Assessing streamflow sensitivity in a complex watershed

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Assessing Streamflow Sensitivity in a Complex Watershed

An integrated approach for assessing the impacts of land-use and climate changes in a highly managed mountainous catchment

THÈSE

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The true sign of intelligence is not knowledge but imagination
[Albert Einstein]

This thesis is dedicated to:

My parents
& my beloved family members

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Abstract:

Half of the world's population depends on fresh water that originates from the mountains. In the present-day, it is apparent that climate change will affect these mountain water resources. Therefore, some crucial questions are often raised: Will Mountain Rivers continue to provide the same amount of fresh water as they have in the past? Have there been any changes in the hydrological regime of mountainous watersheds? Is there a chance that the flow's magnitude and timing will change? In order to answer these questions, this research attempts to understand the hydrological behavior of the Rhone River watershed, located in the southwestern part of Switzerland. The objective was to simulate streamflow and assess its sensitivity due to changes in land-use and climate.

To attain this objective, this thesis work was subdivided into four major subsections, each of which contains a subtopic and an individual research question. The first section answers the question: Are hydrological models capable to simulate such a complex area where both natural and anthropogenic influences are severe? The Soil and Water Assessment Tool (SWAT), a semi-distributed open source hydrological model, was used to simulate the streamflow. A sound agreement of simulated flow was found with the observed flow after implementing all the complexity arises from hydropower networks and water transfer.

The next task was to test the climate generated variables in order to extrapolate an analysis for the future. An evaluation test of different Regional Climate Model (RCM) outputs was used and their performance was assessed to generate similar patterns of runoff. Not all of the RCM generated variables could provide similar hydrographs, but some of them were satisfactory. Among four climate models output DMI was found suitable for reproducing similar patterns of hydrographs.

In the third section the objective was to understand the streamflow generation process and assess its contribution to the hydrograph. To reach this goal, water samples were collected and tested in the laboratory for ion analysis and End Member Mixing Analysis (EMMA) was used to separate hydrograph components. A sign of early summer melt was found when comparing two time periods.

The fourth section predicts land-use and RCM based meteorological variables used to extrapolate for future forecasting. The result obtained indicates that the peak flow reduction occurred due to land-use change and the timing of peak flow occurrence shifted due to climatic change.

Hydrological models are data driven. Collecting various types of data (e.g. spatial, non-spatial) often hinders model development. Moreover, the availability of software is also challenging. In the fifth section, an attempt is taken to develop a hydrological model based on completely open source software and freely available data. The objective was to test the quality of data through model performance evaluation.

The conclusion can be drawn that due to land-use and climatic changes the river flow regime is changing. The findings obtained in this research can provide useful information for water management of downstream processes, especially for hydropower based energy production. For example, a shift in the peak flow will have certain consequences such as the need to change the time for filling and emptying reservoirs. Additionally, energy consumption planning needs to be revised. Apart from hydropower based energy production, biodiversity can also be threatened because the contribution from each flow component (i.e. snow melt and glacial melt) correlates with various species. Therefore, a reduction in this contribution can threaten certain species. Thus, this research

opens a wide range of future research opportunities to explore the impact of climate and land-use change in terms of energy production and biodiversity in connection with hydrology in the studied watershed.

Résumé:

La moitié de la population mondiale dépend de l'eau douce qui provient des montagnes. Dans l'état actuel des connaissances, il est évident que les changements climatiques auront une incidence sur les ressources en eau des montagnes. Par conséquent, certaines questions cruciales se posent: Est-ce que les rivières de montagne continueront à fournir la même quantité d'eau douce dans le futur ? Y a-t-il eu des changements dans le régime hydrologique des bassins versants montagneux ? Quelle est la probabilité que l'ampleur et le rythme des cycles change ? Afin de répondre à ces questions, cette recherche tente de comprendre le comportement hydrologique du bassin versant du Rhône, situé dans la partie sud-ouest de la Suisse. L'objectif principal est de simuler l'écoulement fluvial et d'évaluer sa sensibilité aux variations dans l'utilisation des terres et le climat.

Pour atteindre cet objectif, ce travail de thèse a été subdivisé en cinq grandes sections, dont chacune contient un sous-thème et une question de recherche individuelle. La première section répond à la question: est-ce que les modèles hydrologiques sont capables de simuler un domaine aussi complexe où les influences naturelles et anthropiques sont importantes et se confondent ? L'outil d'évaluation des sols et de l'eau (SWAT), un modèle hydrologique semi-distribué et open source, a été utilisé pour simuler l'écoulement. Un bon accord a été trouvé entre le débit simulé et le débit observé en intégrant la complexité du réseau hydraulique et des transferts de l'eau.

La prochaine tâche était de tester les variables climatiques générées par les modèles climatiques régionaux (RCM) pour simuler la réponse hydrologique du bassin versant. Toutes les variables générées par les RCM fournissent des hydrogrammes assez similaires, mais certains d'entre eux ont sont plus satisfaisants. Parmi les quatre modèles climatiques testé, le DMI a été jugé apte pour reproduire les hydrographes du Rhône.

Dans la troisième partie, l'objectif était de comprendre le processus de génération du débit des cours d'eau glacière. Pour atteindre cet objectif, les échantillons d'eau ont été prélevés et analysés en laboratoire pour l'analyse des ions. La méthode End Member Mixing Analysis (EMMA) a été utilisé pour séparer les composants de l'hydrogramme. Un signe de début de fonte estivale a été trouvé lors de la comparaison de deux périodes.

La quatrième section utilise les prédictions de changements de l'utilisation du sol et du climat. Le résultat obtenu indique que la réduction du débit de pointe a lieu en raison du changement d'utilisation du sol et le moment d'apparition du débit de pointe est décalé par les changements climatiques.

Les modèles hydrologiques sont orientés vers les données. La collecte de divers types de données (spatiales et non spatiales) entrave souvent le développement du modèle. En outre, la disponibilité des logiciels hydrologiques représente aussi un défi. Dans cette cinquième partie, une tentative est faite pour développer un modèle hydrologique basé sur des logiciels entièrement open source et des données librement disponibles. L'objectif est de tester la qualité des données grâce à l'évaluation de la performance du modèle.

La conclusion ne peut être tirée que l'utilisation du sol et les changements climatiques peuvent changer le régime d'écoulement des rivières du bassin versant du Rhône. Les résultats obtenus dans cette recherche peuvent fournir des informations utiles pour la gestion des eaux en aval, en particulier pour la production d'énergie basée sur l'hydroélectricité. Par exemple, un changement dans le débit de

pointe aura certaines conséquences telles que la nécessité de changer le temps de remplissage et de vidange des réservoirs.

En outre, la planification de la consommation d'énergie doit être révisée. En dehors de la production d'énergie basée sur l'hydroélectricité, la biodiversité peut aussi être menacée parce que la contribution de chaque composante de l’eau (par exemple la fonte des neiges et la fonte des glaciers) peut être mis en corrélation avec différentes espèces. Par conséquent, une diminution de cette contribution peut menacer certaines espèces.

Ainsi, cette recherche ouvre un large éventail de possibilités de recherche futures pour explorer l'impact des changements climatiques et de l'utilisation du sol en termes de production d'énergie et d’impacts sur la biodiversité dans le cadre de l'hydrologie du bassin versant étudié.

Publications

This thesis is based on the following publications:

- **Rahman, K**., Maringanti, C., Beniston, M., Widmer, F., Abbaspour, K., and Lehmann, A., 2013, Streamflow Modeling in a Highly Managed Mountainous Glacier Watershed Using SWAT: The Upper Rhone River Watershed Case in Switzerland: **Water Resources Management**, v. 27, no. 2, p. 323-339.

- **Rahman, K**., Etienne, C., Gago da Silva, A.,Maringanti, C., Beniston, M., Lehmann, A.,2013, Performance evaluation of regional climate models for runoff simulation and their grid resolution for mountainous watershed: **Regional Environmental Change** [Status: In review]

- **Rahman, K.**, Monbertrand, A., Castella, E., 2013, Quantification of daily dynamics of streamflow components in a small glacier dominated alpine watershed using end member mixing analysis. [Prepared for **Hydrological Process,** Status: will be submitted after PhD Defence]

- **Rahman K**, Ana Gago da Silva, Enrique Moran Tejeda, Andreas.Gobiet, Martin Beniston, Emmanuel Castella & Anthony Lehmann 'Streamflow Response to Land-use and Climate Change, in the Upper Rhone River Watershed', Switzerland [Journal of **Applied Geography,** Status: will be submitted after PhD Defence]

- **Rahman K**, Nicolas Ray, Grégory Giuliani, Julia Schwank, Gissela Girón, Rocío Escobar, Chris George and Anthony Lehmann Breaking Walls Towards Fully Open Source Hydrological Modeling- **Journal of Environmental Informatics** [Status: submitted]

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1 Introduction

1.1 State of the Art

Mountainous watersheds play an important role in downstream activities such as hydropower production, irrigation, drinking water supplies, and ecosystem functioning (Immerzeel 2008; Miller et al. 2012; Viviroli et al. 2011). The assessment of water resources in mountainous watersheds has increasingly gained attention due to rapid glacial melt (WGMS 2009). More than one-sixth of the world's population depends on snow covered glaciers and seasonal snow melt for water supplies which may be at risk due to a warming climate (Barnett et al. 2005). Mountain rivers are also important sources of energy production. In Switzerland, hydropower provides around 75% of consumed electricity of which approximately 60% is produced in storage reservoirs (Swiss Federal Office for Energy 2003). Glaciers, however, are melting quickly. For example, 84 out of 85 glaciers in Switzerland have a negative mass balance (WGMS 2009). In view of the current and future challenges facing proper water resources management in mountain areas and their related uncertainties, there is an essential need for promoting research and the exchange of knowledge with practitioners (Viviroli et al. 2011).

Freshwater vulnerability due to climatic change in mountainous areas is also receiving growing attention (UNESCO 2012). It is apparent that this vulnerability is a result of strong anthropogenic influence (Ribot 2009). Vulnerability is mainly assessed with indicators which differ according to space, time, and geographic location (Bo et al. 2008; Jubeh. and Mimi 2012; Norman et al. 2012; Plummer et al. 2012; Ravindranath et al. 2011; Ribot 2009; Salman Siddiqui et al. 2012). Mountain vulnerability is strongly influenced by such hydro-climatic factors as snow melt, glacial melt and change in flow regimes. In order to assess hydrological changes we need to understand these physical processes. This is possible with mathematical models. Hydrological modeling is a powerful technique of hydrologic system investigation for research hydrologists and practicing water processes which control catchment response and use physically based equations to describe these processes (Singh 1995). Streamflow simulation is often challenging in mountainous watersheds because of irregular topography and complex hydrological processes. The application of models based on streamflow simulation is rapidly increasing since they provide hydrological information in advance, for example, forecasting the inflow to hydropower plants (Schaefli et al. 2007).

The impact of flow regime change assessment proceeded in many scientific fields, such as ecosystem change as well as hydro-environmental and disaster studies in the context of climate change. The lack of multidisciplinary assessments closely related to policy decisions demonstrates the shortage of traditional assessment. The vulnerability assessment, which links regional or interregional environmental change with socio-economic development, would be more significant and valuable in social practice and theory study. Vulnerability assessments need to combine social science and natural science, as well as focus on integrating information across scales and disciplines, including various human activities. Assessments also need to regard complex social-economic-natural ecosystems as the objects of study. Recent studies have been conducted in mountainous watersheds all over the world in order to better understand various issues linked with hydrology, many of which apparently focus on specific issues like snow melt, (Adam et al. 2009; Bales et al. 2006; Herrero et al. 2009; Hock 1999, 2003) glacier melt, (e.g.Farinotti et al. 2009; Finger et al. 2011; Huss et al. 2008; Jansson et al. 2003; Pellicciotti et al. 2010) as well as changes in precipitation and temperature (Cantelaube and Terres 2005; Chen et al. 2012; Masih et al. 2011; Pepin and Losleben 2002; Salzmann and Mearns 2012).

