4 JULY 2025

Modelling Water and Nutrient Dynamics in a Dutch Sandy Catchment using APEX

Simulating water and nutrient transport to support the assessment of Nature-based solutions

INTERNSHIP REPORT

NANDINI SHAHI

MSC, EARTH, LIFE AND CLIMATE, UTRECHT UNIVERSITY

Supervisors:

DELTARES: DR. JOACHIM ROZEMEIJER

CÉCILE ALSBACH MSC

UTRECHT UNIVERSITY: PROF. DR. MICHELLE VAN VLIET

Table of Contents

List of Figures

List of Tables

Abstract

Agricultural activities are a major contributor to water quality degradation, leading to large amounts of nitrogen and phosphorus runoff to water bodies. Regulatory measures such as manure legislation and fertilizer restrictions have been implemented, but nutrient pollution remains a challenge. Nature-based solutions offer promising alternatives, but the lack of quantitative evidence of their effectiveness poses difficulty in their large-scale implementation and integration into policy frameworks. This research represents the first application of an open-source hydrological model for a Dutch catchment to explore the possibility of quantitative research on nature-based solutions using a modelling approach.

This study presents an attempt to configure an open-source model for simulating hydrological and nutrient transport for the Vinkenloop catchment, which is a 1.97 km^2 sandy agricultural watershed in the Netherlands. The objective of this research was to assess the potential of this model for future studies for modelling nature-based solutions. The Agricultural Policy/Environmental eXtender (APEX) model was selected after reviewing open-source options, due to its advantages for modelling nature-based solutions at catchment scale. A detailed dataset of land use, soil, topography, and weather data for the period 2021–2024 was used for model configuration.

Initial model performance showed that precipitation was the major inflow. Evapotranspiration was the dominant outflow process, accounting for approximately 60% of the total precipitation, followed by total runoff which was about 23% of the total precipitation. A closure error of 200-300 mm was encountered in the water balance, suggesting missing hydrological fluxes or inaccurate processing of the inputs. Upward groundwater seepage dynamics were also missing and likely contributed to model discrepancies since the water table in the Netherlands is at shallow depths (0.5-1 m). At the latest stage, the model yielded a Nash-Sutcliffe Efficiency (NSE) of -0.30 for daily streamflow simulation, indicating that the current setup cannot simulate the hydrological outflow reasonably and hence cannot be used for reliable assessment of nature-based solutions.

Nutrient outputs were also unreliable. The simulated concentration of soluble nitrogen in surface runoff was compared to the observed concentration of nitrogen in total runoff for a qualitative assessment of model output. The model output was in the range of 0-35 mg/l while the actual nitrogen output concentration was much lower, in the range of 2-15 mg/l, indicating possible effect of lack of dilution by water from upward seepage. Phosphorus concentrations were zero throughout the simulation, indicating limitations in the current nutrient setup. Incorporation of upward seepage processes and parameter calibration could improve the results.

With missing hydrological interactions and without complete calibration, the current model configuration was not found to be suitable for modelling nature-based solutions. Future improvements such as incorporating all groundwater interactions and thorough parametrization might be useful to resolve the issues encountered with the different fluxes. Overall, this work is a very initial step in modelling a Dutch catchment using APEX and needs significant improvement before it can be reliably used for catchment-scale nutrient pollution management using context-specific nature-based solutions.

1. Introduction

1.1. Background and motivation

1.1.1. Water quality challenges

Water is an essential resource facing rapid degradation, with estimates suggesting that 40% of the global population is affected by water scarcity, both in terms of quality and quantity (van Vliet et al., 2021). By 2050, the global freshwater demand is expected to increase by one-third, straining supplies for drinking water, agriculture and ecosystems (Denchak, 2022). Simultaneously, climate change is altering the global hydrological cycle, intensifying extreme events such as droughts and floods (Dankers et al., 2014). Increasing temperature of water would result in more eutrophication events. More frequent extreme precipitation events would increase nutrient runoff and sediment transportation to the water, thus disbalancing the existing hydrologic systems (Stroming et al., 2020; Whitehead et al., 2009; van der Brugge and de Winter, 2024). Groundwater quality is also threatened by changing precipitation patterns and concentration of contaminants due to reduced groundwater levels (Dao et al., 2024). Such degradation of water quality poses significant threats to human populations and ecosystems that rely on hydrological systems (Bond et al., 2019).

In urban areas, water pollution often results from point sources, such as industrial effluents and sewage, whereas in agricultural areas, diffuse sources are more prevalent and contribute pollutants from a large area. Diffuse sources account for 38% of the pressures on water bodies, with agriculture being a principal contributor of nitrates and pesticides (European Environment Agency, 2018).

Key agricultural practices that contaminate groundwater and surface water include over-application of fertilizers, herbicides and pesticides, traditional irrigation methods, and poor managing of animal farming operations (Moss, 2008; EPA, 2009). The usual nutrient recommendations for agriculture far exceed the environmental levels (Mueller et al., 1996) and the excess nutrients stay in the soil or leach into drainage water (Vanlauwe et al., 2001; McKergow et al., 2003). Over-irrigation can trigger chemical runoff, soil salinity issues and nutrient accumulation in the root zone, resulting in more eutrophication events, decline in biodiversity and degradation of long-term soil health and crop production (Mckergow et al., 2003, Pereira et al., 2002, Pitman and Läuchli, 2004, Tedeschi and DellÁquila, 2005, as cited in Zia et al., 2013).

Among the chemical fertilizers, nitrogen (N) is used most extensively, followed by phosphorus (P) and potassium (K) (Mancuso et al., 2021; Smith, 2010). Farmers tend to apply more N than what is taken up by crops. Since crops have a limited uptake efficiency, the surplus N finds a way into freshwater systems (EEA, 2005). There are constant efforts to quantify the amount of N lost to soil and water in order to clearly define the agricultural pressure on the environment and develop suitable measures (EEA, 2018). Regulations, including the Drinking Water Directive (1998) and the Water Framework Directive (2000) have pushed for water quality improvements but persistent pressure on most water bodies have led the extension of the WFD deadline to 2027 (European Environment Agency, 2018).

In urban areas, conventional approaches have primarily relied on “grey” infrastructure, such as chemical treatment facilities and engineered drainage systems (Jones et al., 2012). While effective in the short term, these solutions are often expensive, lack long-term sustainability, and impact surrounding ecosystems negatively (Jones et al., 2012; Kitha and Lyth, 2011). In rural and agricultural areas, the increased presence of diffuse sources of pollution makes the application of grey solutions less feasible and more expensive (Hérivaux et al., 2013). Thus, there is reliance on intensive land management practices, efficient irrigation practices and manure legislation (Ryan and Hoes, 2024). However, most of these solutions are effective only for specific pollutants, do not support biodiversity and lack circularity and sustainability. To prevent large losses of nutrients to the environment in a sustainable way, there has been a rise of Nature-based Solutions (NbS) over the past few years (Mancuso et al., 2021).

1.1.2. Nature-based solutions

As an alternative to conventional solutions, Nature-based Solutions (NbS) have gained attention for their ability to harness or mimic natural processes to address environmental challenges in a more sustainable and cost-effective manner (Matos and Roebeling, 2022). These solutions utilize natural processes to provide ecosystem services such as water purification, groundwater recharge, drinking water provision, water storage, coastal protection, carbon sequestration, flood mitigation, and biodiversity support, without relying on chemical or energy inputs (Mancuso et al., 2021).

NbS can be implemented at various spatial and temporal scales. Small-scale examples include rainwater harvesting and green roofs in urban areas, and vegetated buffer strips, constructed wetlands, sedimentation ponds, and purification ditches in agricultural areas. Large-scale projects, such as the Dutch “Room for the River” program, employ strategies like floodplain lowering, bypass channels, and dike relocation (Vojinovic et al., 2021; Matos and Roebeling, 2022).

In agricultural areas, small-scale NbS such as buffer strips, vegetated channels, and sedimentation ponds are typically placed at the edges of fields in order to intercept agricultural drainage water and reduce nutrient loads in water bodies (Mancuso et al., 2021). Such measures have shown promising results, even in the very first season after planting (Dunn et al., 2022).

On the other hand, large-scale NbS, like improved land management practices are effective for handling the root causes of agricultural pollution, like poor nutrient retention in agricultural fields, but usually act on longer time scales. For example, the addition of organic matter may improve soil structure after a short duration (Rivier et al., 2022), but there are other effects on soil functioning that evolve slowly and can improve the soil biological function several years after the addition of organic matter (Diacono & Montemurro, 2010).

Despite NbS offering promising solutions, their long-term effectiveness in managing nutrient pollution and their resilience under future climate scenarios remain poorly understood (Matos and Roebeling, 2022). It should be noted that the focus of earlier projects, like the “Room for the River” has been on restoring the natural floodplains of rivers but none of the main objectives directly targeted reduction of nutrient pollution. Additionally, such projects have been primarily implemented in larger streams, with remeandering or rewetting of stream valleys, but NbS are not yet widely implemented in and around headwaters or in artificial drainage ditches. The few studies looking into the efficiency of NbS for improving water quality are concentrated in European countries (Matos and Roebeling, 2022), with some studies in the Netherlands (De Knegt et al., 2024; Baptist et al., 2019). These studies have focussed on the overall effect of NbS but are not dedicated to an in-depth exploration of the effect of NbS on water quality, and more specifically nutrient pollution.

Also, the experimental studies that have been undertaken so far have usually focused on just one type of NbS and do not evaluate multiple dimensions of their performance simultaneously (Vymazal, 2017, Dollinger et al., 2015, Doran, 2004). This can result in missing out on unintended negative effects of NbS on the environment. For example, using just a single plant species due to its effective properties of nutrient retention might be beneficial for the short term but might reduce the system resilience over time (Zhu et al., 2012). Such consequences make it important to assess multiple aspects of NbS together.

In terms of monitoring the NbS, there is variation in monitoring efforts across measures. For example, land management practices, such as the addition of organic matter are relatively well-studied due to their main impact on just the soil system (Meurer et al., 2020; Mondini et al., 2018). However, NbS near the channel beds and banks, like multifunctional buffer strips, lie at the interface of three systems- soil, surface water and groundwater. They have complex mechanisms of pollutant removal via buffer zones, making them more difficult to monitor properly (Ghimire et al., 2022).

The efficiency of NbS is variable and depends on multiple factors. Constructed wetlands can have plant species that can adapt to the environment and have a high capacity to absorb and store nutrients, directly or through improvement of microbial processes (Cooper et al., 1987; Mancuso et al., 2021). The N removal properties of constructed wetlands is influenced by the plant species, microbial communities, hydraulic conditions, wastewater properties, the geometric configurations of the wetland and other environmental factors (Mancuso et al., 2021). The overall efficiency can be variable and is subjective to the environment. Buffer strips have a different operating mechanism. They are herbaceous or tree vegetation next to a farm or close to the receiving water bodies (Hickey and Doran, 2004; Barling and Moore, 1994). Vegetation in these buffer strips can reduce flow velocity, thus reducing water flow, trapping and depositing the suspended particulate matter that might also have N and P bound to it. N transport can be reduced by plant uptake and other mechanisms in the buffer strips like ammonification or nitrification-denitrification (Mancuso et al., 2021). The variability in their efficiency has been attributed mainly to the width of the buffer strip, but vegetation typology, slopes, seasonal variability and other factors have also been found to play a role.

Vegetated channels and water sediment control basins are other NbS that can be employed in agricultural areas. Water sediment control basins are more suited for sloping fields, where they can divert the outflow, store water temporarily and release it later.

1.1.3. Research gap

As discussed in the previous section, different NbS have been efficient in managing water contamination, but there are gaps in the understanding of these processes, the range of their efficiency and controlling variables (Mancuso et al., 2021). Considering these variations, certain NbS could be more suitable for a given area than others, with more impact towards the desired goal.

There are multiple studies showing that NbS has a positive impact on managing nutrient pollution as well as benefits for climate resilience, biodiversity and carbon-sequestration, yet the adoption of NbS measures remains limited. The reason is that there are few internationally recognized standard methods for testing their multi-faceted performance, making it difficult to clearly demonstrate their advantages over conventional approaches (Nelson et al., 2020). The lack of quantification also poses a challenge in financing these measures and obtaining support from policies (Seddon et al., 2020). Moreover, NbS often occupy space in agricultural fields that could otherwise be used for farming, impose higher initial and maintenance costs, and may conflict with short-term agricultural and economic goals of farmers (Chappin et al., 2024). This can be managed by incentivizing NbS, but a quantification of the benefits of NbS would be required before policies favouring NbS can be implemented.

Since the effects of NbS are multi-dimensional and all aspects cannot be practically monitored in experimental studies (Kumar et al., 2021), modelling NbS can be useful to evaluate the effect of these solutions in multiple scenarios in a relatively shorter period and at a larger scale, with less practical consequences. Even so, the process of modelling is inherently complex and the requirement of large input datasets and computational difficulties in numerical modelling pose a challenge in reliably predicting the response of NbS (Kumar et al., 2021). Outputs can vary significantly depending on the spatial and temporal scales of the model, making it difficult to predict long-term effects of NbS (Griffiths et al., 2024). The simplification of complex ecological systems into mathematical equations also introduces uncertainties in model predictions (Griffiths et al., 2024). To reasonably model the effect of small-scale NbS on the soil, surface water as well as groundwater, suitable models need to have the representation of processes occurring in all these systems, further increasing the complexity and uncertainty.

Considering the variability associated with the effect of NbS as well as modelling, a local-scale modelling study can be useful to obtain reliable insights about the effect of NbS as it would incorporate more context-specific parameters. As part of the RESHAPE project (RESilient DutCH LandscAPEs) (RESHAPE, 2025), this study will focus on testing an open-source hydrological model on a small agricultural catchment in the Dutch sandy landscape. Dutch sandy soils are intensively used for agriculture and are particularly vulnerable to both nutrient pollution and climate extremes due to their low nutrient retention capacity (van Gaalen et al., 2020). This study can also be useful for the GreenHood project, which is a European project on developing region-specific nutrient management strategies (GreenHood, 2025).

1.2. Research objectives and questions

To improve the current understanding of the effect of nature-based solutions on nutrients losses, this study aims to perform the initial task of setting up a scalable, open-source model for water and nutrient transport in a Dutch sandy agricultural catchment. This is intended to provide a basis for future research in assessing the effectiveness of various nature-based solutions under changing climate conditions and identifying optimal strategies for implementation that ensure both environmental impact and adaptability.

As the initial phase of the modelling task, the main research questions for this study are:

1. Which existing open-source hydrological model can be a good choice to simulate a sandy Dutch agricultural catchment and assess the impact of nature-based solutions?
2. What is the performance of the model in terms of initial validation and after calibration in terms of hydrology (streamflow, evaporation, overall water balance) and nitrogen (N) concentrations?
3. How can the model be further improved and used for implementing nature-based solutions?

The first research question was addressed by reviewing existing literature that have carried out similar research. The Agricultural Policy/Environmental eXtender (APEX) model was chosen because of its suitability for small agricultural areas, options to implement nature-based solutions, and ability to monitor nitrogen, phosphorus and carbon transport. The APEX model was configured using data from the Vinkenloop agricultural catchment located in south-east Netherlands and used to simulate water and nutrient transport in this catchment, over a period of four years, from 2021-24. This time period was chosen because data for validation was also available for this period. This configuration was used to assess the answers to the second and third research questions. The fourth research question was answered based on the model setup as well as existing literature on the model usage.

2. Literature Review

2.1. Current status of experimental and modelling studies

Experimental studies so far have usually focused on one kind of NbS for a specific aspect. Vymazal (2017) examined the effectiveness of artificial wetlands in removing nitrogen from agricultural drainage water. They found a close relationship between inflow and removed nitrogen loads, but with increase in inflow nitrogen load, overall percentage of efficiency decreased. Nitrogen removal was found to depend less on the size of the catchment and more on the size of the constructed wetland.

Similarly, Dollinger et al. (2015) and Hickey and Doran (2004) reviewed studies to look at the potential of ditches and buffer strips, respectively, for mitigating agricultural water pollution. Dollinger et al. (2015) concluded that properly managed ditches provide many ecosystem services such as groundwater recharge, water purification, flood attenuation, erosion prevention, biodiversity conservation and water-logging control. Hickey and Doran (2004) found a highly variable efficacy of vegetative buffer strips with any significant nutrient removal found only in cases when the riparian buffers were greater than 30 m wide. They pointed out the lack of experimental studies that demonstrate the efficiency of vegetative buffer strips with a width of 1-10 m, which is a more reasonable width of land that farmers can be expected to use for water quality improvement. More recent studies, like the one by Naka et al. (2024) have also shown that significant reduction in nutrient runoff was obtained when the vegetated buffer strips were at least 15 m wide.

