Chapter

Perspectives of Hydrologic Modeling in Agricultural Research

Miha Curk and Matjaž Glavan

Abstract

For decades agricultural research was done in the field or laboratories, but with the rise of computer science, hydrologic modeling became another essential tool for environmental impact studies. Many types of models can be used, each with its strengths and weaknesses in terms of accuracy, speed, and amount of input data needed. Models can be used on different scales and simulate very different processes. Based on a literature review, APEX (Agricultural Policy Extender) and SWAT (Soil and Water Assessment Tool) models are the most popular for environmental research in agronomy. An important share of modeling work in agronomic studies is focused on pollution research, mainly nutrient and pesticide leaching and soil erosion processes. Other topics include simulating the effects of irrigation and other agricultural practices and studying the impact of extreme weather events and climate change. When working with model results, it is crucial to be mindful of inevitable uncertainties and consider them during interpretation. Modeling is gaining importance in agronomic research in Slovenia, with many studies done in the recent decade and more underway.

Keywords: hydrologic modeling, agriculture, agronomy, model applications, agricultural pollution mitigation, model uncertainty

1. Introduction

For decades, agricultural research was predominantly done in the field or laboratories. Such in situ research results are usually exact, but experiments are time-consuming. Due to different natural conditions, their validity is usually limited to the small area under study. For example, a study on crop yield in a specific area and under a specific agricultural management only applies to such conditions, and for different conditions, a new experiment needs to be devised. Even when results are visible and relatively easy to measure (like crop yield), the spatial differences prevent us from extrapolating them over a large area without some degree of error. This error only gets larger when research goals include measuring more complicated phenomena like pollution.

With strict limitations in environmental policy (Water Framework Directive (WFD) (Directive 2000/60 EC) in EU; Clean Water Act in the USA), an important branch of agricultural research is focused on mitigating pollution from agricultural activities. Nitrate leaching, sediment erosion, ammonia emissions, or pesticide pollution are hard to measure reliably over larger areas. Natural processes like plant growth also take time, making it hard to conduct conventional field trials to study alternative fertilization or pesticide application methods. There is another way to estimate the impact of different practices, which involves modeling. Modeling did not render the field studies useless because their results are indispensable as input and validation data.

Several decades ago, with the rise of computer science, different mathematical model approaches were developed to simulate parts of the natural system. Hydrologic modeling in the 1970s quickly became a trendy way of studying the physical processes behind water and nutrient cycling in soil, plants, and whole ecosystems. By coupling several of the more focused models (plant growth, nutrient and water cycle, etc.), more complex models were developed, enabling fast (relative to in situ research) estimations of outcomes of different climate scenarios, land-use changes, etc.

Hydrologic models are not intuitively connected to agriculture, as their use is far more prevalent in other fields. An article on 'Brief history of agricultural systems modeling' by Jones et al. [1], for example, does not even mention them. Despite that, hydrologic modeling is an essential tool in an increasingly important field of agricultural research, the environmental impact studies. The use of hydrologic models enabled fast advances in understanding pollutant movement in different ecosystems, making pollution mitigation strategies easier to evaluate.

This chapter will discuss different hydrologic models used in agricultural research, their strengths and weaknesses, their potential for agricultural pollution mitigation, and the uncertainty associated with model results. Lastly, we will look into practical applications and present some case studies from Slovenia.

2. Hydrologic models – an overview

Science and research in some fields depend strongly on modeling these days, and the world would probably be different if this tool were not available to us. Hundreds of models were developed over several decades, some simple and some very complex. Each model usually has its particular purpose, though some are quite elaborate and enable the user to model several extensive systems processes simultaneously. In an excellent paper about the evolution of hydrologic models, Clark et al. [2] discussed the challenges of designing hydrologic models that are as close to physical realism as possible while still keeping them simple enough and practical. The authors summarized that there were many noteworthy advances in their development in the last years, as improvements in representations of hydrologic processes by mathematical functions, parameter estimation, and optimizing computing resources by justifiable model simplifications. Some of the main goals for the future they mention are improvements of the basic hydrologic processes understanding, of parallel processing, of cooperation between different model developers in order to find the best methods, of the model analysis methods in order to minimize uncertainty, but also enhancement of the developer-field scientist interaction to promote usability and most importantly improvement and clarification of the construction of the models themselves, to enable more specific add-ons and better modularity.