1.1.1 Climate change scenarios

The last published fourth assessment paper of the Inter-governmental Panel on Climate Change (IPCC-AR4) (IPCC. 2007) summarizes that it is unequivocal that the global warming is happening. It is now proven that this increase is because of ocean and average air temperature, together with rapid melting of ice (WGMS 2009) and widespread melting of snow. The report also emphasizes the future prediction of precipitation and temperature based on atmosphere ocean general circulation models (AOGCM). Figure 1 shows the summary of the multi model results and SRES scenarios. The solid lines are multi-model global averages of surface warming (relative to 1980-99) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the plus/minus one standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at the right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. (IPCC, 2007)

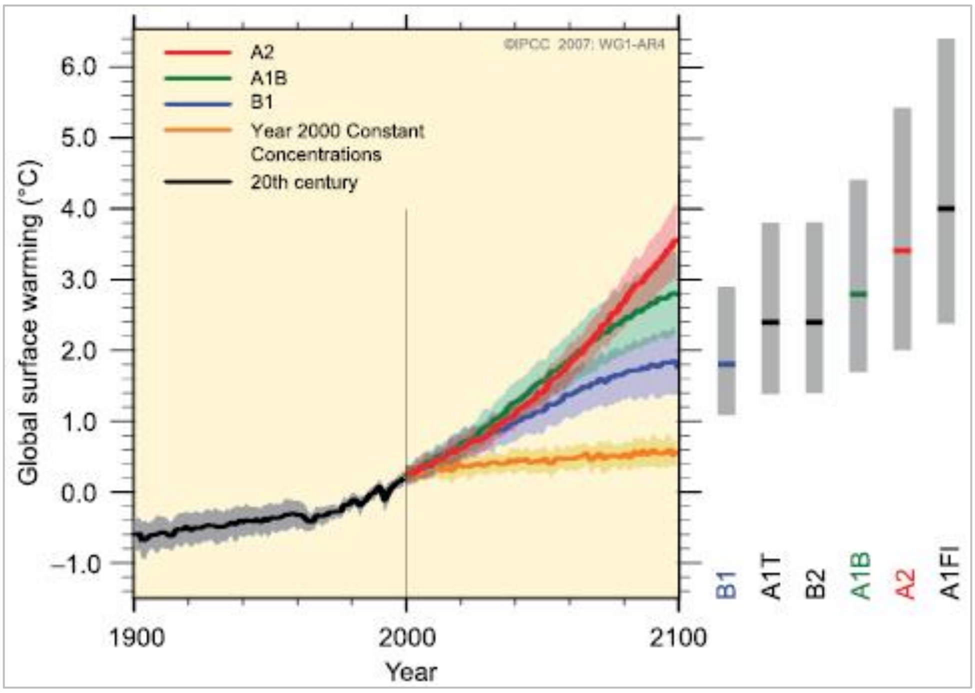

Figure1: Projected global warming (source: IPCC, 2007)

Since the temperature is one of the driving factors of the changes, mountains are the most vulnerable to any change, especially mountains with snow and glaciers. Consequently the vulnerability will transmit from upstream to downstream. The possible vulnerabilities are explained in various studies, among them Bo et al. (2008), quantified as a function of elevation.

1.1.2 Land use change scenarios

Land use change has a significant impact on streamflow generation and its regime (Veldkamp and Lambin 2001; Verbunt et al. 2005; Zégre et al. 2013; Zimmermann and Kienast 2009). Understanding land use change is not only looking at the total area of certain land uses that appeared or disappeared. The change in structure and the underlying reasons of this change are also important. It is the complete picture of different elements that provides insight into land use changes. Scenario development for land use change is often done from historic land use and the relative change in two consecutive time slices (Rutherford G. N. 2006.). Comparing the change between two land use maps the scenario generation is done considering ‘change factor’. For this study, land use maps from 1979-1984 and 1992-1997 were analyzed for change factor calculation. Emphasis was given to the two major groups of land use, which are glaciers and forest. Since the study area is located at a high altitude, demographic changes like human population and increasing number of industries are less significant. Features of land use classes that are non-significant were kept constant, like water bodies, airport etc.

1.1.3 Application of hydrological models

Observation networks in mountainous watersheds are relatively fewer compared to the floodplains, although their density should be higher in order to understand complex hydrological process like snow and glacier melt as well as orographic precipitation. Hydrological models represent a simplification of reality and large uncertainty may arise due to a lack of correct input. In order to understand the dominant processes controlling the hydrology, computer models are widely used to better estimate surface water flow, infiltration, evapotranspiration, snow and glacier melt, etc. Hydrological modeling is becoming increasingly popular as it is used to improve our understating of the aforementioned physical processes.

1.1.4 The Soil and Water Assessment Tool (SWAT)

The Soil and Water Assessment Tool (SWAT) is an open source hydrological model developed to simulate streamflow water quality sediment transport in a large river basins (Arnold et al. 1998). Because of its open source utility SWAT has been used all over the world (Gassman et al. 2007). SWAT subdivides watersheds into smaller units as sub-basin and further smaller unit call Hydrological Response Unit (HRU) (Neitsch et al. 2005). Sub-basins are spatially connected with river network but the HRUs have no spatial connection. HRUs are constructed with land cover, soil and slope. The model was initially built to evaluate the impact assessment of flow in agricultural watershed and it has been continuously updated and modified for solving diverse problems like water quality, best management practices etc.

Data required to build the model can be subdivided by two major groups. They are spatial and non-spatial; in the non-spatial group hydro-meteorological data like precipitation, temperature, winds speed, relative humidity and solar radiation are required to feed the model. Spatial groups can be further subdivided in two groups i.e raster and vector. In the raster group, land use, soil and Digital Elevation Model (DEM) are required and in the vector group, river geometry is needed to define the routing of the flow.

For initialization of the flow path, GIS support is needed. Therefore, an extension of ArcSWAT (Winchell et al. 2007) which requires ESRI (Environmental Systems Research Institute, ESRI, Redlands, California), ArcGIS, (Idaho State University Geospatial Software Lab, Pocatello, Idaho), geographical information system (GIS), and MWSWAT (George and Leon 2007), which uses the MapWindow GIS, both of which delineated and initialized the study watershed equally well. The hydrologic components within SWAT account for snow fall and melt, vadose zone processes (i.e., infiltration, evaporation, plant uptake, lateral flows, and percolation), and ground-water flows. Surface runoff is calculated based on a modified version of the Soil Conservation Service (SCS) Curve Number (CN) method (USDA-SCS, 1972). A kinematic storage model (Sloan et al., 1983) is used to predict lateral flow, whereas return flow is simulated by creating a shallow aquifer (Arnold et al., 1998). The Muskingum method is used for flow routing and SWAT has the flexibility of choosing the evapotranspiration method. They are: Penman–Monteith (Allen RG et al. 1998), Hargreaves (Hargreaves GH 1985) and Pricely tailor method (Neitsch et al. 2005).

1.2 The ACQWA Project

It is unequivocal that human induced climatic change will have consequences in various sectors, especially in field water resources. The magnitude of vulnerability can be different in different levels considering socio-environmental conditions. Mountains are highly sensitive to any change (ex. precipitation, temperature) since the hydrology is driven significantly with the meteorological variables. This PhD research is funded by the EU FP 7 ACQWA project, which stands for ‘Assessing Climate Impacts on the Quantity and Quality of Water’. The objective of this project is to assess the climate change impact of various aspects especially focusing on high altitude mountainous regions. The project originally comprised of several study sites covering Europe, South America and Central Asia. Since mountainous hydrology is quite complex, a suite of hydrological models are employed to understand the various phenomena like snow and glacier melt, orographic precipitation, water transfer etc. A further objective of ACQWA is to assess the potential impact of a changing climate in various sectors such as tourism, agriculture, drinking water supply and domestic use of water. Any changes in water distribution in the sectors mentioned will lead to a conflict; a better understanding of water management based on future forecast is, therefore, essential with good governance.

The project aims to assess the hydrological components based on 100 years period (both historic and forecast). High resolution climate scenarios were analyzed from 1950-2050. Bias correction technique was performed with quantile mapping algorithm and downscaled to 25 km resolution from 16 RCMs. For this PhD study, 30 years of observation period with daily time step were chosen from 1981-2010 to validate the climate model output. After satisfactory results, the climate model outputs were fed into the hydrological model for impact analysis. In most of the impact modeling study, the timeline often chosen for the end of century, the limitation of the modeling horizon to middle of the 21st century allows the development of a more realistic assessment of the possible impact on the social, economic and political systems, which was expected to evolve typically in an adaptive mode on shorter time scales than the centennial ones. The outcome of this project leads better understanding in complex hydrological process especially in the data sparse region (Sorg et al. 2012).

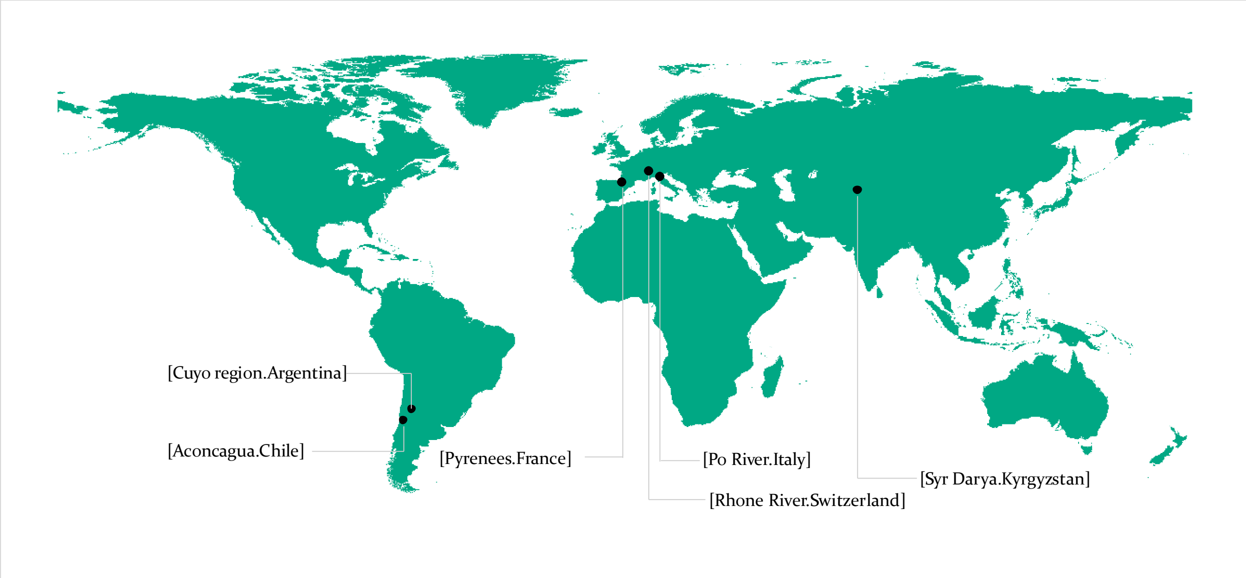

Figure 2: Study sites of ACQWA project

As a consequence of long term impact assessment, guidelines are provided with this project in diversified fields; for example, forecasts on hydropower based energy production and the associated uncertainties (Finger et al. 2012), snow and glacier melt processes (Boscarello et al. 2012; Finger et al. 2011), bio diversity threats in the glacial feed rivers (Jacobsen et al. 2012), irrigation and water management (Smith et al. 2012). Possible combined impact on diversified fields are explained in several scientific literatures based upon this project outcome (Beniston 2012; Beniston et al. 2011a). To know more about this project readers are referred to the associated web site [http://acqwa.ch/].