A three-year monitoring study by Maxwell et al. (2021) looked at the efficiency of nitrate removal by a paired woodchip bioreactor in treating agricultural flow via tile drainage ditches. The in-ditch bioreactor did not significantly reduce nitrate concentrations, likely because its simple flow design allowed water to pass through too quickly, resulting in limited hydraulic exchange and reduced nitrate removal efficiency.

Given that experimental studies can be more time and resource intensive, modelling provides a valuable tool to assess the potential of NbS under varying conditions, by enabling testing across time and space (Krysanova et al., 2005; Højberg et al., 2007). However, limitations associated with data availability, accessibility and complexity of setting up robust models have limited the widespread application of modelling studies related to NbS and water quality (Hutchins et al., 2024; Matos and Roebeling, 2022). Moreover, there are additional challenges when modelling NbS at the bed and bank because their effects are at the interface between soil, groundwater and surface water, and their impact on nutrient transport has hydrological, biochemical as well as physical aspects. Thus, a suitable model needs to reliably simulate all these processes, including overland flow, erosion and sediment transport, vegetation dynamics, groundwater dynamics and in-stream processes.

Hutchins et al. (2024) developed a method for standardizing model assessments of urban water quality and found NbS to be potentially useful and recommended further verification. Other modelling studies for NbS exist but they are focused on assessing the impact of NbS on other factors like natural hazards such as floods, droughts and landslides (Chen et al., 2021; Kumar et al., 2021). As a relatively new field, research in NbS is still evolving in terms of practical applications, modelling methods, and integrated approaches (Bouzouidja et al., 2021; Mancuso et al., 2021).

Existing modelling studies have illustrated the potential of NbS as useful mitigation measures against nutrient pollution. Liu et al. (2023) employed the Catch-SD model in the Wensum and Yare catchments in Norfolk, UK which spans over an area of 1324 km^2, with a dominantly rural and arable land cover (Rowland et al., 2020, as cited in Liu et al., 2023) They concluded that integrated urban-rural NbS planning benefits water availability, quality and flood management, but there exist trade-offs between optimising each of these variables. The effect of NbS on water quality improvement was found to be more significant in rural areas than in urban areas.

Himanshu et al. (2019) employed the Soil and Water Assessment Tool (SWAT) to investigate the effects of best-management practices in a 5092 km^2 watershed of the Krishna River basin in India. Considering a ratio of field area and filter strip area of 40, with a 5 m wide filter strip, they found that contour farming practices and filter strips reduce sediment and nutrients losses but have only a minor effect on surface runoff in the SWAT water balance.

2.2. Choice of model

Matos and Roebeling (2021) reviewed existing literature on water quality modelling in the context of NbS and found only fourteen relevant studies, with most focusing on nitrogen and phosphorus as water quality indicators. They emphasized the importance of case-specific modelling as each case has a specific context, and a generalized solution cannot be recommended for all areas. This emphasizes the importance of the present study since soil in Dutch sandy catchments are different in their processes compared to other common agricultural soils (Fraters et al., 2015).

A range of hydrological models now include modules for NbS (Matos and Roebeling, 2022; Keller et al., 2023). Keller et al. (2023) reviewed 21 hydrological models, assessing their suitability based on various parameters. The project goals, user experience and available resources were also highlighted as factors to be taken into account during model selection. These factors, along with similar studies from the Netherlands, were considered when choosing a model for this study.

There are few studies in the Netherlands which look at water quality or nutrient-runoff modelling using an open-source software. Use of an open-source software would support further development and upscaling of the model by other users. Therefore, accessibility was prioritized for this project. According to Keller et al. (2023), both MIKE-SHE and SWAT (Soil and Water Assessment Tool) perform well in simulating full hydrology and water quality processes. However, MIKE_SHE is not freely available, making SWAT a more accessible choice. SWAT has two other modified versions- EPIC (Environmental Policy Integrated Climate) and APEX (Agricultural Policy/Environmental eXtender), which are also freely available and recommended for modelling at smaller scales (Kikoyo et al., 2023; Gassman et al., 2005). EPIC is suited for field-scale simulations of crop systems, while APEX can handle both field and watershed scales, offering greater flexibility for potential upscaling.

Between the latest version of SWAT (SWAT+) and APEX, the latter was chosen for its ability to model small agricultural catchments with field-level detail (Table 1). APEX outputs can be integrated into SWAT for large-scale analyses, such as through the SWAPP tool (Saleh and Gallego, 2007). APEX also includes modules for groundwater and carbon/nutrient balances, providing a more comprehensive view of nutrient transport processes than SWAT+.

Table 1: Comparison between SWAT+ and APEX to find a suitable modelling tool for the Vinkenloop catchment

	SWAT+	**APEX**
Typical resolution	Catchment scale: 10-10,000 km^2 Subbasins: 1-100 km^2 Smallest unit- Hydrological Response Unit (HRU) - No fixed size (Size based on land use/soil)	Field scale: 0.1-100 km^2 Smallest unit- Subarea: 0.01-1 km^2
Advantages	Compatible with APEX outputs for upscaling - Open-source QSWAT+ GUI (QGIS-based) - Detailed documentation and resources available	- More detailed field-to-field routing - More NbS options (e.g., filter strips, grassed waterways, constructed wetlands) - Includes carbon monitoring
Limitations	- Limited interaction between HRUs - Basic support for best management practices (BMPs) - Less accurate than APEX at small scales (Aflah, 2022)	- Less widely used - Fewer user resources and community support - ArcAPEX requires proprietary ArcGIS software - Weaker performance in daily streamflow prediction than SWAT and MIKE-SHE (Golmohammadi et al., 2025)

2.3. Agricultural Policy/Environmental eXtender (APEX) Model

APEX is a process-based model capable of simulating multiple spatially distributed fields that can interact hydrologically and chemically. It accounts for major physical and biological processes in agricultural systems. The main components are hydrology, weather simulation, nutrient cycling, erosion sedimentation, crop yield and growth, tillage, pesticide fate, plant environmental control and economics (Fig. 1) (Steglich et al., 2023). APEX has been used in multiple studies for assessing sustainable land management strategies and environmental impacts at various spatial scales (Taylor et al., 2015; Gassman et al., 2010). The model operates at a daily time step and allows for user-defined configurations based on field layout, soil and crop types.

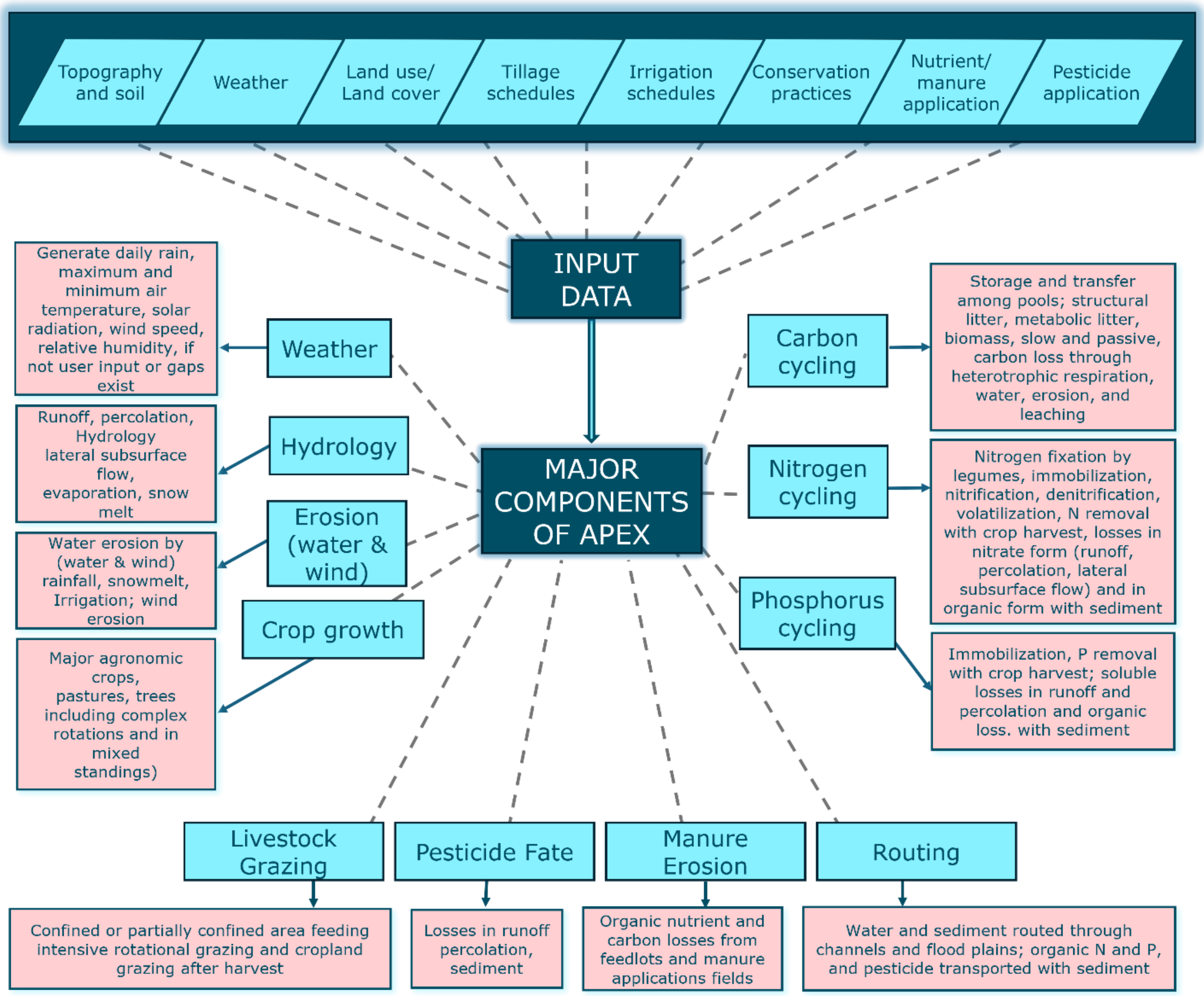


Figure 1. Main components of APEX input, processing and output. (Modified from Wang et al., 2014 and Wang et al., 2012)

Van Liew et al. (2017) evaluated APEX for simulating water quality and streamflow. They found the model performance well for streamflow, moderately well for sediment and nitrogen, and marginally well for phosphorus at a monthly scale when fully calibrated. The model showed reduced robustness when applied to different periods or similar nearby catchments, highlighting the importance of calibration. In groundwater, APEX returns the nitrogen outputs and no other nutrient outputs.

Luo and Wang (2019) applied APEX in the Guizhou Plateau, China, across a 176,128 km^2 watershed and found that it effectively simulated grain yields and sediment yields in sub-catchments when different agricultural management practices were applied to them. The study also used the model to look at the effect of different tillage practices and chemical fertilizers on crop growth.

APEX can simulate filter strips, grassed waterways, artificial wetlands, sedimentation basins, and more NbS, including structural, non-structural and on-channel conservation practices (Waidler et al., 2011). The guide by Waidler et al. (2011) is a useful resource which provides detailed guidelines on how these NbS can be implemented in APEX.

3. Study Area

The Vinkenloop catchment (5.86 °N, 51.57 °E) (Fig. 2, 3) was chosen for this study, since it fulfilled all the necessary requirements of a catchment for this study. As part of the RESHAPE, the catchment had to be sandy and agricultural. To monitor the effects of NbS specifically on nutrients from agriculture, it was favourable that the catchment does not have inlet water from other areas and no point sources. The discharge and nutrient concentration (N and P) data was also available for this catchment, and it was one of the more well-monitored catchments in the Netherlands, with good-quality data available from 2020. Also, the farmers in this catchment have connections with Deltares and details are available such that actual implementation of NbS would be easier in these regions for testing NbS for the RESHAPE and GreenHood projects.

Figure 2. Drainage ditches in the Vinkenloop catchment allow for excess water to be removed quickly from the fields.

The catchment spans approximately 1.97 km^2 and is located in the southeastern part of North Brabant, just southwest of the village of Westerbeek, near the border of Limburg and North Brabant (Fig. 2, 3). Roughly 92% of the catchment is under agricultural use, with increasing cultivation of intensive arable and horticultural crops such as open-field vegetables, flower bulbs, turf sods and dairy farming. The catchment does not receive external water via inlets and rarely dries up, suggesting contributions from deeper groundwater sources (STOWA-KIWK, 2022-23). It borders the Afleidingskanaal on the south and drains northward into the Oploosche Molenbeek, then goes through Westerbeek and Oploo to finally drain into the Maas via the Raam River. There are no known point sources discharging into the catchment (STOWA-KIWK, 2022-23).

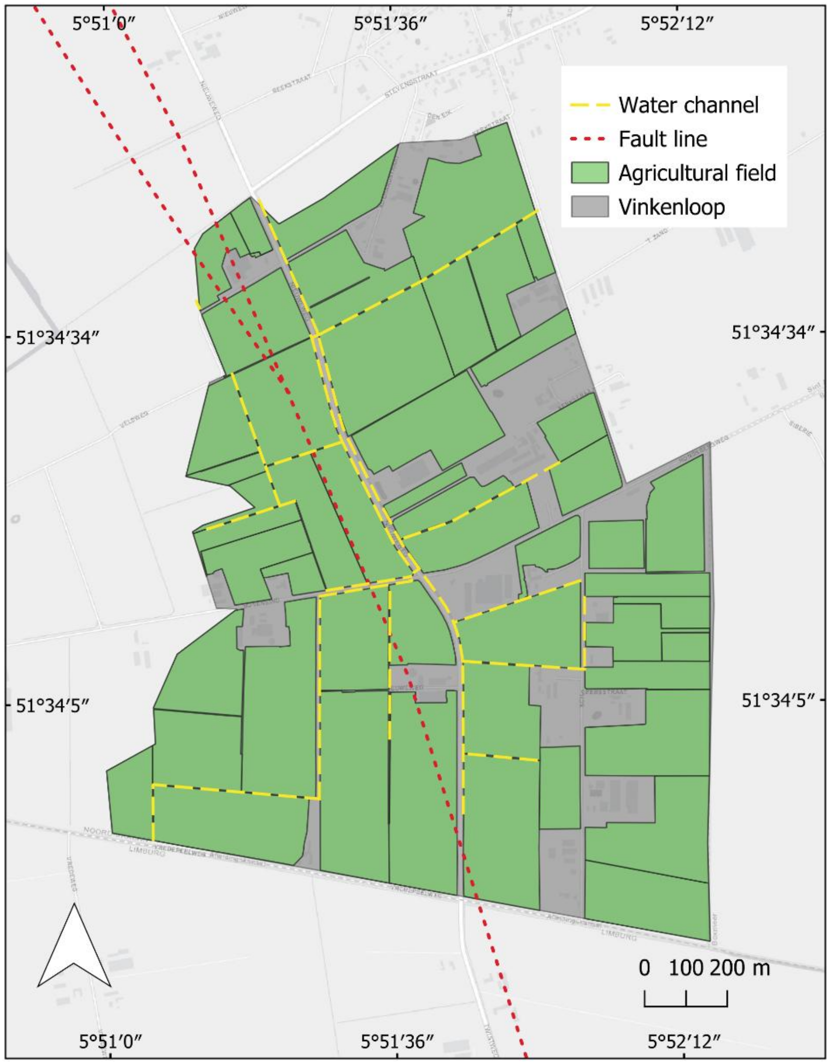


Figure 3. Map of the Vinkenloop catchment area. The central yellow dashed lines mark the main channel.

Originally a marshy area, the catchment was drained via a man-made channel that runs across the catchment (Fig. 2, 3). The sandy subsoil contains compacted layers of loam and iron ore, locally reducing permeability and increasing false groundwater levels. Part of the Peelrand fault runs through the area causing iron-rich seepage and creating contrasts in groundwater levels on the east and west parts of the catchment (STOWA-KIWK, 2022-23).

Soils in the area are primarily field podzols composed of weak loamy fine sand with decreasing humus content at depth. This causes a distinct transition from black topsoil (~30 cm) to yellow sand at deeper layers (~2 m). The area was initially sandy, and it was only over the last century that the upper soil layers were enriched with organic matter when agricultural activities began (Geogementee, 2025). Leaching of organic matter from the upper layers and infiltration into the lower layers is a common process in the soil here (Geogementee, 2025).

