Master Thesis – Master Water Science and Management

Towards regional upscaling of subirrigation as a tool for agricultural climate adaptation

Developing a water balance model in Vensim to explore the feasibility and water management challenges for regional implementation of subirrigation in North-Limburg, the Netherlands.

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Summary

The high Pleistocene sands in the south and east of the Netherlands have been subjected to severe drought in recent years (2018/2019). As a result, agricultural pressure on freshwater resources has increased, with negative impacts on nature as a result. As bans on surface water and groundwater abstraction are looming, it has become evident that there is a need for farmers to adapts to the fickle (political) climate.

In recent years, KWR has been implementing subirrigation (sub-surface irrigation) as an alternative and addition to conventional irrigation at the field scale under the project Klimaat Adaptatie in de Praktijk (KLIMAP). KWR has identified it as a promising tool for regional agricultural climate adaptation. From the field scale modelling and measurements, it was however evident that subirrigation requires substantial amounts of water during the growing season when the resource might be the most limited. Additionally, subirrigation has been shown to impact all components of the field scale water balance which might result in challenges for water management regionally and downstream. A fitting modelling tool to assess the effect of subirrigation when implemented on a regional scale in North-Limburg near the Mariapeel was however not yet in place.

Using Vensim PLE system dynamics modelling (SDM) software, this research aimed to set up a new base water balance model that can operate at the scale in between the current SWAP and national hydrological models (LHM). It did so by simplifying the previous water balance model SWAP for the field scale and explored expanding it to link multiple fields to the regional surface water system. Multiple scenarios for field scale parameterisation and regional implementation of subirrigation were run. This research aimed to answer the following research questions: 1) *How can the hydrological processes at the field scale, and the impact of subirrigation on these processes, be translated into a simplified qualitative field scale water balance at both field and regional scale?* 2) *How can the influence of subirrigation on the field- & regional scale water balance be modelled quantitatively using system dynamics modelling in Vensim?* And 3) *How can the developed Vensim model be applied to explore scenarios for challenges/opportunities faced during the regional upscaling of subirrigation in Limburg?*

The new Vensim model turned out to be capable tool, with the modelled groundwater levels closely matching those as modelled in SWAP. For the area of interest, linear extrapolation of the modelled water balance results translated into a water requirement for subirrigation of 3.3 million cubic metres of water during the growing season. This is however an overestimation, as the regional scenario modelling in this research showed the side-effect of subirrigation by increasing groundwater levels in adjacent fields. Widespread subirrigation could have detrimental effects on downstream surface water availability in times of drought and in cases of large abstractions where demand exceeds supply of surface water. Maintaining higher surface water levels might reduce subirrigation water requirements but could be difficult in times of drought.

Improvements to the model still can be made. Future research should focus on improving the field scale model representation of the unsaturated zone, improving the representation of field area in the model and on improving the parameterisation of the hydraulic conductivities within the soil. The next challenge will be to link multiple fields using the linking types as explored in this research and recreate a real-life area of interest for Waterschap Limburg to more precisely grasp water distribution challenges and requirements in case of large-scale implementation of subirrigation.

Keywords: *Agricultural Climate Adaptation, Subirrigation, Mariapeel, Vensim, System Dynamics Modelling, Regional Upscaling*

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1. Introduction

1.1. Context & problem description: Drought & agricultural climate change adaptation in the Netherlands

In the years 2018, 2019, the Netherlands was subjected to one of the most severe droughts in 50 years. At its peak in 2018, nationwide rainfall shortage amounted up to 300 mm on average, with the effects being more pronounced for specific regions in the Netherlands (van den Eertwegh et al., 2021). Expected climate changes are posed to increase the severity of these extreme weather events, expectation being that overall, year-round precipitation may increase, but summers are likely to experience more extreme showers or prolonged droughts like the ones experienced in 2018/2019 (KNMI, 2006; Philip et al., 2020). The parts of the Netherlands which were predominantly influenced in the recent droughts are situated in the south, southeast and east of the country, in the provinces of Noord-Brabant, Limburg and Gelderland (van den Eertwegh et al., 2021) These areas are characterised by high Pleistocene sandy grounds (van den Eertwegh et al., 2021). They are especially drought prone not only because of the precipitation deficit faced during recent droughts (see figure 2), but also because they are draining water too quickly (van den Eertwegh et al., 2021). Whereas previously, water was in the Netherlands seen as an abundant resource rather than a scarce one in the eyes of the public (van der Boon & Hoekstra, 2020), these recent droughts have increased the awareness that these areas are highly perceptible to these whether extremes, and not well prepared.

Droughts are subdivided in 3 types which propagate into one another (figure 1) (Zargar et al., 2011). The drought of 2018 and 2019 in the Netherlands forms no exception. Droughts start off as meteorological droughts, characterized by a precipitation deficit over a time which can span from "a week up to a few years" depending on the area in which a drought occurs (Zargar et al., 2011). Due to decreased infiltration, percolation and surface runoff, meteorological drought then leads to reduces soil moisture and deeper groundwater levels, in which case we speak of an agricultural drought (Zargar et al., 2011). Due to these decreases in water content in the subsurface, less water is being recharged into surface waters such as streams and lakes, causing a hydrological drought (Zargar et al., 2011). The impact of droughts is very much dependent on the initial conditions of the water system before the start of the meteorological drought. As formulated by van den Eertwegh et al., 2021, if agricultural parcels are drained early in the growing season, with low groundwater and soil moisture levels as a result, the negative impact of drought on crop production will be more pronounced compared to situation in which high groundwater levels are maintained (van den Eertwegh et al., 2021).

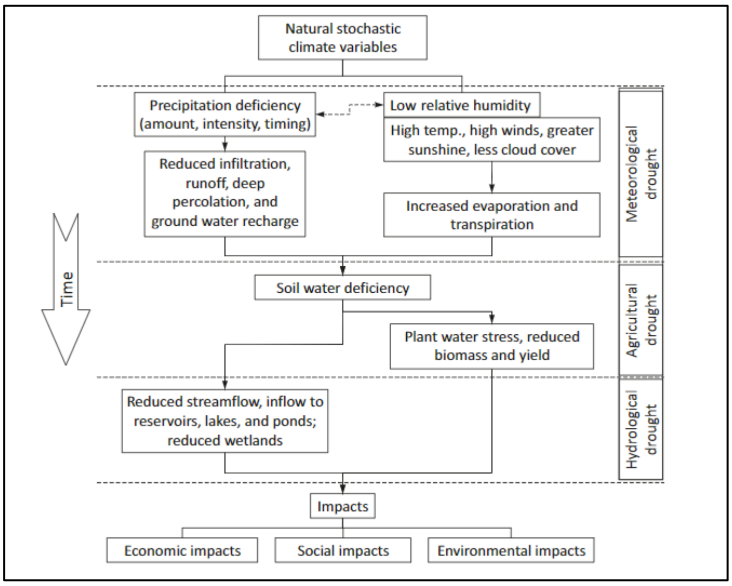


Figure 1: Drought propagation and types. Source: Zargar et al., 2011

The drought of 2018 and 2019 in the Netherlands propagated into these final two categories, with damages to agricultural lands and loss of revenue as a result (van den Eertwegh et al., 2021). Due to the cascade of drought through the water system into soils and surface water, increasingly more groundwater is extracted in the drought prone areas in the south & east (van der Boon & Hoekstra, 2020). When overlapping the precipitation deficit and groundwater well registration maps for the Netherlands, a clear pattern emerges, hinting at an alarming increase in the pressure on groundwater resources (figure 2) (van der Boon & Hoekstra, 2020). Of the new & existing wells in the Netherlands, approximately 35 percent is for agricultural purposes (van der Boon & Hoekstra, 2020). In fact, figure 2 only illustrates the registered wells and does not include the wells which abstract less than 10 m^3 per hour, as these are not supervised under Dutch legislation (Rijksoverheid, 2021). A further desiccation of the area is therefore feared, because of a ‘tragedy of the commons’ effect in which multiple independently acting actors searching for the maximalisation of economic benefits together deplete a commonly shared resource, resulting in natural, and agricultural damages (van der Boon & Hoekstra, 2020). There are calls for the improved restriction and regulation of

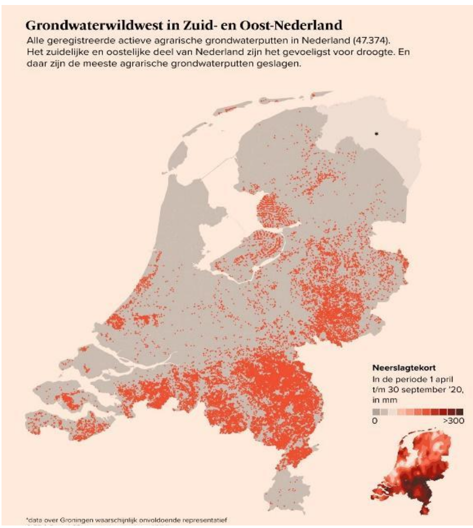


Figure 2: Map comparing precipitation deficit (bottom right) and the number of registered groundwater wells(centre). Orange dots indicate groundwater wells. Darker shades of red indicate a bigger precipitation deficit Source: van der Boon & Hoekstra, 2020

agricultural (ground-) water abstractions (Bezem, 2021; van der Boon & Hoekstra, 2020). These calls for increased regulation will arguably worsen the already tense relationship (Hubers, 2021) and sometimes conflicting interests of farmers, nature conservation groups, the drinking water sector & water authorities in the Netherlands (Reijnen Rutten, 2022)

It is thus clear that the agricultural sector in the Netherlands will have to adapt to an increasingly fickle (political) climate. After all, when looking at the Dutch 'verdringingsreeks'; the priority list of water allocation during periods of water shortage; agricultural practises come only at the very bottom of the ladder (Rijkswaterstaat, 2022b). Initiatives have been started, aiming to make the Netherlands and agriculture more drought resistant. Among these projects is the project 'Klimaat Adaptatie in de Praktijk' (KLIMAP), which is a 4-year project following a consortium of 24 organisations who together aim to identify which processes and measures can contribute to making the high sand grounds in the Netherlands more adaptive to climate change (KLIMAP, 2022). KWR, as one of the parties involved in this project, has lately been exploring the possibility of using subirrigation as an alternative for the commonly applied sprinkler irrigation (de Wit et al., 2021).

Subirrigation systems, abbreviated from sub-surface irrigation, have been applied globally in different forms. The technique has been applied in horticulture since the early nineties with water supply through drip irrigation (Ferrarezi et al., 2015). At the field scale, compared to conventional drainage systems, which often freely discharge into surface waters, modern subirrigation with 'controlled drainage' systems collect all water from individual drainpipes in a closed collection drain and connect these to control wells which regulate the water level within the system (de Wit et al., 2022). These systems can thus actively regulate whether water is being irrigated or drained from the soil based on for example water level monitors in the control wells or based on meteorological forecasts (de Wit et al., 2022). A schematic set up of a subirrigation system with controlled drainage can be seen in figure 3 below.

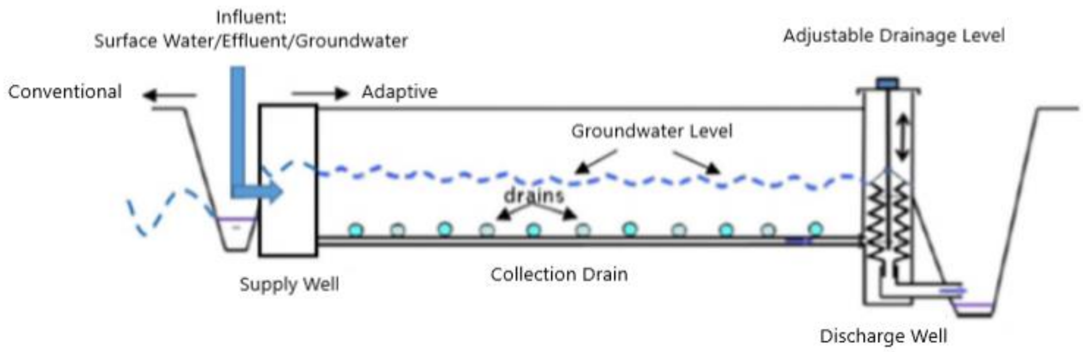


Figure 3: Schematic of a subirrigation system. Adapted from Bartholomeus et al., 2015

Knowledge Gap

Previous pilot projects under the Lumbricus programme (predecessor of KLIMAP) near the Deurnsche- and Mariapeel in North-Brabant and Limburg respectively, have explored the feasibility of subirrigation as an alternative to existing irrigation methods such as sprinkler irrigation. Subirrigation is expected to be a viable alternative or addition to the existing system as it could reduce the percentage of water lost to surface evaporation and runoff compared to sprinkler irrigation whilst increasing water retention & crop production, by supplying water to the root zone directly through raising the phreatic groundwater level at agricultural fields (Bartholomeus et al., 2018a; de Wit et al., 2021). Now that field pilots are nearing completion, the next step is a regional water system analysis to identify if it is feasible to widely implement subirrigation. KWR indicated the following research directions and gaps moving forward:

i. Subirrigation affects all components of the field-scale water balance: it needs a large water supply specifically in growing seasons when natural water supply (precipitation) might be limited. Only a portion is used by plants, the rest can either be 'lost' through infiltration or lateral drainage to surface water (de Wit et al., 2021; van Hintum, 2021). There is a need to identify (1) whether the above-mentioned residual fluxes from subirrigation on individual fields can benefit other fields on a regional scale (2) and how then water/subirrigation is best distributed amongst individual fields/plots in times of water scarcity.
ii. It is therefore needed to understand and quantify the propagation of subirrigation water through different compartments in the regional water balance. It is for example possible that water availability for subirrigation downstream is limited if many farmers put pressure on surface water to supply their own systems with water in the growing season. Therefore, it is needed to define the limits of regional water systems to supply subirrigation systems with water. A few existing projects have explored subirrigation with various sources of irrigation water sources (groundwater, surface water or alternatives like RWZI or industrial effluent) (Bartholomeus et al., 2018b; Brakkee et al., 2021) at the plot scale. The main results of these pilots will be discussed in the next paragraph.
iii. What is currently missing is a quick modelling tool which operates at the scale between the field scale model SWAP and the larger provincial or national level hydrological models (i.e., LHM). KWR strives for a model that can be ran quickly, with an interactive user interface which can convey information about the impact of management decisions for subirrigation within the regional (surface) water system, in an understandable way to interested stakeholders such as farmers or the waterboard. It will need to be used to provide rough estimates of the water requirements if subirrigation were to be implemented regionally.

1.2. Short background of subirrigation pilots in the Netherlands

There have so far been four field pilots with subirrigation under the KLIMAP programme with KWR. The main characteristics of these subirrigation pilots can be found in table 1 below.

Table 1: Overview of field pilot subirrigation specifications. Adapted from de Wit et al., 2021

LOCATION	LIESHOUT	AMERICA	STEGEREN	HAAKSBERGEN
SUBIRRIGATION TYPE	'Vlotter' system	'Vlotter' system	CAD	CAD
WATER SOURCE	Industrial Effluent	Groundwater	Surface Water	WWTP effluent
SOIL CLASSIFICATION	Sand, Loam layer at -1/1.5m	Sand, Loam layer at -2/.2.5m	Sand, no loam layer	Sand, Loam layer from -3m on
CROP TYPE	Grass	Grass	Grass	Maize
MONITORING TIMEFRAME	2015-2020	2017-2020	2018-2020	2016-2020

This research will focus on the area in the vicinity of the pilot near the village of America in North-Limburg. Based on the monitoring and modelling efforts for these pilots, the main effects of subirrigation implementation on the field scale water balance have been identified by Van Hintum (2021) & de Wit et al., (2021). As every pilot had distinct differences in either water source, crop type, subirrigation type or soil properties, these previous studies were able to formulate field specific suitability conditions, or as called in van Hintum (2021), "success criteria" for the implementation of subirrigation (van Hintum, 2021). The conditions are listed below in table 2.

Table 2: Success conditions for the field scale implementation of sub-irrigation. Adapted from: Van Hintum, 2021

Success Criterium	Explanation
Hydraulic permeability and resistance	First, hydraulic resistance plays a key role in the effectiveness of subirrigation. In the vertical direction, a lack of resistance will not result in the required capillary rise and raising of the groundwater level (van Hintum, Bartholomeus et al. 2019). Similarly, lack of resistance in the horizontal direction will lead to large losses of irrigation water to the local surface waters (de Wit et al., 2021). Especially, in the case of America, this last factor was deemed to be problematic as nearly 50 percent of the irrigation water was lost to surface water (de Wit et al., 2021).
Water Supply	It was found that in times where too little water was available for subirrigation (such as in the summers of 2018 and 2019) subirrigation could not maintain the required groundwater levels (de Wit et al., 2021) and can have a drying effect on the soil because it increases drainage to surface water (van Hintum, 2021)
Initial Ground- & Surface Water Levels	Research by van Hintum found that initial groundwater levels can neither be too low or too high for subirrigation to have a meaningful effect (van Hintum, 2021). Additionally, both van Hintum and de Wit et al. found that maintaining higher water levels in the surrounding surface waters was essential to limit drainage of the subirrigation water to surface waters (J. de Wit et al., 2021; van Hintum, 2021).

Additional information about the modelling performed by van Hintum (2021) & de Wit et al. (2021) and its results can be found in appendix 2.

1.3. Aim & Research questions

Based on the above, this research had three main aims. At first, this internship/thesis focussed on building system's understanding. Identifying the processes within-, links between the regional and field scale water balance and the influence subirrigation has on both was done through a literature review of existing publications on previous subirrigation pilots in the Netherlands. As a second aim, this research aimed to translate this conceptual understanding of the water balances into a water balance model in Vensim system dynamics modelling software which links the field scale and regional scale. Third & last, after the field & regional water balance models were completed, the aim was to access the impacts subirrigation might have when regionally implemented in Northern-Limburg. A number of scenarios with different underlying assumptions regarding field hydrological properties, water availability, water distribution amongst fields and water propagation downstream were explored. Three main research questions and corresponding sub-questions were formulated to split the content of this research:

1) *How can the hydrological processes at the field scale, and the impact of subirrigation on these processes, be translated into a simplified qualitative field scale water balance at both field and regional scale?*
   a) *What are the compartments and fluxes in the complete field scale and regional water balances with subirrigation?*
   b) *What simplifications can be made to these complete water balances to create a simplified qualitative field scale water balance model with subirrigation for the field- and regional scale.*

2) *How can the influence of subirrigation on the field- & regional scale water balance be modelled quantitatively using system dynamics modelling in Vensim?*
   a) *What hydrological equations are applicable to describe the hydrological processes within the simplified qualitative field water balance in Vensim?*
   b) *How can a simple field scale water balance be parameterised based on the availability of input data from previous field pilots and local hydrology/climate?*
   c) *Are the modelled water balances & water tables at the field scale verified by matching the SWAP model?*
   d) *How can the field scale water balance be scaled up to predict the regional agricultural water demand for subirrigation in Vensim?*

3) *How can the developed Vensim model be applied to explore scenarios for challenges/opportunities faced during the regional upscaling of subirrigation in Limburg?*
   a) *How do varying soil conductivity and resistance influence the water balance components in the model?*
   b) *How are subirrigation, the field water balance and surface water levels influenced by decreasing surface water supply and precipitation?*
   c) *How does the Vensim model react to altered initial surface water- and groundwater levels?*
   d) *How much surface water supply is needed roughly in the area of interest at a regional scale?*
   e) *In what ways does the parallel or serial connection of sub-irrigated fields to the regional surface water influence the regional surface water availability?*

2. Theory

To understand how to make a Waterbalance model, it is first essential to understand the concepts making up the field-scale and regional groundwater balances and to define the basic concepts underlying the modelling software used for this research.

2.1. Systems Dynamics Modelling (SDM) in hydrological applications

One way to convey information about complex, non-linear physical and social systems and their interactions is by using system dynamics modelling (SDM). SDM has been applied in a variety of fields and has been applied in the field of water resources management for at least 40 years (Turner et al., 2016). In its essence, SDM for water resources management builds on a thorough understanding of the hydrological cycle at different spatial and temporal scales. As argued by Zhang et al. (2002), most environmental problems which are experienced nowadays stem from influencing parts of this cycle without knowing the direct effects of this intervention on the system in its' entirety (Zhang et al., 2002). Natural and social systems constantly interact, and interactions are dynamic over time and space with different feedback processes needing to be considered (Zhang et al., 2002). Using computer modelling of these processes can be a cost-efficient alternative to field trials and experiment. Combined with field experiments, SDM can consider climate variability, cover larger areas and time frames, whilst also depicting linkages and feedbacks in easily understandable and changeable user interfaces which allow for public participation in the set-up of models (Zhang et al., 2002).

The process of SDM is often split into distinct steps. Different visual representations of this process exist, but broadly they follow the framework as introduced by Rubio-Martin et al.,2020, which can be seen below in figure 4.

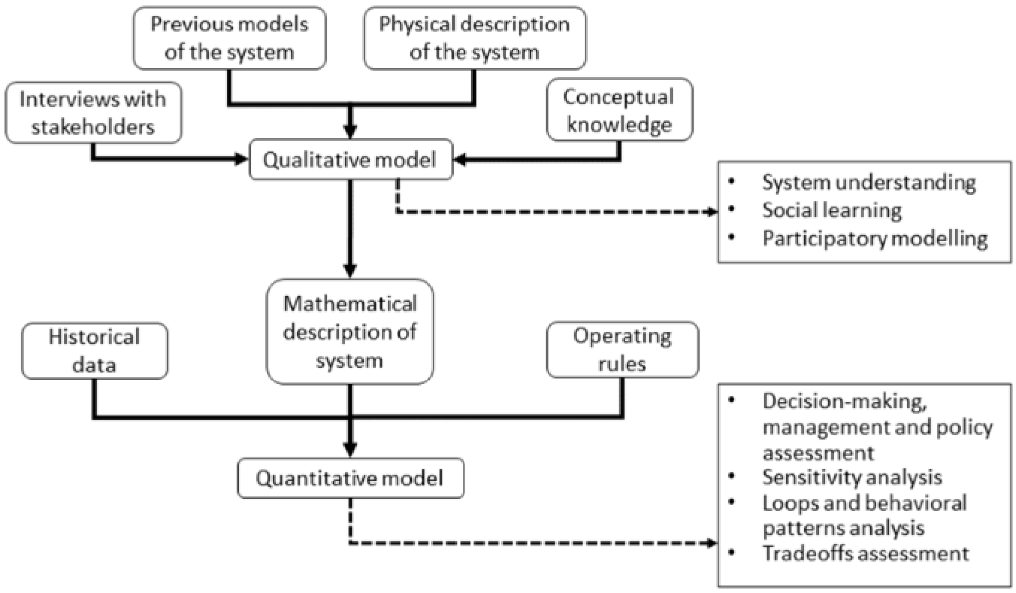
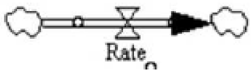
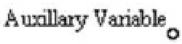


Figure 4: Framework for the process of SDM. Source: Rubio-Martin et al., 2020

The first part of the modelling effort focusses on problem identification and system understanding. A qualitative model is constructed in which different compartments of the water balance and their relation to each other are defined. A physical description of the system and conceptual knowledge about the water balance play a key role. (Rubio-Martin et al., 2020). In this research, Vensim SDM simulation software is used which makes use of a user interface with stock-flow diagrams. The conceptual model will serve the purpose of translating the existing knowledge about the field water balance into a simplified quantitative SD-model. Generally, system dynamics models consists of four building blocks which make up their functionality (table 3).

