CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Civil Engineering
Department of Landscape Water Conservation

Modeling hydrological impacts of management practices in rural catchments using SWAT

DOCTORAL THESIS

Nina Elizabeth Noreika, B.Sc., M.Sc.

Doctoral study programme: Civil Engineering
Branch of study: Environmental Engineering

Doctoral thesis tutor: Dr. Tomas Dostal

Prague, 2022

CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Civil Engineering
Thákurova 7, 166 29 Praha 6

DECLARATION

Ph.D. student’s name: Nina Elizabeth Noreika

Title of the doctoral thesis: Modeling hydrological impacts of management practices in rural catchments using SWAT

I hereby declare that this doctoral thesis is my own work and effort written under the guidance of the tutor Dr. Tomas Dostal.
All sources and other materials used have been quoted in the list of references.

The doctoral thesis was written in connection with research on the projects: H2020 No. 773903 Shui, focused on water scarcity in European and Chinese cropping systems and the Grant Agency of Czech Technical University in Prague, No. SGS20/156/OHK1/3T/11

In Prague on ……………………   ……………………………………………
signature

Abstrakt

V průběhu let došlo v České republice vlivem nevhodného hospodaření s vodou a půdou ke snížení retenční kapacity krajiny. Mnoho nevhodných dopadů lze připsat intenzifikaci zemědělství, které nastalo po transformaci tohoto sektoru po roce 1953. V období kolektivizace došlo ke scelování pozemků a vzniku velkých homogenních polí, byla instalována odvodnění a napřimovány drobné vodní toky. V důsledku tyto zásahy vedly k rychlejšímu odtoku vody po intenzivních srážkách nebo tání sněhu. V současnosti je podstatná část zemědělských ploch obhospodařována velkými akciovými společnostmi nebo korporacemi, které upřednostňují ekonomický faktor nad environmentálním. Jedním z holistických přístupů pro udržitelné hospodaření s vodou v krajině je podpora malého vodního koloběhu. Změny fungování krajinné matrice mohou mít významný vliv na bilanci vody na měřítku jednotlivých povodí. Cílem této práce je kalibrace a validace numerického modelu SWAT na dvou měřítkách (jednotlivý statek a část krajiny na úrovní okresu) a simulace vybraných scénářů hospodaření (např. změny plodin a osevních postupů, využití pozemků, zavedení půdoochranných opatření) pro posouzení efektivity opatření směrem k posílení malého vodního cyklu v krajině. Výsledky naznačují, že velkoplošné vysévání řepky nepřispívá k udržitelnému způsobu hospodaření s vodou, konkrétní dopad řepky závisí i na místu vysetí v povodí. Změny využití území výrazně ovlivňují malý vodní cyklus. Na základě simulací provedených pro situace z let 1852, 1954, 1983 a 2019 je ukázáno, že hydrologickou odezvou si jsou nejpodobnější stavy z let 1852 a 1954. Důvodem je, že během těchto období nedošlo k výrazným změnám v landuse ani k plošnému odvodnění pozemků. Dále je ukázáno, že s ohledem na posílení malého vodního cyklu bylo nejpřívětivější střídání osevních postupů v letech 1920 – 1938, zatímco osevní postupy v letech 1950 – 1989 byly nejméně příznivé. Vrstevnicové obdělávání, následováno zachováním posklizňových zbytků na půdním povrchu, byly vyhodnoceny jako nejúčinnější technická opatření pro zadržení vody a posílení vodního cyklu. Na velkém měřítku je, dle výsledků SWAT modelu, zavedení půdoochranných opatření velmi efektivní a významně podporuje malý vodní cyklus. Nicméně, prostorové rozmístění jednotlivých opatření v krajině, ani jejich relativní zastoupení nemají dle modelu významný vliv.

Klíčová slova: soil and water assessment tool (SWAT); změny využití území; krajinné plánování; malý vodní cyklus; zemědělské ochranné postupy

Abstract

Inappropriate soil, water, and landscape management has decreased the water retention capacity of the landscape in the Czech Republic over time. Many sources of such mismanagement can be traced to an agricultural intensification across the Czech landscape that began after the 1953 collectivization process due to Communist Era policies. During this time large monotonous fields, subsurface tile drainage systems, and artificially straightened streams were incorporated across the landscape. Currently, much of the Czech agricultural landscape is managed by large conglomerates who prioritize profit over all else. Reinforcing the small water cycle is considered to be a holistic approach to water resource management within a landscape. Changes in land use and land management can greatly affect the water balance at a basin-scale. The objectives of this research are to calibrate and validate the Soil and Water Assessment Tool (SWAT) in the Czech landscape at two scales (the farm-scale and the management-scale) and to model various scenarios (e.g., crop changes, land use/management changes, and the incorporation of agricultural conservation practices) to determine management regimes that would reinforce the small water cycle. This research found that rapeseed adoption does not support the goal of developing a sustainable agricultural landscape in the Czech Republic. The adoption of rapeseed had disproportionate effects on a basin’s water balance depending on its location in the basin. In addition to crop changes, it was found that land use changes significantly affected the small water cycle at the basin-scale. Of the four land use change scenarios conducted (1852, 1954, 1983, and 2019), the 1852 and 1954 scenarios behaved the most similarly hydrologically, likely due to minimal landscape transformation and the fact that these two scenarios occur prior to the widespread incorporation of subsurface tile drainages across the landscape. Additionally, the crop rotation of 1920–1938 (Pre-Communist Era) reinforced the small water cycle the most, while that of 1950–1989 (Communist Era) reinforced the small water cycle the least. Regarding the incorporation of agricultural conservation practices at the farm-scale, SWAT modeled contour farming as the most effective practice that reinforced the small water cycle followed by residue incorporation. At the management-scale, the widespread incorporation of agricultural conservation practices significantly reinforced the small water cycle, but the relative scale and spatial distribution of their incorporation were not reflected in the SWAT scenario analysis.

Keywords: soil and water assessment tool (SWAT); land use changes; landscape management; small water cycle; agricultural conservation practices

Table of Contents

Declaration

I, Nina Elizabeth Noreika, hereby declare that the following doctoral thesis is my original work conducted at Czech Technical University in Prague from 2019-2022 and no material in this thesis has been previously submitted to this or any other university.

Name: **Nina Elizabeth Noreika**
Date and place: June 2022 **|** Prague, Czech Republic

https://doi.org/10.14311/dis.fsv.2022.005

Funding

The work presented in this condensed thesis was funded by two international projects. The primary source of funding was from project H2020 No. 773903 Shui, focused on water scarcity in European and Chinese cropping systems. The secondary source of funding for the presented research was obtained from the Grant Agency of Czech Technical University in Prague, No. SGS20/156/OHK1/3T/11.

Publications

The condensed nature of this thesis is based on publication requirements outlined by Czech Technical University in Prague. Each first-author publication corresponds to its own chapter in the following text.

Chapter 2:

Noreika, N.; Li, T.; Zumr, D.; Krasa, J.; Dostal, T.; Srinivasan, R. Farm-Scale Biofuel Crop Adoption and Its Effects on In-Basin Water Balance. *Sustainability* 2020, 12, 10596. https://doi.org/10.3390/su122410596

Chapter 3:

Noreika, N.; Winterová, J.; Li, T.; Krása, J.; Dostál, T. The Small Water Cycle in the Czech Landscape: How Has It Been Affected by Land Management Changes Over Time? *Sustainability* 2021, 13, 13757. https://doi.org/10.3390/su132413757

Chapter 4:

Noreika, N.; Li, T.; Winterova, J.; Krasa, J.; Dostal, T. The Effects of Agricultural Conservation Practices on the Small Water Cycle: From the Farm- to the Management-Scale. *Land* 2022, 11, 683. https://doi.org/10.3390/land11050683

Conference Proceedings:

- **Noreika, N.**; Dostal, T.; Zumr, D.; Krasa, J.; Li, T. Application of SWAT model to assess hydrological balance and mass transport within medium size catchments. SWAT Conference, Vienna, Austria. 17 July 2019
- **Noreika, N.**; Dostal, T.; Li, T.; Zumr, D; Krasa, J. The influence of the spatial distribution of agricultural conservation practices on hydrological balance variables in a small basin. EGU, Virtual. 05 April 2020.
- **Noreika, N.**; Li, T.; Zumr, D.; Krasa, J.; Dostal, T. The Effects of Agricultural Conservation Practices on the Local Water Cycle in conditions of the Czech Republic Modeled by SWAT. EGU, Virtual. 26 April 2021.
- **Noreika, N.**; Winterova, J.; Li, T.; Zumr, D.; Krasa, J.; Dostal, T. Using SWAT to Model the Effects of Land Use Changes in a Czech Agricultural Landscape Since the Pre-Communist Era. AGU, New Orleans, Louisiana, USA. 16 December 2021.

Other Publications:

- Zumr, D.; David, V.; Jeřábek, J.; **Noreika, N.**; Krása, J. Monitoring of the soil moisture regime of an earth-filled dam by means of electrical resistance tomography, close range photogrammetry, and thermal imaging. Environmental Earth Sciences. 2020, 79 ISSN 1866-6280.
- Li, T.; Jeřábek, J.; **Noreika, N.**; Dostál, T.; Zumr, D. An overview of hydrometeorological datasets from a small agricultural catchment (Nučice) in the Czech Republic. Hydrological Processes. 2021 ISSN 1099-1085.
- Winterová J.; Krása J.; Bauer M.; **Noreika N.**; Dostál T. Using WaTEM/SEDEM to Model the Effects of Crop Rotation and Changes in Land Use on Sediment Transport in the Vrchlice Watershed. Sustainability. 2022; 14(10):5748, ISSN 2071-1050.

Acknowledgements

Firstly, I would like to thank my advisory team at Czech Technical University in Prague, including Tomas Dostal, David Zumr, and Josef Krasa. Without their support I never would have been able to acclimate to life in Prague. While I feel that COVID-19 stole a lot of my time as a PhD student, I am happy to have spent the last 3.5 years here. Tomas's hands-off advisory style helped me flourish as a scientist and researcher. I was able to gain the confidence I needed while being able to fall back on him for advice regarding study design and modeling. He was always keen to make travel and food recommendations throughout Central Europe. I am also thankful for my participation in the Shui Project and especially the guidance from Andreas Klik and Peter Strauss who always went above and beyond to challenge me and the other PhD students involved in the project. I'd like to thank Tailin Li, Julie Winterova, and the rest of the PhD students in the Department of Landscape Water Conservation who were always willing to help with my research while making me feel welcome and appreciated.

I firmly believe that a scientist is only as strong as her mind- and I am forever grateful for my support system. I would not have been able to make it through this program without my friends, family, and loved ones, namely my partner, Ryan, who was always willing to help and was constantly a sounding board for my ideas. He is simultaneously my biggest critic and my biggest supporter; I am forever grateful for him. Additionally, I'd like to thank my parents, my *mellons*, and many more friends who have supported me during this time, including: Lauren and Erik Babcock (who adopted me during my time in Prague), Tori Rivers, Megan Barron, Forrest Cortes, and so many more.

Chapter 1: General Introduction

1.1 The Small Water Cycle

Intensive storm events are becoming increasingly frequent in Central Europe according to the Intergovernmental Panel on Climate Change (IPCC) [1]; and these effects can be exacerbated by inappropriate soil, water, and landscape management. Due to the mismanagement of the agricultural landscape in the Czech Republic, its water retention capacity has significantly decreased over time. Hence, Zelenakova et al. suggested the restoration of local water circulation (i.e. reinforcing the small water cycle) within the landscape as a holistic approach to water resource management in the Czech landscape [2]. The small water cycle refers to the local cycling of water in a specific geographic area, i.e., water should fall as precipitation in the same area from which it evapotranspirates (Figure 1.1). The two main objectives for the reinforcement of the small water cycle in the landscape are (i) the restoration of drainage patterns with natural hydromorphology and (ii) the improvement of the water retention capacity across the landscape. By working to reinforce the small water cycle through appropriate landscape management, the effects of extreme precipitation events (e.g., huge spikes in surface runoff ratios as well as extreme soil loss events) may be mitigated at the basin-scale [1].

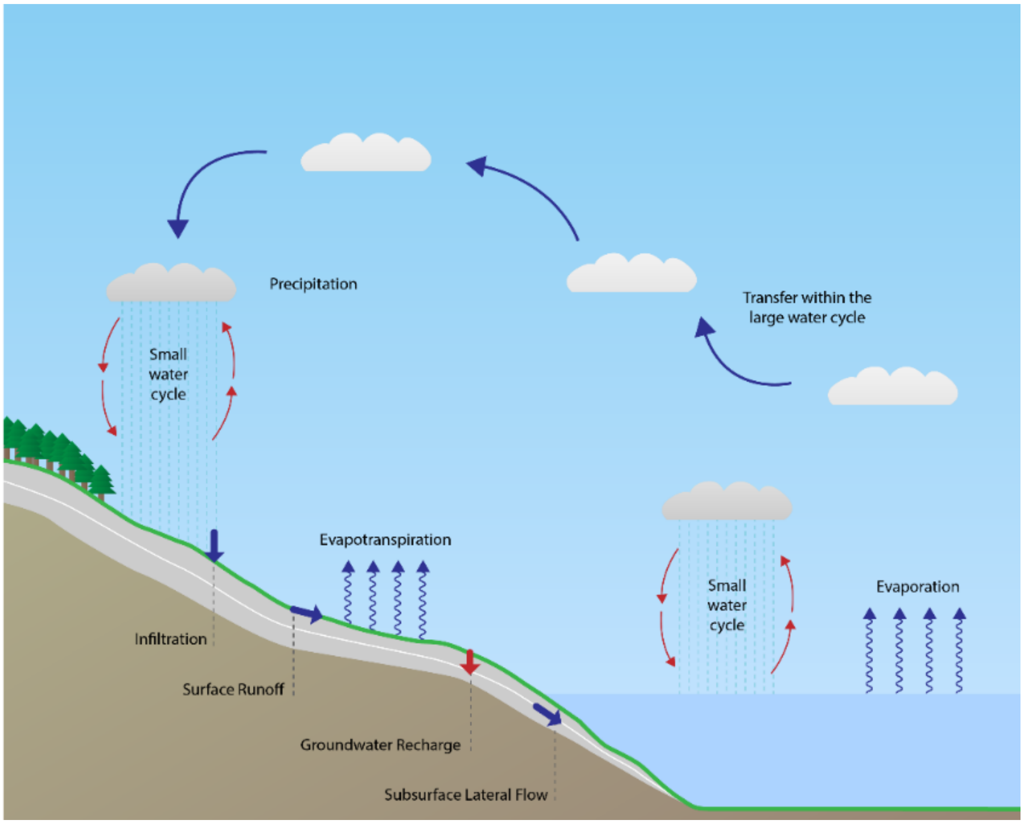


Figure 1.1. A representation of the small water cycle.

1.2 Land Use Changes

Over the last several decades, the local (physical soil quality) and regional (basin hydrology and water balance) impacts of land use changes have been extensively studied [3–10]. Decisions made by basin managers concerning land use and management changes can have big impacts on the hydrology of a system, and managers should tailor their decisions to address specific motivations and water resource goals within their management area. Decisions to develop land, to deforest, to afforest, and to expand agriculture all have varying effects on water yield, soil storage capacity, surface runoff, and evapotranspiration in a basin [11]. Afforestation from grassland and shrubland has been found to decrease surface runoff by up to 44% [12,13]. While deforestation is usually influenced by anthropogenic sources, it also can be a natural process. Deforestation can have significant impacts on annual runoff but has also been found to have seasonally variable impacts [14]. The development of land typically results in an increased area of impervious cover which can result in amplified surface runoff ratios and flooding risk. The variability of precipitation patterns in a basin will also have large influence over the effects of land use changes, depending on the size of the basin [15].

The basin is the logical management unit in a landscape. By managing human disturbance and increasing restoration efforts in the Czech Republic, many issues caused by past mismanagement can be mitigated in the hydrological landscape [16]. When the landscape is managed at the basin-scale, any development or extraction decisions and their subsequent impacts on the surrounding hydrological landscape can be anticipated, rather than extrapolating local impacts at an artificially-defined scale such as those defined by municipalities or borders between landowners.

1.3 The Czech Landscape

Since governmental shifts in the Czech Republic from 1989, there have been some significant land use changes especially regarding the distribution of arable land vs the distribution of forested land [16]. Between 1989 and 2000, many areas of previously arable (deemed infertile) land were replaced by forests and grasslands and arable lands were relocated to more fertile soils [16,17]. But since 2000, there have been minimal shifts in land use changes aside from a slight decrease in the percent cover of arable land, replaced by impervious cover such as expanding industry, developments, and roadways [16]. In addition to the outlined land use changes, crop changes across time in the Czech Republic have been significant.

Another hydrologically significant feature in the Czech landscape is its large network, covering 52,000 hectares, of earthen dammed fishponds [18]. These ponds provide cultural and economic value to the Czech Republic and many are under historical protections as they date back 1000 years [19]. These ponds also serve as constructed wetlands by providing increased biodiversity including water fowl, invertebrates, and amphibians, sediment trapping, and flood mitigation [18]. But, the benefit of flood mitigation decreases with time since the pond’s most recent de-siltation. Since there is no central management of many of these smaller ponds, their hydrological influence can vary greatly depending on decisions made by specific land owners or local managers.

Since the modern era, the Czech Republic has always been an intensively cultivated landscape. Czechs tend to place high value on local produce and livestock.

Agricultural intensification of the Czech Republic began in the 1970s during the Communist Era wherein large monotonous agricultural fields (Figure 1.2), subsurface tile drainage systems, and artificially straightened streams were incorporated across the landscape [16]. Since 1989 (the end of the Communist Era), agricultural land and management has been privatized and has experienced shifts from centrally planned crop rotations to those that are economically-driven; but the large field sizes and tile drainage systems are still mostly in place. Larger field sizes can contribute to surface runoff events resulting in significant soil loss in the landscape while the drainage systems reduce the water holding capacity of the soil.

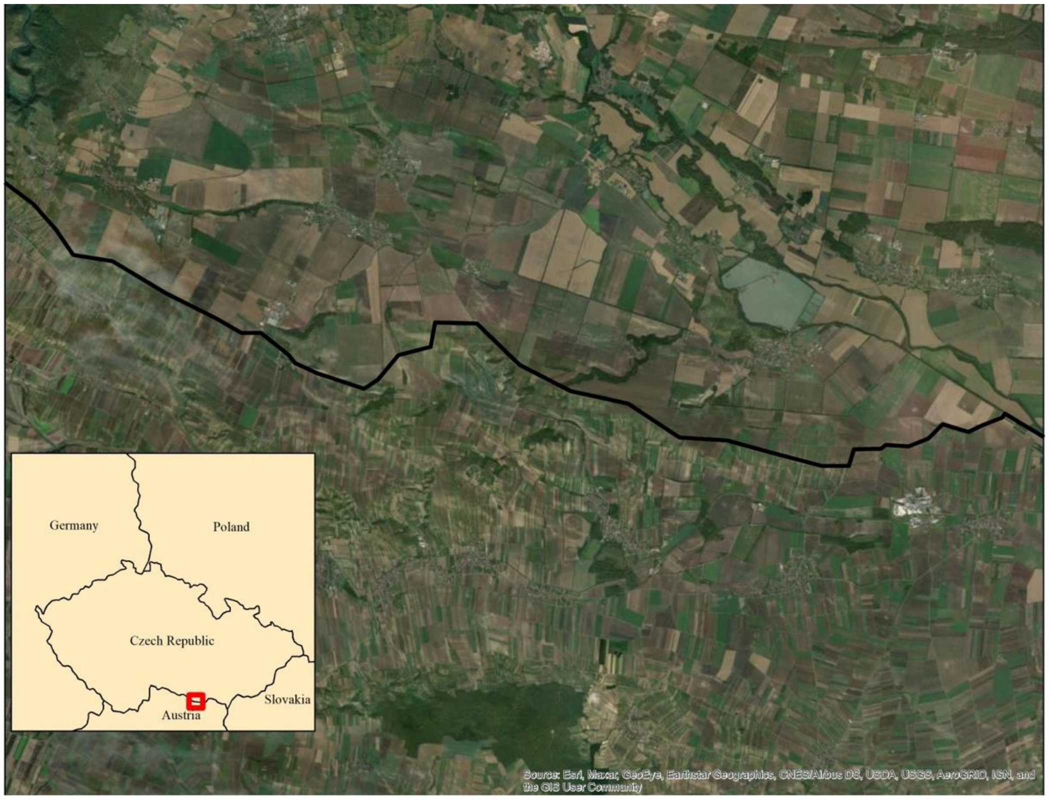


Figure 1.2. Field size discrepancies between the Czech Republic and Austria [20].

1.4 Agricultural Conservation Practices

Much of the Czech agricultural landscape is managed by large conglomerates that prioritize profit and EU monetary incentives. However, many independent Czech farmers are beginning to explore various agricultural conservation practices which have been shown to have as significant of a hydrological impact as land use changes [15]. Agricultural conservation practices have been extensively studied over the last 40 years and have been shown to significantly improve a soil's infiltration capacity and, in turn, significantly decrease the surface runoff in a landscape. Agricultural conservation practices include reduced/no-tillage, mulch cover, cover crops, crop residues, and reduced application of herbicides. The goal of conservation agriculture is to make soils "self-sustainable" by: maintaining sources of organic matter above and below the soil's surface, recycling water and nutrients within the system, and ensuring that the infiltration rate of a soil is greater than the rainfall rate (Figure 1.3) [21]. To maximize the benefits of implementing agricultural conservation practices, managers must: maintain year-round organic matter cover, ensure the health and balance of soil biota, minimize soil disturbance, and diversify crop rotations [21–23].

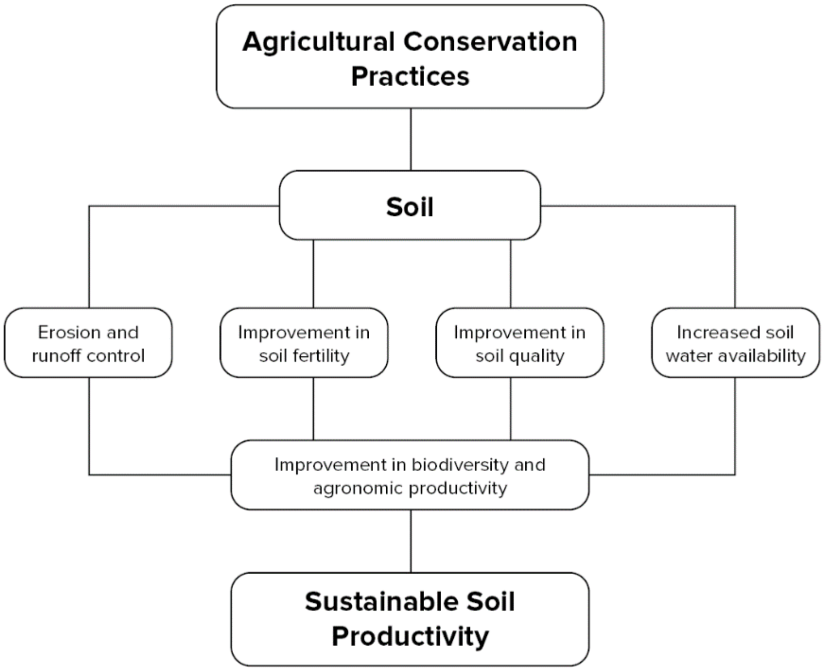


Figure 1.3. A graphical representation of the effects of agricultural conservation practices on soil.

The transition from conventional or reduced tillage to no-tillage has been shown to reduce surface runoff ratios by upwards of 20% [24]. A no-tillage management scheme can increase the infiltration capacity of soil in two ways: by minimizing soil disruption and by preserving the highest percentage of crop residue cover. Rainfall simulations on corn plots at 5% and 10% slopes showed that a no-till treatment produced the lowest surface runoff ratios while chisel ploughing and moldboard ploughing produced increasing runoff ratios, respectively [25]. No-tillage has also been shown to reduce soil and splash erosion as well as surface runoff while increasing the direct infiltration through a soil core sample [22,26,27]. Winter cover crop establishment can greatly increase the water availability for summer crops by: acting as a mulch and reducing soil water evaporation, increasing infiltration, decreasing runoff, increasing organic matter content, and improving soil structure [28,29]. Maintaining adequate plant cover year-round provides numerous benefits including improving soil quality, controlling soil erosion, and increasing soil water availability [30]. Plant cover percentage has a significant, negative relationship with final runoff rate, indicating that the greater the plant cover percentage- the lower the expected hourly runoff [31]. While cover crops provide year-round soil coverage, they also provide an even-coverage mulching (in no-tillage treatments) which has been found to be a more successful mulching strategy in real-life scenarios when compared to artificial mulching with wheat straw, grass clippings, wood chips, etc. [26]. Agricultural conservation techniques can greatly improve the water holding capacity of a soil which can reduce the need for irrigation. Implementing such techniques at the basin-scale can greatly reduce surface runoff and make an agricultural landscape more sustainable in the face of climate change with projected water shortages and greater precipitation variability.

1.5 The Soil and Water Assessment Tool (SWAT)

Hydrologic models are a relatively easy and non-invasive way to predict water balance shifts in a basin and can aid basin managers as decision-making tools with regard to landscape management. The Soil and Water Assessment Tool (SWAT) is a semi-distributed, semi-physically based, basin-scale hydrologic model [32,33]. SWAT divides a basin into hydrologic response units (HRUs), which are defined by unique combinations of soil types, slope classes, and land uses. SWAT is the most popular hydrologic model in modern literature because it is open access and highly flexible since it is composed of hundreds of editable parameters [32,34,35]. SWAT has been able to effectively model basins from <1 km^2 to basins on the continental scale and can be run on daily, monthly, or yearly timescales [36]. Due to its highly flexible nature, it is quite simple to run scenario analyses in SWAT whether they are climate change, land use/management change, or a combination [37].

1.6 Research Objectives

I intend to address the following questions throughout this thesis:

- How do crop changes affect the water balance in a small agricultural basin?
    - Does the percent area change affect the water balance proportionally?
    - How are these shifts affected at the daily, monthly, and seasonal timescales?
- How do land use changes, agricultural conservation techniques, and field size shifts align with the goals of restoring local water circulation in a landscape?
- How do agricultural conservation techniques and field size shifts affect the local water circulation in the landscape at the farm- and management-scales?
    - Do the effects of agricultural conservation practices and field size shifts have an additive or multiplicative effect as they are upscaled within a landscape?
    - How do the effects of the scale of adoption relate to management strategies?

The main goals during this research were outlined as developing, calibrating, and validating SWAT models for two basins (at two scales) in the Czech landscape to be utilized for further scenario analysis. SWAT had rarely been used in the Czech landscape and never at this scale so it was important to determine SWAT's applicability to this region. The two basins of study, Nučice (0.52 km2) and Vrchlice (97 km2), are both dominated by agricultural land cover. The research began by modeling the Nučice basin which is considered to be representative of the farm-scale. The scenario analysis in Nučice included the impacts of various crop rotations and the incorporation of agricultural conservation practices (Chapters 2 & 4, respectively). Then modeling efforts were upscaled to Vrchlice which is representative of the management-scale. At Vrchlice, land use and management changes as well as the impacts of agricultural conservation practice adoption were modeled (Chapters 3 &4). All the research completed during my PhD studies were published in international journals and are each outlined as their own chapter in the following text.