Monitoring efforts for recording hydrological outflow and nutrients N and P began in 2020. Nutrient data is recorded from five stations within the catchment and one at the outlet, while outflow data is recorded only at the final outlet, called the Vinkenloop170 station (Fig. 4). In addition, conventional weekly/biweekly grab samples were collected and analysed to record the N and P concentrations from the different sites.

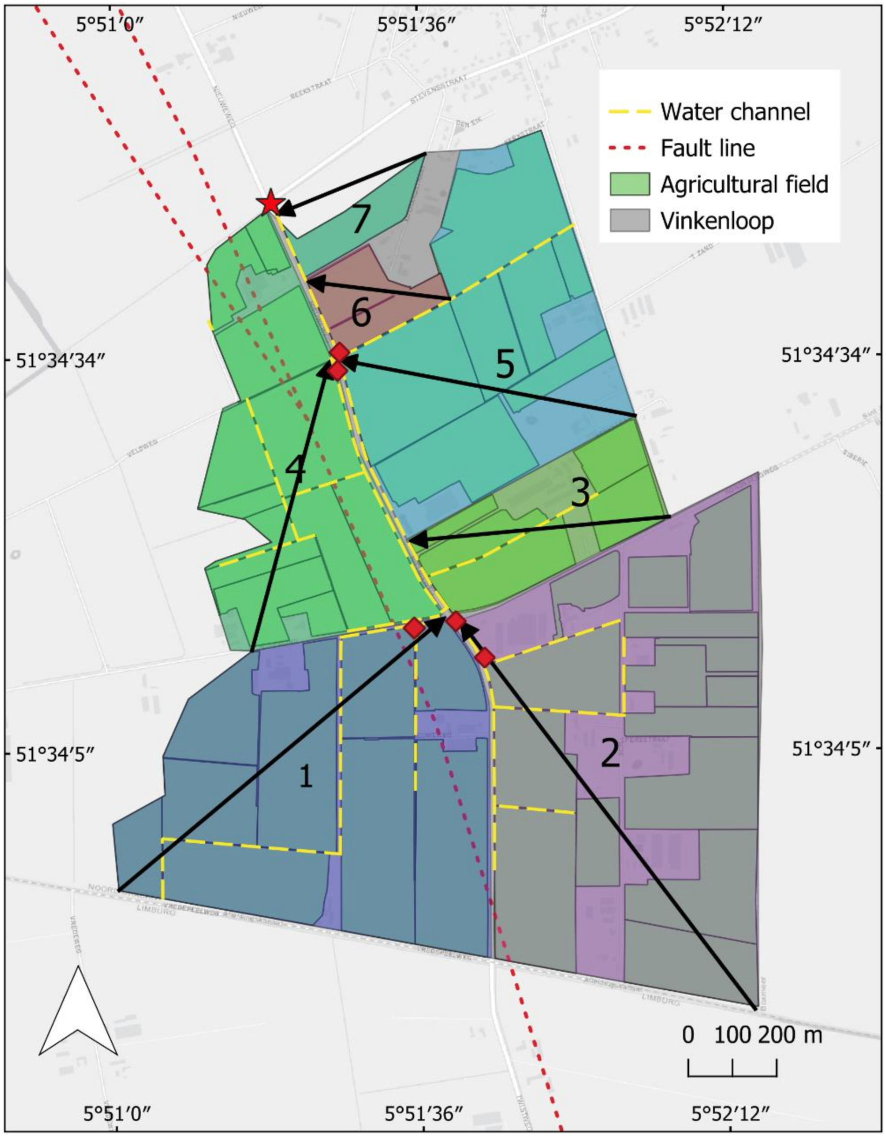


Figure 4. The catchment is divided into 7 subareas and there are 6 monitoring locations. Red diamonds mark intermediate monitoring locations and red star marks the main channel outlet (named the Vinkenloop170 station). The arrows show the general outflow direction and the outlet point of each subarea.

4. Methodology

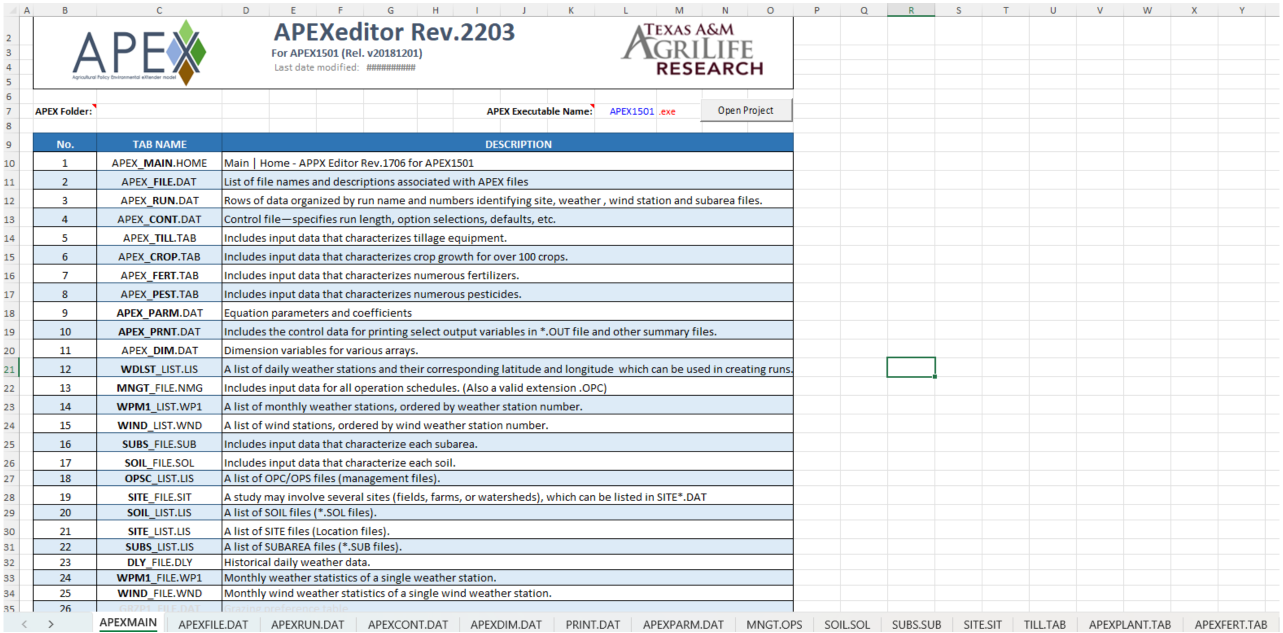
4.1. Input data

The study employed the latest version of the APEX model, APEX1501, which operates on a FORTRAN-based code with text-based input and output files (Steglich et al., 2023). A successful APEX run involves 29 input files and can generate up to 41 output files.

Preparing each input file involved reviewing the APEX documentation to understand the format and function of each parameter, identifying the essential and optional variables, and excluding variables which are not relevant to the Vinkenloop catchment (Steglich et al., 2023). Due to the limited and sometimes outdated documentation available for the latest APEX version, a substantial amount of time was spent troubleshooting model execution issues (Appendix A).

The formatting of the input files is inconsistent across file types, making direct editing inefficient. Therefore, a Graphical User Interface (GUI) is typically used to simplify model setup and execution (Leyton, 2019). Four primary GUI tools exist for APEX: WinAPEX, ArcAPEX, i_APEX and APEXEditor. WinAPEX and ArcAPEX are recommended for more experienced users (Pan et al., 2021). The available version of WinAPEX is a deprecated version programmed in Visual Basic 6 (Leyton, 2019). i_APEX uses an interface for the APEX model programmed into C++ (Leyton, 2019) but it was not accessible at the time of this project. APEXEditor was chosen because it is the only tool that allows direct editing of ASCII-format datasets and does not require administrator privileges to run.

APEXEditor is written in Visual Basic for Applications (VBA) for Microsoft Excel (2010 or later). It operates within an Excel workbook comprising 29 worksheets, each corresponding to a specific input/output file (Fig. 5). Model output files were processed in Python. Custom scripts were written to read and process the text-based outputs.


APEXeditor Rev.2203
For APEX1501 (Rel. v20181201)
Last date modified: ##########

APEX Folder:
APEX Executable Name: APEX1501 .exe
Open Project

No.	TAB NAME	DESCRIPTION
1	APEX_MAIN.HOME	Main | Home - APPX Editor Rev.1706 for APEX1501
2	APEX_FILE.DAT	List of file names and descriptions associated with APEX files
3	APEX_RUN.DAT	Rows of data organized by run name and numbers identifying site, weather , wind station and subarea files.
4	APEX_CONT.DAT	Control file—specifies run length, option selections, defaults, etc.
5	APEX_TILL.TAB	Includes input data that characterizes tillage equipment.
6	APEX_CROP.TAB	Includes input data that characterizes crop growth for over 100 crops.
7	APEX_FERT.TAB	Includes input data that characterizes numerous fertilizers.
8	APEX_PEST.TAB	Includes input data that characterizes numerous pesticides.
9	APEX_PARM.DAT	Equation parameters and coefficients
10	APEX_PRNT.DAT	Includes the control data for printing select output variables in *.OUT file and other summary files.
11	APEX_DIM.DAT	Dimension variables for various arrays.
12	WDLST_LIST.LIS	A list of daily weather stations and their corresponding latitude and longitude which can be used in creating runs.
13	MNGT_FILE.NMG	Includes input data for all operation schedules. (Also a valid extension .OPC)
14	WPM1_LIST.WP1	A list of monthly weather stations, ordered by weather station number.
15	WIND_LIST.WND	A list of wind stations, ordered by wind weather station number.
16	SUBS_FILE.SUB	Includes input data that characterize each subarea.
17	SOIL_FILE.SOL	Includes input data that characterize each soil.
18	OPSC_LIST.LIS	A list of OPC/OPS files (management files).
19	SITE_FILE.SIT	A study may involve several sites (fields, farms, or watersheds), which can be listed in SITE*.DAT
20	SOIL_LIST.LIS	A list of SOIL files (*.SOL files).
21	SITE_LIST.LIS	A list of SITE files (Location files).
22	SUBS_LIST.LIS	A list of SUBAREA files (*.SUB files).
23	DLY_FILE.DLY	Historical daily weather data.
24	WPM1_FILE.WP1	Monthly weather statistics of a single weather station.
25	WIND_FILE.WND	Monthly wind weather statistics of a single wind weather station.
26	GRZP1_FILE.DAT	Grazing preference table

APEXMAIN | APEXFILE.DAT | APEXRUN.DAT | APEXCONT.DAT | APEXDIM.DAT | PRINT.DAT | APEXPARM.DAT | MNGT.OPS | SOIL.SOL | SUBS.SUB | SITE.SIT | TILL.TAB | APEXPLANT.TAB | APEXFERT.TAB

Figure 5. Snippet of APEXEditor tool. Each of the tabs are used for modifying a specific input/output file.

4.1.1. Weather data

Weather data was obtained from the Koninklijk Nederlands Meteorologisch Instituut (KNMI) Volkel station, approximately 20 km north-west of the Vinkenloop catchment. Since this was the nearest station, all subareas used its data, spanning from 1 January 2020 to 23 March 2025. The data was available at daily and hourly time step from KNMI. Since APEX requires daily weather input, the daily data was used, and monthly averages were derived from calculations on daily data. Python scripts were developed to filter the KNMI data and convert it into format compatible with APEX. The scripts were written so that they can be used to obtain APEX-compatible weather input from KNMI data for any time period.

The data was used for generating the Daily Weather File (*.DLY), Monthly Weather File (*.WP1), and Monthly Wind File (*.WND) (Table 2). The monthly files are a necessary input for APEX because in absence of daily data, APEX uses the monthly statistics to generate weather input.

Table 2. Input parameters provided in the weather files in APEX.

Daily Weather File (*.DLY)	***Parameter***	***Unit***
SRAD	Solar radiation	MJ/m^2
TMAX	Maximum temperature	°C
TMIN	Minimum temperature	°C
PRCP	Precipitation	mm
RHUM	Relative humidity	fraction
WSPD	Wind speed	m/s
APEX Monthly Weather Files (*.WP1)		

OBMX	Average monthly maximum air temperature	°C
OBMN	Average monthly minimum air temperature	°C
SDTMX	Monthly average standard deviation of daily maximum temperature	°C
SDTMN	Monthly average standard deviation of daily minimum temperature	°C
RMO	Average monthly precipitation	mm
DAYP	Average number of rain days per month	days
OBSL	Average monthly solar radiation	MJ/m^2
UAV0	Average monthly wind speed	m/s
Monthly Wind Files (*.WND)		
UAVM	Average monthly wind speed	m/s

In the monthly wind file, there are additional parameters like wind direction percentages which were set to zero. These parameters are relevant for calculating wind erosion, which is not a major nutrient transport process in the region (Winteraekan and Spaan, 2010).

In case of monthly weather files (*.WP1), some statistical parameters related to precipitation (RST2, RST3, PRW1, PRW2, WI and RH) were set to zero as they are used for spatial weather generation, but in this case, direct daily rainfall data was available. Similarly, other optional daily weather parameters like CO2I (CO_2 concentration in the atmosphere), REP (Peak rainfall rate) and ORSD (Observed soil surface crop residue) were set to zero due to limited data availability and time constraints.

4.1.2. Soil data

Soil input values were compiled from national databases and published research (Appendix B). Key soil parameters were included, but several optional fields were left blank due to either irrelevance to this catchment or lack of data.

4.1.3. Subarea file

APEX divides the catchment into subareas, which is the smallest hydrological processing unit of the model. The Vinkenloop catchment was divided into seven headwater subareas, each draining independently into the main channel (Fig. 4). Subarea delineation was based on clusters of fields draining into the channel from similar directions and points. Elevation data was sourced from the Actueel Hoogtebestand Nederland- Digital Terrain Model (AHN4-DTM) database (AHN, 2025). The database has elevation information for the whole of the Netherlands so data from map sheet 52AN2 was obtained in TIF format to get elevation data specifically for the area around Vinkenloop. The TIF file was processed in QGIS version 3.40.5.

4.1.4. Operations file

This file contains information about land use and operations in different subareas. Information for crop grown in each field was available by monitoring efforts undertaken at Deltares in 2022 and 2023. Since each subarea contains multiple fields and a subarea can have only a single crop at a given time, the dominant crop grown in the subarea was assigned to each subarea. Management operations provided as model input included addition of manure to grass fields from February to August and for other arable crops, addition of fertilizers followed by sowing around March and harvesting around October. Generally, the winter conditions are not suitable to grow any crops in the catchment so cover crops like ryegrass were planted during the winter in the model input. Where ryegrass was present throughout the year, mowing was scheduled every 6-8 weeks, except during winter (November-February).

4.1.5. Model configuration files

APEX uses files with the extension .LIST to record filenames of individual sites, operations, soil types, weather stations, monthly weather, wind and subareas. Since this was a small catchment, a single soil type, weather station and site were used.

Several standard APEX input files were either left unchanged or excluded, depending on model requirements for this study (Appendix A). APEX provides certain fixed parameters related to standard practices in tillage, crop parameters, fertilizers and pesticides application. They can be changed, or new parameters can be added if required but the default settings were used for this study. Multiple-runs were not employed in this case, neither the effect of grazing nor point-sources because they are not relevant to the Vinkenloop catchment.

4.2. Analysis

4.2.1. Data and equations

To evaluate model performance, discharge and N and P concentration data at the catchment outlet (VInkenloop 170 station) was used (Fig. 4). The data was recorded and made available by the Water Board Aa en Maas. Total water outflow was recorded at 15-minute intervals using a sensor placed at the outlet point of the catchment and was averaged to produce daily discharge values for comparison with the daily discharge values produced by the model. The water yield (WYLD) output from each subarea, available in the .SAD file, was added together to get the total discharge from the catchment since all subareas directly drained into the main channel in the model. There were other output files which provided daily hydrological fluxes that could also be used to get the daily discharge from the watershed. These calculations were not performed in this research due to time constraints.