Table 3: Terminology & explanation of SDM building blocks

SDM Building Block	Vensim model interface	Function	Examples
Stocks		Storages or levels which "Depict the state of a system" (Bai et al., 2021)	Lake, reservoir, groundwater aquifer etc.
Fluxes or rates		"Activities that fill or drain stocks"(Elmahdi et al., 2005)	Rivers, streams, evaporation, precipitation, percolation etc.
Constants/Auxiliaries		Establish & quantify the relationship amongst variables (Elmahdi et al., 2005; Turner et al., 2016)	Temperature, slope, resistance, crop type etc.
Connectors		Establish the relationship amongst variables (Elmahdi et al., 2005)	

Once the quantitative model has been constructed, there is a need for model validation and adjustment (Forrester, 1994). SD-models also lend themselves perfectly to explore different 'what if' scenarios for different management strategies, as models can be easily adjusted to different settings and have short runtimes (Beall et al., 2011). Within the Vensim software used in this research, parameters can easily be adjusted via slider-bars to simulate different land use types or management strategies & scenarios.

2.2. Water Balances (with subirrigation)

Instrumental to the application of SDM in hydrological contexts is the concept of the water balance and having a thorough understanding of its components. The concept of the water balance stems from the thorough understanding of the hydrological cycle and the law of mass conservation (Zhang et al., 2002). In accordance with the law of mass conservation, ''any change in the water content of a soil volume during a specified period must equal the difference between the amount of water added to the soil volume and the amount of water withdrawn from it'' (Zhang et al., 2002) . In its most simplistic form this will look as follows:

$$\Delta\, Storage = Input - Output$$

This form might be too simplistic to describe all the components in the field- and regional scale water balance as these balances are often made of multiple interconnected storages, inputs and outputs.

For the field scale water balance considered in previous research, the soil water balance of figure 5 below is followed.

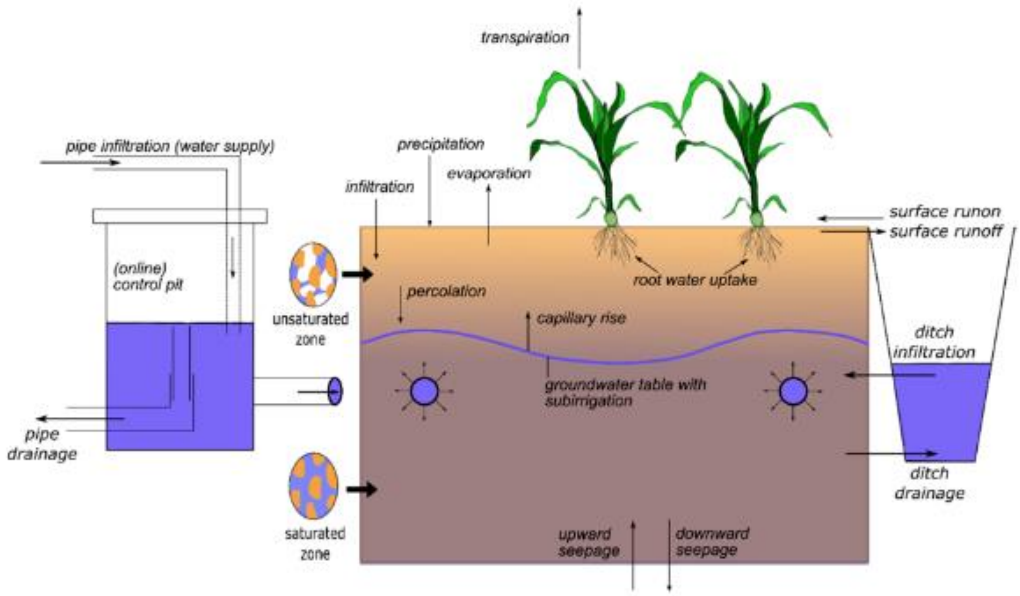


Figure 5: Schematic of soil water balance components at the field scale. Source: de Wit et al., 2022

In its main equation form, the soil water balance at the field scale as seen in figure 5 follows the equation:

$$\text{Precipitation} + \text{surface inflow} + \text{subirrigation} + \text{lateral inflow (from ditch)} + \text{upward seepage} =$$
$$\text{plant evaporation} + \text{surface runoff} + \text{transpiration} + \text{soil evaporation} \qquad (1)$$
$$+ \text{lateral drainage (to ditch)} + \text{pipe drainage} + \text{storage change} + \text{downward seepage}$$

As stressed in literature by Burt (1999), it is of prime importance to clearly define the spatial and temporal boundaries of your water balance (Burt, 1999). In this paper, we will often speak about either field scale or regional scale. Field scale in this case delineates the water balance as shown in figure 5, with the focus on a 1D-cross section of agricultural land with subirrigation requirements and its connection to a surface water body. Regional scale, in this case refers to the sub-catchment scale such as in figure 6 below. At this scale individual fields are linked to the larger catchment system with shared groundwater and surface water flows which need to be divided between multiple land uses. The study area will be further elaborated in section 3.1.

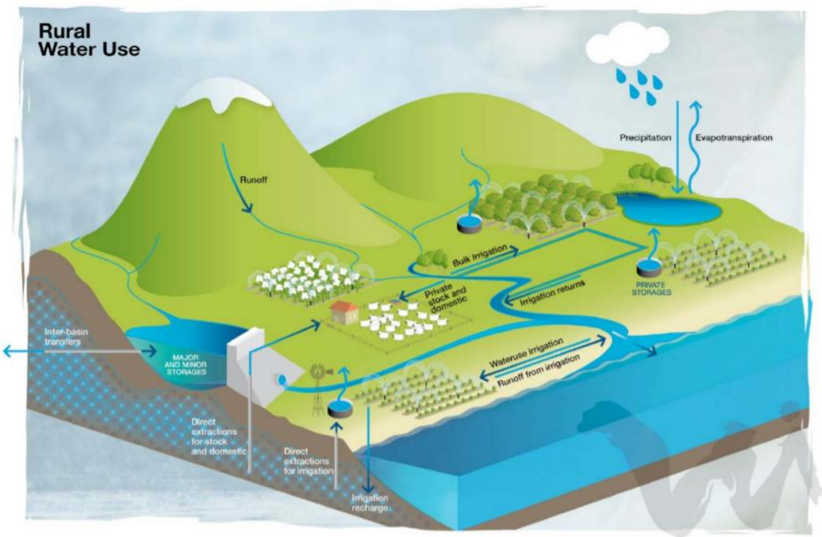


Figure 6: Regional/Catchment Scale water balance. Source: Frost et al., 2010

The field scale and regional scale water balances are linked in multiple ways, as the field scale balance is nested in the regional scale balance (Frost et al., 2010). Therefore, the flows and stocks of both balances are intrinsically linked to one another. As put by the Guidance document on water balances for the implementation of the EU Water Framework Directive (WFD), ‘’agriculture, when irrigated, impacts evapotranspiration, interception & percolation.” This is in line with the previous findings on the implementation of subirrigation which increased water returned to the surface water (lateral flow), groundwater percolation and crop transpiration & evaporation (de Wit et al., 2021). ‘Good’ water management at a field scale by farmers might thus increase evapotranspiration and water being lost to the atmosphere/surface water instead of being recycled, thus influencing the water availability on a regional level (European Commission, 2015). There are positives and negatives to focusing on field scale or regional scale alone in any case. Developing water balances for small scales might result in detailed information but will not be helpful for identifying water management challenges created by policy/strategy changes which are applied at a catchment scale. On the other hand, detail might be lost and interactions between local systems can be overlooked when focusing on the regional scale alone (European Commission, 2015).

2.3. Hypotheses

It was hypothesized that due to the large water requirements in the growing season, when water supply tends to be limited, extensive regional implementation of subirrigation might be problematic. When multiple fields rely on the same surface water supply source, the high water demand for subirrigation during this timeframe might result in declining surface water levels & downstream water shortages. However, it also was hypothesized that the expected raising of the groundwater table by subirrigation would have positive effects that propagate outside of the field scale. Based on the hydraulic gradient which is created by the artificial increase in the groundwater table, it is expected that the plots surrounding the ones that are fed with subirrigation but do not have subirrigation themselves will experience a rise in the groundwater table based on the hydraulic gradient created between the sub-irrigation and the main discharge ditch water table. Therefore, it was expected that subirrigation in small parcels would cost more water compared to conventional sprinkler irrigation due to the large gradient (delta h) with a relatively small length (L/delta x) between the ditch and the elevated groundwater table, causing larger lateral losses to surface water. (Based on vadose zone flow to drains (Ritzema, 1992)).

3. Materials and methods

This section will focus on explaining how the research questions were answered. It briefly describes the area for which the model was developed, the workflow/process that was followed in model development, and the scenario's modelled in Vensim.

3.1. Research Area

This research primarily focussed on the area directly bordering the previous field pilot in America, Limburg (Mariapeel). The region can be seen in figure 7 below. The area contains a large protected 'Hoogveen' area, which is protected under Natura 2000 legislation, and agricultural area (van Hintum, 2021). The main supply of surface water to the area comes via the 'Noordervaart', a repurposed shipping channel now solely used to supply water to the Peelkanalen for the purpose of supplying nature areas and agriculture. Adaptations are underway to increase the water supply to the Noordervaart from 3 m^3/second to 6 m^3/second by 2025 (Rijkswaterstaat, 2022c). In 2025, the day-to-day management of the Noordervaart will also be handed from its current owner, Rijkswaterstaat, to Waterschap Limburg (the regional water board)(Rijkswaterstaat, 2022a).

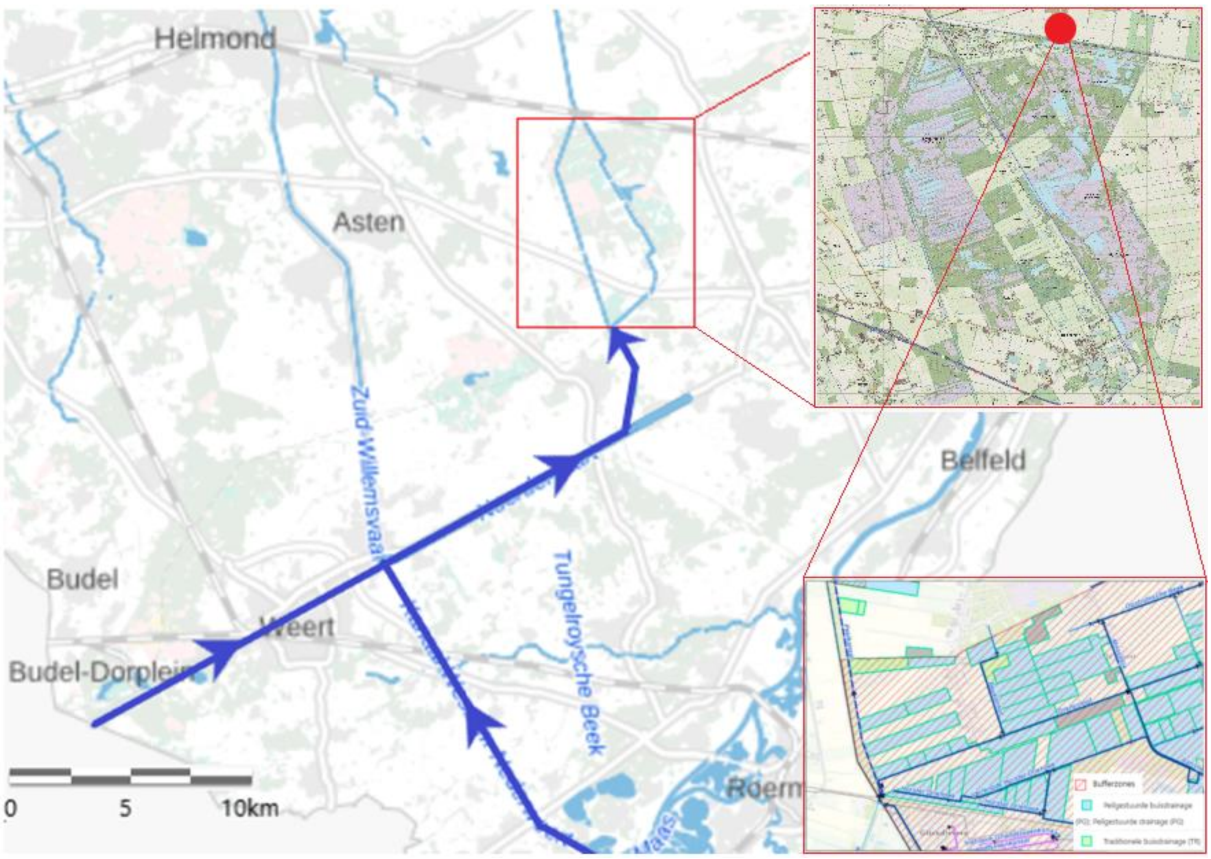


Figure 7: Regional overview of the study area (red) with the main supply direction of surface water (blue). Zoomed in is the area of interest for Waterschap Limburg which is located entirely within the hydrological protection zone of the Deurnsche- & Mariapeel area (dashed red lines). Blue squares indicate fields equipped with controlled drainage (note: not subirrigation). Adapted from: Rijkswaterstaat, 2022a

The subsurface for the America pilot is made up of a sandy topsoil with a more highly resistant clay layer with a thickness of 0.3m at a depth of 2 meters below surface level (de Wit et al., 2021). Below this confining layer, the soil is classified as fine to medium coarse sand again. For the implementation of subirrigation in the America field pilot, groundwater is being pumped with a maximum capacity of 10 m^3 per hour from a well that is situated at a depth of 11-16 meters below surface level (Bartholomeus et al., 2018a).

3.2. General Workflow

The workflow in this research followed the process steps as indicated in the framework by Rubio-Martin et al. (2020) (figure 4). The methodology of this research was subsequently split in 3 phases. For both the field scale and regional scale modelling, these 3 phases where followed. As the field scale model was a required input for the regional scale modelling, it was only after the field scale model had entered phase two that phase one could be started for the regional scale modeling. A visual representation of the workflow followed in this research can be seen in figure 8 below. The phases are:

- Model Setup
- Model Application
- Model Evaluation

A further description of the steps in each phase can be found in appendix 3.

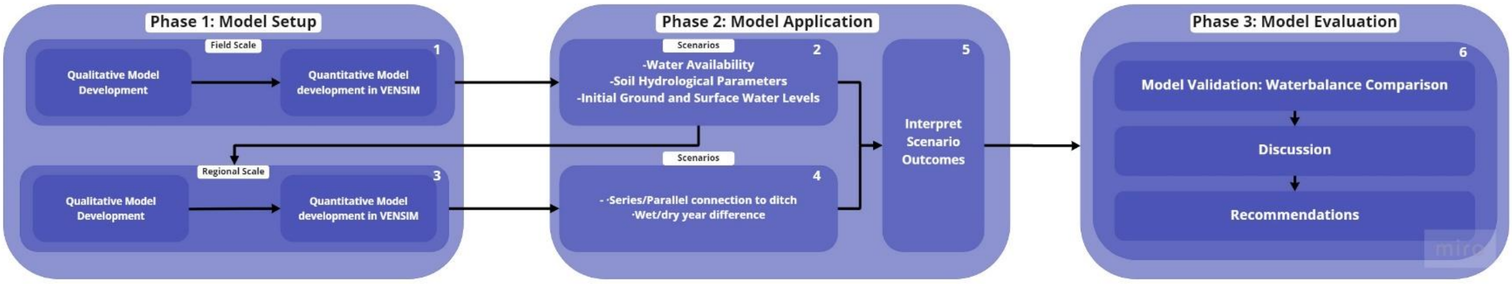


Figure 8: Workflow Diagram

3.3. Phase 1: Model Set-up

3.3.1. Qualitative Model Set-up

3.3.1.1 Field Scale

The modelling effort for this thesis started from scratch and took its inspiration from previous SWAP modelling. The water balance at the field scale is formulated according to equation 1 (paragraph 2.2). This water balance for the soil compartment is accompanied by a stock representing the ditch to which the field discharges. The ditch has an inflow and outflow and further receives water from the field by lateral flow through the soil matrix or via surface runoff. For the basic model, the subirrigation system was kept in its most basic form: there will only be subirrigation when the water level in the ditch is higher than the intake height, and there will be a constant pumping rate for subirrigation in the growing season. Subirrigation in the America-pilot is operating with groundwater, but in this modeling case, the choice was made to switch to surface water based on the research aims.

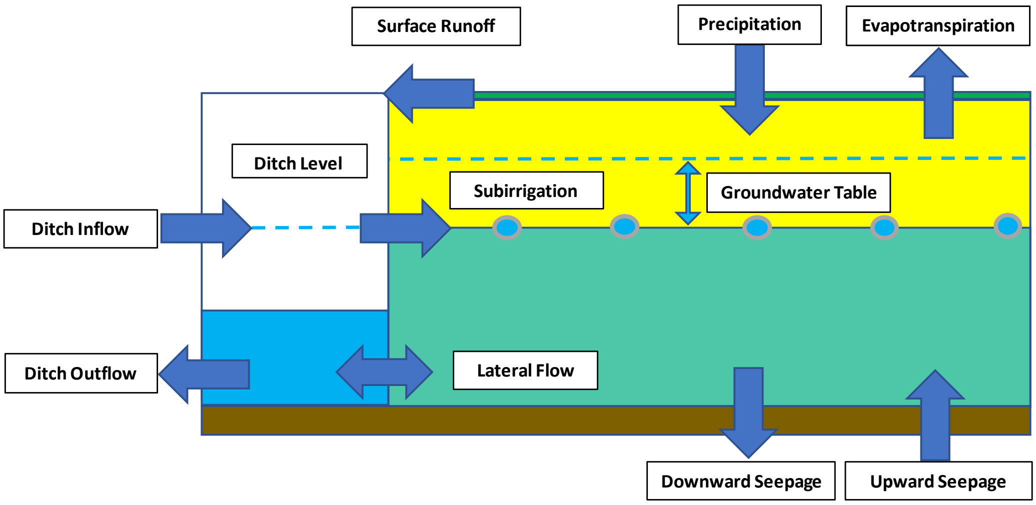


Figure 9: Conceptual model for the field water balance model (cross-sectional view)

As can be seen in figure 9 above, the unsaturated zone was not included as a stock, as the goal of this research was not so much identifying the effect of subirrigation on plant transpiration and crop production, but more to get an idea of the water balance components and influence of subirrigation on the groundwater table & regional surface water availability. The terms plant evaporation, soil evaporation and transpiration where combined under the variable Evapotranspiration. For precipitation, it was assumed that all effective precipitation (thus minus evapotranspiration) either ends up in the phreatic groundwater or runs off to the local surface water. Although the deeper groundwater stock was kept outside of the model boundaries, the annual fluctuations in its hydraulic head were included to grasp the size of the vertical fluxes within the soil. Based on this fluctuation and the hydrological characteristics of subsurface, the seepage fluxes were determined. The upper boundary of the model was set at surface level, or 'maaiveld' in Dutch. Groundwater tables are subsequently expressed in millimetres below surface level/maaiveld (mm -mv).

3.3.1.2 Regional Scale

For the regional scale, different ways of connecting individual fields to waterways were considered. In this paper parallel connection describes the situation where fields are situated on opposite sides of the ditch. Another possible connection is a serial connection. Two types of serial connections are considered within this research. In the first type, both fields are adjacent to one another and discharge on the same part of the waterway in which the groundwater & surface water from the furthest field discharge through the field bordering the main discharge ditch. In the second type, the second field is downstream from the other. All different types of connections influence the regional ground- & surface water levels. These two basic types of connections need to be understood to further expand the model to the regional scale. A visual representation of these concept can be seen in figure 10 below.

Figure 10: Different options for regional connection of individual fields (top view)

3.3.2. Quantitative Model Set-up

3.3.2.1 Data Inventory & Selection

Most of the required input data was stored in online accessible, open databases or in databases owned by KWR or research partners of KWR for the field scale pilots. The meteorological data was abstracted from the nearest KNMI measurement station which is located in Arcen, Limburg (registration number 391) (de Wit et al., 2021) The choice was made to use the input data for the years 2017, 2018 & 2019 as this range covers both average and dry conditions and is well covered in the reports from the previous Lumbricus programme (de Wit et al., 2021). The data on local and regional hydrology or results from the field pilots in/near the research area are supplied by the KWR database for KLIMAP or provided to KWR by Waterschap Limburg. The exact data types and their sources can be seen in table 4 below. No ethical issues are expected as the data used contains no personal confidential information and is owned by KWR or KLIMAP research partners and farmers who have mutually agreed on the data collected under the field pilots.

Table 4: Data Sources and Types

Data from KNMI (meteorological)	Data from KWR (SWAP/HYDRUS & measurements & models)	Data from Waterschap Limburg	Data from Literature
• Precipitation • Reference Evapotranspiration according to Makkink (1957)	• Drain outflow • Hydraulic heads • Soil resistance (horizontal, vertical) • Subirrigation water volume needs per area/time • Ditch level • Operating rules • Pilot field area	• Main channel inflow • Area of interests (size)	• Conductivity of soils • Porosity • Mathematical background on sub-surface flow

3.3.2.2 Operating rules and mathematical background

Field Scale

As the two stocks represented in the Vensim model represent real water storage, a conversion will be needed to obtain the groundwater table above the less conductive loam layer. To move from the groundwater table to groundwater content, the porosity of sandy soils is used, with porosity defining the fraction of void space per volume unit of soil matter. In the Netherlands, this value closely varies around 0.38 or 38% for sandy soils such as those in the research area. For this research, an effective porosity of 0.36 was chosen, at the low end for the effective porosity in fine sand soils (Grondwaterformules.nl, 2022).