1.3 Study Area

The upper Rhone River watershed is located in the southwestern part of Switzerland and originates from the Rhone Glacier (Klok et al. 2001). The watershed area covers 5,220 km^2 with a river length of 167 km (Fette et al. 2007). Elevation ranges from 377 to 4634 meters a.s.l. Three river characterizations have been performed, in which the Rhone River's length was reduced to around 20 percent of its original length. The most important feature of the watershed is that it drains into Lake

Geneva and thus is of great importance to the Swiss economy. Furthermore, the majority of hydropower-based energy is produced in this watershed by capturing the snow and glacier melt in the reservoirs.

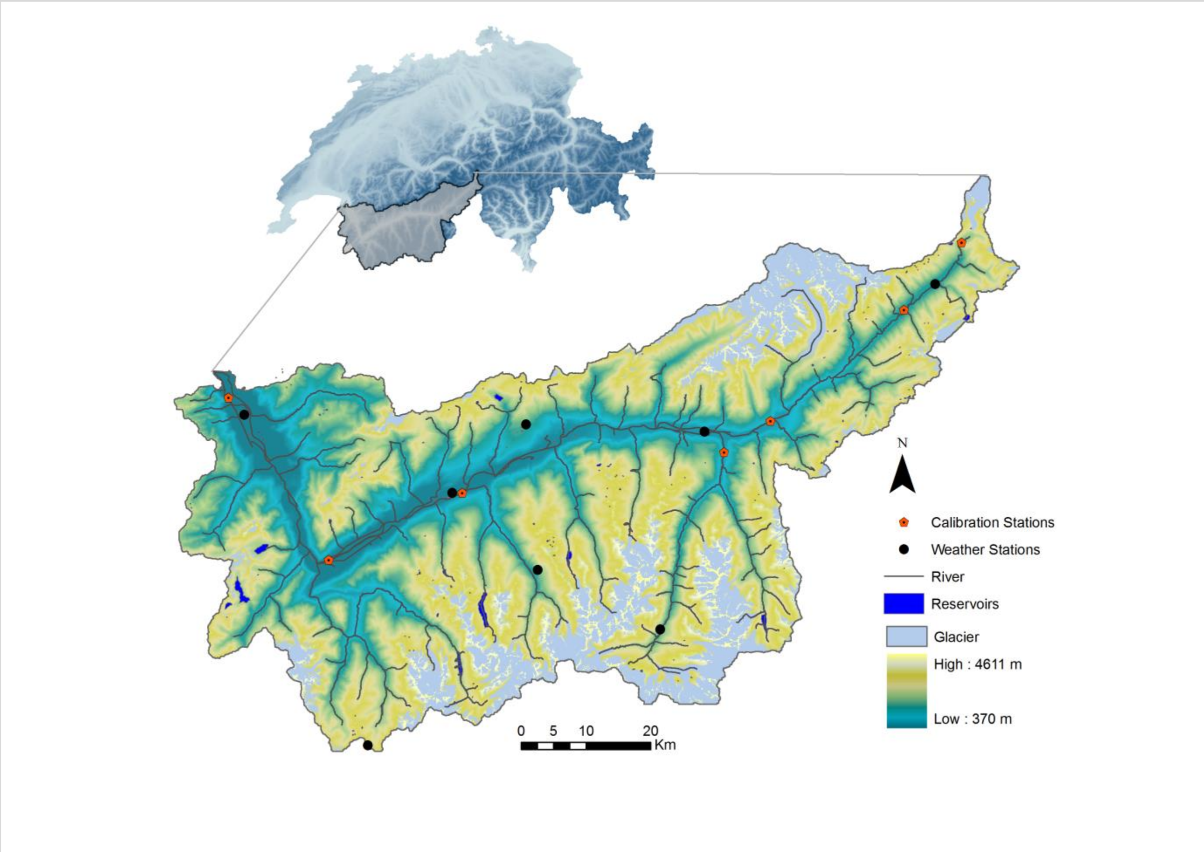

Figure 3: Study Area

This study area poses both natural and anthropogenic influences; therefore understanding of such complex watersheds will give added value to the science of hydrological modeling. Among the various natural variability, snow and glacier melt, orographic precipitation, precipitation and temperature lapse rates are notable. On the other hand, the melted water is stored in the reservoir for a long time, which alters the natural hydrological behavior of this watershed. This long term storage of water is highly correlated with the energy consumption of the neighboring cities. Usually in the winter time the energy consumption is high and in summer time the energy consumption is low, therefore the melted water in summer is stored in the reservoirs and released in the winter. The Rhone River experienced several characterizations which reduced its original length that consequently increased hydro peaking (Meile et al. 2010).

1.4 Existing Studies

Studies related to streamflow simulation in the Swiss Alps are conducted by several groups of researchers (Daniel Farinotti1 2011; Gurtz et al. 2003; Huss et al. 2008; Huss et al. 2010; Klok et al. 2001). Since the hydrology of most of the river watersheds is driven by snow and glacier melt, the application of snow and glacier melt models is apparent. Some studies were conducted that focused only on glacier runoff simulations along with their fate and future taking climate change into account (Daniel Farinotti1 2011; Huss 2011; Huss et al. 2008; Huss et al. 2010; Klok et al. 2001; Pellicciotti et al. 2005; Schaefli et al. 2005; Schaefli and Huss 2011). The sensitivity of climatic models was tested for simulating precipitation, temperature, and other driving variables for hydrology (Bordoy and Burlando 2012). The impact assessment studies were also done by several researchers, for example hydro peaking, (Fette et al. 2007; Meile et al. 2010) evaluation of sediment load, (Loizeau and Dominik 2000) as well as irrigation and agriculture (Smith et al. 2012). Since the impact on hydropower production is a major concern in this region, some studies were conducted on future hydropower production guidelines (Finger et al. 2012; Schaefli et al. 2007). Most of the studies were effectuated upstream and represent a specific part of the entire upper Rhone River.

1.5 Research Gap

The major difficulty that the Rhone watershed presents is the strong influence of hydropower networks. During the summer, melted water from snow and glaciers are stored inreservoirs and released in the winter. This alteration process changes the natural discharge regime. Usually, most of the glacier melt water runoff is captured in small reservoirs and transferred to large reservoirs such as the Grande Dixence, Mattmarks, Mauvoisin, etc. Studies were conducted in small, high altitude catchments, but there was no integrated model that implemented all of the hydropower reservoirs and that could simulate until the downstream discharge station until ‘Porte du Scex’. This downstream station is highly significant because it drains at the mouth of Lake Geneva. Moreover, the unavailability of data hinders model performance since the downstream discharge is highly influenced by the reservoir’s operation rules. Therefore, a model implementing all the capture points and artificial water routing can be important for simulating runoff that is further downstream. The model could later be utilized for a land-use and climate change sensitivity test.

1.6 Objectives and Approach

The overall aim of this thesis is to assess hydro-climatic change in a mountainous watershed in the prevailing climate. The specific objectives are listed below:

- Development of an integrated hydrological model which accounts for complexities due to natural variability and anthropogenic influence.
- Perform evaluation of climatic models in complex watersheds for reproducing streamflow.
- Flow component analysis and its contribution to stream runoff using end member mixing analysis.
- Streamflow response to land use and climate change and its potential impact on the hydrology of the Rhone River watershed.
- Hydrological model development based on freely available data and open source software.

1.7 Research Questions

- Can we simulate streamflow in such a watershed with severe flow alteration due to hydropower reservoirs as well as snow and glacier melt?
- Are Regional Climatic Models performing well enough to generate streamflow given the region's complex topography?
- Can we quantify the contribution of streamflow components in this high altitude watershed and assess their daily dynamics?
- Will flow regime change in the Rhone River watershed? How significant is this change in terms of magnitude and the timing of peak and low flow?
- Can we develop a hydrological model and calibrate it based upon freely available data and open source software?

1.8 Thesis Structure

This thesis consists of four sub-sections, each of which poses an individual research question. The main objective is to assess the sensitivity of streamflow due to climate and land-use change. It should be noted that each research question pertains to a field of science within itself. Therefore, a specific topic has been chosen that supports the main research question. Each topic has resulted in the publication of a peer reviewed paper in an international journal [published/submitted], which will be presented in the subsequent chapters.

Chapter 1: Hydrological model development for the Rhone watershed.

Chapter 2: Performance test of climatic models for simulating streamflow

Chapter 3: Quantification of the streamflow component in a mountainous basin with tracers

Chapter 4: Streamflow sensitivity of Rhone River due to land-use and climate change

Chapter 5: Modeling hydrology with freely available data and open source software.

Chapter 1 describes the complexity that arises for hydrological modeling due to strong anthropogenic influences along with natural variability due to snow and glacier melt. For example, hydropower reservoirs and their water transfer alters the flow behavior by storing water in the summer and releasing it in the winter. Therefore, it is essential to implement a network of hydropower reservoirs wherein water is captured by temporary reservoirs and subsequently transferred to the main reservoir. A hydrological model has been developed that configures all the hydropower networks and implements their operation rules. This work has been published in the **Journal of Water Resources Management.**

Chapter 2 responds to the inquiry: Are climatic models capable enough to simulate stream runoff in a watershed where snow and glacier melt dominates the hydrology? To answer this question, an analysis of such climate model outputs as precipitation, temperature, and simulated streamflow using various RCM outputs from the PRUDENCE project is conducted. The analysis shows that not all the climate generated outputs are good enough, especially for mountainous watersheds. Among the various climatic models, RCMs from the Danish Meteorological Institute generated output that could provide the closest value to the observed runoff. Therefore, a suggestion is given to the bias correction studies, emphasizing the temperature lapse rates since the hydrology is driven with snow and glacier melt. This work has been submitted to the Journal of Regional Environmental Science and it is under review.

Chapter 3 describes the contribution of potential geographic runoff sources for streamflow. These include snow and glacier melt, precipitation, and ground water. In order to quantify their contribution on a sub-daily scale, we used a technique called End Member Mixing Analysis (EMMA). Water samples were collected each year during the summer period from glacier melt, snow melt, and groundwater-fed tributaries. We analyzed the water sample data collected from different tributaries of the Rhone River located at the head water zone and then examined the water samples in the laboratory with a spectrophotometric device in order to analyze the ions. Our findings suggest that the glacier melt rate is faster during the rising period (until August) and that there is a shift in the melting season. Finding from this chapter will be submitted to the Journal of Hydrology

Chapter 4 answers the question: Is the same amount of flow coming to the river as before? This is a frequently asked question in the field of river hydrology since discharge is highly linked with downstream biodiversity and ecosystem functioning. Scenario maps for land-use change and high resolution climate model generated meteorological variables were used to analyze the changes. The model (described in Chapter 1) was recalibrated with the climatic data and extrapolated for future forecasting. The results show that peak flow reduction is occurring for land-use change since the reduction of glaciers and the increase in vegetation will lead more evapotranspiration which will apparently reduce the flow. On the other hand, a sign of early melt is visible due to climatic change. The combined effects yield peak flow reduction along with early high flow and a drop in the peak flow season. Findings from this chapter will be submitted to Journal of Applied Geography

Chapter 5 deals the complexity arises for data requirement of hydrological modeling. The quality of data their spatial and temporal resolution determines the performance of the hydrological model. In this chapter an attempt was taken to build up a hydrological model based on completely freely available data from various sources. The most challenging part of hydrological modeling is to calibrate the model for a better agreement with the observation. This calibration process takes time since it is an iterative process and a set of simulation needs to be done to get a better set of performance statistics. To minimize this iterative process, a set of script developed in the open source statistical programing platform R where all the model performance evaluation statistics are implemented along with plotting capabilities. A case study site was chosen fromSouth America (Mendoza river watershed) to test the method. Results show a sound agreement with the observed streamflow. The outcome of this chapter has been submitted in the Journal of Environmental Informatics which is under review.