1.7 References

1. Flach, B.; Lieberz, S.; Bolla, S. Biofuels Annual Report; Global Agricultural Information Network (GAIN) Report NL9022, 2019.
2. Ministry of Agriculture of the Czech Republic. We support traditions and rural development in the Czech Republic ISBN: 978-80-7434-416-9, Prage, Czech Republic, 2018.
3. David, J.S.; Henriques, M.O.; David, T.S.; Tomé, J.; Ledger, D.C. Clearcutting effects on streamflow in coppiced Eucalyptus globulus stands in Portugal. Journal of Hydrology 1994, 162, 143–154, doi:10.1016/0022-1694(94)90008-6.
4. Stednick, J.D. Monitoring the effects of timber harvest on annual water yield. Journal of Hydrology 1996, 176, 79–95, doi:10.1016/0022-1694(95)02780-7.
5. Neary, D.G.; Gottfried, G.J.; Folliott, P.F. Post-wildfire watershed flood responses. 2nd International Fire Ecology Conference Proceedings 2003.
6. Bruijnzeel, L.A. Hydrological functions of tropical forests: not seeing the soil for the trees? Agriculture, Ecosystems & Environment 2004, 104, 185–228, doi:10.1016/j.agee.2004.01.015.
7. Beck, H.E.; Bruijnzeel, L.A.; van Dijk, A.I.J.M.; McVicar, T.R.; Scatena, F.N.; Schellekens, J. The impact of forest regeneration on streamflow in 12 mesoscale humid tropical catchments. Hydrol. Earth Syst. Sci. 2013, 17, 2613–2635, doi:10.5194/hess-17-2613-2013.
8. Wu, W.; Hall, C.A.S.; Scatena, F.N. Modelling the impact of recent land-cover changes on the stream flows in northeastern Puerto Rico. Hydrol. Process. 2007, 21, 2944–2956, doi:10.1002/hyp.6515.
9. BI, H.; LIU, B.; WU, J.; YUN, L.; CHEN, Z.; CUI, Z. Effects of precipitation and landuse on runoff during the past 50 years in a typical watershed in Loess Plateau, China. International Journal of Sediment Research 2009, 24, 352–364, doi:10.1016/S1001-6279(10)60009-1.
10. Webb, A.A.; Kathuria, A. Response of streamflow to afforestation and thinning at Red Hill, Murray Darling Basin, Australia. Journal of Hydrology 2012, 412-413, 133–140, doi:10.1016/j.jhydrol.2011.05.033.

11. Zhang, M.; Liu, N.; Harper, R.; Li, Q.; Liu, K.; Wei, X.; Ning, D.; Hou, Y.; Liu, S. A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. Journal of Hydrology 2017, 546, 44–59, doi:10.1016/j.jhydrol.2016.12.040.
12. Farley, K.A.; Jobbagy, E.G.; Jackson, R.B. Effects of afforestation on water yield: a global synthesis with implications for policy. Global Change Biol 2005, 11, 1565–1576, doi:10.1111/j.1365-2486.2005.01011.x.
13. Buendia, C.; Batalla, R.J.; Sabater, S.; Palau, A.; Marcé, R. Runoff Trends Driven by Climate and Afforestation in a Pyrenean Basin. Land Degrad. Develop. 2016, 27, 823–838, doi:10.1002/ldr.2384.
14. Ide, J.'i.; Finér, L.; Laurén, A.; Piirainen, S.; Launiainen, S. Effects of clear-cutting on annual and seasonal runoff from a boreal forest catchment in eastern Finland. Forest Ecology and Management 2013, 304, 482–491, doi:10.1016/j.foreco.2013.05.051.
15. Dunn, S.M.; Mackay, R. Spatial variation in evapotranspiration and the influence of land use on catchment hydrology. Journal of Hydrology 1995, 171, 49–73, doi:10.1016/0022-1694(95)02733-6.
16. Zeleňáková, M.; Fialová, J.; Negm, A.M. Assessment and protection of water resources in the Czech Republic; Springer: Cham, Switzerland, 2020, ISBN 9783030183639.
17. Stych, P.; Kabrda, J.; Bicik, I.; Lastovicka, J. Regional Differentiation of Long-Term Land Use Changes: A Case Study of Czechia. Land 2019, 8, 165, doi:10.3390/land8110165.
18. Pokorný, J.; Květ, J. Fishponds of the Czech Republic. In The Wetland Book; Finlayson, C.M., Milton, G.R., Prentice, R.C., Davidson, N.C., Eds.; Springer Netherlands: Dordrecht, 2016; pp 1–17, ISBN 978-94-007-6173-5.
19. Zumr, D.; Václav David; Jakub Jeřábek; Nina Noreika; Josef Krása. Monitoring of the soil moisture regime of an earth-filled dam by means of electrical resistance tomography, close range photogrammetry, and thermal imaging. Environ Earth Sci 2020, 79, 1–11, doi:10.1007/s12665-020-09052-w.
20. Esri. World Map with Imagery; Esri, 2021.

21. Kassam, A.; Friedrich, T.; Shaxson, F.; Pretty, J. The spread of Conservation Agriculture: justification, sustainability and uptake. International Journal of Agricultural Sustainability 2009, 7, 292–320, doi:10.3763/ijas.2009.0477.
22. Choudhary, M.A.; Lal, R.; Dick, W.A. Long-term tillage effects on runoff and soil erosion under simulated rainfall for a central Ohio soil. Soil and Tillage Research 1997, 42, 175–184, doi:10.1016/S0167-1987(97)00005-6.
23. Chow, T.L.; Rees, H.W.; Monteith, J. Seasonal distribution of runoff and soil loss under four tillage treatments in the upper St. John River valley New Brunswick, Canada. Can. J. Soil. Sci. 2000, 80, 649–660, doi:10.4141/S00-006.
24. Sun, Y.; Zeng, Y.; Shi, Q.; Pan, X.; Huang, S. No-tillage controls on runoff: A meta-analysis. Soil and Tillage Research 2015, 153, 1–6, doi:10.1016/j.still.2015.04.007.
25. Dickey, E.C.; Shelton, D.P.; Jasa, P.J.; Peterson, T. Tillage, Residue and Erosion on Moderately Sloping Soils. Biological Systems Engineering 1984, 1093–1099.
26. Hösl, R.; Strauss, P. Conservation tillage practices in the alpine forelands of Austria — Are they effective? CATENA 2016, 137, 44–51, doi:10.1016/j.catena.2015.08.009.
27. Leys, A.; Govers, G.; Gillijns, K.; Berckmoes, E.; Takken, I. Scale effects on runoff and erosion losses from arable land under conservation and conventional tillage: The role of residue cover. Journal of Hydrology 2010, 390, 143–154, doi:10.1016/j.jhydrol.2010.06.034.
28. Unger, P.W.; Vigil, M.F. Cover crop effects on soil water relationships. Jornal of Soil and Water Conservation 1998, 53, 200–207.
29. Frye, W.W.; Blevins, R.L. Economically sustainable crop production with legume cover crops and conservation tillage. Journal of Soil and Water Conservation 1989, 44, 57–60.
30. Zuazo, V.H.D.; Pleguezuelo, C.R.R. Soil-erosion and runoff prevention by plant covers. A review. Agron. Sustain. Dev. 2008, 28, 65–86, doi:10.1051/agro:2007062.
31. Greene, R.S.B.; Kinnell, P.I.A.; Wood, J.T. Role of plant cover and stock trampling on runoff and soil-erosion from semi-arid wooded rangelands. Soil Res. 1994, 32, 953, doi:10.1071/SR9940953.

32. Melaku, N.D.; Renschler, C.S.; Holzmann, H.; Strohmeier, S.; Bayu, W.; Zucca, C.; Ziadat, F.; Klik, A. Prediction of soil and water conservation structure impacts on runoff and erosion processes using SWAT model in the northern Ethiopian highlands. J Soils Sediments 2018, 18, 1743–1755, doi:10.1007/s11368-017-1901-3.
33. Du, B.; Ji, X.; Harmel, R.D.; Hauck, L.M. Evaluation of a Watershed Model for Estimating Daily Flow Using Limited Flow Measurements. JAWRA Journal of the American Water Resources Association 2009, 45, 475–484, doi:10.1111/j.1752-1688.2009.00303.x.
34. Brzozowski, J.; Miatkowski, Z.; Śliwiński, D.; Smarzyńska, K.; Śmietanka, M. Application of SWAT model to small agricultural catchment in Poland. Journal of Water and Land Development 2011, 15, 719, doi:10.2478/v10025-012-0014-z.
35. Peraza-Castro, M.; Ruiz-Romera, E.; Meaurio, M.; Sauvage, S.; Sánchez-Pérez, J.M. Modelling the impact of climate and land cover change on hydrology and water quality in a forest watershed in the Basque Country (Northern Spain). Ecological Engineering 2018, 122, 315–326, doi:10.1016/j.ecoleng.2018.07.016.
36. Hanel, M.; Mrkvičková, M.; Máca, P.; Vizina, A.; Pech, P. Evaluation of Simple Statistical Downscaling Methods for Monthly Regional Climate Model Simulations with Respect to the Estimated Changes in Runoff in the Czech Republic. Water Resour Manage 2013, doi:10.1007/s11269-013-0466-1.
37. Arnold, J.G.; Moriasi, D.N.; Gassman, P.W.; Abbaspour, K.C.; White, M.J.; Srinivasan, R.; Santhi, C.; Harmel, R.D.; van Griensven, A.; van Liew, M.W.; et al. SWAT: Model Use, Calibration, and Validation. Transactions of the ASABE 2012, 55, 1491–1508, doi:10.13031/2013.42256.

Chapter 2: Farm-Scale Biofuel Crop Adoption and Its Effects on In-Basin Water Balance[1]

2.1 Abstract

In the face of future climate change, Europe has encouraged the adoption of biofuel crops by its farmers. Such land-use changes can have significant impacts on the water balance and hydrological behavior of a system. While the heavy pesticide use associated with biofuel crops has been extensively studied, the water balance impacts of these crops have been far less studied. We conducted scenario analyses using the Soil and Water Assessment Tool (SWAT) to determine the effects of farm-scale biofuel crop adoption (rapeseed) on a basin's water balance. We found that rapeseed adoption does not support the goal of developing a sustainable agricultural landscape in the Czech Republic. The adoption of rapeseed also had disproportionate effects on a basin's water balance depending on its location in the basin. Additionally, discharge (especially surface runoff ratios), evapotranspiration, and available soil water content display significant shifts in the rapeseed adoption scenarios.

2.2 Introduction

Over the last several decades land use change and its impacts locally (physical soil quality) and regionally (basin hydrology and water balance) have been extensively studied [1–8]. Depending on the motivation, managers can make decisions concerning land use changes that have big impacts on the hydrology of a system. Decisions to develop land, deforest, afforest, and expand agriculture all have varying effects on water yield, soil storage capacity, surface runoff, and evapotranspiration in a basin [9]. While land use changes from forest or pasture to cropland (and vice versa) have been extensively studied, fewer hydrological studies performed examine such effects based solely on crop changes [10–14].

Between efforts outlined by the EU's biofuel directive (2003), the Kyoto Protocol (2005), the Paris Agreement (2016), and other EU directives (Renewable Energy (2009),

---

[1] Published as Noreika *et al.* (2020)
Sustainability. DOI: https://doi.org/10.3390/su122410596

Fuel Quality (2009), etc.) [15–18]; the EU incentivizes the production of crops utilized for biofuels to reduce greenhouse gas (GHG) emissions. Such crop changes can have significant impacts on agricultural landscape processes and the water balance in a basin. Across crops there are innumerable parameter changes that can affect the water processes in a system, including: rooting zone depth, USLE C-factor (Universal Soil Loss Equation Cover-factor), canopy height, stomatal conductance, leaf area index, and many more [19]. Numerous previous studies showed that each crop has distinctive water requirement patterns throughout a growing season and crop selection can have significant impacts that vary based on local climatic conditions [20-22]. Even the water requirements for crops that are appropriate for the same climate can have significantly different water footprints and thus is something for a manager to consider when making the switch from a food crop to a biofuel crop, especially in the face of future climate change [23].

Intensive storm events are becoming increasingly frequent in Central Europe according to the Intergovernmental Panel on Climate Change (IPCC) [24]; however, inappropriate soil, water, and landscape management has decreased the water retention capacity of the landscape in the Czech Republic. In the Czech Republic, many small streams run dry during the summer while flash floods are becoming more common. Hence, Zelenakova et al. suggested restoring local water circulation within the landscape [25]. The two main objectives for the restoration of the water cycle in the landscape are: (i) the restoration of drainage patterns with natural hydromorphology and (ii) the improvement of water retention capacity across the landscape in the Czech Republic—i.e., water should infiltrate the soil at the same location where it falls as rain. In light of these projected climatic changes, it is more important than ever to predict how a highly agricultural landscape will respond to specific crop changes [24].

Being an intensively agricultural country with nearly 40% of its total land area arable, the Czech Republic benefits greatly from many EU agricultural incentives. The primary crop processed for biofuel production in the EU is rapeseed [26]; according to the Research Institute of Crop Production in the Czech Republic, it is also the most economically important biofuel crop in the Czech Republic [27]. Extreme pesticide use is associated with the production of biofuel crops and the potential freshwater ecotoxicology impacts (PFEIs) of rapeseed cultivation can be up to 1000x greater per biofuel unit than other biofuel crops [28]. In addition to the water/air/soil contamination risks associated with extreme pesticide use, in the Czech Republic rapeseed is also planted in a physically unsustainable way. Rapeseed is sown during the rainy season (August) and soil is intentionally compacted and rolled smooth which can lead to extreme erosion events [29,30]. While previous studies have focused on the negative effects that rapeseed cultivation for biofuel can have on soil processes and water quality [28,29,31], it is the purpose of this study to assess the seasonal shifts in water balance at the farm-scale.

The Soil and Water Assessment Tool (SWAT) is a semi-distributed, semi-physically based, basin-scale hydrologic model [32,33]. SWAT divides a basin into hydrologic response units (HRUs) which are defined by unique combinations of soil types, slope classes, and land uses. SWAT is the most popular hydrologic model in modern literature because it is open access and highly flexible since it is composed of hundreds of editable parameters [32,34,35]. SWAT has been able to effectively model basins from <1 km^2 to basins on the continental scale and can be run at the daily, monthly, or yearly timescale [36,37]. Due to its highly flexible nature, it is quite simple to run scenario analyses in SWAT whether they are climate change, land use/cover change, or a combination [38]. While SWAT has been applied to basins all over the world, it has rarely been applied in the Czech Republic and never to assess the water balance impacts of rapeseed at the farm-scale which is currently a hotly debated topic in the Czech Republic.

This study investigates the following questions: (i) How does a crop change from winter wheat to rapeseed affect the water balance in a small agricultural basin? (ii) Does the percent area change affect the water balance proportionally? (iii) How are the shifts in water balance affected at the daily, monthly, and seasonal timescales? And (iv) How do these changes in water balance align with the goals of restoring local water circulation in a landscape?

2.3 Materials and Methods

2.3.1 Study Watershed

The basin selected for this study is the Nučice experimental catchment ("Nučice"); it is a small (0.52 km^2) agricultural watershed in the Czech Republic (approximately 30 km from Prague; Figure 2.1). The basin's outlet location is 49°57'49.230"N, 14°52'13.242"E. Nučice has been monitored by the Landscape Water Conservation Department of Czech Technical University in Prague since 2011. The climate in this region is humid continental with an average annual precipitation of ~600 mm and an average daily temperature of 7.9°C [39]. The highest monthly precipitation occurs in June with an average of 74.1 mm in rainfall and the lowest occurs in February (18 mm), but the rainy season is typically from May through August. The lowest temperatures occur in January with an average minimum daily temperature of -0.6°C and the highest temperatures occur in August with an average maximum daily temperature of 19.2°C.

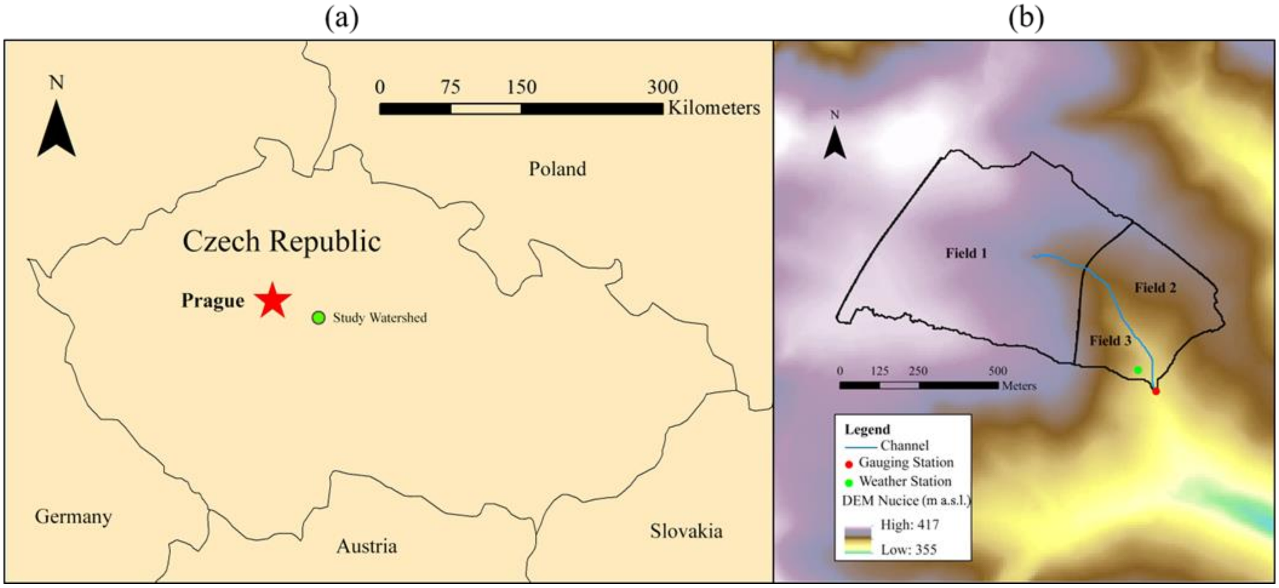


Figure 2.1. (a) Map of the Czech Republic with Prague and Nučice (the Study Watershed) highlighted for reference; (b) 3 m resolution DEM of Nučice and its immediate surroundings along with field IDs, channel, gauging station, and weather station.

Nučice is >95% agricultural and its remaining <5% consists of a narrow riparian zone of brush, the streambed, and a paved single-lane road that bisects the basin horizontally (Figure 2.2). The soils here are classified as Luvisols and Cambisols that overlay sandstone and siltstone [40]. Based on a nearby geological borehole survey, the depth to the bedrock is estimated to range from 6 m to 20 m. The ground water level measured at the catchment is quite deep, having very rarely risen above the level of the streambed, and recharge is quite low especially during the growing season. The deep-water table suggests that the stream discharge and the processes in the shallow part of the soil profile are not significantly influenced by groundwater. Nučice is divided into three fields that are managed by two farmers; the basin is drained by a channeled stream that begins in the upper field as a single tile drain. The average slope of Nučice is 3.9% but ranges from 1% to 12%. The basin is equipped with a meteorological station (measuring precipitation intensity, air temperature, humidity, wind speed, and solar radiation) and stream discharge is measured at the basin's outlet using an H-flume with a capacity of up to 400 L·s^{-1}.

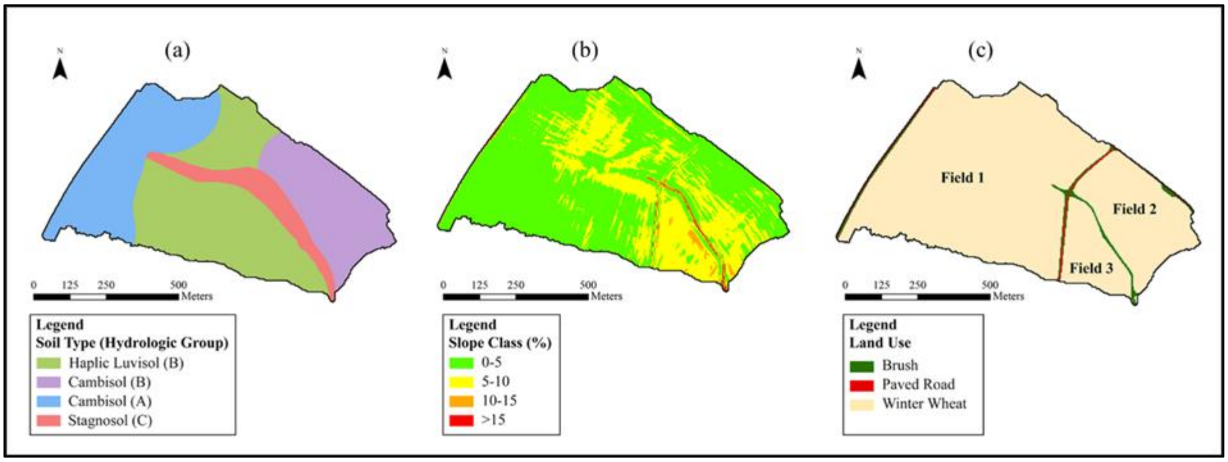


Figure 2.2. (a) Soil map; (b) slope map; (c) land use map (with field IDs) of Nučice.

Fields 1 and 2 are managed by the first farmer ("Farmer A") and Field 3 is managed by the second farmer ("Farmer B") (Figure 2.2c). Fields 1 and 2 have been tilled conservatively since 2000 and Field 3 has been tilled conservatively since 2013 with a maximum of 0.18m of soil disturbance. The farmers in Nučice typically grow the cereal grain winter wheat but occasionally rotate with rapeseed or mustard. It is feasible that the farmers who manage Nučice may shift their primary crops to further benefit from various EU policies that incentivize biofuel crop production.

2.3.2 SWAT Model Description

SWAT is a very flexible and highly customizable model; it allows for hydrological modeling at varying timesteps from daily to annual. Since Nučice is very flashy and has only been monitored since 2011 a daily timestep was selected for SWAT modeling to determine whether SWAT could model the flashiness of the basin and so that enough data points would be available for calibration and validation. The stream definition was digital elevation model-based (DEM-based) and the extent that most closely reflected the actual channel was selected. The slope classes were defined by every 5% increase in slope, resulting in four classes (0-5%, 5-10%, 10-15%, and >15%; Figure 2.2b). Hydrologic response units (HRUs) were defined by each unique combination of soil type, slope class, and land use types with >5% area coverage. The Penman-Monteith method was used for the calculation of potential evapotranspiration (PET) and the SCS (Soil Conservation Service) curve number method was used for the estimation of surface runoff. Generic parameters for a tile drainage system were integrated into the model and later refined during calibration. The model was run from 2014 through 2019 with a one-year warmup period of 2013.

2.3.3 Input Data

The soil map used was distributed by the State Land Office of the Czech Republic and includes basic soil physical properties (Figure 2.2a). The slopes in Nučice were divided into 4 classes as defined in SWAT according to the Digital Elevation Model (DEM) (Figure 2.2b). The DEM was obtained from the fifth generation of the digital relief model of the Czech Republic (DMR5G) and is based on LiDAR surveys with a relative error of 0.18m. The model point cloud was processed to obtain a 3m spatial resolution. The DEM was used to delineate the watershed boundaries. The land use map was composed by digitizing a detailed orthophoto map created during local unmanned aerial vehicle (UAV) surveys conducted by the Department of Landscape Water Conservation at Czech Technical University (Figure 2.2c; Table 2.1).

Table 2.1. Input variables used for SWAT modeling.

	Input Data	Description	Source
Meteorological Data	Extreme Temperatures	Minimum and maximum daily temperatures (2011-2019)	On-site: 107 Temperature Probe (Campbell Sci., UK)
	Precipitation	Total daily precipitation (2011-2019)	On-site: MR3-01s Tipping Bucket (Meteo Servis, Czech Republic)

Spatial Data	DEM	Digital elevation model (3m resolution)	LiDAR Survey: Czech Institute of Geodesy and Cartography
	Soil Type	Soil map of the Czech Republic 1:5,000	State Land Office of the Czech Republic
	Land Use	Digitized from detailed orthophoto	UAV Survey: Czech Technical University

Daily precipitation and temperature data were downloaded from the on-site gauge (Table 2.1) and compared to data from 6 stations provided by the Climate Forecast System Reanalysis database (CFSR) to verify that the on-site gauge is not significantly different for the overlapping years (2011-2014). The data downloaded from CFSR 1976-2014 was then used as climate generator data that is used to fill in any missing data over the timespan of the SWAT model run.

2.3.4 SWAT Sensitivity Analysis, Calibration, Validation, and Performance Evaluation

The sensitivity analysis and calibration for the SWAT model of Nučice was conducted using the SUFI2 method in SWAT CUP 2019 [41]. A global sensitivity analysis was conducted to determine the most sensitive parameters according to model response. After outliers were removed from the observation dataset, the model was calibrated at a daily time step using daily average discharge from 2016-2018 and validated for 2019. Several iterations of over 2000 simulations were executed across 18 parameters (Table 2.2). The stream discharge during the vegetated seasons of each year (approximately 1 April through 31 October) were used for calibration and validation. The reason for using only the vegetated seasons for calibration and validation are threefold: a) when conducting scenario analyses in the Czech Republic it is most important to assess the effects of land use shifts during the vegetated season as the Czech Republic is a very agricultural country and water balance shifts will be most relevant during the growing season, b) the runoff regime during winter months differs greatly from the rest of the year as the soil is typically saturated and baseflow is common- meaning that a separate calibration/validation procedure would be necessary for winter, and c) much of the installed equipment is removed during the winter so it is not damaged by the freeze- making calibration/validation impossible during these periods.

The statistical criteria for model acceptance were based on Nash-Sutcliff efficiency (NSE>0.4), percent bias (PBIAS<10%), coefficient of determination (R^2>0.4), and Kling-Gupta Efficiency (KGE>0.5).

Table 2.2. Parameters used for model calibration in SWAT CUP along with their degree of sensitivity (V: replace, A: absolute, R: relative, **p*<0.05).

Parameter	Definition	File	Method	Min	Max
ESCO	Soil evaporation compensation factor	.bsn	V	0.5	0.95
SURLAG	Surface runoff lag coefficient (days)	.bsn	V	0.001	15
ALPHA_BF	Base flow recession constant (days)	.gw	V	0.001	1
RCHRG_DP*	Deep aquifer percolation fraction	.gw	V	0.001	1
GW_DELAY*	Delay time for aquifer recharge (days)	.gw	A	-45	60
GW_REVAP*	Groundwater revap coefficient	.gw	V	0.02	0.2
GWQMN	Threshold water level in shallow aquifer for base flow (mm)	.gw	A	-2000	2000
OV_N	Manning’s n value for overland flow	.hru	V	0.05	0.8
DEP_IMP*	Depth to impervious layer in soil profile (mm)	.hru	A	-1500	4000
SLSOIL	Slope length for lateral subsurface flow (m)	.hru	R	-0.25	0.25
CN2	Initial SCS curve number for moisture condition II	.mgt	R	-0.2	0.2
DDRAIN_BSN	Depth to subsurface drain (mm)	.mgt	A	-500	500
TDRAIN_BSN	Time to drain soil to field capacity (hours)	.mgt	A	-40	40
GDRAIN_BSN	Drain tile lag time (hours)	.mgt	A	-40	40
CH_N2	Manning’s n for main channel	.rte	V	0.02	0.14
SOL_AWC*	Available water capacity	.sol	R	-0.75	0.75
SOL_K*	Saturated hydraulic conductivity ($mm \cdot h^{-1}$)	.sol	R	-0.5	0.5
CH_K1	Effective hydraulic conductivity of channel ($mm \cdot h^{-1}$)	.sub	V	0.025	150

2.3.5 Scenario Analysis

Three scenarios in addition to the default conditions were determined based upon individual farmer adoption of rapeseed. The scenarios were defined as such so that the effects of farm-scale biofuel crop adoption could be observed and to determine if adoption area and location in the basin disproportionately affect water balance shifts. The percent area of crop change ranged from 6 to 96 depending on the scenario (Table 2.3). All crop parameters were kept to the respective crop's default values outlined by SWAT except for those found in Table 2.4 which were calculated by local experts in local conditions (including crop strain, growing conditions, and climate) [30]. There are several differences in crop parameters and management practices that could result in water balance shifts between winter wheat and rapeseed cultivation. Rapeseed and winter wheat are seeded within a month of each other, but since rapeseed is planted earlier in the year and the soil is compacted to protect the seeds during the rainy season, this may make the soil more vulnerable to erosive events. The minimum USLE C-factors differ greatly between the two crops and this indicates that rapeseed makes a landscape more susceptible to soil loss (Table 2.4). Rapeseed and winter wheat have similar rooting zone depths, with averages of 70 and 80 cm and maximums of 130 and 140 cm, respectively. Rapeseed and winter wheat also have similar optimal, minimal, and maximal temperature requirements but winter wheat requires a higher sum temperature to harvest. Winter wheat has a higher maximum LAI (by 2.0 $m^2 \cdot m^{-2}$) indicating a higher rate of transpiration when compared to rapeseed [30].