All flows in the Vensim model will be considered as 1D fluxes in mm per area unit (m^2). Flow between the soil groundwater reservoir and surface water is governed by Darcy's equation for both the horizontal and vertical flow components in the soil matrix itself (Kroes et al., 2017).

$$q = Q/A \tag{2}$$

And

$$q = -k\,\frac{\partial h}{\partial x} \text{ or} = -k\,\frac{\partial h}{\partial z} \tag{3}$$

A reasonable portion of underlying operating rules have been based on the parameterisation of previous SWAP runs for the America field pilot. The lower boundary condition for the model is formed by the fluctuation in deep groundwater hydraulic head. As formulated by de Wit et al., the fluctuations in hydraulic head for the deep groundwater closely resemble a sinusoid wave with an average head of -1400 millimetres below surface level and an amplitude of 500 millimetres each year (de Wit et al., 2021). Based on the measurement data for January 2017 from the America pilot, the initial groundwater table was set at 1 metre below surface level (de Wit et al., 2021). In the Swap model runs, the system's resistance to downward seepage was set to 1013 days based on model calibration. As the loam layer in the America case has a thickness of roughly 20 centimetres, the hydraulic conductivity (k) value used for the calculation of the Darcy-flux was calculated to be 0.2 mm/day according to formula 4. For the horizontal k-value, a length of 100 metres from the middle of the field was chosen, considering a square field with 200m length and width to measure four hectares of surface area, thereby rounding off the area of the America pilot (3.77 ha). The drainage resistance in SWAP was set to 295 days (de Wit et al., 2021). Therefore, according to formula 4 below, a horizontal k value of 340 mm/day was chosen. As the parameterization of hydraulic conductivity proved difficult, runs with alternative values for vertical and horizontal conductivity have been ran besides the above ones. These can be found in appendix 4.

$$c = \frac{dx}{k} \text{ or } k = \frac{dx}{c} \tag{4}$$

For the upper boundary condition, the groundwater table was limited at 0 mm below surface level, at which point any excess rise would be converted to surface runoff, considering the soil to be saturated. Evapotranspiration was assumed to be based on the reference Evapotranspiration according to Makkink (1957) as provided for the Arcen KNMI station (KNMI, n.d.). Since grass is taken as crop type (see table 1), potential evapotranspiration is assumed to be equal to the reference evapotranspiration. To calculate actual evaporation due to limited soil water availability for crops, a limitation was built in to the potential Evapotranspiration. This was done by multiplying the potential evapotranspiration by a reduction coefficient such as was formulated by Feddes et al., 1978 (see figure 11 below)

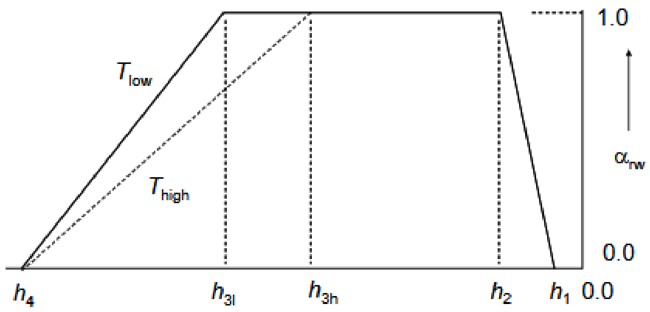


Figure 11: Feddes curve for the reduction coefficient of root water uptake and thus transpiration as a function of the soil water pressure head. Source: Kroes et al., 2017

The curve chosen in the model is only a loose adaptation, as the original Feddes curve is based on pressure head for the unsaturated zone and only accounts for transpiration, whereas we use the groundwater table depth and evapotranspiration similar to the module used for MODFLOW by Zwamborn (1995) (Zwamborn, 1995). The curve was drawn based on Freese (n.d.), who indicated that the extinction depth (where no water is available for evapotranspiration anymore), and thus h4 (figure 11), for sandy soils is between 145 and 170 cm below surface level.

$$Et_{act} = Et_{pot} * \alpha \quad (5)$$

Lastly, for the standard field model, the ditch inflow was equal to subirrigation requirement in the growing season, as it was assumed that it was possible to maintain ditch levels based on waterboard assurances. Although, SWAP uses a 4 mm/day subirrigation requirement, the Vensim model uses a 5 mm daily requirement based on correspondence with experts within KWR. Whereas SWAP uses a constant supply of water by subirrigation in the growing season, the Vensim model was operated such that once a target groundwater table of 50 cm below surface level was reached, subirrigation was turned off. A fixed weir function was used to control the ditch outflow, based on the formulation used in Kroes et al., 2017:

$$q_{dis} = \frac{Q_{dis}}{A_{cu}} = \frac{\alpha_{weir}(\phi_{sur} - z_{weir})^{\beta_{weir}}}{A_{cu}} \quad (6)$$

This formulation of the ditch outflow is based on a power function based 'stage discharge'/Q-h relationship, where α_{weir} is a function of the weir width, which, under the assumption of a rectangular weir is roughly α_{weir} = 1.7 x weir width (Kroes et al., 2017). B_{weir} is a discharge exponent and is formulated in de Wit et al. as being 1.4765 (de Wit et al., 2021; Kroes et al., 2017). A_{cu} is the cross-sectional area of the weir.

Another operating rule was the maintenance of summer and winter levels in the ditch, which were based on the SWAP parameterisation in de Wit et al., 2021. The winter level was set at 1800 mm below surface level, whereas the summer level was set to 1600 mm below surface level (de Wit et al., 2021). A more elaborated description of the parameterisation, operating rules and code underlying the standard field model can be found in appendix 2. Finally, for the application of subirrigation, a deviation was made compared to the SWAP model runs. Whereas in SWAP the initiation date for subirrigation was coinciding with the increase in ditch level towards summer level, the decision was made to split the starting dates for subirrigation and the ditch level change by a month. This decision was made to better distinguish the impact of both management choices on modelled groundwater levels and flows.

Regional Scale

The regional scale models which explore different interlinked fields use the same governing equations and operating rules, with the addition of a Darcy based groundwater flow component for the flow between fields, such as previously described in equation 3. Whereas a completely realistic representation of a field would include flow in both negative and positive x & z directions, the regional models consider either 1 or 2 of these flows, following from the 1D structure of the model. For the remaining directions, no flow has been defined and these thus act as a no-flow boundary in the model.

3.4. Phase 2: Model Application

3.4.1. Field Scale Scenario Modelling

Based on the success criteria by van Hintum (2021), the scenarios which are run for the field scale model will serve the purpose of validating the success criteria and providing an insight into the sensitivity and accuracy of the Vensim model (compared to previous SWAP modelling). It was decided to use the 2017 model as the base for the scenarios which were ran, as 2017 is considered the most representative year, since 2018 and 2019 were very dry and not the most representative for average Dutch weather conditions.

Table 5: Sensitivity scenarios for the field scale model runs. (Bold values indicate standard model parameterization)

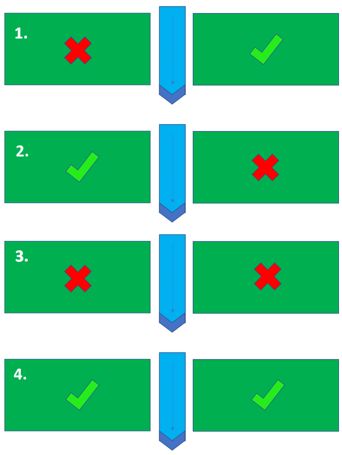
Scenario Set	Goal	Scenario Name	Parameters	Parameter Changes
Variation in conductivity loam layer	Identifying the sensitivity of model behaviour for areas with a thinner, or no resisting layer	Field scenario k vert 0.2	Kvert	**0.2 mm/day**
		Field scenario k vert 2		2 mm/day
		Field scenario k vert 20		20 mm/day
Variation in conductivity sand layer	Identifying the sensitivity of model behaviour for more or less conductive soils	Field scenario k horiz 1	Khoriz	5 mm/day
		Field scenario k horiz 10		10 mm/day
		Field scenario k horiz 50		50 mm/day
		Field scenario k horiz 150		150 mm/day
		Field scenario k horiz 340		**340 mm/day**
Variation in Ditch Inflow	Identifying the model behaviour in times of limited water availability	Field scenario ditch inflow 1	Ditch Inflow Rate	1 mm/day
		Field scenario ditch inflow 3		3 mm/day
		Field scenario ditch inflow 5		**5 mm/day**
		Field scenario ditch inflow 7		7 mm/day
		Field scenario ditch inflow 9		9 mm/day

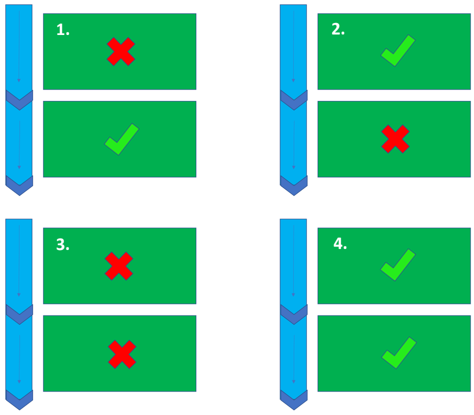
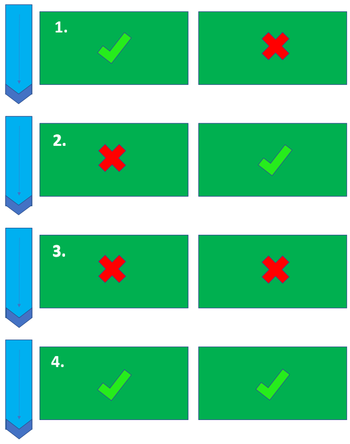
Variation in Initial GW-table	Identify the model behaviour for predicting suitability of subirrigation for areas with deeper groundwater tables	Field scenario Init. GW level -500	Initial Field GW-Table, H GW Deep	-500 mm, base of sinus wave at -900 mm
		Field scenario Init. GW level -1000		**-1000 mm, base of sinus wave at -1400 mm**
		Field scenario Init. GW level -1500		-1500 mm, base of sinus wave at -1900 mm
		Field scenario Init. GW level -2000		-2000 mm, base of sinus wave at -2400 mm
Variation in Ditch Level	Identify the reaction of the model if the management choice would be made to maintain higher surface water levels.	Field scenario Init Ditch Level -1800	Initial Ditch Level, Weir Level	-1800 mm, -1800 mm all year
		Field scenario Init Ditch Level -1800, -1600		**-1800 mm, -1800 mm winter, -1600 mm summer**
		Field scenario Init Ditch Level -1600		-1600 mm, -1600 mm all year
		Field scenario Init Ditch Level -1600, -1400		-1600 mm, -1600 mm winter, -1400 mm summer

3.4.2. Regional Scale Scenario Modelling

In this research, it was assumed that individual plots can be linked either in series or parallel to the surface water or to each other. When linked in series, water from one plot crosses through another plot before discharging on the surfaces water (depending on the regional gradient). When parallel, plots run perpendicular to a drainage ditch.

Table 6: Upscaling scenarios description for different link types between fields & ditch. A red cross indicates the absence of subirrigation whereas a green checkmark indicates that subirrigation was present in the scenario. The dark blue arrow at the end of the ditch indicates a weir.

<table>
<tr><th>Scenario Set</th><th>Scenario runs</th><th>Description</th></tr>
<tr><td>Parallel Connection</td><td>
</td><td>In all the explored scenarios, the main model alterations were either the in- or exclusion of subirrigation for one of the two or both plots. The agricultural plots are located on opposite sides of the main supply ditch.</td></tr>
</table>

Series Connection, Downstream		In all the explored scenarios, the main model alterations were either the in- or exclusion of subirrigation for one of the two or both plots. The agricultural plots are both on the same side of the ditch, with plot 2 downstream from plot 1.
Series Connection, Adjacent		In all the explored scenarios, the main model alterations were either the in- or exclusion of subirrigation for one of the two or both plots. The agricultural plots are on the same side of the ditch, with plot 2 not bordering the ditch but instead being situated adjacent to plot 1.

The main points of interest from these regional upscaling scenarios are the following:

1) Identifying the effect of subirrigation on neighboring fields
2) Identifying the pressure of subirrigation on surface water availability & vice versa
3) Identifying the losses to downward seepage and lateral flow to the surface water

Additionally, based on the known size of the field scale pilot and the water balance resulting from the field scale modelling in Vensim, an extrapolation was made for the subirrigation water requirements at the regional scale. Using the same linear extrapolation methods as applied by van Hintum, 2021 for the Deurnsche peel area and as used by de Wit et al., 2021 for the field pilot in Stegeren, the water requirements for subirrigation near the America pilot were calculated as if it were applied to a larger percentage of the area of interest for Waterschap Limburg. Modelling efforts for the year 2017 were used as the basis. From the standard run with and without subirrigation, the effect of subirrigation according to the model was abstracted. With the known area of the pilot field (3.77 ha) compared to the total area of interest (350 ha), the effects of subirrigation for the region could be extrapolated.

3.5 Phase 3: Model Verification & Evaluation

After model setup & the scenario runs for the field scale model, the model outputs & parameterization were evaluated. Using previous SWAP water balance output data and previously modelled groundwater levels from the field pilot in America by KWR, the deviation between SWAP runs and the new VENSIM model runs were compared. Goal of this evaluation was not to 1:1 reproduce previous SWAP results or to recreate the measurement data, but more to compare &

explore whether the Vensim model with the simplifications and assumption within it, can still produce results within the same order of magnitude as SWAP. Once the model was validated, the research moved to scenario running. If not, the underlying assumptions, operating rules & equations were re-evaluated in an iterative process.

4. Results

The following section will describe the main results for the modelling efforts at the field- and regional scale respectively. Apart from the standard model parameterisation, alternative scenarios were explored (appendix 4).

4.1. Field Scale

4.1.1. VENSIM model

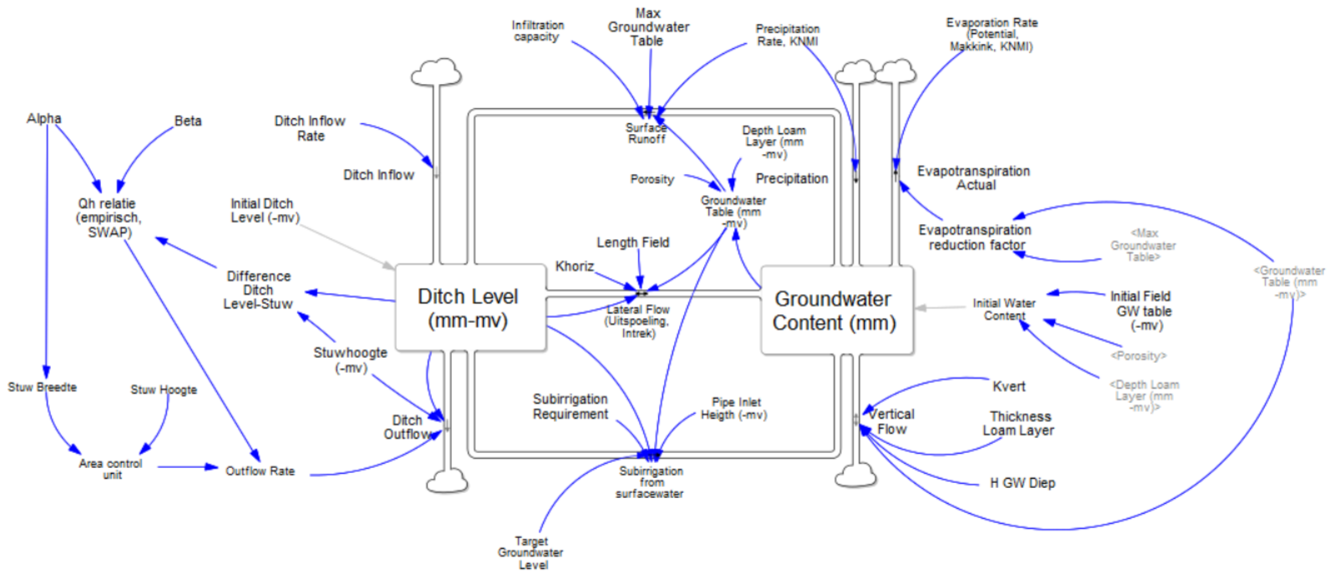


Figure 12: Model structure in Vensim PLE Plus

After the conceptual model structure (figure 12) for the simplified field scale water balance (paragraph 3.3.1.1) was decided upon, it was translated to Vensim with the model interface above as the definitive version for the field scale. The qualitative model in Vensim consists of two main stocks: Ditch level and Groundwater content. As the stocks represent real water volume, the groundwater table was calculated as a separate variable. The upper and lower boundaries are depicted as clouds. For the groundwater content, these are formed by the atmosphere and the subsurface layers below the loam layer. The atmospheric flows which are included are precipitation and evapotranspiration. At the lower boundary, vertical flow is governed by the annually fluctuating deep groundwater pressure head. For the Ditch level, the boundaries are defined by the inflow rate from upstream areas and the outflow rate over a fixed weir. Finally, 3 flows connect both stocks, with subirrigation flowing from the ditch to groundwater, lateral flow being bi-directional and surface runoff flowing from the groundwater towards the ditch stock. In total the basic field scale model includes 2 stocks, 8 flows and 28 parameters. (See appendix 2 for overview Vensim Inputs).

The model was run separately for the years 2017, 2018 and 2019 as well as in a time series of the 3 years together with time steps of 1 day. As can be seen in figure 13 below, subirrigation increased the water table in the growing season by a maximum of 90 centimeters (13A), whilst not causing the ditch level to drop below the weir level (13B). As can be seen in figure 13 C, D & F, the higher groundwater tables because of subirrigation in turn resulted in increased lateral-, vertical flow & evapotranspiration, respectively.

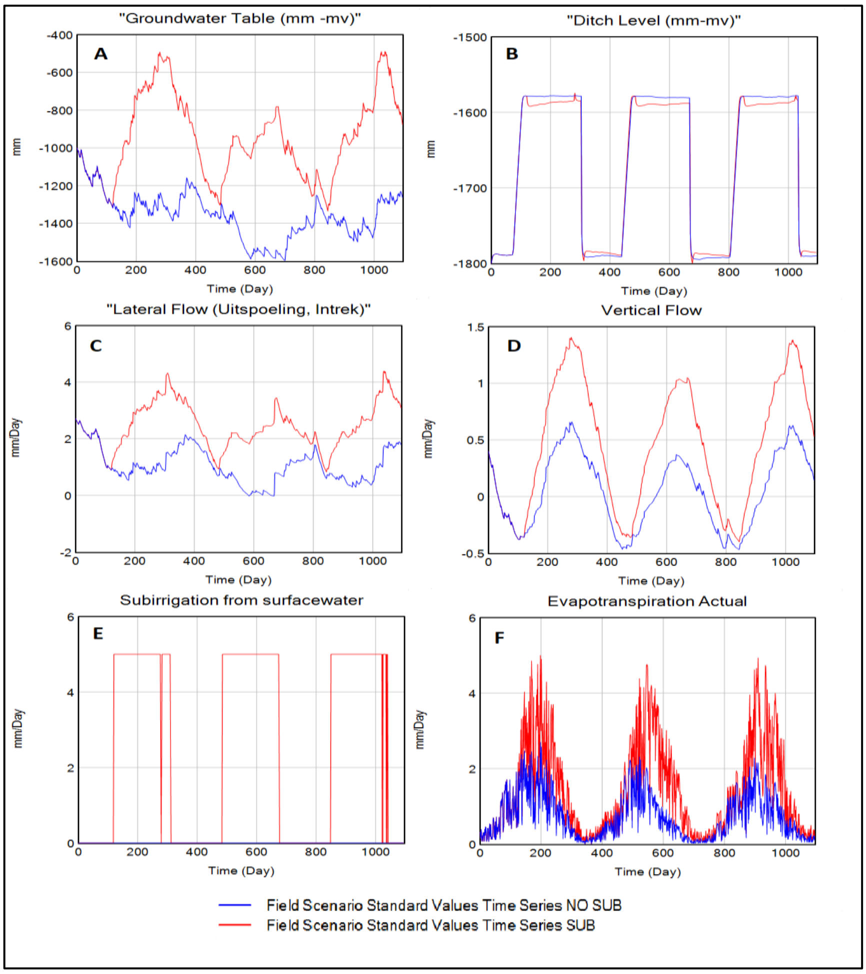


Figure 13: Model outputs for the time series run (2017-2019) of the field scale model with standard input values. The model was run respectively with subirrigation (red line) and without subirrigation (blue line). The scale on the x-axis is in days with the total of 1095 for the three years combined.

Differences in groundwater level due to annual variation in precipitation and evapotranspiration can be distinguished in graph 13A. For the year 2018, it proved to be infeasible to reach the optimal groundwater level in the growing season compared to the years 2017 & 2019 (middle peak, 13A). The achieved highest groundwater table in 2018 is 29 centimeters lower compared to the other two years. It must be noted that running the model for a single year or for a time series produced marginally different outcomes for the water balance, as the initial groundwater table at the start of the years 2018 and 2019 differs from the set value of -1000 mm BSL. Finally, as can be seen in figure 13E, in 2018, because of drought, constant subirrigation was insufficient in maintaining let alone reaching the target groundwater level of -500 mm BSL. This suggest that in dry periods, subirrigation requires either more water, or needs to be supplemented with conventional sprinkler irrigation. Even though the 2019 growing season started of equally dry compared to 2018, wetter conditions in the second half of 2019 resulted in a steep rise of the groundwater table (13A). As a result, the target groundwater level of -50 cm BSL was reached on 5 days, in which subirrigation was turned off (13E).

4.1.2. Scenario Modelling

4.1.2.1. Ditch Inflow Scenarios

To identify the model behavior for different quantities of ditch inflow in times of drought, 4 scenarios were run besides the standard model parameterization of 5 mm ditch inflow per m^2 per day.

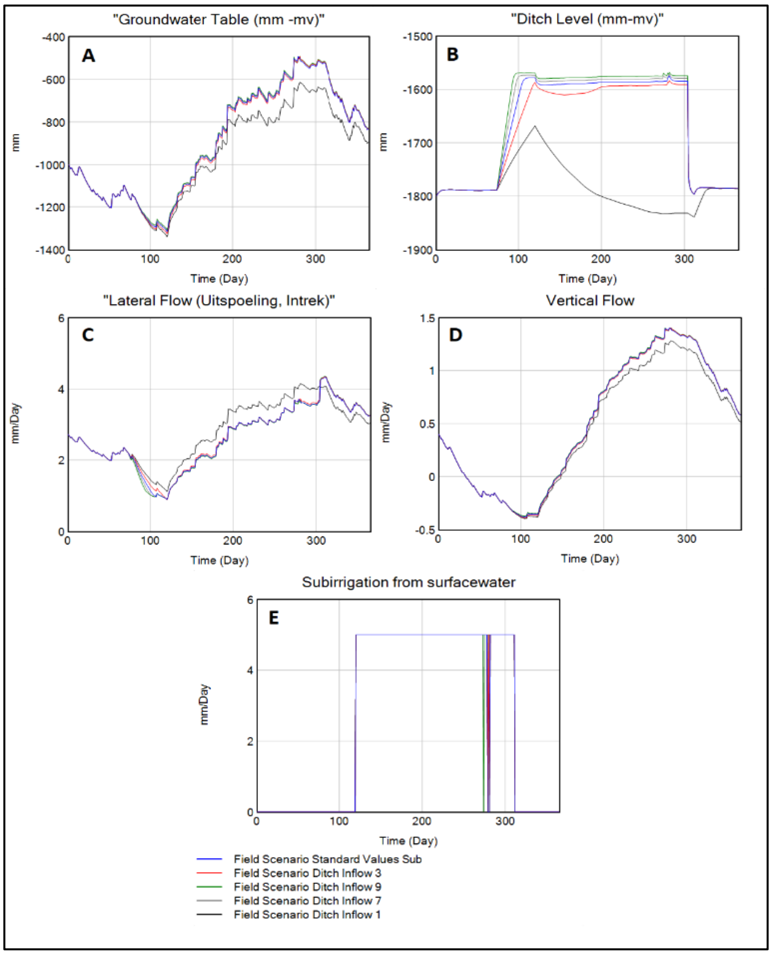


Figure 14: Main model outputs for the ditch inflow field scenarios. Lines represent 1mm(black), 3mm(red), 5mm(blue),7mm(grey) & 9mm(green) per m^2 ditch inflow.