Hydrologic models are divided into several different categories, depending on how they are structured and represent spatial processes [3]. Based on the structure, models are divided into empirical, conceptual, and physical; based on spatial distribution into lumped, semi-distributed, and distributed. Hydrologic models used in agriculture are almost exclusively either conceptual or physical and semi-distributed or distributed. Empirical and lumped models are not practical for such applications because the former models are very exact and depend heavily on large amounts of measured input data, and the latter disregard the spatial variability inside the modeled area. The difference between conceptual and physical models is that conceptual models consist of simplified equations representing water storage in the catchment, and physical models are based on physical laws and equations based on measured hydrologic responses.

Consequently, the latter are more difficult to calibrate and require many parameters, but the former rarely consider spatial variability within the catchment and are better to use in large catchments with limited data and computational times. On the other hand, distributed models are the ones where the modeled area is divided into smaller cells by a grid of specific size, and semi-distributed ones divide it into specific shapes that represent essential features inside the area. Consequently, the former models are data-intense with long computational times, but the latter risk loss of spatial resolution as the sub-catchments get larger [3].

As mentioned before, there are plenty of models a researcher can consider for his work. Malone et al. [4] discussed the parameterization guidelines and considerations and mentioned at least 15 different models. Google Scholar search was performed to assess the popularity of some of the mentioned models in the agricultural context, with a query: "model acronym" model AND (agronomy OR agriculture OR farm). The number of hits is written in brackets after each model acronym: Watershed Analysis Risk Management Framework (WARMF) (400), HYDRUS (8900), European Hydrological System Model (MIKE-SHE) (3900), DRAINMOD (2500), Soil and Water Assessment Tool (SWAT) (45,100), Environmental Policy Integrated Climate and Agricultural Policy/Environmental Extender (EPIC/APEX) (178,000/172,000), Root Zone Water Quality Model (RZWQM) (2000), Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) (1000), Hydrological Simulation Program – FORTRAN (HSPF) (6000). The EPIC/APEX models are the most used in agricultural context with over 170,000 hits, followed by SWAT with 45,000 hits based on the search results. Other models achieved less than 10,000 hits and seemed far less popular. EPIC/APEX, SWAT, and MIKE-SHE models are presented in more detail in **Table 1**, based on a comparison study by Golmohammadi et al. [5].

According to the study [5], SWAT and MIKE-SHE were recognized as very well-performing models (in terms of river discharge), and SWAT was considered the better of the two when simulating processes in agricultural catchments. On the other hand, APEX was recognized as perfect for scenario assessment on farm scale, due to its many options in management practices (different irrigation types, drainage, buffer strips, terraces, fertilization management, etc.), but also economic

Model acronym	Structure	Spatial distribution	Strengths	Weaknesses
EPIC-APEX	Physical	Distributed	Suitable for simulation of many agricultural management scenarios	Only for small-scale watersheds or farms
SWAT	Physical	Semi-distributed	Shorter computational times due to lumping of spatial units in the form of hydrological response units (HRUs)	Simplified spatial distribution
MIKE-SHE	Physical	Distributed	Built-in graphics and post-processor for calibration and analysis of results	Long computational times, data-intensive

Table 1.
Comparison of three models commonly used in agricultural research with model type, strengths, and weaknesses.

analysis of measures. Management practices options are also available in SWAT, but it is usually considered better for larger scale watersheds. However, the authors conclude that no single model is superior under all conditions and that the model's performances are very site-specific. In light of agricultural research, the EPIC/APEX model is most useful in small catchments with lots of known data. MIKE-SHE is most useful for large areas when computational time is not a constraint, and data is plentiful. SWAT seems to be somewhere in between – allowing short computational times even in large watersheds but enabling the reasonably accurate agricultural management simulation. Another advantage of SWAT is its modularity – it is easy to link it to other more specific models.

Therefore, models are the most appropriate and cost-effective method for assessing different agricultural management strategies and their impact on the environment. Outputs can be calculated daily, monthly, and yearly and can be used to study the long-term effects of climate change adaptation and short term influence on crop yields, state of the soil, etc.

3. Agricultural pollution research – a challenge

This chapter will dive further into the important question: What circumstances make the models more suited for agricultural impact studies than field trials? As discussed in the introduction, environmental research is an essential field of science today, and water pollution is the part where hydrologic models can be of great help. Water quality is one of the Sustainable Development Goals in the 2030 Agenda for Sustainable Development, and an FAO report on the topic [6] lists agriculture as one of the three major sources of water pollution, along with human settlements and industry. Main water pollution threats posed by agriculture and some possible mitigation strategies are presented in **Table 2**.