Table 2.3. Scenario ID, crops planted by each farmer, and percent area of basin change from winter what to rapeseed.

Scenario ID	Farmer A	Farmer B	Percent Basin Change
Default	Winter Wheat	Winter Wheat	0
S1	Rapeseed	Winter Wheat	90
S2	Winter Wheat	Rapeseed	6
S3	Rapeseed	Rapeseed	96

The basic water balance output components (evapotranspiration (ET), surface runoff (SURQ), subsurface lateral flow (LATQ), available water capacity (SW), and discharge at the outlet (FLOW)) were evaluated across the three crop change scenarios in addition to the default scenario. The average monthly values from April to October and their respective percent change from the default scenario were calculated. Paired t-tests between the daily values for the water balance variables ET, SW, and FLOW were conducted to compare each rapeseed adoption scenario to the default scenario. For Scenarios 1&2, the values for these parameters were normalized against full rapeseed adoption (Scenario 3) to determine if area adoption had any significant influence on the water balance parameters. Finally, to assess shifts in SURQ and LATQ, the daily contribution ratios were calculated against the default scenario for each rapeseed adoption scenario.

Table 2.4. Adjusted crop parameters from default SWAT values.

Parameter	**Winter Wheat (WWHT)**		**Rapeseed (CANP)**	
	Default	**Adjusted**	**Default**	**Adjusted**
Max Rooting Depth (m)	1.3	1.4	0.9	1.3
Max LAI ($m^2 \cdot m^{-2}$)	4.0	5.0	3.5	3.0
Min USLE C-Factor	0.03	0.05	0.20	0.10

2.4 Results

2.4.1 SWAT Model Sensitivity Analysis

According to the global sensitivity analysis, six parameters significantly influenced the modeled discharge flow out of the Nučice experimental basin (Table 2.5). The first significantly sensitive parameter is related to groundwater processes and local geomorphology. Groundwater delay (GW_DELAY) is the lag time between when water exits the soil profile and enters the shallow aquifer. Groundwater delay is dependent upon water table depth and geologic formations. Five of the six sensitive parameters are related to soil water processes. The deep aquifer percolation fraction (RCHRG_DP) is the fraction of percolation that recharges the deep aquifer from the root zone. The groundwater “revap” coefficient (GW_REVAP) is the ratio of water that may move from the shallow aquifer back into the unsaturated zone but is a parameter that is typically more sensitive in basins where the saturated zone is relatively shallow and the land cover includes deep rooting vegetation. The depth to impervious layer parameter (DEP_IMP) parameter dictates a layer of soil with lower hydraulic conductivity than the layer(s) above it. This parameter facilitates greater subsurface flow in the basin and was included in this model because there is a tile drainage system in the Nučice experimental basin of which very little is known. Soil available water capacity (SOL_AWC) and saturated hydraulic conductivity (SOL_K) are both soil input parameters that dictate the ability of a soil to retain water for plant use and to infiltrate and drain water, respectively.

Table 2.5. Sensitive parameters and their calibrated (adjusted) values. (V: replace, A: absolute, R: relative)

Parameter	**Method**	**Calibration Values**		
		Minimum Value	Adjusted Value	Maximum Value
Groundwater “revap” coefficient	V	0.02	0.086	0.2
Deep aquifer percolation fraction	V	0.001	0.48	1
Delay time for aquifer recharge (days)	A	-45	-32.31	60
Depth to impervious layer in soil profile (mm)	A	-1500	3036.7	4000
Available water capacity (mm)	R	-75%	-59%	+75%
Saturated hydraulic conductivity (mm·h^{-1})	R	-50%	25%	+50%

2.4.2 SWAT Model Calibration and Validation

Successful model calibration and validation was obtained via a semi-automatic calibration method (Table 2.6). The overall model fit for the calibration period is considered to be “good” while the fit for the validation period is considered to be “satisfactory” at a daily timescale [42]. The NSE, PBIAS, R^2, and KGE are all considered very good for calibration at the daily timescale (Table 2.6). During the validation period, the PBIAS is considered good and the other indicators are considered to be satisfactory. Overall calibrated and validated model fit is generally good and the uncertainty reflected in the *p*-factor (0.55 and 0.71, respectively) and the *r*-factor are satisfactory (0.22 and 0.12, respectively; Figure 2.3).

Table 2.6. Model performance indicator values for calibration and validation periods of the SWAT model.

Model Performance Indicator	**Calibration (2016-2018)**	**Validation (2019)**
NSE	0.65	0.40

PBIAS	-0.3%	-6.7%
R^2	0.65	0.42
KGE	0.75	0.47
p-factor	0.55	0.71
r-factor	0.22	0.12

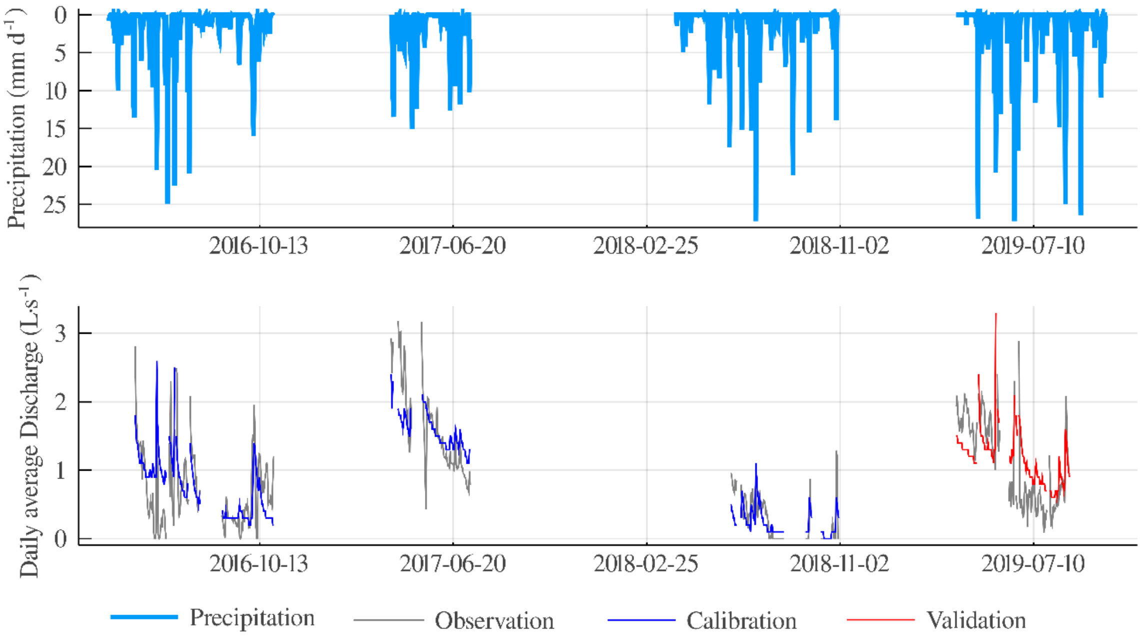


Figure 2.3. Calibration and validation of daily average flow in Nučice during the growing seasons from 2016-2019.

A correlation between observed and modeled discharges for the calibration and validation periods are presented in Figure 2.4 (a) and (b), respectively, a trendline for reference. Paired t-tests comparing modeled to observed discharge values (during both calibration and validation periods) showed no significant differences ($p>0.05$).

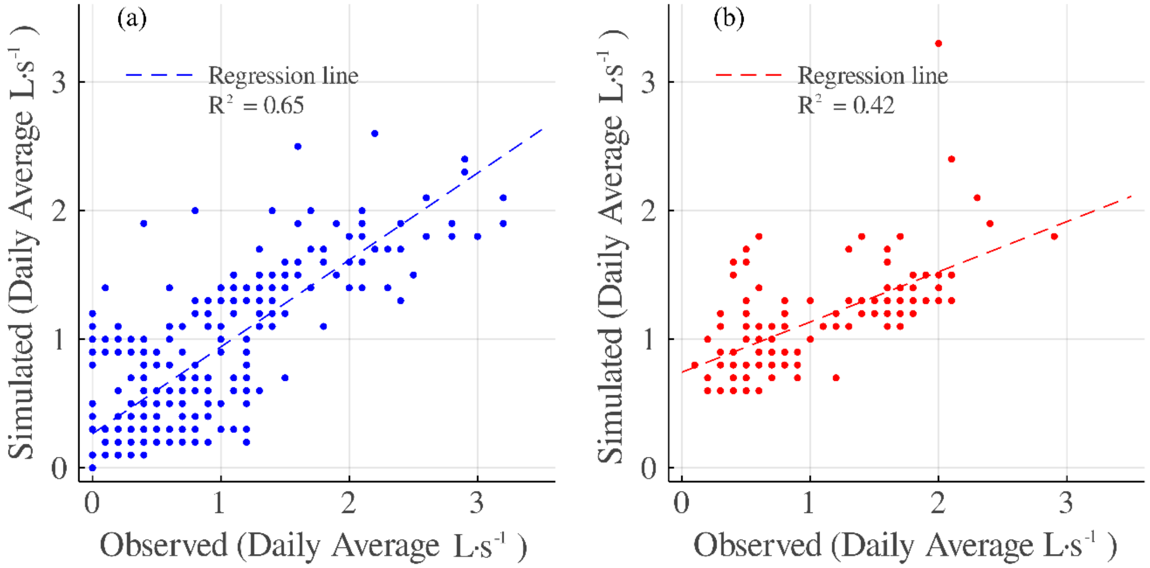


Figure 2.4. Observed daily average flows versus modeled daily average flows for (a) calibration period and (b) validation period.

2.4.3 Crop Change Effects on Water Balance parameters

The following daily basin water balance parameters were analyzed across crop change scenarios: evapotranspiration (ET), soil water content (SW), and stream discharge at the outlet (FLOW). Two sets of paired t-tests were conducted. Firstly, to assess if there were significant basin-wide differences between each scenario and the default. The second set of paired t-tests were based on the percent area adoption in Scenarios 1 & 2 normalized by Scenario 3 (full adoption) and compared to the modeled scenario outputs to determine if percent adoption affected the water balance parameters proportionally. The conducted paired t-tests indicate significant changes in water balance variables across scenarios (Table 2.7). Evapotranspiration ($mm\cdot d^{-1}$) is significantly lower in the rapeseed scenarios when compared to the default winter wheat scenario. Stream discharge (average daily $L\cdot s^{-1}$) is significantly higher in the rapeseed scenarios. Soil water content (average daily mm) is significantly higher in rapeseed Scenario 1 but significantly lower in rapeseed Scenario 2. Once normalized for percent area change from winter wheat to rapeseed, there are significant changes in basin water balance parameters that are likely influenced by slope, soil type, location in the basin, and proximity to stream; indicating a multiplicative rather than additive effect based on area change.

Table 2.7. Key basin water balance parameters, their daily average values (2014-2017), and their significance when compared to the default scenarios and when normalized against full rapeseed adoption in Scenario 3 (normal); (**p<0.001). (ET: evapotranspiration, SW: available soil water content, FLOW: average daily discharge.)

Parameter	Default	Scenario 1		Scenario 2		Scenario 3
		Modeled	Normal	Modeled	Normal	Modeled
ET (mm·d^{-1})	1.27	1.14**	1.41**	1.20**	1.13**	1.12**
SW (mm)	40.96	56.72**	48.04**	39.62**	41.43**	49.15**
FLOW (L·s^{-1})	0.829	1.120**	1.088**	0.989**	0.846**	1.129**

In addition to the lumped daily analysis described above, the daily values were also sorted by month so that patterns through the growing season could be observed (Figure 2.5a). For all three rapeseed scenarios, ET decreased in months April, May, and June and ranged from -7.2 to -35.9% but increased in September and October ranging from +0.9% to +38.3% when compared to the default scenario (Figure 2.5b). There do not seem to be significant differences in ET during the months of July and August. The basin's average available soil water content increased from May through October for Scenario 1, ranging from +9.4 to +132.5% when compared to the default scenario (the greatest % increase was observed in August during which the soil water content increased from 23.5 mm to 54.6 mm); but the average soil water content varied greatly for Scenario 2 across the same time period ranging from -10.9% to +28.9%. In April, July, and October substantial decreases in soil water content were observed in Scenario 2 ranging from -10.9% to -14.2% when compared to the default scenario. Across the entire growing season, any adoption of rapeseed resulted in considerable discharge increases ranging from +5.7% to +180.5%. Lateral flow contribution to total water yield does not seem to be affected by rapeseed adoption whereas surface runoff contribution to total water yield varied across time and percent adoption (Table 2.8). From April through September, surface runoff increased in rapeseed Scenario 1 from 1.02 to 4.15x the amount modeled in the default scenario but in October the surface runoff decreased to 12% of the default scenario. The largest increase in surface runoff in Scenario 2 was observed in June with 1.89x higher values than the default scenario. Since both

Scenarios 1&2 are subsets of Scenario 3, Scenario 3 was used to determine if crop changes in Scenarios 1&2 provided proportional changes to water balance parameters.

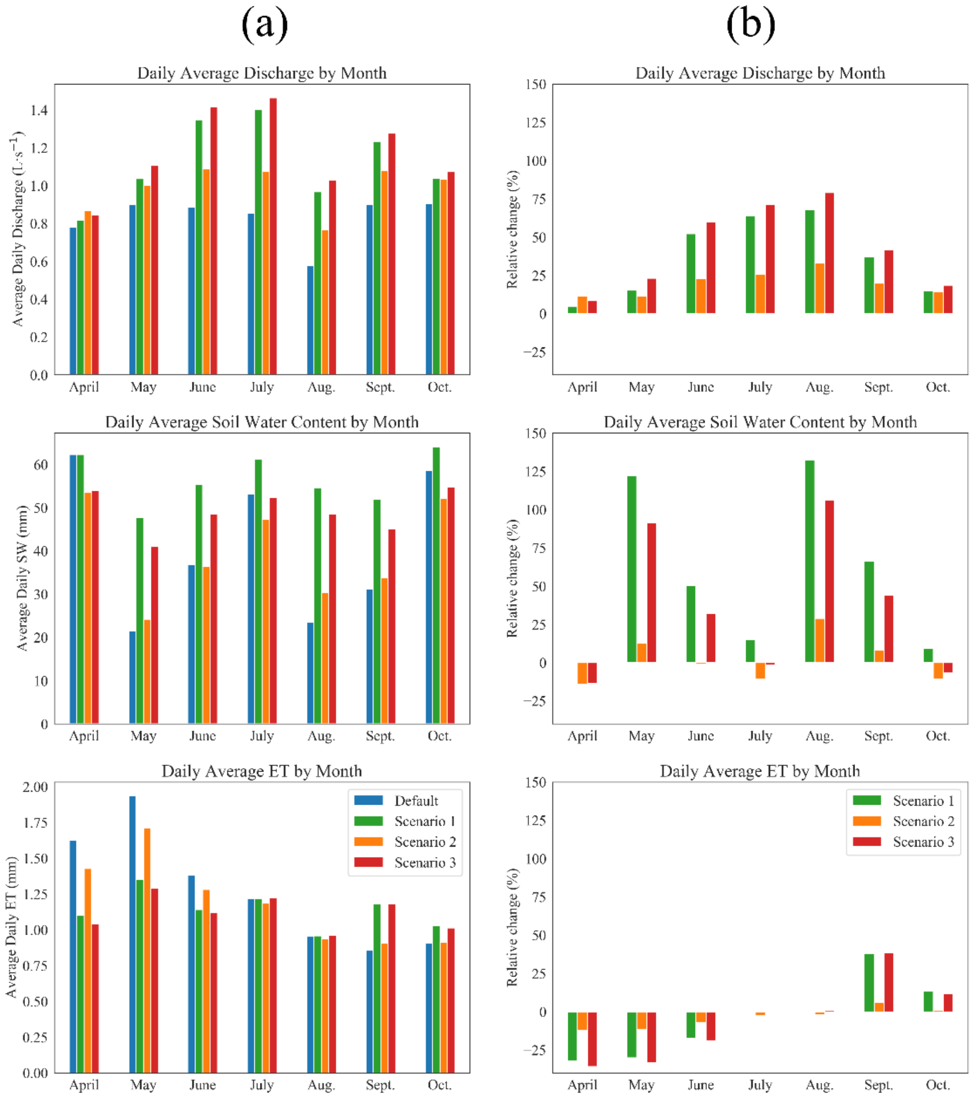


Figure 2.5. (a) Average daily water balance parameters across the growing season comparing the default scenario values to those of scenarios 1-3; (b) the relative percent change of each parameter in each scenario.

Table 2.8. Surface runoff ratios for each scenario (S1-S3) when compared to the default scenario. A value closer to 1.0 reflects minimal differences comparing the crop change scenarios to the default scenario. The further the value is from 1.0, the greater the impact due to the respective crop change scenario. (SURQ: surface runoff, LATQ: subsurface lateral flow)

Month	SURQ			LATQ		
	S1	S2	S3	S1	S2	S3
April	2.83	1.34	2.42	1.03	1.01	1.03

May	1.43	1.02	1.51	1.00	1.00	0.99
June	4.15	1.89	4.04	1.09	1.03	1.10
July	1.93	1.12	1.84	1.00	1.00	0.99
Aug	1.14	1.05	1.07	1.02	1.01	1.01
Sept	1.14	1.04	1.07	1.01	1.01	1.01
Oct	0.12	0.84	0.01	1.02	1.01	1.01

2.5 Discussion

2.5.1 Hydrological Modeling with SWAT

In any hydrological model, there are four major sources of uncertainty: input data, model structural uncertainty, model parameter uncertainty, and output data uncertainty [43,44]. Although SWAT is one of the most widely used hydrological models in modern literature, it does have some limitations as well as the sources of uncertainty outlined above [44]. Since SWAT is semi-physically based many inputs are calculated from equations or obtained from global or regional databases which can introduce uncertainty especially at this scale and SWAT is unable to truly represent physical runoff processes such as preferential flow [45,46]. Nučice has been equipped to monitor generalized processes at the basin’s outlet rather than more distributed, basin-wide processes. SWAT is unable to reflect the true flashiness in the observed discharge data. This may be due to some level of uncertainty in the pressure probe at Nučice which produces very “bouncy” discharge readings. The SWAT model of Nučice may also be improved with sub-hourly precipitation along with using the Green and Ampt Equation instead of the SCS curve number method to simulate infiltration but this is not typically recommended with the current quality of soil data available [47-49]. But overall, the fit of the SWAT model for the Nučice experimental basin ranges from “satisfactory” to “good,” depending on model fit parameter selection, which is more than adequate for our scenario analyses as many other studies have used SWAT to conduct scenario analyses on ungauged basins since relative changes between scenarios are typically of interest [50-52].

2.5.2 Water Balance Response to Crop Changes

The three parameters analyzed in this study that encompass the basin water balance are evapotranspiration, available soil water content, and stream discharge along with the relative ratios of surface runoff and subsurface lateral flow. Concerning water balance loses, springtime evapotranspiration was much lower in the rapeseed scenarios than the default winter wheat scenario (from -7.2% to -35.9%) but the opposite was true during the autumnal months (+0.9% to +38.3%) which is expected since rapeseed begins its growth cycle in the autumn as winter wheat is just being planted. Although evapotranspiration is typically highest in the default winter wheat scenario throughout most of the year, this contributes to the goal of local water recycling rather than it being lost to discharge as in the rapeseed scenarios [25]. Daily average discharge was higher (by up to 180.5%) in all rapeseed scenarios when compared to the winter wheat scenarios. In the rapeseed scenarios, a greater proportion of discharge is composed of surface runoff (up to >4x higher) this could be due to a greater degree of interception by winter wheat due to its higher LAI; this higher proportion of surface runoff may lead to more soil erosion events in the summertime [53]. The fields are already more vulnerable to erosion events during summer for two reasons: a) precipitation patterns (the summer months have higher precipitation rates and the convective storms are more frequent than during the rest of the year) and b) seedbed conditions of the rapeseed fields [54]. Additionally, since increased levels of pesticide use are associated with biofuel crops in general, but especially rapeseed [28], these surface runoff events could lead to much greater pesticide runoff than the winter wheat scenarios, but such is not in the scope of this study. Average daily soil water content is generally much higher in the rapeseed scenarios over the default winter wheat scenario which may make rapeseed a more appropriate crop in years of longer droughts especially since the rapeseed scenarios also have generally lower rates of evapotranspiration. Average daily soil water content varies by scenario and is significantly lower than expected in Scenario 2 when normalized for percent area adoption. We expect that this might be due to higher than basin-average slopes and the close proximity to the streambed in Field 3; which could also explain the significantly higher than expected total water yield in Scenario 2 [55].

2.5.3 Implications for Crop Management in the Czech Republic

The main goal of sustainable agricultural management in the Czech Republic is to build a landscape that restores local water circulation [25]. The substantial increases in discharge at Nučice's outlet resulting from rapeseed adoption do not support this goal. The 400% increase observed in surface runoff also does not support this goal and may contribute to huge soil losses during large rainstorm events in the summertime. There are some disproportionate effects due to location of adoption within the basin that greatly affect the water balance in the basin and should be noted by basin managers who may be able to incentivize farmers to make certain management decisions by location and proximity to a basin's outlet. This manuscript should initiate studies that upscale scenarios related to biofuel crop adoption, which is supported by governmental incentives, and its effects on water balance and water pollution within the Czech Republic.

2.6 Conclusions

This study shows that the SWAT model can be effectively used in the Czech Republic to determine the effects of crop change scenarios on key water balance parameter shifts and can be of future use to determine how and where governmental policies and subsidies should be applied, especially in the case of biofuel crop adoption. Discharge, soil water content, and evapotranspiration were all significantly affected by rapeseed adoption. Discharge, soil water content, and surface runoff were all significantly higher when rapeseed was adopted in the basin. The increased discharge and surface runoff indicate a lesser degree of local water cycling than in the default winter wheat scenario and can also indicate higher potential soil losses from the landscape. The evapotranspiration in the winter wheat default scenario was typically higher than the rapeseed scenarios which reinforces the local water cycle. It is possible that in future climate change scenarios rapeseed may be more beneficial in longer drought periods due to lower average transpiration and higher average soil water content than winter wheat scenarios, but further scenario analyses would need to be conducted at a larger scale in the Czech Republic.

I conclude that rapeseed crop adoption does not support the goal of establishing a sustainable agricultural landscape and does not reinforce the local water cycle. The results of this study can be used by local farmers to make decisions regarding their crop rotation and location of planting with respect to the field's soil and slope properties as well as its proximity to the basin's outlet. This study suggests that upscaling these modeling efforts in the Czech Republic is important and may be able to be used to shape public policy and to work as a decision-making tool for watershed managers.

2.7 References

1. David, J.S.; Henriques, M.O.; David, T.S.; Tomé, J.; Ledger, D.C. Clearcutting effects on streamflow in coppiced Eucalyptus globulus stands in Portugal. *Journal of Hydrology* 1994, *162*, 143–154, doi:10.1016/0022-1694(94)90008-6.
2. Stednick, J.D. Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology* 1996, *176*, 79–95, doi:10.1016/0022-1694(95)02780-7.
3. Neary, D.G.; Gottfried, G.J.; Folliott, P.F. Post-wildfire watershed flood responses. *2nd International Fire Ecology Conference Proceedings* 2003.
4. Bruijnzeel, L.A. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems & Environment* 2004, *104*, 185–228, doi:10.1016/j.agee.2004.01.015.
5. Beck, H.E.; Bruijnzeel, L.A.; van Dijk, A.I.J.M.; McVicar, T.R.; Scatena, F.N.; Schellekens, J. The impact of forest regeneration on streamflow in 12 mesoscale humid tropical catchments. *Hydrol. Earth Syst. Sci.* 2013, *17*, 2613–2635, doi:10.5194/hess-17-2613-2013.
6. Wu, W.; Hall, C.A.S.; Scatena, F.N. Modelling the impact of recent land-cover changes on the stream flows in northeastern Puerto Rico. *Hydrol. Process.* 2007, *21*, 2944–2956, doi:10.1002/hyp.6515.
7. BI, H.; LIU, B.; WU, J.; YUN, L.; CHEN, Z.; CUI, Z. Effects of precipitation and landuse on runoff during the past 50 years in a typical watershed in Loess Plateau, China. *International Journal of Sediment Research* 2009, *24*, 352–364, doi:10.1016/S1001-6279(10)60009-1.

8. Webb, A.A.; Kathuria, A. Response of streamflow to afforestation and thinning at Red Hill, Murray Darling Basin, Australia. *Journal of Hydrology* 2012, *412-413*, 133–140, doi:10.1016/j.jhydrol.2011.05.033.
9. Zhang, M.; Liu, N.; Harper, R.; Li, Q.; Liu, K.; Wei, X.; Ning, D.; Hou, Y.; Liu, S. A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. *Journal of Hydrology* 2017, *546*, 44–59, doi:10.1016/j.jhydrol.2016.12.040.
10. Bauer, A.; Black, A.L. Soil Carbon, Nitrogen, and Bulk Density Comparisons in Two Cropland Tillage Systems after 25 Years and in Virgin Grassland. *Soil Science Society of America Journal* 1981, *45*, 1166–1170, doi:10.2136/sssaj1981.03615995004500060032x.
11. Franzluebbers, A.J.; Stuedemann, J.A.; Schomberg, H.H.; Wilkinson, S.R. Soil organic C and N pools under long-term pasture management in the Southern Piedmont USA. *Soil Biology and Biochemistry* 2000, *32*, 469–478, doi:10.1016/S0038-0717(99)00176-5.
12. Bewket, W.; Stroosnijder, L. Effects of agroecological land use succession on soil properties in Chemoga watershed, Blue Nile basin, Ethiopia. *Geoderma* 2003, *111*, 85–98, doi:10.1016/S0016-7061(02)00255-0.
13. Breuer, L.; Huisman, J.A.; Keller, T.; Frede, H.-G. Impact of a conversion from cropland to grassland on C and N storage and related soil properties: Analysis of a 60-year chronosequence. Geoderma, 133(1-2), 6-18. *Geoderma* 2006, *133*, 6–18, doi:10.1016/j.geoderma.2006.03.033.
14. Bronson, K.F.; Zobeck, T.M.; Chua, T.T.; Acosta-Martinez, V.; van Pelt, R.S.; Booker, J.D. Carbon and Nitrogen Pools of Southern High Plains Cropland and Grassland Soils. *Soil Sci. Soc. Am. J.* 2004, *68*, 1695–1704, doi:10.2136/sssaj2004.1695.
15. European Commission. *Directive 2003/30/EC of the European Parliament and of the council of 8 May 2003*. *On the promotion of the use of biofuels or other renewable fuels for transport*, 2003.
16. European Commission. *Biofuels in the European Union*. *A vision for 2030 and beyond;* European Communities: Luxemborg, 2006, ISBN 92-79-01748-9.