As can be seen in figure 14, the main results from the ditch inflow scenarios are as follows. For every ditch inflow scenario down to as low as 3 mm per m^2 of ditch inflow, the ditch level can be maintained during the growing season with subirrigations active (14B). The time needed to reach the required ditch level does however increase, causing slightly higher lateral flow towards the ditch around t=80, the lower the inflow (14B). Only for a ditch inflow of 1 mm per m^2, the inflow is insufficient to maintain the desired summer levels in the ditch (14B). As can be seen in figure 14, the implementation of subirrigation leads to the ditch falling dry towards day 300 in this scenario. As a result, lateral flow from the groundwater towards the ditch increases and the groundwater table declines compared to the other ditch supply scenarios (14A, C & D). At its peak, this difference in GW-table amounts +/- 10 cm (14A). For the scenario with 9mm of ditch inflow, the preferred groundwater table is reached earlier, causing subirrigation to be shut of earlier in the season (14E).

4.1.2.2. Weir Level Scenarios

In the next scenario runs, the weir level was altered to simulate an intervention by waterboards to maintain higher surface water levels, as was advised in previous research findings (van Hintum, 2021).

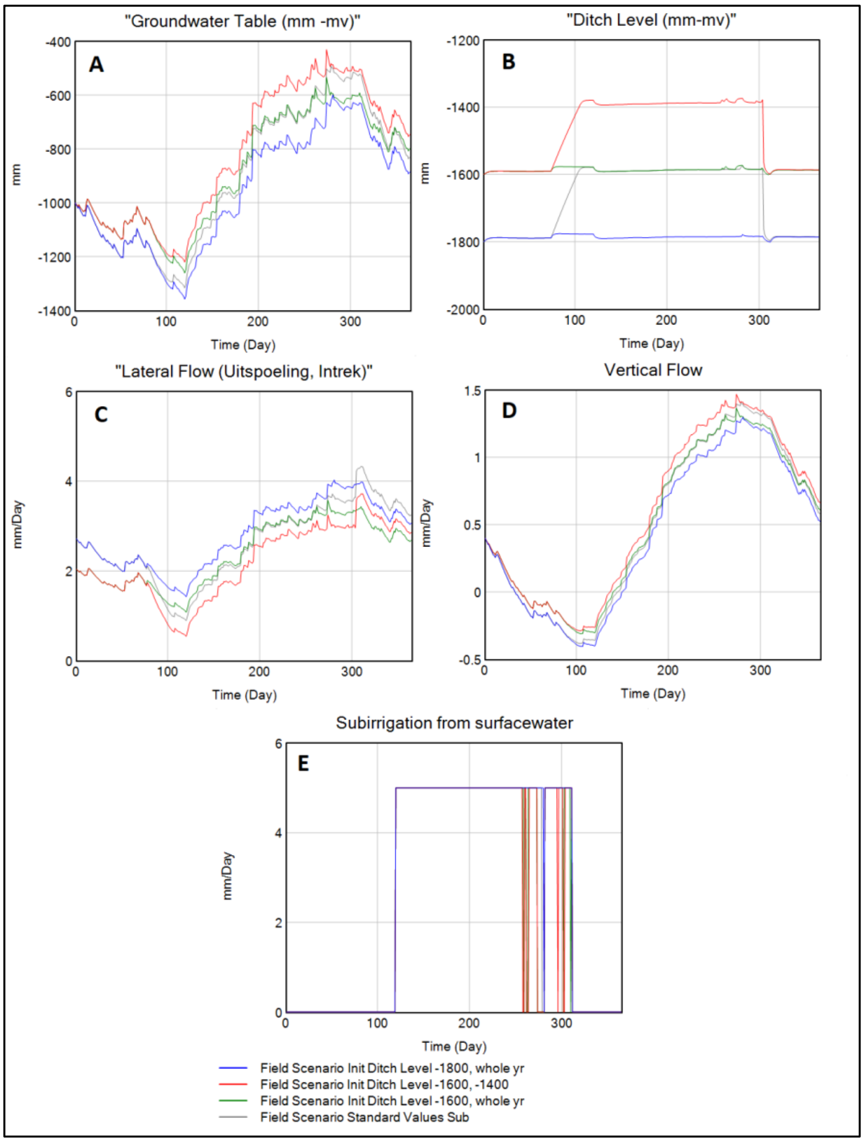


Figure 15: Main field model outputs for the initial ditch level scenarios. The scenarios assume the waterboard maintains higher weir/ditch levels throughout the year. Lines represent a level of -1800 mm below surface level (-mv) all year (blue), -1600 mm -mv in summer & -1800 mm -mv in winter (grey), -1600 mm-mv all year (green) and -1400 mm -mv in summer & -1600 mm -mv in winter (red).

As can be seen in figure 15 above, raising the ditch level has numerous effects. First, raising surface water levels by 20 cm in all seasons (red scenarios, 14B) causes the desired groundwater level of -50 cm -mv to be reached at an early point in the growing season (15A). The achieved GW-tables are approximately 18 centimeters higher between the lowest and highest ditch level scenarios. The increase in groundwater table results in a slight increase in vertical flow but lateral flow (towards the ditch) is decreasing simultaneously when higher ditch levels are maintained (15C & D). Another observation is that subirrigation can be turned off more often and earlier on in the growing season in the scenarios where higher than current weir and ditch levels are maintained (15E).

4.1.2.3. Initial Groundwater Level Scenario

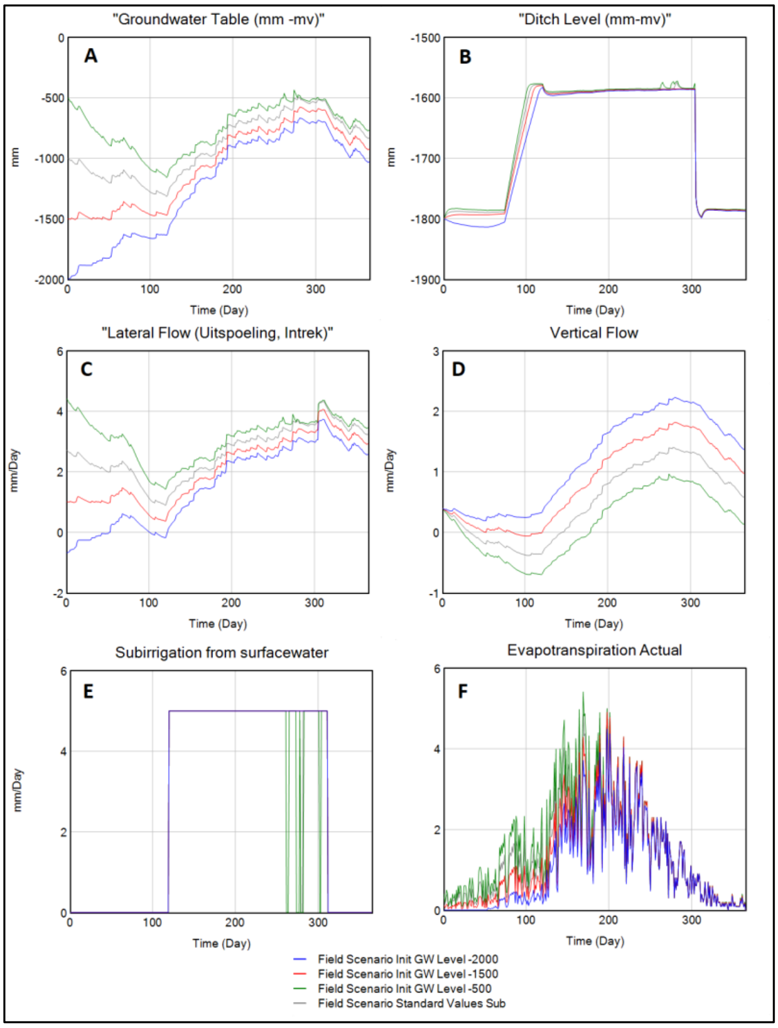


Figure 16: Main field model outputs for the initial groundwater level scenarios. The scenarios explore a change in the lower boundary conditions for the year 2017: Higher or lower pressure heads for the annual fluctuation in the deep ground water. Lines represent an initial water table of -2000mm and the base of the sinus wave for the deep GW pressure head at 2400 mm (blue), -1500mm & -1900mm (red), -1000mm & -1400mm (grey) & -500mm & -900mm (green) respectively.

As can be seen in figure 16A, higher initial groundwater tables and higher pressure heads for the deep groundwater result in higher groundwater tables. Additionally, the target ditch level is reached marginally earlier in the scenarios with high groundwater levels (16B). As a result of the higher groundwater tables, again the higher the lateral flow, vertical flow & evapotranspiration (16 C, D & F). The higher initial value for the groundwater table and the higher base for the sinus wave for the deep groundwater increases the amount of upward seepage (negative value for lateral flow, 16D). The higher function governing the lower boundary result in subirrigation being able to be turned off earlier in the growing season in the scenarios with higher groundwater tables, thus lowering the water requirement (16E).

4.1.2.4. K-Horizontal Scenarios

When it comes to the scenario runs for different horizontal hydraulic conductivity parameters of the soil the results are in line with previous findings. Higher conductivity values result in increased lateral flow towards the ditch and a lower groundwater table as a result (figure 17A & C). Subsequently, lower conductivities lead to increased groundwater tables and decreases in lateral flow towards the ditch. Additionally, lower horizontal conductivities will cause an increase in vertical flow (downward seepage) and evapotranspiration through the increased groundwater tables (17D & F). Subirrigation requirements are also lower when the horizontal conductivity of the soil is lower, as water is more easily retained within the soil matrix (17E). All scenarios eventually reach the target value. The lower the horizontal conductivity, the shorter it takes to reach the target groundwater table with subirrigation, resulting in it being turned off earlier in the season (17A & E). As less water recirculates to the ditch with lower conductivity, it does however take slightly longer to reach the target ditch levels in summer (17B). The lower the conductivity, the easier it is to maintain the high groundwater levels outside of the growing season, thus hinting at more long-term buffering capacity in these soils (17A).

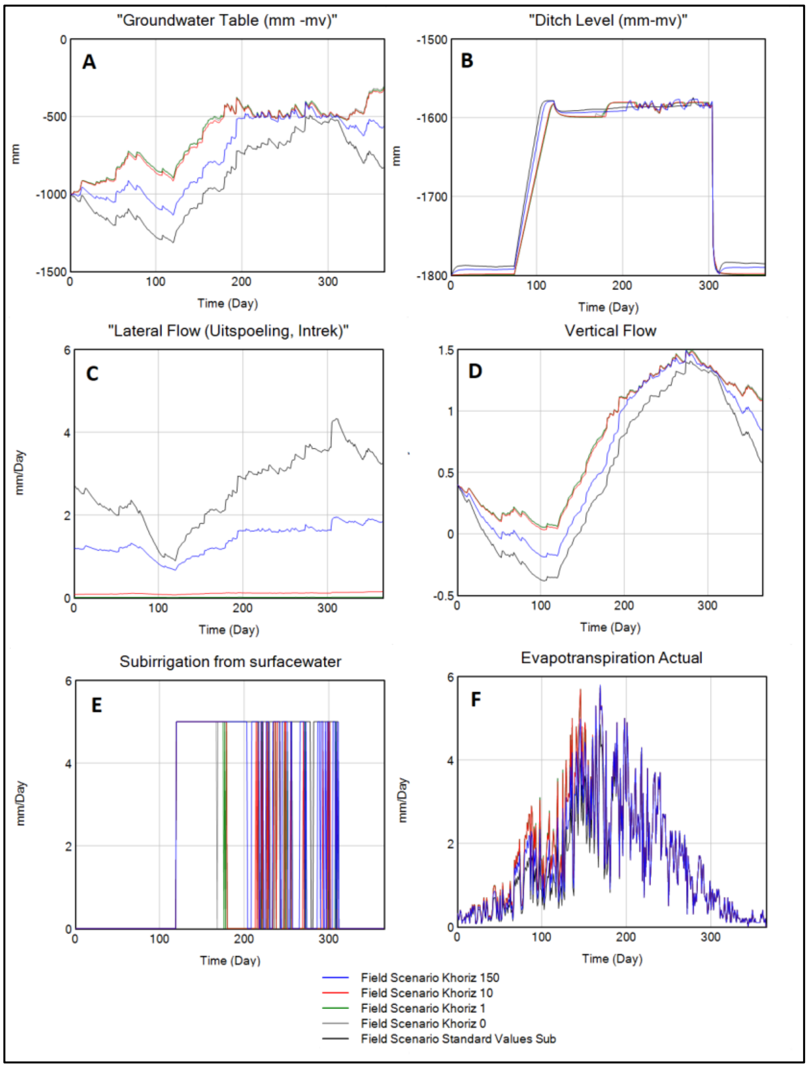


Figure 17: Main outputs for the horizontal conductivity scenarios for 2017. Lines represent a conductivity of 340 mm/day (blue), 50 mm/day (green), 10 mm/day (grey), 5 mm/day (red) and 1 mm/day (black).

4.1.2.5. K-Vertical Scenarios

The vertical conductivity scenarios simulate the absence of a loam layer such as the one in the America field pilot at a depth of 2 meters below surface level. As can be seen in figure 18 below, the absence of such a loam layer or confining layer of sorts, results in lower groundwater tables & evapotranspiration (18A & F) due to a substantial increase in downward seepage (vertical flow, 18D). Even though subirrigation is applied throughout the entire growing season (18E), it does not result in a significant increase in groundwater tables. Instead, the groundwater table closely follows the annual fluctuation of the lower boundary condition set by the deep groundwater pressure head

(18A). This is in line with the findings of van Hintum and de Wit et al., 2021. These low groundwater tables cause infiltration from ditch water into the soil (negative lateral flow, 18C) & thus also lowering ditch levels at the end of the growing season (blue line, 18B).

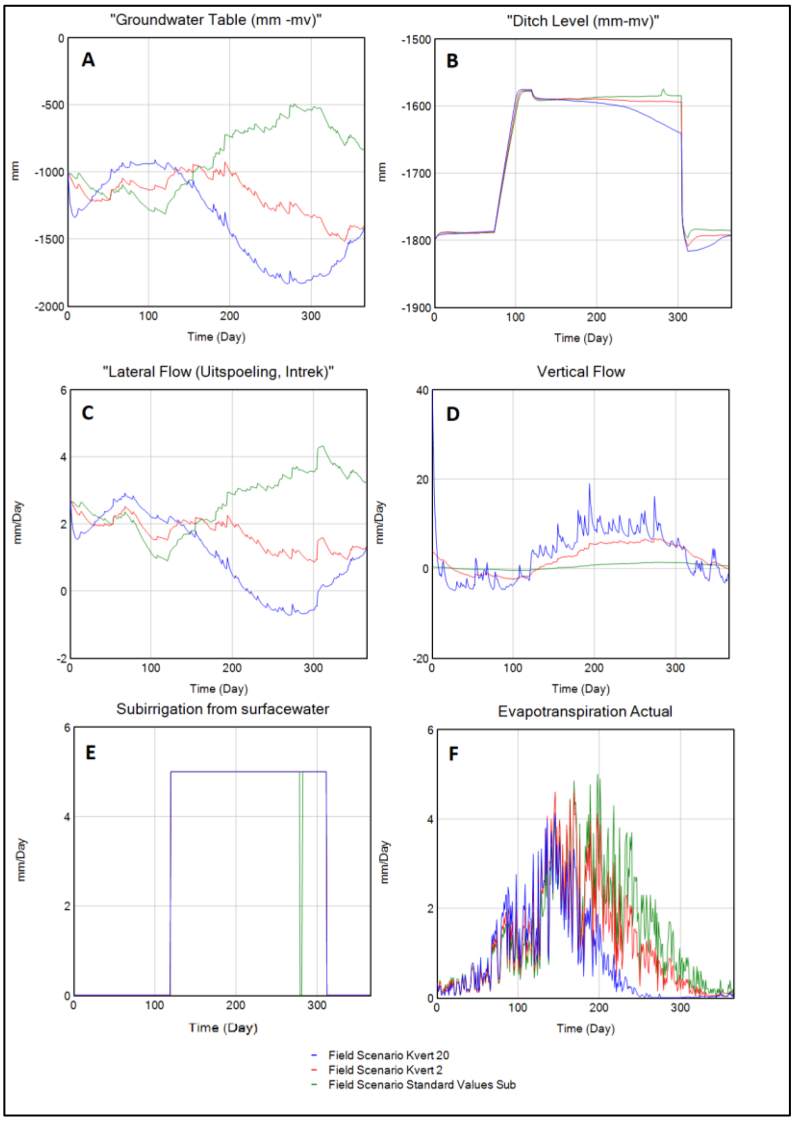


Figure 18: Main outputs for the vertical conductivity scenarios. Lines represent a conductivity of 20 mm/day (blue), 2 mm/day (red) or 0.2 mm/day (green) respectively.

4.1.3 Verification & Comparison

Table 7: Comparison of the water balance for the situation WITH subirrigation as produced by Vensim and SWAP for the years 2017, 2018 & 2019. SWAP water balance data from de Wit et al., 2021. For the SWAP data, the fluxes transpiration, soil evaporation and interception have been combined into evapotranspiration. Lateral flow combined the fluxes lateral drainage and pipe drainage.

Groundwater Content			2017			2018			2019
Inflows	SWAP	Vensim	Difference	SWAP	Vensim	Difference	SWAP	Vensim	Difference
Precipitation	775,6	774	-2	445,2	444	-1	692,2	691	-1
Subirrigation	704,1	945	241	728	960	232	728	935	207
Vertical Flow (upward seepage)	0	25	25	0	23	23	0	26	26
Lateral Flow (Ditch Infiltration)	0	0	0	0	0	0	0	0	0
Som	1479,7	1743	264	1173,2	1427	254	1420,2	1652	232
Outflows									
Vertical Flow (downward seepage)	199,3	202	3	141,2	166	25	178,82	191	12
Evapotranspiration	548	499	-49	439	536	97	505	506	1
Lateral Flow (Ditch Drainage)	708	936	228	617	822	205	724	894	170
Surface Runoff	0	0	0	0	0	0	0	0	0
Som	1455,3	1637	182	1197,2	1525	328	1407,82	1591	183
Storage Change	24,4	106	82	-24	-98	-74	12,38	61	49

Compared to the water balances produced by the modelling in SWAP by de Wit et al. (2021), evapotranspiration is being slightly underestimated for wet years (2017), whilst being overestimated for dry years (2018 & 2019). Additionally, lateral flow, or as it is called in swap lateral drainage to surface water, is overestimated quite heavily in the Vensim model by almost 200 millimetres. The absence of the pipe drainage flux in the Vensim model likely causes groundwater tables to be higher than in the SWAP model, in turn causing increased lateral flow and vertical flow (downward seepage). Whilst Vensim applies 5mm per day, swap uses 4 mm per day as the default value (de Wit et al., 2021), resulting in 200-240 mm of extra water being applied. This extra subirrigation application could also partially explain the higher values for lateral flow, vertical flow & evapotranspiration, as well as the lack of a pipe drainage flux. The water balances for SWAP and Vensim without subirrigation can be found in appendix 5. In 2018, the driest year, Vensim predicted a more negative storage change compared to SWAP, whereas for the other 2 years the storage change in Vensim was more positive due to subirrigation.

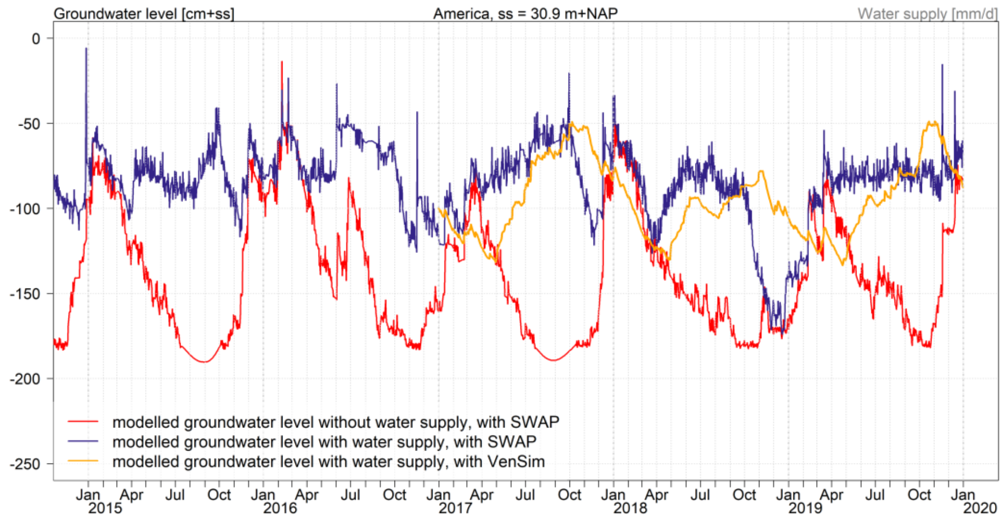


Figure 19: Comparison SWAP model output vs Vensim model output for groundwater levels in America

As can be seen in figure 19, there are currently still notable differences between the SWAP and Vensim outputs. It must be noted that the starting point of subirrigation for the Vensim model was pushed to the beginning of May and continued longer throughout the year to be able to distinguish the individual impacts of the increase/decrease in ditch level and subirrigation. Therefore, the Vensim output (orange line) seems to be shifted on the x-axis slightly to the right compared to the SWAP output (blue line). It does however appear that Vensim is capable of correctly mimicking the influence of subirrigation on the groundwater table dynamics compared to the SWAP model.

4.2. Regional Scale

4.2.1. VENSIM models

Based on the different types of connections outlined, the basic field scale Vensim model was duplicated to create the scenarios as explained in paragraph 3.3.2. The same upper and lower boundaries were applied to both fields. The used parameterization and initial values for the two fields were identical, apart from the subirrigation requirement which has been varied in the scenario runs. As can be seen below, first, the parallel scenarios use a model where two parallel fields are separated by one ditch. Second, the series, adjacent scenarios put the fields side by side, discharging on the same ditch. Third, the series, downstream scenarios place the fields in series to one another, with both discharging on a separate ditch. More detailed images for the Vensim user interface (like figure 12) for the regional scenario models can be found in appendix 6.

