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Modelling the effects of land use change on a peri-urban catchment in Portugal

Modellering av hur förändrad markanvändning påverkar ett avrinningsområde i Portugal

Saga Hävermark

ABSTRACT

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Societal developments are associated with land use change, and with urbanization in particular. Urbanization can influence hydrological processes by decreasing evapotranspiration and infiltration as well as by increasing streamflow, peak flow and overland flow. This causes higher risks of flooding. Although several studies have investigated the impacts of urbanization on streamflow over the last decades, less is known about how urbanization affects the hydrological processes in peri-urban areas characterized by a complex mosaic of different land uses. This study aimed to model the impact of land use change, or more specifically urbanization, on the hydrological responses of the small peri-urban Ribeira dos Covões catchment (6.2 km^2) located in central Portugal. The catchment has undergone rapid land use change since the mid-1950s associated with conversion of agricultural fields (decreased from 48 to 4%) into woodland and urban areas, which increased from 44 to 56% and from 8 to 40%, respectively. For the study, the hydrological modelling system MIKE SHE was used. Parameters and data of climate, vegetation and soil types were used as input. There were also land use maps and daily streamflow values available for the hydrological years 2008/09 to 2012/13, which were used to calibrate and validate the model. The statistics from the calibration and validation both indicated that the model simulated the streamflow well. The model was designed to examine both how past land use change might have affected the streamflow, and to investigate the impacts on hydrology if the urban area was to be increased to cover 50% of the catchment. It was not only the importance of the urban cover's size that was tested, but also the placement of additional urban areas. Three future scenarios were run, all with a 50% urban cover, but distributed differently within the catchment. The study did not indicate that an increase in urbanization leads to higher peak flow or streamflow. Neither could any decrease in infiltration be seen. All three scenarios however gave an increase in overland flow of approximately 10% and a decrease in evapotranspiration by 55%, regardless of where the urban areas were added. The reliability of the models can be enhanced by additional climate, soil and vegetation data. This would improve the results and make them more useful in decision making processes in the planning and management of new urban areas.

Keywords: Urbanization, Land use change, Streamflow, Peak flow, Overland flow, Infiltration, Evapotranspiration, Hydrological modelling, MIKE SHE.

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REFERAT

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Samhällets ständiga utveckling medför förändringar i markanvändning. Utvecklingen och förändringarna är framför allt associerade med urbanisering som kan påverka ett avrinningsområdes hydrologiska processer genom att exempelvis reducera dess evapotranspiration och infiltration samt öka vattenföringen, högsta flödet och ytavrinningen. Det i sin tur ökar risken för översvämning. Trots att många studier har undersökt urbaniseringens inverkan på vattenföring de senaste decennierna saknas viss kunskap om dess påverkan på hydrologin i stadsnära avrinningsområden, kännetecknade av flera olika typer av markanvändning. Denna studie syftade till att modellera hur förändringar i markanvändning, eller mer specifikt urbanisering, påverkar hydrologin i det lilla stadsnära avrinningsområdet Ribeira dos Covões (6,2 km^2) i centrala Portugal. Avrinningsområdet har genomgått snabba markanvändningsförändringar sedan mitten av 1950-talet i samband med en omvandling av åkrar (täckningsarean har minskat från 48 till 4 %) till skogsmark och urbaniserade områden, vilkas storlek har ökat från 44 till 56 % respektive 8 till 40 %. För att uppfylla syftet har den hydrologiska modellen MIKE SHE använts. Parametrar avseende klimat samt vegetations- och jordegenskaper användes som indata till modellen. Det fanns också tillgång till en markanvändningskarta över området samt dagliga flödesvärden mellan de hydrologiska åren 2008 och 2013. Dessa användes för att kalibrera och validera modellen. Statistiken för både kalibreringen och valideringen indikerade en fullt acceptabel modell. Modellen var avsedd att undersöka dels hur tidigare förändring i markanvändning kan ha påverkat vattenföringen, dels för att studera effekten på hydrologin om urbaniseringen fortgår tills dess täckning är 50 % av avrinningsområdet. Det var inte bara betydelsen av de urbana ytornas storlek som testades, utan även placeringen av dem. Tre framtidsscenarier togs fram, alla med en urban yta på 50 % fördelad olika inom avrinningsområdet. Studien indikerade inte att ytterligare urbanisering ökar vare sig flödet eller det högsta flödet. Inte heller gav de någon minskning av infiltration. Alla tre scenarierna gav emellertid en ökning av ytavrinningen med cirka 10 % och en minskning av evapotranspirationen med 55 %, oavsett placering av de urbana ytorna. Modellernas tillförlitlighet skulle kunna förbättras med hjälp av ytterligare klimat-, vegetations- och jordindata. Det skulle förbättra resultaten och göra dem användbara i beslutsfattanden vid planering och utveckling av nya urbana områden.

Nyckelord: Urbanisering, Markanvändningsförändring, Vattenföring, Högsta flöde, Ytavrinning, Infiltration, Evapotranspiration, Hydrologisk modell, MIKE SHE.

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PREFACE

This master thesis is the last step of the Master Programme in Environmental and Water Engineering of 30 ECTS at Uppsala University. The project was initiated and supervised by Zahra Kalantari, post-doctoral researcher at Stockholm University and technical advisor in hydrology at ÅF, Solna. Additional supervision was given by Carla Sofia Santos Ferreira at CERNAS, Agrarian School of Coimbra in Portugal, who has been studying the Ribeira dos Covões catchment for several years. Subject reviewer was Giuliano Di Baldassarre, professor at the Department of Earth Sciences at Uppsala University. Final examiner was Anna Coulson Sjöblom, senior lecturer at the Department of Earth Sciences at Uppsala University.

First of all, I would like to thank my supervisor Zahra Kalantari, who offered me the project to begin with. She has given me great supervision as well as a chance to challenge myself. She has encouraged me to search for answers when there have been problems regarding the modelling, and that has taught me so much. She has been a great support, especially when it comes to the use of MIKE SHE. I would also like to express my appreciation to everyone at ÅF in Solna for how welcoming and helpful they have been.

I would also like to thank Giuliano Di Baldassarre for all the interesting discussions and the helpful material he has given me. He has really improved my ability to use and analyse hydrological models.

A very special thank you is directed to Carla Sofia Santos Ferreira. Without her, I would not even have had the opportunity to go through with this project. She has given me so much information and data associated with the area of study. I have had the fortune to read her PhD thesis, which has increased my knowledge within the subject and I am thankful to her for letting me use it for my thesis. I also want to thank her for letting me use Figure 4 from her thesis (Figure 3.2 in her thesis).

I would like to thank the Danish Hydraulic Institute (DHI), and Sten Blomgren, Mona Sassner and Maria Roldin in particular, for giving me a licence to use MIKE Zero (MIKE SHE and MIKE 11 in my case) in the first place. They have been very helpful throughout the whole project by answering any questions I might have had about the modelling. I also want to thank DHI for letting me use Figure 6 from their MIKE SHE user guide (Figure 1.1 in the guide). On that note, I would last but not least like to thank Elsevier for the permission to use Figure 1 (Figure 2 in the article) and Randall Donahue for the use of Figure 2 (Figure 2 in the article).

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POPULÄRVETENSKAPLIG SAMMANFATTNING

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I takt med att samhället ständigt utvecklas förändras även användningen av mark. Den samhälleliga utvecklingen associeras framför allt med urbanisering, som är övergången från landsbygd till stadsområde. Urbaniseringen tog fart på riktigt världen över i samband med industrialiseringen och har inte avstannat sedan dess. FN menar att hela 80 % av världens bruttonationalprodukt kommer från urbaniserade områden och att 70 % av världens population kommer att bo i städer år 2050. Idag är den siffran 54 %.

Urbaniseringen medför många positiva förändringar för samhället, men även vissa negativa förändringar. Ett negativt exempel är urbaniseringens effekter på hydrologiska processer. Urbanisering av ytor innebär att ytorna blir mer svårgenomträngliga jämfört med jordbruks- och naturliga ytor. Det leder till en ökad vattenföring, och framför allt ett ökat högsta flöde och ytavrinning, vilket i sin tur ökar risken för översvämning. Urbanisering innebär också ett borttag av vegetation, vilket reducerar infiltration och evapotranspiration. Den kan också leda till en så kallad ”värmeö-effekt”, vilken betyder att lokal nederbörd kan förändras till följd av urbanisering.

Urbaniseringsgraden är störst i stadsnära områden, kännetecknade av urbana områden blandade med naturliga och semi-naturliga. Tillväxthastigheten i sådana områden är fyra gånger så stor som den i andra, helt urbana, områden. Det är därför extra viktigt att studera vilken påverkan urbaniseringen har på hydrologin i sådana områden. Det finns många studier som påvisar urbaniseringens inverkan på hydrologiska processer generellt, men det råder en viss kunskapsbrist gällande hur effekten är på just stadsnära områden under urbaniseringstryck. Den här studien fokuserar därför på det stadsnära avrinningsområdet Ribeira dos Covões, beläget nära staden Coimbra i centrala Portugal. Området har en area på 6,2 km^2 och består till största del av skog samt urbana ytor. Så har läget emellertid inte varit särskilt länge. Områdets snabba urbanisering började under 1950-talet, då 48 % av arean var täckt av åkrar. Idag ligger den siffran på 4 %. Den nuvarande dominerande markanvändningstypen är skog (56 %). Urbaniseringen står för 40 % av markanvändningen. Syftet var att modellera vilken effekt urbaniseringen har haft på hydrologin i Ribeira dos Covões genom åren samt att analysera den framtida inverkan om de urbana ytorna fortsätter att växa tills de upptar hälften av områdets totala area. Det har dessutom studerats om placeringen av ytterligare urbanisering har någon betydelse. Det gjordes med hjälp av tre olika urbaniseringsscenarion, där den urbana ytans storlek var densamma i alla, men distributionen inom området skiljde sig dem emellan. Stadsutvecklingen inom området fortsätter ständigt och viss urbanisering är redan planerad. Om det kunde påvisas att vissa områden var mindre lämpliga än andra för urbanisering, ifråga om störning av hydrologi, skulle det kunna ge underlag till var framtida urbanisering bör ske.

Till hjälp har MIKE SHE, ett avancerat och integrerat verktyg för hydrologisk modellering utvecklat av Danmarks hydrologiska institut (DHI), använts. Modellen har en förmåga att simulera hela den hydrologiska cykeln med dess ingående processer. Parametrar avseende klimat samt vegetations- och jordegenskaper användes som indata till modellen. Det fanns också tillgång till en markanvändningskarta över området samt dagliga flödesvärden mellan de hydrologiska åren 2008 och 2013 (ett hydrologiskt år startar den första oktober och slutar den sista september). Dessa användes för att kalibrera och validera modellen samt undersöka känsligheten i olika parametrar och indata. Allt detta gjordes i hopp om att ta fram bästa möjliga modell för att simulera de tre framtidsscenarierna med 50 % urbana ytor placerade olika inom avrinningsområdet.

Studien indikerade inte att urbaniseringen har haft en inverkan på vattenföringen historiskt sett. De visade heller inte att ytterligare urbanisering ger vare sig ett ökat flöde och högsta flöde eller minskad infiltration. Istället verkar flödet endast vara i direkt anslutning till nederbörd. Alla tre scenarierna gav emellertid en ökning av ytavrinningen med cirka 10 % och en minskning av evapotranspirationen med 55 %, oavsett placering av de urbana ytorna. Det indikerade att placeringen av de urbana ytorna inte spelar någon roll för avrinningsområdets hydrologiska cykel.

Modellens tillförlitlighet skulle kunna förbättras med hjälp av ytterligare klimat-, vegetations- och jordindata mer specifika för Portugal. En pålitligare modell skulle också göra det möjligt att sätta den i förhållande till framtida scenarion för klimatförändringar, framför allt avseende regn och temperatur. Om modellen optimeras kan resultaten bli användbara i beslutsfattanden vid planering och utveckling av nya urbana områden.

GLOSSARY

Antecedent conditions	A temporary state in dynamic systems that precedes and influences hazards and their consequences.
Baseflow	Also known as low flow. The streamflow that comes from the deep subsurface flow and delayed subsurface flow.
Drainage system	Patterns shaped by the streams, rivers and lakes in a drainage basin.
Evapotranspiration	The sum of evaporation and plant transpiration from land and water to the atmosphere.
Groundwater recharge	A process where water is transported from surface to groundwater.
Groundwater storage	Water stored in the ground.
Heat island	A built up area that is warmer than the surrounding rural areas.
Hydrograph	A graph that shows the flow rate (y-axis) and time (x-axis) past a specific point in a river.
Hydrological connectivity	The passage of water from one part of the landscape to another.
Infiltration	When water on the ground surface enters the soil.
Initial potential head	Hydraulic head. A measure of the chemical energy that causes groundwater to flow.
Overland flow	Surface runoff. Precipitation runoff over the landscape that occurs when the precipitation amount that is stored on the surface is larger than the soil´s infiltration capacity.
Peak flow	Peak (maximum) of streamflow.
Peri-urban area	Transition zone between urban and rural areas, with a population density of more than 40 inhabitants per km^2.
Streamflow	The flow of water in streams and rivers.
Urbanization	A shift from rural to urban areas. Includes developments of buildings, road, parking lots etc.
Water cycle	The continuous movement of water on Earth.

TABLE OF CONTENTS

1. INTRODUCTION

Many river basins around the world are rapidly changing together with societal development. Such developments may involve changes in land use, and urbanization in particular, which in turn will disturb the surrounding environment in various ways. Urbanization is a land use transformation into built up areas involving developments of e.g. buildings, roads and parking lots (DWUA, 2015). It is often difficult to obtain all the data needed to assess the effects of urbanization on hydrology. According to Ferreira et al. (2015), hydrological properties such as land use, soil and vegetation properties, climate and topography can have differently important roles within a catchment depending on the climatic settings. They state that in a Mediterranean climate, characterised by hot dry summers, wet winters and a mean annual temperature of 15 ºC, the storage capacity and soil moisture control the runoff at a large extent. The difference in precipitation rate between summer and winter in such a climate can increase the risks of overland flow during wintertime. In a colder climate, another parameter (such as snowmelt) might instead have a higher impact on the hydrology.

It is important to be able to mitigate problems related to urbanization, especially with the current urbanization trend. Since the start of the industrial era, the urban areas have expanded worldwide (UN, 2008). As investment and employment opportunities increase, so does the urbanization. According to UN (2008), 80% of the world´s gross domestic product (GDP) comes from urban areas and by the year of 2050, 70% of the world´s population will live in such settings. Today that number is 54% (WHO, 2015).

The increasing urbanization is largest in peri-urban areas, with a growing rate about four times the rate in most other urban areas (Piorr et al., 2015). Peri-urban areas are defined as transition or interaction zones between urban and rural areas (PU-GEC, 2009) with a population density of more than 40 inhabitants per km^2 (Piorr et al., 2015). The mix between natural or agricultural areas and urban areas means that the landscape of peri-urban areas is heterogeneous, with some natural and some urbanized parts. They are often particularly exposed to rapid changes (Janowfsky et al., 2014). Although several studies have been investigating the impacts of urbanization on hydrology over the last decades (e.g. Im et al., 2009; O'Driscoll et al., 2010; Tavares et al., 2012; Janowfsky et al., 2014; Miller et al., 2014; Ferreira et al., 2015), less is known about how urbanization affects the hydrological processes in peri-urban areas (Ferreira et al., 2015). The impact on hydrology can vary within such an area, because of the different types of land use and vegetation, which is why they are particularly important to study. This thesis has focused on a peri-urban catchment located in a Mediterranean environment.