17. European Commission. *Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009*. *amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC*, 2009.
18. European Commission. *Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009*. *On the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC*, 2009.
19. Kiniry, J.R.; Williams, J.R.; Major, D.J.; Izaurralde, R.C.; Gassman, P.W.; Morrison, M.; Bergentine, R.; Zentner, R.P. EPIC model parameters for cereal, oilseed, and forage crops in the northern Great Plains region. *Can. J. Plant Sci.* 1995, *75*, 679–688, doi:10.4141/cjps95-114.
20. Siddique, K.H.M.; Regan, K.L.; Tennant, D.; Thomson, B.D. Water use and water use efficiency of cool season grain legumes in low rainfall Mediterranean-type environments. *European Journal of Agronomy* 2001, *15*, 267–280, doi:10.1016/S1161-0301(01)00106-X.
21. Kar, G.; Kumar, A.; Martha, M. Water use efficiency and crop coefficients of dry season oilseed crops. *Agricultural Water Management* 2007, *87*, 73–82, doi:10.1016/j.agwat.2006.06.002.
22. Siebert, S.; Döll, P. Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *Journal of Hydrology* 2010, *384*, 198–217, doi:10.1016/j.jhydrol.2009.07.031.
23. Gerbens-Leenes, W.; Hoekstra, A.Y.; van der Meer, T.H. The water footprint of bioenergy. *Proc. Natl. Acad. Sci. U. S. A.* 2009, *106*, 10219–10223, doi:10.1073/pnas.0812619106.
24. Kovats, R.S., Valentini, R., Bouwer, L.M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M., Soussana, J.F., 2014. Europe. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S.,

Mastrandrea, P.R., White, L.L. *Climate Change 2014: Impacts, Adaptation and Vulnerability*. *Part B: Regional Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2014.

25. Zelenakova, M.; Fialová, J.; Negm, A.M. Assessment and Protection of Water Resources in the Czech Republic 2020, doi:10.1007/978-3-030-18363-9.
26. Flach, B.; Lieberz, S.; Bolla, S. *Biofuels Annual Report*; Global Agricultural Information Network (GAIN) Report NL9022, 2019.
27. Ministry of Agriculture of the Czech Republic. *We support traditions and rural development in the Czech Republic* ISBN: 978-80-7434-416-9, 2018.
28. Nordborg, M.; Cederberg, C.; Berndes, G. Modeling potential freshwater ecotoxicity impacts due to pesticide use in biofuel feedstock production: the cases of maize, rapeseed, salix, soybean, sugar cane, and wheat. *Environ. Sci. Technol.* 2014, *48*, 11379–11388, doi:10.1021/es502497p.
29. van Zelm, R.; van der Velde, M.; Balkovic, J.; Čengić, M.; Elshout, P.M.F.; Koellner, T.; Núñez, M.; Obersteiner, M.; Schmid, E.; Huijbregts, M.A.J. Spatially explicit life cycle impact assessment for soil erosion from global crop production. *Ecosystem Services* 2018, *30*, 220–227, doi:10.1016/j.ecoser.2017.08.015.
30. Mistr, M. *Determination of crop and management factor values to intensify soil erosion control in the Czech Republic (In Czech)* QJ1530181, 2019.
31. Cwalina-Ambroziak, B.; Stępień, A.; Kurowski, T.P.; Głosek-Sobieraj, M.; Wiktorski, A. The health status and yield of winter rapeseed (Brassica napus L.) grown in monoculture and in crop rotation under different agricultural production systems. *Archives of Agronomy and Soil Science* 2016, *62*, 1722–1732, doi:10.1080/03650340.2016.1171851.
32. Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large Area Hydrologic Modeling and Assessment Part I: Model Development. *J Am Water Resources Assoc* 1998, *34*, 73–89, doi:10.1111/j.1752-1688.1998.tb05961.x.
33. Neitsch, S.L.; Arnold, J.G.; Kiniry, J.R.; Williams, J.R. Soil and Water Assessment Tool Theoretical Documentation. *Texas Water Resources Institute* 2011.

34. Gassman, P.W.; Reyes, M.R.; Green, C.H.; Arnold, J.G. The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. *Transactions of the ASABE* 2007, *50*, 1211–1250, doi:10.13031/2013.23637.
35. Melaku, N.D.; Renschler, C.S.; Holzmann, H.; Strohmeier, S.; Bayu, W.; Zucca, C.; Ziadat, F.; Klik, A. Prediction of soil and water conservation structure impacts on runoff and erosion processes using SWAT model in the northern Ethiopian highlands. *J Soils Sediments* 2018, *18*, 1743–1755, doi:10.1007/s11368-017-1901-3.
36. Du, B.; Ji, X.; Harmel, R.D.; Hauck, L.M. Evaluation of a Watershed Model for Estimating Daily Flow Using Limited Flow Measurements. *JAWRA Journal of the American Water Resources Association* 2009, *45*, 475–484, doi:10.1111/j.1752-1688.2009.00303.x.
37. Brzozowski, J.; Miatkowski, Z.; Śliwiński, D.; Smarzyńska, K.; Śmietanka, M. Application of SWAT model to small agricultural catchment in Poland. *Journal of Water and Land Development* 2011, *15*, 719, doi:10.2478/v10025-012-0014-z.
38. Peraza-Castro, M.; Ruiz-Romera, E.; Meaurio, M.; Sauvage, S.; Sánchez-Pérez, J.M. Modelling the impact of climate and land cover change on hydrology and water quality in a forest watershed in the Basque Country (Northern Spain). *Ecological Engineering* 2018, *122*, 315–326, doi:10.1016/j.ecoleng.2018.07.016.
39. Hanel, M.; Mrkvičková, M.; Máca, P.; Vizina, A.; Pech, P. Evaluation of Simple Statistical Downscaling Methods for Monthly Regional Climate Model Simulations with Respect to the Estimated Changes in Runoff in the Czech Republic. *Water Resour Manage* 2013, doi:10.1007/s11269-013-0466-1.
40. Zumr, D.; Dostál, T.; Devátý, J. Identification of prevailing storm runoff generation mechanisms in an intensively cultivated catchment. *Journal of Hydrology and Hydromechanics* 2015, *63*, 246–254, doi:10.1515/johh-2015-0022.
41. Arnold, J.G.; Moriasi, D.N.; Gassman, P.W.; Abbaspour, K.C.; White, M.J.; Srinivasan, R.; Santhi, C.; Harmel, R.D.; van Griensven, A.; van Liew, M.W.; et al. SWAT: Model Use, Calibration, and Validation. *Transactions of the ASABE* 2012, *55*, 1491–1508, doi:10.13031/2013.42256.

42. Moriasi, D.N.; Arnold, J.G.; van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE* 2007, *50*, 885–900, doi:10.13031/2013.23153.
43. Tuppad, P.; Douglas-Mankin, K.R.; Lee, T.; Srinivasan, R.; Arnold, J.G. Soil and Water Assessment Tool (SWAT) Hydrologic/Water Quality Model: Extended Capability and Wider Adoption. *Transactions of the ASABE* 2011, *54*, 1677–1684, doi:10.13031/2013.39856.
44. Nyeko, M. Hydrologic Modelling of Data Scarce Basin with SWAT Model: Capabilities and Limitations. *Water Resour Manage* 2015, *29*, 81–94, doi:10.1007/s11269-014-0828-3.
45. Beven, K. How far can we go in distributed hydrological modelling? *Hydrology and Earth SYstem Sciences Discussions, European Geosciences Union* 2001, *5*, 1–12.
46. Martínez-Retureta, R.; Aguayo, M.; Stehr, A.; Sauvage, S.; Echeverría, C.; Sánchez-Pérez, J.-M. Effect of Land Use/Cover Change on the Hydrological Response of a Southern Center Basin of Chile. *Water* 2020, *12*, 302, doi:10.3390/w12010302.
47. Geza, M.; McCray, J.E. Effects of soil data resolution on SWAT model stream flow and water quality predictions. *J. Environ. Manage.* 2008, *88*, 393–406, doi:10.1016/j.jenvman.2007.03.016.
48. Daggupati, P.; Douglas-Mankin, K.R.; Sheshukov, A.Y.; Barnes, P.L.; Devlin, D.L. Field-Level Targeting Using SWAT: Mapping Output from HRUs to Fields and Assessing Limitations of GIS Input Data. *Transactions of the ASABE* 2011, *54*, 501–514, doi:10.13031/2013.36453.
49. Chaplot, V. Impact of spatial input data resolution on hydrological and erosion modeling: Recommendations from a global assessment. *Physics and Chemistry of the Earth, Parts A/B/C* 2014, *67-69*, 23–35, doi:10.1016/j.pce.2013.09.020.
50. Qi, J.; Zhang, X.; Yang, Q.; Srinivasan, R.; Arnold, J.G.; Li, J.; Waldholf, S.T.; Cole, J. SWAT ungauged: Water quality modeling in the Upper Mississippi River Basin. *Journal of Hydrology* 2020, *584*, 124601, doi:10.1016/j.jhydrol.2020.124601.
51. Jodar-Abellan, A.; Valdes-Abellan, J.; Pla, C.; Gomariz-Castillo, F. Impact of land use changes on flash flood prediction using a sub-daily SWAT model in five

Mediterranean ungauged watersheds (SE Spain). *Sci. Total Environ.* 2019, *657*, 1578–1591, doi:10.1016/j.scitotenv.2018.12.034.

52. Qi, J.; Li, S.; Bourque, C.P.-A.; Xing, Z.; Meng, F.-R. Developing a decision support tool for assessing land use change and BMPs in ungauged watersheds based on decision rules provided by SWAT simulation. *Hydrol. Earth Syst. Sci.* 2018, *22*, 3789–3806, doi:10.5194/hess-22-3789-2018.
53. Pitman, J.I. Rainfall interception by bracken in open habitats — Relations between leaf area, canopy storage and drainage rate. *Journal of Hydrology* 1989, *105*, 317–334, doi:10.1016/0022-1694(89)90111-X.
54. Krasa, J.; Dostal, T.; Zumr, D.; Tejkl, A.; Bauer, M. *Recent trends in crop rotation in the Czech Republic and associated soil erosion risks*, 2020.
55. Salsabilla, A.; Kusratmoko, E. Assessment of soil erosion risk in Komering watershed, South Sumatera, using SWAT model. *AIP Conference Proceedings* 2017, *1862*, doi:10.1063/1.4991296.

Chapter 3: The Small Water Cycle in the Czech Landscape: How Has It Been Affected by Land Management Changes Over Time?[2]

3.1 Abstract

For the Czech Republic to recover from the effects of past mismanagement, it is necessary to determine how its landscape management can be improved holistically by reinforcing the small water cycle. We conducted a scenario analysis across four time periods using SWAT (Soil and Water Assessment Tool) to determine the effects of land use, land management, and crop rotation shifts since the 1800s in what is now the Czech Republic. The 1852 and 1954 land-use scenarios behaved the most similarly hydrologically across all four scenarios, likely due to minimal landscape transformation and the fact that these two scenarios occur prior to the widespread incorporation of subsurface tile drainages across the landscape. Additionally, the crop rotation of 1920–1938 reinforces the small water cycle the most, while that of 1950–1989 reinforces the small water cycle the least. Diversified crop rotations should be incentivized to farmers, and increasing the areas of forest, brush, and permanent grassland should be prioritized to further reinforce the small water cycle. It is necessary to foster relationships and open communication between watershed managers, landowners, and scientists to improve the small water cycle and to pave the way for successful future hydrological modeling in the Czech Republic.

3.2 Introduction

Since the modern era, the Czech Republic has always been intensively cultivated, and the culture places a high value on Czech produce, livestock, and of course, beer. The Czech Republic is largely self-sufficient in its production of fruit, beef, pork, poultry, and eggs, and is a major exporter of hops and biofuel crops such as rapeseed [1]. While the local mindedness of the Czech people has remained unphased over the years, changes in political management have greatly affected how the Czech landscape retains water and rein-forces the small water cycle. The small water cycle is a

---

[2] Published as Noreika et al. 2021
Sustainability. DOI: https://doi.org/10.3390/su132413757

closed system in which water evaporated from a terrestrial area falls as precipitation in the same terrestrial area [2,3]. To reinforce the small water cycle, great emphasis is placed on increasing the retention capacity of a landscape while reducing the potential for surface runoff [4,5].

In the area that is now the Czech Republic, agricultural intensification started during the Communist regime, wherein large, monotonous agricultural fields, subsurface tile drainage systems, and artificially straightened streams were incorporated across the landscape [6,7].

The large, monotonous cultivated fields that are still present across the Czech Republic can contribute to significant runoff events and increased soil erosion, which in turn in-creases reservoir siltation rates [8]; the average field size in the Czech Republic is >10 ha [9]. The subsurface tile drainage systems that are still widely present across the Czech landscape cover an area >1.1 million ha [10]. although many are no longer properly maintained, these systems drain agricultural soils faster than they would naturally, and divert infiltrated water directly into the stream network, disallowing proper deep percolation and groundwater recharge. Additionally, many streams and rivers throughout the Czech Republic have been concrete-lined and artificially straightened [6], which can lead to several problems in the landscape. The first is the reduction of alluvial processes, which decreases infiltration and groundwater recharge [6]. Secondly, straightening a stream/river can reduce the riffle–pool sequencing, in turn reducing the aquatic biodiversity that would otherwise be present in a natural lotic water body. The straightening and smoothing of a lotic system can also contribute to more sediment leaving the system as resistance is reduced and the slope increased (by straightening), and in-stream resuspension is more likely (by smoothing), which leads to greater reservoir siltation.

Since governmental shifts in the Czech Republic in 1989, there have been some significant land-use changes, especially with the distribution of arable land versus forested land [6]. Between 1989 and 2000, many areas of previously arable (with low productivity) land were shifted to forests and grasslands while arable lands were relocated to more fertile soils [6,11]. However, since 2000, there have been minimal shifts in land-use; there has been a slight decrease in the percent cover of arable land which has been replaced by an impervious cover, such as expanding industry, developments, and roadways [6]. In addition to land-use changes, there have also been significant crop changes over the last century. The Czech Republic has shifted from primarily growing potatoes, oats, and rye to higher-profit crops driven by the free market and government subsidies, such as winter wheat, rapeseed, and maize [12]. While there have been some improvements in Czech landscape management with smaller farms incorporating IPA (integrated pest management for agriculture) guidelines and agricultural conservation practices [1], much of the Czech Republic's cropland cover is managed by large-scale agricultural conglomerates, with profit being the top priority.

Hydrologic models are a relatively easy and non-invasive way to monitor the water balance of a landscape and can aid basin managers as decision-making tools. The Soil and Water Assessment Tool (SWAT) is one of the most widely used hydrologic models in modern literature [13–16]. SWAT divides a basin into sub-basins based on the delineated stream network and then further divides the sub-basins into HRUs (hydrologic response units), which are noncontinuous areas that have identical user-defined soil, slope, and land-use properties. Each HRU is treated as its own individual unit throughout the modeling process. SWAT has been used effectively anywhere from the farm to the continental scale and has been previously applied to the Czech landscape [17–21].

This study investigates the following questions: (i) How do the land-use changes since the 1800s affect the small water cycle in a Czech agricultural landscape?; (ii) Do crop changes have similar impacts on the small water cycle as the land-use and management changes throughout the political eras of the modern Czech Republic?; (iii) Have the management and land-use changes since 1989 improved the Czech landscape by reinforcing the small water cycle?

3.3 Materials and Methods

3.3.1 Study Watershed

The Vrchlice basin ("Vrchlice") outlet is located 65 km from Prague and is approximately 97 km^2 (Figure 3.1). Vrchlice is primarily cropland (54% by area, Figure 3.2) but also includes large forested areas and smaller townships as well as a network of reservoirs (137 in total) that provide cultural, municipal, and hydrological value to the landscape [8]. The basin drains into the Vrchlice reservoir, which provides drinking water to the sur-rounding areas, including the town of Kutná Hora. Vrchlice is primarily a lowland area with altitudes ranging from 308 to 555 meters a.s.l., and its outlet is located at 49°55'37.211" N, 15°13'37.07" E.

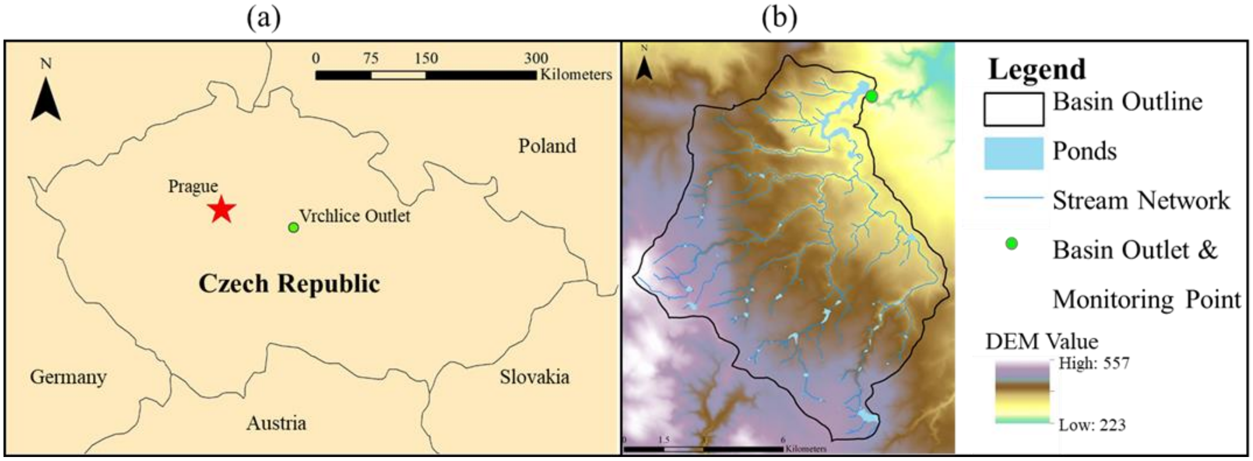


Figure 3.1. (a) Map of the Czech Republic with Prague and the outlet of Vrchlice (the study watershed) highlighted for reference; (b) 5 m resolution DEM of Vrchlice and its immediate surroundings.

The catchment is covered mostly by clayey soils classified as Cambisols [8]. There is minimal groundwater interaction with the surface due to metamorphic bedrock. The few springs that are present are quite dependent on the weather; they flow if there is rain but are dry if there is not. The streams in the Vrchlice basin are quite flashy and reactive to rainfall and can run dry during periods of prolonged drought. The discharge at the basin’s outlet (from the Vrchlice Reservoir) has been measured at the daily timestep since January of 1979 by the Elbe River Basin Authority. The climate of this region is characterized as humid continental. The rainy season spans from May through August, and the highest precipitation rate is typically in July (76 mm/month), while the lowest precipitation rate is in February (23 mm/month).

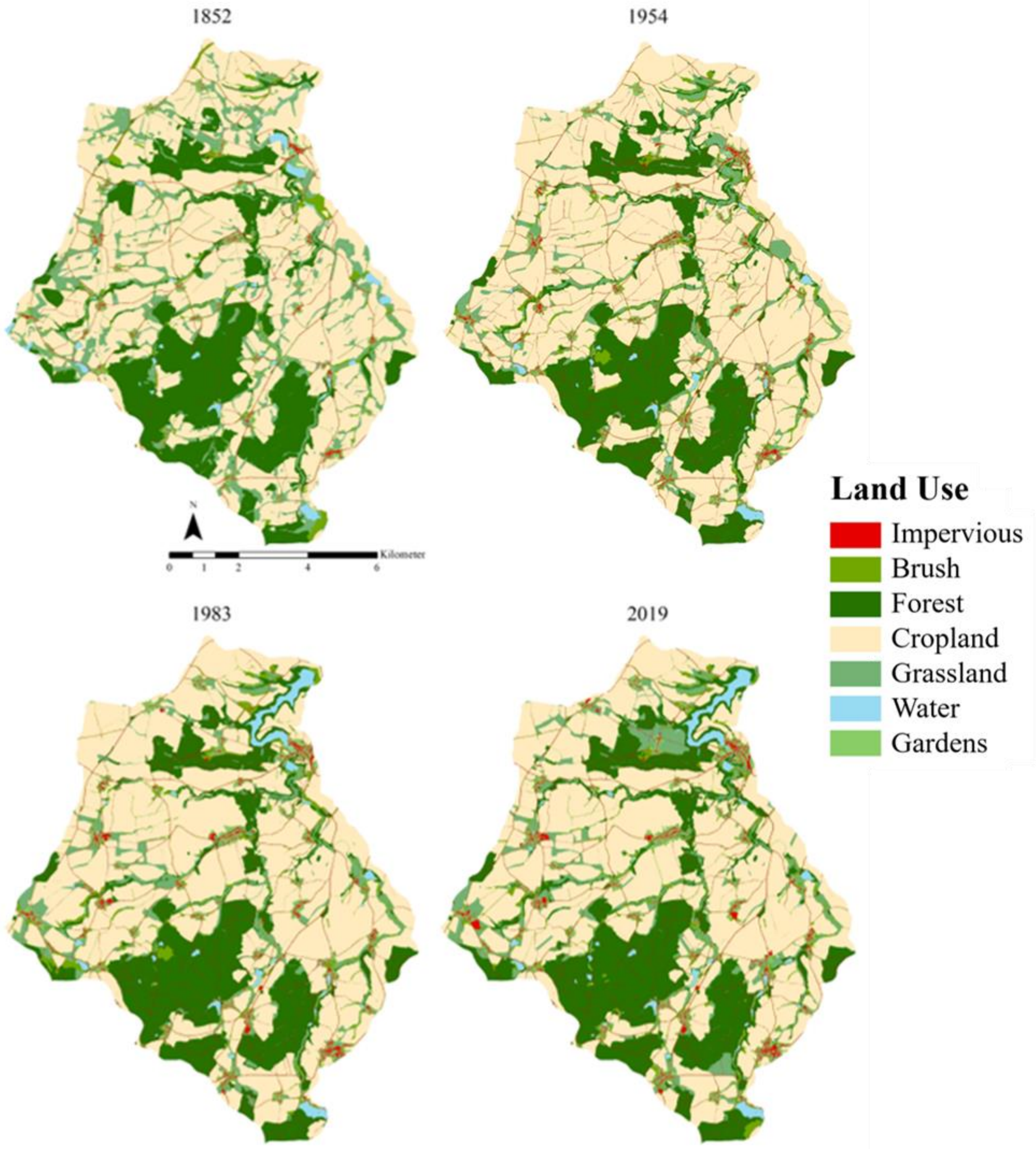


Figure 3.2. Land-use changes across the Vrchlice basin over time.

Vrchlice has a much higher cropland area cover (+15%) than the Czech Republic on average. In Vrchlice, there have been fluctuations in cropland cover over time, reflected by the rise and subsequent fall of communism and its associated policies. The largest percent area change across the basin is seen in the reduction of permanent grasslands (Table 3.1). Otherwise, there are some land-use changes that are consistent with the Czech average (as previously described); many of the land-use changes are not reflected in total percentages but are the result of shifts in the spatial distribution of various land-use classes (Figure 3.2). Vrchlice has a much higher cropland area cover (+15%) than the Czech Republic on average. In Vrchlice, there have been fluctuations in cropland cover over time, reflected by the rise and subsequent fall of communism and its associated policies. The largest percent area change across the basin is seen in the reduction of permanent grasslands (Table 3.1). Otherwise, there are some land-use changes that are consistent with the Czech average (as previously described); many of the land-use changes are not reflected in total percentages but are the result of shifts in the spatial distribution of various land-use classes (Figure 3.2).

Table 3.1. Land-use cover changes (in percent area cover) across the Vrchlice basin over time.

Land Use	1852	1954	1983	2019
Impervious	2	3	3	3
Brush	3	3	4	4
Forest	23	23	23	25
Cropland	56	60	58	54
Grassland	13	7	6	8
Water	1	1	2	2
Gardens	2	3	4	4

3.3.2 SWAT Model Description

The SWAT model for Vrchlice was run at a monthly timestep from 2001 through 2019 with a 5-year warmup period from 1996–2000. Although daily discharge data was available for calibration, a monthly timestep was selected for two reasons: (i) to minimize extreme daily fluctuations in discharge due to extreme precipitation events or reservoir management and (ii) to make the computational time more efficient. The boundaries of the Vrchlice basin, its contained sub-basins, and the stream network were largely DEM-based, but a stream shapefile was available for ground-truthing. Some sub-basins were combined to better reflect the hydrologic conditions in the basin, e.g., several sub-basins near the outlet needed to be combined to reflect one continuous sub-basin to encompass the Vrchlice Reservoir. A total of 63 sub-basins were delineated across the

Vrchlice basin. Individual HRUs were defined by each unique land-use type, 3 slope classes (0−2%, 2−8%, and 8+%, typical for an agricultural landscape), and soils that covered at least 10% of the basin; this classification scheme resulted in 1058 HRUs with an average HRU size of ap-proximately 9 ha.

3.3.3 Input Data

The soil map used to develop this model was compiled from various sources, including unpublished data from the Czech Research Institute of Soil Conservation (which has been conducting an intensive soil sampling effort across the basin) and the State Land Office of the Czech Republic (Table 3.2). The DEM was obtained from the fourth generation of the digital relief model of the Czech Republic (DMR4G). The model point cloud was processed to obtain a 5 m spatial resolution. The land-use maps were obtained from ZA-BAGED (Fundamental Base of Geographic Data of the Czech Republic; provided by the State Administration of Surveying and Cadaster (ČUZK)) that were corrected by LPIS (Land Parcel Identification System; provided by the Czech Ministry of Agriculture) agricultural land surveys which were manually edited over historical orthophotos of the Czech Republic [22].

Table 3.2. Input data and sources used for SWAT modeling.

	Input Data	**Description**	**Source**
Meteorological Data	Extreme Temperatures	Minimum and maximum daily temperatures (1996−2019)	Czech Hydrometeorological Institute
	Precipitation	Total daily precipitation (1996−2019)	Czech Hydrometeorological Institute
Spatial Data	DEM	Digital elevation model (5 m resolution)	LiDAR Survey: Czech Institute of Geodesy and Cartography
	Soils	1:5,000 soil map	Czech Research Institute of Soil Conservation & the State Land Office of the Czech Republic
	Land Use	1:10,000 land use map	ZABAGED & LPIS

The typical crop cover percentages were provided by the Czech Statistical Office (Table 3.3). The current (2019) crop percentages were used for the land-use change scenarios. This was done for two reasons: (i) because the calibrated and validated model is based on this crop configuration and (ii) to isolate the effects of land-use change. Varying crop rotations were incorporated into SWAT as management schedules to reflect their relative per-cent cover and were utilized in a sub-basin scenario analysis.

Table 3.3. Typical crop cover percentages in the Czech Republic, limited to the top 5 most prevalent crops for modeling purposes [21].

