharge (m³/s).

1D Momentum Equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_F}\right) + gA_F\frac{\partial \zeta}{\partial x} + \frac{gQ|Q|}{C^2RA_F} - w_f\frac{\tau_{wind}}{\rho_w} + gA_F * \frac{\xi Q|Q|}{L_x} = 0$$

Where A_F is the flow area (m²), C is the Chézy value ($m^{1/2}/s$), g is the gravitational acceleration, ζ is the water level (m), L_x is the length of the branch segment (m), Q is the discharge (m³/s), R is the hydraulic radius (m), t is the time (s), w_f is the water surface width (m), x is the distance along the channel axis (m), ρ_w is the density of fresh water (kg/m³), τ_{wind} is the wind shear stress (N/m²) and ξ is the extra resistance coefficient (s^2/m^5).

The D-HYDRO Suite 1D2D has been developed over the past 10 years, initially with a focus on 2D (and 3D) functionality and additional features, but in recent years also with a focus on 1D2D functionality to allow the tool to become a suitable successor to SOBEK2. It uses the same RR module as SOBEK2 to simulate hydrological processes, and relies on the new D-Flow FM module for hydrodynamic computations (replacing both CF and Overland Flow). With respect to the 1D computation of hydraulic processes, D-HYDRO Suite 1D2D functions nearly identical to SOBEK2, based on the aforementioned Saint Venant equations. One relevant difference in treatment of drying and wetting is that D-HYDRO Suite 1D2D does not include computational cells with negative water depths in the iterative solving of equations (one computational timestep), whereas SOBEK2 does include these cells and halves the timestep. This leads to differences between both software products related to the drying of cells. With respect to the 2D computation, D-Flow FM uses a 2D depth-averaged model, again employing the shallow water equations obtained by depth-integrating the Navier-Stokes equations (Altaie and Dreyfuss, 2018). Critically, these assume [1] vertical momentum exchange is negligible and the vertical velocity component is significantly smaller than the horizontal velocity component, and [2] the hydrostatic pressure gradient is linear with water depth.

2D Continuity Equation:

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0$$

2D Momentum Equation in x direction:

$$\frac{\partial hu}{\partial t} + \frac{\partial hvu}{\partial y} + \frac{\partial hu^2}{\partial x} = -gH\frac{\partial \eta}{\partial x} + \nu\left[\frac{\partial}{\partial x}\left(H\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(H\frac{\partial u}{\partial y}\right)\right] - fHv + \frac{\tau_u^w - \tau_u^b}{\rho_0}$$

2D Momentum Equation in y direction:

$$\frac{\partial hv}{\partial t} + \frac{\partial hvu}{\partial y} + \frac{\partial hv^2}{\partial y} = -gH\frac{\partial \eta}{\partial y} + \nu\left[\frac{\partial}{\partial x}\left(H\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(H\frac{\partial v}{\partial y}\right)\right] - fHu + \frac{\eta - \tau_v^b}{\rho_0}$$

Where x and y are the horizontal coordinates, t is the time, u is the depth-integrated velocity in the x direction (m/s), v is the depth-integrated velocity in the y direction, H is the water depth (m), ν is the horizontal turbulent viscosity, g is the gravitational acceleration, $f = 1.01*10^{-4}$ rad/s (Coriolis frequency), ρ_0 is the density of fresh water (kg/m³), η is the water level relative to rest (m), τ^w is the bottom stress zonal component and τ^b is the wind stress zonal component.

The primary difference with SOBEK2 is the significantly expanded 2D functionality of D-Flow FM, which enables 2D and 1D2D hydraulic computations with various mesh resolutions in an efficient way. Where SOBEK2 could only perform 1D2D calculations with simple structured grids that overlapped with the 2D network, D-HYDRO Suite 1D2D provides more flexibility win 2D mesh configurations. The 2D meshes allow for local grid refinement: using high accuracy grids locally, without the cost of having such a fine grid everywhere. Additionally, the unstructured meshes may be aligned with landscape features, although this may be more useful in coastal and riverine applications than in rural applications. In addition, meshes can be positioned besides the 1D network (through lateral connections), thereby preventing double storage in both 1D and 2D. Another important feature of the D-Flow FM functionality are the "fixed weirs". These are 1D elements with a specified height along the fixed weir that can be place on top of a grid. For each flow link that crosses the fixed weir, flow is only possible over the height of the fixed weir. Essentially, this enables users to work with lower mesh resolutions, using fixed weirs to account for local elevations (e.g. roads, small dikes), thereby significantly improving computational efficiency while maintaining accuracy.

One potential method to effectively generate a large D-HYDRO model is to convert a (1D) SOBEK2 model to a (1D) D-HYDRO model. Afterwards, 2D schematization can be added to establish the 1D2D model. This schematization includes establishing the meshes, defining fixed weirs, obtaining and interpolating spatial data (e.g. bed levels) and establishing 1D2D links between the 1D network and the 2D meshes. It should also be noted that many tools which can be used for more effective use or post-processing are still being developed for D-HYDRO Suite 1D2D, which may also enable more efficient model generation in the future.

Several remarks should be made with respect to software status and applicability in the context of this study. Currently D-HYDRO Suite 1D2D is still being developed and therefore a beta product. As such, some functionalities available in SOBEK2 are (yet) unsupported and a variety of issues occur in the beta version of D-HYDRO Suite 1D2D used in this study (0.9.7.51931). While doing the research described in this thesis several of these issues were encountered. These have been placed on the development list of Deltares, with several already resolved in upcoming releases.

The modelling done in this research fully falls within scope of the upcoming D-HYDRO 1D2D Suite release 1.0 (official release version). Important consideration, though, is that not only the new software is being tested here, but also new experience is gained in the model schematization process. Therefore, findings for a single model schematization (Soestwetering in this case study), may not be representative for rural models in general, and should not be concluded to apply to all rural models. The implications of used (beta) software and potential limitations of the model approach for the study objective will be further elaborated on in the Discussion (Chapter 4).

1.1.3 Water System Review

One context in which 1D(2D) hydrodynamic tools can be applied is to assess water systems and determine locations which may be at risk of inundation. In the Netherlands, provincial norms are set for water hindrance. The WSR is a standardized guideline for water authorities to determine whether these norms for water hindrance are met (STOWA, 2011). The most important step in the WSR is the WSA, where the water system is schematized in a representative validated model (hydrological and hydraulic). A more elaborate explanation on the WSR can be found in Appendix A.

In the WSR guideline, several (qualitative) requirements for a model to be used in the WSA are provided. To obtain a more specific definition of model suitability, a session was held with Arcadis on calibration and model requirements, yielding various additional considerations. Combined, the model suitability requirements which are important specifically for WSA purposes can be categorized in [1] model performance (quality of model, representativeness), [2] model usability (ease-of-use, practical considerations) and [3] model applicability (which insights can be obtained). A more elaborate list of suitability requirements can be found in Appendix A.

The context in which hydrodynamic models are applied determine relevant model application decisions, which are an important aspect of the model process and can have a significant influence on the suitability of the model. In the case of the WSA, several relevant decisions relate to how model input and output are appropriately assessed to determine whether the system meets the water hindrance norms.

A potential issue arises because the norms are set quantitively related to result (e.g. area X may inundate once every 10 years), but with the complexity of many water systems, it can be difficult to develop an approach on how to assess this using a model. One method is to define normative conditions, where the frequency of the input conditions is linked to the acceptable frequency in the norms. This method has been applied often by both water authorities (STOWA, 2019) and in studies (Ntanganedzeni and Norbert, 2020). With respect to the extreme conditions (model input) historically a design-precipitation event was used, although currently only probabilistic and time series approaches are recommended (STOWA, 2011). As the design-precipitation approach relies on a single extreme event in an isolated context, and reactions to extreme precipitation events differ greatly per water system, this approach does not yield sufficiently reliable results. Both the time-series approach and probabilistic methods account for a wide variety of hydrometeorological conditions, therefore producing more reliable results (STOWA, 2011).

Another issue is that water authorities preferably use a standardized assessment approach to keep results between various analyses comparable and maintain reliability. With new innovations, and water authorities reevaluating on how they can perform their tasks more efficiently and effectively, this may become difficult. For example, in the case of D-HYDRO Suite 1D2D, water authorities could make different model application decisions (e.g. standard grid-resolution), or differ in whether they use certain new functionalities in their assessment (e.g. overland flow). As such, one of the challenges water authorities will be facing is finding a robust standardized approach on the modelling process and model application decisions (Arcadis, personal contact).

In conclusion, literature has shown that there are several potential benefits offered by 1D2D modelling over 1D relevant to the WSA, most importantly the option to simulate inundation (patterns) effectively and efficiently. However, before 1D2D models can be applied, water authorities need to reevaluate their current approaches and determine whether these should be updated to account for novel insights and innovations.

1.2 Problem Statement

Comparative studies between hydrological and hydraulic modelling tools (including 1D2D) are widespread in literature (Tegegne et al, 2017; Paul et al, 2019; Vanderkimpen and Peeters, 2008). However, as a newly emerged modelling tool, D-HYDRO Suite 1D2D's suitability to represent a water system has not yet been compared against proven suitable alternatives in a full-scale representative case. Moreover, it is unknown what the effect of D-HYDRO Suite 1D2D's new functionality, most notably the flexible mesh options, is on the suitability for practical applications such as the WSA. Specifically, literature suggests that (1D)2D calculations can offer valuable new insights on overland flow and inundation characteristics, as well as more accurately simulate flow in complex areas, with the drawback of higher computational demand and data requirements (Teng et al, 2017, Pasquier et al, 2017).

The latter two are important practical considerations for model suitability (specifically usability), also being one of the primary reasons that 1D hydraulic modeling still holds merit in present applications (Teng et al, 2017; Jowett and Duncan, 2011). Although model usability is sometimes discussed in literature as an afterthought (Afshari et al, 2018) or in a qualitative way to provide context for good modelling practices (Risbey et al, 2005), comparative studies between modelling tools rarely consider model usability to the same extent as model performance. This study may shine additional light on the importance of including model usability in comparative studies.

Furthermore, literature discusses various important model application decisions for 1D2D models, such as the relevance of correct mesh properties (Bomers et al, 2019). Investigating such model application decisions on a realistic use-case can contribute to understanding how to effectively apply D-HYDRO Suite 1D2D in the context of the WSA.

Finally, water authorities and other model users are curious as to what D-HYDRO Suite 1D2D's new functionalities can mean for current best practices, and in which cases the new software may offer advantages over currently used alternatives (Arcadis, personal contact).

To summarize the problem statement, D-HYDRO Suite 1D2D's suitability for practical applications, such as the WSA, needs to be compared against a proven suitable alternative in a realistic representative case, to provide insight on model performance, usability and applicability.

1.3 Research Questions

Based on the knowledge gap in the problem statement, various research objectives can be defined where this study can contribute: [1] a comparison between the current standard of a 1D application of SOBEK2 and the 1D2D application of D-HYDRO Suite 1D2D in the context of the WSA, [2] insight in important 1D2D model application decisions from a practical perspective and [3] a framework on when D-HYDRO Suite 1D2D can be effectively applied and when SOBEK2 could still be used. Based on these objectives, the main research question is identified:

How do SOBEK2 and D-HYDRO Suite 1D2D differ in hydraulic modelling when applied in the context of the Water System Analysis and how does this influence their suitability?

Through answering this question, additional insights can be provided on the potential of D-HYDRO Suite 1D2D as successor to SOBEK2. Among others this study aims to highlight the differences between the two tools, providing a basis of understanding to effectively prioritize D-HYDRO Suite 1D2D over SOBEK2. Moreover, it seeks to provide insights in relevant model application considerations for future application in a WSA context. To answer the main question, several sub-questions will have to be investigated:

1. What framework can be used to assess performance, usability and applicability of SOBEK2 and D-HYDRO Suite 1D2D in the context of a Water System Analysis?
2. What are the differences between SOBEK2 and D-HYDRO Suite 1D2D in simulating a water system based on historical peak events?
3. What are the differences between SOBEK2 and D-HYDRO Suite 1D2D in simulating extreme events that may occur?
4. What is the effect of model application considerations on performance and usability for both tools in the context of a Water System Analysis?

Sub-question [1] will provide a framework which is used to compare SOBEK2 and D-HYDRO Suite 1D2D on performance, usability and applicability, which are the primary considerations for tool choice in the context of a WSA; this question is entirely addressed in the Methodology chapter. In sub-question [2], both tools are compared on modelling a water system based on historical data, while in [3] the differences in simulating extreme events and inundation characteristics are investigated. Together, these should shed more light on how tools can be used in a WSA. Sub-question [4] investigates various important model application considerations, which may lead to suggestions on improving best-practices used in the WSA. Together, these questions provide insights in how SOBEK2 and D-HYDRO Suite 1D2D differ, when D-HYDRO Suite 1D2D may be a preferable tool to use, and how D-HYDRO Suite 1D2D could be effectively applied.

1.4 Scope of the study

This study aims to provide valuable insights in the suitability of D-HYDRO Suite 1D2D for hydrological and hydraulic modelling by comparing it against SOBEK2, the current standard. This comparison focuses on several key considerations relevant to organizations who might apply these tools on a regular basis, and thus aims to shed light on if and when D-HYDRO Suite 1D2D may be preferably to use over SOBEK2.

This comparison is performed with a realistic use-case, where both tools are applied as they would be for the WSA. To maintain a fair comparison, it is important that the only differences between both models are inherent (e.g. calculation methods, available options) or related to a realistic use-case (e.g. a commonly used method to significantly improve calculation time). The models which will be used in the analyses in this study should therefore be similar to what a water authority or other organization would use to perform a WSA. However, due to practical considerations extensive calibration or optimization of the model was not possible, which means the models may not meet all WSA model requirements. As the aim of this study is comparing both tools, this should not significantly affect the results.

Moreover, this study aims to provide insights on how D-HYDRO Suite 1D2D can be effectively applied, with a practical application by water authorities in mind, both considering the current best practices and the state of the art in literature. Potentially, this study may provide suggestions for adaptations to the current guidelines or additional investigation based on the experiences in this study.

That being said, this study does not seek to determine whether SOBEK2 is obsolete with the addition of D-HYDRO Suite 1D2D. With this study analyzing a single water system, it is not possible to draw a hard line on whether the results apply for all situations and whether the differences showcased in this study will be present in all contexts. It does however provide a reference point for future comparative studies and a basis for organizations to determine their strategy for choosing the modelling tool on.

2 Methodology

This study employs a case-study approach to make a comparative assessment of the suitability of D-HYDRO Suite 1D2D and SOBEK2 for WSA application, providing insight on model performance, usability and applicability. The choice for a case-study was made as the knowledge gap primarily relates to application of D-HYDRO Suite 1D2D in a practical context (e.g. WSA), as the benefits of 1D2D modelling have already been studied extensively (e.g. Bakhtyar et al, 2020). A representative case study would enable results and insights to be directly related to the knowledge gap and model suitability in a practical context. Table 1 summarizes the connection between research objectives and research activities, while Figure 1 presents the resulting research flow.

Table 1 Overview research objectives and chosen approach.

Research objectives by research question	Approach
1. Definition of how model suitability for the WSA can be comparatively assessed.	Develop an assessment framework based on relevant model requirements for the WSA which can be applied to a case-study.
2. Compare SOBEK2 and D-HYDRO Suite 1D2D on suitability as a hydrological and hydraulic modelling tool.	Use data of historical peak events to compare SOBEK2 and D-HYDRO Suite 1D2D in accordance with the developed assessment framework.
3. Compare SOBEK2 and D-HYDRO Suite 1D2D on their ability to simulate extreme events.	Perform a simulation run with an extreme amount of precipitation, assess whether results are realistic and meet usability requirements.
4. Determine the influence of best-practices or relevant aspects suggested by literature on performance and usability.	Perform an analysis of the influence of grid characteristics and best practices suggested by Deltares and literature.

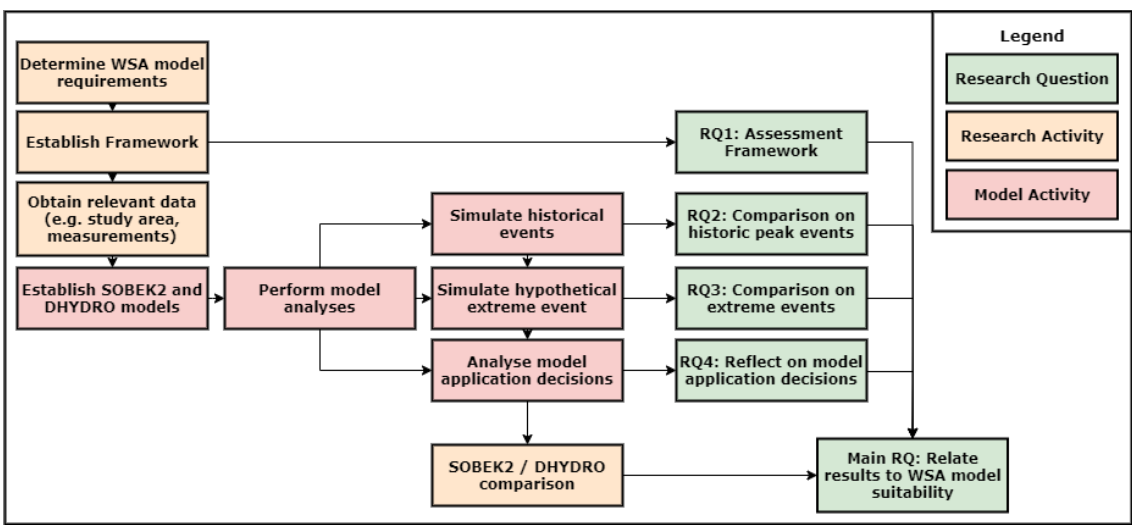

Figure 1 Research flow. Activities on the left are related to preparation, while middle-right are related to the analyses and interpretation of the results.

This chapter elaborates on the study approach and methodology. In 2.1, the assessment context and framework will be established, after which in 2.2 the study area and data will be introduced. Section 2.3 will discuss how the model analyses and assessment were performed. Finally, Section 2.4 will discuss how both models were established and highlight relevant model application decisions.

2.1 Assessment Framework

To determine how SOBEK2 and D-HYDRO Suite 1D2D can be compared, firstly the context in which they will be evaluated needs to be defined. Based on the research questions and scope, this context is composed of two elements:

- A representative case for the WSA combined with realistic model application decisions for the two tools. A further elaboration on relevant choices made to achieve a fair comparison will be discussed in 2.4.
- Aspects of model performance considered important by water authorities to determine whether a tool is suitable for the WSA. More elaboration on WSA model requirements and suitable assessment criteria can be found in Appendix A.

As discussed previously, suitability for the WSA may involve model performance, usability and applicability criteria. For this study, the basis of the criteria that were used for the comparative assessment of both tools were derived from WSA model requirements explicitly stated in the official WSR guideline (STOWA, 2011; Appendix A). These requirements are connected to the reliability of the model, but remain relatively vague on how the model should be calibrated or which specific criteria can be used to assess whether a model is suitable.

To specify the suitability of a model for the WSA further, a session was held with Arcadis to determine best practices when calibrating a model for WSA purposes. During this session, a priority list was made on specific model performance criteria, as well as which role these played during the calibration process. For example, (cumulative) discharges are clear indicators of whether a model provides reliable output and should preferably be as correct as possible, but as long as peak timing is within reasonable margins, this indicator is irrelevant (Arcadis, personal contact). In addition, various additional considerations were mentioned for the calibration, such as model usability or suitability aspects. Furthermore, during this session several checks were mentioned which were used to find schematization errors in the model (e.g. unrealistic water level differences at structures).

Using the STOWA guidelines as a starting point for model suitability and expanding with criteria from Arcadis, which include more specific model performance and usability criteria, a list of criteria was developed based on the WSA model requirements. These criteria should be generically applicable to all WSA models. To verify whether the criteria are appropriate for WSA suitability assessment in the context of this study, they were sent to water authority Drents Overijsselse Delta (WDOD) and Arcadis for review. No further additions were suggested, although there were some elaborations on how certain criteria were assessed in current best practices. Also, it was remarked that the suitability of a model for the WSA can differ based on context (e.g. size of the WSA area, desired level of detail).