A common tool used to study the hydrological impacts of urbanization is modelling (Janowfsky et al., 2014; Miller et al., 2014). Hydrological models used together with observations of hydrological processes have shown a possibility to use said models for scenarios of future urbanization and its hydrological effects (Im et al., 2009). A variety of modelling systems can be used for this, such as the PUMMA model (Janowfsky et al., 2010) and the HBV model (Grillakis et al., 2010). One that has proven well is MIKE SHE (Olesen et al., 2000; Kaiser-Hill, 2001; Chui, T.F.M & Trinh, D.H, 2013), originated from Systeme Hydrologique Européen (Abbott et al., 1986). It has then been further developed by the Danish Hydraulic Institute (DHI) and is today a deterministic, fully distributed and physically-based modelling system (DHI, 2007). According to DHI (2007), MIKE SHE can be used for analysing and managing many different water and environmental problems related both to surface water and groundwater. It is also able to take the geographical distribution of land use into account. The principles behind MIKE SHE, and how to use it, are described in more detail in section 3.2.

1.1. OBJECTIVE

The objective of the project was to model how land use change, and urbanization in particular, affects the hydrological responses of a peri-urban catchment (Ribeira dos Covões) nearby Coimbra, Portugal. The hydrological model MIKE SHE was used to investigate the impact of past land use change within the area, as well as to evaluate the hydrological impact if the urbanization continues. The following issues will be answered:

- How will a possible increase in the catchment´s urban cover affect future streamflow and peak flow?

- How will a possible increase in the catchment´s urban cover affect future overland flow, evapotranspiration and infiltration?

- How will different locations of the urbanization around the area affect the catchment´s future streamflow, peak flow, overland flow, evapotranspiration and infiltration?

1.2. OUTLINE OF THE REPORT

In the following section (2), a background is presented. It includes what impacts land use change (mainly urbanization) have on hydrological processes, why these impacts are important to mitigate and what the effects are on peri-urban areas in particular. Section 2 also contains an introduction to hydrological modelling.

Section 3 introduces the used methods and materials. It includes a presentation of the study site for the thesis, information about how the modelling data was collected and a description of the chosen modelling system; MIKE SHE. It ends with explaining how the model was built, calibrated, validated and run.

Section 4 presents the results of the modelling. It includes figures and tables to give a clear picture of what the results actually are.

Section 5 is where the discussion is held. In it, the results of the modelling are discussed with thoughts of limitations and improvements.

The thesis ends with some conclusions (section 6) to sum up what the study has contributed to and what can be done in the future.

2. BACKGROUND

Water evaporates from all surfaces, such as oceans, lakes and rivers, and from soils (Graham & Butts, 2005). Plants also have an important role in water evaporation and transpiration and, together with remaining water vapour, water reaches the atmosphere before it falls back to planet Earth as precipitation (DHI, 2007). The rain infiltrates into the soil and may partially reach groundwater, flow to channels as baseflow or run off directly to streams and rivers as overland flow (Graham & Butts, 2005). This is the hydrologic cycle; a closed loop from where water cannot be removed but which can be disturbed by human activities. Land use, and urbanization in particular, influences the hydrological processes.

2.1. URBANIZATION AND HYDROLOGY

Urbanization, usually carried out in natural surfaces, comprises removal of vegetation (Carlson & Arthur, 2000). The conversion of green areas, associated with land surface evaporation and vegetation evapotranspiration, into sealed surfaces leads to a decreasing actual evapotranspiration in urban areas (Carlson & Arthur, 2000). Urbanization also causes changes in precipitation at the particular site ("heat island" effect) by increasing the local precipitation, making the catchment response faster to precipitation and reducing the delay between precipitation and runoff (Rose & Peters, 2001).

Urban surfaces have a higher imperviousness than natural and agricultural lands, which means that they have a lower infiltration capacity due to soil compaction and surface sealing (Carlson & Arthur, 2000; EPA, 2012). This in turn can enhance overland flow (Miller et al., 2014), which creates a higher flood hazard (WFRG, 2008). O'Driscoll et al. (2010) write that because of the decrease in water storage capacity and evapotranspiration, more precipitation is available for streamflow. In catchments with various land use types, overland flow can occur on both the pervious (through saturation excess and/or infiltration excess processes) and impervious surfaces, but it is more prone to be generated on the latter (Ferreira et al., 2015).

Urbanization affects streamflow and thus the shape of the hydrograph, particularly peak flow and baseflow as well as response and lag times (Figure 1). In urban areas, although they have great water availability for runoff, the generally smooth surfaces favour quick overland flow transportation. This makes the hydrograph rise abruptly and lets it reach higher peak flows as the imperviousness of the surface area increases. In a study performed by Rose & Peters (2001), where they compared urbanized and less- or non-urbanized watersheds in Atlanta, the peak flows increased for the urbanized watersheds (by about 30 to 100%). Greater peak flows were shown to enhance flood hazards. Baseflows were instead decreased by 25 to 35% because of reductions in groundwater recharge and storage.

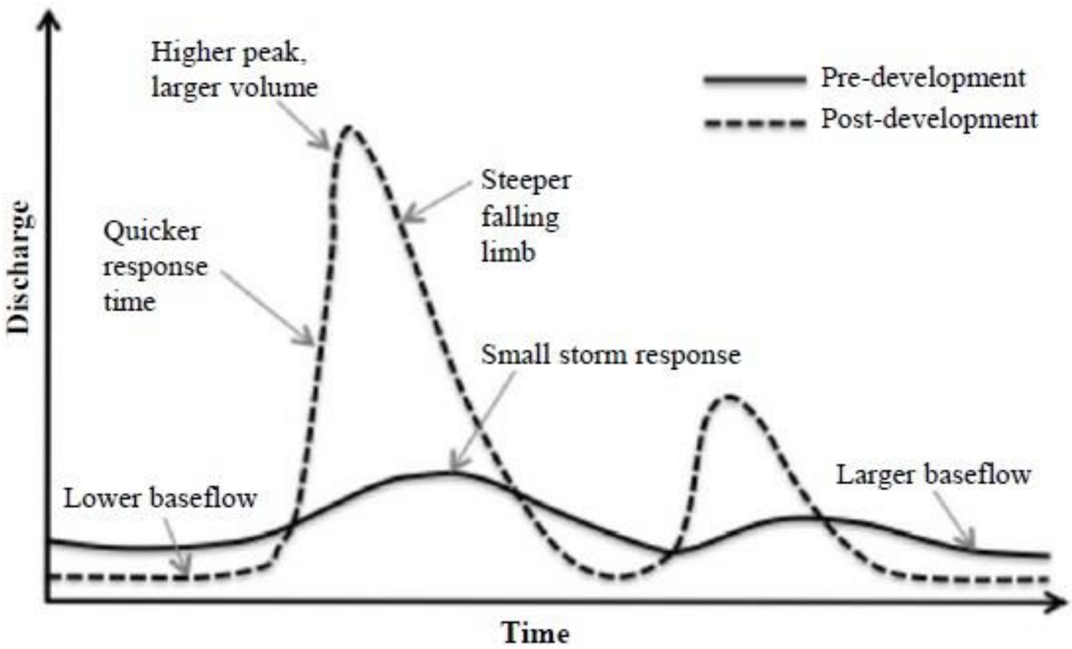

Figure 1. Differences in hydrograph properties between rural (line) and urban (dashed line) catchments. Source: Fletcher et al., 2013.

Urbanization has turned out to have different impacts on the hydrologic cycle in different parts of the world (O'Driscoll et al., 2010). It is not always the most urbanized areas that change the hydrology the most (Arrigoni et al., 2010). Catchment characteristics like geology, lithology, climate, soil properties and mean slope of the catchment affect hydrological processes, and as a consequence there are difficulties in defining the actual hydrological impact of land use change (O'Driscoll et al., 2010). In a warm climate (for example a Mediterranean climate), the temperature is often a controlling factor of runoff (Garcia-Ruiz et al., 2011). If the future temperature in such a climate rises, it will increase the evapotranspiration and decrease the streamflow. In that particular case, the hydrological impact from the temperature may be higher than the impact from the urbanization.

2.1.1. Effects on peri-urban catchments

The fact that peri-urban catchments have urban parts as well as natural and agricultural areas means that the impacts on hydrology may be different within the different parts of such a catchment (Braud et al., 2013a). How the urban areas affect the hydrology was already described previously in this section (2.1). Natural areas may instead be able to mitigate some of those effects. Environments covered by forests, where the vegetation cover is large, maintain high rainfall retention capacity because of the evapotranspiration and interception of vegetation (Nosetto et al., 2012). Viaud et al. (2005) showed that agricultural areas with hedges can increase the actual evapotranspiration because of the deep roots of hedges. However, some agricultural areas can also affect soil permeability by making the soil more compact (Hebrard et al., 2006). This may enhance overland flow generation, which will also contribute to the runoff response in peri-urban catchments.

With the different types of land use in peri-urban areas it also follows that they can have various drainage systems, which means that there can be different types of streams within them (Miller et al., 2014). Natural and agricultural drainage is often controlled by roadside ditches and drainage pipes (Dunn & Mackay, 1996). Urban areas are more complex. They are drained by artificial drainage systems, with extended drainage network that can speed up flow transfer to cause flooding (Braud et al., 2013b).

Overall, peri-urban catchments contain different land uses, which provide sinks and sources of overland flow (Ferreira et al., 2015). Hydrological connectivity – the passage of water from one part of the landscape to another – is a controlling factor of catchment runoff response and flood hazards (Bracken & Croke, 2007). The concept of hydrological connectivity has become more important over the last decade and it is still a research challenge in peri-urban catchments due to the different land uses (Miller et al., 2014).

The hydrological connectivity is also driven by antecedent weather conditions. Easton et al. (2007) mention antecedent weather conditions linked to soil moisture as a factor that affects storage capacity. Bracken & Croke (2007) furthermore state that antecedent conditions affect the hydrological connectivity. Soil moisture is especially related to runoff in Mediterranean climates, but it is hard to predict because of its spatial and temporal variation (Bracken & Croke, 2007). Overall, it is harder to estimate the urbanization´s impact on runoff processes and connectivity in peri-urban catchments, but it is important nonetheless for catchment management (Ferreira, 2015).

2.2. HYDROLOGICAL MODELLING

Hydrological models can be applied to predict a variety of changes in hydrological processes caused by changes in e.g. land use or climate (Song et al., 2014). Hence they can also contribute to solving issues regarding flood events. To obtain the best possible hydrological model, the input parameters have to be well thought through.

2.2.1. Sensitivity analysis

An important step of all modelling is to perform a sensitivity analysis (SA). SA aims to identify the key parameters that have the greatest influence on the model performance (Song et al., 2014). It makes it possible to modify or reduce model inputs that have no effects on the output. It should be applied before the actual modelling, as the selection of sensitive parameters will affect the rest of the calibration, validation and simulations (Beck, 1987). It is important in model parameterisation as well as calibration, optimisation and uncertainty quantification. Along with SA, it is also important to examine the uncertainty of the model results (uncertainty analysis; UA) (Song et al., 2014). In general, SA can be said to answer the question “Where does this uncertainty come from?” and UA to answer “How uncertain is this inference?”. In most modelling, SA and UA are coupled and therefore only SA will referred to for the continuing of this thesis. There are various SA methods and Song et al. (2014) describe some of them. However, many of them require months of time and could therefore not be performed. The methodology of the SA used is described in section 3.2.6.

2.2.2. The Budyko framework

Before modelling catchments of smaller scales, it can be useful to look into the Budyko framework. The Budyko curve (Figure 2) is a curve that describes the observed patterns between climate, evapotranspiration and runoff (Donahue et al., 2007). It has shown great results in predicting catchment energy and water balances. Even though the focus was not on those two, it is interesting to mention the curve since vegetation was the changing factor in this study. Donohue et al. (2007) argue that vegetation is important to include into the Budyko framework before applying it to hydrological models of smaller scales. Due to time limits, the Budyko framework was not included. It is brought up in case there are wishes to include it in future modelling.

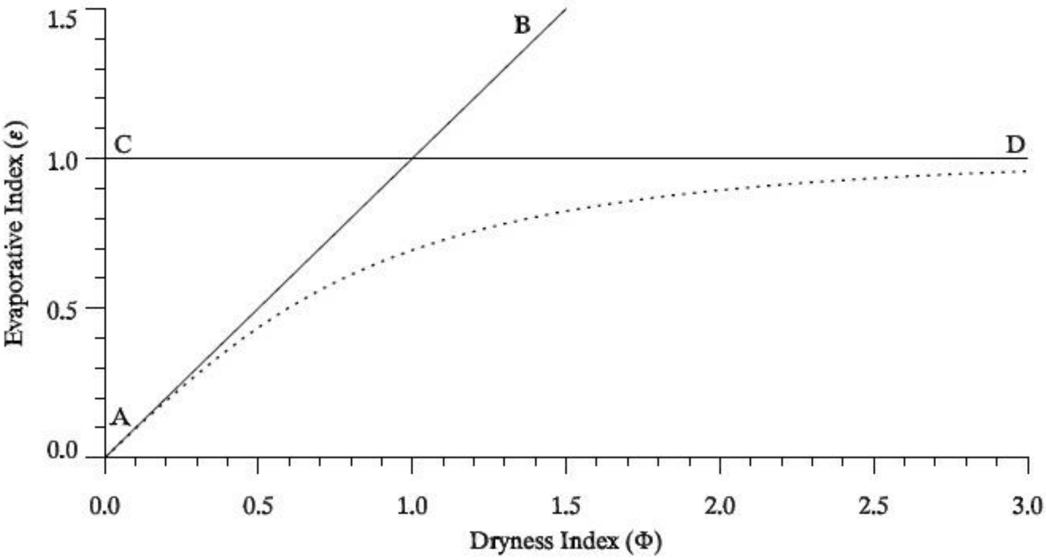

Figure 2. The Budyko curve (dashed line), defined by equation 4 (Appendix A); the relationship between the dryness index and the evaporative index (E/P). Line A-B is the energy limit to evapotranspiration, of which a site cannot plot above unless precipitation is being lost. Line C-D is the water limit, of which a site cannot plot above unless there is an additional input of water other than precipitation. Source: Donahue et al., 2007.

The relationship was tested by Budyko on both moderately sized catchments (areas larger than 1,000 km^2) and large catchments (areas larger than 10,000 km^2), using measured evapotranspiration. It was found that the relationship explained 90% of the variation in observed evapotranspiration values for the moderately sized catchments. The results for the large catchments were even better. There are difficulties in predicting water balances in smaller catchments (like in this study) with Budyko´s curve. This is where the vegetation plays an important part and, as previously stated, it is said that it can be useful to include vegetation into the Budyko curve before approaching hydrological modelling.

3. MATERIALS AND METHODS

The materials and methods used were all chosen to answer the questions specified in the objective of the thesis (section 1.1).

3.1. STUDY AREA

The study site, Ribeira dos Covões, is a small (6.2 km^2), slightly elongated catchment that drains into Mondego River with a south to north orientation. It is located about 3 km from the city centre of Coimbra (40°13’N, 8°27’W), which is the largest city in central Portugal (Figure 3).

Figure 3. The location of Portugal in Europe (marked red) and the location of the Ribeira dos Covões catchment in Portugal (blue dot in the lower right corner).

The site has been studied and monitored since 2005 by previous researchers. Thus, a detailed description of the study site can be found in Ferreira et al. (2000); Ferreira et al. (2010); Ferreira et al. (2011); Ferreira et al. (2012); Tavares et al. (2012); Ferreira et al. (2014); Ferreira (2015); Ferreira et al. (2015); Pato et al. (2015); Ferreira et al. (2016).

3.1.1. Climate and streams

Ribeira dos Covões has a Mediterranean climate, with an annual temperature of 15 ºC and an annual rainfall of 892 mm between the years 1941 and 2000. The summers (June-August) are hot and dry, which means that most of the precipitation falls during the other months. The wettest period is from November to March, when 61% of the year's total rain falls. As many as 83% of the rain events over the period 2001-2013 were small, with less than 10 mm/day. More extreme precipitation events have however been observed during that same period, with the largest maximum daily precipitation rate being 102 mm. It occurred on October 25, 2006 and led to floods that damaged houses. Rain events like that return as seldom as every 10th to 50th year, and it has not been possible to say with certainty if this particular one was caused by urbanization or extreme rainfall.

The catchment is well drained (Figure 4). The main stream is perennial and flows continuously throughout the year. Smaller ephemeral branches, which flow during and directly after precipitation events, and intermittent branches, which only flow during wet seasons, are also present.