Crop	1920−1938	1950−1989	2019
Potatoes	20%	10%	−
Oats	25%	15%	−
Spring Barley	15%	30%	16%
Rye	25%	10%	−
Winter Wheat	15%	35%	40%
Rapeseed	−	−	20%
Corn	−	−	20%
Winter Barley	−	−	4%

3.3.4 Vrchlice Ponds and Reservoirs

Parameters for most of the reservoirs and ponds found across Vrchlice were extracted from 1991 and 1992 maps published by the Czech Republic's Ministry of the Environment. The reservoirs, without parameters available, in the aforementioned maps were located in aerial photographs (mapy.cz) to determine whether they were still present and connected to the stream network. A field campaign was executed during which 23 "un-documented" reservoirs were surveyed, and relevant inputs for SWAT were estimated. Ultimately, 14 reservoirs and 23 ponds were determined to be hydrologically significant (i.e., of substantial size and connected to the stream network) and incorporated into SWAT (according to SWAT, a reservoir is located at the outlet of a sub-basin while a pond is located anywhere else in the sub-basin). There is no central database of reservoir management in the Vrchlice basin, so in SWAT, the reservoir outflow was "simulated controlled outflow-target release," and the monthly target reservoir storage was set equal to the reservoir volume at its principal spillway. The target days needed for a pond to reach its tar-get storage was set to zero, as most of the small pond and reservoir water levels in the Czech Republic are maintained at the principal spillway.

3.3.5 SWAT Sensitivity Analysis, Calibration, Validation, and Performance Evaluation

The sensitivity analysis, calibration, and validation for the SWAT model of Vrchlice were all conducted via the SUFI2 method using SWAT-CUP 2019 v5.4.1. The most sensitive parameters according to the model response were determined through a global sensitivity analysis. Prior to calibration and validation, extreme outlying discharge months were removed; these are likely due to individual reservoir management that is not regulated by any governing body, nor are the reservoir activities recorded in any public data-base. The calibration of the model was run from 2001 through 2012 at the monthly timestep. Many iterations of over 2000 simulations were run across 21 variables until satisfactory statistical criteria were met (Table 3.4); the model performance indicators include the Nash–Sutcliff efficiency (NSE), percent bias (PBIAS), coefficient of determination (R^2), and the Kling–Gupta Efficiency (KGE). The validation of the model was run from 2013 through 2016 at the monthly timestep.

Table 3.4. Parameters used for model calibration in SWAT-CUP. (V: replace, A: absolute, R: relative; *p<0.05, †only applied to land use AGRC).

Parameter	Description	Method	File	Min	Max
SURLAG	Surface runoff lag coefficient (days)	V	BSN	1	12
SMTMP*	Snow melt base temperature (ºC)	V	BSN	−5	5
SFTMP*	Snowfall temperature (ºC)	V	BSN	−5	5
ESCO	Soil evaporation compensation factor	V	BSN	0.5	0.98
GW_DELAY	Delay time for aquifer recharge (days)	V	GW	0	500
GWQMN*	Threshold water level in shallow aquifer for base flow (mm)	V	GW	0	5000
ALPHA_BF	Baseflow alpha factor (days^{-1})	V	GW	0.001	1
GW_REVAP*	Groundwater revap coefficient	V	GW	0.02	0.2
RCHRG_DP	Deep aquifer percolation fraction	V	GW	0.001	1
REVAPMN*	Threshold water depth in the shallow aquifer for “revap” or percolation to the deep aquifer (mm)	V	GW	0	500

CANMX	Maximum canopy water storage (mm)	R	HRU	−0.2	0.2
OV_N	Manning’s n value for overland flow	V	HRU	0.05	0.8
DEP_IMP*†	Depth to impervious layer in soil profile (mm)	A	HRU	−1000	1000
GDRAIN_BSN†	Drain tile lag time (hours)	A	MGT	−40	40
TDRAIN_BSN*†	Time to drain soil to field capacity (hours)	A	MGT	−40	40
DDRAIN_BSN†	Depth to subsurface drain (mm)	A	MGT	−500	500
CN2*	Initial SCS curve number for moisture condition II	R	MGT	−0.1	0.1
CH_K2	Effective hydraulic conductivity of channel (mm h^{-1})	V	RTE	0.025	150
CH_N2	Manning’s n for main channel	V	RTE	0.02	0.14
SOL_AWC	Available water capacity (mm)	R	SOL	−0.2	0.2
SOL_K*	Saturated hydraulic conductivity (mm h^{-1})	R	SOL	−0.2	0.2

3.3.6 Land-use Changes: Basin Scale Scenario Analysis

Three land-use scenarios were run in addition to the calibrated model (Table 3.1). The scenarios are defined by land-use changes across time: 1852 (pre-Communist Era), 1954 (early Communist Era), 1983 (late-Communist Era), and 2019 (default/calibrated model and post-Communist Era; Figure 3.2). In the pre-Communist Era scenario, there were typically buffer zones of forest or brush between agricultural fields. In the Communist and post-Communist eras, the fields were much larger and more monotonous, which in-creased the probability of surface runoff events and erosion; during these time periods, subsurface tile drainage systems were incorporated across all agricultural land-uses in the Vrchlice SWAT model.

3.3.7 Landscape Management Changes: Sub-basin Scale Scenario Analysis

To determine the effects of crop changes across the political eras in the Czech Republic, four primarily agricultural sub-basins were selected and isolated (at least 150 hectares with >80% agricultural land-use cover) from Vrchlice; their water balance properties were compared across three crop-change scenarios (Table 3.3) that included the major crops from 1920−1938 (pre-Communist era), 1950–1989 (Communist era), and the current conditions (post-Communist era) (Table 3.3; Figure 3.3) [23].

Figure 3.3. The four primarily agricultural sub-basins identified for crop-change impact analysis, identified by their SWAT sub-basin ID number; the land-use map is 1954.

3.4 Results

3.4.1 SWAT Model Sensitivity Analysis

Nine of the 21 variables assessed in calibration significantly affected the discharge output of the SWAT model for Vrchlice (Table 3.5). Two of the nine parameters are snowfall (SFTMP) and snowmelt (SMTMP) temperatures, which determine when snowfall accumulates and subsequently melts, which delays discharge reaction time to precipitation events. Three of the nine parameters govern groundwater processes. GWQMN is the threshold depth of water in the shallow aquifer that is required for a return flow to occur. GW_REVAP is the groundwater “revap” coefficient. As this value approaches 0, water movement from the shallow aquifer to the root zone is restricted, whereas as it approaches 1, the rate of transfer from the shallow aquifer approaches the rate of potential evapotranspiration. REVAPMN is the minimum depth of water necessary in the shallow aquifer for percolation to the deep aquifer to occur; this variable controls the movement of water from the shallow aquifer to the unsaturated zone. Two parameters are associated with the in-corporation of generalized tile drainages across the agricultural land-use classes in Vrchlice. The parameter that defines a layer of soil with lower hydraulic conductivity than those above it is DEP_IMP, and TDRAIN_BSN is the time the drainage system takes to drain the soil to field capacity. The SCS curve number (CN2) is a function of a soil's permeability, land-use, and antecedent soil water conditions. On average, the CN2 was 8% lower than the default value for each land use, indicating a higher modeled infiltration than expected. Finally, the last variable that significantly affected the modeled discharge at Vrchlice's outlet is the saturated hydraulic conductivity of the soil, which was modeled to be 19% lower than the input values. This discrepancy may be due to significant generalizations made when aggregating soil data from different governmental and academic sources.

Table 3.5. Sensitive parameters and their calibrated (adjusted) values.

Parameter	**Method**	**Calibration Values**		
		Minimum	Adjusted	Maximum
SMTMP	Replace	5	2.1ºC	5
SFTMP	Replace	−5	−2.1ºC	5
GWQMN	Replace	0	513 mm	5000
GW_REVAP	Replace	0.02	0.18 (coefficient)	0.2
REVAPMN	Replace	0	488 mm	500
DEP_IMP	Absolute	−1000	−538 mm	+1000
TDRAIN_BSN	Absolute	−48	−43 hours	+48
CN2	Relative	−10%	−8%	+10%
SOL_K	Relative	−20%	−19%	+20%

3.4.2 SWAT Model Calibration and Validation

Successful model calibration and validation were obtained via a semi-automatic calibration method using SWAT-CUP 2019. The model performance indicators during the calibration period are considered to be “very good”, while most indicators during the validation period are also considered to be “very good,” and the PBIAS during validation is “good” (Table 3.6) [24].

Table 3.6. Model performance indicators for calibration and validation periods of the SWAT model for Vrchlice.

Model Performance Indicator	**Calibration (2001−2012)**	**Validation (2013−2016)**
NSE	0.84	0.72
PBIAS	3.1	8.1
R^2	0.85	0.72
KGE	0.86	0.81

A scatterplot correlation is presented in Figure 3.4, with a trendline for reference. Paired t-tests comparing the measured versus modeled was conducted individually for the calibration and validation periods, and no significant differences were observed (p>0.05).

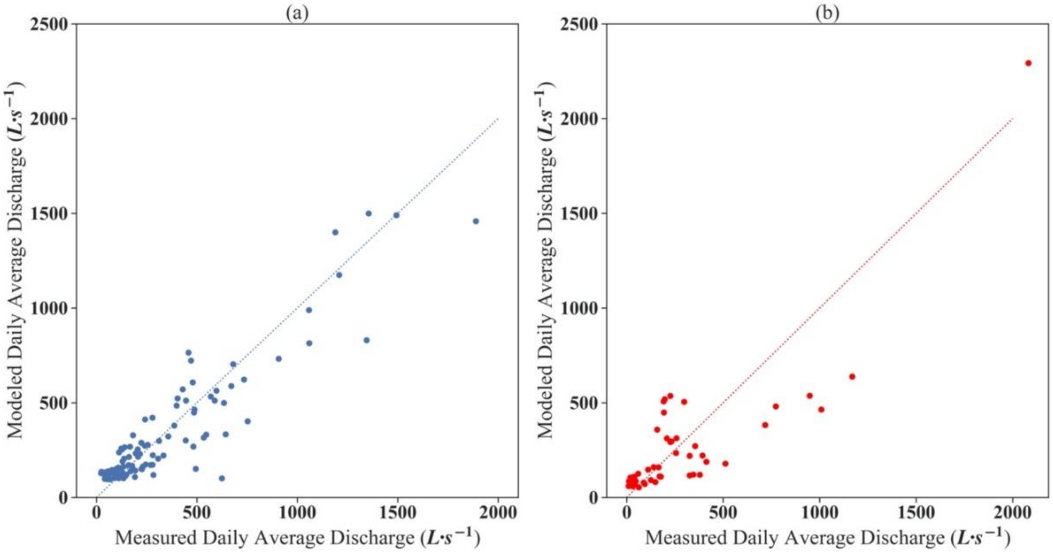


Figure 3.4. Measured daily average flows versus modeled daily average flows for (a) calibration period and (b) validation period at the monthly timescale.

3.4.3 Land-use Change Effects on the Small Water Cycle at the Basin Scale

The following monthly basin-wide water balance parameters were analyzed across the four land-use change scenarios: evapotranspiration, the daily average discharge at the outlet, average soil water content, subsurface lateral flow contribution to streamflow, and percent of the precipitation that results in surface runoff. Evapotranspiration is not represented in a graphical form because the differences between the scenarios were very slight due to the fact that the total land-use changes in percent cover varied little across the four land-use change scenarios. Generally, the discharge at Vrchlice’s outlet was highest in the 1852 scenario; the greatest extremes in streamflow were also observed in the 1852 scenario, while the most stable flows were recorded in the 2019 scenario (Figure 3.5). The 1852 and 1954 scenarios resulted in very similar water balance outputs except in discharge at the outlet, which is likely due to reservoir management. The soil water content across the basin was separated into two obvious groups, with much higher soil water contents in the 1852 and 1954 scenarios (pre-Communist and early Communist eras, respectively). The lower soil water contents in the 1983 and 2019 scenarios (late-Communist and post-Communist eras, respectively) are likely due to the incorporation of widespread tile drainage systems across the landscape in the 1970s (Figure 3.6), which also can explain the patterns observed in the percent rainfall resulting in surface runoff across the scenarios (Figure 3.7). Throughout most of the year, the highest subsurface lateral flow contribution to streamflow was modeled in the 1852 and 1954 land-use scenarios, while the 2019 land-use scenario exhibited the highest values from September through December (Figure 3.8). The lowest subsurface lateral flow contribution to streamflow values occurred in the 1983 land-use scenario across all months, and it also exhibited the greatest range in values across the year.

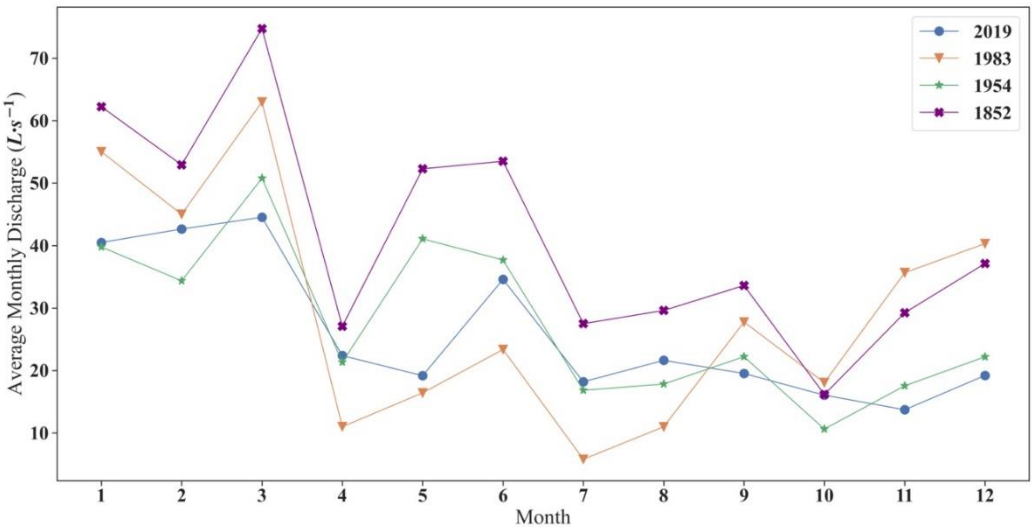


Figure 3.5. Daily discharge values averaged by month across land-use change scenarios.

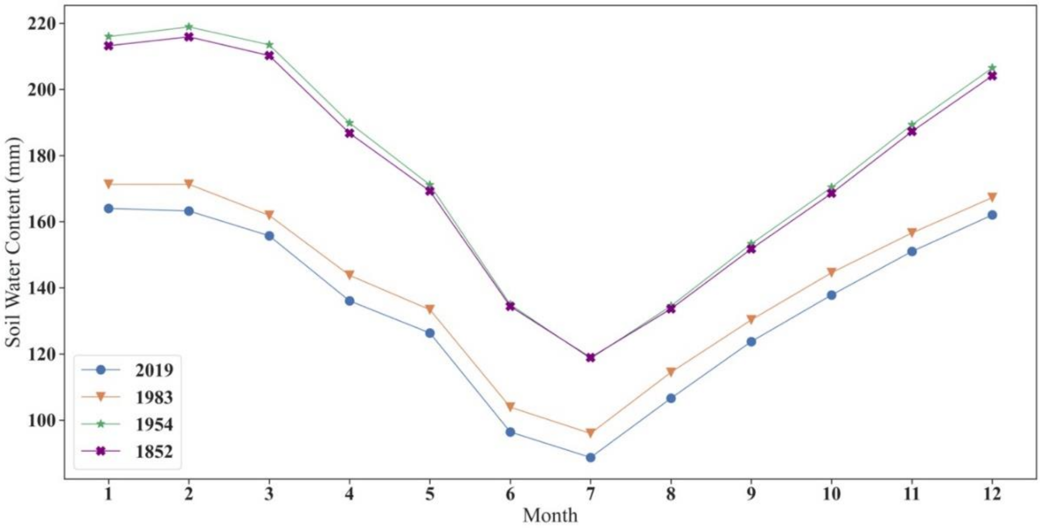


Figure 3.6. Monthly average soil water content across land-use change scenarios.

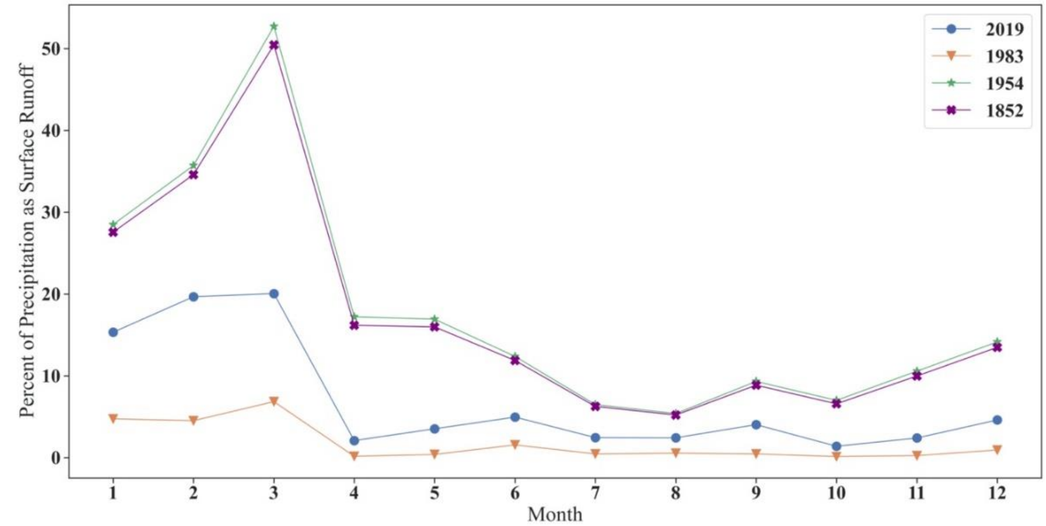


Figure 3.7. Percent of monthly precipitation resulting in surface runoff across land-use change scenarios.

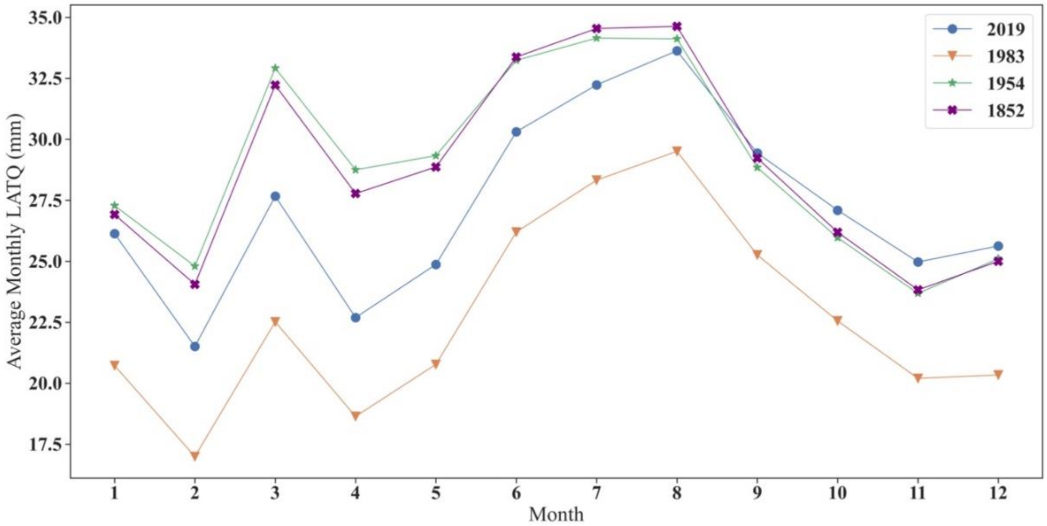


Figure 3.8. Average monthly subsurface lateral flow contribution to streamflow across land-use change scenarios.

3.4.4 Crop Change Effects on the Small Water Cycle at the Sub-basin Scale

The following water balance variables were analyzed across the four agricultural sub-basins outlined in Figure 3.3: evapotranspiration (ET), average soil water content (SW), surface runoff (SURQ), subsurface lateral flow (LATQ), and discharge (Flow) at the sub-basin’s outlet. The results of this sub-basin scenario analysis are summarized in Table 3.7. The average values of each variable are color-coded to represent their reinforcement of the small water cycle i.e., a cell coded green indicates a higher reinforcement of the small water cycle compared to yellow, which is the intermediate value, and red is the crop configuration that contributes the least to the small water cycle. The standard deviations for each variable are also color-coded. The highest standard deviation for each variable indicates a higher hydrological variability within the respective crop rotation and, as such, is coded as red; the intermediate as yellow, and the lowest standard deviation is coded as green, which represents a more stable system and small water cycle. The pre-Communist era crop configuration tends to reinforce the small water cycle the most, followed by the post-Communist Era, with the Communist Era crop rotation having the most negative impact on the small water cycle.

Table 3.7. The effects of crop changes throughout political eras in the Czech Republic. This table compares the averages and standard deviations across water balance variables and is color-coded to rep-resent their reinforcement of the small water cycle; green positively reinforces the small water cycle the most, followed by yellow, then red. (L, M, H correspond to the lowest, middle, and highest values for each parameter across the three scenarios, respectively.).

Parameter		**Pre-Communist Era**	**Communist Era**	**Post-Communist Era**
ET	Average	M	L	H
	Stdev	H	L	M
SW	Average	M	H	L
	Stdev	L	M	H
SURQ	Average	L	H	M
	Stdev	L	M	H
LATQ	Average	M	H	L
	Stdev	M	H	L
Flow	Average	M	H	L
	Stdev	L	H	M

3.5 Discussion

3.5.1 Hydrological Modeling with SWAT

The biggest source of error in any model is the quality of the input data, which influences how a model will perform before it is even run [25,26]. Other sources of error include the model parameter, structural uncertainties, and output data uncertainties [26].

While SWAT may be the most used hydrologic model in modern studies, it is not immune to these sources of error [26]. Additionally, since SWAT is semi-physical based, it calculates many inputs and processes based on global or regional databases or from more generalized equations; some processes such as preferential flow or temporal changes in topsoil hydraulic properties, which are both significant in agricultural soils, cannot be modeled by SWAT [27–29]. All reservoir processes (filling, release, etc.) in Vrchlice were generalized because there is no central management or operations database for such activities in the Czech Republic. Most of the reservoirs across the Vrchlice basin are small fishponds and are independently operated by farmers, more localized municipalities, or local landowners. Although daily discharge data was available at the Vrchlice basin's outlet, it is not practical to calibrate and validate this SWAT model at the daily timestep due to these un-known reservoir management regimes. Additionally, there is no spatial database for crop rotations across the Czech Republic by individual farmers, so the crop rotation was estimated and randomized across the Vrchlice basin based on the major crops provided by the Czech Statistical Office [23]. Even with SWAT's modeling limitations and some data quality limitations, SWAT was still able to effectively model the water balance at the Vrchlice basin, especially in the context of scenario analysis, which can provide insight for managers concerning the localized effects of land-use and management changes across the basin. Additional data would be necessary to model other basin processes or to model Vrchlice at the sub-basin scale, such as actual crop rotation, agricultural management activities, and reservoir management.

3.5.2 Small Water Cycle Response to Land-use and Management Changes

Other than evapotranspiration, all other water balance variables were affected by the land-use changes in the Vrchlice basin. The most stable flows in the Vrchlice basin were modeled in the 2019 land-use scenario, which may be due to an increased forest cover, reduced crop cover, redistributed brush cover, and more reservoirs across the basin, all of which can aid a landscape in retaining and reducing the impact of extreme weather events [30–37]. The systematic incorporation of subsurface tile drainage systems in agricultural lands seems to explain most of the patterns observed in the other water balance variables. The 1852 and 1954 land-use scenarios occur without the tile drainage systems and before the total transformation of the landscape due to the Communist Era policies; these two scenarios exhibit very similar patterns of soil water content, average subsurface lateral flow, and percent precipitation as surface runoff. In these two scenarios, surface runoff and soil water content are higher across the entire year, and subsurface lateral flow is highest from January through August. Reduced surface runoff is expected with the in-corporation of a tile drainage system because the system drains soils faster than they would naturally, allowing water to infiltrate at a greater rate. Further studies would need to be conducted to isolate the effects of the tile drainage system incorporation versus the incorporation of the large, monotonous fields and reduced buffer zones during the Communist Era. The reduced subsurface lateral flow in the 1983 and 2019 land-use scenarios is unexpected and likely an artifact of the incorporation of the subsurface tile drainage systems as SWAT separates tile flow from subsurface lateral flow. However, while this tile flow is technically subsurface, it is transformed into streamflow much faster than a natural subsurface lateral flow, which SWAT is unable to encompass at this timestep [38]. Additionally, the presence of tile drainage systems can cause severe nutrient issues in watersheds, including increased nitrate and phosphorous in stream systems. However, such is not in the scope of this study and should be explored at the sub-basin scale in Vrchlice [39-41]. Sediment and erosion processes are also not included in the scope of this study but again should be explored at the sub-basin scale and in sub-basins with detailed reservoir and agricultural management practices with HRUs defined by the field boundary method [42,43].

When isolating the effects of crop changes across the three most recent political eras of the Czech Republic (pre-Communist, Communist, and post-Communist; Table 3.3), the Communist Era crop rotation reinforced the small water cycle the least, followed by the post-Communist Era, and the pre-Communist Era crop rotation reinforced the small water cycle the most. The post-Communist Era crop rotation is largely driven by winter wheat and rapeseed. Both of these crops exhibit high transpiration rates, and rapeseed is planted in an unfavorable way with seedbed conditions present during the Czech rainy season [20]; these factors lead to the reduced soil water content, increased surface runoff ratios, and the reduced subsurface lateral flow observed in the post-Communist Era. The Communist Era crop rotation reinforced the small water cycle the least, resulting in the most water being transported out of the basin as streamflow. The Communist Era crop rotation is dominated by oats, winter wheat, and spring barley. With spring barley being a major crop during this time period, its management leaves soils bare for longer, which results in an overall higher surface runoff ratio as well as a higher soil water content driven by reduced transpiration.

3.6 Conclusions

This study has shown that SWAT can be effectively used at the management scale in the Czech landscape. The effects on the small water cycle of both land-use changes and landscape management changes were easily isolated through the use of SWAT. While there have been some improvements in the functionality of the Czech agricultural land-scape since the fall of communism, there are still areas that need attention from watershed managers. Increasing forested, brush, and grassland areas can contribute significantly to this goal. While sub-surface tile drainage systems superficially seem to reinforce the small water cycle, they may introduce other water quality issues in the Czech landscape that are not in the scope of this study and should be examined further.

The crop rotation that reinforces the small water cycle the most is the pre-Communist Era configuration. The current crop rotation in the Czech Republic is an improvement over the crop management during the Communist Era concerning the reinforcement of the small water cycle. However, there are still improvements that could be made across the landscape. A more diverse crop rotation should be incentivized to farmers to reinforce the small water cycle and to make the small water cycle more stable. Additionally, as hydrological modeling becomes more commonplace, it is increasingly necessary to foster relationships and collaboration between scientists, landowners, and watershed managers. Central databases for reservoir management and agricultural (crop and practice) management would be invaluable to researchers and basin managers to be able to aid land-owners in making informed decisions.