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Chapter: 1

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Title: "Streamflow modeling in a highly managed mountainous glacier watershed using SWAT: the upper Rhone River watershed case in Switzerland"

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Abstract

Streamflow simulation is often challenging in mountainous watersheds because of irregular topography and complex hydrological processes. Rates of change in precipitation and temperature with respect to elevation often limit the ability to reproduce stream runoff by hydrological models. Anthropogenic influence, such as water transfers in high altitude hydropower reservoirs increases the difficulty in modeling since the natural flow regime is altered by long term storage of water in the reservoirs. The Soil and Water Assessment Tool (SWAT) was used for simulating streamflow in the upper Rhone watershed located in the south western part of Switzerland. The catchment area covers 5220 km^2, where most of the land cover is dominated by forest and 14 % is glacier. Streamflow calibration was done at daily time steps for the period of 2001-2005, and validated for 2006-2010. Two different approaches were used for simulating snow and glacier melt process, namely the temperature index approach with and without elevation bands. The hydropower network was implemented based on the intake points that form part of the inter-reservoir network. Subbasins were grouped into two major categories with glaciers and without glaciers for simulating snow and glacier melt processes. Model performance was evaluated both visually and statistically where a good relation between observed and simulated discharge was found. Our study suggests that a proper configuration of the network leads to better model performance despite the complexity that arises for water transaction. Implementing elevation bands generates better results than without elevation bands. Results show that considering all the complexity arising from natural variability and anthropogenic influences, SWAT performs well in simulating runoff in the upper Rhone watershed. Findings from this study can be applicable for high elevation snow and glacier dominated catchments with similar hydro-physiographic constraints.

Keywords: SWAT, snow melt, glacier melt, hydropower, AMALGAM.

1 Introduction

Snow and glacier melt runoff from mountains is the main source of water at the regional scale, with downstream processes, such as hydropower based energy production (Viviroli and Weingartner 2004), biodiversity and ecological balance (Brown et al. 2006) , controlled by processes at higher elevations. Many models have been applied to the simulation of snowpack- snowmelt processes in the watershed, ranging from simple temperature-based equations to complex and sophisticated process-based equations (Debele et al. 2010). In mountainous regions, runoff from snow and glacier melt provides streamflow which is often regulated by storage reservoirs (Fig. 2). In Switzerland, especially the south western part of the country, the heterogeneity of elevation together with diverse forest cover and glacier dynamics present unique challenges as well as potential research opportunities to understand mountain hydrological processes. Temperature index models have been the most common approach (Hock 2003) for melt modeling for a number of reasons, among them a reasonable availability of air temperature data, relatively easy interpolation and forecasting possibilities of air temperature, generally good model performance despite their simplicity and computational simplicity. Applications are numerous and include the prediction of melt for operational flood forecasting and hydrological modeling. However, two drawbacks are apparent; firstly, because of temporal resolution, their accuracy decreases; secondly, simulating longer time period and topographic effect such as shading slope and aspect is a hindrance to modeling spatial variability These effects are crucial in mountain areas (Hock 2003). Recent existing studies were conducted in this region, mostly focusing on the evaluation of glacier surface area and glacier melt runoff (Daniel Farinotti1 2011; Farinotti et al. 2009; Huss 2011; Huss et al. 2010; Schaefli et al. 2005; Schaefli and Huss 2011), and impact on hydro peaking in a distributed manner (Meile et al. 2010) . In addition, some studies were carried out for long term forecasts of streamflow based on climate model outputs, but with little detail about physical processes such as snow and glacier melt (Beniston 2010). Therefore the specific objective of this research is to assess the capabilities of a physically-based hydrological model (SWAT) for runoff simulation in the upper Rhone watershed, considering the entire range of complexity that arises from natural variability and human influence, such as long term water storage in the hydropower reservoirs.

2 Study area

The upper Rhone river located in the south western part of Switzerland originates from the Rhone glacier (Fette et al. 2007). It is 167.5 km long with a drainage basin of 5220 km^2. According to Meile et al. (2010) 14 % of its land area is covered with glaciers.

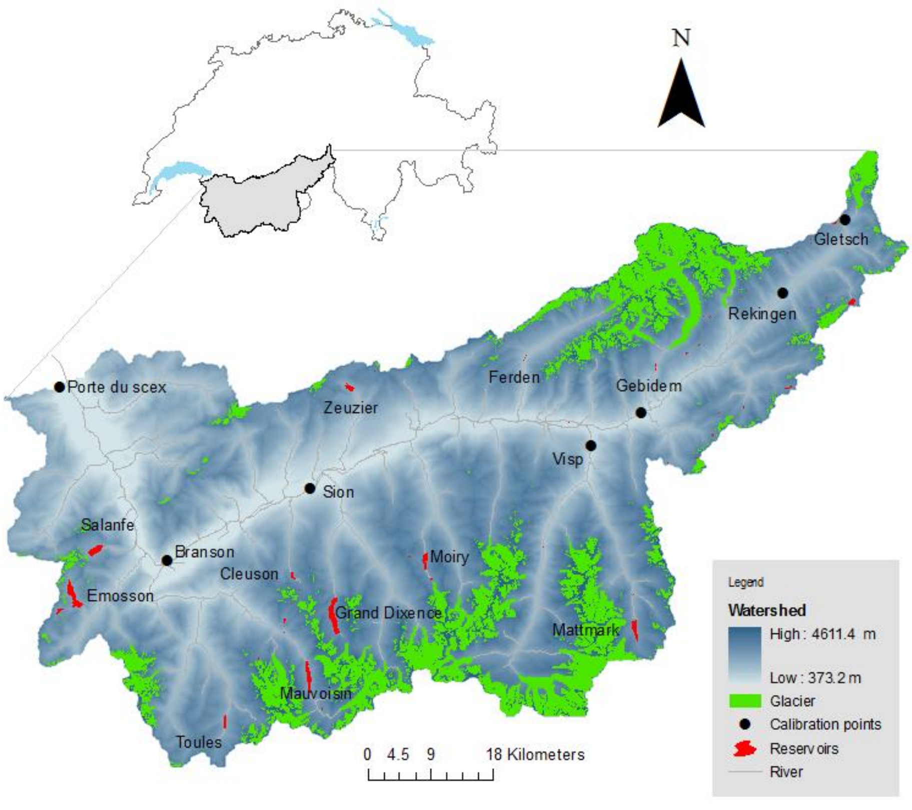

Fig. 1 Upper Rhone river catchment in Switzerland

Runoff behavior is characterized by two important regimes: the high flow period that occurs in summer due to snow and ice melt; and the low flow period that occurs during the winter. The average precipitation of the basin is observed to be 1435 mm/year (Schaedler B and R 2001). The upper Rhone is considered as 7 order tributaries; lower orders are illustrated in Fig.1. Two main characterizations were done in 1930 and 1960 for flood protection for which 91% of its length were affected. This channeling reduced its original length from 424 km to 251 km (Meile et al. 2010). In total 11 high head hydropower plants are located in the upper Rhone and most of them started functioning between 1951 and 1975. Therefore a shift of natural behavior has been observed in high flow and low flow periods since the construction of these dams due to the long term storage of water which is illustrated in Fig. 2.

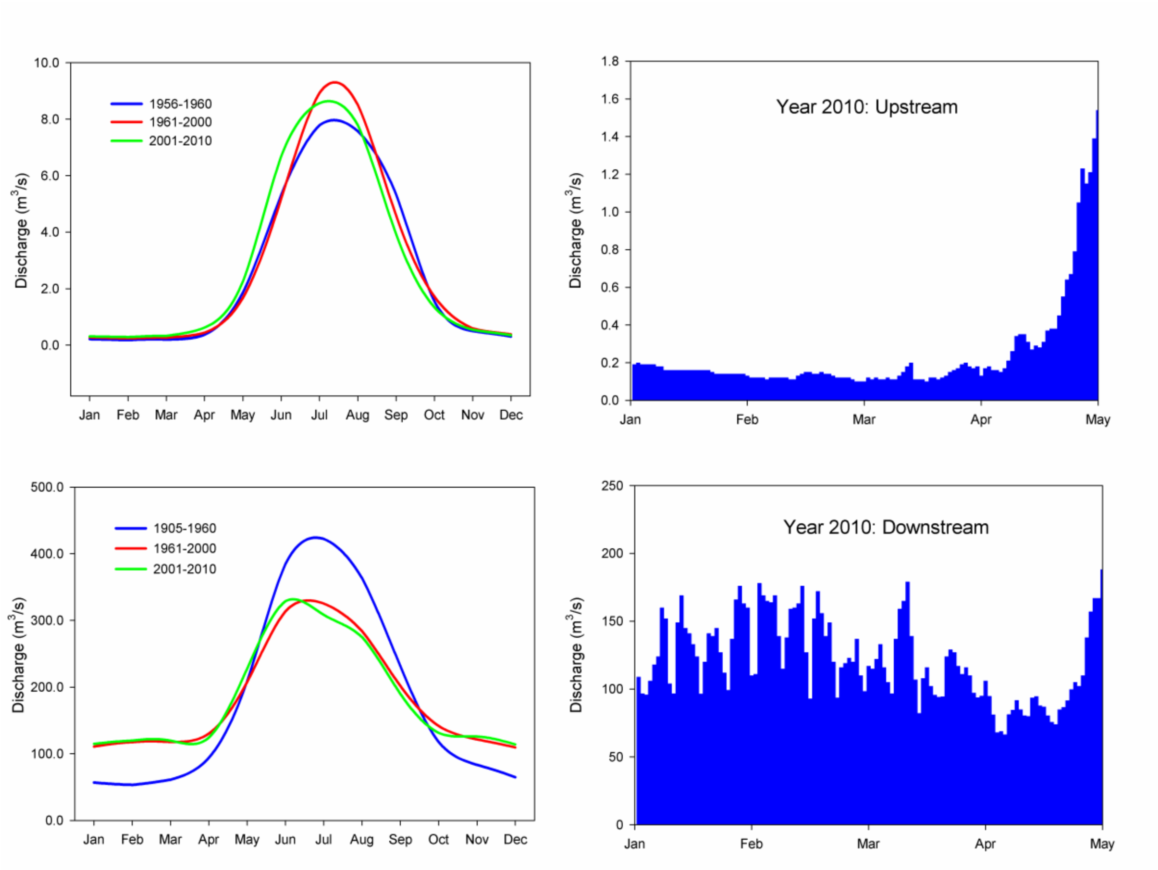

Fig. 2 Upstream [upper left and right] and downstream [lower left and right] discharge comparison Upper left: Monthly average discharge based on daily discharge record of 1956-2010. Upper right: daily discharge from 1st January 2010 to May 2010. Lower left monthly average discharge based on the daily discharge from 1905-2010, lower right daily discharge from 1st January to 1st May 2010.