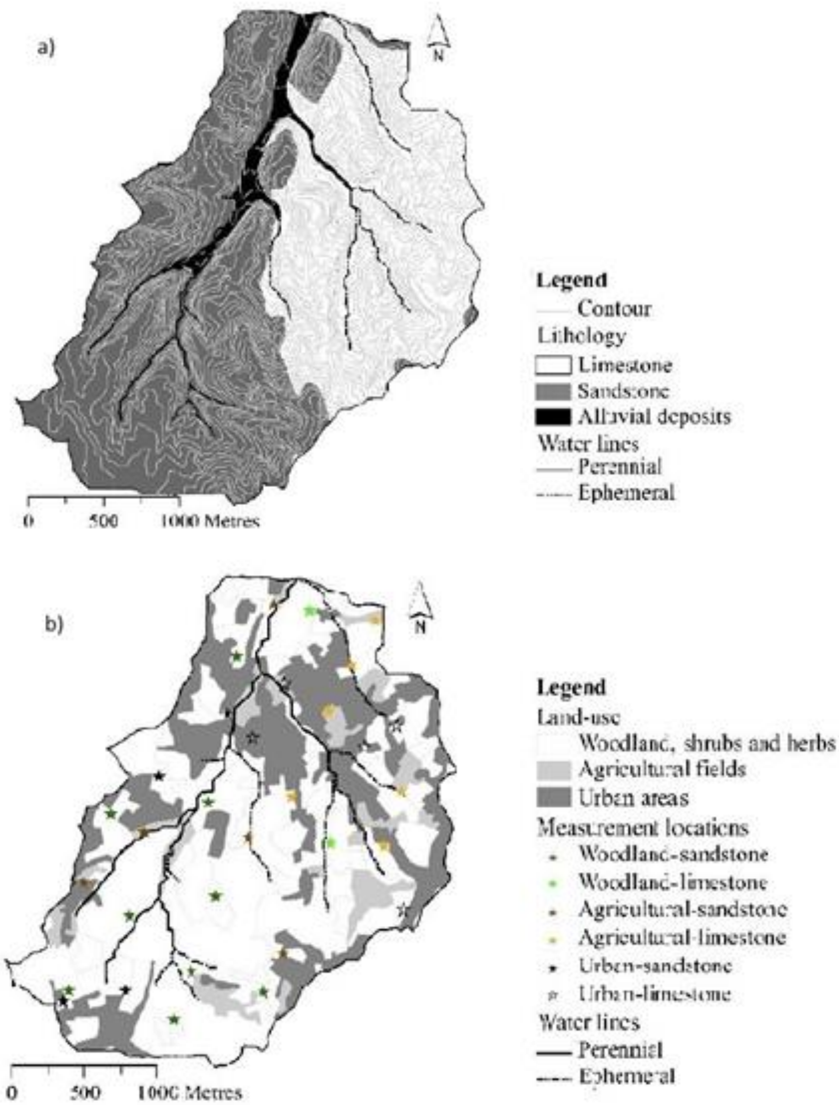

Figure 4. The Ribeira dos Covões catchment. **a)** The geology and streams of the catchment. **b)** The land use types in the catchment. Source: Ferreira, 2015.

The outlet is in the north part of the catchment. Previous studies of the catchment have shown that precipitation is the dominating driver of streamflow.

3.1.2. Geology and lithology

The catchment is dominated by limestone in the east (43% of the area) and sandstone in the west (57% of the area) (Figure 4a). The limestone is partially dolomitic and marl from the Jurassic era, partially from the Cretaceous period. The soils from the Jurassic era (mainly cambisols) are shallow, with a depth of only about 0.1-0.4 m, whereas the Cretaceous ones have depths that range from 7 to 8 m. The sandstone is mainly characterised by deposits and conglomerate of sand and gravel from the Paleogene and Neogene periods. The soils, fluvisols and podzols, are all deeper than 3 m and can reach as deep as 25 m. The altimetry shows values from 29 to 201 m. The average slope of the catchment is about 10º, but steeper values attain 40º in shallower soils.

3.1.3. Land use

Almost half of the Ribeira dos Covões catchment was agricultural until 1972, when urbanization began in the area (Figure 5). The development has been rapid, leaving 40% of the area as urban in 2012. While the urban patches of the catchment have increased, the agricultural areas have decreased. In 2012, the agricultural areas did not cover much more of the catchment than the open spaces with little to no vegetation (4.4% agricultural and 2.8% open spaces) (Figure 4b). The dominating land use type today is woodland.

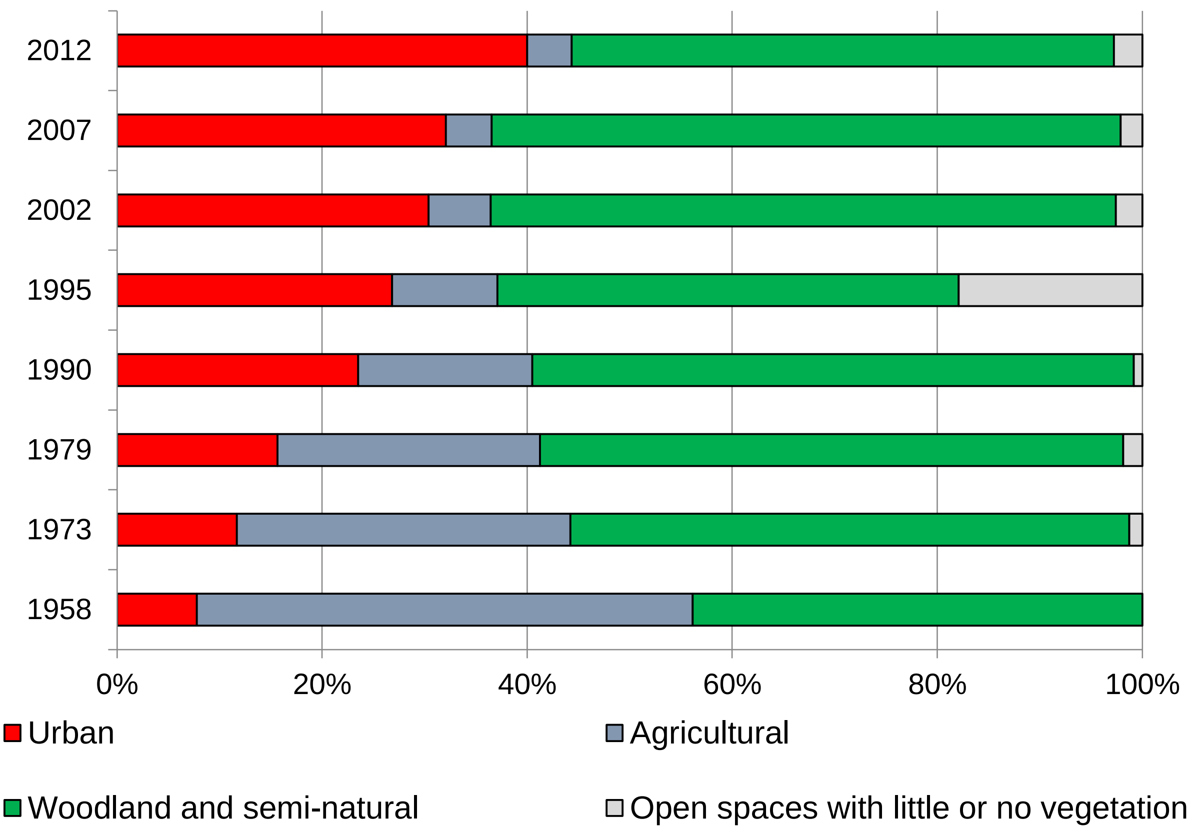

Figure 5. Changes in land use in Ribeira dos Covões between 1958 and 2012.

The remaining agricultural fields mainly consist of olives and arable land. The urban areas are a mixture of older houses and gardens, more recent blocks of apartments, services and recreational areas. The urbanization mostly affects the north part of the catchment.

Eucalypt is the dominant woodland stand, due to a high commercial price of timber. Apart from the eucalypt, which constitutes the majority of the woodland (55%), there are also pine plantations (29%). Smaller areas are oak (1%) and vegetation formed by shrubs, grass and olive (15%) placed in part of the limestone area. Most of the eucalypt is located over sandstone. Different types of woodland affect flow differently. Dense eucalypt provides less water infiltration, due to greater soil hydrophobicity, than sparse eucalypt and oak and is thus exposed to more overland flow. Temporal changes in hydrophobicity have been found to explain 74% of the overland flow variation in a Portuguese catchment. The overland flow is lowest in natural oak stands (with high soil permeability).

Despite the increase in woodland, Figure 5 shows that it decreased from the year 2007 to 2012. That was due to construction work and the building of an enterprise park at the top of the catchment, which caused deforestation. The deforestation in favour of urban areas is expected to continue, since many urban projects are already approved. Since 2012 however, the land use has not changed much due to a peak of economic crises in Portugal. The only ongoing constructions are within the enterprise park, but there have been discussions about urbanizing the south-east part of the catchment.

3.2. MIKE SHE

At the beginning of the project, different hydrological modelling systems such as the PUMMA model and the HBV model were roughly examined in order to find the most suitable one. A spatial model was needed that could not only simulate streamflow and peak flow, but also relate them to changed land use. It was soon discovered that MIKE SHE – together with MIKE 11 – would be a good fit since it is fully distributed and can model the entire water cycle. As previously mentioned (section 1), MIKE SHE has performed well in earlier studies with similar approaches.

The hydrological modelling system MIKE SHE is part of the MIKE Zero tools (DHI, 2015). Mike Zero is a commonly used interface for simulations, analyses, presentations and visualisations of projects concerning aquatic environments (DHI, 2014a). There are several available modelling systems within the framework, but the one mainly used was MIKE SHE. MIKE SHE can however not perform simulations of streams, so in order to include rivers and lakes another tool called MIKE 11 was needed (MIKE 11, 2015). It has a main simulation editor linked to other editors such as a network editor, cross section editor, boundary editor, parameter editor and time series editor (DHI, 2014b). All except the last one were used.

3.2.1. Processes described in MIKE SHE

MIKE SHE is, as mentioned before, a fully distributed physics-based modelling tool. According to DHI (2007), MIKE SHE is able to implement multiple descriptions for every important hydrological process (Figure 6), which makes it suitable for simple applications as well as advanced ones. It allows each process to be solved with the data available for the particular process, i.e. it is not dependent on what data is available for the other processes.

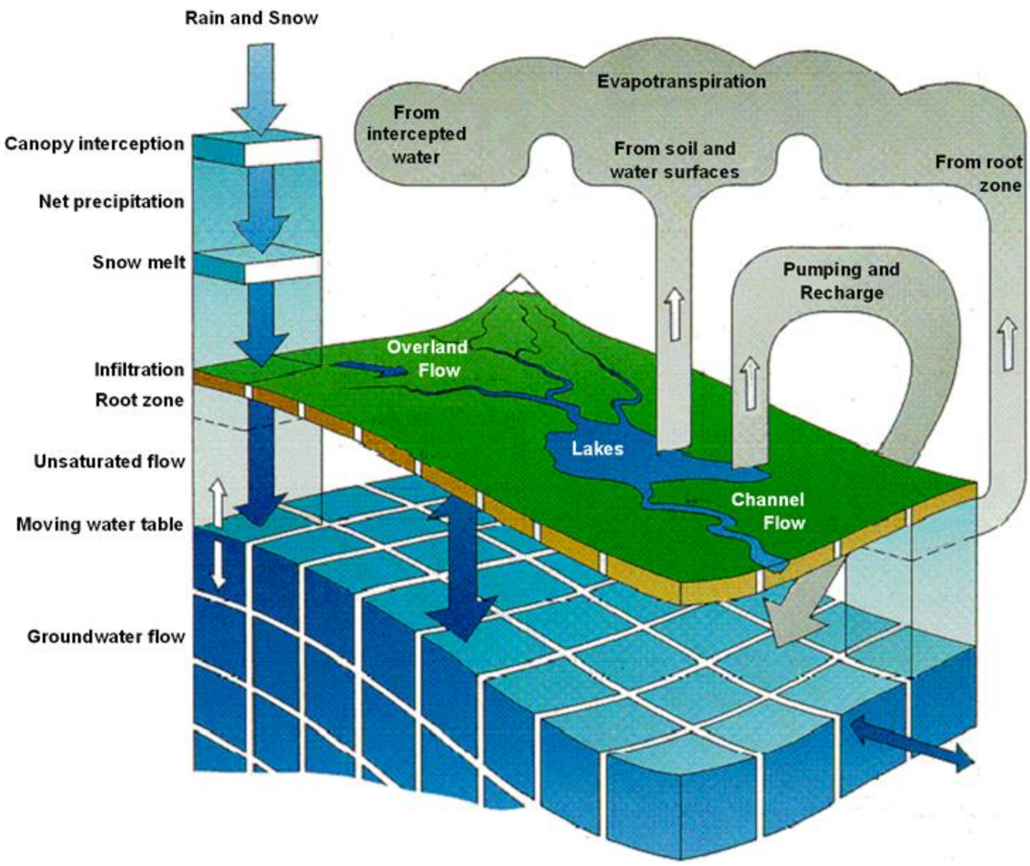

Figure 6. Evapotranspiration, channel and overland flow, infiltration, precipitation, snowmelt, unsaturated and saturated flow; processes which can all be simulated in MIKE SHE (and MIKE 11 for channel flow). Source: DHI, 2007.

MIKE SHE uses differential equations to describe the hydrological processes of channel, overland, saturated (groundwater) and unsaturated flow, evapotranspiration and exchanges between channel and surface (Table 1). However, if the model becomes too complex or if there is some lack of data, for some of the processes there are simpler methods to estimate them with (DHI, 2007).

Table 1. Methods used in MIKE SHE to describe hydrological processes. Source: DHI (2007).

Hydrological process	**Method**
River flow	1D St Venant equation
Overland flow	2D finite difference-diffusive wave
Saturated flow	Darcy´s law
Unsaturated flow	Richard´s equation
Actual evapotranspiration	Kristensen & Jensen (1975)

The data required for the model depends on which hydrological processes are of interest. Even so, three parameters are needed for almost every MIKE SHE model:

- Model domain
- Topography
- Precipitation

These parameters are usually described as polygons, gridded data or as point and station data respectively. Other data that can be included, depending on what the model´s purpose is, are potential evapotranspiration, air temperature and solar radiation (for snowmelt calculations), sub-catchment delineation, geometry and cross sections of the river, land use distribution, soil distribution and subsurface geology (DHI, 2007). In this study, potential evapotranspiration, temperature, geometry and cross sections of the river, land use distribution and soil distribution were input files together with the three basic parameters listed above.

3.2.2. MIKE SHE in other studies

MIKE SHE is commonly used in research of climate and hydrology and has proven to be especially useful for modelling both groundwater and surface water (Graham & Butts, 2005). Chui & Trinh (2013) used the model to evaluate how urbanization affects the overall water balance and water regime of a catchment in Singapore. They also tested the model to see how green roofs and bio-retention systems (which remove contaminants and sedimentation) can affect the results of urbanization. They found that urbanization reduces the catchment´s infiltration by 20%, its baseflow by 66% and increases the peak discharge by 60 to 100%. Green roofs were shown to be able to reduce the peak discharge by 50% and delay it with two hours. Bio-retention systems were also able to mitigate the peak discharge by 50%, as well as increase the infiltration by 30%.

Kalantari et al. (2012) performed a study where four different hydrological models were compared to evaluate which one could best predict peak flow in a small catchment in Norway. MIKE SHE was found to be the most suitable model, but only in cases where there was a wide range of detailed input data.

Kalantari et al. (2013) used MIKE SHE to study the same catchment in Norway. They quantified overland flow in response to four extreme rain events and land use types. They found that the spatial distribution of land use, together with the size and timing of storm events, affected the discharge at the catchment outlet.