Measured N and P concentrations in the outflow (in mg/l) were obtained from conventional weekly to biweekly grab samples. The concentration data was available for at least one day of each month, with sometimes four measurements taken at different dates in a month. Although sensor data was also available at smaller time-steps, the data from grab samples was used because it was most reliable and consistent over all sub-catchment conditions. The model output for soluble N and P concentration (ppm) in surface runoff was available in the .DMR file which was used for initial comparison. Since total N and P outputs were not available at a daily time step in the output, only the soluble forms in surface runoff were used for an initial qualitative comparison with observed data.

4.2.2. Water balance

Based on the model description and equations, the model has three main storages distributed across the surface water, subsurface water and deeper groundwater layer. There are parameters for additional reservoirs and ponds, which are not relevant for the current Vinkenloop area so a simplified version of the exchanges was derived for the calculations (Fig. 6, Table 3). Reservoirs, in this section, refer to storage areas that can be placed at the outlet of any subarea with inflow contribution from that subarea and previous connecting subareas.

Table 3. Description of hydrological flow variables used by APEX

Variable	**Description**	**Variable**	**Description**
DPRK	Deep percolation (goes out of upper groundwater storage layer)	Q	Daily surface runoff
ET	Evapotranspiration	QRF	Quick return flow (Lateral water flow from soil profile which returns to channel)
EF	Evaporation from flood water	RSLK	Reservoir leakage
ER	Evaporation reservoir	RSSF	Return subsurface flow (Water that ends up in channel downstream after travelling via subsurface; part of PRK)
GWST	Groundwater storage	RSVQ	Reservoir storage (Optional storage at the outlet of a subarea that collects water from that and previous connecting subareas)
IRDL	Irrigation distribution loss	SNO	Snow water content
IRGA	Irrigation	SSF	Lateral flow (Horizontal flow that enters the subarea immediately downstream)
IRZ	Inflow to root zone from water table	SW	Soil water in total profile
PRCP	Precipitation	SWLT	Soil water in surface litter
PRK	Percolation (goes below soil water zone)	WYLD	Water yield (=Q+QRF+RSSF)

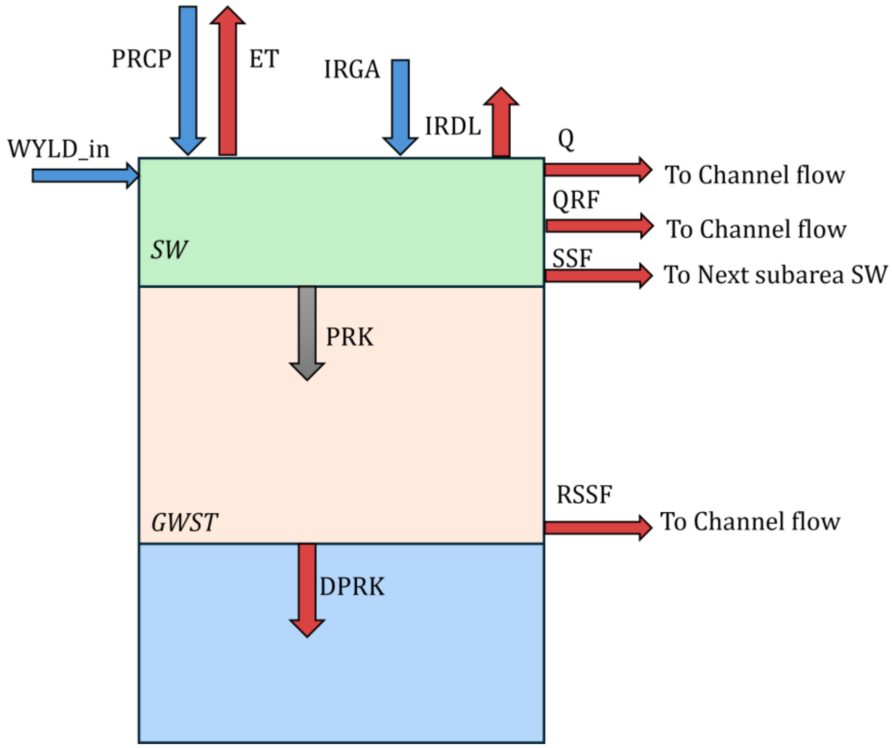


Figure 6. Simplified schematic of the hydrological inflows and outflows from a subarea in APEX. PRCP: Precipitation, ET: Evapotranspiration, IRGA: Irrigation, IRDL: Irrigation distribution loss, Q: Surface runoff, SSF: Lateral flow, QRF: Quick return flow, RSSF: Return subsurface flow, PRK: Percolation, DPRK: Deep percolation, SW: Soil water, WYLD_in: Water yield into the subarea from previous connected subarea.

The water balance was calculated at a daily time step using data from the .SAD file based on the following equation, provided on the EPIC/APEX Modelling Forum by the APEX modelling team (EPIC/APEX Modelling Forum, 2025):

$$E = SW_i + SNO_i + RSVQ_i + GWST_i + SWLT_i + WYLD_{in} - WYLD_{out} - ET - EF - ER - DPRK + IRGA - IRDL + IRZ + RSLK - SW_f - SNO_f - RSVQ_f - GWST_f - SWLT_f \quad (1)$$

where, E is the balance error, SW_i and SW_f are the initial and final soil water content, SNO_i and SNO_f are the initial and final snow water content, $RSVQ_i$ and $RSVQ_f$ are the initial and final water content from external reservoir, $GWST_i$ and $GWST_f$ are the initial and final ground water storage content, $PRCP$ is the precipitation, $WYLD_{in}$ and $WYLD_{out}$ are the water yield into the subarea and water yield that leaves the subarea, ET is the evapotranspiration, EF is the evaporation from flood water, ER is evaporation from external reservoir, $DPRK$ is deep percolation, $IRGA$ is the irrigation, $IRDL$ is the irrigation distribution loss, IRZ is the inflow to root zone from water table and $RSLK$ is the leakage from external reservoir, which then goes into ground water.

Reservoirs have not been used in this study, therefore their contributions become zero in the water balance equation. The snow water content is obtained from the precipitation value itself so it has been dropped from the equation. The evaporation from flood water was also zero for all days so the EF variable was also dropped. With these zero-value variables in the equation for this particular catchment or at this stage of modelling, the equation gets simplified to:

$$E = SW_i + GWST_i + SWLT_i + WYLD_{in} - WYLD_{out} - ET - DPRK + IRGA - IRDL + IRZ + SW_f - GWST_f - SWLT_f \quad (2)$$

Here, water yield is a combined term that represents the total outflow from the subarea or the watershed, such that:

$$Water\ yield = Daily\ surface\ runoff + Return\ subsurface\ flow + Quick\ return\ flow \quad (3)$$

Daily surface runoff travels to channel via the overland flow while return subsurface flow and quick return flow enter the channel in downstream regions after travelling through the subsurface (Fig. 7).

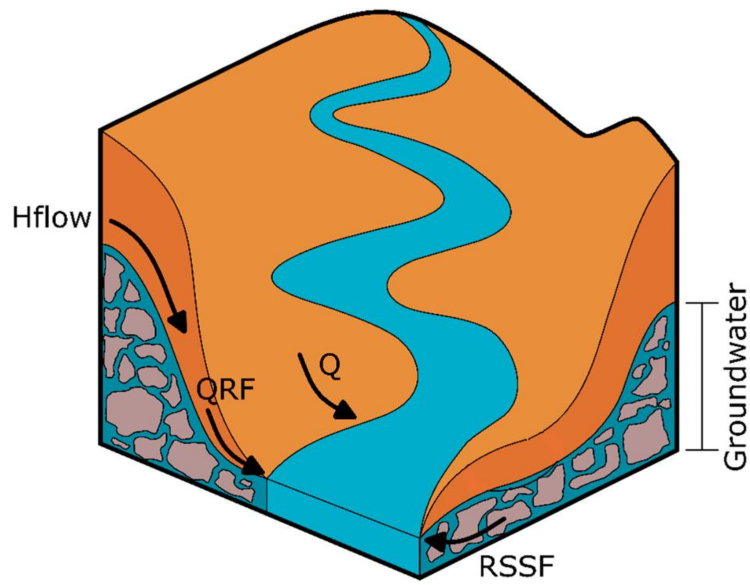


Figure 7. Schematic of fluxes that make up water yield in APEX. Hflow refers to the part of the lateral flow within the soil profile, Q is the quick return flow that returns to the subarea outlet, QRF is the lateral flow from water in the soil profile that enters the channel, Q is the surface water runoff and RSSF is the return subsurface flow, which goes from groundwater to the soil surface downstream. (From Doro et al., 2024)

4.2.3. Sensitivity analysis

Based on the initial results, some of the main parameters with no fixed values were identified and their influence was observed on the output using the following formula:

$$Sensitivity = \frac{Change\ in\ output\ value}{Change\ in\ input\ parameter} \quad (4)$$

The Nash-Sutcliffe Efficiency (NSE) (Nash & Sutcliffe, 1970) is a measure of assessing the performance of hydrological models and is calculated as:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \bar{Q}_o)^2} \quad (5)$$

where $\bar{Q}_o$ is the mean of observed discharges, Q_m^t is the modelled discharge at time t, and Q_o^t is the observed discharge at time t.

A positive value means that the model performs better than using the mean of observed data, a value of zero means that the model is as good as using the mean of the observed values and a negative NSE indicates performance worse than using the mean. NSE value of more than 0.5 is considered acceptable for a good hydrological model (Garrick et al., 1978).

5. Results

5.1. Validation against monitored watershed outflow

Based on the validation data available from December 2021 to December 2023, the range of model output for daily watershed outflow fell within the monitored range of 0-60 mm (Fig. 8). The periods between April 2022 to January 2023 and June 2023 to mid-November 2023 were when the water yield was zero so there was no match with the monitored watershed outflow values. During the periods with positive water yields, there was a match between the outflow peaks of the actual and modelled data, particularly during February to May each year. The NSE of the setup was -0.30, which increased if only periods with positive water yield were considered. For example, NSE for the non-zero water yield period of November and December 2023, was -0.18.

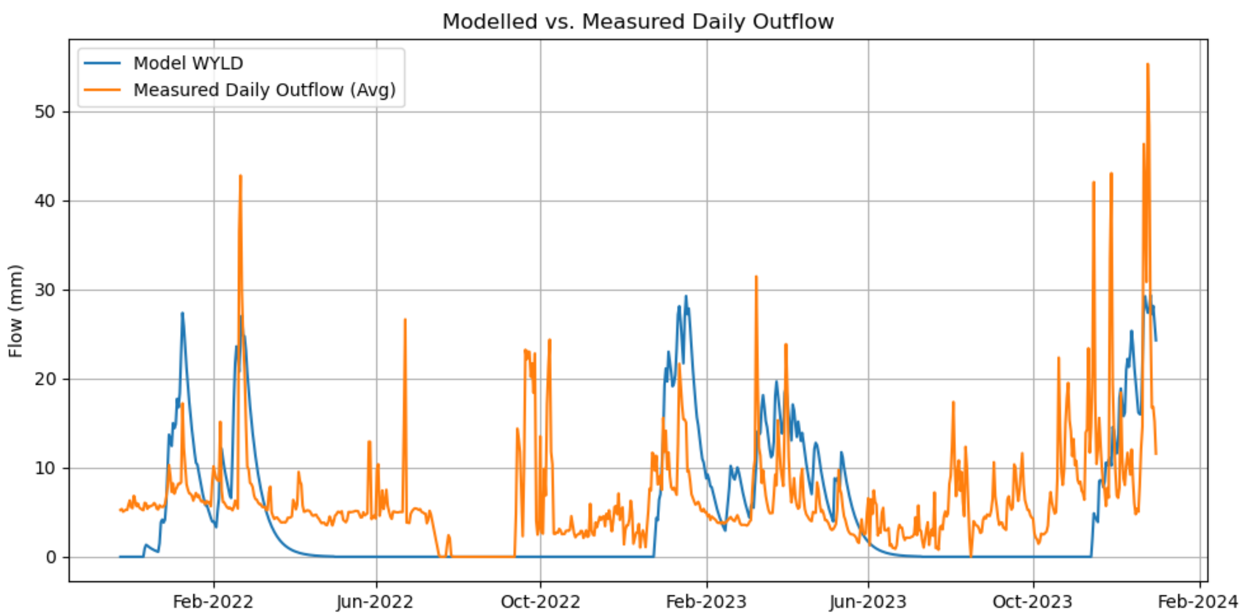


Figure 8. Comparison of watershed water outflow between the model output and measured values from the Vinkenloop170 station. The model peaks follow some pattern similar to the measured values in the periods when it is non-zero. The outflow falls to zero for more than six months every year.

5.2. Daily water balance

Cumulative values of the different hydrological fluxes from .SAD file were used to observe the overall changes in the catchment. Inflows were plotted as positive, and outflows were plotted as negative. Precipitation was found to be a continuous source of inflow to the catchment and evapotranspiration was a dominant outflow, removing approximately 60% of the total precipitation, followed by water yield, which was about 23% of the total precipitation (Fig. 9). Groundwater and soil water storages showed values that fluctuate at a yearly time scale.

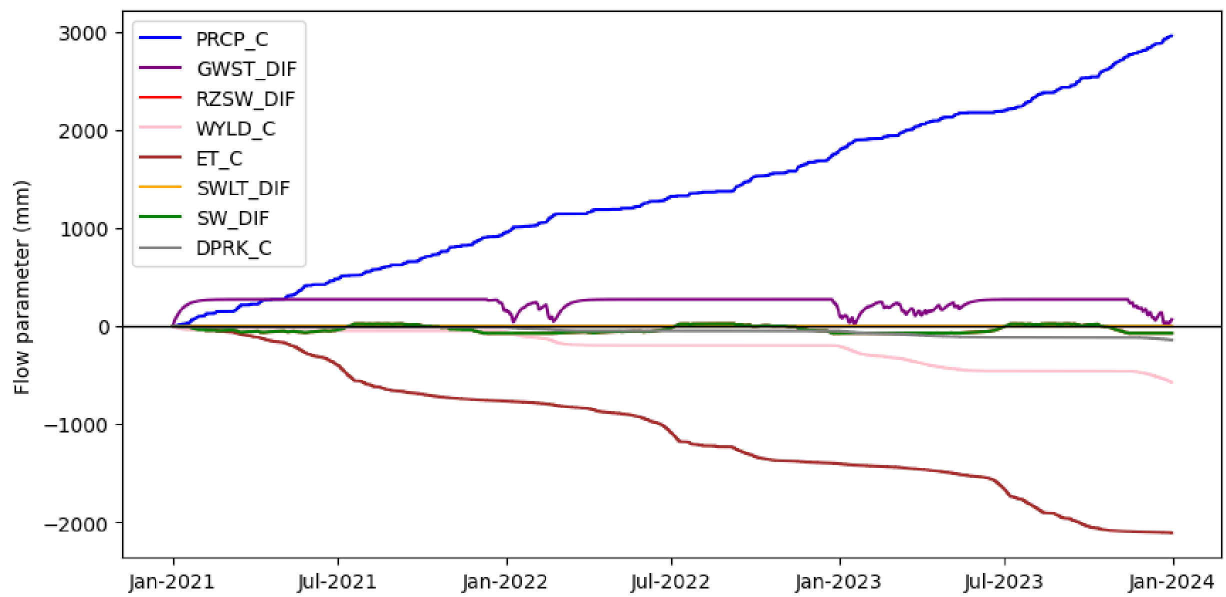


Figure 9. Cumulative values of hydrological fluxes from the catchment. Precipitation is a consistent inflow while evapotranspiration is a major outflux, followed by water yield. Groundwater storage and water yield become constant during the winter months. DPRK: Deep percolation, ET: Evapotranspiration, GWST: Groundwater storage, PRCP: Precipitation, RZSW: Water content in root zone, SW: Total water content in soil, SWLT: Water in soil litter, WYLD: Water yield. The suffix _C refers to the cumulative value of the respective variable and the suffix _DIF refers to the change in the respective storage from the starting day.

There was an average error of 206.9 mm from the water balance (Eqn.2) and the peaks in the error matched the patterns of groundwater storage and soil water storage changes (Fig. 10). There were half yearly periods when the groundwater storage became zero, during which the residual fit matched the fit of the soil water in root zone (Fig. 10). The storage reservoirs of soil water and groundwater storage change were the only variables with values sometimes exceeding 100 mm on a daily time step.