Table 1 Data used and sources

Data Type	Data Sources	Scale	Description
DEM	Swiss-topo	(Grid cell: 25 m · 25 m)	Elevation
Land use	Swiss Federal Statistical Office	(Grid cell: 100 m · 100 m)	Classified land use such as crop, urban forest water etc.
Soil	Swiss Federal Statistical Office	1:200000	Classified soil and physical properties as sand silt clay bulk density etc
Hydro network	Swiss-topo	1:25000	River network-diversion
River flow	FOEN	-	River discharge at daily time step
Weather	Meteo Swiss	-	Precipitation Temperature Wind Speed Solar radiation Wind Speed
Hydropower Discharge	Alpiq, KW Mattmark	-	Inflow and outflow, lake level

Historical discharge data were collected from Swiss meteorological office (FOEN) for upstream (Gletsch) and downstream (Porte du Scex) observation points. Daily discharge data from 1956-2010 for the Gletsch measuring station were analyzed using monthly discharge hydrographs in order to have an idea about the natural behavior of the runoff process. Among other head water catchments, Gletsch was chosen based on the historic data availability of this discharge gauge. Furthermore, 105 years of daily discharge data (from 1905-2010) were collected from Porte du Scex, located downstream close to the entry-point into Lake Geneva, where the discharge is a combination of both natural flows and those released from the hydropower reservoirs. A comparison is given in Fig. 2 where the observation line is split into two different time slices for both points. An important observation can be obtained following the years 1960-2000 where the upstream points indicated the higher runoff in the summer period but winter period remained constant, whereas the downstream points illustrated lower runoff in the summer but higher runoff in the winter; this is due to long term storage of water in the hydropower reservoirs which is linked to the energy consumption.

3 Methodology

3.1 SWAT model

The Soil and Water Assessment Tool (SWAT) Arnold et al(1998) is a process-based distributed parameter watershed scale simulation model. It subdivides an overall watershed into sub watersheds connected with the river network and smaller units called Hydrological Response Units (HRUs), which each represent a combination of land use, soil and slope. HRUs are non-spatially distributed assuming there is no interaction and dependency (Neitsch et al. 2005). SWAT has been successfully applied all over the world for solving various environmental issues for water quality and quantity studies like diffuse surface water pollution (Panagopoulos et al. 2011; Varanou et al. 2002). But relatively less in snow and glacier dominated mountainous terrain. However, several studies have been performed and a few studies are ongoing to explore hydrological fluxes in mountain regions (Abbaspour et al. 2007; Ahl et al. 2008; Debele et al. 2010; Fontaine et al. 2002; Morid 2004; Pradhanang et al. 2011; Wang and Melesse 2005; Zhang et al. 2008). The meteorological variables needed to run the model are precipitation, temperature, wind speed, solar radiation, and relative humidity on daily or sub-daily time steps. SWAT simulates energy, hydrology, soil temperature, mass transport and land management at subbasin and HRU level. For this specific study, variables related to discharge and snow melt on mountainous domain will be addressed; more detailed information about the other processes can be obtained from (Neitsch et al. 2005). The hydrological routine of SWAT consists of discharge, snow melt, and evapotranspiration both actual and potential. The SCS curve number method from USDA was used for surface runoff volume estimation. SWAT evaluates evapotranspiration in various methods such as FAO Penman–Monteith, Hargreaves, and Priestley-Taylor. For this study Penman–Monteith was found suitable based on initial model performance before calibration.

3.2 Implementing the hydropower network:

The built-in command [ROUTRES] in SWAT allows water transfer from one subbasin to another with three different specifications, a fraction of the volume of water in the source, a volume of water left in the source, and the volume of water transferred. In the Rhone watershed, most of the capture points are located downstream of glacier tongues and in most cases all the water is transferred to the reservoir. Based on the site-specific knowledge, geographic coordinates of all the pumping stations were collected and the listed subbasins (Table 4) were used for water transfer. However, it is cumbersome work to modify each of the subbasins affected for pumping station. Also inconsistency may arise for manual operation. In order to avoid inaccuracy a routine was developed in MATLAB considering each of reservoirs inflow outflow scenarios modifying the configuration file (fig.fig) for reservoir routing in SWAT. Several simplifications were made considering the backwater pumping since the water transection does not occur outside of the basin. As an example, hydropower infrastructures are classified into two major groups based on re-pumping of water. Re-pumping mostly occurs when the energy price is high: a compensation pool is used to store the water during high consumption periods and the water is pumped back at night using nuclear power. More details of the networks of water transaction can be obtained from (Hernández 2011; Jordan 2007).

Table 2 list of high head hydropower dams with the affected subbasins

Reservoir Name	Volume [mio m^3]	Surface area [ha]	Collecting points	Release points	Reach number
Grande Dixence	401	430	248-150-152-156-157-161-162-166-167-173-174-176-177-178-181-184-186-191-192-193-195-197-204-205-206-207	164	111-114
Emmosson	227	327	153-159-187-208-212-213-216	170	141 -123
Mauvoisin	211.5	208	182-185-188-196-198	201	145
Mattmark	101	176	125-128-138-151-155-172-180-168	183	87
Moiry	78	140	106-115-121-127-144	139	64
Les Toules	20.15	61	211-214-219	218	209

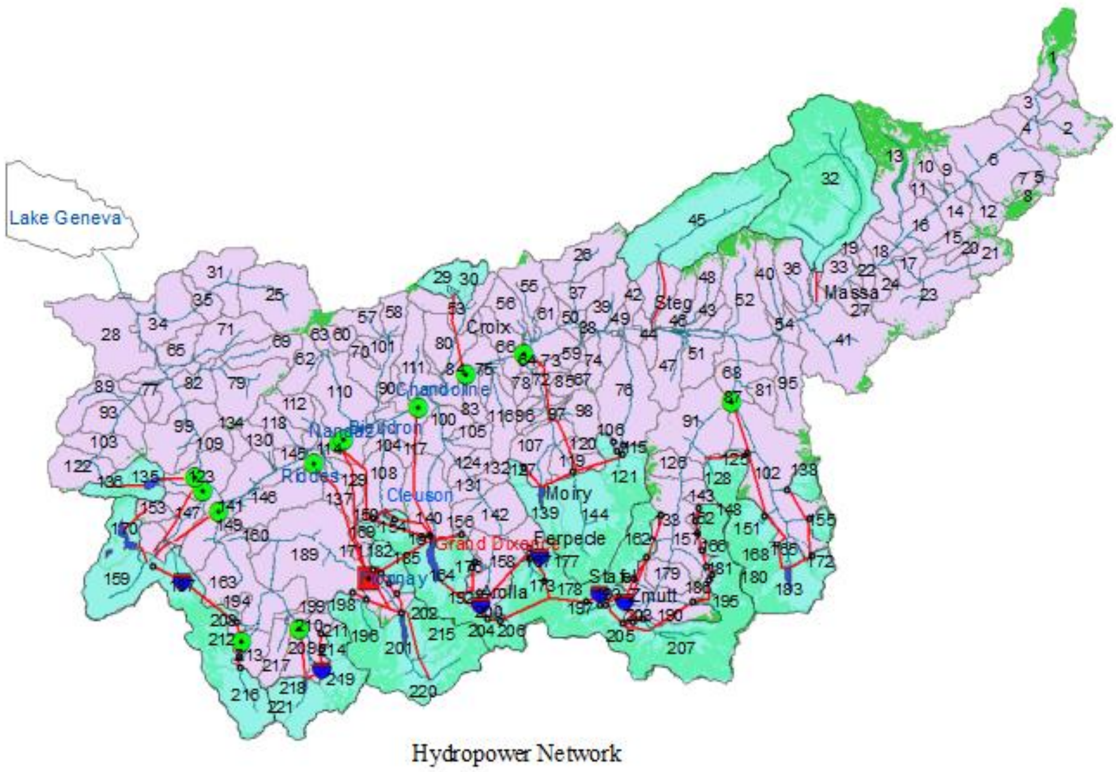

Fig. 3 (a) Hydropower networks of upper Rhone watershed.

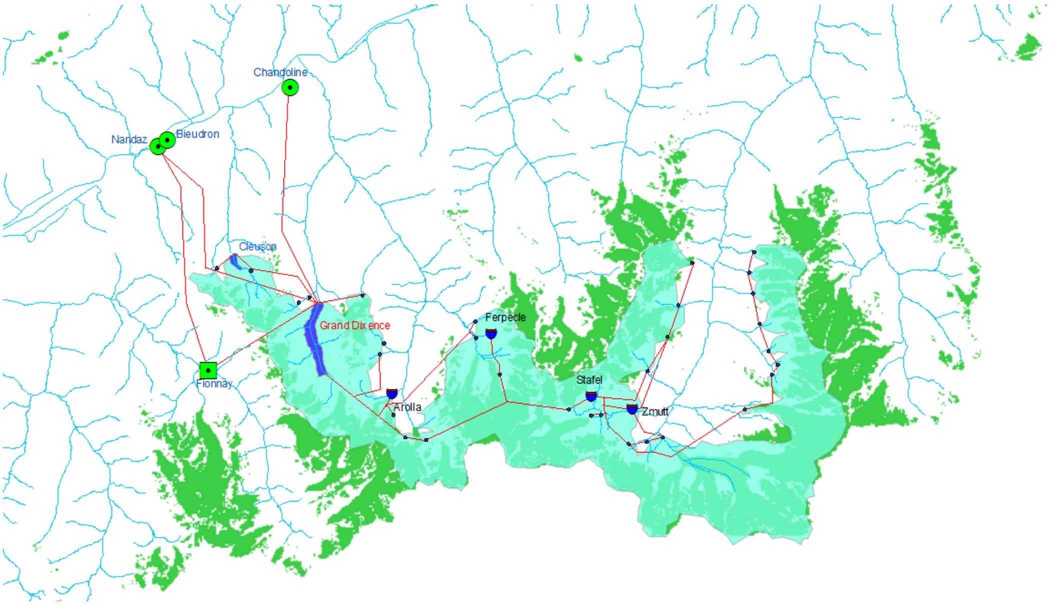

Fig. 3 (b) Hydropower networks of Grande Dixence

Subbasin discretization was achieved using the location of the capture points. The shaded area in Fig. 3 shows the area where natural flow is regulated for storing water in the high-head hydropower reservoirs. Subbasins located inside the shaded area are grouped into one category and the subbasins where natural flow occurs are grouped into another category. Pipe networks and the capacity of pipes were implemented based on a pre-existing study (Frédéric Jordan et al. 2007). Discharge information, for instance, inflow to the lake and outflow from the lake was implemented on a daily time step. However it is to be mentioned that some generalization has been done through correlation with energy prices based on long term target levels, since some of the reservoir outflow data were not available.

3.3 Snowmelt routing algorithm

Mean daily air temperature is the indicator for precipitation in SWAT, and the boundary temperature (T_{s-r}) is used to categorize precipitation as rain or snow by the user. It is defined in such a way that if the mean daily air temperature is below the boundary temperature, the precipitation will be modeled as snow. Similarly if the temperature is above the boundary temperature, precipitation will be considered to be in the form of liquid rain. Snowfall is stored at the ground surface in the form of an accumulating snow pack, and the amount of water stored there is reported as snow water equivalent.