Im et al. (2009) used MIKE SHE to quantify the effects of land use change on a watershed in Korea. The area contained large rice paddies and was exposed to rapid urbanization. The aim was to estimate how that affected the streamflow, overland flow, evapotranspiration and infiltration. The results showed an increase in the first two and a decrease in the two latter. The authors came to the conclusion that the model worked well for simulating streamflow at the outlet, especially with respect to total flow and baseflow. The peak flows were often underestimated because of unsatisfying input data. The main problem, however, was the model´s difficulty to model the hydrological behaviour of rice paddies. The model was therefore not found ideal for simulating flooded paddy fields.

3.2.3. Limitations and uncertainties

As with all modelling tools, MIKE SHE does face some challenges. Uncertainties when modelling with MIKE SHE are often related to input data and model structure (Beven, 2012). Im et al. (2009) write about the importance of long-term experimental data associated with MIKE SHE. A large amount of data means that the model will require a long execution time and may become unnecessarily complex. DHI (2007) therefore proposes that only the one or two most important processes are included in the model. Simpler equations for the processes can also be used as well as a smaller model size, larger grid spacing or shorter calibration period. According to previous studies (e.g. Zhiqiang et al., 2008), the most important thing for achieving good modelling results is as mentioned input data of decent quality.

3.2.4. Data and initial preparations

In order to perform hydrological modelling, input data is needed. Data needed for the study was handed by Carla Sofia Santos Ferreira (Personal communication). Most of the gathered data files had been created using ArcGIS 10 software (Table 2).

Table 2. Available GIS files used for modelling in MIKE SHE.

Data	Comment
Catchment area	A map of the study site including a background map of the area and a drainage area outlining the catchment.
Digital elevation model (DEM)	5 x 5 m grid size.
Land use map	Containing polygons representing different land use types. It included for types of surfaces: -Impermeable surfaces -Semi-permeable surfaces -Permeable surfaces -Water detention basins
Soil type map	File containing polygons representing different soil types.
Streams	Files containing the three different types of streams (perennial, ephemeral and intermittent).

Additional to the GIS files, files containing precipitation between the years 1941 and 2013 were available. Some years only included monthly rainfall averages, but daily values were given for the periods studied in the thesis (section 3.2.7). Daily values of potential evapotranspiration were available from October 1, 2008 to September 30, 2013. Those values were used in all the models. The potential evapotranspiration was dependent on the provided climatic data and calculated using the Thornthwaite and Mather method (Thornthwaite & Mather, 1955). Daily streamflow values for the hydrological years 2008/09 to 2012/13 were also provided. They were based on field measurements. Monthly temperature values, available for the same years as the precipitation, were provided from meteorological stations. Land use distributions (open spaces, agricultural, urban and woodland areas) from the years 1958, 1973, 1979, 1990, 1995, 2002, 2007 and 2012 were also given. The land use and soil maps were both originally set with resolutions of 12 x 12 m but changed into maps with grid sizes of 10 x 10 m, whereas the resolution of the topography was initially 5 x 5 m. The catchment grid was eventually set to 10 x 10 m to speed up the model.

3.2.5. Building the model

The model was built to simulate the water movement in the land phase of the entire catchment. All useful data sets were verified, and corrected when needed, to create a fully distributed model. Besides the data received from Carla Sofia Santos Ferreira, soil and vegetation properties including Leaf Area Index (LAI) and root depth were used. They came from (Briel, 2013), representing a cold Swedish climatic setting. It was not possible to get similar data files for a Mediterranean climate. Parameters such as roughness coefficients (Manning´s M for calculating overland flow) and hydraulic conductivities were set after studying Chow (1959), Knutsson & Morfeldt (1995) and HydroSOLVE (2015). The streams of the catchment were simulated in MIKE 11 by creating cross sections. To include them in the flow model, MIKE 11 and MIKE SHE were coupled via river links.

When the model was completely set up, it was pre-processed and edited where necessary. The model could then be run for calibration, followed by validation and then finally the simulations.

3.2.6. Calibration, validation and sensitivity analysis

The model was calibrated between the hydrological years 2008/09 and 2009/10. It was decided to calibrate it with a trial and error method (Im et al., 2009) focusing on how to best simulate the streamflow at the outlet of the catchment, since there were observed daily values available for that. It was considered especially important to capture the peak flow and hydrograph recession. To avoid over-fitting, the number of adjusted parameters during the calibration was minimized (Refsgaard & Storm, 1996). After discussions with Zahra Kalantari (Personal communication), some parameters were considered more important to investigate than others. The parameters that were examined were the horizontal and vertical hydraulic conductivities, initial potential head, drainage time constant and level, roughness coefficient for overland flow and river bed roughness. Only four of these parameters improved the results when they were changed from their initial values (Table 3).

Table 3. Initial and final parameter values defined when calibrating the MIKE SHE model to simulate land use change.

	Model parameter	**Initial value**	**Final value**
Saturated zone	Horizontal cond. (K_h (m/s))	1e-009	5e-013
	Vertical cond. (K_v (m/s))	1e-010	2.5e-013
	Initial potential head (m)	-3 (below ground)	-2.4
Drainage	Drainage time constant (T_c (/s))	5e-006	5e-005

During the calibration, the simulation statistics were calculated. Focus was laid on achieving a good correlation coefficient (R) (equation 1) and Nash Sutcliffe correlation coefficient (NSE) (equation 2) between the observed and modelled streamflow. The mathematical expression for R is defined in e.g. DHI (2013) and Liuxin et al. (2015):

$$R = \frac{\sum(Calc_{i,t} - \overline{Calc}_{i,t})(Obs_{i,t} - \overline{Obs}_{i,t})}{\sqrt{\sum(Calc_{i,t} - \overline{Calc}_{i,t})^2 \sum(Obs_{i,t} - \overline{Obs}_{i,t})^2}} \tag{1}$$

, where $Obs_{i,t}$ and $Calc_{i,t}$ are the observations and calculations at location, i, with respect to time, t, and $\overline{Obs}_{i,t}$ and $\overline{Calc}_{i,t}$ are the means of them. R calculates the linear dependency between simulated and observed data. It is equal to 1 if the modelled values match the observed ones perfectly (DHI, 2013), but $R > 0.8$ indicates a strong linear dependency. (Liuxin et al., 2015). If there are a lot of measured values, R is a good indicator of how well the simulations fit the observations. R was therefore one of the two chosen statistics to focus on during the calibration.

The mathematical expression of NSE, when n observations exist:

$$NSE = 1 - \frac{\sum(Obs_{i,t} - Calc_{i,t})^2}{\sum(Obs_{i,t} - \overline{Obs}_{i,t})^2} \tag{2}$$

, measures how well the variability in simulated streamflows can explain the variability in observed streamflows. It should also be as close to 1 as possible (Kalantari et al., 2012). $NSE > 0.75$ is considered a good result, $0.36 \leq NSE \leq 0.75$ is desirable and $NSE < 0.36$ is not good (Liuxin et al., 2015). NSE is the most used criteria in calibrations of hydrological models and evaluations of their performances (Gupta et al., 2009), which is why it was chosen.

The calibrated model was then validated for the three hydrological years following after the calibration period. For this, a land use map representing the land use in 2012 was used instead of the land use map in the calibration period. The same criteria applied for the simulation statistics as in the calibration process.

A sensitivity analysis (SA) was also performed. Many SA methods are quite time consuming and it was therefore decided, after deliberation with Giuliano Di Baldassarre (Personal communication), that a simpler method should be applied. In this SA, all parameters except one were kept fixed. The parameter that was not kept constant was changed within a given range to see how the model performance was affected by that parameter. This process was then repeated for several different parameters to identify which parameters affected the model performance the most. The parameters and input data that were changed, other than the ones in Table 3, were:

- Precipitation (input data)
- Potential evapotranspiration (input data)
- Surface roughness coefficient (Manning's M) (parameter)

They were all changed with an increase and a decrease of 30% each.

3.2.7. Scenarios

The model was used to simulate historical land use change as well as a few possible future scenarios (Table 4). Due to time limits, only three of the given historical land use distributions (not including the calibration and validation) were modelled. Land use maps resembling the defined land use distributions in 1973 ("1973 scenario"), 1990 ("1990 scenario") and 2002 ("2002 scenario") were used. The past change in land use was considered interesting in terms of studying how the hydrology has changed while the urban areas have extended.

The first question in the objective was which effect the size of the urban cover has on the streamflow, and especially on the peak flow. To answer that, a future scenario assuming an urban cover of 50% was run. Im et al. (2009) used MIKE SHE to not only find changes in streamflow and peak flow due to land use change, but also to relate it to changes in e.g. infiltration, evapotranspiration and overland flow. All the scenarios were therefore run to examine what impact the urbanization has on those three processes too (as defined in the second question in the objective). The third question was whether or not the location of the urban cover within the catchment has any effect on the flow. To explore that, the urban 50% scenario consisted of a few sub-scenarios that examined if there were any changes in streamflow if the urban cover was moved. In the first sub-scenario ("urban 1"), the additional urban cover was placed at the top of the catchment, near the enterprise park where urbanization is currently happening. In the second sub-scenario ("urban 2"), the additional urban cover was instead placed in the south-east part (mainly on limestone) of the catchment. The third and last scenario ("urban 3") assumed that the future additional urban cover would be nearby the existent urban core downslope. The three future scenarios were run in comparison to the calibration.

Table 4. Distribution of urban areas, woodland areas, agricultural areas and open spaces with little or no vegetation in the Ribeira dos Covões catchment from five different years and for three future scenarios, listed in order of increasing urbanization.

			Land use distribution (%)			
Scenario	**Start date**	**End date**	**Urban**	**Woodland**	**Agricultural**	**Open spaces**
1973	Oct 1, 1972	Sep 30, 1974	11.7	54.5	32.6	1.20
1990	Oct 1, 1989	Sep 30, 1991	23.5	58.7	17.0	0.80
2002	Oct 16, 2001	Oct 15, 2003	30.4	61.0	6.00	2.60
Calibration (2009)	Oct 1, 2008	Sep 30, 2010	34.1	59.8	4.30	1.80
Validation (2012)	Oct 1, 2010	Sep 30, 2013	40.0	52.9	4.40	2.80
Urban 1	Oct 1, 2008	Sep 30, 2010	50.0	47.0	2.40	0.60
Urban 2	Oct 1, 2008	Sep 30, 2010	50.0	44.5	3.50	2.00
Urban 3	Oct 1, 2008	Sep 30, 2010	50.0	48.2	0.00	1.80

The historical and future scenarios were all run for the same amount of time as the calibration, starting from the previous hydrological year and ending after two hydrological years. This gave the models a chance to warm up.

The 2002 scenario started a few weeks into October 2001, simply because there were no daily measured precipitation values available before that. To make sure that all simulations (except for the validation) lasted two years, the 2002 scenario ended a few weeks into October 2003 as well.

For the creation of the urban scenario, with its three sub-scenarios, how the distribution of the other land use types has changed was not taken into consideration. This was done purely because of convenience. It means that the distribution (mainly the woodland) varied with every model (Figure 7).

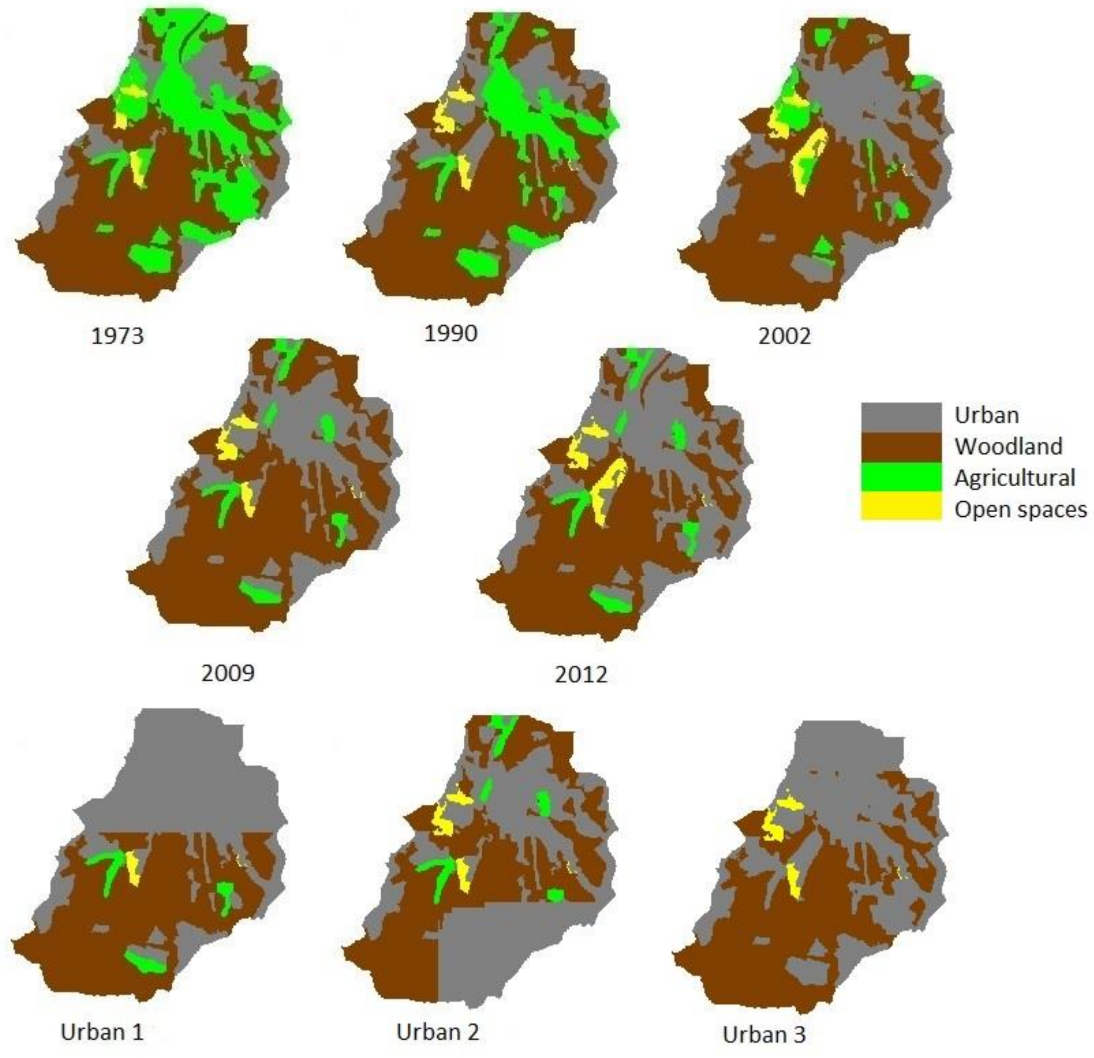

Figure 7. Spatial distribution of woodland, urban areas, agricultural areas and open spaces within the Ribeira dos Covões catchment used to model five past years and three urban scenarios in MIKE SHE.

The most prominent changes were in the urban and agricultural areas, while the size of the open spaces remains more or less consistent. The woodland areas have always been dominant in the past, but decrease most in size in favour of urbanization in the future scenarios.

4. RESULTS

All models calculated streamflow, peak flow, overland flow, evapotranspiration and infiltration. In all eight models, the peak flow occurred sometime between October and April during the second hydrological year (third for the validation) of the simulation period. Because of that, only those seven months of each simulation are presented. The entire simulation periods are found in Appendix B.

4.1. CALIBRATION, VALIDATION AND SENSITIVITY ANALYSIS

The calibration represented the streamflow and peak flow, as well as the recession after the peak, well (Figure 8). One major peak in streamflow occurred, on the same day (November 16, 2009) as the heaviest precipitation. Other than that, there were no extreme rain or flow events during the period.