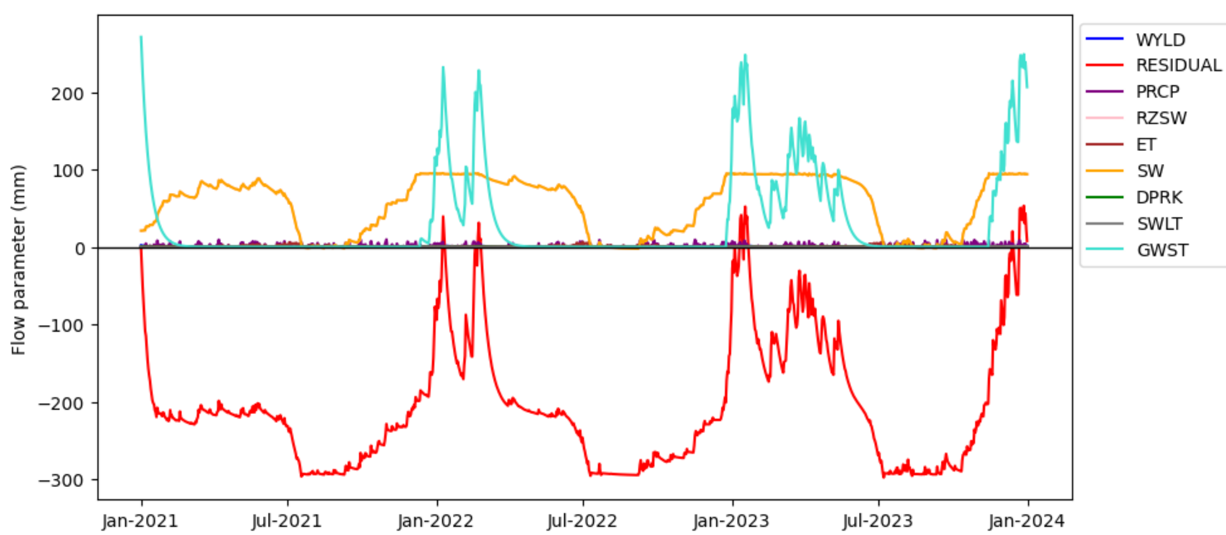


Figure 10. Daily values of hydrological fluxes from the catchment and the residual from the water balance. The residual follows a pattern resembling changes in groundwater storage and soil water. DPRK: Deep percolation, ET: Evapotranspiration, GWST: Groundwater storage, PRCP: Precipitation, RZSW: Water content in root zone, SW: Total water content in soil, SWLT: Water in soil litter, WYLD: Water yield.

5.3. Validation against monitored nutrient data

The dominant fluxes contributing to the nitrogen concentration in the discharge output were nitrification, mineralized N, particulate N in watershed outflow and volatilization. At the daily time step, the soluble N loss in surface runoff was in the range of 0-35 mg/l while the range in the monitored values of total N in daily outflow was 2-12 mg/l. The output values were of the same order as that of the monitored values and the model output was constantly higher than the monitored values, except during summer (Fig. 11). The summer patterns resembled the water yield pattern from the hydrological balance (Fig. 9). The phosphorus output was zero from the latest setup.

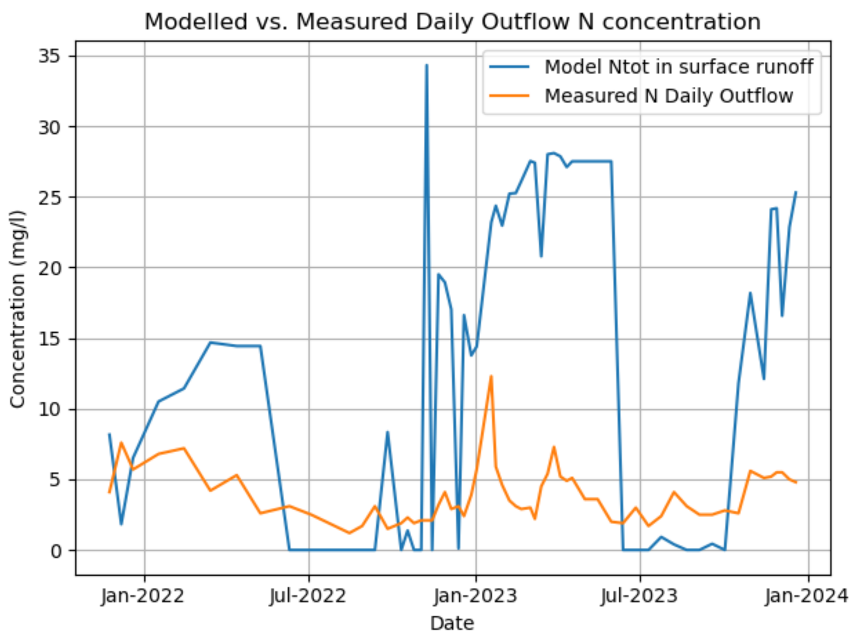


Figure 11. Comparison of measured and model N outflow concentration values from the Vinkenloop170 station (in mg/l). The values are of the same order with model output becoming zero during summer months.

5.4. Sensitivity analysis of groundwater parameters

For calibration and validation of the model, a sensitivity analysis of groundwater residence time and maximum groundwater storage to the water yield and water balance residual was performed (Fig. 12). Initially, groundwater parameters were modified since they have a major effect on the subsurface component of the water yield and the error in water balance seemed due to problems in the subsurface storage components.

The values of the variables for the starting test case were as follows:
GW residence time=200 days, NSE=-0.35, WYLD: 388 mm, Water balance residual: 301 mm

Table 4. Sensitivity analysis of water yield and water balance residual to groundwater residence time set in APEX. Maximum NSE and lowest water balance residual is obtained when the residence time is 10 days.

GW residence time (Days)	GW storage maximum (mm)	Total water yield in 3 years (mm)	Water balance residual	NSE	Sensitivity of water yield	Sensitivity of water balance error
200	30	388	301	-0.35		
10	30	447	207	-0.30	0.79	0.49
150	30	416	251	-0.37	0.56	1
100	30	445	214	-0.42	0.57	0.87
50	30	476	208	-0.53	0.59	0.62

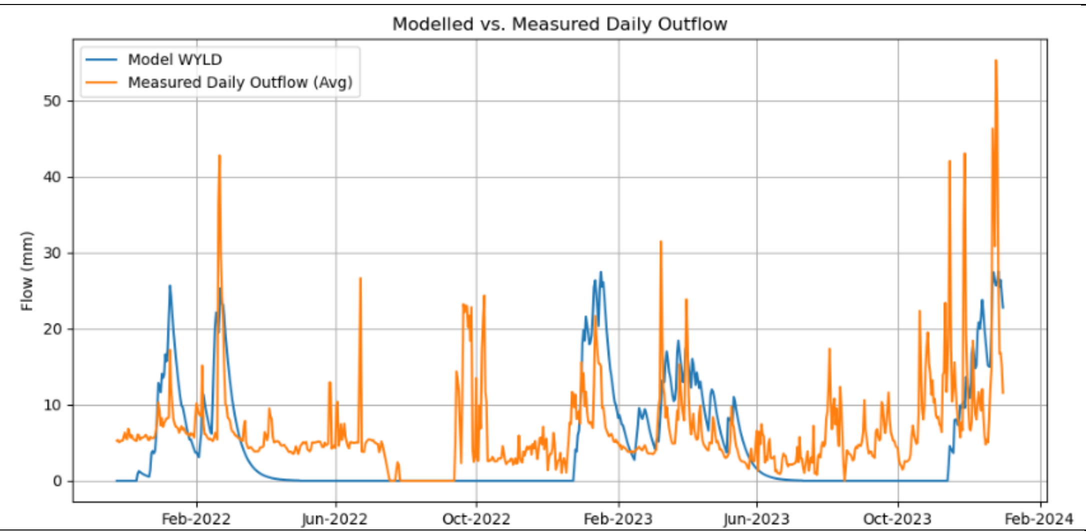
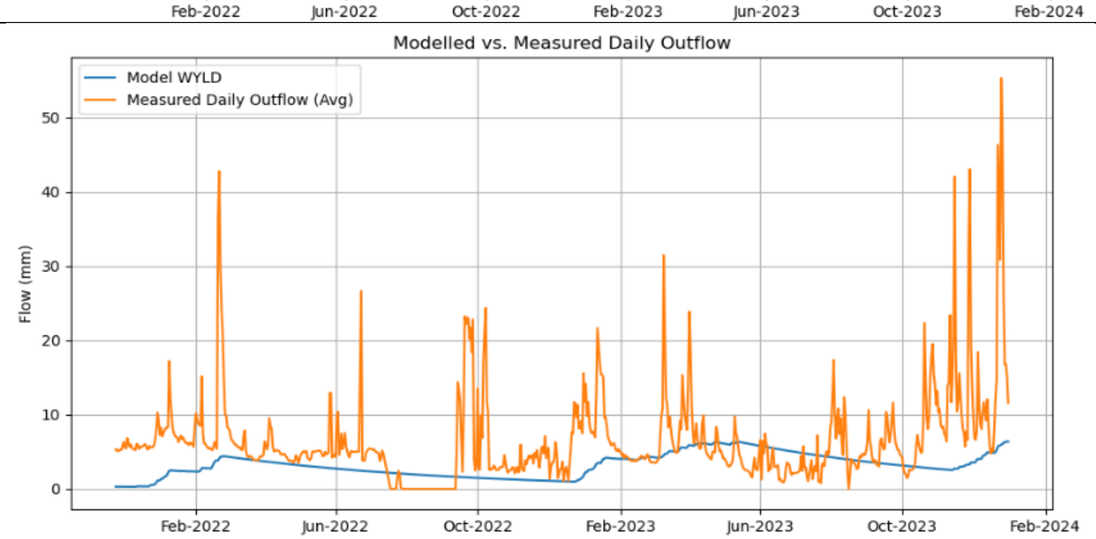
Groundwater residence time (days)	
10	
200	

Figure 12. Watershed outflow comparison when groundwater storage residence time is 10 and 200 days respectively. The daily response matches well with the monitored values when the residence time is less and long term, slow changes are presented better when residence time is 200 days. WYLD: Water yield

Among the tested residence times, maximum NSE value and least water balance residual was obtained when groundwater residence time was 10 days (Table 4, Appendix C). Fixing this as the residence time, further analysis was done by changing the maximum groundwater storage and obtaining its influence on the total water yield and total error (Table 4). The sensitivity of total water yield was higher to the change in storage than it was to change in residence time (Table 4, 5). NSE did not vary with the change in storage of up to 40 mm.

Table 5. Sensitivity analysis of water yield and water balance residual to groundwater maximum storage set in APEX. NSE remains constant with change in maximum storage but water balance residual decreases when maximum storage decreases.

Groundwater residence time (Days)	Groundwater maximum storage (mm)	Total water yield in 3 years (mm)	Water balance residual (mm)	NSE	Sensitivity of water yield	Sensitivity of water balance error
10	30	447	207	-0.30		
10	40	471	300	-0.30	2.4	0.005
10	50	472	390	-0.30	1.25	-0.5
10	10	424	70	-0.30	1.15	1.2
10	100	353	185	-0.40	-1.34	0.6

6. Discussion

6.1. Initial model performance

6.1.1. Hydrology

The model showed a comparable fit for the watershed outflow during the winter months (Fig. 8), with less negative NSE values for the winter periods. Upward seepage from groundwater is an important process in the Netherlands since the water table is at shallow depths of less than 2 m (Witte et al., 2019), but the current model setup does not have dynamics for upward seepage. In addition, soil water stores more than 100 mm of water at times, which is much higher than actual amount of water stored in the soil. These issues likely result in inaccurate baseflow during the summer months such that the groundwater storage becomes zero, all water from the small precipitation events gets stored in the soil water, and there is no water yield from the catchment. During winter months, when groundwater storage is above a threshold value, water yield is positive, and the peak flows resemble the actual flow patterns.

Qualitatively, the simulated water balance components of precipitation, evapotranspiration and soil water storage show expected patterns (Fig. 9). Precipitation and evapotranspiration increase over time in small increments, soil water levels rise during wetter winter months and decline during the relatively hot and dry summer, which is consistent with observed trends (NHV, 1998).

However, the two output variables of groundwater storage and water yield are not simulated correctly yet. For the case of Vinkenloop, the current setup for fluxes from groundwater is oversimplified and lacks seepage simulation. As explained in section 6.1., the effect is also seen in the cumulative water balance where water yield is zero for the periods when cumulative groundwater storage is constant because all precipitation is buffered in the soil water (Fig. 9).

The resulting error in water balance can be attributed to soil water and groundwater storage (Fig. 10). Calibrating the model to correctly simulate these two storage reserves would reduce the error considerably and can be done by adjusting the soil water and groundwater storage parameters.

Despite these issues, the model's ability to simulate seasonal transitions to some extent and response to rainfall variability indicates that its hydrological dynamics are responsive and can be refined further.

Based on the sensitivity analysis of groundwater storage, among all the tested parameter values, a residence time of 10 days and maximum groundwater storage in the range of 30-50 mm results in the least negative NSE values (Table 4, 5). Peak flows are captured better at shorter residence times while base flow is captured better at longer residence times (Fig. 12). The residence time of 10 days is much shorter than the initial input residence time of 200 days. This suggests the possibility that groundwater storage, for the model, is a part of the very shallow water layers which have shorter residence times, and does not include the deeper groundwater layers. The process of deep percolation transports the excess water from groundwater storage to deeper groundwater layers. The storage of 30-50 mm is reasonable as only the shallow layers would not hold a lot of water (de Vries, 2007). The negative NSE values suggest that significant improvements are still required for reasonable estimations as hydrological models are usually considered acceptable when the NSE is higher than 0.5.

6.1.2. Nutrient transport

The output for N is not yet aligned with the actual patterns (Fig. 11) and the P output is currently zero throughout. This is expected since the hydrological fluxes are inaccurate themselves and the fluxes carry around the nutrients. The lack of seepage dynamics might also affect the output N concentrations in the water outflow as there is no dilution. This results in higher concentrations from model output, in the range of 15-35 mg/l, as compared to the actual range of less than 12 mg/l.

The zero P outflow concentration in the model output is likely so because the processes simulating P transport are not active in the setup or due to missing parameters.

Additionally, there are certain parameters which are not surely known for the fields which would also be affecting the output. For example, fertilizer inputs were set at approximately 90% of the Dutch regulatory limits and planting/harvest schedules were generalized based on regional norms (Silva et al., 2017). These input approximations introduce uncertainty that can be addressed during future calibration.

6.2. Strengths and weaknesses of APEX for modelling Dutch sandy catchments

The model allows for defining field-level parameters even though the catchment itself is quite small (~2 km^2), and also allows for further divisions of the catchment into smaller subareas. The current division into 7 subareas is useful for initial analysis and can be further increased to include more specific field-level analysis. Computational performance is efficient such that simulations of three to ten years are completed within seconds. This allows for quick iteration and testing during model development.

APEX provides the flexibility to specify detailed parameters but considering that precise local data can be missing, it also allows the use of default or null values for multiple non-essential parameters. APEX can approximate these parameters on its own, and perform computations accordingly. It is possible that some default values among these parameters are not suitable for the Dutch soils, thereby resulting in the errors that are seen in the output.

In terms of managing and formatting the input files, APEXEditor was found to be a useful tool and it also allowed direct access to the raw text input files. The available documentation (Leyton, 2019) was clear and sufficient to use the GUI. ArcAPEX can be used at a later stage to integrate with spatial information and presentation, but it can be executed as an additional development in order to maintain the open-source status of the current project.

Work in the last decade on the APEX model has been focused on improving functionality, and not on user accessibility (Leyton, 2019). Due to this, there were some challenges including inconsistencies in the example dataset available on the website, incomplete documentation on input/output variables added in the latest version and unclear hydrological and nutrient balance equations. The EPIC/APEX Modelling

Forum was useful in managing these problems (EPIC/APEX Modelling Forum, 2025) but it still involved going through more than thirty or more threads before a sufficient answer was found.

An important hydrological limitation in the current APEX setup is the absence of a mechanism to simulate upward groundwater seepage, which is a significant process in lowland Dutch catchments with shallow water tables (de Vries, 2007). This results in challenges for correctly simulating summer baseflows in the output.

Another major issue noticed was that APEX does not provide any explicit warning if the daily weather file (.DLY) is unreadable for it. It can be unreadable due to errors in formatting the fixed-space format of the input file. In such cases, APEX defaults to using monthly weather statistics (from .WP1 file), which lead to incorrect diagnostics. In order to ensure correct reading of the daily files, it was found that verification of rainfall (RFV) values from the daily hydrology (.DHY) output with the actual daily precipitation was useful. Another way for verification is to set the precipitation to zero in the daily weather files and note the change in other fluxes and storages. There will not be any change in precipitation and potential evapotranspiration seen in the daily hydrology output if monthly files are being used.