The snow pack will increase with additional snowfall or decrease with snow melt or sublimation. The mass balance for snow pack is

$$\mathrm{SNO} = \mathrm{SNO} + \mathrm{R_{day}} - \mathrm{E_{sub}} - \mathrm{SNO_{mlt}} \qquad \mathbf{1}$$

Where SNO is the water content of pack on a given day (mm H_2O), $\mathrm{R_{day}}$ is the amount of precipitation on a given day (added only if $\overline{\mathrm{T_{av}}} \leq \mathrm{T_{s-r}}$) (mm of H_2O). $\mathrm{E_{sub}}$ is the amount of sublimation on a given day (mm H_2O) and $\mathrm{SNO_{mlt}}$ is the amount of snow melt on a given day (mm of H_2O). The snow pack distribution is not uniform over the entire watershed due to large number of influencing factors such as irregular topography, drifting and shading. This results in a fraction of the subbasin area that is bare of snow. This fraction must be computed for the quantification of the snow melt in the subbasin. The factor that contributes to variable snow cover usually has similar values from year to year, making it possible to correlate the areal coverage of snow with the amount of snow present in the subbasin at any given time. For this study, an aerial depletion curve was used to express the seasonal growth and decay of the snow pack as a function of the amount of snow present in the basin. This curve is based on a natural logarithm and is calculated as

$$\mathrm{SNO_{cov}} = \frac{\mathrm{SNO}}{\mathrm{SNO_{100}}} \times \left[\frac{\mathrm{SNO}}{\mathrm{SNO_{100}}} + \exp(\mathrm{cov_1} - \mathrm{cov_2} \times \frac{\mathrm{SNO}}{\mathrm{SNO_{100}}})\right]^{-1} \qquad \mathbf{2}$$

Where $\mathrm{SNO_{cov}}$ is the fraction of HRU area that covered by snow, SNO is the water content of the snow pack on a given day (mm of H_2O), $\mathrm{SNO_{100}}$ is the threshold depth of snow at 100 % coverage (mm of H_2O), $\mathrm{cov_1}$ and $\mathrm{cov_2}$ are coefficients that define the shape of the curve. The values used for $\mathrm{cov_1}$ and $\mathrm{cov_2}$ are determined by solving two known points; these are at 95% coverage at 95% $\mathrm{SNO_{100}}$ and 50% coverage at a user specific fraction of $\mathrm{SNO_{100}}$.

3.4 Snow pack temperature

The snow pack temperature of current day is calculated using the equation

$$\mathrm{T_{snow(d_n)}} = \mathrm{T_{snow(d_n-1).(1-l_{sno})}} + \overline{\mathrm{T_{av}}}.\mathrm{l_{sno}} \qquad \mathbf{3}$$

where $T_{snow(d_n)}$ is the snow pack temperature on a given day (°C), $T_{snow(d_n-1)}$ is the snow pack temperature on the previous day (°C) l_{sno} is the snow temperature lag factor, and $\overline{T_{av}}$ is the mean air temperature on the current day (°C). As l_{sno} approaches to 1.0, the mean air temperature on the current day exerts an increasingly greater influence on the snow pack temperature while the snow pack temperature from the previous day exerts less and less influence

3.5 Snowmelt process

The temperature index approach and temperature index with elevation band approach are both used for this case study (Hock 2003). Snow melt is controlled by the air and snow pack temperature, the melting rate and the area coverage of snow. The SWAT model considers melted snow as rainfall in order to compute runoff and percolation. Rainfall energy from the fraction of snow melt is set to zero while computing snowmelt and is estimated assuming uniformly melted snow for 24 hours of the day. Total runoff process explained with the Fig. 4.

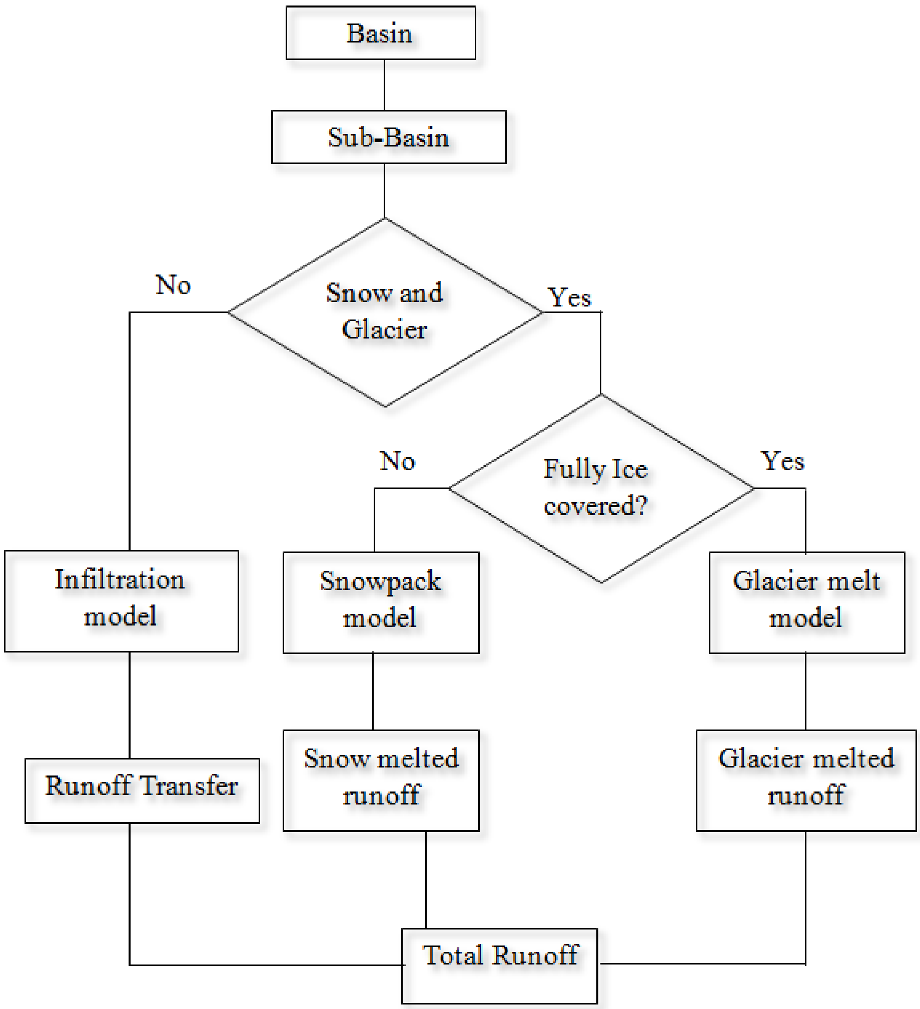

Fig. 4 Schematic diagram of snow and glacier melt process

3.6 Temperature-index approach:

Temperature is considered as a major controlling factor for snow melt in the temperature index method (Hock 2003). The snow melt in SWAT is calculated as a linear function of the difference between the average snow pack-maximum air temperature and the base or threshold temperature for snow melt

$$SNO_{mlt} = b_{mlt} \, . \, sno_{cov} \, . \left[\frac{T_{snow} + T_{mx}}{2} - T_{mlt}\right] \qquad \mathbf{4}$$

SNO_{mlt} is the amount of snow melt on a given day (mm H_2O), b_{mlt} is the melt factor for the day (mm H_2O/day-^oC), sno_{cov} is the fraction of HRU area covered by snow, T_{snow} is the snow pack temperature on a given day (^oC), T_{mx} maximum air temperature on a given day (^oC),T_{mlt} base temperature above which snow melt is allowed (^oC).The melt factor is allowed seasonal variation with maximum and minimum values occurring on summer and winter solstices

$$b_{mlt} = \left(\frac{b_{mlt6} + b_{mlt12}}{2}\right) + \left(\frac{b_{mlt6} - b_{mlt12}}{2}\right) \times \sin\left(\frac{2\pi}{365}(d_n - 81)\right) \qquad \textbf{5}$$

Where, b_{mlt} is the melt factor for the day (mm H_2O/day-^oC), b_{mlt6} is the melt factor for June 21 (mm H_2O/day-^oC), b_{mlt12} is the melt factor for December 21 (mm H_2O/day-^oC) , d_n is the day number of the year.

3.7 Temperature index with elevation band approach

Elevation is considered one of the very important variables related to meteorological parameters (Zhang et al. 2008), in particular temperature but also snow amount. SWAT allows the sub-basin to be split into a maximum of ten elevation bands, and snow cover and snowmelt are simulated separately for each elevation band (Fontaine et al. 2002). The temperature and precipitation for each band was adjusted using

$$T_B = T + (Z_B - Z).\,dT/dZ \qquad \textbf{6}$$

$$P_B = P + (Z_B - Z).\,dP/dZ \qquad \textbf{7}$$

where T_B is the elevation band mean temperature (^oC). T is the temperature measured at the weather station (^oC), Z_B is the midpoint elevation of the band(m), Z is the weather station`s elevation (m), P_B is the mean precipitation of the band (mm), P is the precipitation measured at the weather station(mm), dT/dZ is the precipitation lapse reate(mm/km) and dP/dZ is the temperature lapse rate (^oC/km). Four elevation bands were set up for the snow and glacier dominated subbasins keeping equal vertical distance from the mean elevation of the centroid of the subbasins. Snow water equivalents were calculated from the ice thickness map of Huss et al. (2008) based on a contour map of the study area and plugged into each elevation band. Precipitation lapse rate (dP/dZ) and temperature lapse rate (dT/dZ) were set to 0.5 mm/km and -0.5 (^{o}C/km) following local lapse rate calculation (Klok et al. 2001).

3.8 Glacier melt routing

Subbasins were categorized into two major classes based on the presence of glaciers. The HRUs located within glaciers were treated as solid ice and the glacier information was obtained from (Farinotti et al. 2009). The temperature index approach was used for glacier melt modeling (Hock 2003). In the temperature index model, it is assumed that the melt rate is a linear function of daily positive air temperature. Surface melt rate M is calculated with

$$M = \begin{cases} (F_M + r_{ice/snow}\, I)T & : T > 0°C \\ 0 & : T \leq 0°C \end{cases} \qquad \mathbf{8}$$

where F_M indicates the melt factor, $r_{ice/snow}$ is the radiation factor of ice and snow. I denotes the clear sky radiation. Daily air temperatures for each elevation band are computed using a lapse rate (dT/dZ) and similarly precipitation lapse rate (dP/dZ) also computed assuming a linear increase with elevation.

It is worth mentioning that due to the large number of glaciers, it was not possible to analyze the mass balance of individual glaciers; however, we evaluated the model performance based on the downstream discharge to a large glacier (Rhone Glacier) where a good correlation was obtained with observed flow. (NSE =0.78, R^2=0.82, PBIAS=3.27).

Several sources of uncertainties can be identified when modeling the conceptual snow and glacier melt process. Among these, one can mention the hydrologic model parameterization, orographic effects, the heterogeneity of forest cover, slope, and aspect. These are notable processes that are not well represented by the simple temperature index-driven snow and glacier melt process, and therefore lead to uncertainty in the estimation of glacier-influenced streamflows. Here we focus only parameter uncertainty, our goal was to see whether the parameters follow any specific distribution which is described in the uncertainty section (Fig.7)

3.9 Model performance evaluation

Several studies have proposed a standard hydrological model performance criterion. For this study we followed NSE, PBIAS and R^2 as model evaluation statistics (Moriasi et al. 2007). Model performance were considered satisfactory if NSE > 0.5, PBIAS = ± 25%. NSE is the strength of the relationship of observed and simulated values where Qm,t is the observed data value at time t and Qs,t is the simulated data value at time t. NSE values lies between -∞ to +1, (Nash and Sutcliffe 1970). Values close to +1 indicates the better model performance.