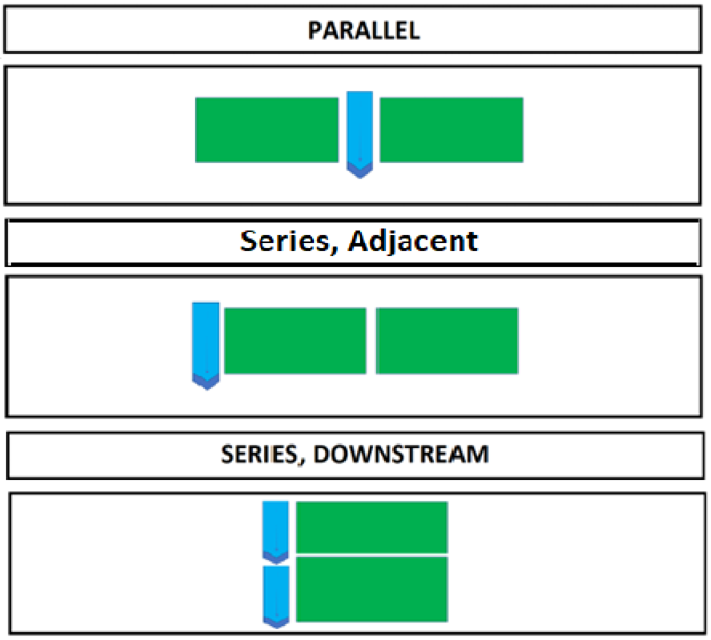


Figure 20: Regional Scale Model Concepts: Parallel connection, Series, adjacent & series, downstream connection

4.2.2. Scenario Modelling

4.2.2.1. Parallel

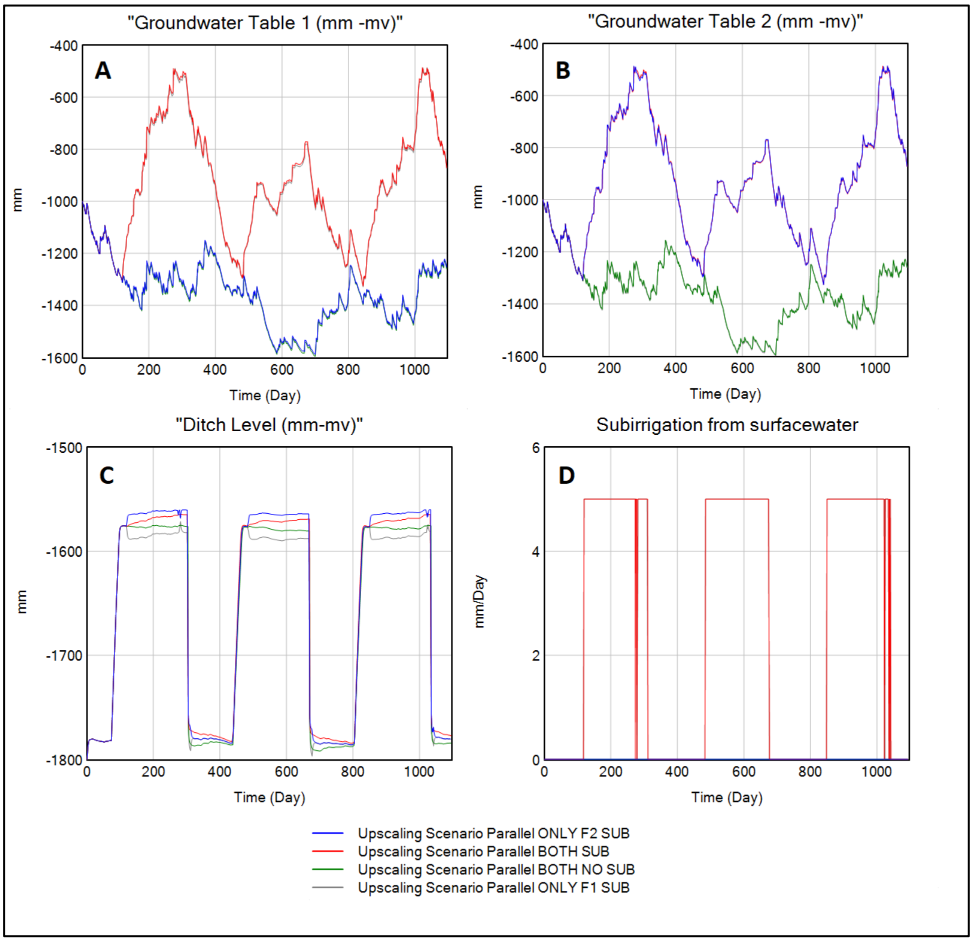


Figure 21: Main model outputs for the parallel regional scenario. Displayed are the respective groundwater tables of field one (A), field two(B), the ditch level of field 1 (C) & ditch level of field 2 (D). The lines indicate the four scenarios. These are: Both fields with subirrigation (red), both field NO subirrigation (green), only field one subirrigation (grey) & only field two subirrigation (blue).

As put in paragraph 3.3.2, the 4 scenario lines in the figures indicate 1) No subirrigation, 2) All subirrigation, 3) only field one subirrigation and 4) only field two subirrigation. For the parallel scenario's outputs (figure 21), no notable difference to the basic time series run could be observed between the situations with either 1 or 2 fields with subirrigation supply. The model output is in fact identical to that of the basic field model with only one field with subirrigation. This suggests that due to the large amount of subirrigation water which is recirculated to the surface water the ditch level can be maintained with 10 mm being abstracted for subirrigation even if the inflow is only 5 mm of surface water per day.

4.2.2.2. Series, Adjacent

For the scenario set in which the two fields were situated adjacent to one another with only one of the two directly bordering the ditch, some clear (in-)direct effects of subirrigation can be noted in figure 22 below. First, the groundwater tables which can be realized in field one (directly bordering the ditch) are systematically lower than those in field two (not bordering the ditch) due to the extensive amount of drainage towards the ditch (lateral flow) from field 1 (Figure 22 A, B &E). Second, the highest groundwater levels were realized in the scenario where both fields are fed with subirrigation (grey) (22A & B). The added value in groundwater table rise accomplished when both fields are fed with subirrigation is about 5cm compared to the situation where only 1 field had subirrigation. However, due to the lower amount of recirculation to the surface water compared to the parallel scenario, now, 10mm of water abstraction will cause declines in ditch level (22C), which in turn cause increase in lateral flow towards the ditch, but also stops to the availability of water to subirrigation (22G & H). As a result, clear drops in groundwater table for field 1 can be observed during the entire 2018 growing season and in the start of the 2019 growing season. Third, supplying only one of the two fields with subirrigation indirectly raises the groundwater table in bordering fields with as much as 25 centimeters compared to the scenario without subirrigation (22A & B). Finally, a clear gradient can be observed in the groundwater table, with flow towards the lowest pressure. i.e., the ditch (22D & E). The groundwater tables in plot 2 can more easily be maintained at the target level, due to the lower gradient between the two fields compared to the ditch and field 1. As a result, subirrigation on field two will require significantly smaller water volumes, which is reflected by the prolonged periods of time in the model in which subirrigation is switched off when only field 2 receives subirrigation (green scenario, 22G, H).

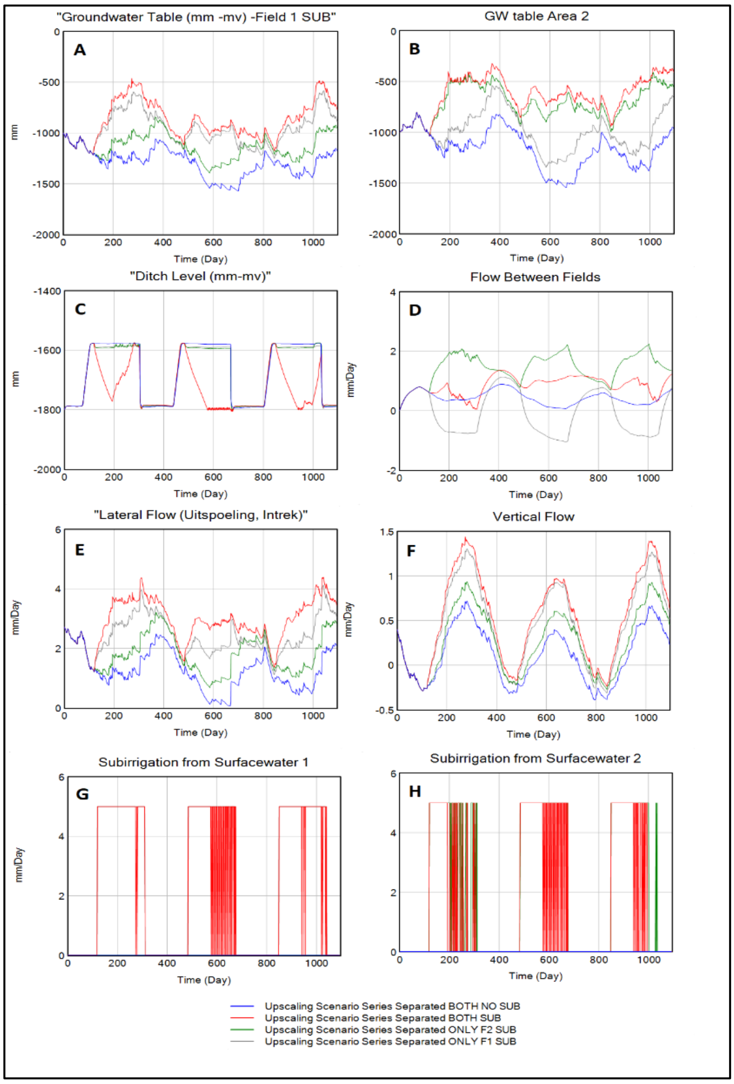


Figure 22: Main model outputs for the upscaling scenario set with 2 adjacent fields, with one separated from the ditch by the other. Scenario 1 (green): No subirrigation, Scenario 2 (red): only field 1 has subirrigation, Scenario 3 (blue): only field 2 has subirrigation, Scenario 4 (grey): both fields have subirrigation.

4.2.2.3. Series, Downstream

For the scenario with one upstream and one downstream field, many of the observations correspond to that of the ‘Adjacent’ scenario set. As can be seen in figure 23 below, the added value of having subirrigation on both fields is now bigger and amounts to up to 15 cm (green line vs red/blue, 23A & B). However, the indirect effect of subirrigation on the neighbouring field is smaller as it now only amounts a maximum groundwater table rise of 19 cm compared to 25 cm previously at the height of the growing season. Additionally, the overall achieved groundwater levels are lower as more water is lost to drainage to the ditch (23E). Additionally, potentially negative consequences of the implementation of subirrigation for downstream areas can also be observed, as the ditch level downstream declines in case of limited surface water supply (of 5mm) when both fields are irrigated with subirrigation (23D).

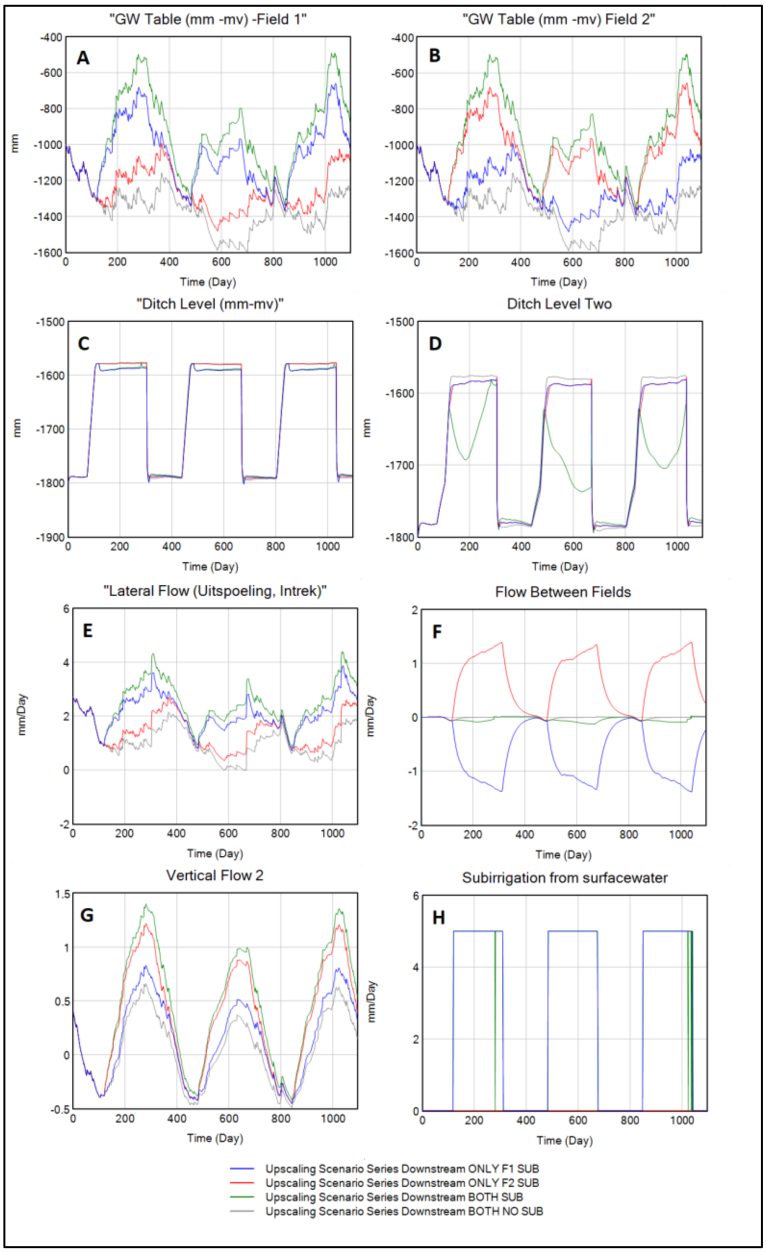


Figure 23: Main model outputs for the regional upscaling scenario with a field downstream of the first sub-irrigated field. Both fields share the same surface water supply, as the output from field one is used as the ditch inflow for field two. Scenario 1 (green): No subirrigation, Scenario 2 (red): only field 1 has subirrigation, Scenario 3 (blue): only field 2 has subirrigation, Scenario 4 (grey): both fields have subirrigation.

4.2.3 Linear Area Extrapolation: Regional Water Needs

The regional water requirement for subirrigation has been extrapolated from the field scale water requirements. Given the known area of the subirrigation pilot field and that of the total agricultural area in the region, the water requirements for subirrigation have been calculated for different percentages of total area coverage with subirrigation. As can be seen in table 9 below, for the field scale, yearly water requirements in cubic meters would amount to 35626.5 cubic meters. When extrapolated to the entire area of interest, this would result in a subirrigation requirement of 3.3 million m^3 of water on a yearly basis for 350 hectares. As can be seen in table 8, nearly 50% of the added subirrigation water is recirculated to the surface water.

Table 8: Linear extrapolation of the water balance for the regional water requirements for subirrigation. Units in mm per total area region/sub-catchment

Total Water Balance				
Area (Ha)	4	70	140	210
Area (%)	1	20	40	60
Inflow				
Precipitation	774	774	774	774
Subirrigation	10	189	378	567
Vertical flow (upward)	33	32	30	28
Lateral flow (from ditch)	0	0	0	0
Som	817	994	1182	1369
Outflows				
Vertical flow (downward)	83	106	130	154
Evapotranspiration	305	342	381	420
Lateral Flow (to ditch)	499	583	671	760
Surface Runoff	0	0	0	0
Som	887	1031	1182	1334
Bergingsverandering	-70	-36	-1	35

Table 9: Subirrigation water requirements per unit total area coverage

Area (ha)	Area (%)	Requirement (m^3)
1	0,29	9450
3,77	1,08	35626,5
70	20	661500
140	40	1323000
210	60	1984500
350	100	3307500

5. Discussion

In this chapter, first the reliability of the model, its outcomes and underlying assumptions will be discussed. Afterwards, the societal/management and scientific implications following from this research will be discussed. Finally, this chapter will indicate directions for future research to expand on this research.

5.1. Model Reliability & Assumptions

5.1.1. General Discussion on SD Models

The usage of SD Models for Water- & Natural Resources Management is well established as a tool for addressing water resources management issues in a holistic way (Mashaly & Fernald, 2020). Some limitations however still exist. First, a lack of system knowledge and experience with SDM might cause model results to be incorrect due models becoming too simplistic or focusing on irrelevant details (Mashaly & Fernald, 2020). Wrong causal links between variables are easily drawn (Mashaly & Fernald, 2020). Second, model verification and validation are often difficult due to subjective choices for the model frame & boundaries (Mashaly & Fernald, 2020). Mashaly & Fernald also stress the urgent need to combine SD models with other modelling methods to improve model parameterization, structural set-up, and formulation of operating rules (Mashaly & Fernald, 2020). Also, the degree of simplification and the model scale can be of influence on the reliability of model results. Both small scale (simplified) models and large scale (detailed) models have their pros and cons. According to Pruyt (2013), small models allow for thorough experimentation and sensitivity analysis and a better analysis/interpretation of the impact of parameter changes (Pruyt, 2013), but as indicated earlier, are prone to over-simplification (Mashaly & Fernald, 2020). Big models might come closer to a true depiction of reality, but “are also nearly impossible to understand, test (by the modeler or a third party), and evaluate critically” (Pruyt, 2013)..

For the application of Vensim in the context of this research, the upscaling can encounter the same pitfalls as mentioned above, with model complexity rapidly increasing when coupling multiple field scale balances, limiting the ease of use. The troubleshooting of errors or model parameterisation can become a tedious, time consuming process if one must navigate through a spider’s web of increasingly more connectors and fluxes (Elsawah et al., 2017). Important as well, is the agreement on a sufficiently accurate base model, as changes to the base model after running scenarios requires extensive and time consuming reruns for model verification and scenario simulation (Elsawah et al., 2017). Some degree of automation such as using Python or R for (pre-) processing of input data or for sensitivity analysis runs could turn out beneficial (Glass-Husain, n.d.)

5.1.2. Field Scale Model

In the process of building the field scale model, which forms the basis for all subsequent modelling efforts, the combination of qualitative model, input parameterization, underlying equations and operating rules influenced model behavior and the reliability of model results.

For the qualitative model, the decision was made to simplify the water balance and its total amount of components. As a result, some processes might not have been accurately accounted for in the Vensim model. First, the choice to not include a separate flow for drain discharge likely caused an overestimation of predicted groundwater tables (and as a result slightly increased lateral-, vertical flow, and evapotranspiration components). Additionally, the representation of evapotranspiration in the model could have been improved by a more accurate description of the unsaturated zone. The model slightly overestimates the evapotranspiration in cases where there is subirrigation compared to the SWAP runs and underestimates it once subirrigation is not included (table 7, paragraph 4.1.3). However, it needs to be weighed whether the extra effort and time which is needed to implement these functionalities makes the model that much better at reaching the goal: predicting water requirements for subirrigation and its impacts on surface water availability & groundwater levels on a regional scale in times of drought.

For the parameterization of the model, SWAP input values were used, as these were in this case the most readily available input data. Based on the calibrated resistances in SWAP, hydraulic conductivity (k) values were calculated for the field scale model based on these resistances. As only the drainage resistance of 295 days as used by de Wit et al. (2021) was used in the calculation of the horizontal k-value, the current model overestimates the amount of lateral flow towards the ditch. A more accurate method would combine the drainage and entrance resistance (Kroes et al., 2017; Massop & van der Gaast, 2006), culminating in a value with much lesser losses to surface water, higher groundwater tables and lower subirrigation water requirements. The entrance resistance was however also set to a high value of 10000 days in SWAP to prevent unreasonable values for ditch infiltration during times of low groundwater levels (de Wit et al., 2021) and thus could be better parameterized in general. As for the conductivity of the vertical layer, the resistance that was used as an input in SWAP is a summation of multiple resistances, as it sums the resistance of the semi confining layer and that of the regional system (Kroes et al., 2017). Imposing this resistance over only the 20 centimeters of the semi-confining layer thus resulted in a conductivity that in hindsight was too low, resulting in smaller down- & upward seepage flows compared to the real-life situation. The correct parameterisation of the horizontal and vertical hydraulic conductivity (k) values has proven to be the most influential for model behavior, as they govern the lateral- & vertical flows (and thus indirectly the maximum achievable groundwater levels), and the degree to which subirrigation feeds the regional surface water system (see paragraph 4.1.2). Besides, the assumptions of vertical and horizontal homogeneity for the hydraulic conductivity were necessary for model functioning, whereas the exact conductivity varies even on very local scale in the area surrounding the Mariapeel (Massop et al., 2005). New model runs with improved k-values, (appendix 4) showed decreased water recirculation to the surface water compared to the standard scenario displayed in the results, and thus potentially earlier problems with surface water availability downstream compared to the results in section 4.2.2. The lower conductivity values however also result in less water requirement for subirrigation and higher groundwater tables.

The difficulty of finding an optimal parameterisation of the vertical and horizontal hydraulic conductivities is intrinsic to the choices made for combining or leaving out fluxes and soil layers for model simplicity, and a result of time constraints. Improving the calibration of the model will be no easy task, as finding correct values for saturated hydraulic conductivity proves to be difficult in practice (Massop & van der Gaast, 2006; Meter Group, n.d.). The use of effective porosity also needs to be further verified as the term effective porosity is used for both the storage coefficient (Dutch: 'bergingscoefficient') and the effective porosity (Grondwaterformules.nl, 2022). In this research the latter interpretation was used whereas the former might be more correct, in which case a value closer to 0.28 might be suitable for the calculation of the Groundwater table (Grondwaterformules.nl, 2022).

As was evident from section 4.1.3, the current Vensim model, and SWAP model outcomes still exhibit some distinct differences, caused by model structure simplifications and the assumptions for hydraulic conductivity and model operation rules. Linked to the parameterisation of horizontal & vertical hydraulic conductivity, the current model seems unable to replicate the recharge of the groundwater table in winter periods (figure 19) as predicted by SWAP. However, it must be kept in mind that the goal of this research was not to reproduce the findings of SWAP 1:1. Instead, it was built to provide a base model which in rough lines can simulate the impact of subirrigation on the groundwater table dynamics & surface water availability at a regional level. Additionally, the period of subirrigation application chosen in this research differs from the actual situation, to get a better view of model sensitivity to separate changes in the parameters subirrigation and surface water level.

5.1.3. Regional Scale Model

For the regional scale models, some additional points of attention need to be stressed. For a start, only groundwater flow in the direction of the ditch and/or the second field was assumed. Leaving the other x & z directions as no-flow boundaries. In a realistic situation, groundwater flow can occur in these directions, causing an overestimation of both the positive effects of subirrigation on neighboring fields' groundwater level as well as those predicted for the subirrigated field. As shown by Ahmad & Simonovic (2004), this functionally can easily be built in based on Darcy fluxes to all 4 directions (Ahmad & Simonovic, 2004)

The inclusion of the spatial dimension within SD modelling environments such as Vensim has been acknowledged by previous studies to be problematic, especially when dealing with components of different spatial scale (Elsawah et al., 2017), such as the fields considered in this research. A solution might be combining the model with GIS software, which has been widely applied in other SD-modelling of water resources management, and for which Vensim provides the tools needed (although possibly requiring an update version from the one used for this research) (Elsawah et al., 2017). First steps were taken in the modelling part of this research to better include the spatial domain/field area component in the Vensim field model. It is important to also consider that if this upscaling is performed not only field area, but ditch area needs to be incorporated as well to come to correct volumetric indications of the storage volume per field and/or ditch.

The fact that no further reference frame yet exists for the regional scale Vensim model makes it hard to validate the results. The validity of the regional results depends on the validity of the field scale models in this case.