Based on the initial modelling results, the current setup is not suitable for simulating the water and nutrient transport in the Vinkenloop catchment realistically and cannot be used for NbS modelling. Following the collection and preparation of all the input datasets, the relevant output values were found to be of the same order as expected values, but proper parametrization is essential.

6.3. Recommendations for future work

6.3.1. Model behaviour improvement

The current division of the catchment into seven subareas suffices for initial analysis. Going forward, future improvements could involve subdivision into more subareas to make improved connections between the fields and detailed channel routing. There are about sixty fields in the area so each field being a subarea may not be ideal but more divisions for detailed routing could improve field-specific outputs. Something to consider in this case is that different crops are grown on each field and clustering fields into a single subarea means that all fields in that subarea have the same crop at a given time. This poses a limit to simulating exact crop patterns in the model.

Potential parameters to refine the hydrological outputs include groundwater storage capacity (GWS0) and groundwater residence time (RFT0) in the control file (APEXCONT.DAT). These parameters have a direct influence on the baseflow timing and can be further adjusted with reference to local groundwater table depths of 0.5 – 1 m (STOWA-KIWK, 2022-23).

The seepage process can be simulated in the system, possibly based on parameters of water table in the subarea file or by adding a subsurface pipe irrigation which can provide a constant upward flow to mimic the groundwater seepage. The issue of excess water in soil storage could be resolved by testing with reduced depth of the soil, reduced storage capacity or increased permeability. Identifying which parameters are playing a part in soil water storage would be an important step to resolve this issue. Testing the water balance on monthly and annual time steps might also give an insight into how the model manages the water fluxes and if there are any other fluxes which are not being accounted for in the water balance equation.

Improved comparison of nutrient outflow concentrations can be made by identifying which output files have the total concentration in outflows. Alternatively, the comparison of daily concentration in surface runoff can be made with the observed concentration data of only the soluble nutrient species.

The soil input file (SOILCOM.DAT) has multiple variables that are not necessary but parameters such as soil water content at wilting and field capacity could be useful to replicate the area better. Parameters in the operation file (.OPS) like the planting and harvesting dates and the potential heat units for planting can be adjusted to improve the model, otherwise early planting or late harvest dates can make the crops ripe earlier and affect the nutrient yields from the fields.

Once all the relevant parameters are established, the 'Agricultural Policy Environmental eXtender – auto-Calibration and UncerTainty Estimator' (APEX-CUTE) tool can be employed to calibrate the mode for improving the representation of the area. The tool can use observed and model data to perform sensitivity analysis and calibrate the relevant parameters (Wang et al., 2019).

A large chunk of time was spent on understanding the model, a lot of which could be saved if the latest, updated documentation was available. Additional verified resources for APEX use cases can be helpful to make the model more accessible.

6.3.2. Implementing NbS

If the hydrological and nutrient transport are successfully simulated, APEX can be used for the overall objective of assessing the effect of NbS. NbS-modelling was not tried yet but based on available literature, the model can implement the effects of multiple NbS such as grass waterways, terrace systems, buffer strips, and sedimentation ponds, all of which except terrace systems are relevant for the Vinkenloop catchment (Waidler et al., 2011). The flexibility to modify parameters also opens the possibility of using these options to create NbS setups even if direct implementation of these solutions might not be available. The operations file in APEX provides the option to implement different sets of crop rotations, and demonstrates the crop yield as well as changes to nutrient concentrations in the output, which can be used to come up with cropping plans that are in the interest of the farmers as well as the environment. APEX also has separate input and output files for implementing buffer strips, which can be useful for understanding the effect of buffer strips. The Vinkenloop catchment has a woodchip bioreactor and methods to integrate it in the model can be explored. The quantification of the effect of these different NbS can be useful to support these practices at both the ground level as well as for policy making.

7. Conclusion

Water quality is a concerning global issue with agricultural activities playing a prominent role in nutrient pollution. Nature-based solutions offer a potential way of managing nutrient pollution, but their impact is not well-quantified. Experimental studies can take long before the impacts are seen, and modelling studies are few due to the initial complexity of configuring reliable models. This study aimed to address this gap by identifying a suitable open-source model and configuring it for a Dutch sandy agricultural catchment to assess whether it can be used for future NbS-modelling studies.

The first research objective was to identify an appropriate model through literature review. Comparison between multiple models and review of existing NbS modelling studies supported the choice of the APEX model. APEX was selected for its flexibility, ability to simulate nutrient transport (N, P, and organic C), options for implementing NbS on a field-scale, scalability, and possibility of integrating with widely-used models like SWAT.

The second objective focused on the performance of the model after configuring it for the Vinkenloop catchment. Detailed input datasets were created using APEXEditor and validation with existing monitored data was performed. Initial calibration was performed on groundwater parameters. In the latest configuration, the behaviour of total outflow was not representative of the actual outflow, especially during summer months. The water balance resulted in closure errors of about 200-300 mm, which indicate that the model cannot be used for NbS-modelling at this stage. The Nash-Sutcliffe Efficiency (NSE) of -0.30 for daily outflow indicated a need for significant improvement. Evapotranspiration and runoff were found to be dominant outfluxes, contributing to about 60 and 23% outflow of the total precipitation respectively. Inaccurate hydrological fluxes clearly affected the nutrient behaviour such that the model could not predict nitrogen and phosphorus concentrations correctly. Due to lack of daily output on total N concentration in total runoff, soluble N concentrations in surface runoff were compared with the observed total N concentration in total runoff and the modelled concentrations were found to be much higher than the observed concentrations. P concentrations were not simulated at all, with zero concentration values in surface runoff, suggesting that relevant parameters affecting P transport were not activated or configured correctly.

The final objective was aimed at finding recommendations to improve the existing model. The root of multiple issues was deduced to be the lack of upward seepage dynamics in the model, which can likely be incorporated externally, and could improve the results significantly. Correcting properties of the soil so that it does not store large amounts of water could be another improvement to bring about reasonable flow into the groundwater and hence runoff from it. Calibration using the APEX-CUTE tool could give useful insights. After calibration is completed and if the model successfully simulates the hydrological and nutrient transport such that NSE values are 0.5 or higher, APEX has functionalities that can be used to simulate NbS interventions, including land management practices as well as field-scale structures such as buffer strips and sedimentation basins, although they were not tested in this study.

In summary, this study is an initial step in the direction of applying open-source models to study a Dutch catchment in terms of nutrient pollution. Significant refinement and complete calibration are necessary before clear comments can be made on the suitability of APEX to model the effect of NbS. The configuration produced by this study can be used for further testing. If future improvements succeed, APEX could serve as a valuable tool for NbS-modelling in similar landscapes. If not, this work still provides insights into the limitations of APEX for modelling Dutch catchments and makes way for exploring alternative modelling options to assess the effect of NbS on Dutch sandy soils.

Data availability

All the scripts and data used for this study are publicly available on nshahi60/Modelling-water-quality-using-APEX-for-Vinkenloop-catchment-Netherlands.

REFERENCES

Aflah, W. N. (2022). *Modeling the impacts of conservation agriculture on hydrological processes and crop yield using the swat model: a study case in the Hupsel Catchment, East Netherlands* (Master's thesis, University of Twente).

AHN4. (2020-2022). Actueel Hoogtebestand Nederland DSM. Retrieved from https://www.ahn.nl.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams, 1998. Large Area Hydrologic Modeling and Assessment. Part I: Model Development. Journal of the American Water Resources Association (JAWRA) 34(1): 73-89.

Baptist, M., van Hattum, T., Reinhard, S., van Buuren, M., de Rooij, B., Hu, X., ... & Selnes, T. (2019). *A nature-based future for the Netherlands in 2120*. Wageningen University & Research.

Barling, R. D., & Moore, I. D. (1994). Role of buffer strips in management of waterway pollution: a review. *Environmental management*, *18*, 543-558.

Biswas, A. K., & Tortajada, C. (2018). *Assessing global water megatrends* (pp. 1-26). Springer Singapore

Bond, N. R., Burrows, R. M., Kennard, M. J., & Bunn, S. E. (2019). Water scarcity as a driver of multiple stressor effects. In *Multiple stressors in river ecosystems* (pp. 111-129). Elsevier.

Bouzouidja, R., Béchet, B., Hanzlikova, J., Sněhota, M., Le Guern, C., Capiaux, H., ... & Lebeau, T. (2021). Simplified performance assessment methodology for addressing soil quality of nature-based solutions. *Journal of Soils and Sediments*, *21*, 1909-1927.

Bouzouidja, R., Cannavo, P., Bodénan, P., Gulyás, Á., Kiss, M., Kovács, A., ... & Rodriguez, F. (2021). How to evaluate nature-based solutions performance for microclimate, water and soil management issues–Available tools and methods from Nature4Cities European project results. *Ecological Indicators*, *125*, 107556.

Chappin, M. M., Punt, M. J., Toxopeus, H. S., van Tilburg, N., de Jongh, C. L., Runhaar, H. A., & Spaas, G. H. (2024). How can networks address barriers to nature-based solutions? The case of agriculture and construction in the Netherlands. *Landscape and Urban Planning*, *251*, 105147.

Chen, V., Bonilla Brenes, J. R., Chapa, F., & Hack, J. (2021). Development and modelling of realistic retrofitted Nature-based Solution scenarios to reduce flood occurrence at the catchment scale. *Ambio*, *50*, 1462-1476.

Church, S. P., Floress, K. M., Ulrich-Schad, J. D., Wardropper, C. B., Ranjan, P., Eaton, W. M., ... & Rissman, A. (2021). How water quality improvement efforts influence urban–agricultural relationships. *Agriculture and Human Values, 38*, 481-498.

Cooper, P. F., & Boon, A. G. (1987). The use of Phragmites for wastewater treatment by the root-zone method: the UK approach. *Aquatic Plants for Water Treatment and Resource Recovery (edited by K. R. Reddy and W. H. Smith). Magnolia Publishing Inc., Orlando, Fla.*, 153-174.

Dankers, R., Arnell, N. W., Clark, D. B., Falloon, P. D., Fekete, B. M., Gosling, S. N., ... & Wisser, D. (2014). First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. *Proceedings of the National Academy of Sciences, 111*(9), 3257-3261.

Dao, P. U., Heuzard, A. G., Le, T. X. H., Zhao, J., Yin, R., Shang, C., & Fan, C. (2024). The impacts of climate change on groundwater quality: A review. *The Science of the Total Environment, 912*, 169241. https://doi.org/10.1016/j.scitotenv.2023.169241.

Dao, P. U., Heuzard, A. G., Le, T. X. H., Zhao, J., Yin, R., Shang, C., & Fan, C. (2024). The impacts of climate change on groundwater quality: A review. *Science of the Total Environment*, *912*, 169241.

De Knegt, B., Breman, B. C., Le Clec'h, S., Van Hinsberg, A., Lof, M. E., Pouwels, R., ... & Alkemade, R. (2024). Exploring the contribution of nature-based solutions for environmental challenges in the Netherlands. *Science of the Total Environment*, *929*, 172186.

de Vries, J. J. (2007). Groundwater. In Geology of the Netherlands (pp. 295-315). Th.W. Wong, D.A.J. Batjes & J.de Jager.

Debele, S. E., Kumar, P., Sahani, J., Marti-Cardona, B., Mickovski, S. B., Leo, L. S., ... & Di Sabatino, S. (2019). Nature-based solutions for hydro-meteorological hazards: Revised concepts, classification schemes and databases. *Environmental Research, 179*, 108799.

Dehghani Tafti, A., Houweling, D., Perron, J. M., Bencsik, D., Johnson, T., Vanrolleghem, P. A., & Comeau, Y. (2024). Towards a modelling framework for nature-based solutions in wastewater treatment. *Water Science & Technology*, *90*(3), 758-776.

Denchak, M. Water Pollution: Everything You Need to Know. Available online: https://www.nrdc.org/stories/water-pollution-everything-you-need-know (accessed on 27 March 2025).

Diacono, M., & Montemurro, F. (2010). Long-term effects of organic amendments on soil fertility. A review. Agronomy for Sustainable Development, 30(2), 401–422. https://doi.org/10.1051/agro/2009040.

Dollinger, J., Dagès, C., Bailly, J. S., Lagacherie, P., & Voltz, M. (2015). Managing ditches for agroecological engineering of landscape. A review. *Agronomy for Sustainable Development*, *35*, 999-1020.

Dunn, R. M., Hawkins, J. M. B., Blackwell, M. S. A., Zhang, Y., & Collins, A. L. (2022). Impacts of different vegetation in riparian buffer strips on runoff and sediment loss. Hydrological Processes, 36(11), e14733. https://doi.org/10.1002/hyp.14733.

EEA (2018) European waters; Assessment of status and pressures 2018. *European Environment Agency*. EEA Report No 7/2018. ISBN 978-92-9213-947-6. https://doi:10.2800/303664.

EEA. (2015). The European environment–state and outlook 2015: synthesis report. *European Environment Agency, Copenhagen*.

EPA, U. (2009). National water quality inventory: report to Congress. *Environmental Protection Agency, Washington*.

European Environment Agency. (2005). *Agriculture and Environment in EU-15: The IRENA Indicator Report*. Office for Official Publications of the European Communities.

Feng Pan, Qingyu Feng, Ryan McGehee, Bernard A. Engel, Dennis C. Flanagan, Jingqiu Chen (2021). A framework for automated and spatially-distributed modeling with the Agricultural Policy Environmental eXtender (APEX) model. *Environmental Modelling & Software, 144*. 105147, ISSN 1364-8152, https://doi.org/10.1016/j.envsoft.2021.105147.

Fraters, D., van Leeuwen, T., Boumans, L., & Reijs, J. (2015). Use of long-term monitoring data to derive a relationship between nitrogen surplus and nitrate leaching for grassland and arable land on well-drained sandy soils in the Netherlands. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, *65*(sup2), 144-154.

Garrick, M., Cunnane, C., & Nash, J. E. (1978). A criterion of efficiency for rainfall-runoff models. *Journal of Hydrology*, *36*(3-4), 375-381.

Gassman, P. W., Williams, J. R., Wang, X., Saleh, A., Osei, E., Hauck, L. M., ... & Flowers, J. D. (2010). Invited review article: The Agricultural Policy/Environmental eXtender (APEX) model: An emerging tool for landscape and watershed environmental analyses. *Transactions of the ASABE*, *53*(3), 711-740.

Gassman, P.W., J. Williams, V. Benson, R. Izaurralde, L. Hauck, C. Jones, J.D. Atwood, J. Kiniry & J. Flowers (2005) "Historical Development and Applications of the EPIC and APEX Models." Working paper 05-WP 397. Center for Agricultural and Rural Development, Iowa State University.

GeoGemeente Putten op de kaart (n.d.). Retrieved on June 2, 2025, from geogemeente.nl/putten/index.html.

Ghimire, S. R., Nayak, A. C., Corona, J., Parmar, R., Srinivasan, R., Mendoza, K., & Johnston, J. M. (2022). Holistic Sustainability Assessment of Riparian Buffer Designs: Evaluation of Alternative Buffer Policy Scenarios Integrating Stream Water Quality and Costs. *Sustainability*, *14*(19), 12278.

Golmohammadi, G., Prasher, S., Madani, A., & Rudra, R. (2014). Evaluating three hydrological distributed watershed models: MIKE-SHE, APEX, SWAT. *Hydrology, 1*(1), 20-39.

GreenHood Project. (n.d.). Retrieved July 09, 2025, from https://greenhoodproject.eu.

Griffiths, J., Borne, K. E., Semadeni-Davies, A., & Tanner, C. C. (2024). Selection, Planning, and Modelling of Nature-Based Solutions for Flood Mitigation. *Water*, *16*(19), 2802.

Hérivaux, C., Orban, P., & Brouyère, S. (2013). Is it worth protecting groundwater from diffuse pollution with agri-environmental schemes? A hydro-economic modeling approach. *Journal of Environmental Management*, *128*, 62-74.

Hickey, M. B. C., & Doran, B. (2004). A review of the efficiency of buffer strips for the maintenance and enhancement of riparian ecosystems. *Water Quality Research Journal*, *39*(3), 311-317.