Based on the aforementioned model performance, usability and applicability criteria from STOWA and Arcadis, an Assessment Framework has been established in which SOBEK2 and D-HYDRO Suite 1D2D can be compared (Table 2). Model performance criteria are assessed comparing simulations of the regional water system with the observed system, especially for high-flow situations. Several other criteria will only be qualitatively assessed or shortly explored in this study, due to insufficient spatial inundation data and practical considerations. Based on performance on the various criteria, WSA suitability can be derived.

It should be noted that the assessment of several criteria used in this framework are case-dependent, most notably ''inundation characteristics'', ''model robustness'' and ''clarity of model processes. For the ''inundation characteristics'', expert elicitation will be used to determine whether simulated patterns are realistic. For robustness, this will be shortly explored by analyzing whether the performance differs greatly between a summer or winter event. Seasonal factors, such as reduced friction due to removal of vegetation on floodplains, could have a (local) effect on water levels. Depending on the context, such factors may significantly affect model performance. For the clarity of the model tools, this will be qualitatively assessed and discussed with hydrologists from Arcadis and WDOD.

In this section, the Assessment Framework will be discussed, along with how each criterion can be assessed. Section 2.3 will further elaborate on how this Assessment Framework was applied in this study and the assessment were performed.

Table 2 Established assessment framework for comparative assessment of SOBEK2 and D-HYDRO Suite 1D2D.

Assessment Framework Water System Analysis – SOBEK2 and D-HYDRO Suite 1D2D		
Criterion	Indicator	Description
(Cumulative) discharge volumes	Volumetric Efficiency (VE) RVE	Important criterion during calibration and for general reliability of the model. Unless there are good explanations for reasonable deviations, (cumulative) discharges should be correct.
Peak water levels	NSE	Very relevant for the bottleneck and inundation analyses. Although these preferably are as accurate as possible, a positive bias is preferred over a negative one, to prevent bottleneck locations to be overlooked.
Q50 water levels	MAE	Water levels should be correct under normal (mean) conditions.
Peak timing	Lag correlation with NSE	Irrelevant when similar to observed values, otherwise it can indicate errors in the model (data or schematization).
Inundation characteristics*	Inundation map Qualitative assessment	Realistic inundation patterns and extent are needed if the tool is to be used reliably for inundation analyses.
Simulation Time (ST)	Model hours / hour	Time required to run the model. Less relevant than schematization time, but still an important consideration for model suitability.
Schematization Time	Schematization (1D) Optimization (1D) Schematization (2D)	Time required to (re)build the model, assuming the builder has experience with the tool. Includes all activities required to move from the obtained data to a functioning model. Quite relevant, as modelling often is a trade-off between schematization time and performance.
Clarity of model processes*	Clarity of interface Clarity of computations Clarity of files	Extent to which relevant processes of the model software are understandable for the user. This includes the interface, error messages, file storage, input parameters and so on.
Model robustness*	Relative bias summer/winter Performance in extreme event	Relates to how reliable the model performs under a variety of scenario's. Robustness if often case-dependent. In this case, this was briefly explored by checking whether performance in summer and winter was similar, and if the model provided realistic results for extreme events. The latter was investigated by whether [1] discharges and water levels are realistic, [2] extreme processes were reliably accounted for, [3] residence time of the peak was realistic and [4] 2D inundation characteristics were as could be expected.
Simplification extent (2D)*	Qualitative assessment on how 2D processes are accounted for (storage, dynamics)	Approach used to simplify hydraulic processes outside of the primary water channels, such as storage or overland flow. Simplification is often a trade-off between efficiency and accuracy, and potentially relevant insights are lost when 2D characteristics are too simplified.
Inundation analysis*	Inundation characteristics Simulation time Schematization time Simplification extent	Applicability of the tool to establish inundation maps of potential bottleneck locations, mostly related to the storage outside of the primary water channels.
Overland flow analysis*	Simulation time Schematization time Simplification extent	Applicability of the tool to (accurately) account for overland flow processes or obtain insight in these processes.
WSA Suitability*	Influenced by all criteria: Model performance Model usability	Collection of all criteria mentioned above. Certain criteria may be more relevant than others. A combination of expert elicitation and model results will be used to perform a final assessment based on the criteria in this assessment framework.

**Various criteria are subjective or context-dependant and therefore difficult to quantify or objectively assess. In this study, they are still included due to their relevance, and they will be assessed qualitatively.*

Assessment of usability and applicability criteria, as well as the inundation characteristics, is mostly done qualitatively due to practical considerations (further elaborated upon below). This provides additional considerations with respect to bias and subjectiveness. Input for assessment for most of these criteria will be obtained in an expert elicitation session with Arcadis (expert hydrologists) and WDOD (both expert hydrologists and experts on the study area). More information on the expert elicitation session, including the protocol and relevant context, can be found in Appendix C.

Table 3 Used goodness-of-fit indicators.

Goodness-of-fit indicator	Formula
Volumetric Efficiency (VE)	$VE = 1 - \frac{\sum_{i=1}^{n} \lvert y_i - x_i \rvert}{\sum_{i=1}^{n} (x_i)}$
Relative Volume Error (RVE)	$RVE = \frac{\frac{1}{n}\sum_{i=1}^{n} (y_i - x_i)}{\frac{1}{n}\sum_{i=1}^{n} (x_i)}$
Nash-Sutcliffe Efficiency (NSE)	$NSE = 1 - \frac{\frac{1}{n}\sum_{i=1}^{n} (y_i - x_i)^2}{\frac{1}{n}\sum_{i=1}^{n} (y_i - \overline{x}_i)^2}$
Mean Absolute Error (MAE)	$MAE = \frac{1}{n}\sum_{i=1}^{n} \lvert y_i - x_i \rvert$
Relative Bias (RB)	$RB = \frac{\sum_{i=1}^{n} (y_i)}{\sum_{i=1}^{n} (x_i)} - 1$

The first criterion for model performance concerns the (cumulative) discharges, which is considered an important indicator for general model performance (Arcadis, personal contact). The volumetric efficiency (VE) will be applied, which allows for a quick assessment on how cumulative errors in discharge relate to the total discharge volume. The relative volume error (RVE) instead provides perspective on the relative size of the errors. In hydrology, both metrics are often recommended in combination with other efficiency metrics (Krause et al, 2005). The Nash-Sutcliffe Efficiency (NSE) will be used as a suitable metric for peak water levels to determine how well the model represents flow dynamics in general and high flows in particular, because it is both a staple metric used in hydrology and is biased towards high flows (Gupta et al, 2009). The frequency in which the NSE has been applied in literature will allow for better comparison with similar studies, which is why it was chosen over other indicators also biased towards high flows. For water levels under normal conditions, the Mean Absolute Error is used to provide an indication of the error in absolute units, which is preferred over the RMSE as it reduces bias towards large events (Bennet et al, 2012). In literature, lag correlation is applied to determine the accuracy of peak timing by shifting the values over timesteps and observing if better results would be achieved if the time-series is shifted (Jackson et al, 2019). To determine whether results are improved, this study will use the NSE metric, as due to the bias towards high flows it should be more sensitive to the peak volume, which is the most relevant period in a WSA analysis.

Finally, inundation characteristics will be evaluated in a mostly qualitative manner. Inundation maps will be established for the areas schematized in a 2D grid. These will be discussed with area experts from WDOD to determine whether the inundation patterns are realistic for these locations, indicating whether the 2D representation is representative. Moreover, the inundation maps will also be reflected upon with experts from both Arcadis and WDOD to assess [1] credibility of inundation patterns (does the software compute/simulate flow as could be expected based on input) and [2] potential consequences for applicability in the WSA, such as the ability to analyse new processes. Quantitative evaluation of inundation extent is not possible for the Soestwetering case, as no data is available on inundation extent (WDOD, personal contact).

Model usability is a combination of quantitative and qualitative criteria. The calculation time of both models will be recorded. Schematisation time is a more difficult metric to interpretate, as reproduction of the same schematisation is naturally quicker, and several tools exist to efficiently establish a SOBEK2 model based on available data. However, a general indication of the time required to build up a model will provide a basis for comparison. In this case, the indicator value will be estimated as the time required for an experienced model builder (similar to reproduction) to establish the model in accordance with best practises. For SOBEK2, Arcadis will be asked to estimate how long this would take them. For D-HYDRO, the schematization time will be estimated in two parts: the 2D schematization time (how long does it take to develop the grids and prepare the spatial data) and the time required to convert a (1D) SOBEK2 model to a (1D) D-HYDRO model. As the current best-practise approach for D-HYDRO Suite 1D2D is to import a SOBEK2 model, the final indicator will be calculated as the sum of the SOBEK2 schematization time, conversion time and 2D schematization time. As such, insight is provided in [1] time required for conversion and import of the model (which may be significantly reduced with further improvements to D-HYDRO Suite 1D2D), [2] time related to the additional (1D)2D functionality of D-HYDRO Suite 1D2D (which may be useful when considering if 2D schematization is worthwhile) and [3] total time to set up a working (1D2D) D-HYDRO model compared to a (1D) SOBEK2 model.

Model robustness will be explored shortly by comparing the performance for both winter and summer events, as well whether the models remain representative for extreme events, providing insights in whether they are able to reliably perform in different conditions. More specifically, this will be assessed by comparing simulated and measured water levels and calculating the relative bias. Differences in the relative bias between summer and winter might point towards systematic errors for summer and winter events (e.g. vegetation causing significant friction, resulting in higher observed water levels). To determine whether the tools remain representative for extreme events, it will be briefly investigated if [1] models are able to represent extreme conditions (such as submerged weir crests), [2] if the resulting discharge graphs for the catchment are as could be expected, [3] whether residence time of the peak event in the system is realistic (less than a few days for the Soestwetering catchment) and [4] whether 2D processes in D-HYDRO Suite 1D2D also seem to be realistic (Arcadis, personal contact).

Model clarity, indicating how easy it is to interpret and use the tool, will be evaluated through a qualitative assessment related to the WSA model requirements. In an expert session with experienced hydrologists from WDOD and Arcadis, their opinion on [1] the user interface and [2] the background files will be assessed. One potential methodological issue is that they are experienced in SOBEK2, while their knowledge on D-HYDRO Suite 1D2D may be limited, potentially biasing results. To still account for model clarity in the comparative assessment, experts will be asked to [3] provide relevant model clarity criteria. These will then be qualitatively assessed based on experiences during this study.

2D simplification extent concerns the method used to account for relevant 2D processes. For the WSA, the most important is the storage outside of the water channels, with overland flow dynamics being less relevant (Arcadis, personal contact). This will be qualitatively assessed with experts from WDOD and Arcadis by discussing how the chosen simplification of these processes relate to WSA suitability. More specifically, this includes whether the simplification is reasonable (e.g. an appropriate trade-off between schematization time and accuracy) and whether it may lead to oversimplification of the model.

Model applicability criteria will be assessed in two ways. Firstly, relevant criteria from the performance and usability criteria will be considered to provide a baseline insight. For example, if a (1D2D) D-HYDRO model requires a significantly longer calculation time, it might become less suitable for a WSA. Secondly, during the expert elicitation session with Arcadis and WDOD, the three applicability criteria (WSA, Inundation Analysis, Overland Flow) will be separately discussed. Similarly to model clarity, lack of experience could be an issue for them to accurately assess D-HYDRO Suite 1D2D. Therefore, they will be asked on their most important considerations for each of the three topics, after which experiences in this study will be used to reflect on those considerations. For WSA applicability, a distinction will be made between the current situation and the future situation, as it is expected that 2D will be more actively considered in future best practises (Arcadis, personal contact). Both inundation and overland flow analyses are more specific than a WSA, which is why fewer criteria are relevant.

The effect of D-HYDRO Suite 1D2D's new features (investigated in this study) on the suitability for the WSA, most notably the option for a flexible mesh, will be incorporated under the related criteria during the final assessment. During assessment, it is important to consider that different components of D-HYDRO Suite 1D2D and SOBEK2 packages affect different criteria, namely the interface (Graphical User Interface for D-HYDRO Suite 1D2D), the computational kernel or both. Although these components are part of the same software system, being specific on what aspects of the tool influence which criteria is important for both transparency and understanding.

2.2 Study area and data

To provide usable insights following the comparative assessment related to the knowledge gap, it is important that a representative case is chosen. For the scope of the study, this means that the water system should be of realistic scale to WSA studies. Furthermore, a relatively complex water system would be preferred (e.g. influenced by a variety of structures), as results of this study may then become more generically applicable.

For this study, the choice was made for the Soestwetering catchment in the west of Overijssel (The Netherlands). Due to its complexity, where the water system covers a large area and is influenced by many weirs and pumps, it should be a suitable case for the purposes of this study. The availability of several years of usable measurement data and the unrelated development of a newly updated SOBEK2 model of the system were further reasons this case was chosen

In Figure 2, an overview of the study area is provided. The Soestwetering is a man-made channel with a length of 46 km. The entire catchment is 534 km², where several waterways (combined called the "Sallandse Weteringen") mouth into the Soestwetering, which flows through Zwolle into the "Zwarte Water". The water system consists of a variety of water channel types (from small creeks to larger canals), many pumps, weirs and culverts, as well as a spread of retention areas throughout the system. Several sub-catchments do not flow naturally into the Soestwetering, but are artificially drained using pumps. Various datasets and sources were used in this study to both establish the SOBEK2 and D-HYDRO models, calibrate and validate with. The most relevant are described in Table 4.

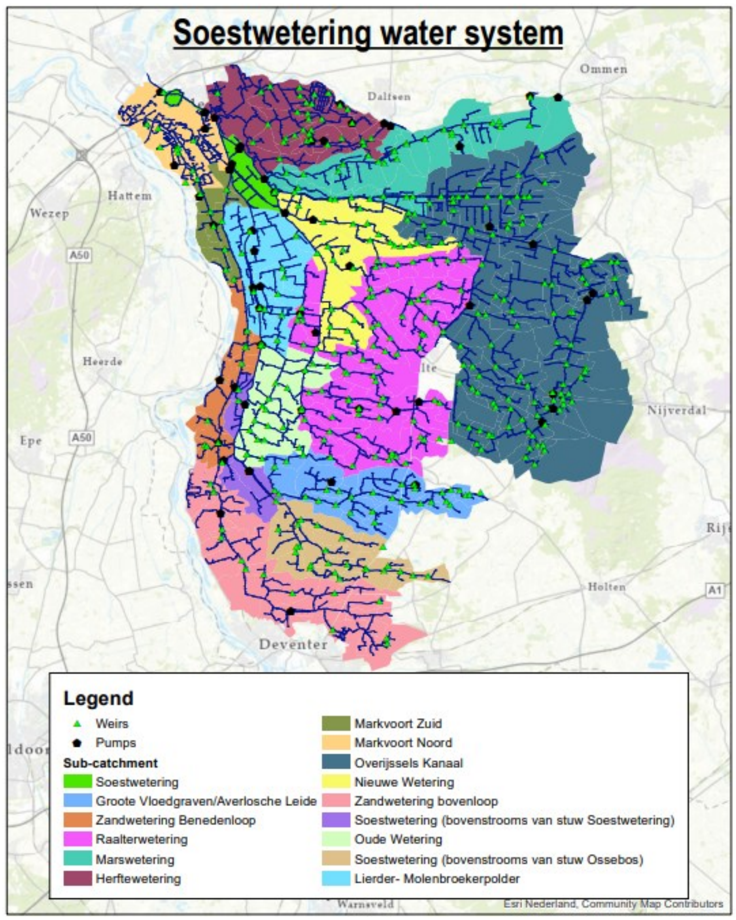

Figure 2 Overview of the Soestwetering water system.

Table 4 Used datasets and sources to establish the SOBEK2 and D-HYDRO models.

Purpose	Notes	Source
Bed levels for 2D	AHN3 is a Digital Elevation Model from 2014-2019. A spatial resolution of 5m was used to interpolate bed levels on the 2D grids.	AHN3
Establish model.	This dataset contains information on the water system (e.g. channels, structures, dimensions).	WDOD (registry and profile measurements)
Model simulation	Various measurement stations spread throughout the catchment for precipitation, evaporation, water levels and discharges. For calibration and validation specifically, discharges and water levels at certain locations of interest were used.	WDOD (water system measurements)
Friction based on land-use (2D)	This land-use classification was combined with a land-use friction table (Deltares, 2010) to provide spatial roughness.	LGN6

With respect to measurement data of the water system, five historic events were used in this case-study for calibration, validation and the analyses. These include the peak events in summer 2010, 2011 and 2017, and winter 2013 and 2020, and consist of measurements at meteorological stations, water level measurements throughout the system and a discharge measurement at Zwolle (outflow of the catchment). For more information on how these were used for calibration and validation, see Section 2.4.

To analyze the 2D features of D-HYDRO Suite 1D2D, several locations were chosen based on proximity to functioning measurement locations and likelihood to experience inundation (Figure 3). These include two water retention areas near Sekdoorn and the Zandwetering, as well as a location where in 2010 inundation occurred. These should provide insight in the ability of D-HYDRO Suite 1D2D to accurately simulate inundation and overland flow.

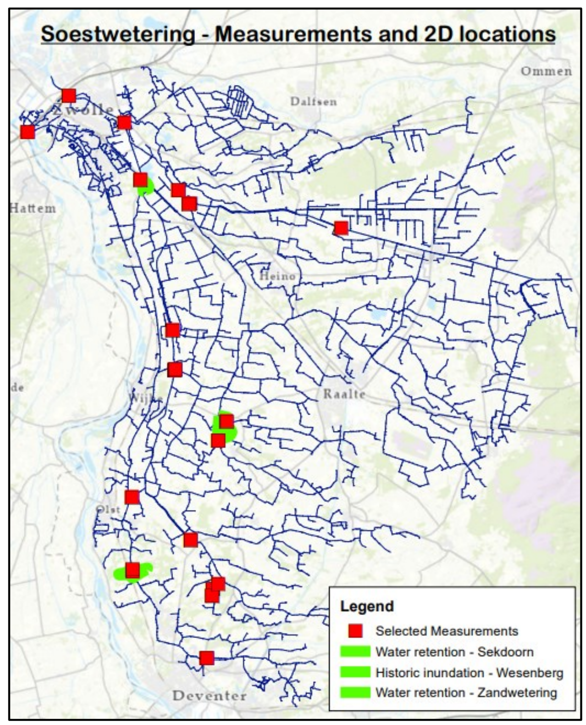

Figure 3 Overview calibration measurement locations and chosen locations to schematize in 2D (green).

It is important to note that the models will be established reflecting the most up-to-date data, which means they will represent the 2020 situation. Since 2010, several changes to the water systems have occurred (e.g. construction of several new weirs and water retention areas). However, their combined effect on the water system should not be significant enough to affect their usability for assessments in the scope of this study, as changes had mostly a local impact (WDOD, personal contact). For this reason and practical considerations, the choice was made to use the same water system schematization (2020) for all events.

2.3 Model simulations performed for controlled model comparison

In Section 2.1, an Assessment Framework was established which will be applied to evaluate model suitability for the WSA. This paragraph discusses how and which model simulations were performed to provide the necessary input for the comparative assessment using the Assessment Framework.

For the main comparison between SOBEK2 and D-HYDRO Suite 1D2D, historic peak events and a hypothetical extreme precipitation event will be used. In addition, various different model application decisions will be evaluated using slight alterations to the base models. The base models refer to the models established based on best-practices, and are used in the main analyses. A summary of all analyses performed can be found in Table 5.

Table 5 Simulations performed in this study.