5.2. Research Implications

This research showed that Vensim can be a useful tool to model the impacts of subirrigation on the field & regional scale water balance. The water balance model, which was simplified from the SWAP model, was still able to relatively closely predict the fluctuations in the groundwater table as a result of subirrigation. The resulting fluxes to surface water, the atmosphere and the deep groundwater proved to be less accurate as a good parameterisation of the model was found to be more difficult due to the choices made for the structure of the qualitative (& resulting quantitative) model & underlying governing equations and operating rules. However, the modularity of Vensim and the resulting different regional connections are part of the strong suit of SD-modelling, as it can be used to replicate real world (surface) water systems and couple them to groundwater dynamics in a user interface that is understandable to non-professionals. Vensim has proven to be capable tool of recreating the interactions between these coupled systems (given a number of improvements are made to overcome the shortcomings addressed in the previous paragraph) with more potential yet to be extracted.

The main modelling results echo the conclusions drawn with respect to the success conditions formulated by van Hintum (2021) & de Wit et al. (2021). Field and Regional scale scenario modelling have indicated drops in ditch level and thus the potential inability to supply sufficient surface water for irrigation and nature downstream in case of regional upscaling or decreased surface water availability upstream where demand exceeds supply. Additionally, the waterboard should consider maintaining higher surface water levels, as this has been shown to decrease the lateral flow back to the surface water and reduces the water requirements of subirrigation. In times of limited supply however, it might be challenging to maintain sufficiently high water levels (van Hintum, 2021) without depriving downstream areas of surface water or having to stop subirrigation supply. The hydraulic conductivity of the soil is experienced crucial in determining the maximum achievable groundwater tables with subirrigation, with a lack of vertical resistance and horizontal resistance resulting in large losses to the deep groundwater or surface water, respectively.

As mentioned in paragraph 3.1, Rijkswaterstaat is increasing the capacity of the Noordervaart with 3 m^3 per second (Rijkswaterstaat, 2022c). This increased water supply would account for roughly 94.6 million cubic meters of additionally available surface water (assuming all water would be routed into the 'peelkanalen'). Based on the requirements calculated from linear extrapolation of the field water balance as can be seen in table 9, this would indicate that roughly 5840 ha can additionally be provided with sufficient water for subirrigation during the growing season. An area 17 times the size of the currently proposed area. The extrapolated requirements are likely overestimated however, as the positive side-effect of subirrigation on adjacent fields is not included when extrapolating. What also needs to be considered, is that in this calculation no minimum flow requirements for the ditch were considered, whereas in a real-life situation these are in place to protect water supply to the Natura2000 areas de Grote Peel and Maria/Deurnsche Peel (van Hintum, 2021). It is important to note that drawing conclusions from these linear extrapolations should be done with great care based on the model limitations and assumptions described in the previous paragraph. Regardless, these linear extrapolations can provide a quick and rough indication of regional water requirements and thus suitability/feasibility of subirrigation implementation on a large scale.

5.3. Recommendations for Future Research

One of the main goals of this paper was to create a base model in Vensim. With this base model now being established in this research, a few directions were identified to further progress the modelling of subirrigation upscaling in the Mariapeel-region. Recommendations on how to further progress the modelling performed in this research are listed below.

Table 10: Recommendations for further model development & surface water management

Field Scale Model Vensim	
What?	**How?**
1. Improve the representation of unsaturated zone dynamics for the calculation of Evapotranspiration.	Either adjust the reduction factor based on field measurements or fully include water content in the unsaturated zone as a stock for each field.
2. Include a separate pipe drainage flux which drains water after the target groundwater level has been reached	Include a separate flow from groundwater towards surface water besides the subirrigations flux. Only pipe drainage when GW table> target GW-level at that time of the year. Two options: 1) Flow based on max discharge capacity pipe 2) or based on gradient with separate drainage resistance
3. Improve parameterisation of the horizontal and vertical fluxes	Replace k* dh/dx by resistance: c*dh. C values are known based on SWAP calibration as these

	combine a set of different k's and dx's for different layers/components of the subsurface. Using k and dh thus is problematic as you would need to have an exact measure of these values which is not easily available whereas C is already known from calibration and can be applied right away(de Wit et al., 2021; Kroes et al., 2017).
Regional Scale Modelling	
What?	**How?**
1. Improve inclusion of the field & ditch area components in Vensim	Apply a scaling factor to the fluxes and stocks in the model based on the new area compared to the area of the reference pilot project field after which the model was parameterized. But for the extra millimeter added the percentages going to lateral, vertical and evapotranspiration might not be the same, how to account for this? (i.e., if groundwater table rises with 10 cm, is the division of water/ratio between outgoing fluxes the same compared to when the table would rise with 50cm) Currently, the size of fields is only included through a resistance factor/(dx/k), assuming a square field.
2. Replicate the area of interest to WL as closely as possible with Vensim	Explore the possibilities of combining Vensim with GIS software (look at the possibilities and weigh the extra time needed vs. the benefits), otherwise connect fields and ditches based on connection principles shown in this research. Current research assumes square shape of fields. Future research must determine if it is possible to account for shape in a better way.
3. Include deep groundwater. As of now, downward seepage is a bottomless sink which does not alter the dynamics of the underlying sinus function	Add separate deep groundwater compartment(s). But: Where to draw model boundaries? And how to deal with differences in scale between deep groundwater storage volume & area and the groundwater above the loam layer available to the fields. Hard to make concrete in Vensim.
4. Include real-life supply ditch inflow instead of fixed value	Data in m^3/sec already supplied. Based on the area of interest, for each timestep calculate the max available inflow in mm/m^2 (assuming all supplied water is divided between fields and no minimum flow requirement is implemented)

Within the Klimap project, many smaller sub-projects exist, which make use of different modeling software such as WEAP (Sieber & Purkey, 2015). Future research will have to list the pros and cons of using Vensim for modeling of water systems' dynamics as opposed to for example WEAP or MODFLOW subirrigation module used by van Hintum (2021). As shown by Elsawah et al. (2017), combining SD-software with other software like GIS and MODFLOW can be used to come to a more accurate representation of dynamic systems in space and time (Elsawah et al., 2017). Future research should identify if this is a preferable research direction or if Vensim can more adequately be used as a standalone model.

The direction in which future research will have to develop the current Vensim model also depends on the objective for which the model will be used. This objective will have to be more clearly specified by Waterschap Limburg. In case the model application is determining crop production/agricultural efficiency, the current model requires a clearer definition of the hydrological processes in the unsaturated zone, as this is currently excluded from the model. On the other hand, if the discharge into surface waters or percolation to deep groundwaters are of the main concern to the waterboard, it might be suitable to better quantify surface water propagation and include the deeper groundwater as a separate stock. The required increases in number of fluxes and parameters (and thus model complexity) would however likely reduce ease of operation of the model in terms of runtimes and parameterization time (Elsawah et al., 2017).

6. Conclusion

Finally, this paragraph will shortly restate the main research questions and answer them in concise fashion.

1) *How can the hydrological processes at the field scale, and the impact of subirrigation on these processes, be translated into a simplified qualitative field scale water balance at both field and regional scale?*

For the modelling performed in this research, the field scale water balance with subirrigation from previous SWAP modelling under the Lumbricus programme, has been simplified substantially. The unsaturated zone was not included as stock, with infiltration and capillary rise being left out entirely. The terms interception, soil evaporation and transpiration were combined in the evapotranspiration term. Instead, evapotranspiration and precipitation were assumed to directly contribute to the groundwater table. The groundwater compartment was covered by vertical flow from- and towards the deep groundwater & and lateral flow from- and towards a main supply ditch. A second surface water stock (ditch) was included with a separate in and outflow and a subirrigation flow from the ditch towards the groundwater stock.

For the regional scale, several linkages of independent field scale balances were explored. These were split into three main sets. 1) parallel: two fields split by one ditch 2) series downstream: two fields downstream of one another, abstracting water at different points alongside the ditch & 3) series adjacent: two fields adjacent to one another, using the same ditch compartment for water supply.

2) *How can the influence of subirrigation on the field- & regional scale water balance be modelled quantitatively using system dynamics modelling in Vensim?*

The inflows, outflows and storages from the field scale water balance were translated into Vensim PLE SDM software as 1D fluxes and stocks in millimetres. For the underlying groundwater fluxes, Darcy's equation was applied, whereas a fixed weir function was used to govern ditch outflow. The lower boundary conditions were set based on the annual fluctuations in the pressure head of the deep groundwater which followed a sinusoid wave. For the upper boundary conditions, a reduction factor limited the amount of Evapotranspiration based on the Feddes curve. Parameterisation was based on KNMI data for precipitation and reference evapotranspiration and the calibrated data from pervious SWAP modelling for the subirrigation pilot in America.

On the regional scale, individual fields were connected with additional Darcy fluxes. Additionally, a linear extrapolation of the field scale water balance was performed to get a grasp of subirrigation water requirement if implemented regionally in the entire area of interest for Waterschap Limburg. The resulting base model closely matched the influence of subirrigation on the groundwater table as predicted by the SWAP model runs, although some points for improvement were noted. The inclusion of a pipe drainage flux as well as a better parameterisation of evapotranspiration and the vertical and horizontal conductivities could improve future modelling.

3) *How can the developed Vensim model be applied to explore scenarios for surface water management challenges & opportunities faced during the regional upscaling of subirrigation in Limburg?*

The possibility in Vensim to run sensitivity runs, easily change model parameters and do reruns with limited model runtime made it easy to run scenarios for exploring surface water management opportunities and challenges. Soil conductivity was shown to have the biggest impacts on modelling results. Due to the large amount of recirculation of water to the surface water with the used standard parameterisation, surface water supply was sufficient under nearly all scenarios (even for multiple parallel fields) except for the scenarios with the lowest supply (1/5th of the demand). There is a trade-off however, where higher conductivity of fields lowers the downstream risks of water shortage but makes the field itself less suitable as it is harder to maintain higher groundwater levels and vice versa. In dry years, with decreasing precipitation (2018), the modelled 5mm subirrigation was shown to be insufficient to reach the target groundwater table, even though it was turned on the entire growing season. Higher initial surface water- and groundwater levels were shown to decrease the required amount of water for subirrigation as either the hydraulic gradient was lower, resulting in less losses to the surface water via lateral flow, or less water was needed to reach the target groundwater table. It might however not always be able to maintain these high surface water levels if surface water supply is limited.

At the regional level, linear extrapolation resulted in an expected water requirement of 3.3 million cubic meters of water during the growing season for the area of interest (350 ha). This is however likely a large overestimation, as regional upscaling scenarios showed that large parts of the subirrigation requirement are recirculated to the surface water and there is a side effect of subirrigated fields on adjacent fields’ groundwater table. In series-scenarios with lower conductivities however, the large water requirement for subirrigation resulted in drops in ditch level, indicating potential negative effects on surface water availability downstream.

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7. Annexes

7.1. Appendix 1: Additional Information Field Pilot Results

According to van Hintum (2021) & de Wit et al. (2021), crop yields and transpiration are substantially increased by subirrigation as a result of increased capillary rise. The hydraulic resistance massively influence the effectiveness with low resistance being detrimental to reaching the target groundwater levels. Limiting water supply for subirrigation caused reductions in transpiration and crop production once again. The higher water tables in the areas surrounding the Natura 200 area created a counter pressure that limited desiccation of the nature area (de Wit et al., 2021; van Hintum, 2021)

The research by van Hintum tried to scale up the implementation of subirrigation to a larger area which was done by attributing a higher area percentage to subirrigation in regional groundwater model that was used in that study (van Hintum, 2021). A similar linear extrapolation approach was followed in de Wit et al., 2021 who extrapolated the results from SWAP water balances for the KLIMAP pilot in Stegeren (de Wit et al., 2021). Upscaling was found to raise groundwater levels in neighboring land plots, thus hinting at a buffering effect for the larger region (van Hintum, 2021). Moreover, year round application of subirrigation could result in permanently increased subsurface storage (de Wit et al., 2021). Regional water authorities did however stress that the required amount of water supply was deemed unfeasible for pilots near the Deurnsche peel , especially when making use of surface water as a source for subirrigation systems (de Wit et al., 2021).

Apart from the parameters within the water balance itself and the scale of application, the timeframe for the application of subirrigation was also found to matter. The scenarios by van Hintum & de Wit et al., explored the effects of year round subirrigation versus subirrigation only in the growing season. It was found that stopping subirrigation supply in winter months did not negatively impact plant transpiration and crop development in the growing season, neither did it significantly increase transpiration and crop development. Subirrigation supply stops in the growing season did however cause drought damages to crops and a lowering of the groundwater level to near previous levels (de Wit et al., 2021; van Hintum, 2021). The stored water from subirrigation in winter months did not results in significant benefits to crop development or the groundwater table in the next growing season (J. de Wit et al., 2021; van Hintum, 2021). It was concluded that when water supply is not limited subirrigation performed as well if not better than conventional sprinkler irrigation. However, the overall water requirements were larger compared to sprinkler irrigation as a lot of water percolated to groundwater or partially drained to surface water (de Wit et al., 2021; van Hintum, 2021).

In de Wit et al. (2021), the impact of different climates and future climate scenarios with subirrigation was also modelled based on the ’14 KNMI scenarios. With 5mm subirrigation during the entire growing season, the difference were only minor for different climate scenarios (de Wit et al., 2021). There are however increases in the yearly average lowest groundwater level and in the driest scenario, subirrigation was capable of almost entirely alleviating the reduction in transpiration as a result of climate change (de Wit et al., 2021).

7.2. Appendix 2: Field Scale: Standard model parameterization

*Table 1: Description of input parameters. V2.4series_PrefGWtable. * = alternative parameterisation for different hydraulic conductivity runs*

Parameter	Unit	Initial/Constant Value (If applicable)
Precipitation rate (KNMI, 2017, t/m 2019)	mm/Day	Time series, See Model_Inputs Tab Excel. GET XLS DATA('Model_Parameters.xlsx','Model Input','1','B23')
Evapotranspiration rate (Potential) (KNMI, 2017 t/m 2019)	mm/Day	Time series, See Model_Inputs Tab Excel GET XLS DATA('Model_Parameters.xlsx','Model Input','1','B24')
Hydraulic head GW diep	mm	Time series, See Model_Inputs Tab Excel GET XLS DATA('Model_Parameters.xlsx','Sinus Golf(Onderrand H_GW diep)','F' ,'H2')
Kvert	m/Day	0,2/ 10* Thickness Loam Layer/Resistance System
Khoriz	m/Day	340/ 5*
Initial Ditch Level	mm	-1800
Initial Field GW table	mm	-1000
Ditch Inflow Rate	mm/Day	IF THEN ELSE(PULSE TRAIN(74,230,365,1034),5,0)
Subirrigation Requirement	mm/Day	IF THEN ELSE(PULSE TRAIN(120,192,365,1042),5,0) OR IF THEN ELSE(PULSE(120,192),5,0)
Max GW table height	mm	0
Length Field	mm	200000
Thickness loam layer	mm	200/10000*
Weir Level (-mv)	mm	In season (-1600), outside season (-1800)
Area control Unit (Weir cross sectional)	m^2	0,87 (Stuw Breedte*Stuw hoogte)
Beta	-	1,4765
Alpha	m^3-Beta/Day	3
Evaporation Reduction Factor	-	Lookup, Max Groundwater Table + "Groundwater Table (mm -mv)", ([(0,0) -(10,10)], (-2000,0), (-1800,0.2), (-1600,0.4), (-1400,0.6), (-1200,0.8), (-1000,1), (-800,1), (-600,1), (-400,1), (-200,1), (0,1))
Weir Width	m	0,87
Weir Height (dimensions)	m	1
Infiltration Capacity	mm/Day	100
Porosity	-	0,38
Depth Loam Layer	mm (-mv)	-2000
Pipe Inlet Height	mm	-1900
Target Groundwater Level	mm	-500
Resistance System	Days	1000
Initial Water Content	mm	("Depth Loam Layer (mm -mv)"-"Initial Field GW table (-mv)")*-Porosity

Table 2: Operating rules for the Vensim model

Parameter	**Unit**	**Current Code**
Ditch Outflow	mm/Day	IF THEN ELSE ("Ditch Level (mm-mv)"<"Stuwhoogte (-mv)",0, Outflow Rate)
Subirrigation from surfacewater	mm/Day	IF THEN ELSE("Ditch Level (mm-mv)"<"Pipe Inlet Heigth (-mv)" :OR: "Groundwater Table (mm -mv)">"Target Groundwater Level (In growing Season)",0,Subirrigation Requirement)
Vertical Flow	mm/Day	Kvert*(("Groundwater Table (mm -mv)"-H GW Diep)/Thickness Loam Layer)
Lateral Flow (neg=to ditch, pos=from ditch)	mm/Day	IF THEN ELSE ("Groundwater Table (mm -mv)"="Ditch Level (mm-mv)",0, Khoriz*("Groundwater Table (mm -mv)"-"Ditch Level (mm-mv)")/ (0.5*Length Field))
Ditch Level (mm-mv)	mm	Ditch Inflow+"Lateral Flow (Uitspoeling, Intrek)"+Surface Runoff-Ditch Outflow-Subirrigation from surfacewater
Groundwater Content (mm)	mm	Precipitation+Subirrigation from surfacewater-Evapotranspiration Actual-"Lateral Flow (Uitspoeling, Intrek)"-Surface Runoff-Vertical Flow
Outflow Rate	mm/Day	("Qh relatie (empirisch, SWAP)"/Area control unit) *1000
Evapotranspiration Actual	mm/Day	Evaporation Rate (Potential, Makkink, KNMI) * Evapotranspiration reduction factor
Difference Ditch Level-Stuw	m	("Ditch Level (mm-mv)"-"Stuwhoogte (-mv)")/1000
Ditch Inflow	mm/Day	Ditch Inflow Rate
Q-h relatie	m^3/Day	IF THEN ELSE ("Difference Ditch Level-Stuw"<0,0, Alpha*("Difference Ditch Level-Stuw”) ^Beta)
Precipitation	mm/Day	Precipitation Rate, KNMI
Surface Runoff	mm/Day	IF THEN ELSE ("Precipitation Rate, KNMI">Infiltration capacity, ("Precipitation Rate, KNMI" -Infiltration capacity),0) + IF THEN ELSE ("Groundwater Table (mm -mv)">Max Groundwater Table,("Groundwater Table (mm -mv)" -Max Groundwater Table),0)
Groundwater Table	mm	Groundwater Table (mm -mv)"= "Depth Loam Layer (mm -mv)"+("Groundwater Content (mm)"/Porosity)

7.3. Appendix 3: Methodology Additional information

Additional description of the research workflow.

In phase 1, model set-up, the focus was on building the qualitative model for the field scale water balance at first. Following the System Dynamics methodology, it was important to identify the main stocks flows and parameters which were available to make up the structure of the water balance. As model complexity and simplicity was an important goal to make model results easily explainable to the different stakeholders involved within the Klimap project, there was a constant lookout for simplifications of the model structure whilst still maintaining its capabilities to give a rough estimate of the influence of subirrigation on the field scale and regional hydrology. Based on discussions with experts within KWR, and literature study on the previous field pilots under the Lumbricus and Klimap projects, as well as previous SD-models, the final structure of the conceptual water balance models was decided upon. The simplified field scale balance was then translated into quantitative models in Vensim and the resulting water balances from these models were then compared against the ones produced in previous modelling efforts in SWAP and Hydrus by de Wit et al., 2021 for general validation.

In phase 2, after the quantitative models were built (& validated), the developed models were applied to explore multiple scenarios of field parameterization and regional upscaling. At the basis for field scale scenarios were the success conditions as they were formulated by van Hintum, 2021 (see paragraph 1.2). The explored scenarios serve as a further validation of the accuracy of the field scale model, as well as test for the success conditions formulated by van Hintum. For the regional scale, different connections and parameterizations of multiple individual field water balances were explored.

In phase 3, model performance will be discussed based on sensitivity analysis and a discussion of model assumptions and shortcomings. Afterwards, considering this discussion, recommendations will be given for future research directions, and the implications of this research for regional water management and managers will be highlighted.

7.4. Appendix 4: Alternative model run outputs for adapted horizontal and vertical Hydraulic conductivity

For the runs with alternative hydraulic conductivity values, the horizontal conductivity was altered to 5 mm/day whereas the vertical conductivity was calculated via a new system resistance, which did not make the mistake of imposing the resistance from SWAP (1000 days) over only the loam layer but instead over the entire system of 10 metres. This resulted in a vertical conductivity of 10 mm/day.

Standard Model Runs

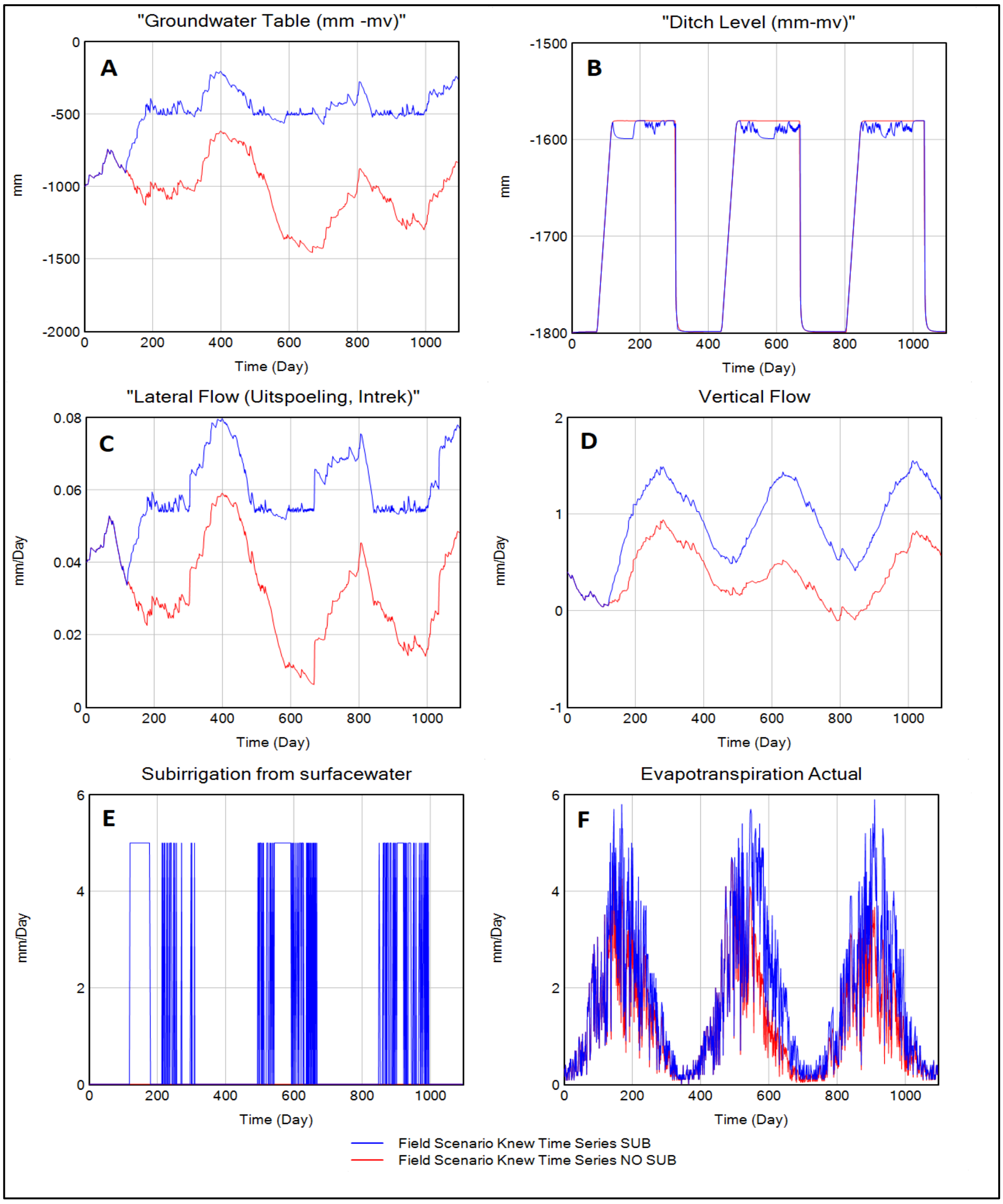

Figure 1: Vensim model outputs for the basic model with adjusted parameterisation of the vertical (10 mm/day) and horizontal (5mm/day) hydraulic conductivities. Two scenarios were run: Field scenario WITH subirrigation (blue) & Field Scenario WITHOUT subirrigation (red). As can be seen, compared to standard values, lateral flow is much lower, resulting in subirrigation being turned off for an extended period of time during the 3 years (E), and much higher groundwater tables, also throughout winter (A).