3.7 References

1. Ministry of Agriculture of the Czech Republic. *We Support Traditions and Rural Development in the Czech Republic*; Ministry of Agriculture of the Czech Republic: Prague, Czech Republic, 2018; ISBN 978-80-7434-416-9.
2. Massy, C. Transforming landscapes: Regenerating country in the Anthropocene. *Griffith REVIEW* 2019, 247–261, doi:10.3316/INFORMIT.186708076823750.
3. Marlow, D. Small water cycles: What they are, their importance, their restoration. In Proceedings of the Royal Society of Queensland, 2020. Available online: http://www.royalsocietyqld.org/wp-content/uploads/documents/Stewardship/Rangelands%20Policy%20Dialogue/Rangelands%20Briefs/Marlow-small-water-cycles.pdf (accessed on 1 September 2021).
4. Kravčík, M.; Lambert, J. A Global Action Plan for the Restoration of Natural Water Cycles and Climate. Available online: http://ircsa.ir/files/site1/files/149_kravcik_global_action_plan.pdf (accessed on 1 September 2021).
5. Kravčík, M.; Pokorný, J.; Kohutiar, J.; Kováč, M.; Tóth, E. (Eds.) Water for the recovery of the climate—A new water paradigm. In Proceedings of the APLU and ICA, Prague, Czech Republic, 23–26 June 2009.
6. Zeleňáková, M.; Fialová, J.; Negm, A.M. *Assessment and Protection of Water Resources in the Czech Republic*; Springer: Cham, Switzerland, 2020; ISBN 9783030183639.
7. Esri. *World Map with Imagery*; Esri: Redlands, CA, USA, 2021.
8. Krasa, J.; Dostal, T.; Van Rompaey, A.; Vaska, J.; Vrana, K. Reservoirs' siltation measurments and sediment transport assessment in the Czech Republic, the Vrchlice catchment study. *CATENA* 2005, *64*, 348–362, https://doi.org/10.1016/j.catena.2005.08.015.
9. Fiener, P.; Dostál, T.; Krása, J.; Schmaltz, E.; Strauss, P.; Wilken, F. Operational USLE-Based Modelling of Soil Erosion in Czech Republic, Austria, and Bavaria—Differences in Model Adaptation, Parametrization, and Data Availability. *Appl. Sci.* 2020, *10*, 3647, https://doi.org/10.3390/app10103647.

10. Tlapáková, L. Development of drainage system in the Czech landscape—Identification and functionality assessment by means of remote sensing. *Eur. Countrys.* 2017, *9*, 77–98, https://doi.org/10.1515/euco-2017-0005.
11. Stych, P.; Kabrda, J.; Bicik, I.; Lastovicka, J. Regional Differentiation of Long-Term Land Use Changes: A Case Study of Czechia. *Land* 2019, *8*, 165, https://doi.org/10.3390/land8110165.
12. European Commission. *Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009: On the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC*; European Commission: Brussels, Belgium, 2009.
13. Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large Area Hydrologic Modeling and Assessment Part I: Model Development. *JAWRA J. Am. Water Resour. Assoc.* 1998, *34*, 73–89, https://doi.org/10.1111/j.1752-1688.1998.tb05961.x.
14. Neitsch, S.L.; Arnold, J.G.; Kiniry, J.R.; Williams, J.R. *Soil and Water Assessment Tool Theoretical Documentation*; Texas Water Resources Institute, College Station, Texas, USA: 2011.
15. Gassman, P.W.; Reyes, M.R.; Green, C.H.; Arnold, J.G. The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. *Trans. ASABE* 2007, *50*, 1211–1250, https://doi.org/10.13031/2013.23637.
16. Melaku, N.D.; Renschler, C.S.; Holzmann, H.; Strohmeier, S.; Bayu, W.; Zucca, C.; Ziadat, F.; Klik, A. Prediction of soil and water conservation structure impacts on runoff and erosion processes using SWAT model in the northern Ethiopian highlands. *J. Soils Sediments* 2018, *18*, 1743–1755, https://doi.org/10.1007/s11368-017-1901-3.
17. Ondr, P.; Pečenka, J.; Polenský, J.; Ciml, J. Effect of land use changes on water run-off from a small catchment in the Czech Republic. *Ekológia (Bratislava)* 2016, *35*, 78–89, https://doi.org/10.1515/eko-2016-0006.
18. Du, B.; Ji, X.; Harmel, R.D.; Hauck, L.M. Evaluation of a Watershed Model for Estimating Daily Flow Using Limited Flow Measurements. *JAWRA J. Am. Water*

Resour. Assoc. 2009, *45*, 475–484, https://doi.org/10.1111/j.1752-1688.2009.00303.x.

19. Brzozowski, J.; Miatkowski, Z.; Śliwiński, D.; Smarzyńska, K.; Śmietanka, M. Application of SWAT model to small agricultural catchment in Poland. *J. Water Land Dev.* 2011, *15*, 157–166, https://doi.org/10.2478/v10025-012-0014-z.
20. Noreika, N.; Li, T.; Zumr, D.; Krasa, J.; Dostal, T.; Srinivasan, R. Farm-Scale Biofuel Crop Adoption and Its Effects on In-Basin Water Balance. *Sustainability* 2020, *12*, 10596, https://doi.org/10.3390/su122410596.
21. Gregar, J.; Petrů, J.; Novotná, J. Evaluation of the SWAT model as an integrated management tool in the Švihov drinking water supply catchment. *Soil Water Res.* 2019, *14*, 76–83, https://doi.org/10.17221/46/2018-swr.
22. Winterova, J. Sediment Transport in Vrchlice Reservoir Watershed. Master’s Thesis, Czech Technical University in Prague, Prague, Czech Republic, 2020. (In Czech)
23. Czech Statistical Office. Harvest Estimates. 2021. Available online: https://www.czso.cz/csu/czso/ari/harvest-estimates-september-2020 (accessed on 1 September 2021).
24. Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Trans. ASABE* 2007, *50*, 885–900, https://doi.org/10.13031/2013.23153.
25. Tuppad, P.; Douglas-Mankin, K.R.; Lee, T.; Srinivasan, R.; Arnold, J.G. Soil and Water Assessment Tool (SWAT) Hydrologic/Water Quality Model: Extended Capability and Wider Adoption. *Trans. ASABE* 2011, *54*, 1677–1684, https://doi.org/10.13031/2013.39856.
26. Nyeko, M. Hydrologic Modelling of Data Scarce Basin with SWAT Model: Capabilities and Limitations. *Water Resour. Manag.* 2015, *29*, 81–94, https://doi.org/10.1007/s11269-014-0828-3.
27. Beven, K. How far can we go in distributed hydrological modelling? *Hydrol. Earth Syst. Sci.* 2001, *5*, 1–12.
28. Martínez-Retureta, R.; Aguayo, M.; Stehr, A.; Sauvage, S.; Echeverría, C.; Sánchez-Pérez, J.-M. Effect of Land Use/Cover Change on the Hydrological Response of a

Southern Center Basin of Chile. *Water* 2020, *12*, 302, https://doi.org/10.3390/w12010302.

29. Zumr, D.; Jeřábek, J.; Klípa, V.; Dohnal, M.; Sněhota, M. Estimates of Tillage and Rainfall Effects on Unsaturated Hydraulic Conductivity in a Small Central European Agricultural Catchment. *Water* 2019, *11*, 740, https://doi.org/10.3390/w11040740.
30. Zhang, M.; Liu, N.; Harper, R.; Li, Q.; Liu, K.; Wei, X.; Ning, D.; Hou, Y.; Liu, S. A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. *J. Hydrol.* 2016, *546*, 44–59, https://doi.org/10.1016/j.jhydrol.2016.12.040.
31. David, T.; Henriques, M.; Tomé, J.; Ledger, D. Clearcutting effects on streamflow in coppiced Eucalyptus globulus stands in Portugal. *J. Hydrol.* 1994, *162*, 143–154, https://doi.org/10.1016/0022-1694(94)90008-6.
32. Stednick, J.D. Monitoring the effects of timber harvest on annual water yield. *J. Hydrol.* 1996, *176*, 79–95, https://doi.org/10.1016/0022-1694(95)02780-7.
33. Neary, D.G.; Gottfried, G.J.; Folliott, P.F. (Eds.) Post-wildfire watershed flood responses. In Proceedings of the 2nd International Fire Ecology Conference, Orlando, FL, USA, 16–20 November 2003.
34. Beck, H.E.; Bruijnzeel, L.A.; van Dijk, A.I.J.M.; McVicar, T.R.; Scatena, F.N.; Schellekens, J. The impact of forest regeneration on streamflow in 12 mesoscale humid tropical catchments. *Hydrol. Earth Syst. Sci.* 2013, *17*, 2613–2635, https://doi.org/10.5194/hess-17-2613-2013.
35. Wu, W.; Hall, C.A.S.; Scatena, F.N. Modelling the impact of recent land-cover changes on the stream flows in northeastern Puerto Rico. *Hydrol. Process.* 2007, *21*, 2944–2956, https://doi.org/10.1002/hyp.6515.
36. Webb, A.A.; Kathuria, A. Response of streamflow to afforestation and thinning at Red Hill, Murray Darling Basin, Australia. *J. Hydrol.* 2011, *412–413*, 133–140, https://doi.org/10.1016/j.jhydrol.2011.05.033.
37. Bruijnzeel, L. Hydrological functions of tropical forests: Not seeing the soil for the trees? *Agric. Ecosyst. Environ.* 2004, *104*, 185–228, https://doi.org/10.1016/j.agee.2004.01.015.

38. Moriasi, D.N.; Rossi, C.G.; Arnold, J.G.; Tomer, M.D.; Tufekcioglu, M.; Isenhart, T.; Schultz, R.; Bear, D.; Kovar, J.; Russell, J. Evaluating hydrology of the Soil and Water Assessment Tool (SWAT) with new tile drain equations. *J. Soil Water Conserv.* 2012, *67*, 513–524, https://doi.org/10.2489/jswc.67.6.513.
39. Smith, D.R.; King, K.W.; Johnson, L.; Francesconi, W.; Richards, P.; Baker, D.; Sharpley, A.N. Surface Runoff and Tile Drainage Transport of Phosphorus in the Midwestern United States. *J. Environ. Qual.* 2015, *44*, 495–502, https://doi.org/10.2134/jeq2014.04.0176.
40. Randall, G.W.; Goss, M.J. Nitrate Losses to Surface Water Through Subsurface, Tile Drainage. In *Nitrogen in the Environment: Sources, Problems, and Management*, 2nd ed.; Hatfield, J.L., Follett, R.F., Eds.; Academic Press: London, UK, 2008; pp. 145–175, ISBN 9780123743473.
41. Amado, A.A.; Schilling, K.E.; Jones, C.S.; Thomas, N.; Weber, L.J. Estimation of tile drainage contribution to streamflow and nutrient loads at the watershed scale based on continuously monitored data. *Environ. Monit. Assess.* 2017, *189*, 426, https://doi.org/10.1007/s10661-017-6139-4.
42. Pai, N.; Saraswat, D.; Srinivasan, R. Field_SWAT: A tool for mapping SWAT output to field boundaries. *Comput. Geosci.* 2012, *40*, 175–184, https://doi.org/10.1016/j.cageo.2011.07.006.
43. Daggupati, P.; Douglas-Mankin, K.R.; Sheshukov, A.Y.; Barnes, P.L.; Devlin, D.L. Field-Level Targeting Using SWAT: Mapping Output from HRUs to Fields and Assessing Limitations of GIS Input Data. *Trans. ASABE* 2011, *54*, 501–514, https://doi.org/10.13031/2013.36453.

Chapter 4: The Effects of Agricultural Conservation Practices on the Small Water Cycle: from the farm- to the management-scale.[3]

4.1 Abstract

Reinforcing the small water cycle is considered to be a holistic approach to both water resource and landscape management. In an agricultural landscape, this can be accomplished by incorporating agricultural conservation practices; their incorporation can reduce surface runoff, increase infiltration, and increase the water holding capacity of a soil. Some typical agricultural conservation practices include: conservation tillage, contour farming, residue incorporation, and reducing field sizes; these efforts aim to keep both water and soil in the landscape. The incorporation of such practices has been extensively studied over the last 40 years. The Soil and Water Assessment Tool (SWAT) was used to model two basins in the Czech Republic (one at the farm-scale and a second at the management-scale) to determine the effects of agriculture conservation practice adoption at each scale. We found that at the farm-scale, contour farming was the most effective practice at reinforcing the small water cycle, followed by residue incorporation. At the management-scale, we found that the widespread incorporation of agricultural conservation practices significantly reinforced the small water cycle, but the relative scale and spatial distribution of their incorporation were not reflected in the SWAT scenario analysis. Individual farmers should be incentivized to adopt agricultural conservation practices, as these practices can have great effects at the farm-scale. At the management-scale, the spatial distribution of agricultural conservation practice adoption was not significant in this study, implying that managers should incentivize any adoption of such practices and that the small water cycle would be reinforced regardless.

4.2 Introduction

The small water cycle is the local cycling of water, wherein water should fall as rain in the same geographic area from which it evapo(transpi)rates. The small water

---

[3] Published as Noreika et al. 2022
Land. DOI: https://doi.org/10.3390/land11050683

cycle also greatly emphasizes a reduction in surface runoff generation in a landscape, and the cycle's reinforcement is considered to be a holistic approach to managing water resources at the catchment scale [1,2,3]. In an agricultural landscape, certain conservation techniques can greatly improve the water holding capacity of a soil and can, in turn, strongly reinforce the small water cycle, making an agricultural landscape more resilient in the face of climate change.

Agricultural conservation practices have been extensively studied over the last 40 years and have been shown to significantly improve a soil's infiltration capacity and, consequently, significantly decrease the surface runoff in a landscape [4,5,6,7,8]. The most common agricultural conservation practices in modern literature include reduced/no-tillage, mulch cover/crop residues and cover crops, and reduced application of herbicides. The goal of conservation agriculture is to make soils "self-sustainable" by: maintaining sources of organic matter above and below the soil's surface, recycling water and nutrients within the system, and ensuring that the infiltration rate of a soil is greater than the predicted rainfall rate [9]. To maximize the benefits of implementing agricultural conservation practices, managers must maintain year-round organic matter cover, minimize soil disturbance, and diversify crop rotations [9,10,11]. The transition from conventional or reduced tillage to no-tillage has been shown to reduce surface runoff by upwards of 20% at the plot-scale [12]. A no-tillage management scheme can increase the infiltration capacity of a soil in two ways: by minimizing soil disruption and by preserving the highest percentage of crop residue cover. No-tillage has also been shown to reduce soil loss, splash erosion, and surface runoff, while increasing direct infiltration [10,13,14]. Maintaining adequate plant cover year-round provides numerous benefits, including improving soil quality, controlling soil erosion, and increasing soil water availability [15]. Plant cover percentage has a significant, negative relationship with final runoff rate, indicating that the greater the plant cover percentage, the lower the expected hourly runoff [16]. While cover crops and crop residues provide year-round soil coverage, they also provide an even-coverage mulching, which has been found to be a more successful mulching strategy in real-life scenarios when compared to artificial mulching with wheat straw, grass clippings, wood chips, etc., [13].

The Intergovernmental Panel on Climate Change (IPCC) predicts that in the face of future climate change, Central Europe will encounter more frequent, intensive storm events, which will magnify landscape management issues in the Czech Republic [17]. The Czech Republic is a highly agricultural country, with nearly 40% of its land area being arable. Agricultural intensification in the Czech Republic began in the 1970s when the landscape was publicly managed. Large fields, subsurface tile drainage systems, and artificially lined and straightened streams were incorporated across the landscape in an effort to increase crop production [18]. Unfortunately, these practices resulted in increased soil loss and reduced deep percolation and groundwater recharge. Since privatization in 1991, some small Czech farms have begun incorporating agricultural conservation practices and IPA (integrated pest management for agriculture) guidelines; however, much of the Czech agricultural landscape is managed by large agricultural conglomerates driven by profit [1,18]. By working to reinforce the small water cycle through the incorporation of agricultural conservation practices, the effects of extreme precipitation events (e.g., huge spikes in surface runoff ratios as well as extreme soil loss events) may be mitigated at the basin-scale, which should incentivize their incorporation to land managers and farmers [17].

The two basins of interest have been monitored for a number of years. The farm-scale basin (Nučice) is equipped to monitor localized basin processes, and previous studies have primarily focused on rainfall–runoff mechanisms and temporarily variable soil properties [19,20,21,22,23]. Sediment transport and erosion have been extensively studied in Vrchlice (the basin utilized for management-scale analysis), especially regarding the sediment trap efficiencies of the nearly 140 reservoirs across the basin [24,25,26,27]. The Soil and Water Assessment Tool (SWAT) has been previously utilized at both basins to assess the effects of land use changes on in-basin water balance [26,27], but since the Czech Republic is likely to remain quite agricultural for the foreseeable future, it is of great interest to assess the impacts of agricultural conservation practice incorporation at each of these scales. While sometimes data intensive, hydrologic models are a relatively easy and non-invasive way to run scenario analyses in a landscape. SWAT is a semi-distributed, semi-physically based, basin-scale hydrologic model. SWAT divides a basin into smaller elements called hydrologic response units (HRUs) that are each comprised of the same soil type, slope class, and land use classification [28,29,30,31]. SWAT was selected for this study because of its flexibility and applicability to agricultural catchments. SWAT makes running scenario analyses simple, and there is significant precedent for its incorporation of agricultural conservation practices [32,33].

The purpose of this study is to investigate the following questions: (i) do the incorporation of agricultural conservation practices impact the small water cycle proportionally at various scales? (ii) Which practice is most effective at reinforcing the small water cycle at the farm-scale? (iii) Does the spatial distribution of agricultural conservation practices affect their impacts on the small water cycle at the management scale? (iv) What do these results imply regarding catchment management and incentivizing farmers to adopt these practices?

4.3 Materials and Methods

4.3.1 Study Watersheds

Both study watersheds are located in the Central Bohemia region of the Czech Republic (Figure 4.1). This region is characterized by a humid continental climate and receives approximately 600 mm of precipitation per year. The rainy season in this region occurs from May through August, and the driest month is usually February. These two basins were selected for this study because they are typical of an intensively agricultural Czech landscape. Nučice is a simply-shaped catchment and represents the farm-scale, containing three large fields, each with very similar crop rotations and management. Vrchlice represents the management-scale. It is much larger (~100 km^2), with a more diverse landscape, and its water resources are managed to meet municipal needs. It is valuable to land owners as well as basin managers to determine the effects of agricultural conservation practice adoption at each scale.

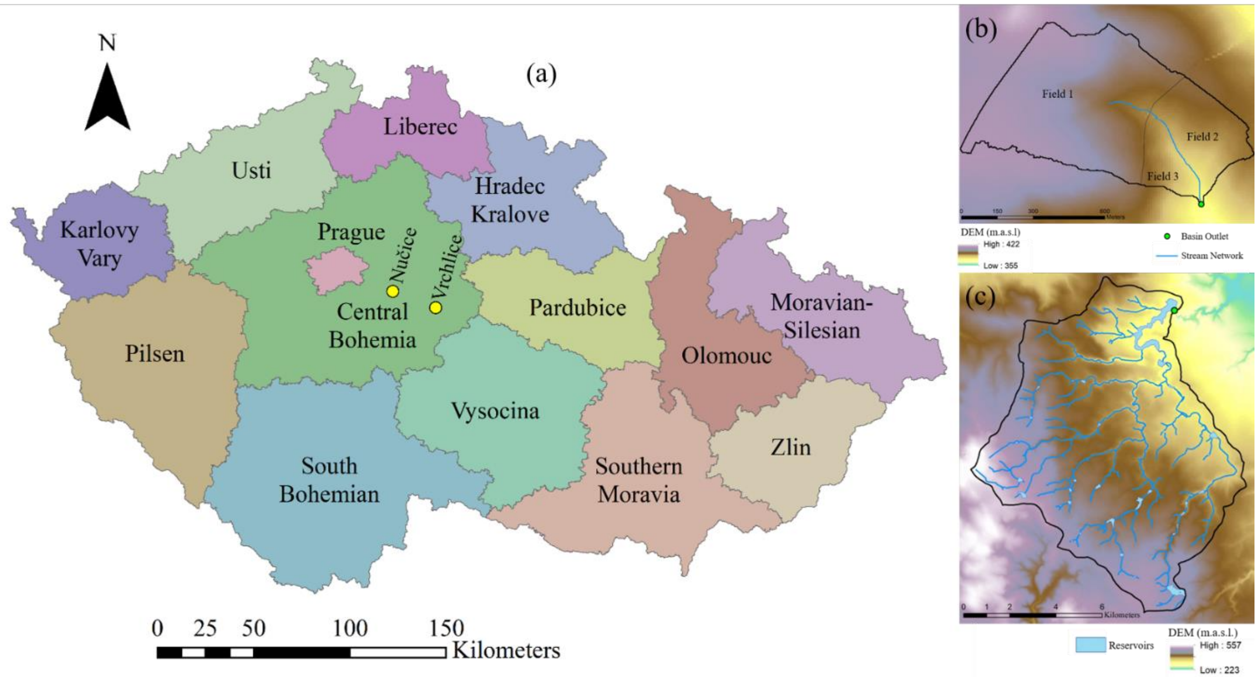


Figure 4.1. (a) A map of the Czech Republic. Prague is highlighted for reference as well as the outlet locations of the two study watersheds, Nučice (b) and Vrchlice (c).

The Nučice experimental catchment (“Nučice”) has been monitored since 2011 by the Landscape Water Conservation Department (in the faculty of Civil Engineering) of Czech Technical University in Prague. It is a small watershed (~0.52 km^2) consisting of three fields that are managed by two farmers and is appropriate for modeling at the “farm-scale” in the Czech Republic. Its outlet is located at 49°57′49.230″ N, 14°52′13.242″ E (Figure 4.1b). The soils in Nučice are classified mainly as Luvisols and Cambisols overlaying siltstone and sandstone. The average slope in Nučice is 3.9% but ranges from 1 to 12%. Nučice is primarily cropland, with a very narrow riparian/brush zone around the stream; the basin is bisected horizontally by a 2-lane road (Table 4.1).

Table 4.1. Land use percent cover over the experimental basins.

Land Use	Nučice	Vrchlice
Impervious	2	3
Brush	2	4
Forest	-	25
Grassland	-	8
Cropland	95	54
Water	1	2
Gardens	-	4

The Vrchlice Basin (“Vrchlice”) is much larger than Nučice, at ~97 km^2 (Figure 4.1c). Vrchlice also has a more diverse land use, with large areas of forested land as well as many townships (Table 4.1), but it is still primarily cropland. The Vrchlice Reservoir provides drinking water to the nearby town of Kutná Hora, serving approximately 40,000 inhabitants. Its outlet is located at 49°55′37.211” N, 15°13′37.07” E. The basin is covered in clayey soils classified as Cambisols overlaying a metamorphic bedrock [24]. Vrchlice contains a network of nearly 140 reservoirs, mostly small fish ponds, that serve cultural and hydrologic significance. The discharge at the outlet of the Vrchlice Reservoir has been monitored by the Elbe River Authority since 1979. The Vrchlice Basin is considered to be an appropriate size for modeling at the “management-scale” in the Czech Republic.

4.3.2 Soil and Water Assessment Tool (SWAT)

SWAT requires the following as its bare minimum regarding data requirements: soils, slopes, land uses, and daily weather data. The input data used for each of the models present in this study are outlined in Table 4.2.

Table 4.2. Input variables and their sources used for Soil and Water Assessment Tool (SWAT) modeling.

Input Data		Basin	Description	Source
Meteorological Data	Extreme Daily Temperatures	Nučice	2011–2019	On-site: 107 Temperature Probe (Campbell Sci., UK)
		Vrchlice	1996–2019	Czech Hydrometeorological Institute
	Precipitation (Total Daily)	Nučice	2011–2019	On-site: MR3-01s Tipping Bucket (Meteo Servis, Czech Republic)
		Vrchlice	1996–2019	Czech Hydrometeorological Institute
Spatial Data	DEM	Nučice	3 m resolution	LiDAR Survey: Czech Institute of Geodesy and Cartography
		Vrchlice	5 m resolution	LiDAR Survey: Czech Institute of Geodesy and Cartography
	Soils	Nučice	1:5000 soil map	State Land Office of the Czech Republic
		Vrchlice	1:5000 soil map	Czech Research Institute of Soil Conservation & the State Land Office of the Czech Republic
	Land Use	Nučice	Digitized from detailed orthophoto	UAV Survey: Czech Technical University
		Vrchlice	1:10,000 land use map	ZABAGED (Fundamental Base of Geographic Data of the Czech Republic) & LPIS (Land Parcel Identification System)

The daily meteorological data for the Nučice SWAT model was obtained from on-site gauges (Table 2). The climate data for this model was obtained from the Climate Forecast System Reanalysis (CFSR) database; these data are used in case there are any gaps in the observed weather dataset. The digital elevation model (DEM) was obtained from the fifth generation of the digital relief model of the Czech Republic (DMR5G) and was point-cloud processed to obtain a 3 m spatial resolution. The SWAT model for Nučice was developed using the field boundary method [34]. In the field boundary method scheme, each field is defined as its own HRU by aggregating the primary soil type and elevation class for each field. This method was selected in order to incorporate reduced field sizes at the farm-scale and was accomplished through the use of soil dummy variables. The SWAT model for Nučice was run during the growing seasons (~April through October) from 2014 through 2019, using 2013 as a warmup period. Calibration and validation procedures followed those outlined in Noreika et al. 2020 [26].

The Vrchlice SWAT model was developed originally for Noreika et al. 2021 to study the effects of land use and management changes over time in the basin [27]. The model it-self has not been edited further. This model was run at the monthly timestep from 2001 through 2019 with a 5-year warmup period (1996–2000). The monthly timestep was chosen to minimize daily effects due to reservoir processes that are not publicly available and therefore unable to be represented in SWAT. The model was calibrated (2001–2012) and validated (2013–2016) at the monthly timestep with discharge data from the basin's out-let. The basin boundaries and stream network were largely DEM-based, but groundtruthed to existing data. Vrchlice was divided into 63 sub-basins, containing 1058 HRUs that were defined by their unique combinations of land use, slope class, and soil type. For further detail, parameterization, and intricacies of the model setup, please refer to Noreika et al. 2021 [27].

4.3.3 Scenario Analysis

Literature Review

Contour farming results in a reduction of surface runoff by impounding water in small depressions, as well as a reduction of sheet and rill erosion by reducing the erosive power of surface runoff and preventing or minimizing the development of rills. This practice is represented by adjusting the Soil Conservation Service (SCS) curve number in SWAT. Residues are meant to slow down surface and peak runoff by increasing surface roughness. They also increase infiltration and reduce surface runoff by decreasing surface sealing and slowing down overland flow. Finally, residues reduce sheet and rill erosion by reducing surface flow volume. In SWAT, there is significant literature precedent to in-corporate these practices; conservation tillage and residue management are typically rep-resented by adjusting the curve number and Manning's roughness coefficient for overland flow, respectively. In order to incorporate these practices appropriately, a literature review was conducted using the following keywords: SWAT, best management practice, and conservation agriculture [35–67]. A total of 33 articles were downloaded and narrowed down to 25 based on relevance. The 25 remaining papers addressed the incorporation of conservation tillage operations, contour farming, and residue management into SWAT (Figure 4.2). Of the 25, 12 took place in the Midwest (of US and Canada), 1 in Texas, 6 in Europe, 1 in Africa, and 6 in Asia. Overwhelmingly, 17 of the 25 papers referenced Arabi et al. 2008 and Neitsch et al. 2011 publications [32,33], meaning that conservation practices were incorporated via the curve number (CN) method. Three publications introduced till-age operation changes and no CN edits (TO). Two introduced tillage operation changes along with the CN edits (CN + TO). Two modified the CN by a percent change, and two did not specify (NS) how the practices were incorporated into SWAT. We then conducted a scenario analysis at the Nučice basin to determine whether it is necessary to incorporate both CN shifts and tillage operation changes. We found no significant differences between water balance variable outputs (discharge at the basin's outlet, subsurface lateral flow, surface runoff, evapotranspiration, and soil water content, $p > 0.05$) when only the CN method was utilized versus shifting both the CN and the tillage practices. We concluded that the CN method is appropriate to incorporate agricultural conservation practices and is also more efficient in the modeling process.