Model Analyses	Research Objective (Question)	Notes (used model type)
Simulation based on historical data (main analysis)	Determine whether the model can well represent the water system (2)	2010, 2011, 2013, 2017 and 2020 events with base models (SOBEK2 (1D), D-HYDRO Suite 1D2D (1D) and D-HYDRO Suite 1D2D (1D2D)).
Simulation based on extreme event (main analysis)	Determine whether the model could be applied for extreme events (3)	Hypothetical T100 extreme rainfall event in accordance with STOWA precipitation statistics. (SOBEK2 (1D) and D-HYDRO Suite 1D2D (1D2D)).
Simulations with various grid characteristics	Determine influence of relevant 2D schematization choices (4)	Various resolutions of flexible meshes (max. 5, 10 and 15 meters cell size) and structured meshes (5 and 10 meters) simulated in a cut-out model for the 2017 event. (D-HYDRO Suite 1D2D (1D2D)).
Simulation with alternate set of numerical parameters	Determine influence of relevant model application choices (4)	Different set of numerical parameters related to computation time, most notably the online coupling time and wet/dry threshold using the 2017 event. (D-HYDRO Suite 1D2D (1D2D))
Simulation with online coupling RR / Flow	Determine influence of relevant model application choices (4)	Online computation of SOBEK2 run for 2017. (SOBEK2 (1D))

To answer research questions 2 and 3, both base models were simulated using the historic peak events and a hypothetical extreme event derived from normative conditions. Five locations of interest were chosen specifically to perform the comparative assessment based on either proximity to the locations of interest or being in a relevant location in the main water system (Figure 4). The discharge measurement at Zwolle (Keersluis Zwolle) captures the entire water system and can be used to evaluate general performance of the models. Water level measurements near Sekdoorn, Wesenberg and the Zandwetering will be used to quantify the local effect of nearby 2D grids, as well as a measurement representative of the lower reaches of the Soestwetering (Rietberg).

The total simulation period was at least three months for each, which gives between one to two months warmup time before the peak event. Afterwards, model performance was assessed in line with the Assessment Framework for the related model performance criteria, discarding the first two weeks of simulation as warmup. These consist of the VE, RVE, NSE, MAE and lag correlation metrics, as well as inundation maps for D-HYDRO and graphs of observed and simulated (SOBEK2 and D-HYDRO) water levels and discharges at the five locations of interest.

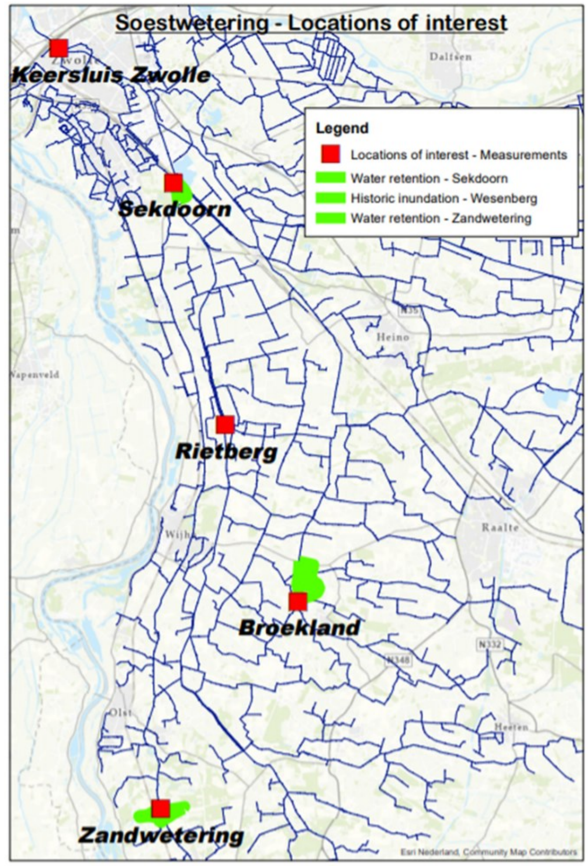

Figure 4 Overview of measurement locations chosen to use in assessment.

No observed data is available for extreme events (approaching normative conditions). To still assess model performance for extreme events, a hypothetical rainfall event was established derived from rainfall statistics. A rainfall event with a return period of 100 years was chosen in such a way that both short-term and long-term rainfall has a return period of 100 years. It should be noted that such an approach is not acceptable for actual assessment of water systems in the WSA (STOWA, 2011), but for the purposes of this analysis it is a practical method to quickly obtain an extreme event. This rainfall event was coupled with a preceding stationary rainfall (warmup) and used in the simulation of both models. The output of this simulation was used to obtain insights in whether the model is capable to reliably simulate extreme events. This includes qualitatively assessing if the simulated water levels, discharge, peak residence time in the water system and 2D flow dynamics are realistic, and whether extreme processes (e.g. drowning of weirs) are accurately accounted for.

2.3.1 Sensitivity of performance to model application decisions

To further shed light on D-HYDRO Suite 1D2D's suitability for the WSA, several additional features were investigated. Firstly, the grid characteristics will be discussed, after which the effect of several numerical parameters for the calculation time and quality will be analyzed. Finally, a short analysis on parallel coupling in SOBEK2 will be done to determine what the effect is.

Grid properties are a significant theme in literature. Various studies have showcased the importance of how a grid is established for both model accuracy and calculation time (Lai, 2010; Bomers et al, 2019; Voullième et al, 2012; Hardy et al, 1998). However, no generally applicable guidelines are provided for a standard reasonable mesh resolution. This is likely because required resolution is strongly dependent on the model purpose and spatial characteristics, which would make it difficult to provide generally applicable suggestions. To obtain insights in the effect of mesh resolution and shape of the cells, various configurations were tested in a cut-out version of the model near the Sekdoorn grid (Table 6). It is relevant to note that D-HYDRO Suite 1D2D also offers local refinement functionality and is able to calculate with various grid resolutions (e.g. high resolution at a location of interest, low resolution in the rest of the mesh). As the 2D locations investigated in this study were not expected to provide relevant insights in this functionality, this was not included in this analysis. For each of the grid configurations, the effect of the addition of the grid to the total calculation time and average timestep was determined. Furthermore, inundation maps were qualitatively assessed on inundation characteristics with experts from Arcadis to interpret the results.

Table 6 Grid configurations analyzed.

Mesh name	Maximum cell size (# of cells)	Cell shape	Notes
FM15	15 meters (1255 cells)	Triangular, unstructured	Aligned on spatial attributes
FM10	10 meters (2856 cells)	Triangular, unstructured	Aligned on spatial attributes
FM5	5 meters (10882 cells)	Triangular, unstructured	Aligned on spatial attributes
S10	10 meters (1341 cells)	Square, structured	Not aligned
S5	5 meters (5767 cells)	Square, structured	Not aligned

The base model of D-HYDRO is established in accordance with best practices. Various numerical parameters can play a significant role in the computation time of the model however, and could potentially reduce the calculation time. This may be interesting if results are not affected significantly. To test the effect of these, two parameters were changed with the intent of a fast run: the maximum allowed Courant number was increased from 0.7 to 1 (identical to SOBEK2) and the wet-dry threshold was increased from 1 cm to 2 cm. Computation time and resulting graphs at the five locations of interest for the 2017 event were compared between the base model and the "fast" model.

Lastly, SOBEK2 is usually applied with sequential coupling between RR and D-Flow FM (D-HYDRO Suite 1D2D currently always has online coupling with RR). To determine to what degree this may affect the results, the 2017 run will also be done in SOBEK2 with online coupling (interaction every minute instead of each hour) and resulting graphs at the five locations of interest and computation times will be compared between SOBEK2-sequential, SOBEK2-online and the (1D) D-HYDRO model.

2.4 Model description

In this paragraph, information will be provided on relevant model characteristics and how both tools were used to schematize the study area. First, the workflow used to establish a (1D) SOBEK2 and a (1D2D) D-HYDRO model will be presented. Afterwards, several differences between the model tools, their schematization and model application decisions which may be relevant for the study results will be discussed.

The SOBEK2 model forms the basis for the study and was developed by Arcadis using aforementioned data provided by WDOD and current best-practices, resulting in an up-to-date 1D model of the Soestwetering catchment. Using data from WDOD's registry, the Channel Builder and Catchment Builder tools (developed by Hydroconsult) were used to automatically generate a SOBEK2 network. This includes (1D) schematization of the Rainfall-Runoff module (hydrological) and the Channel-Flow module (hydraulic).

Afterwards, the SOBEK2 model was further improved using measurement data. Firstly, schematization errors were solved (e.g. incorrect weir dimensions) or more up-to-date information was used (e.g. cross-section measurements in Soestwetering). Secondly, the model calculation time was improved by solving bottlenecks for calculation time in the model. Most commonly, these were solved by improving local storage, reducing the sensitivity of local water levels to changes in discharge.

A split-sample approach was used for calibration and validation of the model, where 2013, 2017 and 2020 were used for calibration. The SOBEK2 model already performed quite well in initial iterations, so fairly little calibration was necessary (Arcadis, personal contact). The calibration process mostly consisted of changing the characteristics of the Rainfall-Runoff module (hydrological processes), including the drainage resistance and catchment characteristics (surface level). The goal of the (partial) calibration was to produce a model with correct model schematization representative for the water system in general, but not fully optimize it for a perfect fit or calibrate for local measurements or minor channels. Besides removing schematization errors from the hydraulic model (CF/D-Flow FM), no further calibration was done, as results were already deemed acceptable (Section 3.1). As such, the model was deemed of sufficient quality when discharges and cumulative discharges at Zwolle were similar (shape and amount), (peak) timing was clearly similar in locations of interest and water levels on various measurement locations were similar. In Appendix B, more information can be found on the specifics in the calibration process.

For the D-HYDRO model, the SOBEK2 model was imported in D-HYDRO Suite 1D2D. As the software is still in the beta phase, some minor adjustments or workarounds were needed to allow the model to run, none of which should affect the model output. Next, a short optimization procedure was performed for the D-HYDRO model as well (further discussed in Appendix B). This was done by finding significant bottleneck locations for the Courant number and either removing the calculation point or increasing local storage. It should be noted that the model could not be optimized for another limiting factor for calculation time (related to water balance errors), as these are not clearly reported in the used version of D-HYDRO Suite 1D2D. Also, initial conditions for the model were created using an Arcadis tool designed for D-HYDRO Suite 1D2D based on target water level in water level control areas. In some locations, these may differ (slightly) from SOBEK2, but after a brief warmup time, this should not affect the model output.

Finally, the 2D schematization was added to the D-HYDRO model. Initially, different triangular flexible meshes were developed for the three locations of interest, with maximum grid sizes of 5, 10 and 15 meters. To reflect realistic model application decisions, the choice was made for the lowest grid resolution that reasonably captures spatial characteristics, in this case a 10-meter flexible mesh. The influence of various mesh characteristics, including structured and unstructured meshes of various sizes, has also been explored (see Section 2.3). These grids were optimized using RGFGRID (a tool by Deltares to create and edit meshes) to meet D-HYDRO Suite 1D2D's orthogonality requirements, while attempting to maximize for smoothness. The bed level and spatial roughness datasets were interpolated on the grid using D-HYDRO Suite 1D2D's triangulation function (Figure 5). An important step in the 2D schematization process includes importing the fixed weirs. These were generated using the DEM files, and represent local elevations smaller than the grid resolution (e.g. small dikes, roads). With this addition, these local elevations are taken into account during the 2D computation, where otherwise simplification due to a coarse mesh resolution could lead to leakage or inaccuracies. In Figure 5, among others these account for the embankments besides the canal and local elevations not accurately captured by the 10m flexible mesh. As such, they can enable use of lower mesh resolutions while maintaining accuracy.

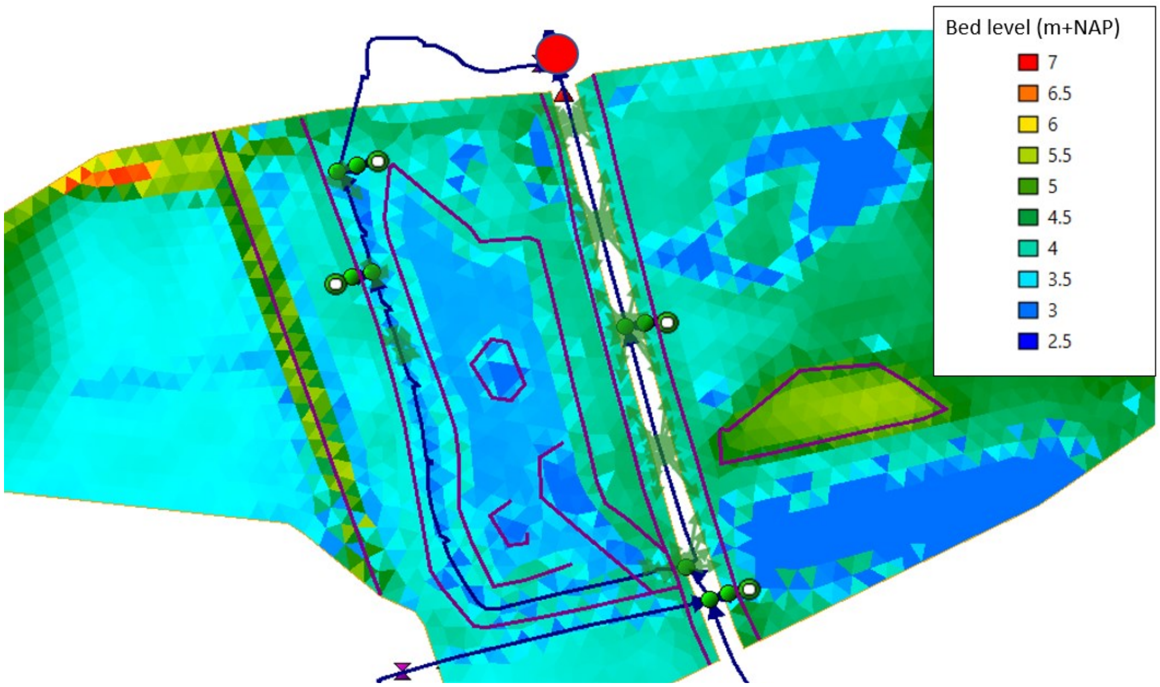

Figure 5 Zandwetering schematization used in D-HYDRO Suite 1D2D.

Blue arrows indicate the 1D water channels. Purple lines indicate the fixed weirs. Red dot indicates the measurement location. The retention area (left) is schematized both in 1D and 2D (max grid cell size of 10m).

1D2D connections between the 1D schematization and the 2D grids were established in accordance with Deltares' suggestions. This means that 2D grids in direct connection with the 1D system, such as at Sekdoorn, embedded 1D2D connections are used (to allow momentum to be properly transferred). Each 1D computational node was connected to all directly adjacent (<10 m) grid cells to allow interaction in all directions. For the other Zandwetering and Wesenberg locations, lateral 1D2D connections were established. As the "flow width" of the 1D2D connection is limited by the size its 2D grid cell, each 2D cell adjacent to the water channel is connected to the closest 1D calculation point. This way, flow across the entire length of the water channel is schematized. For a visual representation of the used 1D2D connections, see Figure 6.

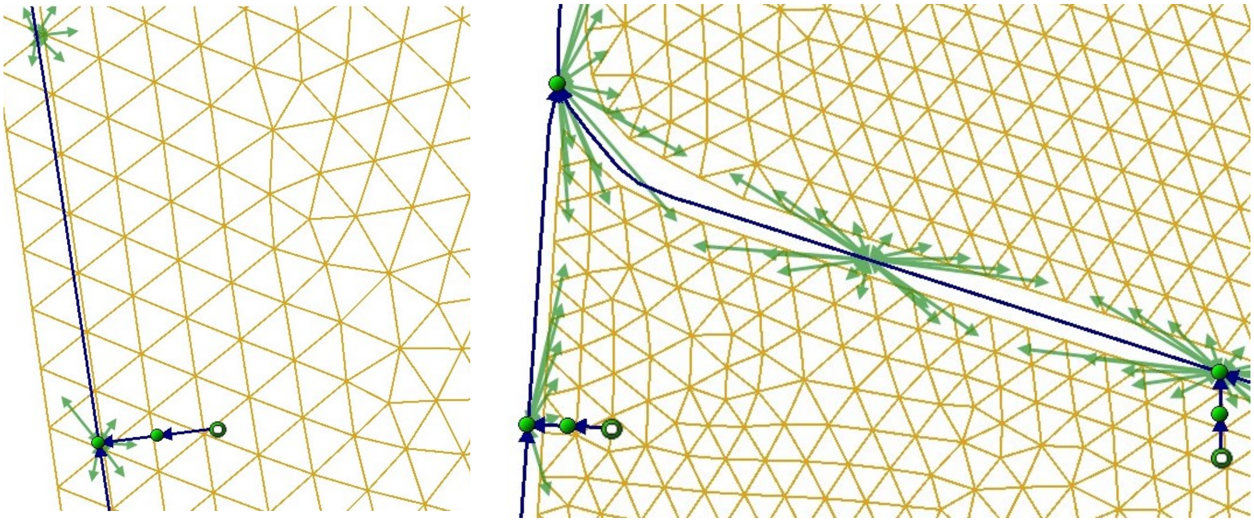

Figure 6 Embedded and lateral 1D2D connections in D-HYDRO Suite 1D2D.

Left: Embedded 1D2D connections where the 1D network overlaps with the 2D grid. Right: lateral connections where the 1D network does not overlap with the 2D grid. Blue arrows indicate the 1D water channels, green arrows indicate the 1D2D connection.

2.4.1 Relevant model differences

Between SOBEK2 and D-HYDRO Suite 1D2D, several differences in schematization or available features could be relevant for the model output. These include the 1D representation of 2D characteristics, 2D schematization in D-HYDRO Suite 1D2D, sequential and parallel coupling between the hydrological and hydraulic models, optimization choices and technical limitations.

In reality, storage of water cannot only occur within the water channels, but also on land (through inundation). To account for this, both the SOBEK2 and D-HYDRO models use virtual dummy branches, each representing a small area of the catchment (sub-areas of water level control areas), where cross-sections are derived from the SCS curves. For example, a dummy branch with a very large width in the top of the cross-section could indicate that in that specific area, a lot of inundation can occur outside of the water system. For locations which are schematized in 2D in the D-HYDRO model, the schematized storages are removed from dummy branches by deleting the cross-section, preventing double storage in these locations.

Another important difference is the coupling between the hydrological (RR) and hydraulic (CF and D-Flow FM) modules of SOBEK2 and D-HYDRO Suite 1D2D. In accordance with current best-practices, SOBEK2 uses sequential coupling. This means the hydraulic module does not have an effect on the hydrological module (and thus on the runoff entering the hydraulic model). D-HYDRO Suite 1D2D currently only offers the option for online coupling. Still, interaction intervals can be user-defined. As RR data is only calculated once every hour, the choice was made for a 1-hour interaction interval. To assess the consequences of this difference, an additional SOBEK2 computation on the 2017 event will be made using online coupling.

With respect to the optimization process, two relevant choices were made. Firstly, the SOBEK2 model used in this study employs Preissmann slots: an extra narrow gully in the lowest parts of cross-sections (middle of the channel), which artificially increases the water-depth in channels. For the numerical computation, this reduces instability caused in SOBEK2 due to very low water levels (e.g. in dry channels). In the used (1D2D) D-HYDRO model schematization, these Preissmann slots are removed, as they do not improve stability but instead slow down the calculation due to the high flow velocities in the very shallow parts (Deltares, personal contact). Secondly, a wide variety of numerical parameters can be tweaked in D-HYDRO Suite 1D2D. For parameters available in SOBEK2 (e.g. stop criterium for non-linear iteration), these were set identical to SOBEK2, unless Deltares recommended otherwise (e.g. the maximum Courant number). For other parameters, either the D-HYDRO default was used or Deltares' recommendations were followed. To study the effect of several important parameters, an additional analysis was performed (Section 2.3.1).

A minor difference is that initial water levels for the D-HYDRO model were generated using an Arcadis tool based on target water levels in the related water level control area, which may differ slightly from SOBEK2. After a brief warmup time, these should not affect the results.