Field Scenario: Ditch Inflow Change

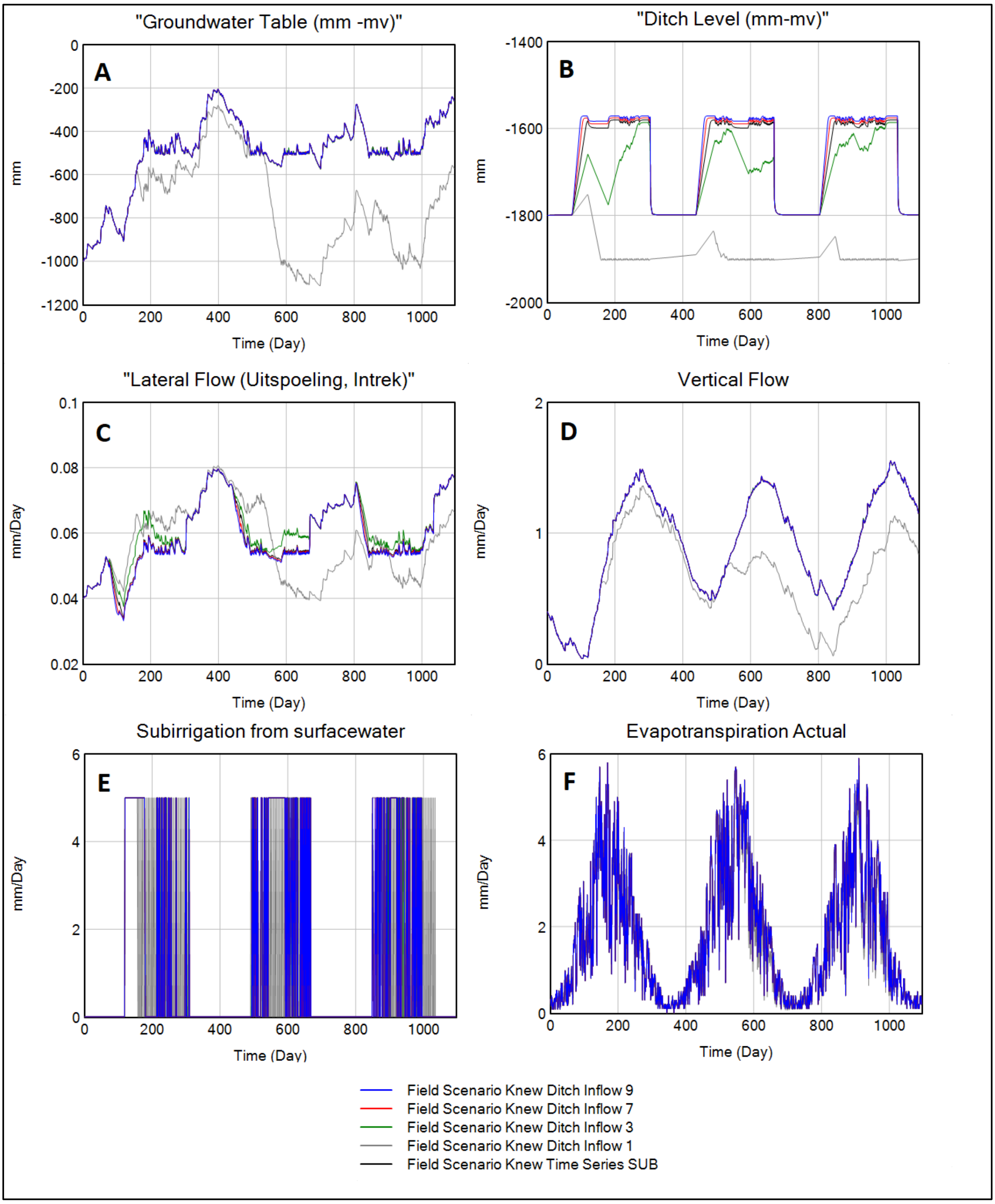

Figure 2: Vensim Model outputs for the scenario runs with alternative hydraulic conductivity values. The scenario outputs above are for the scenarios with varying ditch inflow. The lines represent an inflow of respectively 1 mm (grey), 3mm (green), 5 mm (black) ,7 mm (red) & 9 mm (blue) ditch inflow. As can be seen, the lowest inflow scenarios (1 &3 mm) cause drops in ditch level as the subirrigation requirement exceeds the ditch inflow (B). As a result, subirrigation is turned off and groundwater tables drop drastically in the second year (1mm scenario) (A & E). This results in lower lateral flow, vertical flow, and evapotranspiration from 2018 onwards (C, D, F)

Field Scenario: Initial Ditch/Weir Level Change

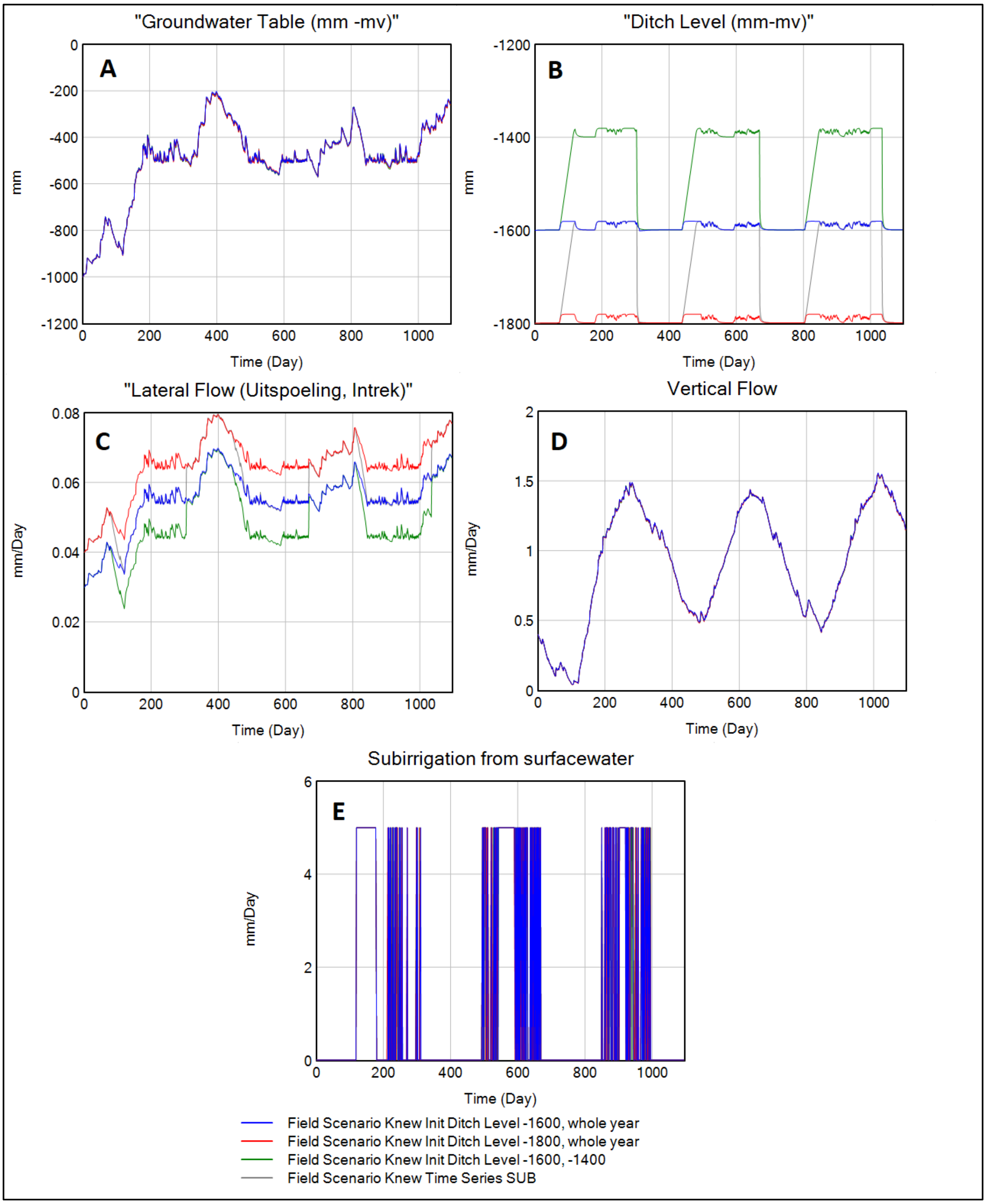

Figure 3: Vensim model output for the scenario runs with alternative hydraulic conductivity values. The scenario above alters the initial ditch level and weir level. The lines represent an initial level of 1600mm -mv and weir level of 1600 mm – mv all year (blue), 1800 mm -mv all year (red), 1600 mm -mv initially and 1400 mm in summer (green) and finally 1600 mm-mv in summer and 1800 mm -mv initially (grey). As can be seen, under the new alternative k-values, changes in ditch level only affect the lateral flow, but as k-horizontal is very low, the order of magnitude of the resulting change is insignificant, causing hardly any changes in groundwater levels.

Field Scenario: Initial Groundwater Level/H GW Deep Change

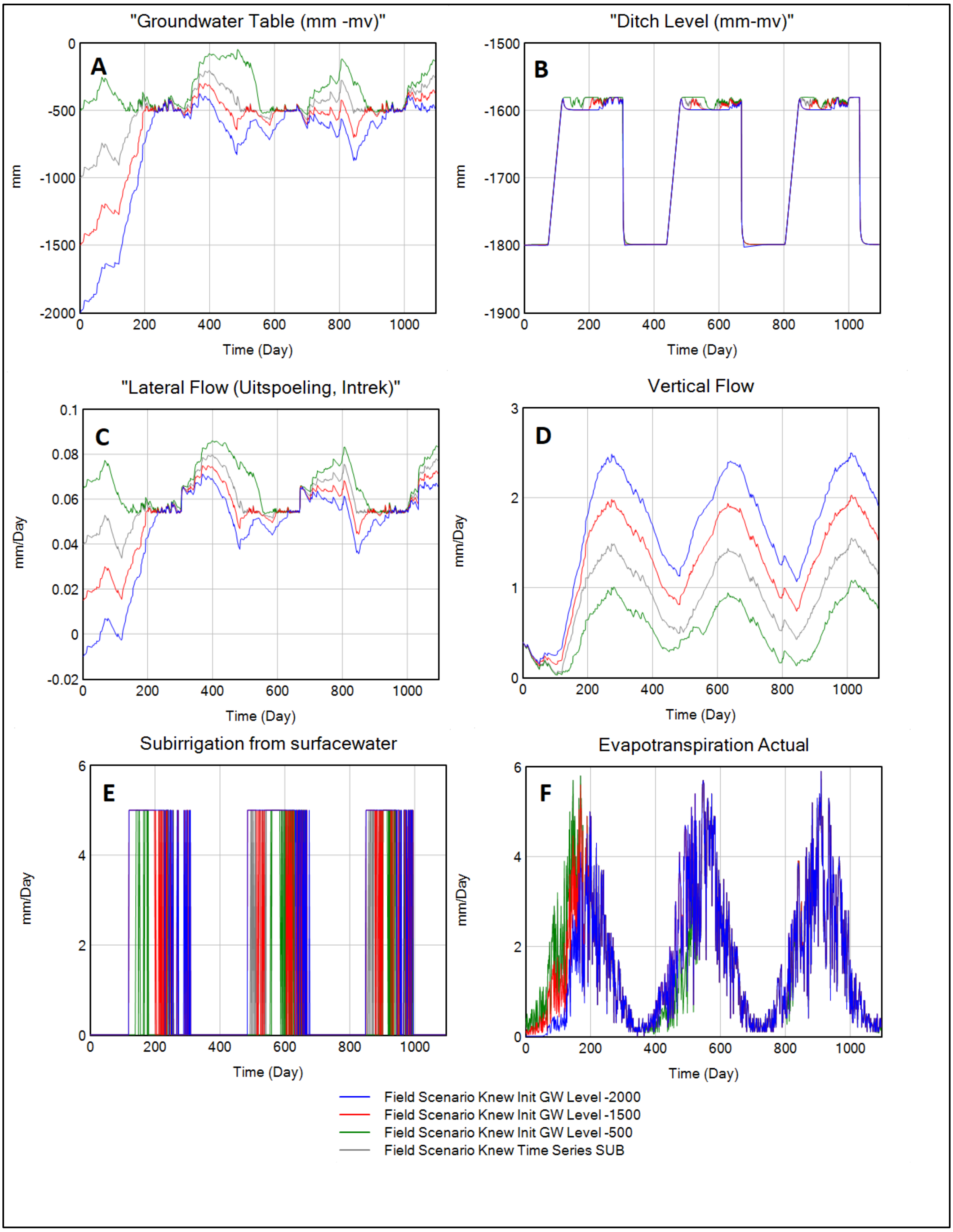

Figure 4: Vensim model output for the scenario runs with alternative hydraulic conductivity values. The outputs displayed above are for the field scale scenario with a different initial GW table and base for the sinusoid curve governing the lower boundary of the model. The lines depict an initial depth of 500 mm – mv and average H GW Deep of -900 (green), 1000 mm-mv and average H of 1400 mm – mv (grey), initial depth of 1500 mm -mv and H average of 1900 mm -mv (red) and initial depth of 2000 mm – mv and H average of 2400 mm – mv (blue). As can be seen, lower initial values for the water table cause the maximum reachable groundwater table to be lower as well (A). This results in less lateral flow and evapotranspiration, but increased vertical flow (C, D, F). The higher the initial groundwater table, the earlier subirrigation can be turned off (E)

Field Scenario: Horizontal Conductivity Change

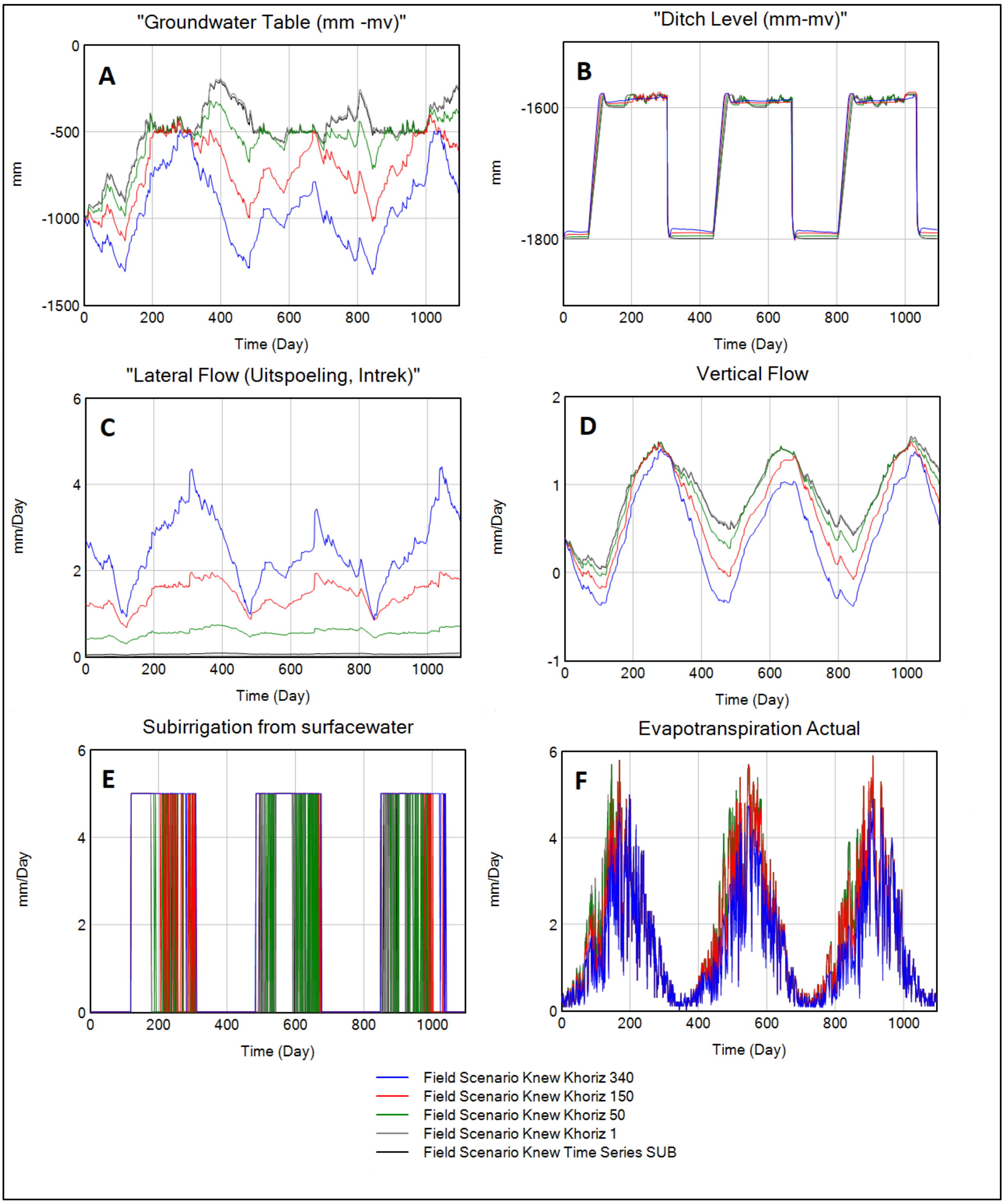

Figure 5: Vensim model output for the scenario runs with alternative hydraulic conductivity values. The outputs displayed above are for the field scale scenario with a different horizontal hydraulic conductivity. The lines depict a horizontal conductivity of 1 mm/day (grey), a horizontal conductivity of 5 mm/day (black), a horizontal conductivity of 50 mm/day (green), a horizontal conductivity of 150 mm/day (red) and a horizontal conductivity of 340 mm/day (blue). As can be seen higher conductivities result in more lateral flow (C), and as a result lower maximum groundwater tables and higher ditch levels (A&B). Lower conductivity, will thus cause higher groundwater tables, resulting in more vertical flow, evapotranspiration & subirrigation being turned off more often (D, E, F).

Regional Scenario: Series Downstream

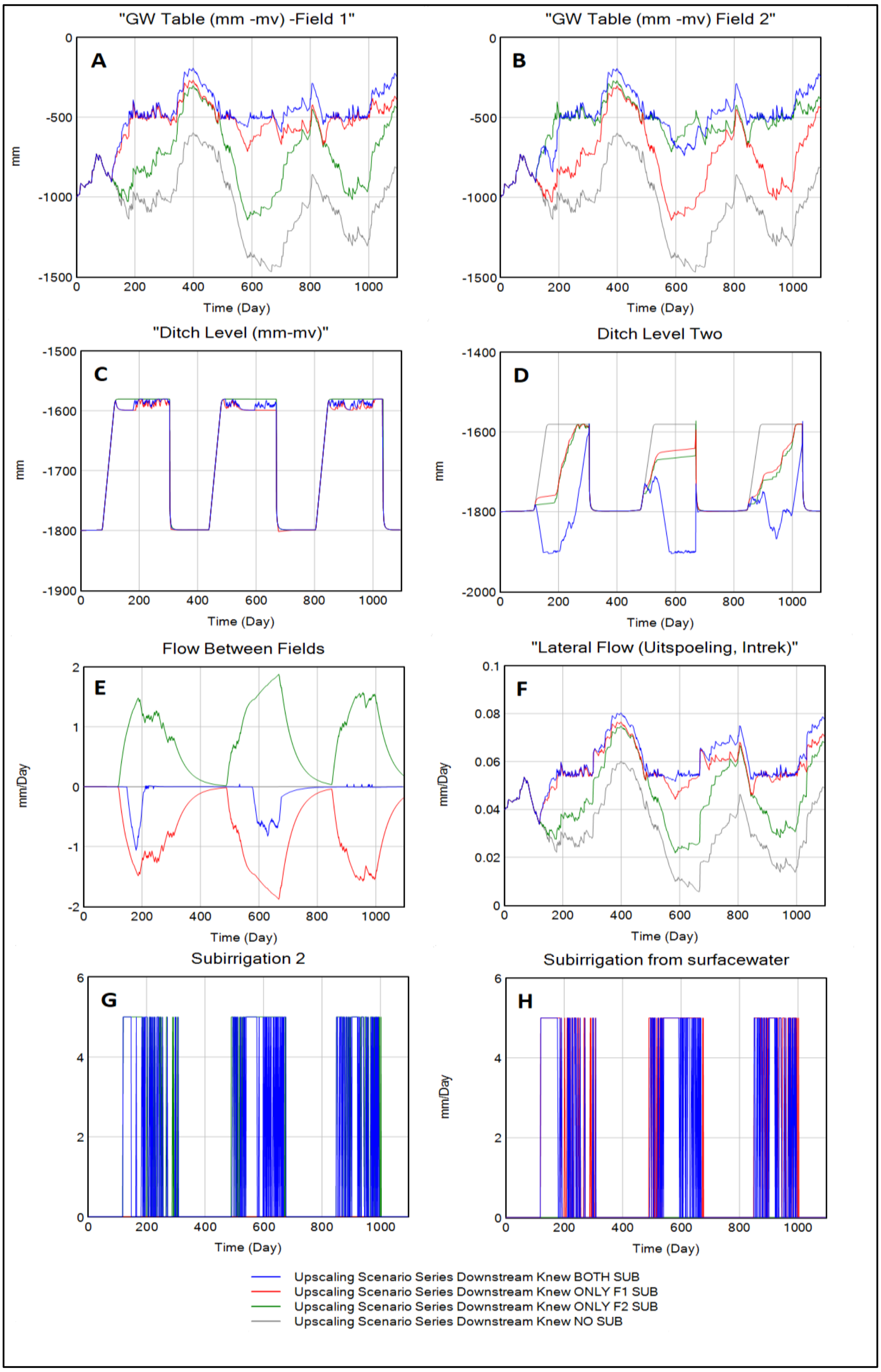

Figure 6: Vensim model outputs for the regional scenarios with alternative hydraulic conductivity values. The outputs above are for the series downstream scenario, in which two separate ditches are included as well as to fields downstream of one another. The lines represent the situation where both fields have subirrigation (blue), none of the fields has subirrigation (grey), only the upstream field has subirrigation (red) or only the downstream field has subirrigation (green). As can be seen there is a side effect of subirrigated fields on adjacent groundwater tables of almost 40 cm (A, B, E). Due to the little recirculation of subirrigation water, there are however downstream problems with maintaining the ditch level, causing subirrigation to be turned off in 2018 for field 2, resulting in a drop of +/- 20 cm in the groundwater table (D, F, H)