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{T}\left(Q_{m,t} - Q_{s,t}\right)^2}{\sum_{t=1}^{T}\left(Q_{m,t} - \bar{Q}_m\right)^2} \qquad \mathbf{9}$$

$$\mathrm{PBIAS} = \left[\frac{\sum_{t=1}^{T}\left(Q_{s,t} - Q_{m,t}\right)}{\sum_{t=1}^{T} Q_{m,t}}\right] \times 100 \qquad \mathbf{10}$$

$$R^2 = \left[\frac{\sum_{t=1}^{T}\left(Q_{m,t} - \bar{Q}_m\right)\left(Q_{s,t} - \bar{Q}_s\right)}{\sum_{t=1}^{T}\left[\left(Q_{m,t} - \bar{Q}_m\right)^2\right]^{0.5} \sum_{t=1}^{T}\left[\left(Q_{s,t} - \bar{Q}_s\right)^2\right]^{0.5}}\right]^2 \qquad \mathbf{11}$$

PBIAS indicates the average tendency of the simulated data to be larger or smaller than their observed value's. According to Gupta et al. (1999), PBIAS can be utilized as an indicator of under- or over-estimation. Negative PBIAS indicates a slight underestimation of model generated values against the measured values. The square of Pearson's product moment correlation is indicated with R^2 which represents the proportions of total variance of measured data that can be explained by simulated data. Higher values of simulated data close to 1 represent better model performance.

4 Results

4.1 Calibration

Our main goal was to evaluate model performance at the most downstream point (Porte du Scex) considering all the complex processes that arise from both natural and human influences. Fig. 5 shows the observed and simulated flows at the downstream and upstream points at different phases of calibration. The major problems identified before implementing elevation bands and parameter optimization were that the rising limb of the simulated hydrograph started earlier than the measured hydrograph, and systematic under estimation of both low and high flows of the entire calibration period. Moreover, the simulated hydrograph produced secondary peaks which are not valid in the observed hydrograph. Ultimately, the correlation statistics were also poor (R^2=0.16).

4.2 Manual calibration

The systematic underestimation problem was solved using the elevation band approach which has results consistent with Fontaine et al. (2002). Several trial and error experiments were made setting up the number of elevation band since SWAT has maximum of 10 bands to set for each subbasin. From the different experiments, we observed that lower numbers with proper configuration of ice thickness result in improved model performance. Similar results have been reported by Pradhanang et al. (2011). Parameter sensitivity was done using the LHOAT technique and the most sensitive parameters were found related to snow melt process. Detailed information about LHOAT can be found in van Griensven et al. (2006). Among the listed selected 9 parameters in table 4, temperature lapse rate (TLAPS) was found to be the most sensitive, since it is directly related with the melt process of snow and glaciers. The melt factor for snow on June 21 is parameterized by SMFMX, which is responsible for the maximum melt rate ; any increase of this value results in rapid melt. Snow melting process occurs mostly from March to June in the Rhone watershed therefore, the value was adjusted to 3.8 with several trial and error experiments in the manual calibraion process. The snow temperature lag factor TIMP is also linked with SMFMX since it considers the previous days situation. Along with TIMP suface water lag time, SURLAG plays important role for the model performance as the melted snow routing process is related to the geology of the watershed where most of the melted water flows as surface runoff over impervious rock formations. SMTMP is sensitive since it is the indicator of the starting and ending of melt, taking into account the availability of snow for melting on a specific day. As a result model-generated streamflow, especially peaks, are significantly influenced by the variation in SMTMP. The snow accumulation process mostly occurs between October and December, and the simulation period was started from January. As a consequence, the initial water content of each elevation band was filled up with SNOEB 150 mm for each elevation band.

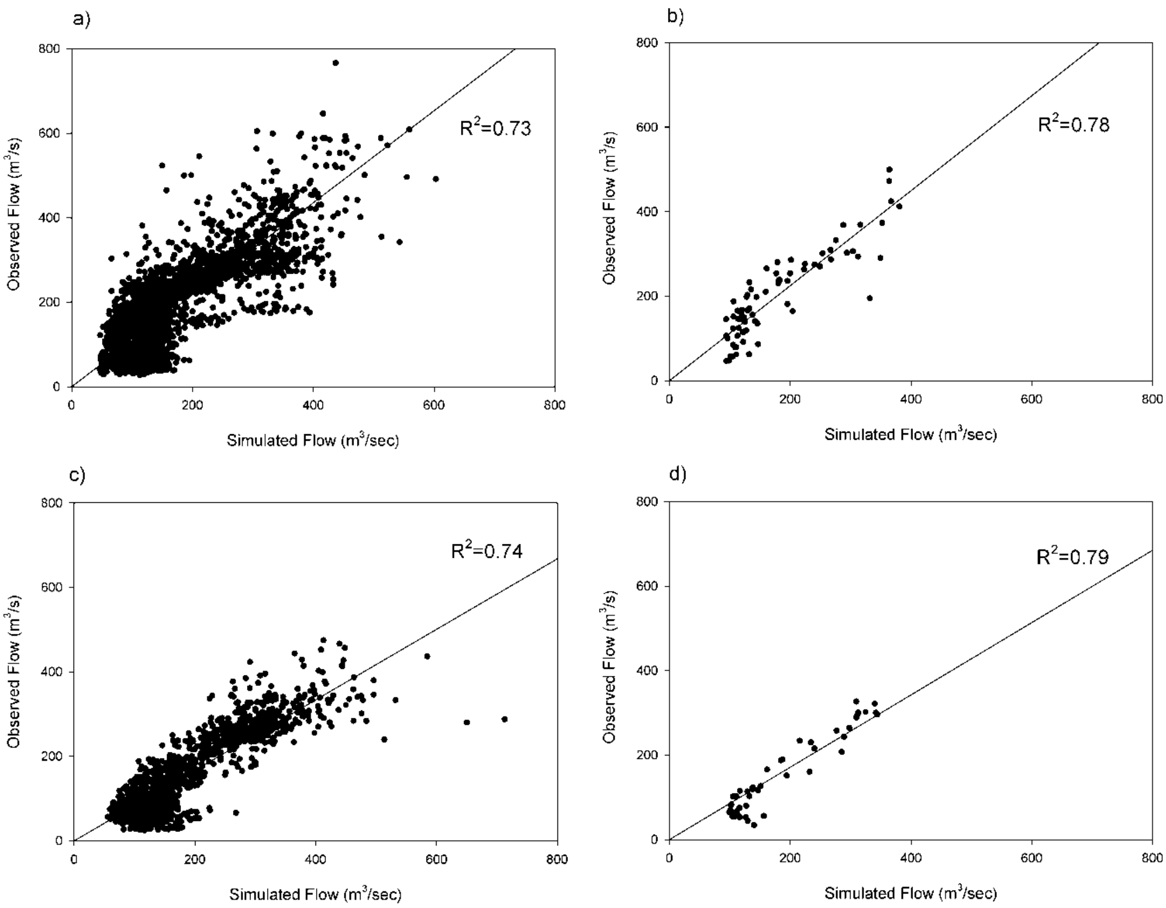

Fig. 6 Co-efficient of determination for calibration and verification period at daily and monthly time steps, upper left and right denotes calibration period lower left and right indicates verification period.

Table 3 list of calibrated parameters and their optimized value

Parameter	Description	Range	Optimized value
TLAPS	Temperature lapse rate [°C/km]	0,-10	-3.8
PLAPS	Precipitation lapse rate [mm H_2O/km]	0,100	5.8
SFTMP	Snowfall temperature[°C]	-5,+5	1.221
SMTMP	Snow melt base temperature [°C]	-5,+5	2.1
SNOEB	Initial snow water content in elevation band [mm]	0,300	150
TIMP	Snow pack temperature lag factor	0.01,1	1
SMFMN	Melt factor for snow on December 21 [mm H_2O/°C-day]	0,10	2.1
SMFMX	Melt factor for snow on June 21 [mm H_2O/°C-day]	0,10	3.2
SURLAG	Surface runoff lag time [days]	1,4	1

4.3 Automatic calibration

Automatic calibration was performed for this study in order to optimize the parameter values. Automatic calibration techniques are becoming increasingly popular in hydrological modeling since the iterative procedures can be performed by different algorithms until a possible solution is found. Model parameters were optimized based on the objective function set for model performance (NSE, MSE, and PBIAS). AMALGAM, an automatic calibration technique used for this study which searches for the objective function with the specified set of parameter assigned. AMALGAM comprises four different optimization routines, they are Non-dominated Sorting Genetic Algorithm (NSGA-II) (Deb et al. 2002), Particle Swarm Optimization (PSO), Adaptive Metropolis Search (AMS), and Differential Evolution (DE). Detailed information about AMALGAM can be obtained from Vrugt and Robinson (2007). The parameters obtained from the sensitivity analysis using LH-OAT (van Griensven et al. (2006)) are chosen for automatic calibration. Fig. 5(d) is the outcome of 10,000 generations where model performance improved from 0.61 to 0.69 considering NSE as the objective function. Results from the best simulations among the 10,000 generated are plotted in this Figure.

An independent time period was chosen for model verification without changing the parameter values obtained during the calibration period. We selected five years (from 2006-2010) as a verification period in order to test the acceptability of the optimized parameters. Fig 5(d) represents the outcome of the verification period with the statistical performance provided in table 4.

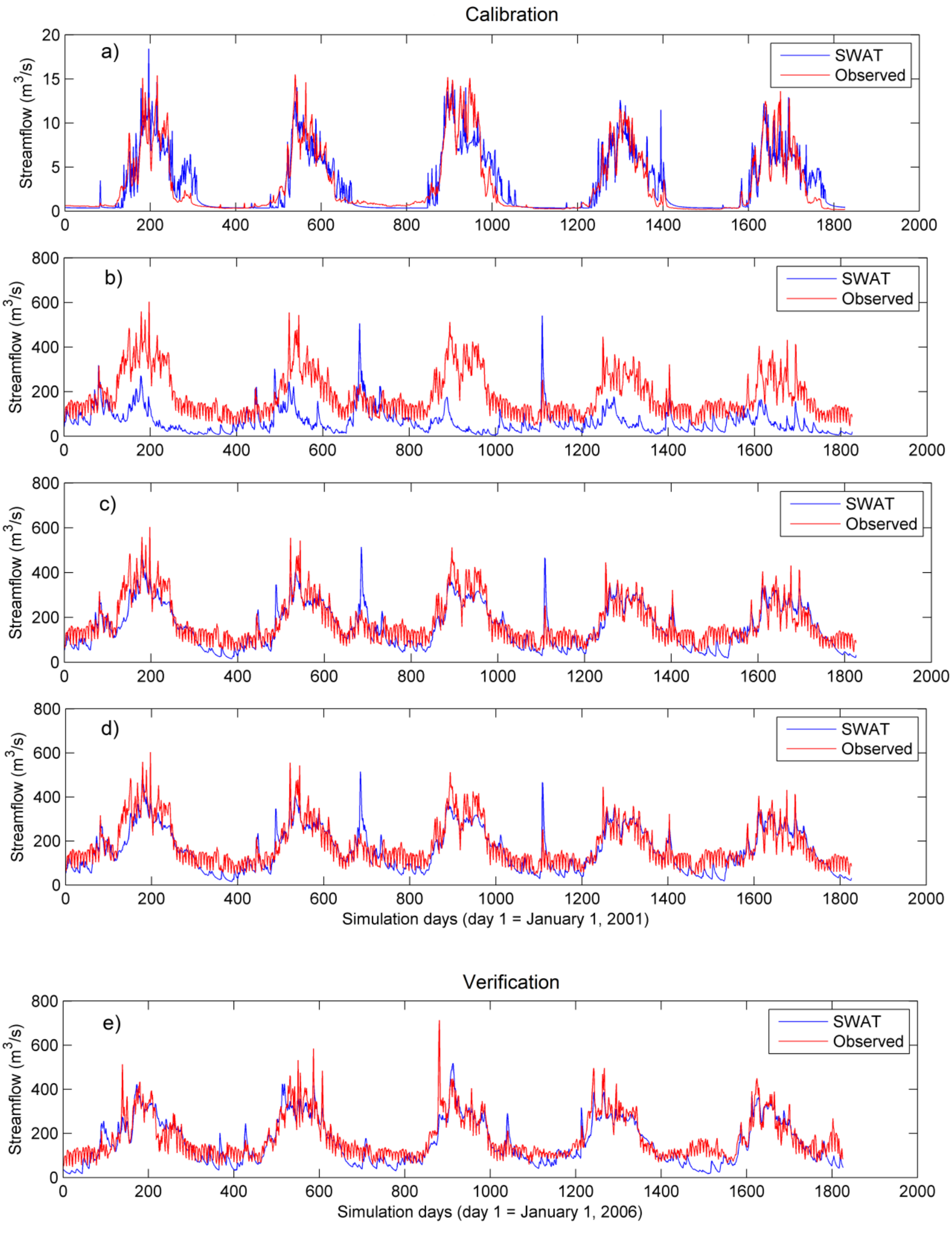

Fig. 5 Observed and simulated relationship for calibration and verification period. 5(a) Observed and simulated discharge at upstream. 5(b) Observed and simulated relationship before calibration. 5(c) Observed and simulated relationship with manual calibration. 5(d) Observed and simulated relationship with automatic calibration. 5(e) Observed and simulated relationship at the verification period