Lastly, one issue for which no solution could be found is that open water (total 2.8% of the catchment area) cannot yet be schematized in D-HYDRO Suite 1D2D. After a brief lookup in SOBEK2, it was determined that the sum of seepage, precipitation and evaporation for these open water catchments generally results in a net inflow of water, which means the D-HYDRO model should generally have a lower inflow of water. The magnitude of this error may not be completely negligible however, potentially being between 0-8% of the cumulative discharges.

All in all, both models were established using realistic model application decisions. For the most part, the two models are identical (e.g. schematization, 1D model parameters, pump settings), keeping the comparison fair. For the differences that do exist, primarily due to different suggested model application decisions for the two tools, a summary is presented in Table 7.

Table 7 Differences between the SOBEK2 and D-HYDRO models.

Difference	Explanation
2D schematization	D-HYDRO Suite 1D2D's new features include a flexible mesh functionality where 2D grids can be included in the model. As in future applications of D-HYDRO Suite 1D2D, these 1D2D models are expected to be the new standard, they are included in the model (albeit on a small scale), so they can be evaluated in the context of the WSA. Storage in 1D meant to represent 2D storage was removed for locations schematized in 2D to prevent double storage.
Sequential and parallel coupling with RR	In a sequential run, there is no feedback from the hydraulic (CF/D-Flow FM) to the hydrological (RR) module (which is faster). D-HYDRO Suite 1D2D only computes online (which is more realistic). The interaction interval between the Flow and RR modules has been manually set to be identical to SOBEK2.
Preissmann slots	In SOBEK2, artificial Preissmann slots are included to reduce model instability. For D-HYDRO Suite 1D2D, they actually increase calculation times, and are therefore removed.
Numerical parameters	Followed Deltares' best practices and recommendations for D-HYDRO parameters. Unless suggested otherwise, parameters used in SOBEK2 and D-HYDRO models are identical.
Initial conditions	Due to practical considerations, the D-HYDRO model uses slightly different initial water levels compared to SOBEK2. As the simulation for all events include a warmup time of at least one month, this should not affect the quality of the model output.
Open Water Catchments	D-HYDRO Suite 1D2D does not yet support open water catchments. This means 2.8% of the catchment area is neglected during the calculation, which should generally result in a lower inflow of water from RR into the flow model for the D-HYDRO model.

3 Results

In this chapter, the results of the various analyses will be discussed. Firstly, the results of calibration and validation of the (1D) SOBEK2 and D-HYDRO models will be discussed (Section 3.1). Secondly, relevant findings of the model simulations will be presented (Section 3.2). Thirdly, in Section 3.3 the reflection of (hydrological) experts on the findings of the study and how they relate to WSA-suitability will be considered. Finally, the results obtained from the model simulations and expert-elicitation session will be applied to the established Assessment Framework to make a comparative assessment of SOBEK2 and D-HYDRO Suite 1D2D in the context of the WSA in (Section 3.4).

3.1 Calibration and validation

Calibration of the SOBEK2 model was done with the intent of providing an acceptable hydrological and hydraulic model representation of the Soestwetering catchment. The D-HYDRO model was assumed to have similar calibration values compared to SOBEK2, although it may be that due to computational differences, these may not be 1-on-1 transferable. Extensive calibration was beyond the scope of the SOBEK2 model and the D-HYDRO model for this study, and assessment of whether the calibration was sufficient was done qualitatively by an expert from Arcadis.

The validation was performed with the (1D) D-HYDRO model for two reasons. Firstly, it provides insight in whether the results are similar to SOBEK2, as besides several minor changes, both models should be identical. Secondly, the (1D) D-HYDRO results provide a reference for the (1D2D) D-HYDRO results. Five measurement locations were chosen to perform the assessment based on their proximity to the 2D locations of interest and relevance for the entire water system (main Soestwetering channel and outflow point of entire catchment). An overview of the location of these measurement locations can be found in Figure 4.

In Figures 7 and 8, the simulated and observed discharges at Zwolle (outflow of the catchment) for the main calibration event (August 2017) are shown, while Figures 9 and 10 show the simulated and observed discharges for the 2011 validation event.

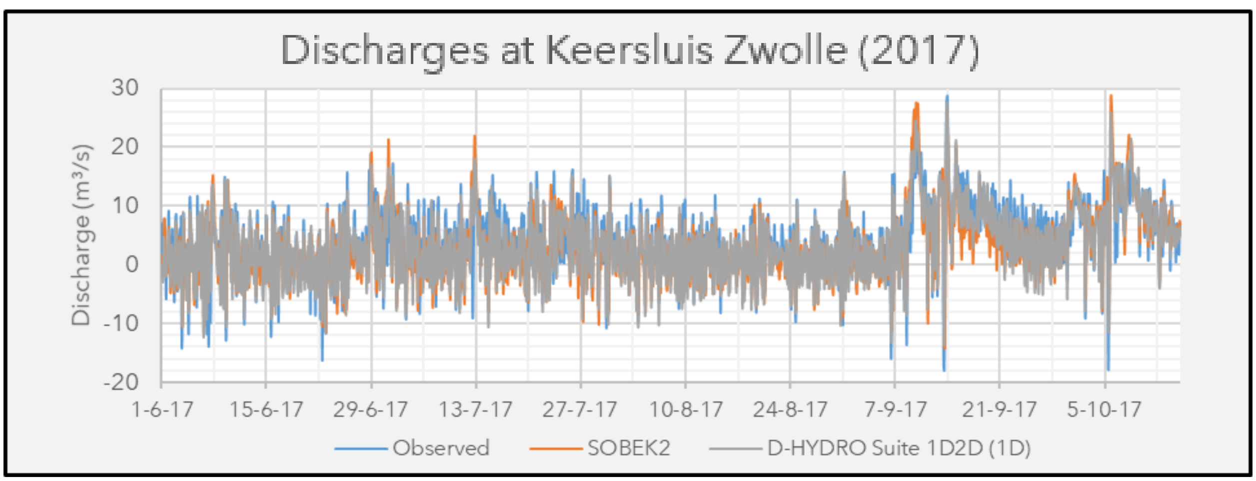

Figure 7 Discharges at Keersluis Zwolle for the 2017 calibration event.

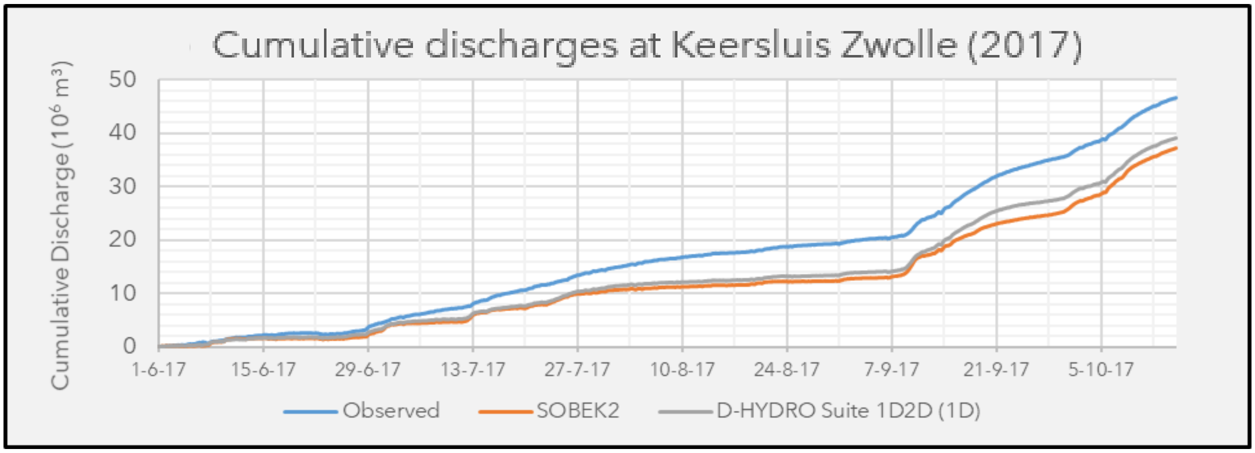

Figure 8 Cumulative discharges at Keersluis Zwolle for the 2017 calibration event.

From the calibration and validation results, both SOBEK2 and (1D) D-HYDRO seem to provide a reasonably realistic representation of the Soestwetering catchment and show a clear correlation with observed values, among others displaying correct peak timing, similar cumulative discharge curves and similar peak flows. For a partially calibrated model, this fit was deemed appropriate for this stage of model development (Arcadis and WDOD, personal contact).

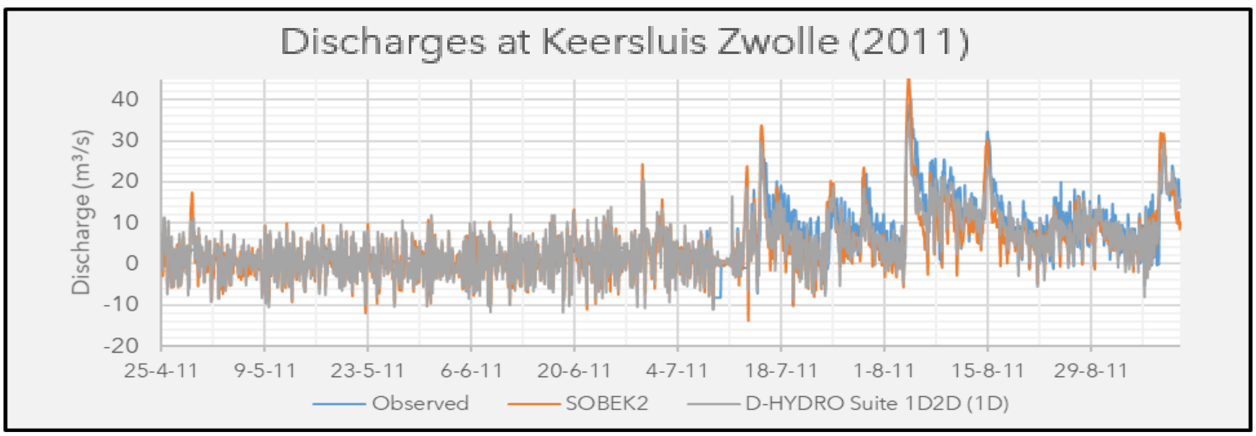

Figure 9 Discharges at Keersluis Zwolle for the 2011 validation event.

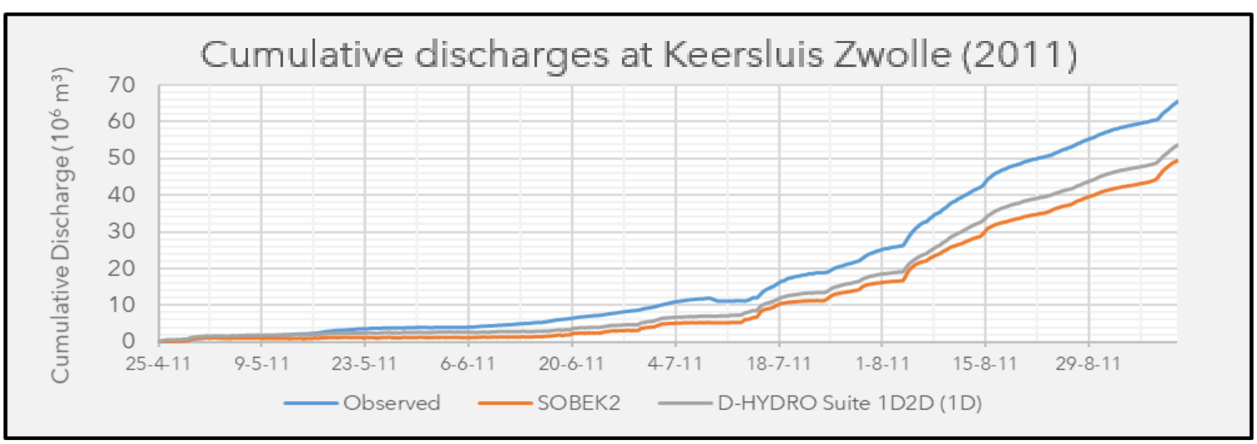

Figure 10 Cumulative discharges at Keersluis Zwolle for the 2011 validation event.

However, it is clear further optimization and calibration could be done for both models, and their current state would be insufficiently reliable for WSA purposes (Arcadis, personal contact). In addition, clear differences between simulated values of both tools can be observed in both discharges and cumulative discharges. These differences may be partially attributed the parallel coupling of D-HYDRO Suite 1D2D (instead of the sequential coupling in SOBEK2), as well as the absence of precipitation and evaporation on open water, which is not supported in the current version. As discussed previously, the latter should not have a significant impact on model output (max. 8% of cumulative discharges). For example, if it would be assumed that the sum of evaporation and precipitation on open water would be 100 mm for the computational period, this would be equal to 3.6% of the cumulative discharges (0.14*10^7 m³). This error is of similar scale to the observed error, but on the other hand one would expect both higher peaks in the D-HYDRO values and lower cumulative discharges (which does not seem to be the case).

Another important observation is that both tools are not providing accurate values for any of the calibration of validation events for one location of interest. This location is the Broekland measurement station near the Wesenberg (2D location of interest where inundation was observed in 2010). Simulated water levels are inaccurate, both tools are overestimating water level peaks compared to observed values, and certain observed peaks are not simulated at all. Two examples of simulated and observed values are shown in Figure 11 and 12.

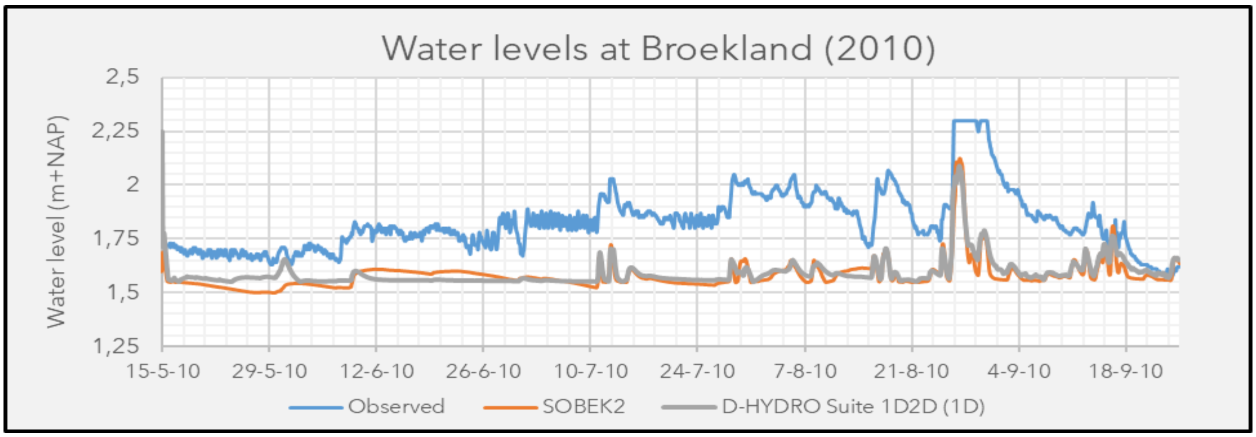

Figure 11 Water levels at Broekland (2010). Both models greatly underestimate water levels.

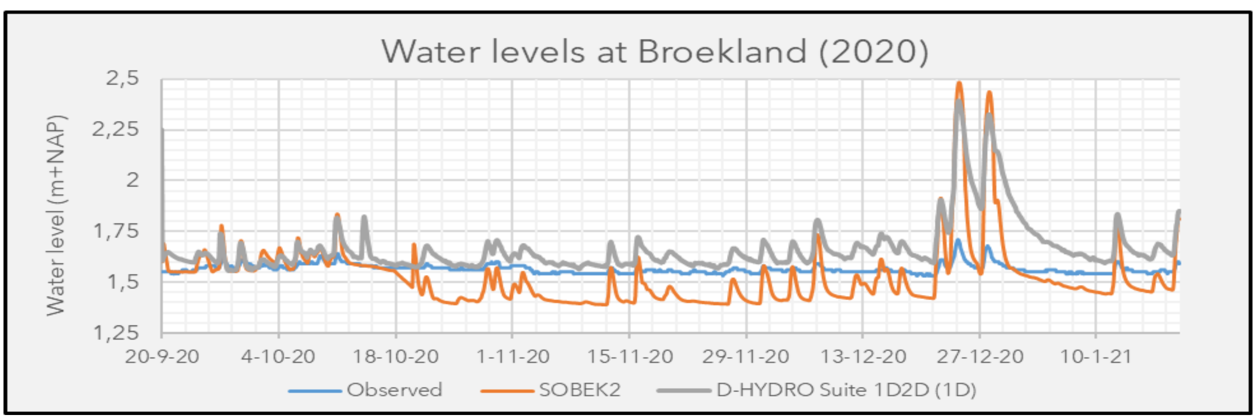

Figure 12 Water levels at Broekland (2020). It is clear the models do not provide an accurate representation.

Especially the 2010 water levels are relevant, as it is clear the peak event was not simulated by either model and this was the event where historic inundation occured. Note that the water levels exceeded the maximum measurable value (2.3 m+NAP), which is why the observed values seem to be cut-off. The results at this location point towards a likely schematization error, as the water levels under normal conditions differ considerably and seem to have a different target water level (e.g. potentially a weir or pump operation scheme error). As this location was not critical for the water system as a whole, the choice was made not to calibrate further.

In conclusion, the calibration and validation results for (1D) SOBEK2 and (1D) D-HYDRO were sufficient to perform the various analyses in this study with. These were performed using the (1D2D) D-HYDRO model rather than the 1D model, to investigate a potential future application of the tool where the majority of the system is schematized in 1D, and several locations of insight are schematized in 1D2D. A (small) verification step was included for the 2D schematization to verify that the 1D2D connections and grid were correctly schematized (e.g. inundation when water levels exceed bed levels, flow in a realistic direction). This can be seen in Figure 13 for the Sekdoorn location, and shows that flow seems to be realistic, as it both prefers the lower lying areas and uses the 2D grid as a wider flow profile in the dominant flow direction.

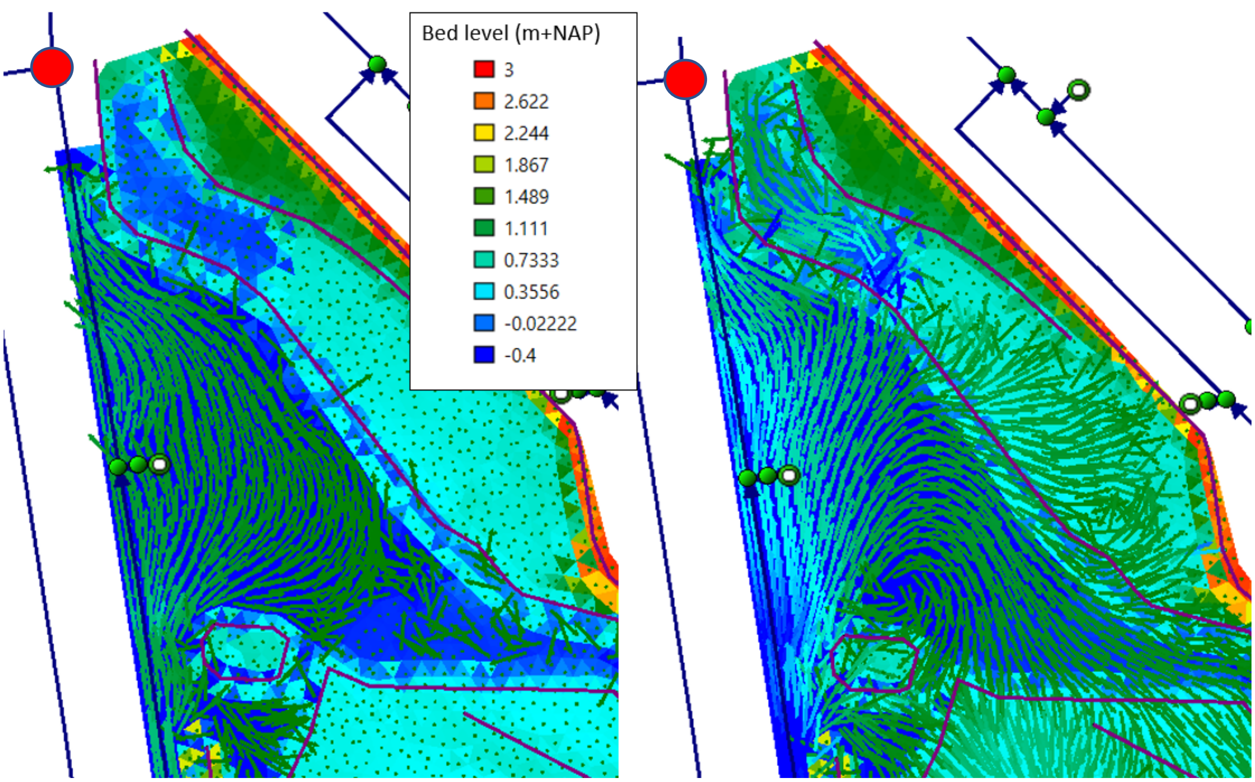

Figure 13 Verification step of the 1D2D model using the Sekdoorn grid. Arrows indicate flow direction and speed. Red dot represents the Sekdoorn measurement location.