Different environments are very diverse, and natural conditions are spatially specific. The dynamics of processes leading to pollution can differ from place to place, even if they are not far apart. Testing the impacts of different mitigation

Threat	Main sources	Threatened waterbody	Possible mitigation strategies
Nitrate	Fertilization, manure storage	Surface and groundwater	Balanced fertilization, manure storage in contained areas, managed grazing, catch crops
Phosphorus	Fertilization, soil erosion	Surface water	Balanced fertilization, reducing soil erosion
Sediment	Soil erosion	Surface water	Cover crops, reduced tillage, tilling parallel to contour lines, terracing, managed grazing
Pesticides	Plant protection	Surface and groundwater	Planting hardy or resistant varieties, increasing biodiversity, balanced application, proper waste disposal
Veterinary medicines	Livestock healthcare	Surface and groundwater	Use according to international guidelines
Salinization	Irrigation	Surface water	Minimize drainage, use less water demanding crops

Table 2.
Main pollutants from agriculture, their sources, threatened water bodies, and theoretical mitigation strategies.

strategies on a large scale would be very slow and expensive if the only tool we had were field trials. Luckily, the models provide an alternative. An FAO report [6] describes it very clearly: "Models provide … holistic understanding of problems by identifying relationships (cause and effect), and future predictions (scenarios). Models can simulate the fate of pollutants and the resulting change in the state of water quality and help understand the impacts on human health and ecosystems. Models can also help in determining the effectiveness and costs of remedial actions."

Models are not only useful in predicting the efficiency of potential mitigation measures; they are just as often used as a tool to help understand the current state of pollution. Except in some cases (i.e., soil erosion), most pollutant threats are generally invisible to human eyes, and the only way to understand the extent of pollution is often (besides monitoring by point measurements) through the model simulations. Of course, this does not mean that field monitoring is outdated. Measurements can provide important starting points and input or calibration data for models to perform accurately. Let us put it this way: Monitoring is a way to detect that a natural system is threatened, field trials allow us to obtain important data about processes on a local scale, and modeling is a tool that helps us understand the extent of pollution in a broader scale and provide information on promising mitigation strategies.

Which model to use depends strongly on the scope of research one intends to conduct. Apart from the already discussed division by structure or spatial distribution, models can also be divided into groups based on the expected outcomes. Field-scale models are generally only capable of simulating local processes, like plant growth with water and solutes movement through soil, but do that quickly and quite reliably because little input data (like soil type, weather, cropping system etc.) is needed, and most of it can be measured in the field. No particular skill is usually required to set up such a model. As models transition into regional or catchment scale, more and more of the input data is interpolated across larger areas or not known precisely. In such cases, merely inputting the available measured data will not result in a well-performing model because gaps in the so-called "hard data" (the measurements) are usually too big. The modeler needs to find a way to fill those gaps with "soft data" – possible data ranges characteristic to specific conditions in the area. Ways to learn about soft data are technical field trips, consulting local experts, examining data from similar areas elsewhere etc.

Besides the already discussed pollution studies, hydrologic models can also be used in other agronomic research branches. They can be set up to analyze impacts of droughts, other weather events, and even climate change, simulate effects of irrigation or drainage, study the water balance of different crops, model water retention capabilities of soils, etc. [7–9].

4. Model uncertainty – why models can be misleading

As discussed in the previous chapter, model simulations are a blessing to researchers, but they can be misleading. If the models are used negligently or if the results are misinterpreted, they can very well be a curse, providing us with dubious information. No model is entirely accurate, and even the most experienced modelers in the world do not claim their model results are 100% certain. Quite the opposite experienced modelers will know very well what their setups' flaws and uncertainties are. It is often said that modeling is an art as much as a science because the modeler needs to balance process resolution, computational speed, and accuracy to ensure a reasonable output. Furthermore, he or she needs to overcome the challenge of presenting an enormous amount of information in a way that can be used to increase understanding of the system [10].

So how does one ensure that his model performs well enough? Several operations optimize the performance and improve our understanding of uncertainties: parameterization, sensitivity analysis, calibration, validation, and uncertainty analysis. Parameterization is the process of assigning data to model parameters. Theoretically, all the input data would be measured, but there are obstacles to that – firstly, not everything can be measured, and secondly, even some measurements are not entirely realistic. Therefore, "hard" data is input first, followed by "soft" data to the best of our knowledge. An article by Malone et al. [4] discusses parameterization in more detail. Once input data is inserted, sensitivity analysis is performed to find out what parameters are sensitive. If a parameter is sensitive, its changes significantly influence model results. If it is not, no matter how much we change it, the results will be similar. Sensitive parameters and those of which values we are uncertain are then modified during the process of calibration to match the model results as closely with observed values for river discharge, nutrient loads, crop yields, etc. Validation is executed next, possibly for different seasons, to ensure robustness and verify that the calibrated parameters results show good model performance outside of the calibration period. Moreover, uncertainty analysis shows us what the uncertainties in the model results are. Sensitivity and uncertainty analysis might seem like the same thing, and they are in a way, but the former points out how much different input parameters influence the final results, while the latter focuses on the uncertainty of final results directly [11].