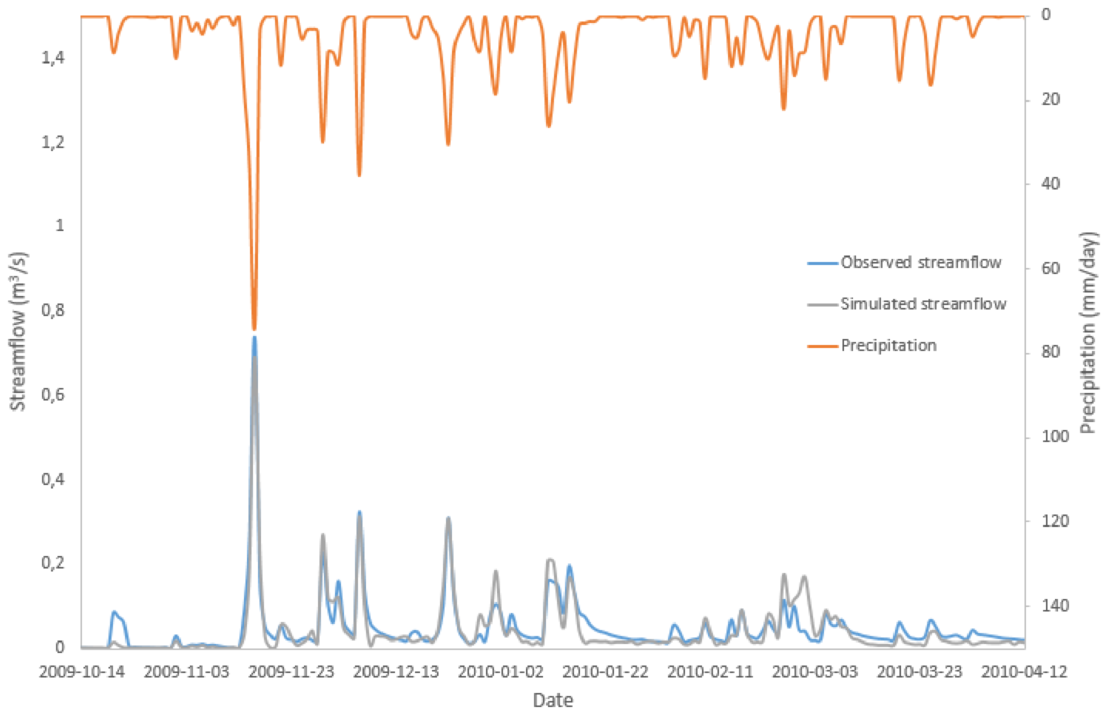

Figure 8. The observed (blue) and MIKE SHE simulated (grey) streamflow plotted against the precipitation (orange) for the period of the calibration when there was a peak in flow.

The validation represented the streamflow well (Figure 9). The several peaks in flow and the recession after each peak was captured. The simulated largest peak flow was delayed one day compared to the observed (March 8, 2013 and March 9, 2013). The streamflow overall was a bit heavier this period than during the calibration period.

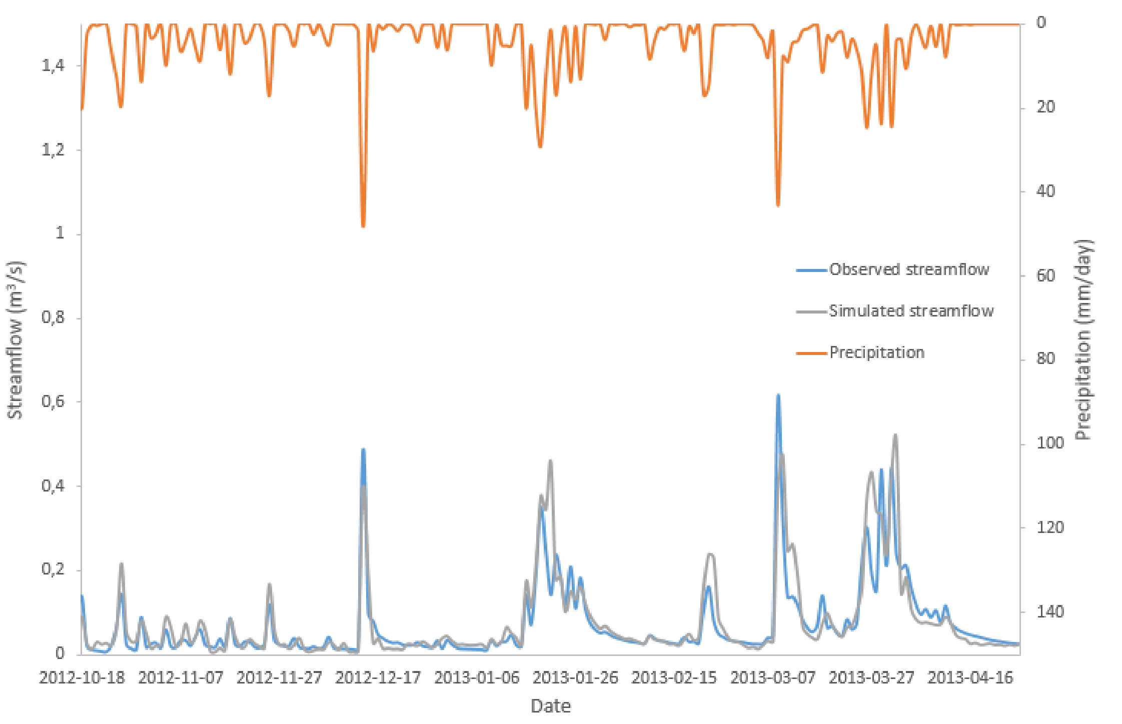

Figure 9. The observed (blue) and simulated (grey) streamflow plotted against the precipitation (orange) for the period of the validation when there was a peak in flow.

The statistics indicated a strong linear dependency (R) between the observed and simulated values for the calibration period (Table 5). They also stated that the variability in simulated data explained the variability in observed data well (NSE). The results for the validation period were not as good as for the calibration period, but very close and still acceptable. The validation period contained several peaks and most of them were well simulated. The main difference was that the highest peak flow was better captured within the calibration period than in the validation period.

Table 5. Comparison between the observed and simulated peak flow, with corresponding precipitation and simulation statistics (correlation coefficient (R) and Nash Sutcliffe correlation coefficient (NSE)) for the calibration and validation periods, calculated in MIKE SHE.

	Date	**Precipitation (mm/day)**	**Peak flow (m^3/s)**	$\boldsymbol{R}$	$\boldsymbol{NSE}$
Obs. 1	Nov 16, 2009	73.8	0.74	-	-
Calibration	Nov 16, 2009	73.8	0.69	0.80	0.59
Obs. 2	Mar 8, 2013	43.1	0.61	-	-
Validation	Mar 8, 2013	43.1	0.39	0.79	0.58

The SA showed that the model was very sensitive to changes in precipitation (Table 6). A higher precipitation rate enhanced the peak in the calibrated model and a lower rate reduced it. An increase in potential evapotranspiration gave a smaller decrease in peak flow, while an increase did not affect the results much. The input values for surface roughness had no significant effect on the output.

Table 6. Values and percentage change in peak flow (calculated in MIKE SHE) when the precipitation (P), surface roughness coefficient (M) and potential evapotranspiration (PET) were increased/decreased with 30%.

	Calibration	**P +30%**	**P -30%**	**M +30%**	**M -30%**	**PET +30%**	**PET -30%**
Peak flow (m^3/s)	0.69	0.90	0.14	0.68	0.68	0.55	0.70
Percentage change (%)	-	+30.4	-79.7	-1.45	-1.45	-20.3	+1.45

Aside from the large changes in precipitation, the model was also sensitive to the changes made in hydraulic conductivity, drainage time constant and initial potential head (Table 3), as already defined in section 3.

4.2. SCENARIO RESULTS

The scenarios can be divided into two groups; historical and future. The historical ones show how past land use change has affected the hydrology, whereas the future scenarios show what might happen if the urbanization continues in different ways. All the scenarios, as well as the calibration and validation periods, were run under normal temperature conditions (Appendix C). There were no observed temperature values below 0 ºC.

4.2.1. Historical scenarios

The streamflow was generally low between the hydrological years 1972/73 and 1973/74 (Figure 10). There were no heavy precipitation or peak flow events.

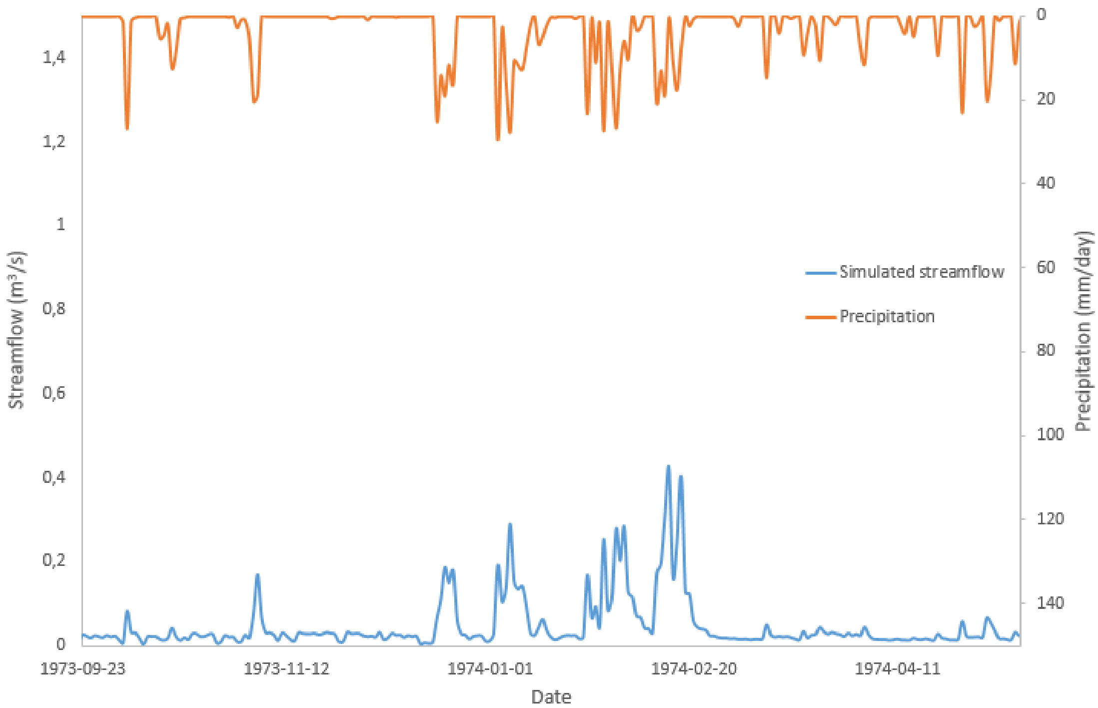

Figure 10. MIKE SHE simulation of streamflow plotted against the precipitation for the period between the hydrological years 1972/73 and 1973/74 when peak flow occurred.

The streamflow for the hydrological years 1989/90 to 1990/91 had a few large peaks (Figure 11). The highest peak flow occurred after a week of heavy precipitation, when the catchment was saturated.

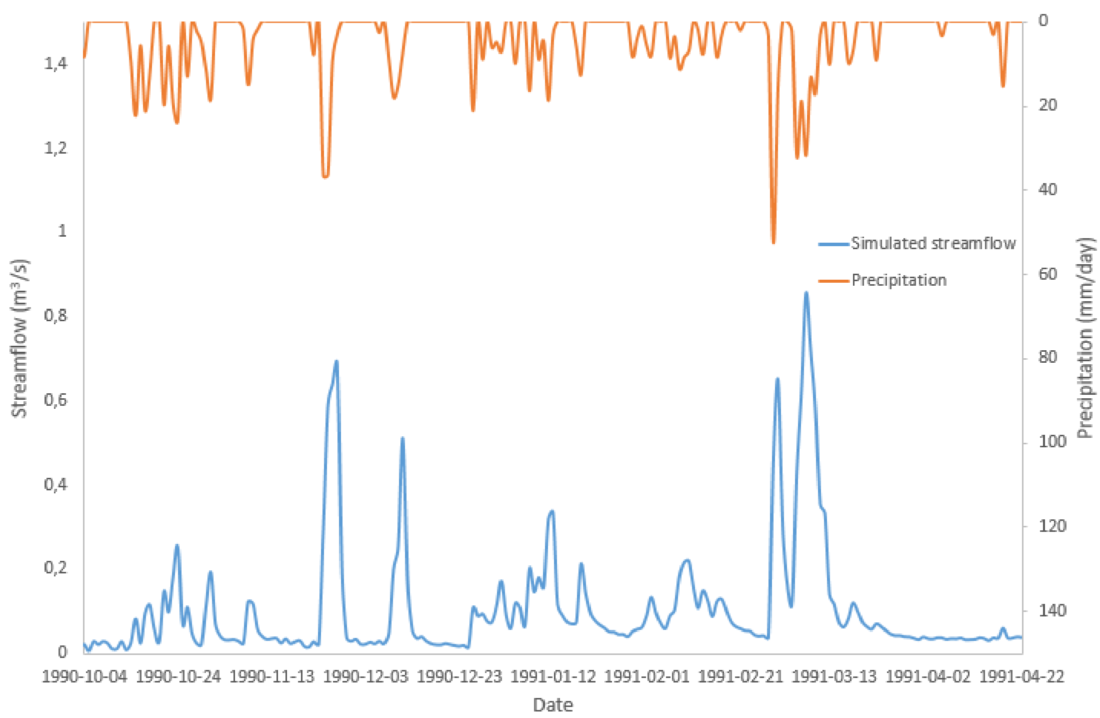

Figure 11. MIKE SHE simulation of streamflow plotted against the precipitation for the period between the hydrological years 1989/90 and 1990/91 when peak flow occurred.

A generally low streamflow for the hydrological years 2001/02 to 2002/03 was modelled (Figure 12). There were no extreme rain or peak flow events.

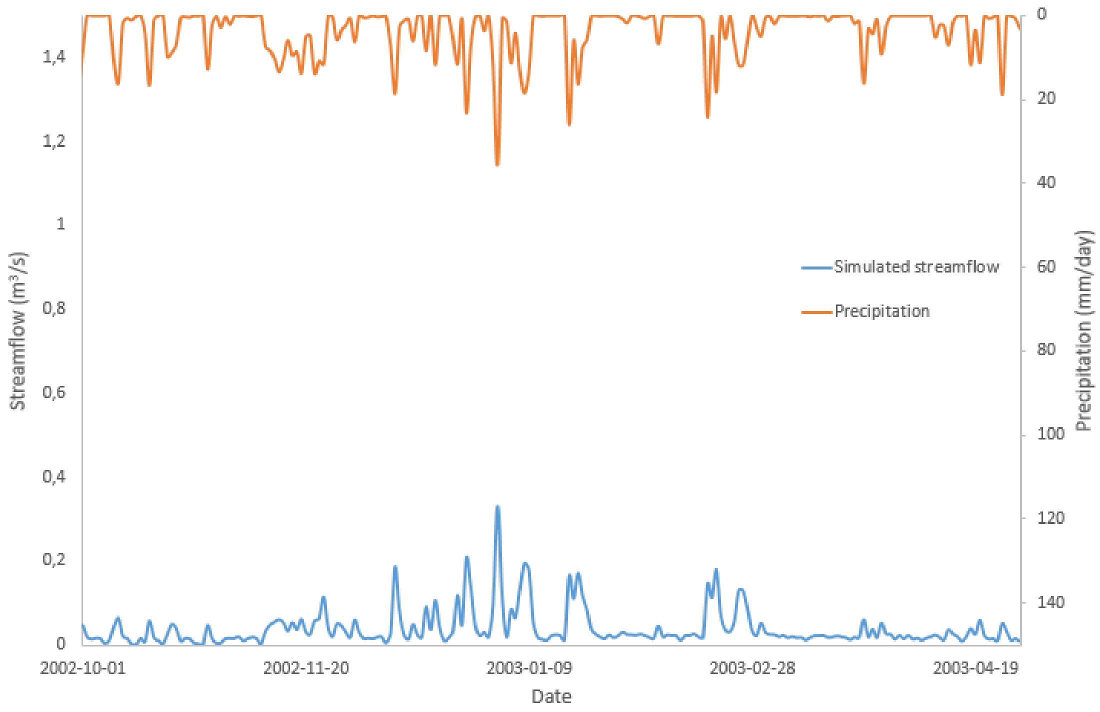

Figure 12. MIKE SHE simulation of streamflow plotted against the precipitation for the period between the hydrological years 2001/02 and 2002/03 when peak flow occurred.