Left: Flow through the 2D grid under normal conditions. Right: Flow through the 2D grid at the beginning of peak. flow.

3.2 Simulation results

To be able to assess (1D) SOBEK2 and D-HYDRO Suite 1D2D in the context of the WSA and apply the established assessment framework, several analyses were performed to obtain insight in the model accuracy, usability and applicability.

The accuracies of both tools were assessed using various indicators related to relevant criteria for WSA reliability. For the main analysis, five historic events were simulated in SOBEK2 and D-HYDRO and these indicator values were calculated (Table 8). For the NSE and MAE, the water levels at Rietberg are used, as results here were representative for both models in all events, and the VE and RVE were calculated with discharges at Zwolle. In addition, graphs were made for the (cumulative) discharges at the catchment outflow point in Zwolle and water levels at the chosen locations of interest, which were used to provide additional context to the performance indicators.

Table 8 Model performance indicators (blue =SOBEK2, white = D-HYDRO Suite 1D2D).

Indicator	2010S		2011S		2013W		2017S		2020W	
VE	0.17	0.12	0.28	0.32	0.57	0.65	0.32	0.48	0.56	0.61
RVE	-0.45	-0.41	-0.24	-0.18	0.06	0.03	-0.20	-0.15	0.31	0.26
NSE	0.83	0.86	0.85	0.91	0.80	0.69	0.89	0.89	0.34	-0.06
MAE	0.06	0.06	0.04	0.03	0.06	0.09	0.03	0.03	0.12	0.15
RB	-0.24	-0.18	-0.45	-0.41	0.06	0.03	-0.20	-0.15	0.31	0.26

With respect to the model performance indicators, likely the most relevant observation is that SOBEK2 and (1D2D) D-HYDRO generally perform similar . Therefore, it could be assumed that if the SOBEK2 model could be calibrated to a sufficiently good quality for a WSA, D-HYDRO could be as well. An outlier of the VE is for 2010 (0.17 for SOBEK2, 0.12 for D-HYDRO Suite 1D2D), which is significantly lower compared to other years, indicating that discharges were simulated less accurately. A possible explanation for this is that unlike a 2-hourly update of the measured discharges at Zwolle, in 2010 these were daily averages (Figure 14). As the VE represents the portion of discharges arriving at the correct time (and does not cancel out), a large mismatch between the simulated and observed timescales will introduce an error, especially during a peak (where 2-hourly values are very different from averages). However, from the graph it also becomes evident that the worse performance cannot fully be explained by the timescale mismatch, as the peak size and shapes differ significantly as well. It should also be noted again that both models were established to reflect the 2020 water system. Although it was stated earlier that the changes between 2010 and 2020 should not significantly affect the model performance, it could be expected that the schematization used in the models is least representative for the 2010 event.

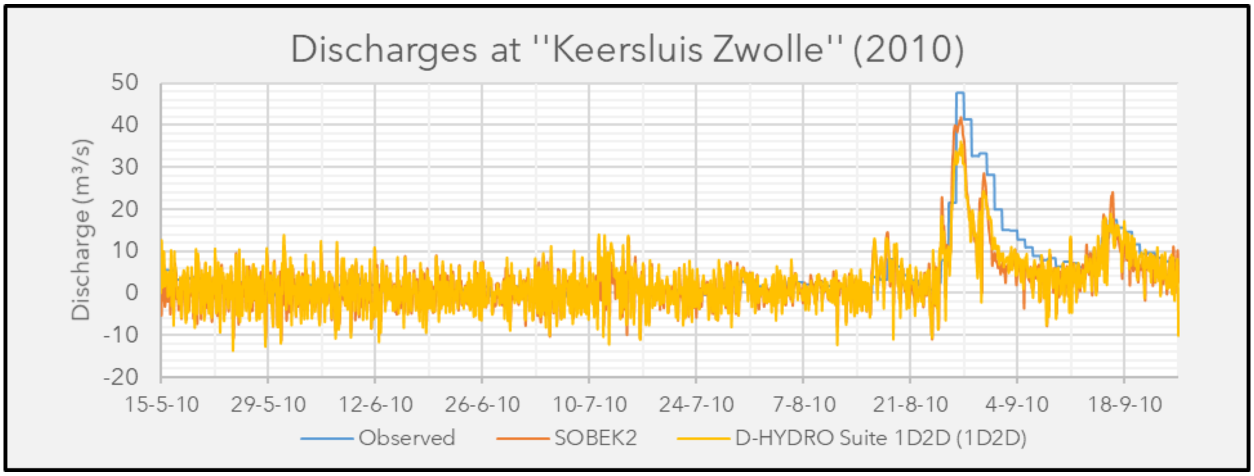

Figure 14 Discharges at Keersluis Zwolle (2010). While both models are relatively accurate during normal conditions, clear differences can be observed with the discharge peak.

For the RVE, it can be observed that 2013 was a particularly good year where both SOBEK2 and D-HYDRO were in good agreement with the cumulative discharges (0.06 and 0.03 respectively), but other years show quite significant discrepancies. Because of the magnitude of the differences between the observed and simulated cumulative discharges (up to 45%), there are some doubts on whether the discharge measurements at Zwolle are trustworthy (WDOD, personal contact). NSE values of the simulated water levels show a good agreement with the observed values (generally above 0.8), with the exception for 2020, where NSE values were 0.34 and -0.06 for SOBEK2 and D-HYDRO respectively. In this case, both SOBEK2 and D-HYDRO systematically over-estimate the water levels (Figure 15). Potentially with further calibration, these results can be significantly improved, as the simulated values in other events do have good agreement. With respect to the MAE, water levels deviate between 3 and 9 cm generally, with a large outlier in 2020, where water levels were much higher, which could be explained similarly to the NSE value.

Peak timing was correct for most simulations, as the NSE values for water levels at Rietberg (representative) did not improve for 2010, 2011, 2017 and 2020, and only improved slightly for 2013 (0.68 to 0.70) when assuming a time lag of 2h (smallest possible, as the model timestep was 2 hours). This was observed by shifting the simulated time series 2 hours forward (e.g. the output at 8.00 to 10.00). As such, simulated timing of high and low water levels was within 2 hours of the observed peak timing.

With respect to model robustness, drawing hard conclusions is difficult as the model is not fully calibrated. Both the SOBEK2 and D-HYDRO models are significantly underestimating (cumulative) discharges for the summer events. On the other hand, NSE values for the summer events are generally better than the winter events. It does seem that in summer, discharges are generally underestimated and water levels are relatively accurate, while in winter, discharges are relatively accurate, but water levels are overestimated. When considering the discharges, this is also reflected by the relative bias in Table 8. The inaccuracies of both tools compared to simulated values are likely related to two different (schematization or measurement) issues, as they cannot be explained by the same cause. For example, it may be that for summer events, the hydrological schematization is incorrect (and too little surface-runoff occurs), while for winter events, the friction value is overestimated (increasing water levels at the same discharges). However, with the models not being calibrated fully, it is impossible to pinpoint the exact cause of these inaccuracies.

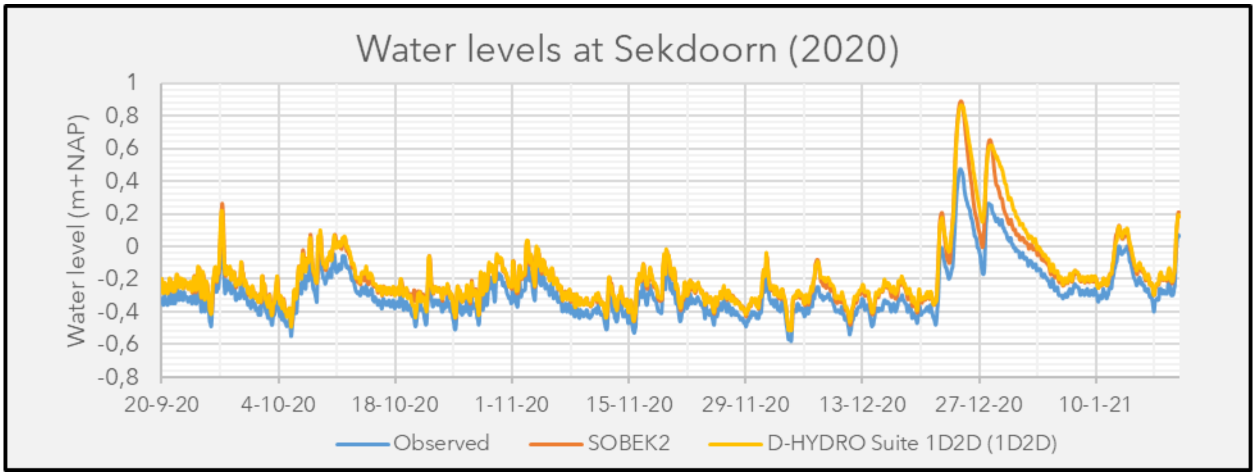

Figure 15 Water levels at Sekdoorn (2020). Both models are systematically overestimating water levels.

Another element of model robustness was whether the model was still working reliably during the extreme event simulation, which was briefly investigated in this study. From the results, computational time was similar to other D-HYDRO runs. Peak discharges at Zwolle for the T100 precipitation event were within realistic margins (52 m^3/s) when compared to a T200 event which reported 75 m^3/s (Infram, 2018). With respect to residence time of the peak, maximum discharges at Zwolle were simulated to occur 16 hours after the hypothetical extreme rainfall event (T100), and the total peak residence time was around 6 days, which would be realistic for a system as large as the Soestwetering (Arcadis, personal contact). With respect to 2D inundation characteristics, these were as expected (more inundation, faster flows during the extreme event). Whether the system reliably accounts for extreme processes (e.g. drowning of weirs) was not possible to accurately verify, as the used 2D schematization wasn't designed to account for these processes.

Another topic investigated during the analyses was the additional value (1D)2D modelling could provide. Based on the observations however, it seems the addition of 2D schematization to the Soestwetering 1D model does not seem beneficial. The new insights this schematization provides are limited for the chosen case study, and there are significant practical considerations for the chosen 2D schematization approach. If 1D2D modelling would effectively be applied, the benefits of improved model accuracy of new insights should outweigh the costs (e.g. more schematization time). This tradeoff and the potential new insights 1D2D modelling could offer were also considered in the expert elicitation session (Section 3.3).

When analyzing the differences between the (1D) D-HYDRO model (used in calibration and validation) and the (1D2D) D-HYDRO model, overall results were nearly identical and accuracy does not seem to have clearly improved. In addition, of the three locations which were chosen to schematize in 2D due to the expectation that inundation would occur, only the Sekdoorn grid was working as expected, displaying (realistic) 2D flow patterns which account for spatial characteristics and inundation in areas where it could be expected.

For the Sekdoorn 2D location, the actual difference between schematization in (1D) D-HYDRO (using the virtual dummy branches) and (1D2D) D-HYDRO (with a grid and fixed weirs) seems to be small. It should be noted that the storage of the retention area was also included in the 1D schematization in the cross-section (1D storage). As such, the difference between 1D and 1D2D should not be in the available storage, but rather more accurate dynamics in the retention area. Figure 16 and 17 provides insight in how the simulated water levels and discharges differ at the closest measurement point to the Sekdoorn location. As can be seen, differences in water levels are very small (<3 cm difference). Discharges do differ quite substantially with up to 3 m³/s difference, which compared to simulated peak flow of 14 m³/s is quite significant. However, no clear pattern can be observed for the discharges (e.g. 1D2D displaying lower discharges during peak events). In addition, it should be noted that no discharge measurements are available at this location, which make it more difficult to determine which is more accurate.

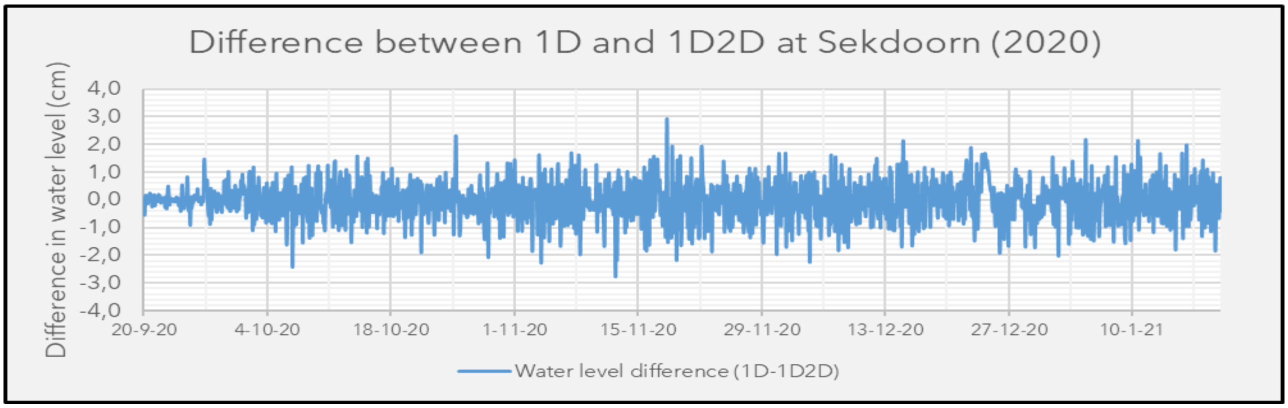

Figure 16 Water level differences between the 1D and 1D2D D-HYDRO models.

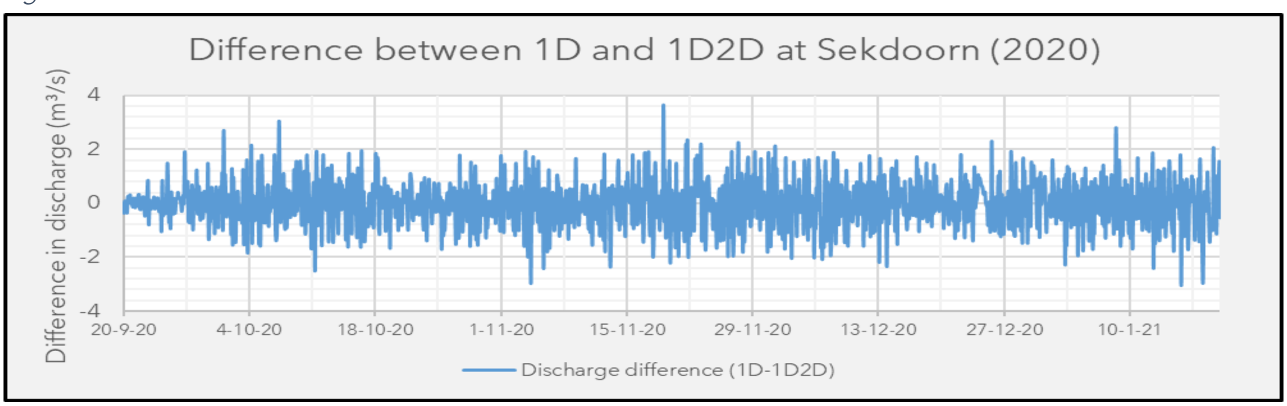

Figure 17 Discharge differences between the 1D and 1D2D D-HYDRO models.

From the water levels (Figure 18), it could be observed that the water levels seem slightly smoother for the 1D2D model compared to the 1D model, generally averaging between the peaks and drops of the 1D values. This effect is minimal, but it might also indicate a more accurate representation of the hydraulic effect of the water retention area in direct connection with the Soestwetering (buffer effect). In contrast, discharges do seem to be more affected, where part of the buildup seems to be attenuated by the 2D grid, and the decrease of the peak flow seems smoother (Figure 19)

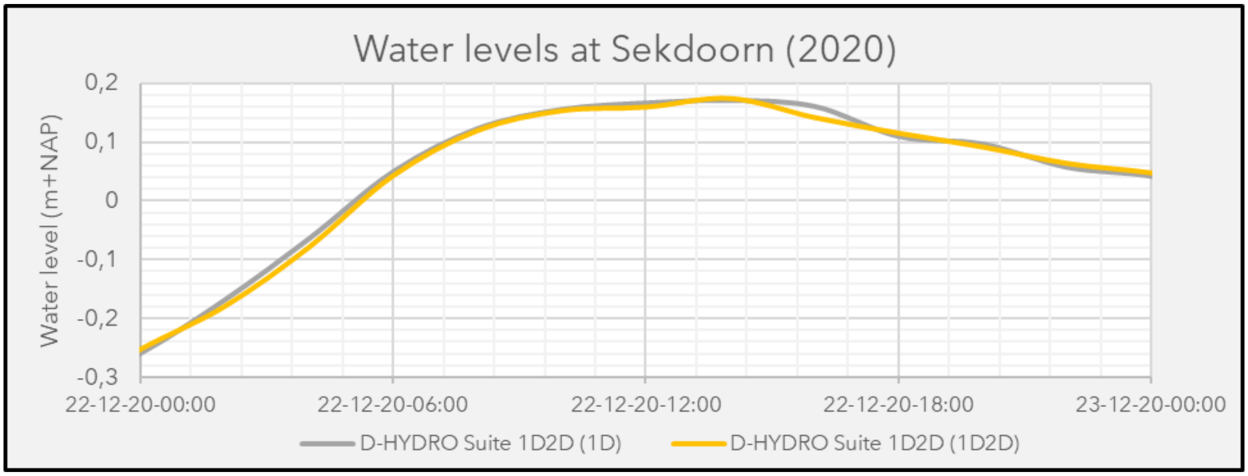

Figure 18 Water levels at Sekdoorn during a peak flow.

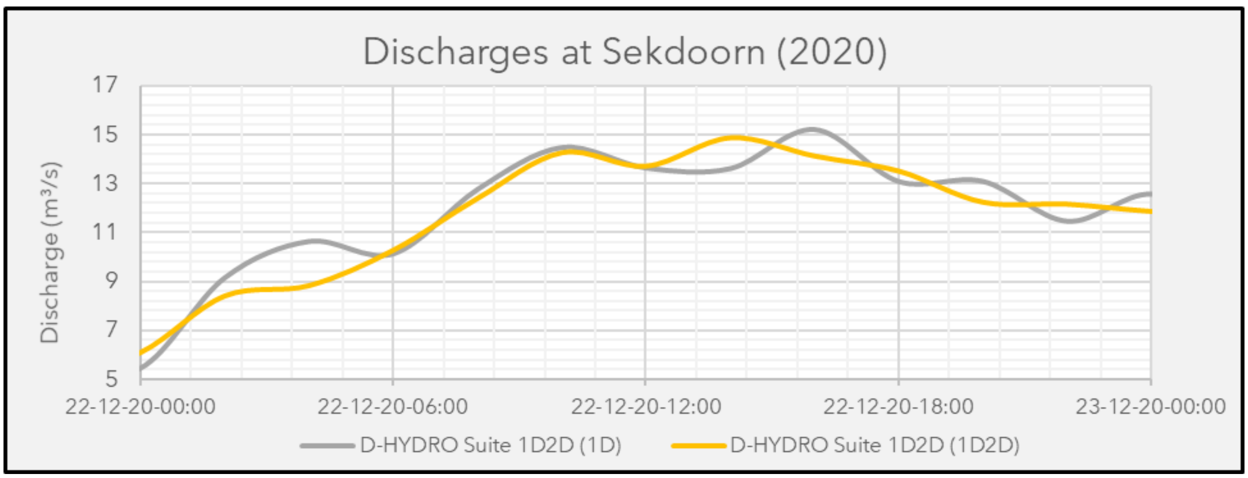

Figure 19 Discharges at Sekdoorn during a peak flow.