With each model, there are several ways one might go about the abovementioned procedures. In the past, manual calibration was the norm, and it meant manually changing different parameter values until the desired matching of observed and simulated data was achieved. With large numbers of parameters in models, this method is time-consuming and requires quite some experience, and some authors suggest against using it [12] because it is hard to achieve a range of possible simulations in this way. This leads us to the next topics, which are automated calibration, sensitivity, and uncertainty tools. Many models have a built-in or standalone program developed specifically for them (MIKE-SHE has a built-in tool, SWAT-CUP [13] is a standalone tool for SWAT, etc.). There are also quite advanced but universal tools that can work with different models, like PEST: Model-Independent Parameter Estimation and Uncertainty Analysis [14].

For parameterization, it is essential to have good data. Any type of data is not equally useful in modeling work, and different types of data may be useful in different situations. Soil data, for example, can be carefully measured, or pedotranspher functions can be applied to calculate it. But which is better depends on what type of model is used. For a field-scale model, acquiring measured data is usually beneficial, and the scale of operation is also feasible. For larger-scale models, though, it depends on the accuracy of measurements, heterogeneity of soil in an area, and many other factors. Usually, large scale models require so many measurements that acquiring them is no longer feasible, and one must rely on data provided by different databases for the area. Interestingly, measured and calculated soil characteristics can vary quite a lot, as shown by our data in **Table 3**.

Differences in the presented data could result from soil cracks, earthworm burrows, agricultural management, and others, which were not accounted for in one of the methods. Conveniently, soil parameters are almost always calibrated because they influence the water cycle significantly. Based on previous modeling experience, we found that for large-scale models (especially since soil hydraulic properties measurements are expensive, time-consuming, and require special equipment), it is usually more than adequate to use pedotranspher calculations as a basis. From there,

		Hydraulic conductivity [mm/h]		Available water capacity [cm^3 water/cm^3 soil]	
Soil type	*Soil layer*	*Measured*	*Calculated*	*Measured*	*Calculated*
Calcaric Fluvisol	A1	6.0	14.0	0.14	0.14
	A	1600.8	14.2	0.14	0.14
	Bv	92.1	19.2	0.17	0.14
	I	316.9	24.4	0.10	0.12
	II	107.3	43.4	0.10	0.11
	III	417.3	30.8	0.10	0.07
Dystric Cambisol	A	4257.9	9.5	0.14	0.14
	Ap	85.4	3.9	0.17	0.14
	Bv	1301.0	2.0	0.17	0.12
Calcaric Fluvisol	Ap	160.4	9.6	0.14	0.16
	AB	160.4	10.0	0.14	0.16
	Bv	163.3	9.9	0.17	0.16
	Bg	169.2	9.7	0.10	0.16

Table 3.
Presentation of soil hydraulic properties in cases of measurement and calculation.

the most realistic values can be determined during calibration, thus not modifying the "expensive" measured soil data.

Another note concerns the calibration data. It is vital to choose the data that represents a prevailing hydrological process in the catchment. For example, suppose discharge is altered too much by human activity or other processes not accounted for in the model structure, or point sources in the watershed contribute a significant share of the water into the cycle. In that case, it might be better to use an alternative dataset, although most other model applications used discharge data for basic calibration. Besides discharge, soil moisture measurements (both satellite and in situ data) are gaining significance in the last years [15–17] and can be a useful alternative in areas where discharge data is not convenient or possible to use.

Model calibration and uncertainty analysis are a vast field of study, so we will not detail them here. There are several comprehensive papers and manuals on the topic [12, 14, 18, 19], and before diving into the calibration of a model, it is crucial to get as much knowledge on the topic as possible.

5. Model applications – recent case studies in Slovenia

Slovenia, as a European Union member state, had transposed the WFD to state law in 2002, and since then, much work was done in the field of environmental studies in agricultural areas. Slovenia's biggest issue regarding water protection is groundwater bodies under large river plains with relatively shallow soil profiles. While being very appropriate for agricultural and urban activities, they are also very vulnerable to nitrate and pesticide leaching. The state of water bodies is mostly good, except for some aquifers in the Northeast part of the country, where it seems groundwater recharge is not as strong due to less precipitation in the area. More details on water protection measures and laws in Slovenia can be found in [20].