The past urbanization was also examined to study its effects on overland flow, evapotranspiration and infiltration. The evapotranspiration has decreased throughout the years, regardless of the magnitude of the peak flow (Table 7). The overland flow has increased when an overall increase in streamflow, and especially peak flow, has been observed. The modelled infiltration has stayed constant.

Table 7. Peak flow (m^3/s) with corresponding precipitation, overland flow (OL, horizontal and vertical direction) (m^3/s), evapotranspiration (AET) (mm/day) and infiltration (mm/day) calculated in MIKE SHE for the three historical scenarios.

	1973	**1990**	**2002**
Date	Feb 14, 1974	Mar 7, 1991	Jan 2, 2003
Precipitation (mm/day)	30.0	31.8	35.7
Peak flow (m^3/s)	0.42	0.86	0.33
OL x-direction (m^3/s)	$1.24*10^{-3}$	$2.48*10^{-3}$	$1.17*10^{-3}$
y-direction (m^3/s)	$7.04*10^{-5}$	$0.14*10^{-3}$	$7.38*10^{-5}$
AET (mm/day)	1.29	1.03	0.88
Infiltration (mm/day)	$8.60*10^{-3}$	$8.60*10^{-3}$	$8.60*10^{-3}$

The peak flow in the 1973 scenario was delayed with one day, due to heavy rain the days before but not on the actual day.

4.2.2. Future scenarios

The urban scenarios 1, 2 and 3 are presented with reference to the calibration model, which means that they are not presented as future years but as the hydrological years 2008/09-2009/10. The change in streamflow was slightly different compared to the calibrated values depending on in which part of the catchment more urbanization was added (Figure 13). When the urban cover was added to the north part (urban scenario 1), it had no effect on the streamflow much in the beginning, but it was higher towards the end of the simulation. An additional urban area concentrated to the south-east part of the catchment (urban scenario 2) increased the heavier streamflow even more. Urban scenario 3, where the urban cover was added close to the existent urban areas downslope, also increased the heavier streamflow.

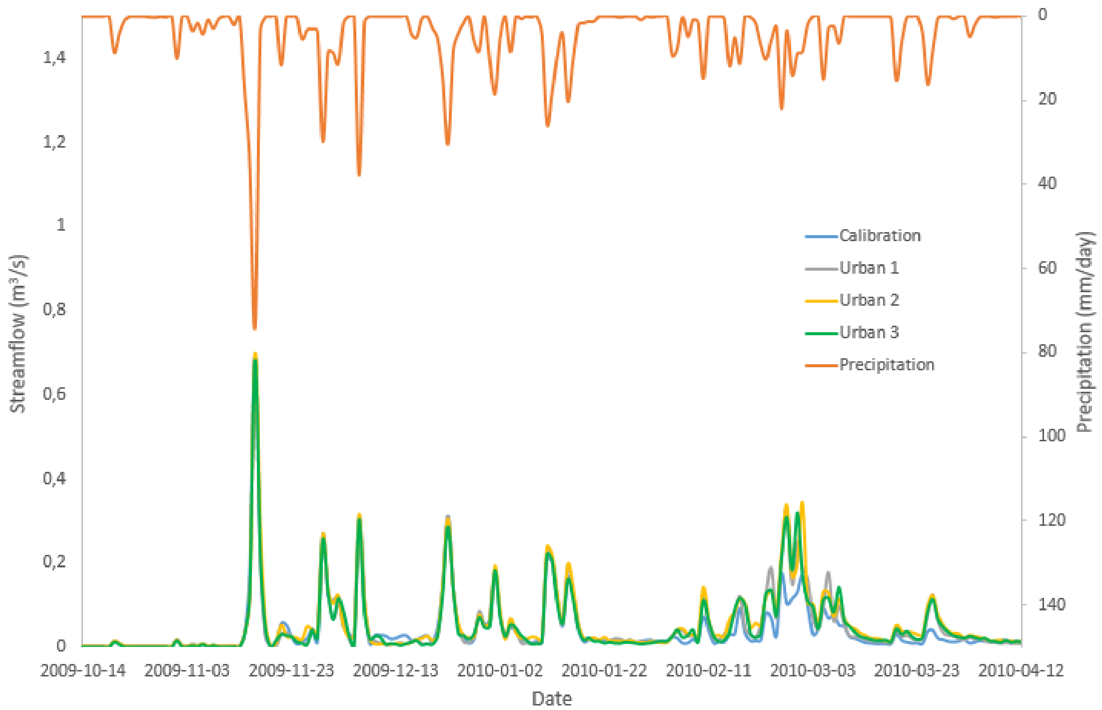

Figure 13. Streamflow plotted against precipitation for a calibrated MIKE SHE model and three urban scenarios (1, 2 and 3).

All the future scenarios with an urban cover of 50% gave slightly different results in peak flow compared to the calibration period (Table 8), where the urban area covered 34% of the catchment. None of them had any major effect on the peak. When the urban area was added to the north part of the catchment (urban 1), almost no difference in the peak could be noticed compared to the calibration. The increase was slightly larger when the urbanization was added to the south-east part of the catchment (urban 2), where an increase in peak flow by approximately 1% on November 16, 2009 compared to the calibration was seen. In the event of more urbanization around the existent urban areas (urban 3), the simulation did not increase the peak flow, but reduced it with a little more than 1%.

Table 8. Change in peak flow (m^3/s), overland flow (horizontal and vertical direction) (m^3/s), evapotranspiration (mm/day) and infiltration (mm/day) on November 16 and percentage change for three urban scenarios compared to the calibration period (calculated in MIKE SHE). The precipitation was 73.8 mm on the day and used in all three scenarios.

	Calibration	**Urban 1**	**Urban 2**	**Urban 3**
Peak flow (m^3/s)	$6.90*10^{-1}$	$6.91*10^{-1}$	$6.94*10^{-1}$	$6.83*10^{-1}$
Percentage change (%)	-	+0.18	+1.11	-1.09
OL x-direction (m^3/s)	$2.90*10^{-3}$	$3.20*10^{-3}$	$3.20*10^{-3}$	$3.20*10^{-3}$
y-direction (m^3/s)	$0.20*10^{-3}$	$0.20*10^{-3}$	$0.20*10^{-3}$	$0.20*10^{-3}$
Percentage change (%)				
x-direction	-	+10.3	+10.3	+10.3
y-direction		-	-	-
AET (mm/day)	1.18	0.54	0.54	0.54
Percentage change (%)	-	-54.6	-54.6	-54.6
Infiltration (mm/day)	$8.60*10^{-3}$	$8.60*10^{-3}$	$8.60*10^{-3}$	$8.60*10^{-3}$
Percentage change (%)	-	-	-	-

The urban scenarios 1, 2 and 3 all gave basically the same changes in overland flow, evapotranspiration and infiltration on the day of the peak flow (November 16, 2009) compared to the calibration. An urban cover of 50% gave an increase in horizontal overland flow, but the vertical flow remained the same compared to the calibration. The evapotranspiration decreased with more than 50% in all scenarios, but the infiltration was constant. The increase in overland flow and decrease in evapotranspiration were the same in all scenarios.

5. DISCUSSION

Both past and possible future land use change was investigated to try to determine the effects of urbanization on the hydrology of the Ribeira dos Covões catchment in central Portugal.

5.1. URBANIZATION'S IMPACT ON THE CATCHMENT'S HYDROLOGY

Urbanization has in many previous studies proven to have major effects on the hydrology of catchments. The aim was to examine if that has been and/or will be the case for the Ribeira dos Covões catchment. The results were somewhat different to previous studies (e.g. Im et al., 2009) and those differences are discussed here.

5.1.1. Historical urbanization's impact on hydrology

Past land use maps were studied in order to investigate how the urbanization has affected the streamflow, peak flow, overland flow, evapotranspiration and infiltration historically. The streamflow and peak flow could not be shown to increase with increasing urbanization (Figures 10, 11 and 12). Instead it seems that they were directly connected to precipitation. Most of the (smaller) peaks occurred on the same day as a larger rainfalls. However, the only really large peak within any of these three different periods (Hydrological years 1972/73-1973/74, 1989/90-1990/91 and 2001/02-2002/03) was on March 7, 1990 (Figure 11). The precipitation rate was high the whole month before that and the precipitation was continuously high, up to around 52 mm/day the week before March 7, which possibly caused the largest peak (0.86 m^3/s) to appear when the soil moisture was high and the catchment was saturated. Precipitation seems to be a major parameter influencing streamflow, with greater influence than the urbanization, as reported elsewhere (e.g. Dottori et al., 2014). The heavy precipitation (antecedent condition) and soil saturation probably explain why the peak flow in the validation period was delayed as well (Figure 9). The model must have simulated that the precipitation would delay the peak more than it actually did according to the observations. The peaks in the 1973 and 2002 scenarios were about the same (~0.4 m^3/s), which seems strange since there has been an urban increase of around 20% between the years. However, the precipitation values corresponding to both those peaks were low (about 30 mm and 36 mm) and that might explain why the peak was so low in the 2002 scenario.

The infiltration remained constant in all three scenarios (Table 7). Why there was no decrease is difficult to say. It is possible that the compaction of the urban soils was not captured in the models. Many models ignore just that, which can cause errors since infiltration depends on the soils' pore size (Pitt et al., 2002). The overland flow was high when the peak flow was high in the historical scenarios, i.e. it was only high in the 1990 scenario. The urbanization's effect could again have been underestimated in favour of the influence of the precipitation. The past urbanization's effect on evapotranspiration was better simulated than its effects on flow and infiltration, as a decrease in evapotranspiration with increasing urbanization was captured (evapotranspiration decrease by approximately 32% and urban increase by 20% from 1973 to 2002). Evapotranspiration is more influenced by temperature than it is by precipitation, which can explain why the evapotranspiration trend was not affected by precipitation.

5.1.2. Possible future urbanization's impact on hydrology

First of all, it is worth to mention that the calibration (and validation) could not capture the peak flows entirely. The urban scenarios were all compared to the calibration, and since the peak in the calibration was not exactly as high as the observed one, all the scenario results of peak flow would show a decrease if they were to be compared to the observed flow.

That aside, the three urban scenarios showed no big increases in either streamflow or peak flow compared to the calibration (Figure 13). That was not expected, since it conflicts with what has been found in most other studies on the subject (e.g. Rose & Peters, 2001; Im et al., 2009). This is however not very surprising since the historical land use scenarios implied that more urbanization has almost no effect on the flow (the peak flow was around 0.4 m^3/s both in the 1973 and 2002 scenario). Urban scenario 3, where the additional urban cover was added around the existent urban areas, even gave a small decrease (1%) in peak flow on November 16, 2009. The first scenario, urban 1, with the urban cover concentrated to the north part of the catchment, showed almost no changes (approximately +0.1%). The only scenario that showed some kind of increase in peak flow compared to the hydrological years 2008/09 to 2009/10 was scenario 2, where the urban cover was added to the south-east part of the catchment. It gave a rise in the peak flow of approximately 1% (Table 8). The urban cover in this scenario was mainly placed on clayey limestone soils, which infiltrate less water than sandy sandstone soils. The higher peak flow in that scenario therefore seems reasonable. However, the increase in peak flow compared to the calibration was so small that it might not be trustworthy and should therefore be investigated further (section 5.3). Scenario 2 also resulted in the highest streamflow overall. This becomes especially clear when studying the flow in February and March, 2010. For that period, all scenarios actually indicated that an additional urban cover will increase the heavier streamflow. This is consistent with other studies (e.g. Rose & Peters, 2001; O'Driscoll et al., 2010), but the increasing streamflow during February and March alone is not enough to state that the models captured an overall increase in streamflow due to an additional urban cover. The soil moisture is greater at late winter (like February and March) than it is during e.g. summer (Carla Sofia Santos Ferreira, Personal communication), thus, the greater flow this period is also linked with greater flow connectivity favoured by partial soil saturation.

It seems very unlikely that an increase in urbanization of almost 16% will not affect the peak flow significantly, regardless of where the urban cover is added. It seems especially unlikely that it would decrease the peak, which was the case in scenario 3 (Table 8). If it is true that more urbanization of the catchment does not increase the flood risks, that is positive for the continuing development of the area, but the scenarios cannot state with certainty that the urbanization does not influence the peak flow. Considering previous research within the subject of urbanization, it is most likely that the urbanization of Ribeira dos Covões affects the flow negatively.

While the infiltration remained constant in all three scenarios compared to the calibration (section 5.1.1), the overland flow and evapotranspiration increased and decreased with about 10 and 55% respectively (Table 8). This supports what has been found in previous studies (e.g. Im et al., 2009). It especially confirms that the urbanization affects the catchment's evapotranspiration, since the historical scenarios gave similar results. Perhaps the catchment's evapotranspiration is simply more sensitive to urbanization than the flow is, since it is not as affected by precipitation as the flow is. One particularly interesting thing is that the changes in both overland flow and evapotranspiration were the same in every scenario. It does not seem as if the spatial distribution of the urban area has any impact on the processes. This contradicts with the results from some other studies, which state that the streamflow depends on both the extent and distribution of impervious and pervious surfaces (e.g. Hammer et al., 1972; Parikh et al., 2005; Hawley and Bledsoe, 2011). As previously stated, urbanization on limestone should be more problematic than urbanization on sandstone since the water infiltration is lesser in limestone soils than it is in sandstone soils.

5.2. METHODOLOGICAL UNCERTAINTIES

First of all, it is important to mention that there will always be uncertainties associated with modelling. Some of the processes included in the models had to be simplified (e.g. calculations for unsaturated flow) and the grid had to be extended from 5 x 5 m to 10 x 10 m. This was necessary to speed up the model due to time restrictions. Ideally, those changes should not have been made.

5.2.1. Certainty and uncertainty in parameters and data

According to the SA, the model was very sensitive to changes in precipitation, but not to changes in surface roughness (Table 6). That could explain why the streamflow did not respond more to the addition of urban areas, since urbanization changes surfaces and makes them more impermeable. Although, as stated in section 5.1.1, precipitation was the main controller of streamflow (and peak flow) and that was captured in the simulations. The SA showed that the potential evapotranspiration affected the modelling when it was increased, but not when it was decreased. It is strange that a change in potential evapotranspiration affects the peak flow in one direction but not the other. This indicates that the quality of the input potential evapotranspiration was not optimal. Carla Sofia Santos Ferreira (Personal communication) actually brought up the uncertainty in those values a few times during the project. The added urban cover affected the actual evapotranspiration in the same way as in previous studies and it is possible that the input of potential evapotranspiration had no impact on the output of the actual evapotranspiration, which means that the potential evapotranspiration might have been redundant. The same might apply for the surface roughness coefficient. The SA could have been done more thoroughly, with the sensitive parameters further compared to literature values, to make sure that the parameters put in did not impair the performance of the model.

The fact that precipitation turned out to be a sensitive factor in the model is not surprising when studying all the figures of streamflow (both historical and future). The behaviour of the streamflow corresponds well to how the precipitation changes. In the calibration (and the scenarios) there was only one day with extreme precipitation. That was also the day when the peak flow occurred. Rose & Peters (2001) write about the heat island effect, which causes the urbanization to change the local precipitation in a catchment by making the catchment respond faster to precipitation and thereby reduce the delay between precipitation and runoff. That could explain why almost all peaks occurred on the same day as the heaviest precipitation. For the scenarios when the peak was delayed, it was instead a longer period of precipitation that caused the peak flow. This does however not explain why the peaks in the scenarios were so low compared to the calibration. It seems as if the precipitation will continue to have most impact on the hydrological response of the Ribeira dos Covões catchment. Perhaps the precipitation itself is highly affected by the urbanization in the way that the heat island effect describes.

More frequent temperature measurements could have increased the importance of potential evapotranspiration in the models, which in turn would have made the results more reliable. The calibration model was once (by accident) run without any temperature as input. The results were not very different from those of the simulation with the temperature included, which indicates that the input temperature was redundant. The fact that the same potential evapotranspiration was used in all models might also have had an impact on the results, at least for the historical streamflow.