The Wesenberg location experienced inundation at two locations in the 2010 event (Figure 20) when water levels surpassed the bed levels (>2.25 m+NAP). However, during the 2010 1D2D simulation, no inundation occurred. As previously discussed, the model does not simulate accurate water levels at this location (Broekland), with a maximum peak in 2010 of 2.1 m+NAP (Figure 11). Therefore, in the 2010 simulation, no inundation could occur in the 2D grid. In the 2020 winter event however, incorrectly simulated water levels did exceed 2.25 m+NAP, resulting in inundation on one of the two locations reported to have inundated in 2010. The quantitative difference between the peaks of the 1D and 1D2D D-HYDRO models is again quite low with 2 cm (Figure 21), although the 1D2D model does show more attenuation, where water levels rise slower and the peak is slightly wider. This can more clearly be seen in simulated discharges further downstream. As there are no discharge measurements here, it is difficult to say which is more accurate, but there seems to be an attenuating effect due to the 2D flow (Figure 22).

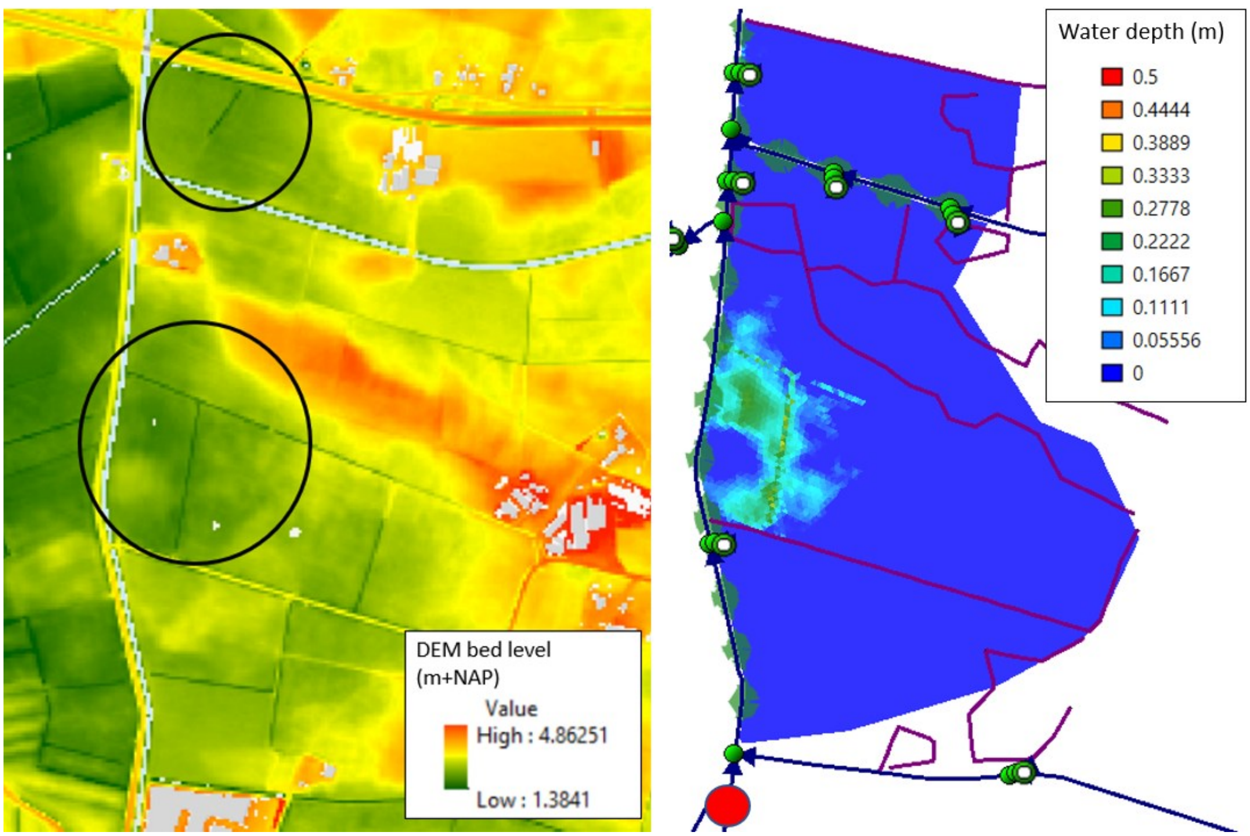

Figure 20 Wesenberg inundation.

Left: DEM of the Wesenberg location. Circles indicate the location where inundation occurred in 2010. Right: D-HYDRO Suite 1D2D simulated inundation for the 2020 event. Red dot indicates the Broekland measurement station.

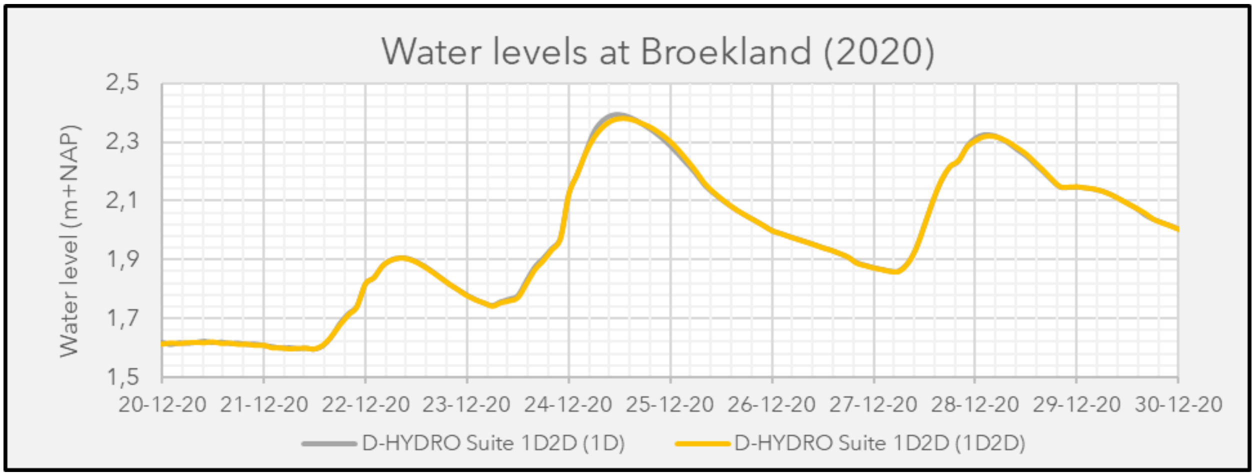

Figure 21 Water levels downstream of the inundation location at Broekland (2020) during two peaks.

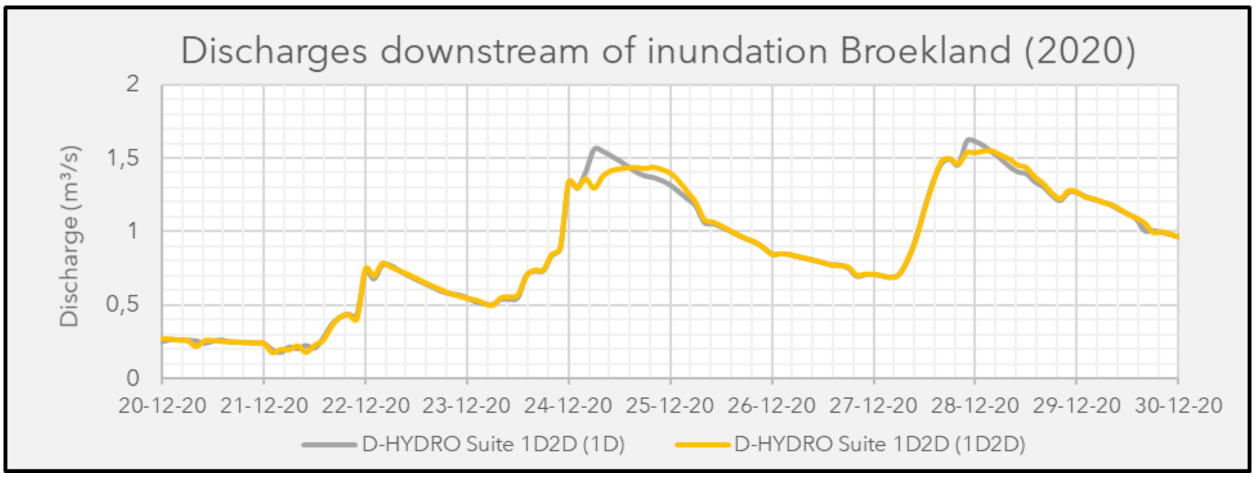

Figure 22 Discharges at Broekland (2020) during two peaks.

The third grid location, the Zandwetering, had no inundation or flow through the 2D grid. This seemed to be caused by insufficient quality of spatial data. From even the high resolution DEM files (50x50 cm), the bed levels of the relatively overgrown retention area are stated to be around 3.2 m+NAP at minimum. However, when assessing the 1D schematization, the bed level of the channel running through the retention area was 1.4 m+NAP. During the simulation, water remained within the 1D grid, as bed levels in the 2D grid were too high. Measured values also indicate that water levels generally remained below 3m+NAP except for 2010, and in the simulations, water levels also remained below 3.1 m+NAP during all events. Instead of (partial) inundation of the 2D grid, this resulted in virtually no inundation or flow from 1D to 2D (Figure 23). As such, it seems that the DEM files used are of insufficient quality and overestimate the bed levels in this location, and more accurate spatial information would be necessary for a realistic 2D representation of the retention area.

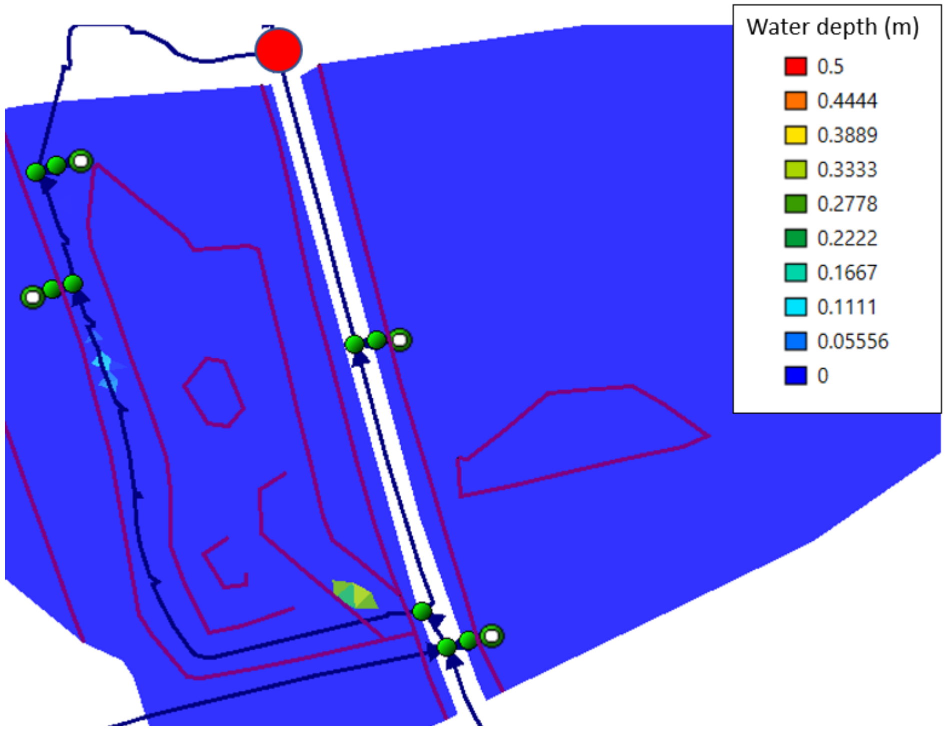

Figure 23 Simulated inundation at the Zandwetering grid during the peak flow (2020). As can be seen, only a few cells in 2D are active (all flow is through 1D). Water levels in the 1D network do not exceed the schematized bed level in 2D.

Besides model accuracy, an important part for usability is the computation time of the simulations. To provide a clearer overview of the results in this case study and allow for better comparison, this includes the computational speed (simulated model hours per calculation hour) and the average timestep, as well as the calibration and validation results for the (1D) D-HYDRO model. The latter is included to also highlight the effect of the used 2D schematization for this case study. In Table 9, the results are presented for the analyses performed.

Table 9 Computational speed of the model. D-HYDRO (1D) results from calibration and validation were included to provide a reference for 1D2D results.

Event year	SOBEK2 (simulated hours/hour)	D-HYDRO (1D) (simulated hours/hour and average timestep)		D-HYDRO (1D2D) (simulated hours/hour and average timestep)	
2010	206	177	48s	98	16s
2011	228	186	48s	99	17s
2013	237	192	49s	101	17s
2017	272	178	59s	106	18s
2020	195	148	34s	100	19s
Extreme (T100)				113	21s
2017-Numerical				115	24s

It shows that both the 1D and 1D2D models of the D-HYDRO Suite 1D2D version used in this study have a lower computational speed compared to (1D) SOBEK2 in these analyses. The addition of three relatively small 2D grids (total 20,310 cells) compared to the entire water system did create a significant slowdown, with the 1D2D model being between 1.5 and 1.8 times slower than the 1D model (which consists of 20,177 computational 1D nodes). When analyzing Table 9, it seems this slowdown is most likely caused by a significant decrease in the average timestep.

It should also be noted that these results are likely not representative of how D-HYDRO Suite 1D2D will be applied in the future. Due to an existing bug in the software, the maximum timestep (numerical parameter) was set to 60 seconds, which effectively slows down the model if the model could run smoothly with larger timesteps. For reference, the timestep of SOBEK2 was also maximized at 60 seconds, which was chosen to reduce instability and allow the model to run smoothly (Arcadis, personal contact). During initial testing with the 2017 (1D2D) D-HYDRO model, the limit of the timestep was set to 80, D-HYDRO would compute 340 model hours per hour on average, indicating the ability to be significantly faster. Moreover, an older version of D-HYDRO Suite 1D2D was used (0.9.7.51931), because the newer version (0.9.9.52575) was unable to run for the 1D2D Soestwetering model. As such, various improvements to the computational speed of D-HYDRO Suite 1D2D in newer versions were not included in these analyses. For the official release version of D-HYDRO Suite 1D2D, it is the expectation that calculation speed for 1D models is as least as fast as SOBEK2, with the ambition to run multiple times faster (Deltares, personal contact).

One interesting observation is that the 2017-Numerical computation, where the Courant number was slightly increased (from 0.7 to 1) and the wet/dry threshold was also increased (1 to 2 cm), had little effect. From the simulation logs, this run had higher average timestep compared to the 2017 1D2D run (24s compared to 18s), but the amount of setbacks was significantly larger (about 1.8 times). These setbacks are timestep reductions which could indicate model instability. For example, if a timestep is too large and takes too long to solve numerically (within acceptable error margins), the computational timestep is halved, and another computational iteration is started. If this occurs too often, the computational speed can be throttled. To maximize computational speed, an appropriate balance needs to be found between a high average computational timestep and a low amount of setbacks (Deltares, personal contact).

Finally, an analysis was performed in this study to obtain more insight in 2D schematization considerations, more specifically on the trade-off between calculation and schematization time on the one hand, and a more realistic schematization on the other hand. Various mesh compositions were tested for a cut-out version of the water system at the Sekdoorn location, including three flexible meshes (FM) at different resolutions (5 meters, 10 meters, 15 meters) and two structured meshes (S) at different resolutions (5 meters, 10 meters). The resulting computation speed for the various setups is shown in Table 10, and a comparison of the FM10 and S5 meshes are shown in Figure 24.

Table 10 Grid analyses results.

Grid configuration (max cell size)	Structured (10m)	Structured (5m)	Flexible mesh (15m)	Flexible mesh (10m)	Flexible mesh (5m)
Number of cells	1341	5767	1255	2856	10882
Total computation time	6.0h	20.2h	5.2h	9.8h	35.6h
Computation speed (simulated hours / hour)	544	162	628	333	92

One of the expected advantages of the FM grid is that with a lower resolution, similarly accurate insights could be obtained, as grid cells are outlined to spatial characteristics (e.g. roads or dikes), which historically demanded a higher spatial resolution to account for them, which can be done with the fixed weirs in D-HYDRO Suite 1D2D. Although it is difficult to discern from Figure 24 whether a structured high-resolution grid is preferable over a flexible grid with lower resolution when considering quality, it is clear that high-resolution grids have a significant computational demand. From the results, simulations with flexible meshes took more than 1.5 times longer than that of simple structured meshes (Table 10). Note that this can be partially explained by the greater number of cells. For example, for a maximum cell size of 10 m (measured in maximum length, rather than surface in m²), there is a significant difference between the structured and flexible mesh (1341 and 2856 respectively). In addition, schematization time is also a relevant factor for mesh considerations. Building flexible meshes required between 30 minutes and 1 hour each (including alignment and optimization), while structured meshes could be quickly generated in D-HYDRO Suite 1D2D, each in less than five minutes. Despite the structured mesh not being aligned correctly, the relatively small mesh size provides similar results to the flexible mesh. In the expert elicitation session, the (relative) importance of schematization and computation time is further discussed (Section 3.3) and in the Discussion, a reflection will be made on potential implications for mesh generation for the WSA (Chapter 4).

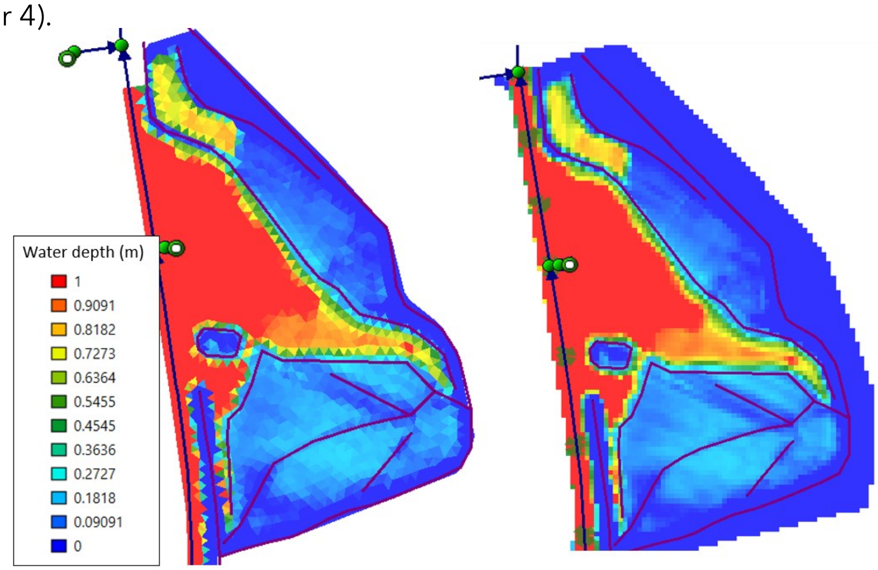

Figure 24 Inundation maps of the 2020 simulation at peak flow in the Sekdoorn grid for a flexible mesh with a 10m resolution (left) and a structured mesh with a 5m resolution (right).

3.3 Qualitative assessment criteria

For an appropriate assessment of SOBEK2 and D-HYDRO Suite 1D2D, the simulation results alone are insufficient for a fair assessment in the context of the WSA. To account for relevant considerations for WSA-suitability, an expert elicitation session was held with experts from both Arcadis and WDOD to discuss the model process, the results, and what the consequences may be for the WSA.