Himanshu, S. K., Pandey, A., Yadav, B., & Gupta, A. (2019). Evaluation of best management practices for sediment and nutrient loss control using SWAT model. *Soil and Tillage Research*, *192*, 42-58.

Huang, J., Xu, C. C., Ridoutt, B. G., Wang, X. C., & Ren, P. A. (2017). Nitrogen and phosphorus losses and eutrophication potential associated with fertilizer application to cropland in China. *Journal of Cleaner Production*, *159*, 171-179.

Hutchins, M., Qu, Y., Seifert-Dähnn, I., & Levin, G. (2024). Comparing likely effectiveness of urban Nature-based Solutions worldwide: The example of riparian tree planting and water quality. *Journal of Environmental Management*, *351*, 119950.

Jones, H. P., Hole, D. G., & Zavaleta, E. S. (2012). Harnessing nature to help people adapt to climate change. *Nature climate change, 2*(7), 504-509.

Keller, A. A., Garner, K., Rao, N., Knipping, E., & Thomas, J. (2023). Hydrological models for climate-based assessments at the watershed scale: A critical review of existing hydrologic and water quality models. *Science of the Total Environment*, *867*, 161209.

Kikoyo, D., & Oker, T. (2023). Comparative Evaluation of the Performance of SWAT, SWAT+, and APEX Models in Simulating Edge of Field Hydrological Processes. *Open Journal of Modelling and Simulation*, *11*(2), 37-49.

Kılıç, O., Boz, I., & Eryılmaz, G. A. (2020). Comparison of conventional and good agricultural practices farms: A socio-economic and technical perspective. *Journal of Cleaner Production*, *258*, 120666.

Kitha, J., & Lyth, A. (2011). Urban wildscapes and green spaces in Mombasa and their potential contribution to climate change adaptation and mitigation. *Environment and Urbanization, 23*(1), 251-265.

Krysanova, V., Hattermann, F., & Wechsung, F. (2005). Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment. *Hydrological Processes: An International Journal*, *19*(3), 763-783.

Kumar, P., Debele, S. E., Sahani, J., Rawat, N., Marti-Cardona, B., Alfieri, S. M., ... & Zieher, T. (2021). An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards. *Earth-Science Reviews*, *217*, 103603.

Leyton, J. (2019) APEXeditor: A Spreadsheet-Based Tool for Editing APEX Model Input and Output Files. *Journal of Software Engineering and Applications*, **12**, 432-446. 10.4236/jsea.2019.1210027.

Liang, L. Z., Zhao, X. Q., Yi, X. Y., Chen, Z. C., Dong, X. Y., Chen, R. F., & Shen, R. F. (2013). Excessive application of nitrogen and phosphorus fertilizers induces soil acidification and phosphorus enrichment during vegetable production in Yangtze River Delta, China. *Soil use and management*, *29*(2), 161-168.

Liu, L., Dobson, B., & Mijic, A. (2023). Optimisation of urban-rural nature-based solutions for integrated catchment water management. *Journal of Environmental Management*, *329*, 117045.

Luo, Y., & Wang, H. (2019). Modeling the impacts of agricultural management strategies on crop yields and sediment yields using APEX in Guizhou Plateau, southwest China. *Agricultural Water Management*, *216*, 325-338.

Mancuso, G., Bencresciuto, G. F., Lavrnić, S., & Toscano, A. (2021). Diffuse water pollution from agriculture: a review of nature-based solutions for nitrogen removal and recovery. *Water*, *13*(14), 1893.

Matos, F. A., & Roebeling, P. (2022). Modelling impacts of nature-based solutions on surface water quality: a rapid review. *Sustainability, 14*(12), 7381.

McKergow, L. A., Weaver, D. M., Prosser, I. P., Grayson, R. B., & Reed, A. E. (2003). Before and after riparian management: sediment and nutrient exports from a small agricultural catchment, Western Australia. *Journal of Hydrology*, *270*(3-4), 253-272.

Meurer, K. H. E., Chenu, C., Coucheney, E., Herrmann, A. M., Keller, T., Kätterer, T., ... & Jarvis, N. (2020). Modelling dynamic interactions between soil structure and the storage and turnover of soil organic matter. *Biogeosciences Discussions*, *2020*, 1-34.

Mondini, C., Cayuela, M. L., Sinicco, T., Fornasier, F., Galvez, A., & Sánchez-Monedero, M. A. (2018). Soil C storage potential of exogenous organic matter at regional level (Italy) under climate change simulated by RothC model modified for amended soils. *Frontiers in Environmental Science*, *6*, 144.

Moss, B. (2008). Water pollution by agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1491), 659-666.

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I—A discussion of principles. *Journal of hydrology*, *10*(3), 282-290.

Nelson, D. R., Bledsoe, B. P., Ferreira, S., & Nibbelink, N. P. (2020). Challenges to realizing the potential of nature-based solutions. *Current Opinion in Environmental Sustainability*, *45*, 49-55.

Pan, F., Feng, Q., McGehee, R., Engel, B. A., Flanagan, D. C., & Chen, J. (2021). A framework for automated and spatially-distributed modeling with the Agricultural Policy Environmental eXtender (APEX) model. *Environmental Modelling & Software*, *144*, 105147.

Pereira, L. S., Oweis, T., & Zairi, A. (2002). Irrigation management under water scarcity. *Agricultural water management*, *57*(3), 175-206.

Pitman, M. G., & Läuchli, A. (2002). Global impact of salinity and agricultural ecosystems. *Salinity: environment-plants-molecules*, *3*, 20.

Refsgaard, J. C., Storm, B., & Mike, S. H. E. (1995). Computer models of watershed hydrology. *Water Resources Publication*, 809-846.

RESHAPE Project. (n.d.). Resilient Dutch Landscapes. Retrieved January 17, 2025, from https://reshape.labs.vu.nl/.

Rivier, P.-A., Jamniczky, D., Nemes, A., Makó, A., Barna, G., Uzinger, N., Rékási, M., & Farkas, C. (2022). Short-term effects of compost amendments to soil on soil structure, hydraulic properties, and water regime. Journal of Hydrology and Hydromechanics, 70(1), 74–88. https://doi.org/10.2478/johh-2022-0004.

Rowland, C., Marston, C., Morton, D., & O'Neil, A. (2020). Land Cover Change 1990-2015 (25m raster, GB).

Ryan, M., & Hoes, A. C. (2024). Justice and Sustainability Tensions in Agriculture: Wicked Problems in the Case of Dutch Manure Policy. *Ethics, Policy & Environment*, 1-18.

Saleh, A., & Gallego, O. (2007). Application of SWAT and APEX using the SWAPP (SWAT-APEX) program for the upper north Bosque River watershed in Texas. *Transactions of the ASABE*, *50*(4), 1177-1187.

Seddon, N., Chausson, A., Berry, P., Girardin, C. A., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B*, *375*(1794), 20190120.

Silva, J. V., Reidsma, P., & van Ittersum, M. K. (2017). Yield gaps in Dutch arable farming systems: analysis at crop and crop rotation level. *Agricultural Systems*, *158*, 78-92.

Skaggs, R. W., Brevé, M. A., & Gilliam, J. W. (1994). Hydrologic and water quality impacts of agricultural drainage∗. *Critical Reviews in Environmental Science and Technology*, *24*(1), 1–32. https://doi.org/10.1080/10643389409388459.

Smith, K. (Ed.). (2010). *Nitrous oxide and climate change*. Earthscan.

Steglich, E.M., Osorio, J., Doro, L., Jeong, J. & Williams, J.R. (2023). Agricultural Policy/ Environmental Extender Model. User's Manual, Version 1501.

STOWA-KIWK (2023). Vergrijzing van Grondwater: handelingsperspectieven voor de voortschrijdende aantasting van grondwaterkwaliteit door menselijke invloeden- Eindrapport van het KIWK-project Grondwater. KIWK 2022-23.

Stroming, S., Robertson, M., Mabee, B., Kuwayama, Y., & Schaeffer, B. (2020). Quantifying the human health benefits of using satellite information to detect cyanobacterial harmful algal blooms and manage recreational advisories in US Lakes. *GeoHealth*, *4*(9), e2020GH000254.

Sutton, M. A., Mason, K. E., Sheppard, L. J., Sverdrup, H., Haeuber, R., & Hicks, W. K. (Eds.). (2014). *Nitrogen deposition, critical loads and biodiversity*. Springer Science & Business Media.

Taylor, R. A., Jeong, J., White, M., & Arnold, J. G. (2015). Code modernization and modularization of APEX and SWAT watershed simulation models. *International Journal of Agricultural and Biological Engineering*, *8*(3), 81-94.

Tedeschi, A., & Dell'Aquila, R. (2005). Effects of irrigation with saline waters, at different concentrations, on soil physical and chemical characteristics. *Agricultural water management*, *77*(1-3), 308-322.

van der Brugge, R., & de Winter, R. (2024). *Deltascenario's 2024—Zicht op Water in Nederland* (Deltares 11209219-000-ZKS-0004).

van der Brugge, R., & de Winter, R. C. (2024). *Deltascenario's 2024 - Zicht op Water in Nederland*. Deltares-report 11209219-000-ZKS-0004.

van Gaalen, F., Osté, L., & Van Boekel, E. (2020). *Nationale Analyse Waterkwaliteit. Onderdeel van de Delta-aanpak Waterkwaliteit* (4002). Planbureau voor de Leefomgeving.

Van Liew, M. W., Wortmann, C. S., Moriasi, D. N., King, K. W., Flanagan, D. C., Veith, T. L., ... & Tomer, M. D. (2017). Evaluating the APEX Model for simulating streamflow and water quality on ten agricultural watersheds in the US. *Transactions of the ASABE*, *60*(1), 123-146.

van Vliet, M. T., Jones, E. R., Flörke, M., Franssen, W. H., Hanasaki, N., Wada, Y., & Yearsley, J. R. (2021). Global water scarcity including surface water quality and expansions of clean water technologies. *Environmental Research Letters, 16*(2), 02402

Vanlauwe, B., Wendt, J., & Diels, J. (2001). Combined application of organic matter and fertilizer. *Sustaining soil fertility in West Africa*, *58*, 247-279.

Vojinovic, Z., Alves, A., Gómez, J. P., Weesakul, S., Keerakamolchai, W., Meesuk, V., & Sanchez, A. (2021). Effectiveness of small-and large-scale Nature-Based Solutions for flood mitigation: The case of Ayutthaya, Thailand. *Science of The Total Environment, 789,* 147725.

Vymazal, J. (2017). The use of constructed wetlands for nitrogen removal from agricultural drainage: A review. 82-91.

Waidler, D., White, M., Steglich, E., Wang, S., Williams, J., Jones, C. A., & Srinivasan, R. (2011). *Conservation practice modeling guide for SWAT and APEX*. Texas Water Resources Institute.

Wang, X., Jeong, J., Yen, H., & Sharifi, A. (2015). APEX-CUTE 2.0 user's manual. *Temple, Texas: Blackland Research and Extension Center*.

Wang, X., Williams, J. R., Gassman, P. W., Baffaut, C., Izaurralde, R. C., Jeong, J., & Kiniry, J. R. (2012). EPIC and APEX: Model use, calibration, and validation. *Transactions of the ASABE*, *55*(4), 1447-1462.

Wang, X., Yen, H., Liu, Q., & Liu, J. (2014). An auto-calibration tool for the Agricultural Policy Environmental eXtender (APEX) model. *Transactions of the ASABE*, *57*(4), 1087-1098.

Whitehead, P. G., Wilby, R. L., Battarbee, R. W., Kernan, M., & Wade, A. J. (2009). A review of the potential impacts of climate change on surface water quality. *Hydrological sciences journal, 54*(1), 101-123.

Williams, J. R., Izaurralde, R. C., & Steglich, E. M. (2008). Agricultural policy/environmental extender model. Theoretical Documentation, Version 604, 2008-2017.

Winteraeken, H.J. & Spaan, W.. (2010). A new approach to soil erosion and runoff in South Limburg-The Netherlands. *Land Degradation & Development. 21*. 346 - 352. 10.1002/ldr.1009.

Witte, J. P. M., Van Ek, R., Runhaar, J., & Van den Eertwegh, G. A. P. H. (2020). Verdroging van de Nederlandse natuur: Bijna een halve eeuw goed onderzoek en falende politiek. *Stromingen, 26*(2), 65–79.

Witte, J. P. M., Zaadnoordijk, W. J., & Buyse, J. J. (2019). Forensic hydrology reveals why groundwater tables in the province of Noord Brabant (the Netherlands) dropped more than expected. *Water*, *11*(3), 478.

Zacharias, I., Liakou, P., & Biliani, I. (2020). A review of the status of surface European waters twenty years after WFD introduction. *Environmental Processes*, 7(4), 1023-1039.

Zhu, K., Woodall, C. W., & Clark, J. S. (2012). Failure to migrate lack of tree range expansion in response to climate change. *Global Change Biology, 18*(3), 1042-1052.

Zia, H., Harris, N. R., Merrett, G. V., Rivers, M., & Coles, N. (2013). The impact of agricultural activities on water quality: A case for collaborative catchment-scale management using integrated wireless sensor networks. *Computers and electronics in agriculture*, *96*, 126-138.

APPENDIX A

DETAILED METHODS AND TROUBLESHOOTING:

Multiple issues were encountered while carrying out this study. Many of the challenges had to be solved by going through multiple resources or trying multiple methods to find what works. Below is a record of the process and most of the issues which did not have clear solutions documented elsewhere. They can be helpful in saving time for further research and for new APEX users.

Unlike usual Windows software, APEX doesn't run by double-clicking it but must be run via the Windows Command Prompt. To do so, the following commands are provided in the Command Prompt window:

cd "C:/Users/…<folder_path_where_apex1501_is_stored>"
apex1501.exe

Buttons in the APEXEditor Excel workbook are the alternative way to run APEX. It should be noted that errors messages encountered when running the model are only seen when the model is run via Command Prompt and not when it is run using the APEXEditor buttons.

1. Compatibility of example dataset

The example dataset available on the website at the time of this study was incompatible with the latest version (APEX1501) therefore APEX crashed if that dataset was used. The dataset available with the older APEX0806 was correct for the 0806 version but did not work correctly with newer versions due to file format changes.

In response to this issue, the modelling team was contacted and a compatible example dataset for APEX1501 was obtained from them within three weeks. This dataset formed the starting point for configuring the Vinkenloop catchment.

2. WinAPEX limitations

While exploring alternatives to APEXEditor, WinAPEX was tested but its pre-defined sets of parameters were specific to the United States (e.g., USA location IDs and USDA soil IDs), and ways to easily customize them for the Netherlands were not found. Therefore, WinAPEX was not pursued further.

3. Input file configuration

The different input files were modified by adding the Vinkenloop parameters one by one, starting with the weather, wind and soil files, in this sequence. Their respective .LIST files were modified simultaneously. These files have input for the subarea file so the subarea file was generated after these, followed by the operations file. Finally, the control files were modified as stated next.

The APEXFILE.DAT, APEXRUN.DAT, APEXCONT.DAT, APEXDIM.DAT were modified to include catchment-specific parameters and simulation parameters such as the simulation time period and methodology used for runoff estimation, soil erosion, evapotranspiration, etc.

Several standard APEX input files were either left unchanged or excluded, depending on model requirements for this study. TILL****.DAT, CROPCOM.DAT, FERTCOM.DAT, PESTCOM.DAT and PARM***.DAT were not modified as they contain the fixed parameters for tillage, crops, fertilizers, pesticides and model parameters respectively. The default parameters given in these files were used.

MLRN***.DAT, HERD***.DAT, PSOCOM.DAT, FILENAME.PSO, RFDT***.DAT and FILENAME.HLY are respectively for multiple-runs, herd grazing, point sources, within-storm rainfall. They were not used as these parameters are not relevant for the Vinkenloop.

APEX uses several list files to reference inputs. The SITE.LIST, MNGT.LIST, SOLC.LIST, WDLY.LIST, WPM1.LIST, WIND.LIST and SUBA.LIST are respectively for including filenames of the site, operations, soil types, weather stations, monthly weather, wind and subarea files. Since this was a small catchment, single input of soil type, weather station and sites were used. Two kinds of operations were used, for grasslands and arable crops.

4. APEXEditor bug

When using APEXEditor, the command buttons, “Get files”, “Run”, “Write” and “Read” became larger in some sheets with each use, eventually occupying the entire Excel screen. To fix this issue, the following steps were followed:

Press ‘Alt + F11’ → Opens VBA code → Enable ‘Designer mode’ → Right-click on button to be resized → Select ‘Properties’ → Set ‘Autosize’ = ‘False’ and ‘Move and Size with cells’ = ‘False’.