Regional Scenario: Series Adjacent

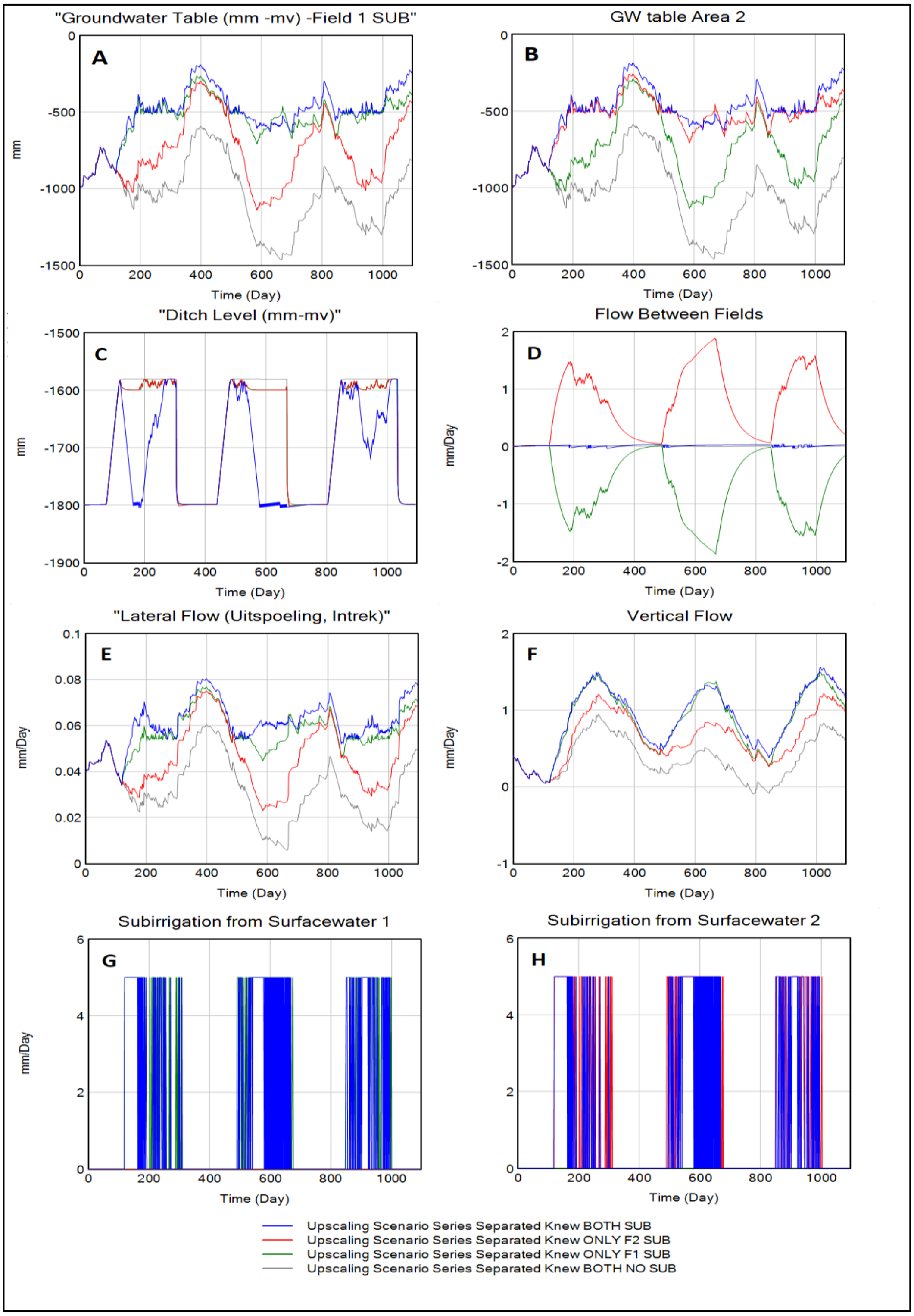

Figure 7: Vensim model outputs for the regional scenarios with alternative hydraulic conductivity values. The outputs above are for the series adjacent scenario, in which only one of the two fields is directly adjacent to the ditch. The lines represent the situation where both fields have subirrigation (blue), none of the fields has subirrigation (grey), only the upstream field has subirrigation (green) or only the downstream field has subirrigation (red). As can be seen, the side effect of sub irrigation is comparable to the downstream scenario, be it slightly lower (30-35 cm at max.) (A&B). The ditch Level is only affected in the scenario where both fields require subirrigation, implicating possible downstream shortages for surface water, with subirrigation being turned off during a large part of 2018 growing season (C, G, H)

Regional Scenario: Parallel

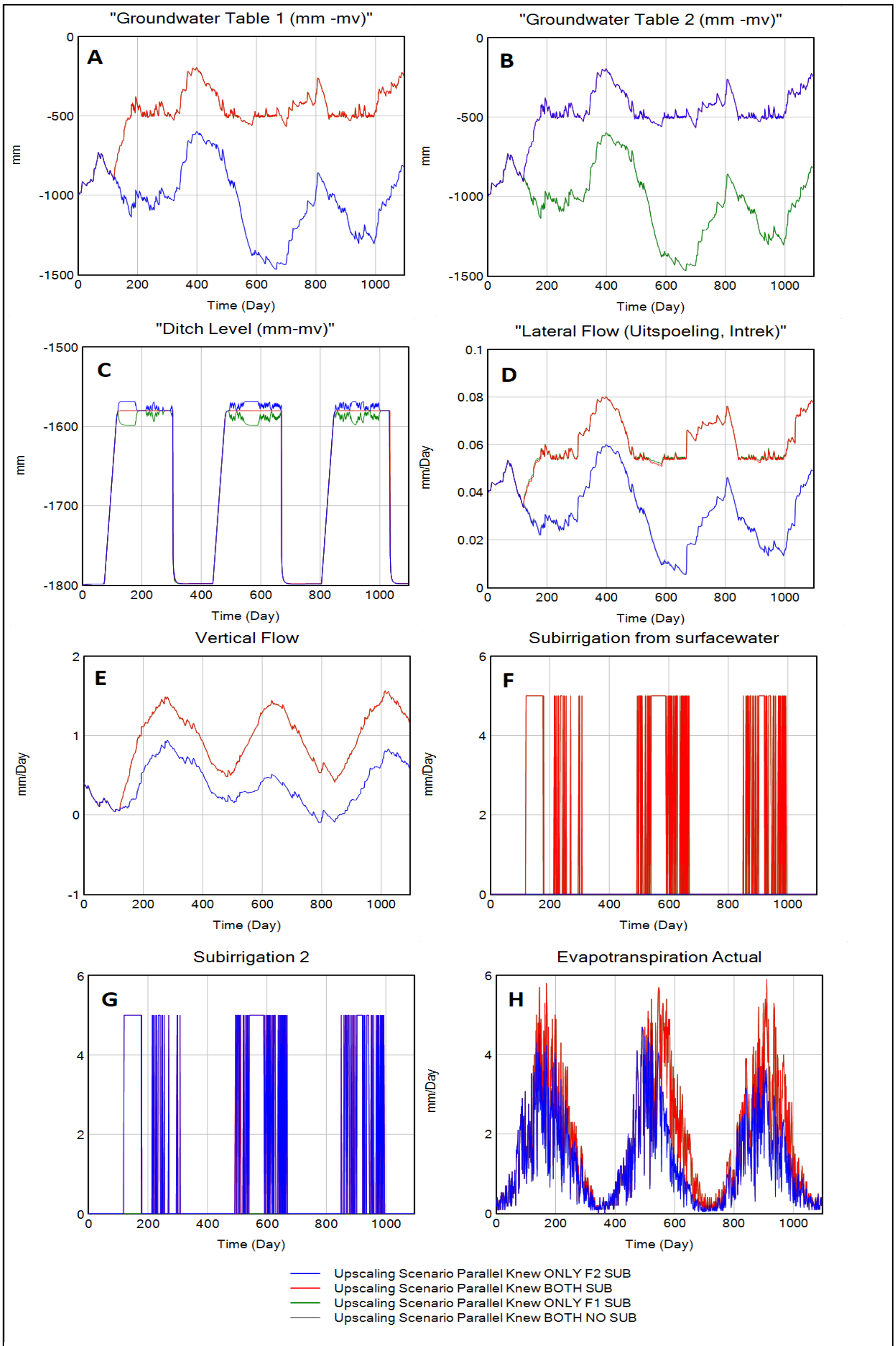

Figure 8: Vensim model outputs for the regional scenarios with alternative hydraulic conductivity values. The outputs above are for the parallel scenario, in which both fields are on opposite sides of the ditch. The lines represent the situation where both fields have subirrigation (red), none of the fields has subirrigation (grey), only the upstream field has subirrigation (green) or only the downstream field has subirrigation (blue). As can be seen there is no side effect of subirrigation in one plot on the other, and both fields can be fed with subirrigation, resulting in higher groundwater tables, vertical flow, evapotranspiration, and subirrigation being turned off (A, B, D, F, G, H). The ditch level does not seem to be affected negatively (C).

7.5. Appendix 5: Water balances SWAP & Vensim without subirrigation

Table 1: Water balance for the years 2017,2018 & 2019 for the Vensim Model runs with standard model parameterisation. Inc. indicates the situation with subirrigation whereas exc. indicates the situation without subirrigation

Groundwater Content	2017		2018		2019	
Inflows	**Inc.**	**Exc.**	**Inc.**	**Exc**	**Inc.**	**Exc.**
Precipitation	774	774	444	444	691	691
Subirrigation	945	0	960	0	935	0
Upward Seepage (Kwel)	25	33	23	46	26	55
Ditch Infiltration (Intrek)	0	0	0	0	0	0
Som	1743	807	1427	491	1652	747
Outflows						
Downward Seepage (Wegzijging)	202	82	166	36	191	66
Evapotranspiration	499	303	536	246	506	254
Ditch Drainage (Uitspoeling)	936	494	822	296	894	365
Surface Runoff	0	0	0	0	0	0
Som	1637	879	1525	578	1591	684
Storage Change	**106**	**-72**	**-98**	**-87**	**61**	**62**

Table 2: Water balance for the years 2017, 2018 & 2019 for the SWAP model runs. 1 indicates absence of subirrigation while 2 indicates the situation with subirrigation. Source: De Wit et al., 2021

		2017		2018		2019	
		1	2	1	2	1	2
In	Neerslag	775.6	775.6	445.2	445.2	692.2	692.2
	Oppervlakkige aanvoer	0.00	0.00	0.00	0.00	0.00	0.00
	Subirrigatie	0.00	704.1	0.00	728.0	0.00	728.0
	Infiltratie buisdrainage	0.00	0.00	81.1	0.00	7.9	0.00
	Kwel	14.79	0.00	0.00	0.00	0.00	0.00
	Som	790.39	1479.7	526.3	1173.2	700.1	1420.2
Uit	Interceptie	43.28	45.09	22.62	23.45	37.65	41.63
	Oppervlakkige afvoer	0.00	0.00	0.00	0.00	0.00	0.00
	Transpiratie	372.9	404.4	265.7	332.7	312.4	372.4
	Bodemverdamping	103.0	99.0	83.6	84.7	92.1	91.9
	Laterale drainage (drainage naar opp. water)	174.0	614.0	184.0	486.0	218.0	560.0
	Buisdrainage	63.5	94.2	0.00	131.0	0.00	164.4
	Wegzijging	0.00	199.3	3.62	141.2	23.78	178.82
	Som	756.68	1455.99	559.54	1199.05	683.93	1409.15
	Bergingsverandering	33.71	23.69	-33.24	-25.8	16.17	11.05

7.6. Appendix 6: Vensim user interface for the regional scale models

Parallel

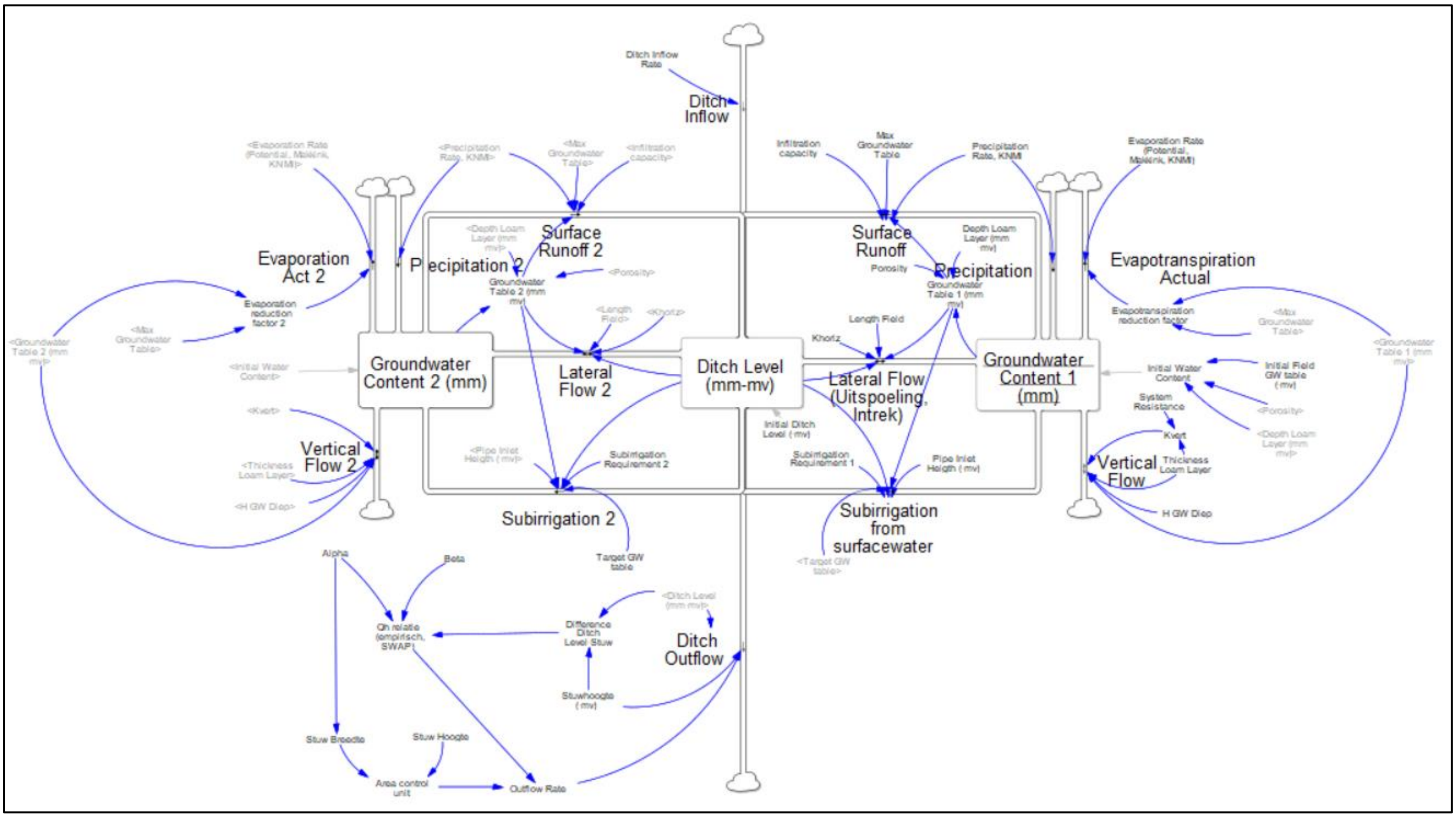

Figure 1: Vensim User Interface for the Regional Upscaling model with parallel ditches to the main ditch. As can be seen, the model contains 3 main stocks

Series, adjacent

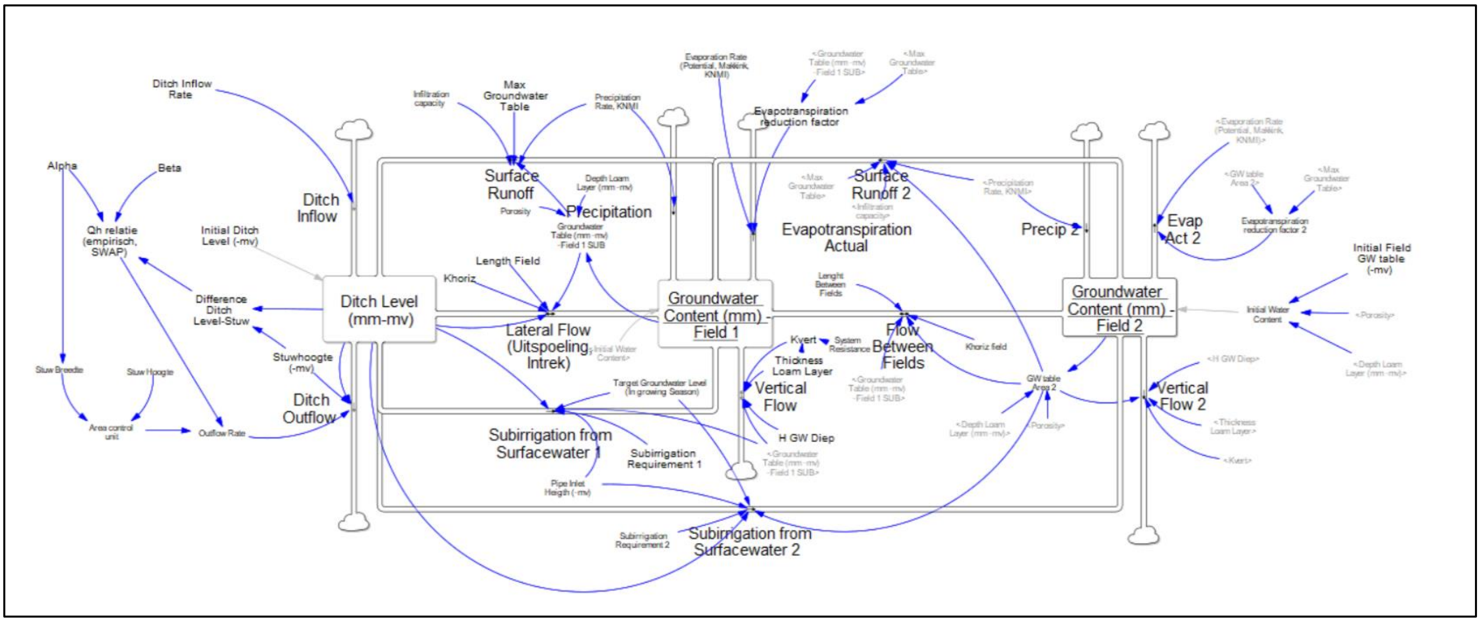

Figure 2: Vensim User Interface for the Regional Upscaling model with adjacent ditches in series to the main ditch. As can be seen, the model contains 3 main stocks, with 2 field scale balances being combined and connected to 1 ditch stock.

Series, downstream

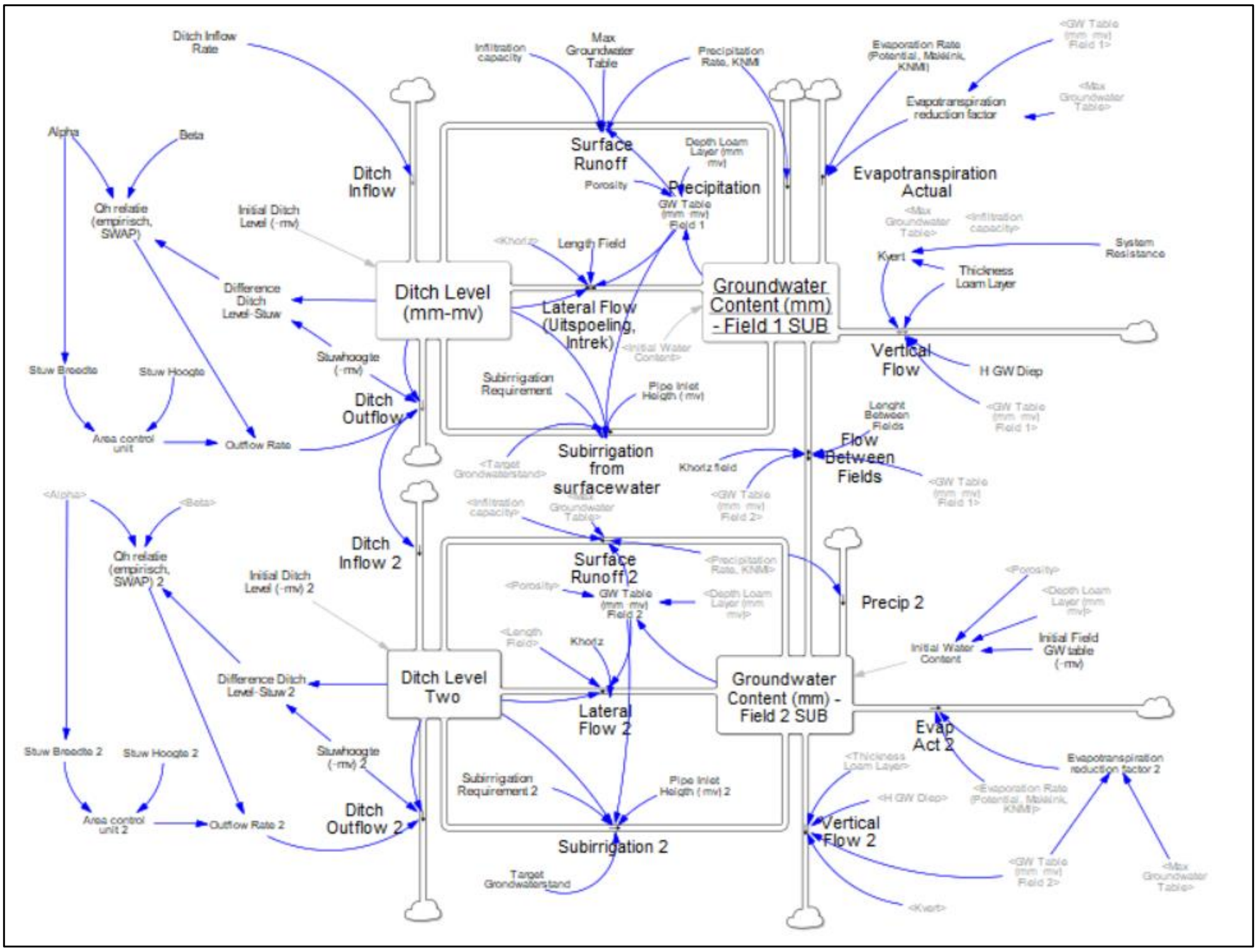

Figure 3: Vensim User Interface for the Regional Upscaling model with downstream ditches parallel to the main ditch. As can be seen, the model contains 4 main stocks and two complete field scale models with field two being positioned downstream from field one, with the ditch being split into two different compartments.