Reviewing different modeling efforts in Slovenian agricultural areas is an excellent way to get insight into implementing hydrologic modeling in general. For this chapter, another Google Scholar search was conducted, this time with a query: (hydrologic OR water) AND model AND (agronomy OR agriculture OR farm) AND "Slovenia". The search was repeated in Slovene to find more studies that were not published in English. After a scan through the results, several interesting studies were selected, joined by some others we have known from previous work, and were for some reason not included in the search. Selected publications all fit into the category of hydrologic modeling in agricultural areas. In terms of scale, some of them feature large scale modeling of the whole country, some catchment scale, and another field-scale modeling. In terms of the type of model used, there are several of them, but SWAT model applications are the most frequent. Topics range from nitrate leaching and concentration in groundwater to sediment, phosphorus, and nitrate loads in surface waters, and even to weather extremes modeling, including droughts and climate change.

The whole country modeling effort to determine nitrogen reduction levels necessary to reach groundwater quality targets was a program led by Slovenian Environment Agency [21]. Hydrological model GROWA–DENUZ was coupled with agricultural N balances to simulate nitrate leaching for the whole country. Results indicate that stricter measures in vulnerable areas are crucial to meeting WFD thresholds, while additional state-wide measures are not necessary.

Several studies [22–24] were conducted in vulnerable areas where groundwater is not a good state. While studying nitrate leaching, just like the work above, they were limited to catchment scale, and the model used was SWAT. Several agricultural management scenarios were simulated to determine what type of management is the most effective at reducing nitrate leaching. Among many other findings, an important message is that careful placing of local measures based on soil characteristics can be just as effective at reducing nitrate leaching as applying more general limitations on a broader scale while allowing a much healthier socio-economic development agricultural sector.

One study [25] dealt with simulating the effect of different historical land-use scenarios on surface water quality. The SWAT model was used to determine how the land use documented on historical maps (18th, 19th, 20th' and 21st centuries) would impact river quality. Interestingly, the authors found that historical land-use patterns generally caused more erosion than the present, but even the present one is not the best for water organisms.

Another study [26] evaluated the effects of deforestation and increasing vineyard land use on surface water quality with the APEX model. Results show that though pollution increases with deforestation, proper protective measures (like vegetative buffer strips) can limit its scope.

In one case [27], a new model was developed based on equations from existing ones to simulate the effects of wastewater treatment implementation in an agricultural catchment. Results suggest that applying the measure of wastewater treatment did reduce nitrogen concentrations in the stream and increase phosphorus concentrations, which could worsen the situation in that specific catchment.

Finally, there were two studies [28, 29] dealing with controlling erosion and nutrient leaching in catchments with accumulation lakes.

Most of the described case studies took advantage of modeling to gain insight into differences between several agricultural management scenarios, which would be much more expensive and time-consuming if done with field trials. Interestingly, several studies also included some fieldwork, partially for input data acquisition, but mostly to collect reliable validation data like crop yields, nitrate concentration, soil properties, soil water showing that the "old" ways are still very viable. The best results can only be acquired if we employ the power of modeling and fieldwork combined.

6. Conclusions

In this chapter, we have discussed the perspectives of hydrologic modeling in agricultural research. The most frequently used hydrologic models were identified and reviewed in terms of their suitability for different applications in agronomy. A section evaluated the strengths and weaknesses of hydrologic models for agricultural research and highlighted potential applications. The importance of modeling in light of agricultural pollution mitigation was also be presented. Furthermore, the importance of input data quality and uncertainty analysis was discussed to highlight the potential risks associated with modeling. Examples of different case studies in Slovenia were referenced to review the recent agricultural modeling work in this country.

Future development in the field should concentrate on strengthening the interaction between model developers and users on one side and field scientists and farmers on the other, to make models more adept to specific practices and applications in different areas. This would strengthen the trust in modeling among agricultural scientists while expanding the recognition of modeling among the public and policymakers.

Overall, through this chapter and with every single one of the highlighted case studies, we hope to have strengthened the importance of hydrologic modeling in the agricultural sector. While model results cannot foretell the future, they can give us a useful range of possibilities to consider and discuss further despite their shortcomings and uncertainties. In conclusion, modeling has enabled important advances in agricultural hydrology studies and sped up research that would otherwise take much longer to conduct.

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