In this session, the various (qualitative) assessment criteria were discussed, as well as the interpretation of the results by the experts (related to applicability and suitability). These include model clarity, simplification extent, reflection on simulation and schematization time, reflection on 1D and 1D2D results and a concluding reflection on the suitability of D-HYDRO Suite 1D2D for the WSA (compared to SOBEK2).

Firstly, with respect to the clarity of the model tool and processes, common issues were considered an unclear interface (e.g. icons), insufficient/unclear error messages and a clear display of the results. As D-HYDRO Suite 1D2D's interface is more user-friendly than SOBEK2, with clear icons and a layout similar to common GIS tools, this should be an improvement. On the other hand, D-HYDRO Suite 1D2D stores information in netCDF files, which are more difficult to manually edit or review. This may make understanding of the model processes (e.g. where certain information is stored), as well as the creation of tools, more difficult.

For the simplification extent for 2D processes, the general consensus was that the additional information 2D provided may not be extremely relevant for the WSA. Storage outside of the water channels is accounted for in 1D in the cross-sections, which means the primary difference between 1D and 1D2D concerns the dynamics. While these certainly are critical for flood inundation studies, in the WSA these are generally not relevant, with two exceptions. Firstly, when certain extreme processes occur next to structures (e.g. culverts bypassed by overland flow, overland flow causing shortcuts at extreme water levels), a 1D2D schematization could lead to more accurate results of the model overall. Secondly, overland flow processes can be interesting when more detail is preferred, such as when costs are to be minimized. For example, if by accounting for high elements correctly, inundation occurs only on agricultural land, measures can be different than if the inundation was assumed to also occur in a village.

Schematization time was considered more important than simulation time for WSA purposes. Arcadis noted that they have to effectively allocate working hours in projects, whereas the computational time on a dedicated calculation computer is less relevant (as they can continue with other work). On the other hand, computation time does become more relevant for probabilistic analyses or during the schematization itself (to quickly check errors). The computational times of the D-HYDRO models were (significantly) higher than SOBEK2, which was unexpected, which could very well deter usage of D-HYDRO Suite 1D2D unless 2D modelling was specifically required. However, it was also noted that the results in this study are likely not representative for the intended official release version of D-HYDRO Suite 1D2D and the tool may be significantly faster than SOBEK2, because the computational speed in this study was throttled due to an existing bug related to the current beta version.

For a fair comparative assessment of the 1D results of SOBEK2 and D-HYDRO, they were presented blindly at first (experts were unaware which model was which). They observed that simulated values of both models were very similar, although the D-HYDRO model was considered to perform slightly better than SOBEK2 for both simulated discharges and water levels. Both models seemed to be making similar errors, but the magnitude of these errors was generally slightly smaller for D-HYDRO. This was also the case at Broekland, where both models performed insufficiently. Peak shapes in D-HYDRO seem to be more comparable to peak shapes of observed values, although SOBEK2 simulated values decrease to observed values faster after peak discharges occur (Figure 25). The final assessment was that for a partially calibrated model, SOBEK2 and D-HYDRO Suite 1D2D perform similarly and sufficiently for the intended model purposes, but results are not yet sufficiently reliable for the WSA (due to inaccuracies in simulating peak water levels and discharges).

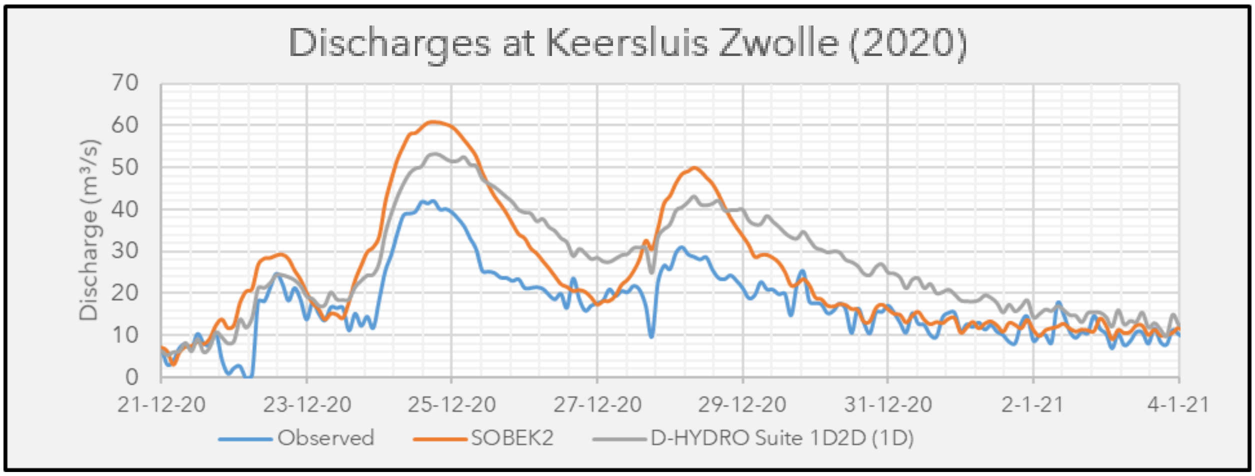

Figure 25 Discharges at Keersluis Zwolle for two peaks in the 2020 event.

With respect to the additional value of 2D schematization, the experts were unable to provide specific insights based on the (1D2D) D-HYDRO results, as the results related to inundation were limited (Section 3.2). That being said, the inundation patterns and characteristics seem to be realistic for the retention area (Sekdoorn), but as concerns a spatially simple area (few spatial variations or local elevations), this was to be expected. The (minimal) effect of this retention area is realistic, as WDOD's approach was to have a large amount of small retention areas that together create a buffer effect of sufficient magnitude in the water system as a whole (WDOD, personal contact). Two potential (niche) applications for 2D schematization were suggested in the context of the WSA. Firstly, when applied correctly, 2D schematization could improve model accuracy by better accounting for overland flow processes, although it is context dependent whether these are relevant beyond inundation patterns (e.g. when shortcuts or bypasses are formed at high water levels). Secondly, more detailed inundation analyses could be performed. This improved insight could enable more effective and efficient design (e.g. where to take local measures) or contribute to communication (more realistic inundation maps), although in general the experts agreed that the current practice of generating inundation maps (based on 1D interpolation over DEM files) was sufficiently accurate at the moment for most WSA applications.

When reflecting on the WSA in general, both Arcadis and WDOD do not feel that 1D2D simulations are superior to 1D simulations, with the potential exception where 2D processes are expected to play an important role. The aforementioned specific uses could be examples of when 2D might provide additional value. However, due to various best practices for the current 1D approach (e.g. storage schematization in 1D, ability to correct for interpolation errors), it was considered to also be possible to obtain reliable inundation results with a 1D model. One interesting remark was that 2D analyses may become more common, or even required, in future WSA guidelines. This change in best practices would require an effective 1D2D modelling tool.

When asked for a concluding reflection of the suitability of D-HYDRO Suite 1D2D compared to SOBEK2 for the WSA, both Arcadis and WDOD feel that D-HYDRO Suite 1D2D in its current state is not usable compared to SOBEK2. Especially some practical considerations, such as unsupported or missing features in D-HYDRO Suite 1D2D, computational times and storage of model information and output are reasons which prevent effective use of the tool. In addition, the (1D)2D functionality does not seem to be relevant for the WSA in general at this point. On the other hand, all experts were of the opinion that most of these issues will likely be resolved in the official release version of D-HYDRO Suite 1D2D, and expect the tool to be better than SOBEK2 in the future with respect to accuracy and computational speed. Both Arcadis and WDOD are planning to transition to D-HYDRO Suite 1D2D, among others because of the more user-friendly interface, the ability to better develop tools, and the ability to do nearly all analyses with one tool (WSA, flood simulations, water quality simulations etc.).

3.4 Comparative assessment of SOBEK2 and D-HYDRO Suite 1D2D

From the simulations and reflection on the results and process, the assessment framework can be applied to compare SOBEK2 and D-HYDRO Suite 1D2D. The results can be found in Table 11. For greater transparency, the results concerning D-HYDRO have been split in two categories: the current state of D-HYDRO Suite 1D2D which was used to perform this study, and the expected official release version of D-HYDRO Suite 1D2D.

Model performance of the SOBEK2 and D-HYDRO models is very similar, with both models simulating near identical discharges and water levels at the locations of interest. Compared with the observed values, both provide a reasonable representation of reality for an uncalibrated model, with nearly perfectly simulated peak timing. With respect to simulated water levels and discharges, a clear correlation with observed values exist, although it is clear further calibration would be necessary for WSA application. The inundation characteristics simulated by D-HYDRO Suite 1D2D seem realistic based on the results in this study, but as discussed in Section 3.3, these results in this study are too limited to assess this criterion in detail.

Model usability concerns many relevant aspects in model application. Simulation time was significantly higher for D-HYDRO results, although it is expected that for the official release, D-HYDRO Suite 1D2D should be at least as fast as SOBEK2 (and likely faster). Schematization time is relatively low for both models, where the SOBEK2 model could be constructed within a day, which could be converted in a working (1D2D) D-HYDRO model within half a day. Correct 2D schematization of flexible meshes, including alignment and optimization, would be fairly time-consuming however. Clarity of model processes for SOBEK2 seems to be lower than D-HYDRO Suite 1D2D in general, although the storage of D-HYDRO output may be difficult to review and edit manually. Model robustness was briefly investigated, as the models were only partially calibrated, but indicated a systematic underestimation of discharges in the summer events, and an overestimation of water levels in winter events. Further calibration may be necessary in both the hydrological and hydraulic components of the models to obtain more consistently reliable values. From a brief qualitative assessment, the D-HYDRO model seemed to perform correctly for the extreme event, where realistic values are simulated for both 1D and 2D.

When considering the model applicability criteria for overland flow and inundation analyses, the additional value of D-HYDRO Suite 1D2D's 2D functionality is not directly apparent. (1D) SOBEK2 is not suitable to realistically schematize overland flow processes, but in general these processes are not relevant in WSA studies. For the inundation analyses, the current best practices of a 1D modelling approach and using interpolation to obtain inundation maps is considered to be generally sufficient for the WSA by experts. However, the (1D)2D functionality of D-HYDRO Suite 1D2D could be useful in certain niche applications, such as when either overland flow processes are required to be accurately accounted for, or a greater detail of the inundation analyses is desired.

A final comparative assessment of WSA-suitability can be made for both tools based on the results of the Soestwetering case. Model performance for both tools are similar. However, in its current beta state, D-HYDRO Suite 1D2D has several issues that reduce applicability to the WSA, among others including greater simulation and schematization times, several bugs and unsupported features. Furthermore, the 1D2D functionality of D-HYDRO Suite 1D2D did not provide a clear benefit in this case study. All in all, the used beta version of D-HYDRO Suite 1D2D does not appear to be suitable for the WSA at this point based on this case study, mostly because of usability considerations.

That being said, experts of Arcadis and WDOD expect D-HYDRO Suite 1D2D to become a suitable replacement of SOBEK2 in the future. Among others, current bugs and practical issues would likely be resolved in the official release version of D-HYDRO Suite 1D2D. In fact, during this research process several relevant issues have already been fixed or included in the development agenda of Deltares. Furthermore, the new software should be more user-friendly, provide an all-in-one package for water authorities for a wide variety of analyses (including the WSA) and being supported in the future by several tools to help with establishing and analyzing D-HYDRO models. Moreover, although at this point 2D modelling is not common practice for the WSA, it may be possible that the ability to more accurately model 2D processes becomes more relevant in the future.

Table 11 Comparative assessment of SOBEK2 (1D) the used beta version of D-HYDRO Suite 1D2D, and considerations for the expected official release of D-HYDRO Suite 1D2D.

Assessment Framework Water System Analysis – SOBEK2 and D-HYDRO Suite 1D2D				
Criterion	Indicator	SOBEK2 (1D)	D-HYDRO Suite 1D2D (1D2D – used beta version)	D-HYDRO Suite 1D2D (expected release version)
(Cumulative) discharge volumes	VE RVE	VE = 0.38 (average) RVE = -0.10 (average)	VE = 0.44 (average) RVE = -0.09 (average)	-
Peak water levels	NSE	NSE = 0.74 (average)	NSE = 0.66 (average)	-
Q50 water levels	MAE	MAE = 0.06 (average)	MAE = 0.07 (average)	-
Peak timing	Lag correlation with NSE	<2h time lag.	<2h time lag.	-
Inundation characteristics	Inundation map Qualitative assessment	Not investigated in this study. Current best practices (1D) yield sufficiently accurate inundation maps.	Can provide an accurate representation of inundation characteristics when schematized correctly.	-
Simulation Time (ST)	Model hours / hour	195 -272 (1D)	148 – 192 (1D) 98 – 115 (1D2D)	*At least as fast as SOBEK2 for 1D, expected to be faster.*
Schematization Time	Schematization (1D) Optimization (1D) Schematization (2D)	<8 hours to build and optimize the SOBEK2 model with current knowledge	1D schematization in SOBEK2 (<8 hours) Conversion to D-HYDRO and optimization (2 hours) Schematization 2D (3 hours)	*Expected to resolve various bugs and issues related to importing the model or unsupported features. Especially conversion and optimization should be faster.*
Clarity of model processes	Clarity of interface Clarity of computations Clarity of files	Requires quite some learning time. Unclear errors can take up significant time. Files are clear and easy to review/edit.	Significantly more user-friendly interface. Error message reporting seems to be improved (but not fully supported in beta). NetCDF files may be more difficult to review and edit manually.	*Similar to beta version. Validation and error messages should be more clearly reported..*
Model robustness	Relative bias summer/winter Performance in extreme event	RB = -0.30 / 0.19 (average) Extreme event not investigated in this study, but proven to be applicable.	RB = -0.24 / 0.15 (average) Results indicate model is working correctly in extreme conditions.	-
Simplification extent (2D)	Qualitative assessment on how 2D processes are accounted for (storage, dynamics)	For WSA purposes 2D schematization in 1D (storage) generally sufficient.	Higher complexity enables more accurate inundation analyses and overland flow. May have niche uses. Otherwise 1D schematization preferred.	*Expanded options to generate grids in D-HYDRO Suite 1D2D. Otherwise similar to used beta version, likely 1D schematization preferred for WSA applications.*
Inundation analysis	Inundation characteristics Simulation time Schematization time Simplification extent	Acceptable for WSA purposes. More difficult to communicate with public, more rough estimate.	More accurate results at the cost of simulation and schematization time. Could be useful when more insight is desired.	*Compared to beta version: likely requires less schematization and computation time with new features and optimizations. 2D functionality might be more usable.*
Overland flow analysis	Simulation time Schematization time Simplification extent	Unsuitable for this purpose, but generally little effect on WSA results.	Potentially offers more accurate results and insights for how a water system behaves under extreme conditions.	-
WSA Suitability	Influenced by all criteria: Model accuracy Model usability	Proven to be suitable in the past, likely remains the preferred tool for now.	Currently unsuitable due to several beta related issues, lack of existing tools and experience, which prevent effective use. It does achieve similar model performance compared to SOBEK2 and enable more detailed inundation studies.	*Expected to be able to become a better alternative than SOBEK2 for the WSA, mostly due to improved model usability.*

4 Discussion

The primary objective of this study was to comparatively assess (1D) SOBEK2 and D-HYDRO Suite 1D2D using a realistic case-study, to determine whether D-HYDRO Suite 1D2D would be suitable for WSA application, as well as shed light on the implications of 1D2D modelling for WSA purposes.

When relating the findings of this study to existing literature in this field, a lot of overlap can be found. The found preference to establish the model in 1D unless 2D processes are relevant are also recurring themes in comparative studies between 1D and (1D)2D models (Fleischmann et al, 2020, Jowett and Duncan, 2011). Potentially the most relevant implication of this study is that 1D modelling may be suitable and even favorable to (1D)2D modelling depending on the context, even when 2D processes are the subject of the analysis (e.g. inundation). In the tradeoff between the potentially greater model accuracy of 2D, and the practical usability considerations, this study found 1D modelling to generally be preferable for the WSA. Although several studies have made clear that (1D)2D modelling is not superior to 1D modelling in all cases (Pasquier et al, 2019; Pinho et al, 2013), this was somewhat contradicting existing literature stating that (1D)2D modelling is required when 2D processes are relevant (Afshari et al, 2018, Teng et al, 2017). A potential explanation is that such literature may be more focused on model accuracy (and how to properly represent a water system in a model), rather than the tradeoff between performance and usability that is made by model users in practice.

This study highlighted several issues related to 2D modelling also discussed in literature, such as greater schematization and computation times, as well as dependency on spatial data of sufficient quality (Papaioannou et al, 2015, Sarchani et al, 2020, Horrit and Bates, 2002; Dimitriadis et al, 2016). In fact, the Zandwetering location showcased that when DEM-files are inaccurate, the 2D schematization could lead to more unrealistic simulations than with 1D simulation. This further underlines the importance for careful 2D schematization, which both includes obtaining spatial data of sufficient quality and deciding on how the water system can best be represented in a model. Additionally, the practical usability considerations were relevant to the expert's opinions on suitability of a tool. 2D schematization of flexible meshes took considerably more time than establishing the structured (simple) meshes. With the fixed weir functionality of D-HYDRO Suite 1D2D, for WSA purposes (which may not require a high level of detail) it may actually be preferable to use structured (unaligned) meshes. Careful consideration of 2D schematization, where tradeoffs are made between accuracy and usability are also stressed in literature (Bomers et al, 2019 ; Bern and Plassman, 2000).

The practical implications of this study seem to generally support current best practices, where careful considerations must be made on how the water system is schematized in the model, accounting for model purpose, accuracy and model usability. As such, the WSR guideline and current (1D) approach for the WSA is likely still an effective and efficient approach to obtain reasonable insights in the inundation characteristics. As storage is taken into account in this schematization, the primary difference between the 1D and 1D2D approach would be a more realistic representation of flow dynamics outside of the water channels. However in a WSA context, flow speeds over land are generally very low, and inaccuracies in modelling these flow dynamics should mostly affect either the timing of inundation. Note that the timing of inundation is less relevant for the WSA (it matters fairly little when an area inundates, but more so if and to what extent). As such, the WSA is very different from flood studies, where these flow dynamics are critical to accurately simulate the timing of the flood wave and 2D would be necessary to realistically simulate flow velocities.

That being said, this study implies several potential improvements to the WSA approach that 1D2D may offer. Firstly, it may be that in a water system, overland flow processes are critical for a realistic representation. For example, at high water levels water may flow around a weir, or bypasses may be formed where water flows over land from one water channel to another. Both are difficult to schematize in 1D, but even simple 2D grids (with sufficiently accurate bed levels) could enable the model to take these processes into account. Another potential change to best practices in the future would be applying 2D grids only in specific areas of interest to obtain more detailed insights. Results in this study may not be fully representative for such applications, and 2D schematization can actually be done quite efficiently depending on the context. As such, it may be possible that with little effort (e.g. <30 minutes), a simple 2D grid of sufficient quality can be established, which could already provide useful insights. Finally, when considering the D-HYDRO Suite 1D2D, this study implies it may actually be preferable for WSA applications to employ simple structured grids (potentially aligned) with correctly schematized fixed weirs, rather than flexible meshes (e.g. triangular) which are properly aligned and optimized. This would (significantly) reduce 2D schematization time, and while computation times are likely higher (because the resolution would need to be higher for a similar accuracy), this may not be very relevant when using modern calculation computers.