5. Repetition and inconsistencies in output files

There are multiple output files, some of which have overlapping output variables. For instance, both .DLL file and .KKK files have precipitation for the subarea. In many cases, a choice had to be made between the different output files to select a file which had all the relevant water variables for the area.

The .OUT file contains run-wide details but is extremely long and the manual does not have an explanation of how to read this file. This makes it difficult to use data from this file even if it may have relevant output. The APEX/EPIC Modelling Forum Google Group has explanations of variables in the .OUT file and some are present in the final sections of the APEX manual, while most of the explanation is lacking.

The variable names in the manual and the actual output files are not consistent at times. For instance, the ENMA variable from the .OUT file is mentioned in the manual but no description of this variable is provided. This makes it necessary to consult the 400+ threads on the APEX/EPIC Modelling Forum or infer variable meanings by comparison with other files.

6. Variable Identification for Water and Nutrient Balances

A significant portion of the work involved identifying correct output variables to construct the daily water balance and nutrient balance. This was complicated by lack of clear equations linking outputs, differences between variable names in the theoretical documentation, user manual and actual output files.

This also makes it difficult to confirm the reason behind the irregularities seen in the results, whether they are due to modelling issues or if the verification method itself is incorrect.

7. Weather file format

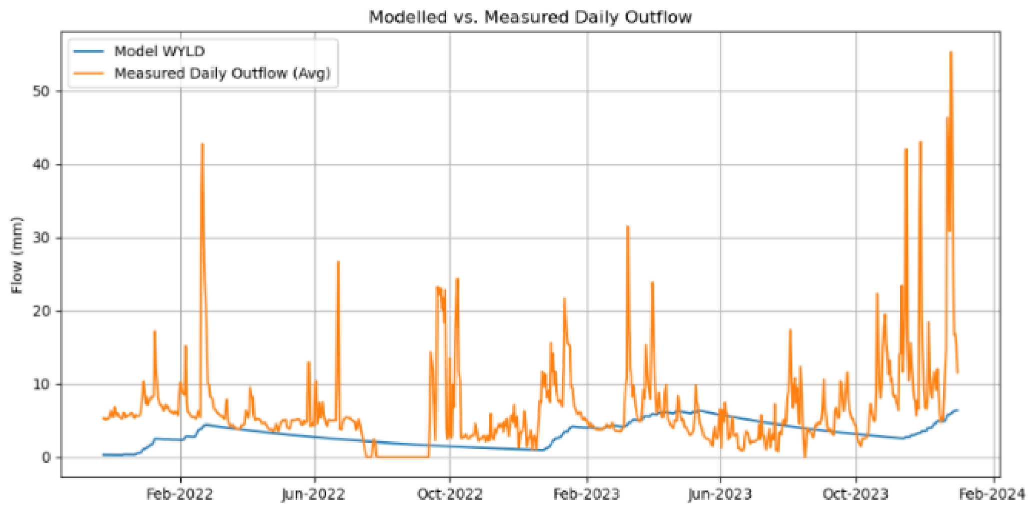
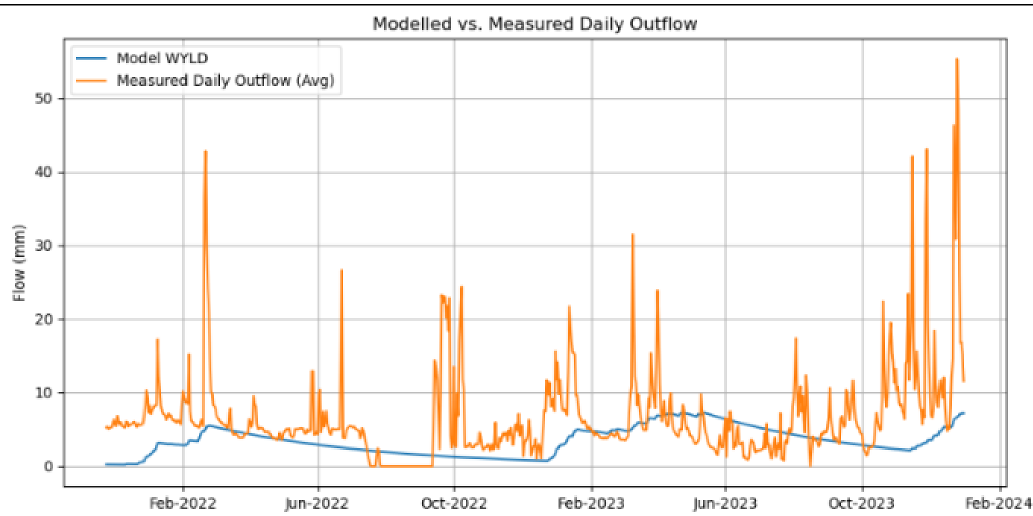
The weather file is supposed to have nine valid fields of six columns, even if they are blanks. If the format is incorrect, APEX does not give any warning and defaults to using weather generated from monthly statistics. This can lead to erroneous results in the output, especially if monthly statistics which may not include critical values.

APPENDIX B

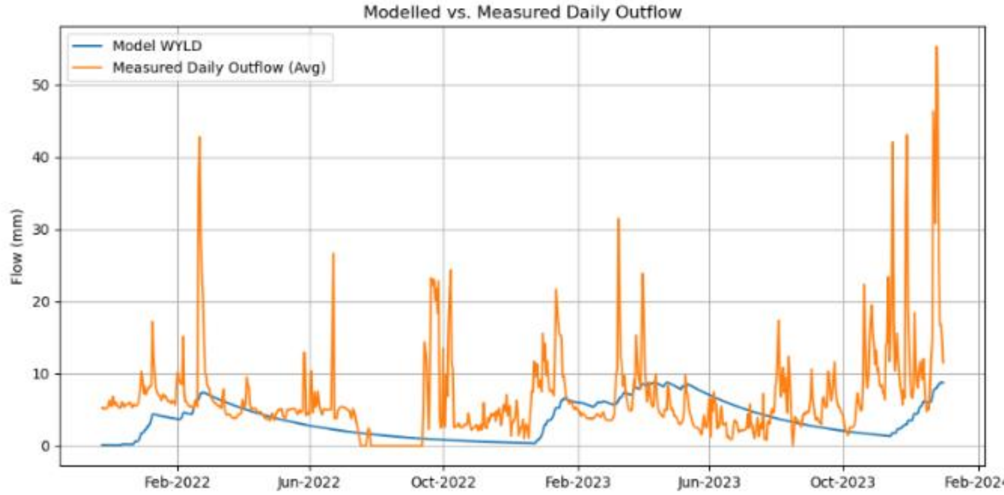
Table B1. Data and sources used for input into the soil input file (.SOL file)

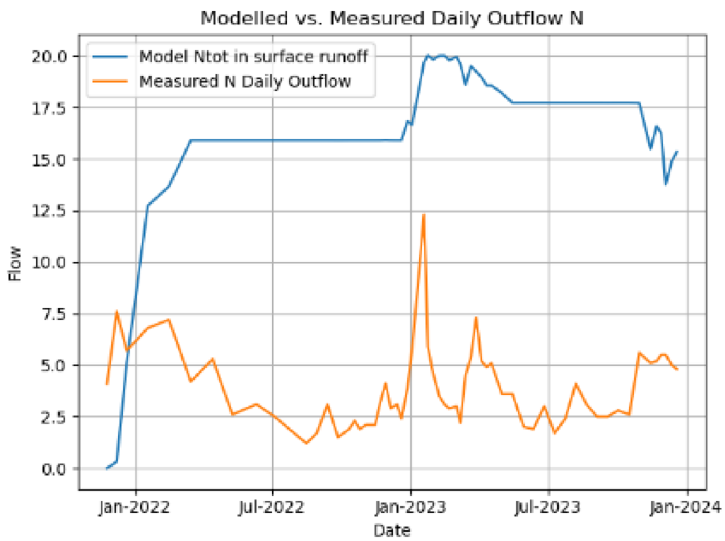
# Layer:	Description:	Layer 1	Layer 2	Layer 3	Layer 4	Source
Z:	Depth from the soil surface to the bottom of the layer (m) (Range: 0.01-10)	0.25	0.4	0.6	1.2	
BD:	Moist Bulk Density (Range: 0.5-2.5) (t/m3) ρb = MS/VT.Bulk density values should fall between 1.1 and 1.9 Mg/m3.	1.3752	1.5759	1.6327	1.6718	Soil Physical Data of The Netherlands
UW:	Soil water content at wilting point (Range: 0.01-.5) Soil water content at 1500 KPa or -15 bars (m/m) (0 if unknown).					
FC:	Soil Water Content at field capacity (Range: 0.1-0.6) Soil water content at 33 KPa or -1/3 bars (m/m) (0 if unknown).					
SAN:	Sand Content (Range: 1-99) The percentage of soil particles which have a diameter between 2.0 and 0.05 mm.	87	89	89	91	Soil Physical Data of The Netherlands
SIL:	Silt Content (Range: 1-99) The percentage of soil particles which have an equivalent diameter between 0.05 and 0.002 mm.	10	8	8	6	Soil Physical Data of The Netherlands
WON:	Initial organic N Concentration (Range: 100-5000) APEX will initialize levels of organic nitrogen. (g N/Mg or ppm) (0 if unknown).					
PH:	Soil pH. (Range: 3-9) The pH of a solution in equilibrium with soil.	4.8	4.5	4.4	4.3	Tier 4 maps of soil pH at 25 m resolution for the Netherlands (dataset)
SMB:	Sum of Bases (Range: 0-150) The sum of bases (Ca++, K+, etc.) on the cation exchange complex. (cmol/kg) (0 if unknown).					
WOC:	Organic carbon concentration (%). (Range: 0.1-10)	2.91	1.16	0.58	0	(SOM/1.72) https://www.soilphysics.wur.nl/

APPENDIX C

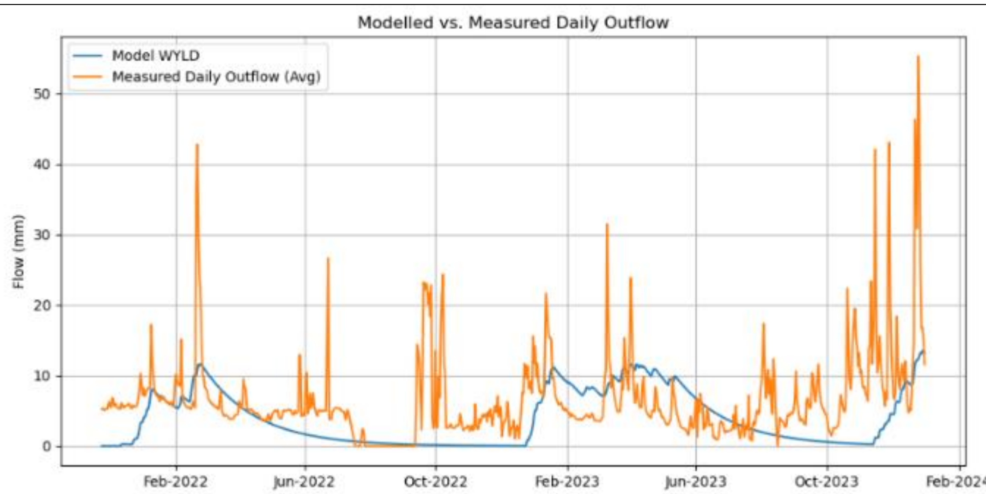
Groundwater residence time (days)	Watershed outflow and N concentration
200	
150	

100


Modelled vs. Measured Daily Outflow
Model WYLD
Measured Daily Outflow (Avg)
Flow (mm)
0
10
20
30
40
50
Feb-2022
Jun-2022
Oct-2022
Feb-2023
Jun-2023
Oct-2023
Feb-2024


Modelled vs. Measured Daily Outflow N
Model Ntot in surface runoff
Measured N Daily Outflow
Flow
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
Jan-2022
Jul-2022
Jan-2023
Jul-2023
Jan-2024
Date

50


Modelled vs. Measured Daily Outflow
Model WYLD
Measured Daily Outflow (Avg)
Flow (mm)
0
10
20
30
40
50
Feb-2022
Jun-2022
Oct-2022
Feb-2023
Jun-2023
Oct-2023
Feb-2024

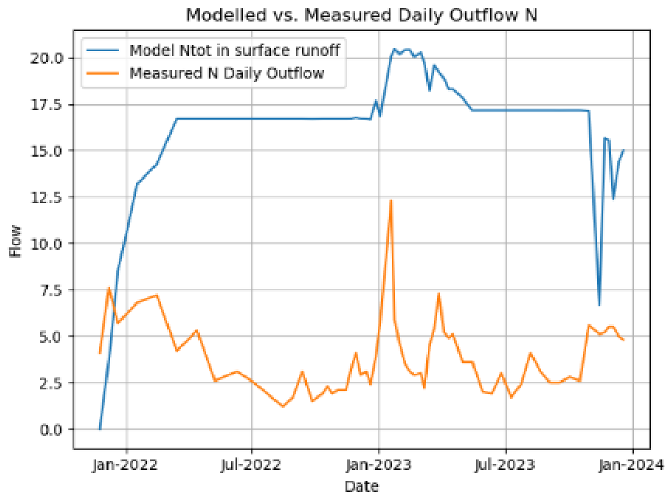
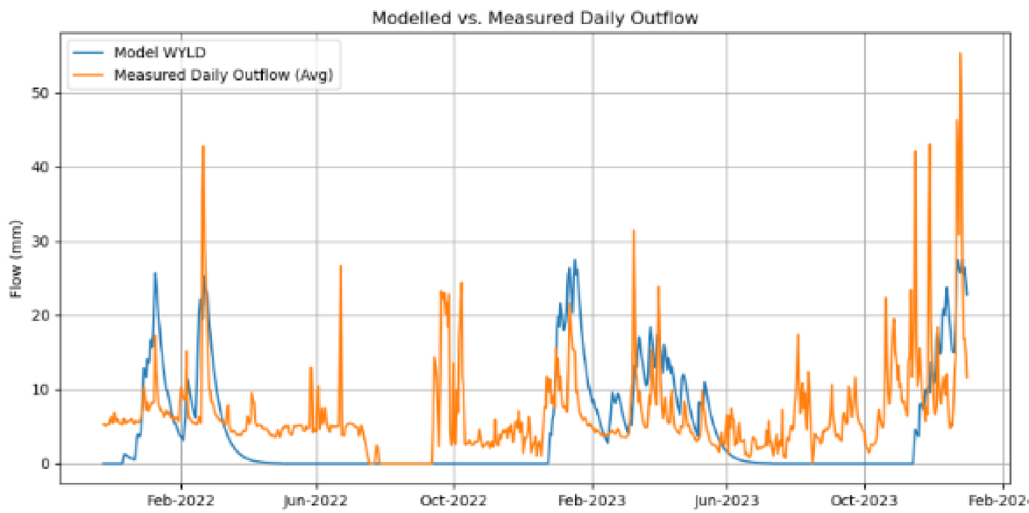
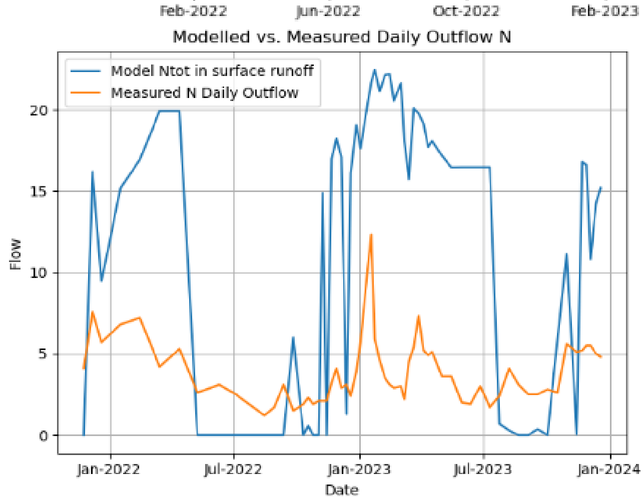
	
10	

Figure C1. Watershed outflow and surface runoff N concentration comparison with changing values of groundwater residence times. As residence time decreases, the output captures more of the immediate flow responses. At higher residence times, the long-term response is relatively well-represented.