Another uncertainty is that the urban scenarios 1, 2 and 3 only have been compared to the calibration model, with the same climate, vegetation and soil data as in it. If the aim is to simulate how an increase in urbanization might affect the hydrology, the time of that scenario will surely be sometime in the future. If the urbanization trend continues in the same direction as it has within the Ribeira dos Covões catchment, an urban cover of 50% could be reality in the next 10 to 20 years. Using precipitation and temperature from 2008 to 2010 will therefore not be ideal to simulate a possible future, especially when much science indicates that the temperature on Earth is getting warmer and that many rainfall events are becoming heavier (e.g. IPCC, 2014).

One strong argument for choosing MIKE SHE to describe the hydrology of the Ribeira dos Covões catchment was its ability to include vegetation in the calculations. According to Donohue et al. (2007), not all hydrological models are able to do that. Due to time limits, the Budyko framework was not used. The catchment was small and it was of highest importance to include reliable vegetation data into the model. Using the Budyko curve would have been a good assurance of the quality of the input data. It is something that should have been done before the modelling even started, but the modelling was thought to be time consuming enough. The Budyko framework was simply discussed (section 2.2.2) in order to highlight why parameters associated with vegetation (evapotranspiration, LAI, root depth, precipitation and runoff) need to be included in the model. Taking the importance of those parameters into account, it becomes clear that the vegetation data used can basically make or break the model. The vegetation and soil properties from Briel (2013) were not the most suitable for Portugal, since they represented typical Swedish vegetation. It was simply too difficult to find the right type of data files for Portugal. The types of vegetation chosen to represent each land use type was therefore not based on the actual catchment, but still selected as carefully as possible. After the modelling, more research was done to try to find some information about typical soil and/or vegetation properties for a Mediterranean climate. It was found that LAI is typically close to zero during the summer in such a climate (Ruget et al., 2015). The LAI values used here did not correspond to that (Appendix D). They were actually quite the opposite, since most of them were at their highest during that time of the year. However, the flow events in all of the models happened during the winter. It is therefore of higher importance to be able to represent that time of the year. It cannot be said for certain how correct the input files of root depth and other vegetation and/or soil properties are, but chances are that they have similar errors as the LAI values.

Since the Budyko curve is associated with water (and energy) balance, and this project has not been about that, the use of it would not have changed the results. Although, it would still have been more ideal to use vegetation and soil properties that better resembled the catchment. More effort should have been put into assuring that they represented the catchment from the beginning. Along with that, the calibration could of course have been done even more thoroughly. Both it and the validation however gave good statistics (R and NSE), which indicates that they were able to simulate what was desired. The fact that the peak flows (and streamflows) were not increased more in the scenarios compared to the calibration however contradicts the quality of the calibration. The horizontal and vertical conductivities might have been too low, but they were still within reasonable range according to the literature studied. The same uncertainties might apply for them as for the data from Briel (2013) though, since the values for conductivities were not chosen solely based on typical Portuguese climatic settings. It was also not optimal to include redundant, uncertain parameters, which the SA indicated that the potential evapotranspiration and overland flow coefficient were. Ideally, if time limit was not an issue, the parameters should probably have been changed a few more times, maybe with increases and decreases of 10, 30 and 50%.

A last possible source to uncertainties is the frequency of the precipitation values, which were daily. Ribeira dos Covões is a small catchment, which means that the response from it is quite fast (Giuliano Di Baldassarre, Personal communication). Peak flow occurs and falls rapid in an urban catchment (Figure 1). To best capture it, hourly precipitation values would have been more optimal than daily values. The models could then have been run at hourly time steps. However, it is difficult to get a hold of such frequent precipitation values.

5.3. FURTHER RESEARCH

Ferreira et al. (2016) writes that there are only a few studies discussing how the other types of land use in peri-urban catchments, such as woodland, mitigate the impact of urbanization on the hydrology. An extension of the work could therefore be to change the land use map in terms of woodland type to see if a peri-urban catchment with a 50% urban cover containing a lot of natural oak stands instead of dense eucalypt mitigates the effects of the urbanization, since the overland flow is smaller in natural oak stands. This, of course, would have to be done for a study that has shown negative hydrological effects of urbanization. If it was to be done on this particular catchment, the model would first have to be improved to better simulate the impacts of urbanization in the area. A way to do that could be to modify the soil and vegetation properties used in the model. As written above, those values represent Sweden. If it is possible to find data and create vegetation and soil files that represent Portugal, that would probably enhance the results and make them more trustworthy. If there are wishes to look at the water balance of the catchment, the Budyko curve could be of great use. It is something that could also be done in future work.

Since it became clear that the precipitation had the biggest influence on streamflow, another extension could be to investigate the effects of climate change based on IPCC scenarios on the catchment´s hydrology. Scenarios of precipitation around the area of the catchment could be used together with the urban scenarios. This could help to assess the impact of extreme weather conditions, such as extreme precipitation, will have any negative effects on the catchment hydrology. If it is possible to get more frequent temperature values than just monthly averages, effects of global warming could be investigated.

Furthermore, if the model is optimised, an idea associated with extreme weather conditions could be to look more closely into the cause of the flooding in the area on October 25, 2006. Precipitation for that year should make it possible.

Also, with a more optimised model, it might be an idea to look into how the hydrological processes would be disturbed with an urban cover of 60 or 70%. This might give an opportunity to mitigate eventual problems at a planning stage, before they face the risk of even occurring. An optimised model could also be used to examine more thoroughly if the spatial distribution of the urban cover is of importance. Since the only scenario that showed some kind of increase in peak flow due to urbanization was the one where the urban cover was added to the part of the catchment covered mainly by limestone, the effects of urbanization there could be further investigated. It could be interesting to see if limestone responses more to urbanization than sandstone. If the model is optimised, it could hopefully be used to support the decision making process in planning and developing new urban areas.

6. CONCLUSIONS

- The modelled urbanization has not affected the Ribeira dos Covões catchment's streamflow, peak flow or infiltration significantly in the past. The streamflow, peak flow and overland flow have been influenced by the precipitation. The evapotranspiration has decreased with the increasing urbanization throughout the years (by approximately 32% between the years 1973 and 2002).

- A modelled possible future urban increase from 40 to 50% of the catchment's area does not affect the streamflow and peak flow significantly.

- A modelled possible future urban increase from 40 to 50% of the catchment's area does not affect the infiltration. The modelled increase in urban cover within the catchment has been shown to increase the overland flow by approximately 10% and decrease the evapotranspiration by almost 55%.

- The modelled peak flow is not significantly affected by the spatial distribution of the urbanization process. An urban cover added to the south-east part of the catchment increases the peak flow slightly more than if it is added to the north part or around the existent parts (around +1%, +0.1% and -1% respectively). The responses of streamflow in general, overland flow, evapotranspiration and infiltration are not affected by the three different spatial distributions examined.

- The reliability of the model developed here can be enhanced by additional climate, soil and vegetation data. This would improve the results of the study and make them more useful in decision making processes in the planning and managing of new urban areas.

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APPENDIX A. THE BUDYKO FRAMEWORK

In the middle of the 1900´s, Budyko described the water balance of a catchment as:

$$\frac{dS_w}{dt} = P - E - Q \qquad (3)$$

, where P stands for precipitation (kg s^{-1}), E for evapotranspiration (kg s^{-1}), Q for runoff (kg s^{-1}) and S_w for soil water storage (kg). The Budyko curve assumes that catchments are at steady-state, i.e. the change in soil water storage is zero. In reality, because of fluctuations in the three hydrological processes described in equation 3, that is never completely true. Budyko integrated equation 3 over a finite time period (described in more detail by Donahue et al. (2007)). Integrating gave an equation combining the water and energy balance. This turned out useful because evapotranspiration is limited by the supply of either water or energy. The final curvilinear relationship was finally defined by:

$$\bar{E} = \left(\frac{\overline{R_n}\bar{P}}{\lambda} tanh \frac{1}{\Phi} (1 - cosh\Phi + sinh\Phi)\right)^{1/2} \quad (4)$$

, where R_n is the net radiation (J s^{-1}), λ the latent heat of vaporisation (J kg^{-1}) and Φ is the radiative index of dryness (the ratio of seasonal sums of net radiation to those of the latent heat of precipitation). It is this equation that is called the Budyko curve (Figure 2).

The evaporative index in the Budyko curve describes the partitioning of average precipitation into average evapotranspiration and runoff. Deviations from the curve indicate changes in partitioning between evapotranspiration and runoff (vertical deviations) or changes in climatic conditions (horizontal deviations). As the dryness index increases, the catchment reaches the limits of water and energy, i.e. it becomes warmer and drier. An increase of the evaporative index equals less runoff.

APPENDIX B. STREAMFLOW FOR THE ENTIRE SIMULATIONS

The modelled streamflow in the report is only presented for the periods with peaks. The entire simulation periods for the calibration (Figure 14), validation (Figure 15), 1973 scenario (Figure 16), 1990 scenario (Figure 17), 2002 scenario (Figure 18), urban 1, 2 and 3 (Figure 19) are presented below. The SA is also presented (Figure 20).

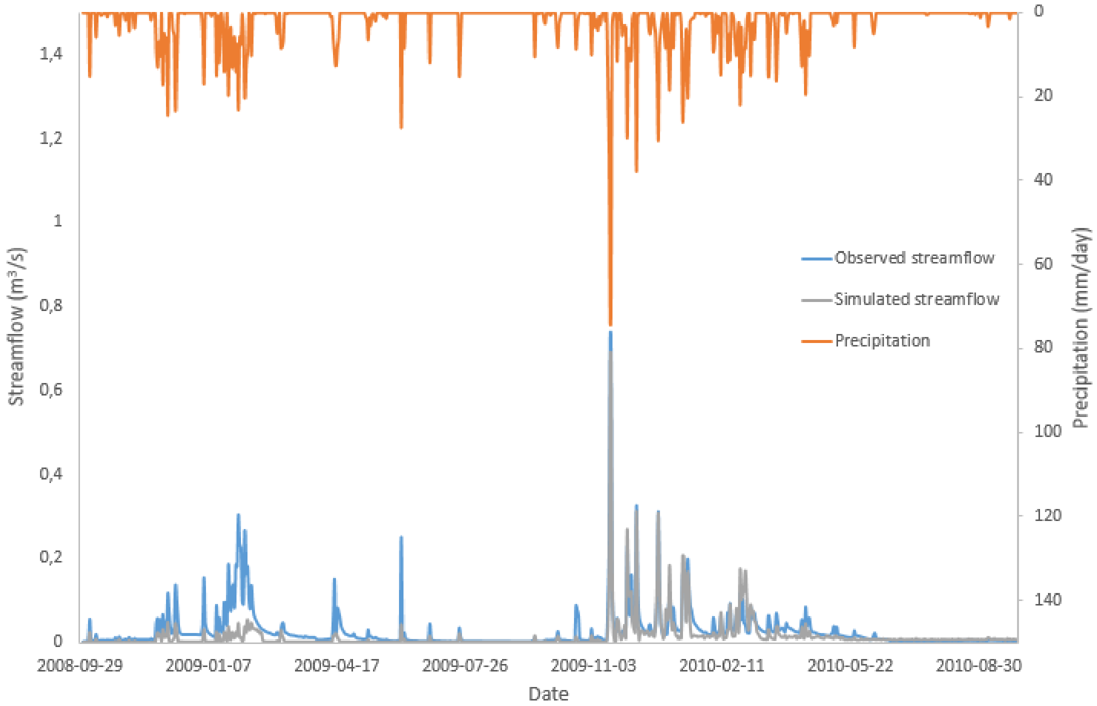

Figure 14. Observed and modelled streamflow plotted against precipitation for the calibration period (October 1, 2008-September 30, 2010).

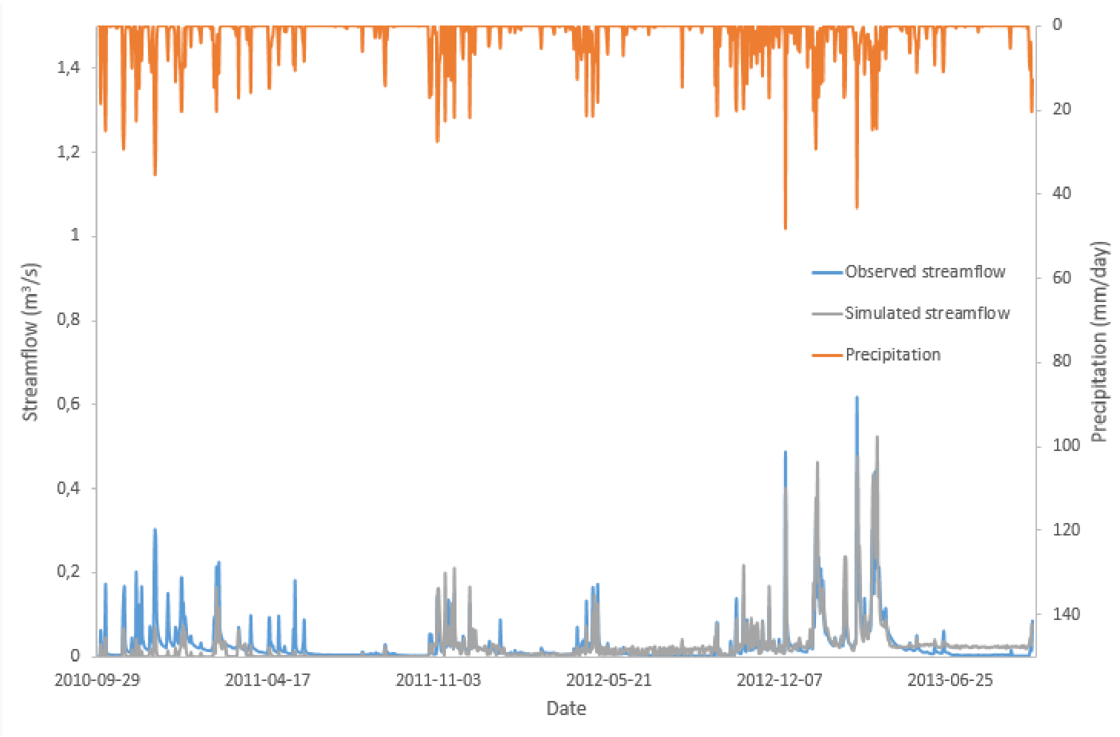

Figure 15. Observed and modelled streamflow plotted against precipitation for the validation period (October 1, 2010-September 30, 2013).

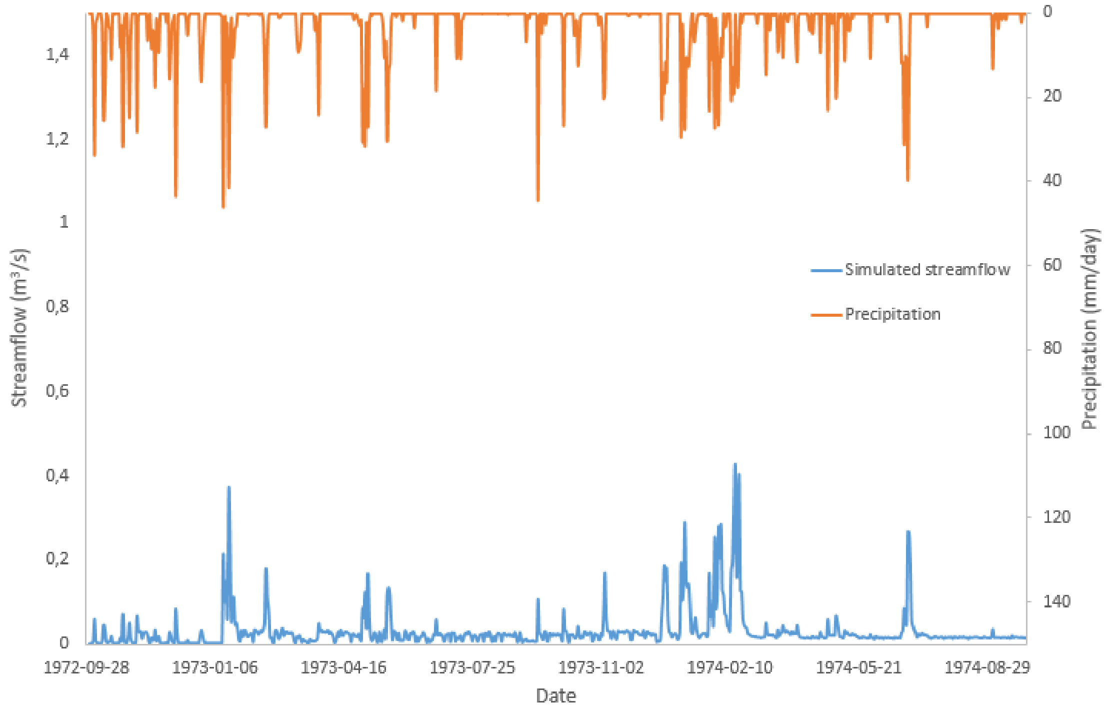

Figure 16. Modelled streamflow plotted against precipitation for the 1973 scenario (October 1, 1972-September 30, 1974).