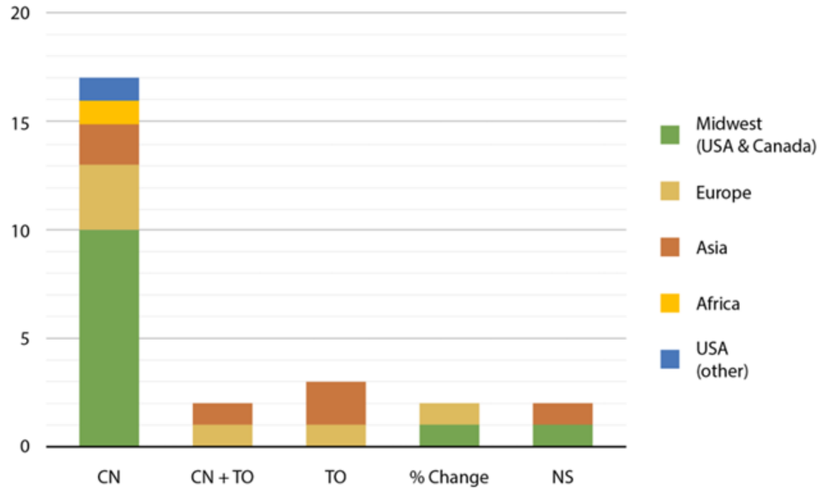


Figure 4.2. Literature review results of 25 articles outlining the incorporation of agricultural conservation practices into SWAT.

Scenarios Outlined

Five scenarios were run at the farm-scale for this study (Table 4.3). These scenarios in-corporate contour farming, small residues (0.5–1 t/ha), large residues (1–9 t/ha), conservative tillage, and field size reductions at Nučice. To incorporate field size reductions, in-stead of three fields averaging 17 ha each, Nučice was divided into 52 fields averaging 1 ha each through the use of dummy soil variables. The other scenarios were incorporated as presented in Table 4.4.

Table 4.3. Outline of scenarios implemented in the Nučice and Vrchlice Basins. (* denotes the original calibrated model for each).

Scale	Practice
Farm-Scale: Nučice	Conventional Tillage (Conv)
	Conservation Tillage * (Cons)
	Contour Farming (Cont)
	Small Residues (Res1)
	Large Residues (Res2)
	Field Reductions (SmFld)
	Conventional Tillage *
Management-Scale: Vrchlice	Full Adoption
	Lower Adoption
	Lower Extended
	Middle Adoption
	Upper Adoption
	Upper Extended
	Random Adoption

Table 4.4. Agricultural conservation measures applied to the Nučice Basin and how they are parameterized in SWAT. The Soil Conservation Service (SCS) Curve Number (CN) and Manning's Roughness values represent a relative change from the respective calibrated model [32,33]. * Conventional tillage is present because the Nučice model was calibrated based on conservation tillage, and this is how the effects of conservation tillage will be compared to conventional tillage. † These general measures are applied to the Vrchlice scenarios at various levels of incorporation across the basin.

Scenario	CN	USLE P	Manning's Roughness
Conventional Tillage *	+2	-	-
Contour Farming	−1	0.5	-
Small Residues	-	-	+0.07
Large Residues	-	-	+0.15
General Measures †	−3	0.5	+0.15

In Vrchlice, only the "General Measures" agricultural conservation scenario was adopted (Table 4.4) at various scales across the basin (Table 4.3, Figure 4.3). The "General Measures" outlined in Table 4.4 are considered to be "best case scenarios" to represent conditions if the practices were incorporated properly and if the landscape responds as expected, but it is likely that any real-world result would fall somewhere between the calibrated model without any conservation practices and the "General Measures" scenarios. Vrchlice was divided into three regions based on location in the basin and percent area cropland (Figure 4.3). Each area (Upper, Middle, Lower, Random) comprises approximately 1/3 of the cropland cover in the Vrchlice Basin. Additionally, the Upper Extended and Lower Extended scenarios encompass the Upper + Middle and Lower + Middle areas, respectively, to encompass approximately 2/3 of the cropland cover in the Vrchlice Basin. A requirement for the Random scenario is that no selected sub-basins should be adjacent. The Random scenario controls for the effects of connectivity of agricultural conservation practices to determine if individual farm adoption is “enough” or if regional adoption is necessary to more greatly reinforce the small water cycle. These scenarios were outlined so that the individual impacts of agricultural conservation practice continuity and spatial adoption within the basin could be evaluated.

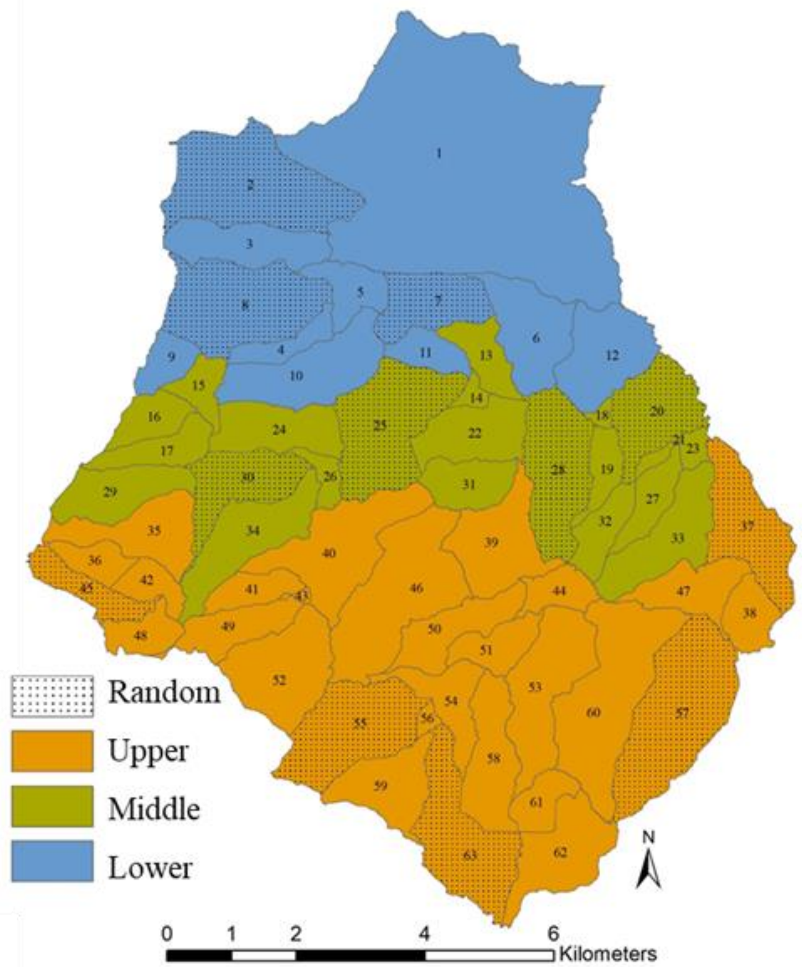


Figure 4.3. A map of the Vrchlice Basin, color coded to represent the various scenarios analyzed.

4.4 Results

According to the global sensitivity analysis that was conducted, three parameters significantly influenced the modeled discharge flowing out of the Nučice experimental basin (Table 4.5). RCHRG_DP is the deep aquifer percolation fraction; this value should fall between 0 and 1 as it is the fraction of percolation past the root zone which recharges the deep aquifer. Since this value is very close to 0, this indicates that a very small fraction of water entering the Nučice Basin recharges the deep aquifer. Saturated hydraulic conductivity (SOL_K) and the available water capacity of the soil (SOL_AWC) govern how water is infiltrated and retained in a soil, respectively, were also significantly sensitive parameters.

Table 4.5. Sensitive parameters and their calibrated (adjusted) values. (V: replace, A: absolute, and R: relative).

Parameter	Method	Calibration Values		
		Minimum	Adjusted	Maximum
RCHRG_DP	V	0.001	0.001	0.999
SOL_K	R	−0.5	−0.11	0.5
SOL_AWC	R	−0.90	0.88	0.90

Calibration (2016–2018) and validation (2019) for the Nučice basin were conducted with SWAT-Cup 2019, which is a semiautomatic calibration methodology [28]. Table 4.6 presents the selected model performance indicators during the calibration and validation periods for the Nučice SWAT model. Figure 4.4 presents a scatterplot, correlating the modeled discharge values with the observed discharge values at Nučice during the calibration and validation periods.

Table 4.6. Model performance indicators for the calibration and validation periods of the Nučice SWAT model.

Calibration	Performance Indicator	Validation
0.76	*p*-factor	0.80
0.46	*r*-factor	0.21
0.77	R^2	0.52
0.77	NSE	0.48
6.9	PBIAS	12.1
0.80	KGE	0.64

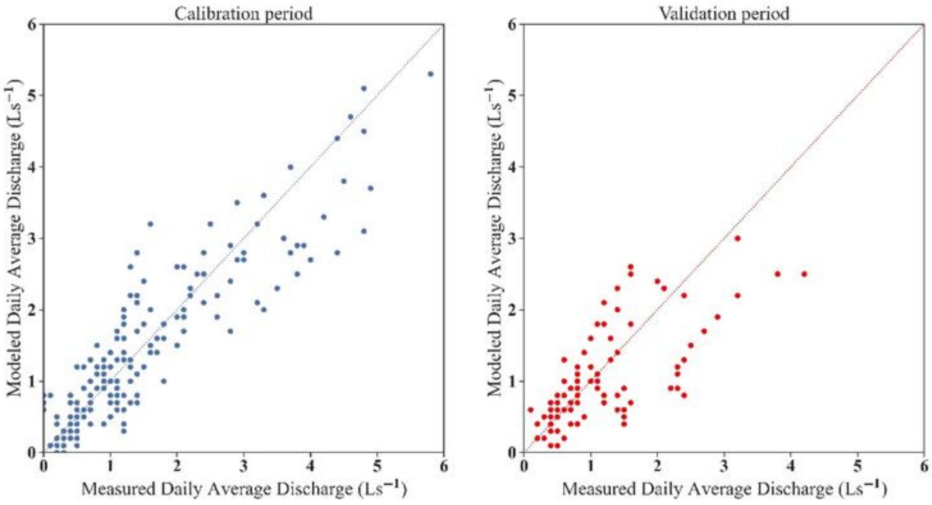
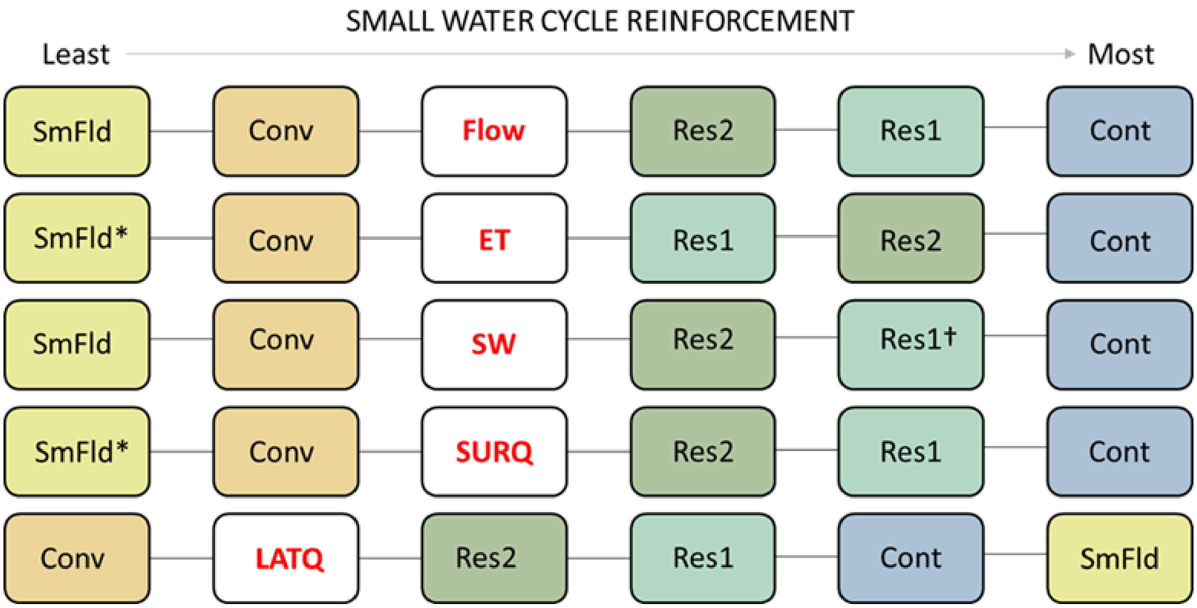


Figure 4.4. Correlation of modeled and observed discharge values at Nučice's outlet during the calibration and validation periods; a 1:1 line is included for reference.

There were significant shifts across water balance parameters with the incorporation of agricultural conservation practices at the Nučice scale (Figure 4.5). The incorporation of residues and contour farming reinforced all of the small water balance parameters when compared to the calibrated scenario, which included generalized conservation tillage. Re-sorting to conventional tillage from conservation tillage was consistently contradictory to the goal of reinforcing the small water cycle. Field size reductions resulted in the highest amount of streamflow contribution from subsurface lateral flow, but the model indicated that otherwise the adoption of smaller fields does not reinforce the small water cycle.



SmFld	Conv	**Flow**	Res2	Res1	Cont
SmFld*	Conv	**ET**	Res1	Res2	Cont
SmFld	Conv	**SW**	Res2	Res1†	Cont
SmFld*	Conv	**SURQ**	Res2	Res1	Cont
Conv	**LATQ**	Res2	Res1	Cont	SmFld

Figure 4.5. A ranking of each scenario (in the Nučice basin) according to its reinforcement of specific small water cycle parameters. All values are significantly different from the calibrated scenario (parameters in red, bold) unless indicated by *. † indicates a significant difference between Res1 and Res2.

All small water cycle parameters, except for discharge at Vrchlice's outlet, were significantly affected by the incorporation of agricultural conservation practices across the basin. Interestingly enough, neither the scale of adoption nor the spatial distribution of agricultural conservation practices significantly affected any small water cycle parameters at this scale; further figures presented compare only Vrchlice's conventional tillage (calibrated model) and the full adoption scenario. Both the available water content and evapotranspiration in the conventional tillage scenario are consistently lower than the full conservation adoption across the entire year (Figure 4.6 and Figure 4.7). Both the surface runoff ratios and subsurface lateral flow were significantly higher throughout the year in the conventional tillage scenario when compared to the General Measures full adoption scenario (Figure 4.8 and Figure 4.9). Generally surface runoff in the conventional tillage scenario is greater than 2× that of the conservation scenario (Figure 4.9).

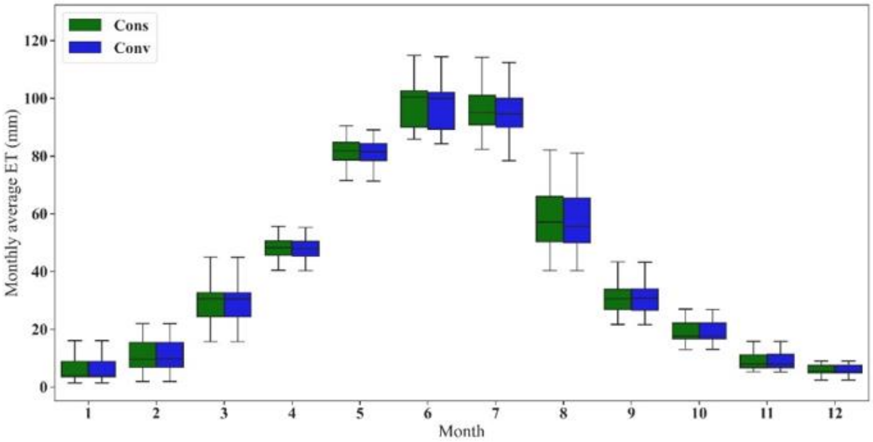


Figure 4.6. Average monthly evapotranspiration rates (mm) across the modeled time period in Vrchlice.

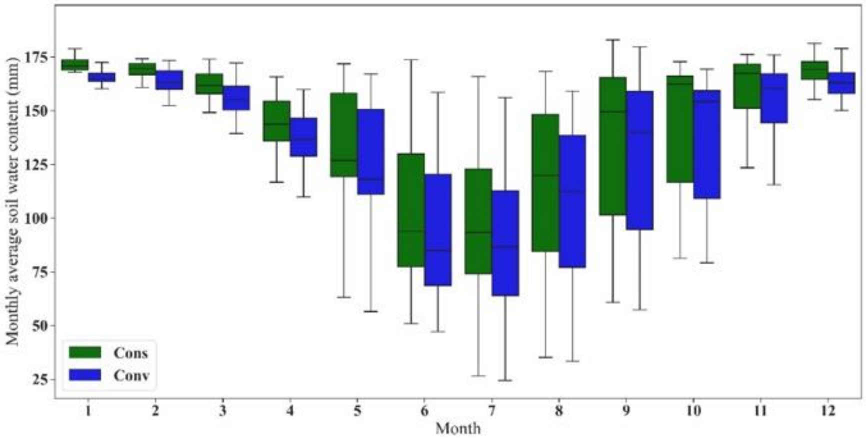


Figure 4.7. Average soil water content (mm) by month across the modeled time period in Vrchlice.

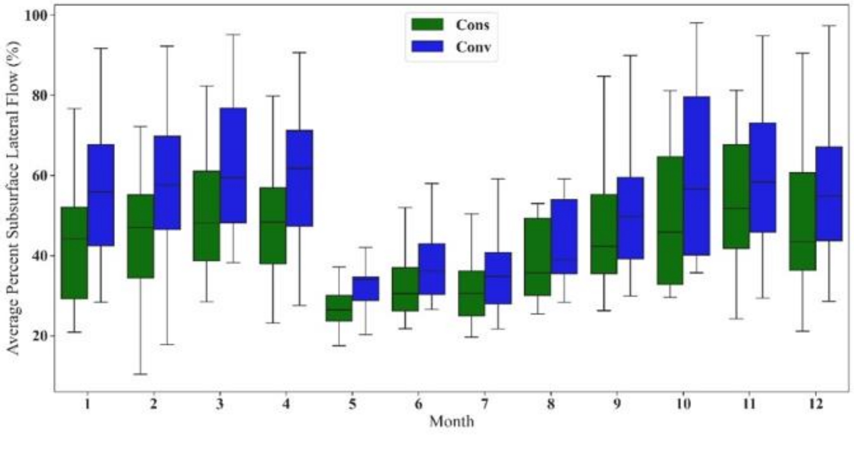


Figure 4.8. Average monthly percentage subsurface lateral flow contribution to streamflow across the modeling period in Vrchlice.

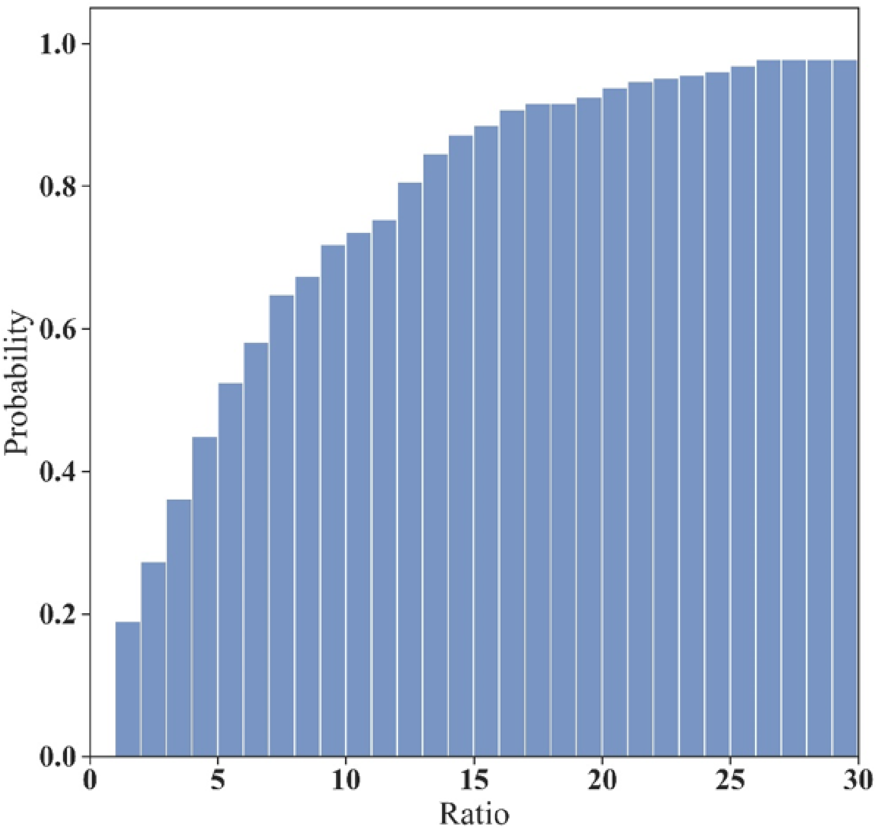


Figure 4.9. Surface runoff ratios between full agricultural conservation practice adoption and the default conventional tillage scenario. The histogram bars represent the cumulative probability that a value falls at or below the respective ratio.

4.5 Discussion

4.5.1 Hydrological Modeling with SWAT

There are several possible sources of error in any hydrologic model; the first is input parameter uncertainty, which is the largest possible source of error and also influences uncertainties associated with output data. Model parameterization and model structural uncertainties are additional possible sources of error [62,68]. Furthermore, since SWAT is neither fully physically based nor fully distributed, some processes may not be properly represented, such as temporal changes in topsoil hydraulic properties, preferential flow, or the influences of the spatial distribution of fine-scale land management [28,69,70]. While there are some drawbacks to the SWAT model (as stated above), it is a very useful tool for hydrologic modeling, especially regarding scenario analysis. Currently, Nučice is equipped to model generalized processes rather than more spatially distributed processes (piezometer clusters and a cosmic-ray neutron sensor are currently being installed). The soil data at this scale is fairly coarse and is nearing the lower spatial range of SWAT's modeling capabilities, but SWAT was still able to model Nučice effectively with "good" or "very good" performance across the selected indicators [71–73]. The uncertainties associated with the Vrchlice model primarily include generalized reservoir processes and crop rotations [27]. Vrchlice was able to be effectively modeled at the monthly timescale, also with "good" and "very good" performance indicators [71–73]. While SWAT was able to model significant shifts in water balance parameters with the incorporation of agricultural conservation practices in Vrchlice, it was unable to represent significant differences at varying scales and distributions of incorporation across Vrchlice. This could be due to the fact that Vrchlice, while primarily cropland, contains significant areas of forested areas and riparian zones, which may disguise the effects of agricultural conservation adoption. Additionally, since Vrchlice is of significant size and SWAT is not fully distributed, the effects of the scale of agricultural conservation practice adoption may be aggregated across the basin, leading to insignificant changes across the agricultural conservation practice adoption scenarios.

4.5.2 The Small Water Cycle at the Farm-Scale

At the farm-scale, SWAT was able to model significant differences in water balance parameters across agricultural conservation practice scenarios. According to SWAT, residue incorporation and contour farming were the most effective at reinforcing the small water cycle and should be prioritized by farmers to aid the holistic management of their land in the face of future climate change [17]. Although it was not in the scope of this study to investigate the effects of crop changes in addition to the incorporation of agricultural conservation practices, the previous SWAT study of the Nučice basin indicated that crop changes also have significant impacts on the small water cycle [26]. For instance, winter wheat reinforces the small water cycle to a greater degree than rapeseed in the Czech landscape. The incorporation of contour farming and crop residues may be able to mitigate water balance issues that arise from less-sustainable crop choices, and the inter-action should be studied further.

SWAT was not able to effectively model the impacts of incorporating smaller field sizes at Nučice. This may be due to several factors: SWAT is not fully distributed and cannot model the spatial effects influenced by smaller field incorporation, crop changes were not incorporated across the smaller fields, and SWAT does not model true border effects between fields. To replicate this in future studies, a trap efficiency would need to be applied to each HRU to simulate flow disruption between fields. The field boundary HRU method may be more useful to identify “hotspot” fields that may be susceptible to erosive events due to their slopes, crops, and soil types [28,30,34,69,70].

4.5.3 The Small Water Cycle at the Management-Scale

The adoption of agricultural conservation practices in at least 33% of the cropland across Vrchlice had significant effects on the small water cycle within the basin. Neither the distribution nor the scale of adoption (anything above 33%) significantly affected the small water cycle variables at Vrchlice any further. While Vrchlice is a very agricultural basin (>50% cropland), there are also very large forested and riparian areas that may mask the effects of various intensities of agricultural conservation practice adoption. It may also be due to SWAT’s model structure, being semi-distributed and semi-physically based, that some effects at this scale may be lost due to HRU aggregation or generalizations due to using the curve number method [34,74,75]. While SWAT models significant impacts on the small water cycle due to the adoption of agricultural conservation practices, SWAT cannot represent realistic effects when additional spatial distribution and connectivity scenarios are introduced; a fully distributed model would be necessary for this purpose. However, SWAT was able to model general trends and could represent significant differences between conventional agricultural practices and full conservation adoption.

When compared to the effects of land use changes at Vrchlice [27], average soil water content and subsurface lateral flow shifts fell in similar ranges to that of agricultural conservation practice incorporation scenarios. However, the modeled adoption of agricultural conservation practices reduced the proportion of surface runoff at the management scale by up to 30x, which greatly outweighs the effects of the land use change scenarios previously modeled [27]. These findings indicate that, at the management-scale, the incorporation of agricultural conservation practices can have similar effects to land use changes on the small water cycle and can greatly reduce the overall proportion of surface runoff contribution to streamflow.

4.5.4 Implications for Agricultural Conservation Practice Incorporation in the Czech Republic

The incorporation of agricultural conservation practices tend to reinforce the small water cycle regardless of scale of incorporation. These effects are more obvious at the farm-scale than at the management-scale, which should motivate individual farmers to adopt such practices. At the management-scale, the effects of agricultural conservation practices were still significant but the scale and the spatial distribution of adoption were not. This implies that managers should incentivize any willing famers/conglomerates within their management area to adopt such practices. In addition to agricultural conservation practices, other land and crop management factors can also have significant effects on the small water cycle and their interactions should be studied further [26,27]. While soil erosion and sediment transport were not explored in this study, agricultural conservation practices have also been shown to have positive effects concerning these issues and can lead to increased soil conservation [14–16,76,77].

4.6 Conclusions

This study reinforces SWAT's applicability to the Czech landscape at both the farm- and management-scales. SWAT is very effective in its ability to model various management, land use, and crop change scenarios. While likely exaggerated by the scale, agricultural conservation practice adoption at the farm-scale has significant effects on the small water cycle. The most effective practice modeled at this scale was the incorporation of contour farming. The effects of small field incorporation at the farm-scale tended to have significantly negative impacts on the small water cycle, but this result is likely an artifact due to the HRU processing in SWAT. At the management-scale in the Czech Republic, any degree of incorporation of agricultural conservation practices makes significant impacts on the small water cycle, according to the Vrchlice SWAT model. SWAT was able to model that the incorporation of agricultural conservation practices in a primarily agricultural landscape can have significant effects on the small water cycle, especially regarding sur-face runoff ratios. While SWAT is not fully distributed and real-world effects would likely vary, this study indicates that managers should encourage agricultural conservation practices, regardless of scale or spatial distribution. As this study only focuses on the effects of agricultural conservation practices on the small water cycle, further studies should be conducted to model their effects on erosion as well as the interactions between agricultural conservation practices and land use/management changes in the Czech landscape.