Various remarks should be made on the limitations that affected this study. First and foremost, despite the Soestwetering being a representative case for the WSA with respect to size and complexity, in hindsight the suitability of this case to assess 2D functionality was limited. Unfortunately, no (spatial) data was available on inundation, and inundation is rare in the Soestwetering catchment in the first place (WDOD, personal contact). To make a reasonable assessment of 2D functionality, one would preferably have access to spatial data which shows the extent of inundation, ideally at different timeframes. With such data, one could compare the accuracy of 1D interpolation (current practice) with the 2D modelling by comparing the inundation maps with observed inundation extent. Additionally, with snapshots at different timestamps, one could also compare the timing of the inundation extent, although as discussed, that is less relevant for the WSA. Second, with the time available and the model scope not requiring a fully calibrated model (yet), the model was only partially calibrated. The Soestwetering model is a very large and complex model, and correctly calibrating for the entire system was not feasible in the time available. On the other hand, if more time would be available for calibration, there is confidence that this should be possible, especially considering the partially calibrated model is already performing reasonably (Arcadis, personal contact). Among others, the result of performing the analyses with only a partially calibrated model led to the water levels near the 2D areas to be inaccurate (further limiting the usable insights), as well as limited the ability to assess model performance. Thirdly, the stationarity of the water system is relevant: many changes occurred to the water system since 2010. Because the model was schematized using 2020 data, this could lead to greater inaccuracies in earlier events (e.g.

model schematization accounting for retention areas that were not constructed yet). Although the influence of these changes should be relatively small (WDOD, personal contact), they can play a role in greater inaccuracies with observations further in the past. It would have been possible to properly account for these changes through a variety of means (e.g. five different models, or virtual structured with a time-dependent scheme). However, because this model would function as a basis for a model that could be used later, the main goal was to establish a model that represents the current state of the water system. Because of this, and due to time considerations, the choice was made not to account for these changes. Lastly, lack of experience with D-HYDRO Suite 1D2D most likely affected the results as well. Experience with the software, recommended settings and model application decisions are relevant for efficient and effective application of D-HYDRO Suite 1D2D, and thus greater experience could affect several relevant WSA criteria (e.g. schematization and computation times). It could also be expected that the experts, who had limited experience with the new tool, are not aware of all functionalities and best practices, and thus based their opinion potentially incomplete information. For example, it was noted earlier that the choice for storage in netCDF files may affect model usability because it is more difficult to review manually, but this file convention also reduces storage size of output files, is used worldwide, and can be more easily accessed and processed by tools (Deltares, personal contact).

Consideration of the study scope is also relevant. SOBEK2 was only applied in 1D, which reflects the current standard approach. However, the software also enables 1D2D modelling, which was not investigated. When 2D processes are relevant or necessary to model, SOBEK2 has the functionality to investigate this. As such, also including (1D2D) SOBEK2 in the comparison could have led to a more complete overview and better investigate expected improvements to 1D2D modelling in D-HYDRO Suite 1D2D. It is also important to note that this study employed the beta version of D-HYDRO Suite 1D2D (0.9.7.51931), where several features are unsupported or not working correctly, which likely affected the results. As such, results of this study may not be completely representative for the official release of D-HYDRO Suite 1D2D.

A final remark should be made on the results related to the expected official release version of D-HYDRO Suite 1D2D. Especially in the expert elicitation session, various considerations were presented on how D-HYDRO Suite 1D2D is expected to perform in the future. As the experts have little experience with D-HYDRO Suite 1D2D, it is uncertain if these expectations are completely accurate. On the other hand, clear examples can be made that the unsuitability of the D-HYDRO Suite 1D2D beta version used in this study are linked to (currently) unsupported features and unintended issues. Also, during the process of this study, Deltares has made significant advances in resolving many previously existing issues. Furthermore, with D-HYDRO Suite 1D2D being intended as the successor of SOBEK2, it is unlikely it would not be superior when it is released by Deltares. Because of this, there exists a high degree of confidence among the experts that (most of) these issues can and will be resolved by Deltares, and that if this study would be repeated with a future version of D-HYDRO Suite 1D2D, it may well be a better alternative than SOBEK2 for the WSA.

5 Conclusion

Hydrologic and hydraulic modelling tools are critical for water authorities to obtain an understanding of their water systems, evaluate whether they meet water hindrance norms and design appropriate measures. Historically in the Netherlands, the SOBEK2 (1D) tool has been used to perform Water System Analyses (WSA), which entails assessing whether inundation frequency caused by overflow of streams complies with set norms. However, recently D-HYDRO Suite 1D2D has been developed as the intended successor to SOBEK2, most notably improving (1D)2D modelling functionality, which entails a higher numerical efficiency as well as the addition of new features such as flexible meshes.

To better understand the consequences of this development, this study investigated how SOBEK2 and D-HYDRO Suite 1D2D differ in hydraulic modelling when applied in the context of the WSA, and how this affects their suitability for WSA purposes. This was done by comparatively assessing both tools in a representative case-study using realistic model application decisions.

Suitability of a modelling tool for the WSA relies on various criteria, which are a combination of model performance, usability and applicability considerations. Models for WSA purposes should provide sufficiently reliable results in extreme conditions to assess inundation characteristics, while also accounting for practical considerations such as available data, desired level of detail and schematization effort.

Model performance of (1D) SOBEK2 and D-HYDRO Suite 1D2D are very similar in the Soestwetering case study, both able to provide a reasonable representation of the water system, including correct peak timing and reasonably accurate discharges and water levels for historic peak events. Additionally, the results indicate that, similar to SOBEK2, D-HYDRO Suite 1D2D is able to realistically simulate extreme events. However, the used beta version of D-HYDRO Suite 1D2D (0.9.7.51931) cannot be used effectively, mostly due to various (unintended) issues and unsupported features, which make it unsuitable for WSA application at this moment. The expectation is that for the future official release of D-HYDRO Suite 1D2D, most of these issues are resolved, and the tool should be at least on par, but likely superior to SOBEK2 for the WSA.

Investigated model applications yielded interesting results.1D2D modelling does not outperform 1D modelling in the context of the WSA, most notably due to the greater schematization and simulation times, the ability of the current 1D approach to account for inundation storage sufficiently, and the consideration that increased accuracy of 2D modelling will generally be irrelevant for the WSA. That being said, (1D)2D modelling may have a use in specific contexts in a WSA, allowing for a greater model accuracy or improved level of detail in locations of interest. In addition, the study highlighted the importance of carefully considering 2D schematization and the dependency of 2D modelling on accurate spatial data.

Based on the findings and implications of this study, three specific recommendations for future studies can be made. First, it is recommended to repeat this study for a representative WSA case where overland flow processes are known to be relevant on a larger (model) scale, as well as where sufficient spatial data is available on inundation extent. This would enable a better assessment of the effect of (1D)2D modelling on accuracy, allowing for a more fair assessment of potential benefits of 1D2D modelling over 1D modelling for the WSA. Second, it would be beneficial to obtain a clearer understanding of how model usability criteria influence model choice in practice. This study suggests there is a trade-off between model performance and obtained insights on the one hand, and model usability on the other. An improved understanding of what determines model suitability may help development of better modelling tools in the future. Lastly, it would be interesting if a more systematic investigation on suitable 2D schematization in the context of inundation studies could be done. It is difficult to provide specific guidelines or best practices for 2D schematization as it is highly context and model dependent. On the other hand, demand exists for practical guidelines to establish an appropriate 2D mesh without an elaborate sensitivity analysis. It would be interesting to see whether it is possible to provide generally applicable recommendations for 2D schematization for inundation studies (e.g. mesh resolution, grid type), as they could allow for more efficient application of (1D)2D analyses.

Studies such as these are relevant to help model users to employ innovations and apply these to improve day-to-day practices. Hopefully the insights of this study can contribute to more efficient and effective modelling of water systems in the future.

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Appendix A – Water System Review and model requirements

The WSR is a standardized guideline for water authorities to determine whether the provincial norms for water hindrance are met, aimed at determining bottlenecks in the current system (STOWA, 2011). The process consists of three steps: the Water System Analysis (WSA), a bottleneck analysis and a solution analysis. A summary for each step in the process is shown in Table 12. This guideline discusses both policy-related choices, such as which norms apply or how to deal with climate scenarios, as well as technical choices, such as how bottlenecks should be defined or calculation methods.

Table 12 Water System Review process.

Activity	Result	Description
Water System Analysis (WSA)	Inundation maps Insight in model / water system	The Water System Analysis is the process in which a model is developed or actualized, with the aim of testing whether it is suitable to perform a bottleneck analysis with. After this verification, extreme scenarios are simulated, which result in inundation maps and insight in how the water system would behave under such conditions. It consists of 1) defining the base for the WSA, 2) collecting relevant data, 3) establishing, calibrating, and validating the model, 4) simulating extreme conditions and 5) obtaining inundation maps.
Bottleneck Analysis	Bottleneck maps Shortage of water storage (m^2)	In the bottleneck analysis, the inundation maps are analyzed. If inundation occurs in locations where it should not, or at a higher frequency than the norms, a bottleneck is found.
Solution Analysis	Measures, design or final report	The analysis of solutions is not discussed in-depth in the WSR guideline, apart from its relation with the previous steps.

In Table 13, an overview is presented of the various model requirements for the WSA, along with the source. Various requirements and important model considerations are listed in the guidelines, with three explicit goals for model performance (STOWA, 2011):

- Water levels under extreme conditions should be computed sufficiently accurate.
- Inundation should be calculated sufficiently accurate (either through 1D interpolation or 2D).
- Water levels should be calculated in all channels where assessment is performed.

To achieve these primary goals, various requirements for the model are provided. In Table 13, the first four requirements are explicitly stated under the calibration requirements (STOWA, 2011), while the other parameters are either derived from the guidelines or from expert-advice.

Table 13 Model requirements Water System Analysis.

Model requirement	Description
STOWA - Processes influencing water levels during extreme discharges, such as flooding of structures or storage/flow over land, need to be accounted for.	The model simulation should take into account processes which may not occur during normal conditions, it should be representative of reality during extreme events.
STOWA - Acceptable deviations from observed values are related to the differences in inundated surface (e.g. if a 10 cm increase would lead to a 50% increase in flooded surface, a higher precision is desired).	An indication of a stop criterion for calibration and model accuracy. Inundation extent is a critical factor here, which means the same deviation can be acceptable in one location in the model, but unacceptable in another, leading to additional model improvements or calibration.
STOWA - Establishment of the model and further improvements are supported as much as possible based on the physics of the water system.	Errors should preferably not be solved by virtual solutions, as it can reduce model representativeness.
STOWA - Prior to calibration, each parameter is fixed (when possible) based on sources or available data. For parameters with uncertainty, a probable bandwidth is defined.	Reduce the chance calibration will mask errors in the model.
Arcadis/STOWA - (Cumulative) discharges for the model need to match the observed quantities.	No water should be "lost" in the water system, unless there is a strong explanation.
Arcadis/STOWA - Peak water levels should be accurate, with preferably no positive or negative bias. **Arcadis** - Water levels under normal conditions should also match the observed values.	If a bias exists, a positive bias is more desirable for peak water levels to reduce the chance locations which do not comply with the set norms and regulations (related to inundation) are overlooked.
Arcadis/STOWA - Peak timing and peak characteristics should be comparable to observed values.	Lag of the peaks should be within reasonable margins, peak form (e.g. elongated, very narrow) should be comparable so peak volumes are not over- or underestimated.
Arcadis - Time required to establish the model should be related to the study objective, and calculation time of the model should be within reasonable margins.	Model should be suitable for its intended goal (e.g. simulate inundation extent), so if the model underperforms in aspects outside of the scope, a pragmatic approach is desired.

Based on these general requirements, criteria were derived. To verify whether these criteria accurately reflect the model requirements relevant for Arcadis and WDOD, the Assessment Framework was sent to them for review and verification. No further changes were needed. However, in the final expert-elicitation session, additional considerations were mentioned. These were also included in the results chapter, although they were not included in the Assessment Framework as they were quite case-specific (e.g. a single model package being able to be used for a variety of purposes improves model usability).

Appendix B – SOBEK2 and D-HYDRO Suite 1D2D workflow

This appendix presents the workflow used to establish the (1D2D) D-HYDRO model when using the SOBEK2 model as a starting point.

SOBEK2 model:

1. Establish model based on registry data of water authority using Catchment Builder and Channel Builder tools.
2. Perform a stationary simulation to determine schematization errors and fix these.
   These were determined by determining if unrealistic head differences occurred at structures (e.g. weirs, bridges) and if water levels / discharges were reasonably close to measurements in relevant locations.
3. Optimize model by removing bottleneck locations (increasing local storage), primarily for main water system.
4. Calibrate the RR-module to better improve model performance in general.
   For calibration, especially (cumulative) discharges in Zwolle were used to finetune the RR specifics. More specifically, changes were made in how the schematization of RR catchments (unpaved nodes), such as bed slope or surface level to more accurately estimate processes in the Soestwetering Catchment.

Preperation:

5. Change inverted culverts to normal culverts (with 50% additional resistance) as these are not yet supported in D-HYDRO.
6. Clean-up the SOBEK2 model.
7. Clean boundary data information (required for offline coupling) which greatly improves import times.
8. Overwrite the cross-section file to remove Preissmann slots.
9. Overwrite the Unpaved.3B to account for initial groundwater levels (as import in D-HYDRO does not fully support linked values yet).

Conversion to D-HYDRO

10. Import the SOBEK2 model (RR+FlowFM+RTC).
11. Import precipitation and evaporation data.
12. Fix errors.
13. Export to dimr-model.

Optimization and calibration

14. Improve numerical parameters from default to recommended settings.
15. Import Initial Water Level file.
16. Perform a short simulation.
17. Find main bottlenecks (Courant limiting) and fix these (e.g. increasing storage).
18. Repeat process until no significant bottlenecks exist.

2D schematization.

19. Use high-resolution DEM files (AHN3 0.5m) to draw structural lines and fixed weir lines in ArcMap.
20. Estimate reasonable grid size to account for spatial characteristics. (Preferably, the aim is to test this out by interpolating the bed levels on several grid configurations and determining when spatial characteristics are well enough accounted for).

21. Using structural lines, establish a flexible mesh in SMS Aquaveo.
22. Convert .2dm mesh to .nc mesh and import in RGFGRID.
23. Optimize orthogonality (to ~0.01) and maximize smoothness.
24. Import improved flexible mesh in D-HYDRO.
25. Interpolate (triangulation) spatial data (DEM files 0.5x0.5m and spatial roughness 10x10) on the mesh.
26. Import fixed weirs (Arcadis tool to assign correct elevations).
27. Establish 1D2D links.
28. Export to dimr-model.
29. Perform additional model calibration if necessary for 2D grids.

Appendix C. Protocol for expert-elicitation session

To comparatively assess SOBEK2 and D-HYDRO Suite 1D2D in the context of the WSA, various criteria are relevant which are difficult to quantify. To obtain valuable insights on these, the expert-elicitation session (1 hour) will collect input on the following criteria of the assessment framework:

- Inundation characteristics
- Clarity of model processes
- Model robustness (specifically 2D, rest is done only with Arcadis due to practical reasons)
- Simplification extent
- Applicability for the WSA
- Applicability for Inundation Analyses
- Applicability for Overland Flow Analyses

Previous experience with SOBEK2, but limited experience with D-HYDRO Suite 1D2D, pose difficulties with fair assessment on all criteria, as attendees are aware of SOBEK2, but have little information on D-HYDRO (if any), and existing information is most likely in promotional talks or update meetings on development of D-HYDRO.

Notes Expert Elicitation Session

During the 1-hour online session at the 18th of June 2021 two specialists from Arcadis (hydrological and hydraulic modelling) and three hydrologists from WDOD attended (of which two were also experts on the Soestwetering catchment). All attendees were experienced with SOBEK2 and are intending to transition to D-HYDRO Suite 1D2D in the coming years. Their involvement in this study was for a large part to learn and gain experience with the new modelling tool. For the WDOD attendees, experience with D-HYDRO Suite 1D2D is limited (mostly from communication with Deltares or from workshops), whereas Arcadis was also closely involved in the modelling process of this study, and therefore likely have a better idea of the new tool. Both parties are working together with Deltares in a "TKI" project (Topconsortium Knowledge and Innovation), which is aimed at collaboratively innovating. In this project, Arcadis and Deltares gain experience with D-HYDRO Suite 1D2D and work on developing tools, while Deltares provides support on the software (e.g. fixing issues, providing guidance or advice).

To attempt to prevent potential bias (either positive or negative) because of the limited first-hand experience, three measures were taken during the session. First of all, at the start it was explicitly discussed, and attendees were requested to consider this bias in their reflection (e.g. are they basing an expectation of D-HYDRO on personal experience, or only on PR). Secondly, when the results for SOBEK2 and D-HYDRO were presented comparatively (the 1D results), these were shown blind (model 1 and model 2) where the experts were unaware of which tool was which. For the qualitative assessment of model accuracy/performance, this should have prevented potential bias. Note that this was not done for the computation times (as they were already aware of the computational issue with the beta version). Thirdly, experts were requested to support their opinion or reflection by elaborating on what they base it. For example, when requested on why they assume D-HYDRO Suite 1D2D will be at least as fast as

SOBEK2 for 1D on release, they both stated previous statements from Deltares and the logical assumption that if software is intended as a successor to an old tool, it should be at least as good.

Finally, expectations for the future/official release of D-HYDRO Suite 1D2D were, insofar possible, mostly discussed at the end of the session in a separate section. At several times, experts were specifically asked to provide a reflection if all they could base it on was the information provided by the simulation results of this study. Results on the final release and future application of D-HYDRO were more speculative, but did provide interesting remarks and new insights relevant to include in this study (either as a remark on the current results, or for the discussion).

Protocol Expert Elicitation Session

This protocol is established to attempt to avoid bias during the meeting insofar possible, as well as make it possible to provide valuable insights on all mentioned criteria. Elaborate notes will be made during the sessions. A summary of the conclusions will be discussed at the end of each section to verify if it was recorded correctly.

1. Introduction on the study, goals and this session.

Among others attendees are made aware of the potential risk of bias, which may stimulate them to be critical of potential input during this session.

2. Discussion on clarity of model processes.

Attendees are asked on relevant aspects for model processes, as well as to reflect on the clarity of SOBEK2 (strengths and weaknesses). Furthermore, they are asked on which ideas they have on the current clarity of D-HYDRO with their current knowledge. Zoom in on the background files and the user interface.

3. Discussion on simplification extent (2D).

Present simplification steps used in both models (as objectively as possible). Attendees are asked on their opinion of the way 2D attributes (e.g. storage) are schematized in SOBEK2 (1D) and D-HYDRO (1D and 1D2D). Afterwards, they will be asked what this means for usability in a WSA context (preferably as concretely as possible).

4. Presentation of 1D results (blind) in measurement locations.

Use a location of interest with representative measurements (e.g. not the only one where D-HYDRO performs significantly better than SOBEK2) and discuss how they interpret them and how they can relate these results to applicability in the context of the WSA.

Afterwards, additional relevant results are showcased (e.g. measurements where one performs significantly worse) where also a critical reflection is asked.

5. Presentation of 1D2D results of D-HYDRO (inundation characteristics)

Discuss inundation characteristics and whether they consider these realistic for the schematized areas, as well as whether they feel the inundation patterns (e.g. overland flow) are realistic.

6. Discuss applicability for Inundation Analyses.

Ask attendees to reflect on the way inundation analyses are made currently (with SOBEK2-1D) and how they might be done in the future with D-HYDRO (1D2D). When considering the 2D results of D-HYDRO today, how do they consider the applicability of SOBEK2 and D-HYDRO for inundation analyses (present/future).

7. Discuss applicability for Overland Flow Analyses.

Only D-HYDRO can show this process, but attendees are asked if they consider such analyses of additional value and what the current results mean for their opinion of the applicability of D-HYDRO in this context.

8. Discuss applicability for the WSA.

Most important reflection with attendees. First of all, present the assessment framework and discuss whether any relevant criteria are missing (shouldn't be the case, as they were asked for feedback on this version). If there are, ask them to reflect on those first (both SOBEK2 and D-HYDRO). Afterwards, ask them to provide their opinion on the applicability to the WSA (preferably linked to mentioned criteria) of both models. One risk is that they will be enthusiastic of D-HYDRO in the future (not bad in itself), so it is important to attempt to relate their opinion to the presented results. E.g. they may say 2D will be very useful to determine more specifically where inundation occurs. In this case, they could be asked if the figures shown today would be sufficient to achieve that insight.

9. Closure