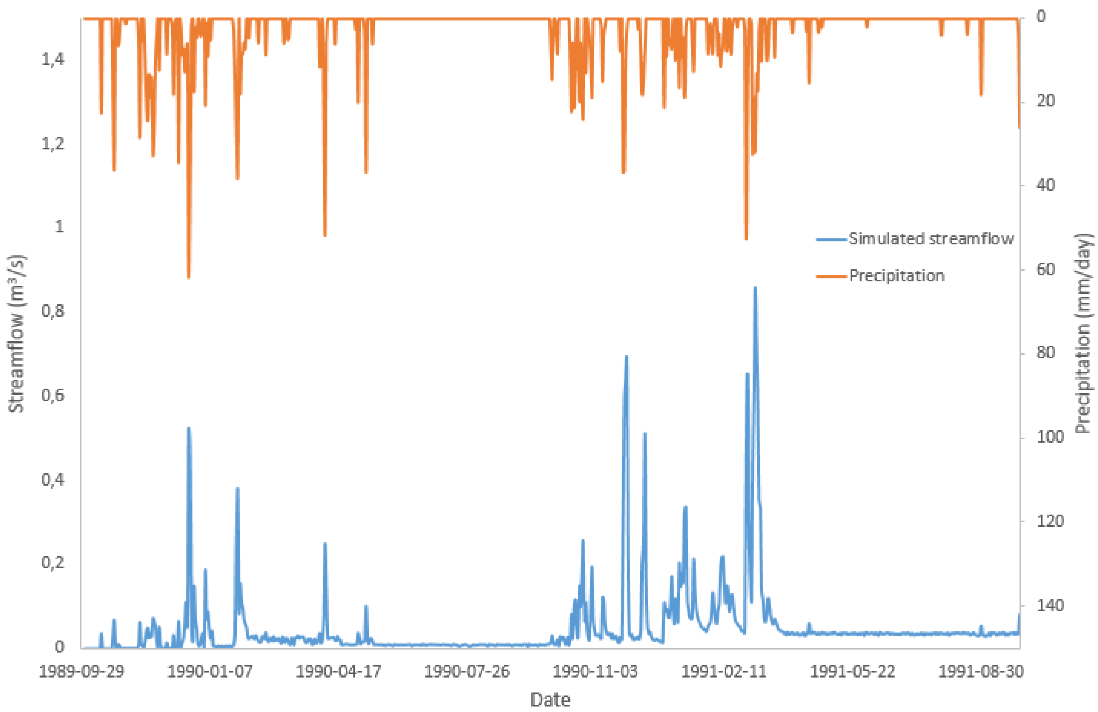

Figure 17. Modelled streamflow plotted against precipitation for the 1990 scenario (October 1, 1989-September 30, 1991).

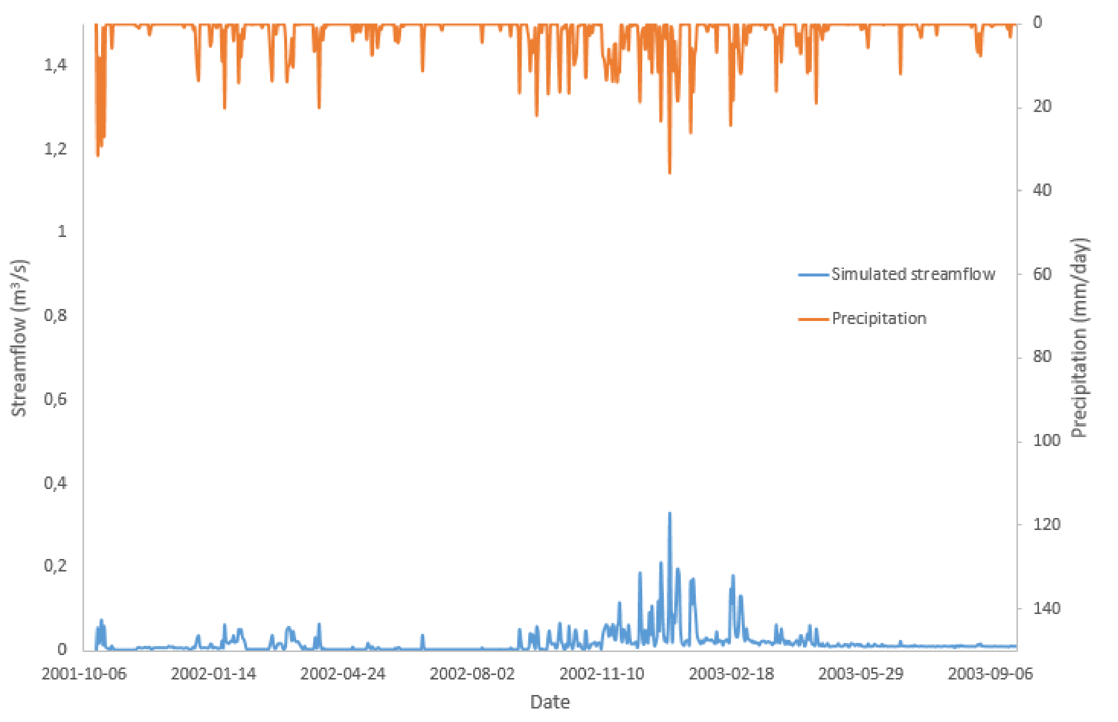

Figure 18. Modelled streamflow plotted against precipitation for the 2002 scenario (October 1, 2001-September 30, 2003).

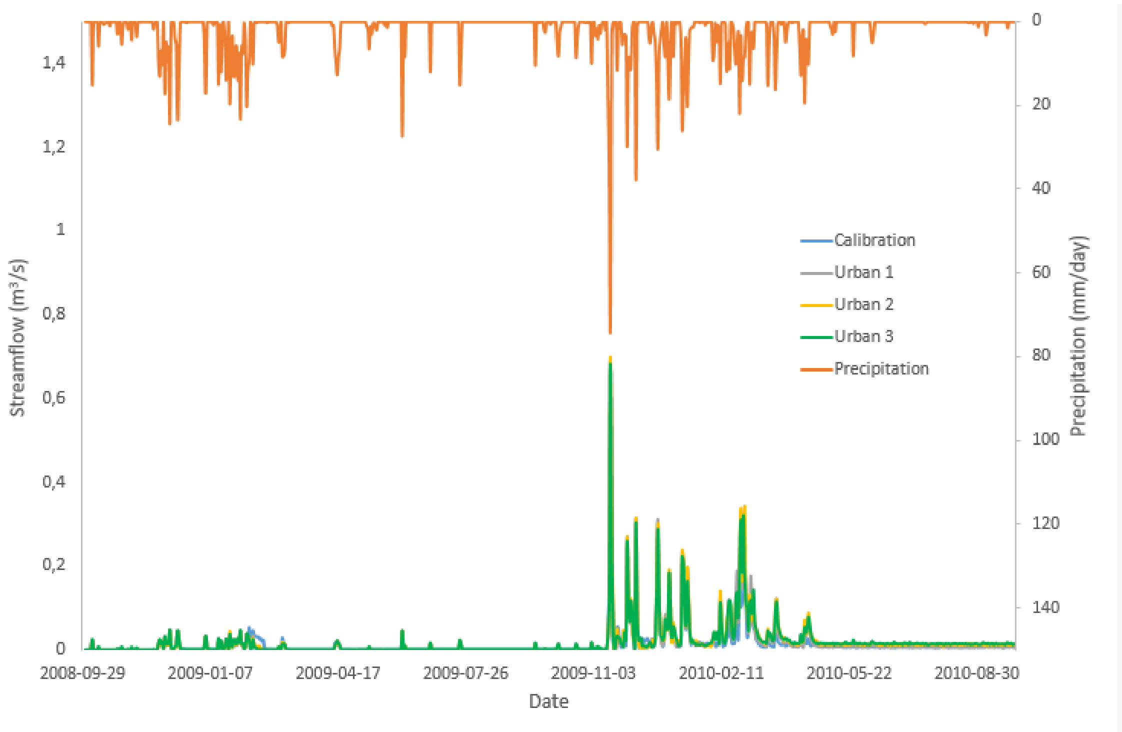

Figure 19. The modelled streamflow for the calibration period, urban scenario 1, 2 and 3 plotted against precipitation.

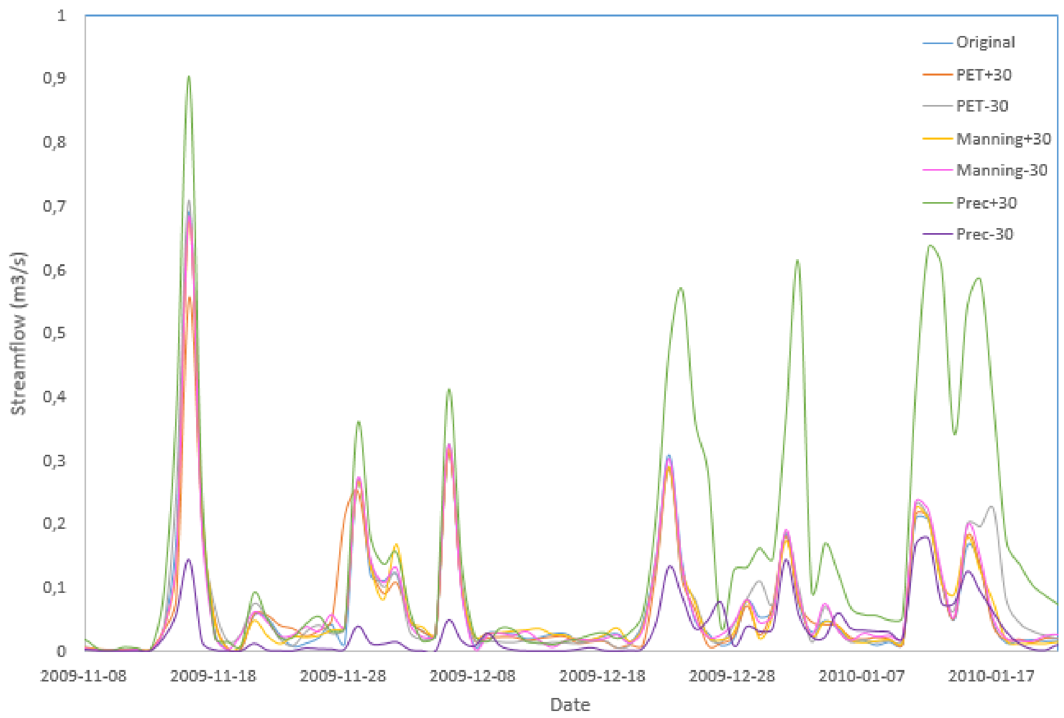

Figure 20. Plotted streamflow between November and January (2009-2010) when the potential evapotranspiration (PET), surface roughness coefficient (Manning) and precipitation (Prec) have been increased and decreased with 30% compared to the initial model (Original).

APPENDIX C. TEMPERATURE DATA

The temperature data used for the modelling was monthly mean temperatures. The values for each month of each simulation are presented in Table 9.

Table 9. Monthly mean temperatures for the hydrological years simulated in MIKE SHE.

						Month						
Hydr. year	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**
1972-1973	15.4	12.4	9.5	8.3	8.7	11.2	14.0	16.0	19.8	20.3	22.0	19.0
1973-1974	16.4	13.0	7.8	11.0	9.7	11.0	12.6	16.2	18.8	21.6	19.8	17.0
1989-1990	20.3	14.5	13.9	9.7	13.4	14.6	13.2	18.6	20.0	23.2	23.6	21.7
1990-1991	17.0	12.2	9.7	9.6	8.0	13.2	13.7	18.6	19.7	22.8	23.4	21.7
2001-2002	18.1	11.7	9.3	11.8	11.2	14.1	14.0	15.4	18.1	20.7	20.4	20.3
2002-2003	18.0	13.4	12.8	9.2	10.2	14.2	14.5	17.9	20.5	20.8	24.3	22.2
2008-2009	15.3	10.5	10.6	10.0	11.7	15.3	12.6	18.1	20.4	20.1	22.5	21.7
2009-2010	19.6	13.2	11.5	9.1	10.8	11.6	16.1	16.7	19.5	23.6	24.1	20.9
2010-2011	16.6	12.4	11.3	10.8	11.1	13.0	18.3	19.5	20.1	20.6	20.7	21.2
2011-2012	20.1	13.6	10.1	9.6	9.8	15.4	11.7	18.2	19.5	20.9	21.1	22.0
2012-2013	17.1	12.1	11.4	10.4	9.7	11.7	13.8	15.2	19.5	22.9	23.2	22.5

APPENDIX D. LEAF AREA INDEX (LAI)

For the model, a growth cycle with changes in LAI from season to season was used (Figure 20). The values are typical for a cold climate.

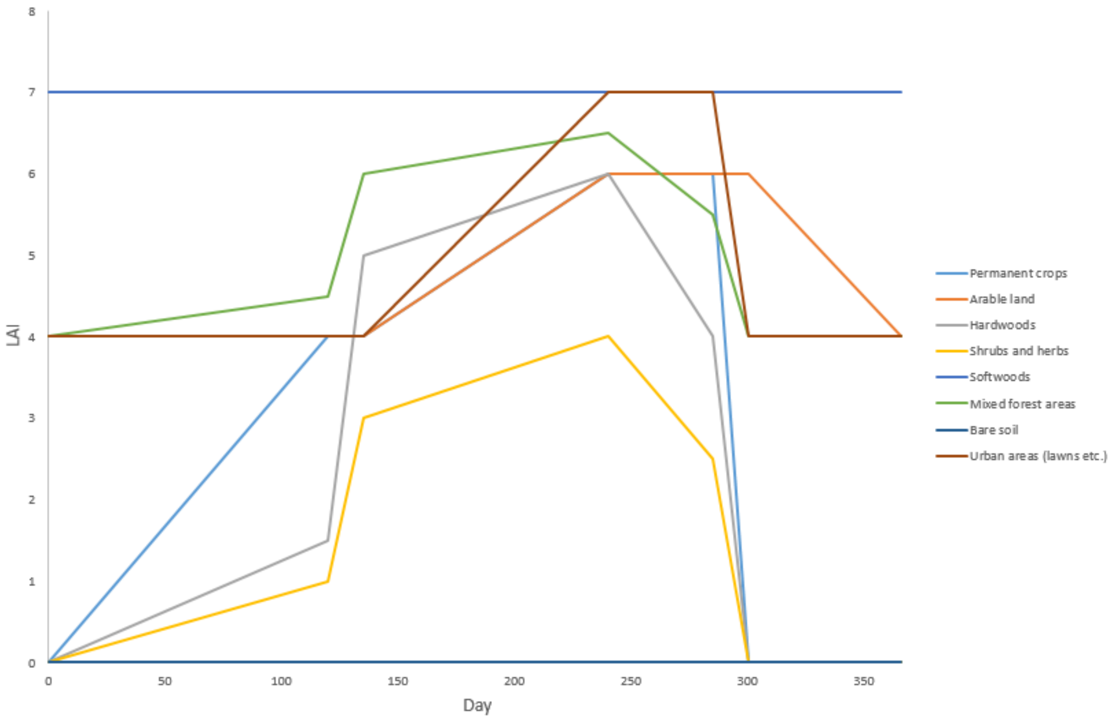

Figure 20. Changes in LAI (in a cold climate) during one year.