4.7 References

1. Zelenakova, M.; Fialová, J.; Negm, A.M. *Assessment and Protection of Water Resources in the Czech Republic;* Springer: Cham, Switzerland, 2020. https://doi.org/10.1007/978-3-030-18363-9.
2. Marlow, D. *Small Water Cycles: What They Are, Their Importance, Their Restoration*; Proceedings of the Royal Society of Queensland, 127 2019.
3. Kravčík, M.; Pokorný, J.; Kohutiar, J.; Kováč, M.; Tóth, E. Water for the Recovery of the Climate-A New Water Paradigm. In Proceedings of the Joint Conference of APLU and ICA, Prague, Czech Republic, 23–26 June 2009.
4. Basch, G.; Friedrich, T.; Kassam, A.; Gonzalez-Sanchez, E. Conservation Agriculture in Europe. In *Conservation Agriculture*; Farooq, M., Siddique, K.H.M., Eds.; Springer: Cham, Switzerland, 2015; pp 357–389, ISBN 978-3-319-11619-8.
5. Rockström, J.; Karlberg, L.; Wani, S.P.; Barron, J.; Hatibu, N.; Oweis, T.; Bruggeman, A.; Farahani, J.; Qiang, Z. Managing water in rainfed agriculture—The need for a paradigm shift. *Agric. Water Manag.* 2010, *97*, 543–550. https://doi.org/10.1016/j.agwat.2009.09.009.
6. Stevenson, J.R.; Serraj, R.; Cassman, K.G. Evaluating conservation agriculture for small-scale farmers in Sub-Saharan Africa and South Asia. *Agric. Ecosyst. Environ.* 2014, *187*, 1–10. https://doi.org/10.1016/j.agee.2014.01.018.
7. van Wie, J.B.; Adam, J.C.; Ullman, J.L. Conservation tillage in dryland agriculture impacts watershed hydrology. *J. Hydrol.* 2013, *483*, 26–38. https://doi.org/10.1016/j.jhydrol.2012.12.030.
8. Gómez Calero, J.A.; Krása, J.; Quinton, J.N.; Klik, A.; Fereres Castiel, E.; Intrigliolo, D.S.; Chen, L.; Strauss, P.; Yun, X.; Dostál, T. *Best Management Practices for Optimized Use of Soil and Water in Agriculture*; Spanish National Research Council (CSIC); 2021.

9. Kassam, A.; Friedrich, T.; Shaxson, F.; Pretty, J. The spread of Conservation Agriculture: Justification, sustainability and uptake. *Int. J. Agric. Sustain.* 2009, *7*, 292–320. https://doi.org/10.3763/ijas.2009.0477.
10. Choudhary, M.A.; Lal, R.; Dick, W.A. Long-term tillage effects on runoff and soil erosion under simulated rainfall for a central Ohio soil. *Soil Tillage Res.* 1997, *42*, 175–184. https://doi.org/10.1016/S0167-1987(97)00005-6.
11. Chow, T.L.; Rees, H.W.; Monteith, J. Seasonal distribution of runoff and soil loss under four tillage treatments in the upper St. John River valley New Brunswick, Canada. *Can. J. Soil. Sci.* 2000, *80*, 649–660. https://doi.org/10.4141/S00-006.
12. Sun, Y.; Zeng, Y.; Shi, Q.; Pan, X.; Huang, S. No-tillage controls on runoff: A meta-analysis. *Soil Tillage Res.* 2015, *153*, 1–6. https://doi.org/10.1016/j.still.2015.04.007.
13. Hösl, R.; Strauss, P. Conservation tillage practices in the alpine forelands of Austria—Are they effective? *CATENA* 2016, *137*, 44–51. https://doi.org/10.1016/j.catena.2015.08.009.
14. Leys, A.; Govers, G.; Gillijns, K.; Berckmoes, E.; Takken, I. Scale effects on runoff and erosion losses from arable land under conservation and conventional tillage: The role of residue cover. *J. Hydrol.* 2010, *390*, 143–154. https://doi.org/10.1016/j.jhydrol.2010.06.034.
15. Zuazo, V.H.D.; Pleguezuelo, C.R.R. Soil-erosion and runoff prevention by plant covers. A review. *Agron. Sustain. Dev.* 2008, *28*, 65–86. https://doi.org/10.1051/agro:2007062.
16. Greene, R.S.B.; Kinnell, P.I.A.; Wood, J.T. Role of plant cover and stock trampling on runoff and soil-erosion from semi-arid wooded rangelands. *Soil Res.* 1994, *32*, 953. https://doi.org/10.1071/SR9940953.
17. Kovats, R.S., Valentini, R., Bouwer, L.M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M., Soussana, J.F., 2014. Europe. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. Climate Change 2014: Impacts, Adaptation and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth

Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2014.

18. Ministry of Agriculture of the Czech Republic. *We Support Traditions and Rural Development in the Czech Republic;* Prague, Czech Republic, 2018, ISBN: 978-80-7434-416-9.
19. Zumr, D.; Kubicek, J.; Dostal, T. Temporary Variable Soil Structure and Its Effect on Runoff Mechanism on Intensively Cultivated Land. European Geosciences Union. In *EGU General Assembly Conference Abstracts, Vienna, Austria, 7–12 April 2013*, Copernicus; Göttingen, Germany; EGU2013-9408.
20. Bauer, M.; Zumr, D.; Krása, J.; Dostál, T.; Jáchymová, B.; Rosendorf, P. Sediment and Phosphorus Fluxes-Monitoring and Modelling from Field to Regional Scale-Connectivity Implications. In *EGU General Assembly Conference Abstracts, Vienna, Austria, 12–17 April 2015*; Copernicus; Göttingen, Germany; EGU2015-11171.
21. Jeřábek, J.; Zumr, D.; Strouhal, L. Predominant Runoff Components During Heavy Rainfall Events on Cultivated Catchment. American Geosciences Union. In *AGU Fall Meeting Abstracts, 14–18 December 2015*, Copernicus; Göttingen, Germany; AGU 2015 H43I–1664.
22. Zumr, D.; Strouhal, L.; Kavka, P. Runoff Generation and Flow Paths on an Inclined Cultivated Soil. In *EGU General Assembly Conference Abstracts, Vienna, Austria, 12–17 April 2015*; Copernicus; Göttingen, Germany; EGU2015-6718.
23. Zumr, D.; Vláčilová, M.; Dostál, T.; Jeřábek, J.; Sobotková, M.; Sněhota, M. Spatial Analysis of Subsoil Compaction on Cultivated Land by Means of Penetrometry, Electrical Resistence Tomography and X-Ray Computed Tomography. In *EGU General Assembly Conference Abstracts, Vienna, Austria, 12–17 April* 2015, EGU2015-12926.
24. Krasa, J.; Dostal, T.; van Rompaey, A.; Vaska, J.; Vrana, K. Reservoirs' siltation measurements and sediment transport assessment in the Czech Republic, the Vrchlice catchment study. *CATENA* 2005, *64*, 348–362. https://doi.org/10.1016/j.catena.2005.08.015.
25. Krasa, J.; Dostal, T.; Jachymova, B.; Bauer, M.; Devaty, J. Soil erosion as a source of sediment and phosphorus in rivers and reservoirs-Watershed analyses using

WaTEM/SEDEM. *Environ. Res.* 2019, *171*, 470–483. https://doi.org/10.1016/j.envres.2019.01.044.

26. Noreika, N.; Li, T.; Zumr, D.; Krasa, J.; Dostal, T.; Srinivasan, R. Farm-Scale Biofuel Crop Adoption and Its Effects on In-Basin Water Balance. *Sustainability* 2020, *12*, 10596. https://doi.org/10.3390/su122410596.
27. Noreika, N.; Winterová, J.; Li, T.; Krása, J.; Dostál, T. The Small Water Cycle in the Czech Landscape: How Has It Been Affected by Land Management Changes Over Time? *Sustainability* 2021, *13*, 13757. https://doi.org/10.3390/su132413757.
28. Arnold, J.G.; Moriasi, D.N.; Gassman, P.W.; Abbaspour, K.C.; White, M.J.; Srinivasan, R.; Santhi, C.; Harmel, R.D.; van Griensven, A.; van Liew, M.W.; et al. SWAT: Model Use, Calibration, and Validation. *Trans. ASABE* 2012, *55*, 1491–1508. https://doi.org/10.13031/2013.42256.
29. van Liew, M.W.; Veith, T.L.; Bosch, D.D.; Arnold, J.G. Suitability of SWAT for the Conservation Effects Assessment Project: Comparison on USDA Agricultural Research Service Watersheds. *J. Hydrol. Eng.* 2007, *12*, 173–189. https://doi.org/10.1061/(ASCE)1084-0699(2007)12:2(173).
30. Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. LARGE AREA HYDROLOGIC MODELING AND ASSESSMENT PART I: MODEL DEVELOPMENT. *J. Am. Water Resour. Assoc.* 1998, *34*, 73–89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x.
31. Moriasi, D.N.; Arnold, J.G.; van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Trans. ASABE* 2007, *50*, 885–900. https://doi.org/10.13031/2013.23153.
32. Arabi, M.; Frankenberger, J.R.; Engel, B.A.; Arnold, J.G. Representation of agricultural conservation practices with SWAT. *Hydrol. Process.* 2008, *22*, 3042–3055. https://doi.org/10.1002/hyp.6890.
33. Neitsch, S.L.; Arnold, J.G.; Kiniry, J.R.; Williams, J.R. *Soil and Water Assessment Tool Theoretical Documentation*; Technical Report for Texas Water Resources Institute: College Station, TX, USA, 2011.

34. Daggupati, P.; Douglas-Mankin, K.R.; Sheshukov, A.Y.; Barnes, P.L.; Devlin, D.L. Field-Level Targeting Using SWAT: Mapping Output from HRUs to Fields and Assessing Limitations of GIS Input Data. *Trans. ASABE* 2011, *54*, 501–514. https://doi.org/10.13031/2013.36453.
35. Abouabdillah, A.; White, M.; Arnold, J.G.; De Girolamo, A.M.; Oueslati, O.; Maataoui, A.; Lo Porto, A. Evaluation of soil and water conservation measures in a semi-arid river basin in Tunisia using SWAT. *Soil Use Manage.* 2014, *30*, 539–549. https://doi.org/10.1111/sum.12146.
36. Bosch, N.S.; Allan, J.D.; Selegean, J.P.; Scavia, D. Scenario-testing of agricultural best management practices in Lake Erie watersheds. *J. Great Lakes Res.* 2013, *39*, 429–436. https://doi.org/10.1016/j.jglr.2013.06.004.
37. Bosch, N.S.; Evans, M.A.; Scavia, D.; Allan, J.D. Interacting effects of climate change and agricultural BMPs on nutrient runoff entering Lake Erie. *J. Great Lakes Res.* 2014, *40*, 581–589. https://doi.org/10.1016/j.jglr.2014.04.011.
38. Briak, H.; Mrabet, R.; Moussadek, R.; Aboumaria, K. Use of a calibrated SWAT model to evaluate the effects of agricultural BMPs on sediments of the Kalaya river basin (North of Morocco). *Int. Soil Water Conserv. Res.* 2019, *7*, 176–183. https://doi.org/10.1016/j.iswcr.2019.02.002.
39. Chen, Y.; Marek, G.W.; Marek, T.H.; Porter, D.O.; Brauer, D.K.; Srinivasan, R. Simulating the effects of agricultural production practices on water conservation and crop yields using an improved SWAT model in the Texas High Plains, USA. *Agric. Water Manag.* 2021, *244*, 106574. https://doi.org/10.1016/j.agwat.2020.106574.
40. Daloğlu, I.; Nassauer, J.I.; Riolo, R.; Scavia, D. An integrated social and ecological modeling framework—impacts of agricultural conservation practices on water quality. *Ecol. Soc.* 2014, *19*, 19. https://doi.org/10.5751/ES-06597-190312.
41. Daloğlu, I.; Nassauer, J.I.; Riolo, R.L.; Scavia, D. Development of a farmer typology of agricultural conservation behavior in the American Corn Belt. *Agric. Syst.* 2014, *129*, 93–102. https://doi.org/10.1016/j.agsy.2014.05.007.
42. Dechmi, F.; Skhiri, A. Evaluation of best management practices under intensive irrigation using SWAT model. *Agric. Water Manag.* 2013, *123*, 55–64. https://doi.org/10.1016/j.agwat.2013.03.016.

43. Elçi, A. Evaluation of nutrient retention in vegetated filter strips using the SWAT model. *Water Sci. Technol.* 2017, *76*, 2742–2752. https://doi.org/10.2166/wst.2017.448.
44. Engebretsen, A.; Vogt, R.D.; Bechmann, M. SWAT model uncertainties and cumulative probability for decreased phosphorus loading by agricultural Best Management Practices. *CATENA* 2019, *175*, 154–166. https://doi.org/10.1016/j.catena.2018.12.004.
45. Gitau, M.W.; Gburek, W.J.; Bishop, P.L. Use of the SWAT Model to Quantify Water Quality Effects of Agricultural BMPs at the Farm-Scale Level. *Trans. ASABE* 2008, *51*, 1925–1936. https://doi.org/10.13031/2013.25398.
46. Gitau, M.W.; Veith, T.L.; Gburek, W.J. Farm level optimization of bmp placement for cost–effective pollution reduction. *Trans. ASAE* 2004, *47*, 1923–1931. https://doi.org/10.13031/2013.17805.
47. Himanshu, S.K.; Pandey, A.; Yadav, B.; Gupta, A. Evaluation of best management practices for sediment and nutrient loss control using SWAT model. *Soil Tillage Res.* 2019, *192*, 42–58. https://doi.org/10.1016/j.still.2019.04.016.
48. Jang, S.S.; Ahn, S.R.; Kim, S.J. Evaluation of executable best management practices in Haean highland agricultural catchment of South Korea using SWAT. *Agric. Water Manag.* 2017, *180*, 224–234. https://doi.org/10.1016/j.agwat.2016.06.008.
49. Kalcic, M.M.; Frankenberger, J.; Chaubey, I. Spatial Optimization of Six Conservation Practices Using Swat in Tile-Drained Agricultural Watersheds. *J. Am. Water Resour. Assoc.* 2015, *51*, 956–972. https://doi.org/10.1111/1752-1688.12338.
50. Lamba, J.; Thompson, A.M.; Karthikeyan, K.G.; Panuska, J.C.; Good, L.W. Effect of best management practice implementation on sediment and phosphorus load reductions at subwatershed and watershed scale using SWAT model. *Int. J. Sediment Res.* 2016, *31*, 386–394. https://doi.org/10.1016/j.ijsrc.2016.06.004.
51. Liu, R.; Zhang, P.; Wang, X.; Wang, J.; Yu, W.; Shen, Z. Cost-effectiveness and cost-benefit analysis of BMPs in controlling agricultural nonpoint source pollution in China based on the SWAT model. *Environ. Monit. Assess.* 2014, *186*, 9011–9022. https://doi.org/10.1007/s10661-014-4061-6.

52. Liu, Y.; Guo, T.; Wang, R.; Engel, B.A.; Flanagan, D.C.; Li, S.; Pijanowski, B.C.; Collingsworth, P.D.; Lee, J.G.; Wallace, C.W. A SWAT-based optimization tool for obtaining cost-effective strategies for agricultural conservation practice implementation at watershed scales. *Sci. Total Environ.* 2019, *691*, 685–696. https://doi.org/10.1016/j.scitotenv.2019.07.175.
53. Liu, Y.; Wang, R.; Guo, T.; Engel, B.A.; Flanagan, D.C.; Lee, J.G.; Li, S.; Pijanowski, B.C.; Collingsworth, P.D.; Wallace, C.W. Evaluating efficiencies and cost-effectiveness of best management practices in improving agricultural water quality using integrated SWAT and cost evaluation tool. *J. Hydrol.* 2019, *577*, 123965. https://doi.org/10.1016/j.jhydrol.2019.123965.
54. López-Ballesteros, A.; Senent-Aparicio, J.; Srinivasan, R.; Pérez-Sánchez, J. Assessing the Impact of Best Management Practices in a Highly Anthropogenic and Ungauged Watershed Using the SWAT Model: A Case Study in the El Beal Watershed (Southeast Spain). *Agronomy* 2019, *9*, 576. https://doi.org/10.3390/agronomy9100576.
55. Merriman, K.; Daggupati, P.; Srinivasan, R.; Toussant, C.; Russell, A.; Hayhurst, B. Assessing the Impact of Site-Specific BMPs Using a Spatially Explicit, Field-Scale SWAT Model with Edge-of-Field and Tile Hydrology and Water-Quality Data in the Eagle Creek Watershed, Ohio. *Water* 2018, *10*, 1299. https://doi.org/10.3390/w10101299.
56. Merriman, K.; Russell, A.; Rachol, C.; Daggupati, P.; Srinivasan, R.; Hayhurst, B.; Stuntebeck, T. Calibration of a Field-Scale Soil and Water Assessment Tool (SWAT) Model with Field Placement of Best Management Practices in Alger Creek, Michigan. *Sustainability* 2018, *10*, 851. https://doi.org/10.3390/su10030851.
57. Park, J.-Y.; Yu, Y.-S.; Hwang, S.-J.; Kim, C.; Kim, S.-J. SWAT modeling of best management practices for Chungju dam watershed in South Korea under future climate change scenarios. *Paddy Water Environ.* 2014, *12*, 65–75. https://doi.org/10.1007/s10333-014-0424-4.
58. Phomcha, P.; Wirojanagud, P.; Vangpaisal, T.; Thaveevouthti, T. Modeling the impacts of alternative soil conservation practices for an agricultural watershed with

the SWAT model. *Procedia Eng.* 2012, *32*, 1205–1213. https://doi.org/10.1016/j.proeng.2012.02.078.

59. Ricci, G.F.; Jeong, J.; De Girolamo, A.M.; Gentile, F. Effectiveness and feasibility of different management practices to reduce soil erosion in an agricultural watershed. *Land Use Policy* 2020, *90*, 104306. https://doi.org/10.1016/j.landusepol.2019.104306.
60. Rocha, J.; Roebeling, P.; Rial-Rivas, M.E. Assessing the impacts of sustainable agricultural practices for water quality improvements in the Vouga catchment (Portugal) using the SWAT model. *Sci. Total Environ.* 2015, *536*, 48–58. https://doi.org/10.1016/j.scitotenv.2015.07.038.
61. Tripathi, M.P.; Panda, R.K.; Raghuwanshi, N.S. Development of effective management plan for critical subwatersheds using SWAT model. *Hydrol. Process.* 2005, *19*, 809–826. https://doi.org/10.1002/hyp.5618.
62. Tuppad, P.; Kannan, N.; Srinivasan, R.; Rossi, C.G.; Arnold, J.G. Simulation of Agricultural Management Alternatives for Watershed Protection. *Water Resour. Manage.* 2010, *24*, 3115–3144. https://doi.org/10.1007/s11269-010-9598-8.
63. Ullrich, A.; Volk, M. Application of the Soil and Water Assessment Tool (SWAT) to predict the impact of alternative management practices on water quality and quantity. *Agric. Water Manag.* 2009, *96*, 1207–1217. https://doi.org/10.1016/j.agwat.2009.03.010.
64. Uniyal, B.; Jha, M.K.; Verma, A.K.; Anebagilu, P.K. Identification of critical areas and evaluation of best management practices using SWAT for sustainable watershed management. *Sci. Total Environ.* 2020, *744*, 140737. https://doi.org/10.1016/j.scitotenv.2020.140737.
65. Wang, W.; Xie, Y.; Bi, M.; Wang, X.; Lu, Y.; Fan, Z. Effects of best management practices on nitrogen load reduction in tea fields with different slope gradients using the SWAT model. *Appl. Geogr.* 2018, *90*, 200–213. https://doi.org/10.1016/j.apgeog.2017.08.020.
66. Yang, W.; Liu, Y.; Simmons, J.; Oginskyy, A.; McKague, K. SWAT Modelling of Agricultural BMPs and Analysis of BMP Cost Effectiveness in the Gully Creek

Watershed. Available online: http://www.abca.on.ca/downloads/wbbe-huron-swat-modelling-2013-08-21.pdf (accessed on 05 February 2022).

67. Zhang, X.; Zhang, M. Modeling effectiveness of agricultural BMPs to reduce sediment load and organophosphate pesticides in surface runoff. *Sci. Total Environ.* 2011, *409*, 1949–1958. https://doi.org/10.1016/j.scitotenv.2011.02.012.
68. Nyeko, M. Hydrologic Modelling of Data Scarce Basin with SWAT Model: Capabilities and Limitations. *Water Resour. Manage.* 2015, *29*, 81–94. https://doi.org/10.1007/s11269-014-0828-3.
69. Beven, K. How far can we go in distributed hydrological modelling? *Hydrol. Earth SYstem Sci. Discuss. Eur. Geosci. Union* 2001, *5*, 1–12.
70. Martínez-Retureta, R.; Aguayo, M.; Stehr, A.; Sauvage, S.; Echeverría, C.; Sánchez-Pérez, J.-M. Effect of Land Use/Cover Change on the Hydrological Response of a Southern Center Basin of Chile. *Water* 2020, *12*, 302. https://doi.org/10.3390/w12010302.
71. Qi, J.; Li, S.; Bourque, C.P.-A.; Xing, Z.; Meng, F.-R. Developing a decision support tool for assessing land use change and BMPs in ungauged watersheds based on decision rules provided by SWAT simulation. *Hydrol. Earth Syst. Sci.* 2018, *22*, 3789–3806. https://doi.org/10.5194/hess-22-3789-2018.
72. Qi, J.; Zhang, X.; Yang, Q.; Srinivasan, R.; Arnold, J.G.; Li, J.; Waldholf, S.T.; Cole, J. SWAT ungauged: Water quality modeling in the Upper Mississippi River Basin. *J. Hydrol.* 2020, *584*, 124601. https://doi.org/10.1016/j.jhydrol.2020.124601.
73. Jodar-Abellan, A.; Valdes-Abellan, J.; Pla, C.; Gomariz-Castillo, F. Impact of land use changes on flash flood prediction using a sub-daily SWAT model in five Mediterranean ungauged watersheds (SE Spain). *Sci. Total Environ.* 2019, *657*, 1578–1591. https://doi.org/10.1016/j.scitotenv.2018.12.034.
74. Chaplot, V. Impact of spatial input data resolution on hydrological and erosion modeling: Recommendations from a global assessment. *Phys. Chem. Earth Parts ABC* 2014, *67–69*, 23–35. https://doi.org/10.1016/j.pce.2013.09.020.
75. Geza, M.; McCray, J.E. Effects of soil data resolution on SWAT model stream flow and water quality predictions. *J. Environ. Manage.* 2008, *88*, 393–406. https://doi.org/10.1016/j.jenvman.2007.03.016.

76. Dickey, E.C.; Shelton, D.P.; Jasa, P.J.; Peterson, T. Tillage, Residue and Erosion on Moderately Sloping Soils. *Biol. Syst. Eng.* 1984, *27*, 1093–1099.
77. Unger, P.W.; Vigil, M.F. Cover crop effects on soil water relationships. *J. Soil Water Conserv.* 1998, *53*, 200–207.

Chapter 5: General Conclusions

The chapters presented in this thesis show that land use and management changes in the Czech landscape can significantly affect the dynamics of the small water cycle. Crop changes, land use changes, and the incorporation of agricultural conservation practices all affect the hydrology in a basin. The Soil and Water Assessment Tool (SWAT) was utilized to assess these effects at the basin-scale in the Czech Republic. SWAT is the most widely used hydrologic model in modern literature, but it had rarely been used to model the Czech landscape. We were able to show that SWAT is applicable in this region and that it is also able to model the effects of landscape management changes that are unique to the Czech Republic. In Chapter 2 it was demonstrated that the adoption of a specific biofuel crop (rapeseed) did not positively reinforce the small water cycle at the farm-scale. The available water content in the soil, discharge at the basin's outlet, and surface runoff ratios were all significantly higher in the rapeseed adoption scenarios. The increased available water content does reinforce the small water cycle and may indicate that rapeseed could be a more appropriate crop in future climate change scenarios (with longer drought periods expected). Increased surface runoff ratios and discharge do not reinforce the small water cycle and may indicate higher potential soil losses from the landscape especially as rapeseed is planted during the rainy season. The winter wheat scenarios resulted in higher evapotranspiration which does contribute to the local cycling of water. The adoption of rapeseed also had disproportionate effects on the small water cycle depending upon its position of adoption within the basin, which may be of interest to farmers and local land managers to make decisions regarding rapeseed field locations within the basin.

Chapter 3 showed that SWAT is also applicable to the Czech landscape at the management-scale in addition to the farm-scale. While there have been some improvements in the small water cycle reinforcement since the end of the Communist Era, there is still much room for improvement. The 2019 land use scenario reinforced the small water cycle the most, but the crop rotations from the pre-Communist Era reinforced the small water cycle the most followed by the current rotation while the crop rotation during the Communist Era reinforced the small water cycle the least. This study suggests that to reinforce the small water cycle, a more diverse crop rotation should be established throughout the Czech landscape as well as reverting some agricultural areas back to brushland, permanent grassland, or forest. In this study, many generalizations had to be made regarding reservoir processes and management- the SWAT model of Vrchlice could be improved if such practices were public knowledge.

Chapter 4 reinforced SWAT's applicability to the Czech agricultural landscape. SWAT is an extremely flexible tool that makes scenario analysis in a landscape relatively easy. SWAT was able to effectively model the incorporation of agricultural conservation practices at both the farm- and the management-scale. Contour tillage at the farm-scale was the practice that reinforced the small water cycle the most, followed by residue incorporation. At the management-scale, there was no influence due to continuity nor scale (above 33% by area) of agricultural conservation practice adoption across the basin. This indicated that basin managers should incentivize any willing farmer to incorporate such practices. Agricultural conservation practice adoption across both scales (the farm- and the management-scale) significantly affected the small water cycle to a similar degree as land use changes. Being that the Czech Republic is a highly agricultural country, agricultural conservation practice adoption could greatly influence the dynamics of the small water cycle and could aid in its holistic landscape management.

The largest potential source of error in any model is the quality of its input data. While our efforts were somewhat limited regarding soil data quality (at both Nučice and Vrchlice) and reservoir and landscape management (at Vrchlice), SWAT was able to model the water balance variables at both basins with either “good” or “very good” performance indicators. SWAT is semi-distributed and semi-physically based, which also leads to some possible sources of error as it does not realistically represent some processes and it can be highly influenced by user discretion (such as HRU aggregation). Regardless of these possible sources of error, SWAT is still an extremely flexible model especially when it comes to scenario analysis and can only be improved as additional data become more available.

In the face of future climate change, it is more important than ever to try to manage landscape and water processes in a holistic manner. To accomplish this, a management goal outlined in the Czech Republic is to reinforce the small water cycle. This thesis has shown that reinforcing the small water cycle is possible in an agricultural landscape by varying crop rotations, re-establishing riparian zones with forest, brush, or permanent grasslands, and to incentivize widespread agricultural conservation practice adoption. The studies presented in this thesis also reinforce the necessity of cooperation. Central databases for reservoir and agricultural management would be invaluable to researchers. As hydrological modeling becomes more commonplace, it becomes increasingly necessary to foster relationships and collaboration between scientists, landowners, and watershed managers. This cooperation would greatly aid land owners and basin managers in making informed decisions regarding landscape management.

List of Tables

List of Figures