Table 4 model performance evaluation for initial, calibration and verification period

Stages	NSE	R^2	PBIAS
Initial setup	-1.38	0.16	64
Manual calibration	0.61	0.73	5.5
Automatic calibration	0.69	0.81	6.7
Model verification	0.63	0.73	10.23

4.4 Uncertainty Estimation

Fig. 7 represents the frequency distribution of the selected parameters used for calibration using a threshold value of NSE greater than 0.50 from 10,000 generations of AMALGAM. The y-axis represents parameters and the x-axis represents their ranges. As shown in Fig. 5(e) most of the parameters do not exhibit any specific distribution. However, a sign of normal distribution can be found with the snowfall temperature (SFTMP), which lies between +1 and -1.

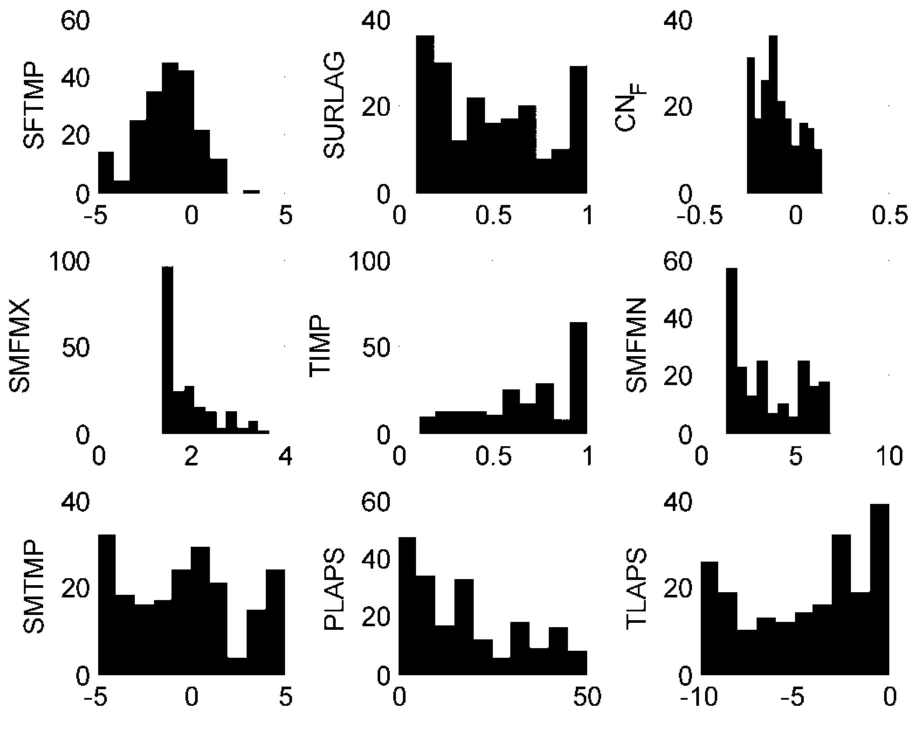

Fig. 7 Frequency distribution of model parameter (NSE > 0.5)

Surface water lag time (SURLAG) does not seem to follow any significant distribution, but there is a tendency towards lower values for higher frequencies. This is due to the steep gradient of the slope of the watershed; greater uncertainty of SURLAG indicates that runoff lag time plays a significant role for model performance. Higher frequency of occurrence can be obtained from the SCS moisture curve number (CN_F) between 0 and -0.5, it is to be noted that the frequency distribution of CN_F values were chosen based on percent changes and the remainder are based on absolute changes. The maximum melt factor for snow on June 21(SMFMX) follows a strongly-skewed distribution with the highest frequency of occurrence lying between 0 and 2. This has a very significant implication since the study area is located in the Northern hemisphere; for the Southern hemisphere it would be considered as the minimum melt factor. The snow pack temperature lag factor (TIMP) followed a bell shaped distribution with a trend of higher values close to 1. It is visible between the parameters related to the precipitation lapse rate (PLAPS) and the temperature lapse rate, PLAPS followed a systematic lower frequency of occurrence on higher values but for TLAPS there is no systematic trend of higher frequency distribution indicating the higher uncertainty of rate of change of temperature. It is obvious that with the change of elevation the temperature will follow a negative trend but there is no significant trend seems the parameter is highly uncertain. In general we have observed that the SWAT model parameters affecting the snow and glacier melt characteristics were highly uncertain when compared to the surface flow driving parameters. Also it was observed that a different set of SWAT model parameters would lead to similar performance index (NSE in this case) and is termed as equifinality (Beven 2001).

5 Conclusions

This study assessed the performance of the SWAT model's when applied to the complex topography of south-west Switzerland where runoff is a subtle mix of both natural and anthropogenic influences. The results indicate that, based on the historic discharge analysis (Fig. 2) high-head hydropower storage reservoirs have a very strong influence on the downstream catchments, which can be modeled with a proper configuration of the affected basin for water transaction. We performed both manual and automatic calibrations; manual calibration were undertaken to understand the hydrological behavior based on the parameter sensitivity, whereas automatic calibrations based on genetic algorithms were performed to obtain the optimal values for a set of iterations. We found relatively better model performance using automatic calibration. The sensitivity analysis indicated that among the 9 parameters considered, snow and glacier melt-related parameters, namely temperature lapse rate, snowmelt temperature, maximum snowmelt factor, and snowpack temperature lag factor, were sensitive for the model performance. The justification is that the temperature index-based snowmelt estimation is seemingly good enough to account for all the physics of snowmelt processes, provided that the calibration parameters are well-adjusted, but application of elevation band with temperature index gives a better understanding of snow and glacier melt processes for different elevation zones. In addition, the model performance statistics improved when using the elevation band approach; as a consequence, it is highly recommended to apply this approach to the case of mountain watersheds. When taking into account the full range of complexity, the model-generated runoff better matches the observed runoff. Despite the limitation of model performance at the sub-daily scale, information gained from this study may be applied to similar regions of complex terrain in order to assess the impacts of land-use change and climatic change on water availability and use.

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Chapter: 2

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Title: Streamflow response to regional climate model output in the mountainous watershed: A case study from the Swiss Alps

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Abstract

Regional climate model outputs are often used for hydrological modeling, in particular for streamflow forecasting. The heterogeneity of the meteorological variables such as precipitation, temperature, wind speed and solar radiation often limit the ability of the hydrological model performance. This paper assessed the sensitivity of Regional Climate Model (RCM) outputs from the PRUDENCE project and their performance in reproducing the streamflow. The Soil and Water Assessment Tool (SWAT) was used to simulate the streamflow of the Rhone River watershed located in south-western part of Switzerland, with the climate variables obtained from four RCMs. We analyzed the difference in magnitude of precipitation, maximum and minimum air temperature, and wind speed with respect to the observed values from the meteorological stations. In addition we also focused on the impact of the grid resolution on model performance, by analyzing grids with resolutions of 50*50 km^2 and 25*25 km^2. The variability of the meteorological inputs from various RCMs is quite severe in the

studied watershed. Among the four different RCMs, the Danish Meteorological Institute (DMI) provided the best performance when simulating runoff. We found temperature lapse rate plays significant importance in the mountainous snow and glacier dominated watershed comparing to other variables like precipitation, and wind speed for hydrological performance. Therefore emphasize should be given in minimum and maximum temperature in the bias correction studies for downscaling climatic data for impact modeling in the mountainous snow and glacier dominated complex watersheds.

Key words RCM, SWAT, grid size, runoff, Hydrological model.

Supplementary document:

[1] Meteorological variable conversion: NetCDF_SWAT_PRUDENCE.[Provided in appendix]

1 Introduction

Regional climate models (RCMs) are frequently used for climate change studies (Beniston and Goyette 2007; Beniston et al. 2011b; Christensen et al. 2002). Since they provide climatic variables such as precipitation and temperature, they are used by hydrological modelers to simulate streamflow and flood frequency analysis for climate change studies (Ahl et al. 2008; Pradhanang et al. 2011; Wang and Melesse 2005; Zhang et al. 2008; Graham et al. 2007). The heterogeneity of the meteorological variables is often reported as a drawback for simulating a range of processes in climate models (Christensen et al. 2002). Several studies were performed on the impact of grid size of the Digital Elevation Model (DEM), land use and type of soil datasets. The influences of the catchment subdivision on flow simulations were also studied, but it was seen that meteorological parameters exert the most significant influence on model performance. Different methodological inputs have been tested with Soil and Water Assessment Tool (SWAT) such as areal precipitation (Masih et al. 2011), interpolation techniques of radar driven precipitation (Liechti et al. 2012), and multi model comparison with different sources of meteorological datasets (Chen et al. 2012). Climatic data for developing hydrological models is basically of two types: one is local meteorological station data and the other is gridded data obtained from the Global Circulation Models (GCMs) and RCMs. They are often useful when the available local meteorological data is sparse and when predicting future changes. Climate models provide meteorological data mostly with the reanalysis based on the availability of the local stations, and thus it is important to test the sensitivity of the individual models before applying their results to the mountainous watershed.

It is obvious that the climate model generated variables are not often homogeneous to the observed variables, therefore, the bias correction studies are conducted for the impact modeling studies (Bordoy and Burlando 2012; Murphy 1999; Schoetter et al. 2012). Various techniques are used for bias correction studies starting from simple scaling to rather sophisticated method. Among the different techniques, widely accepted 'delta change approach' (Bosshard et al. 2011; Lettenmaier et al. 1999) where it is recommended to use the RCM simulated future change (e.g. anomalies) for a perturbation of observed data rather than to use direct RCM generated variables. The linear-scaling approach (Lenderink et al. 2007) works based on monthly correction values on the differences between measured and present-day model generated values. By definition, corrected RCM generated variables will perfectly agree in their monthly mean values with the observations. Meanwhile linear scaling considers for a bias in the mean, it does not account differences in the variance to be corrected. It is important to mention that high altitude watersheds where snow and glacier melt plays significant role in streamflow generation the mean value often limits the statistical performance of the model as the hydrology is quite sensitive to melt rate. Therefore, a nonlinear correction studies are often conducted (Leander and Buishand 2007), which helps to specify the adjustment of variance statistics of a precipitation time series. The advantages and limitation of various bias correction technique is beyond the scope of our study because the hydrological model structure often determines the simulated flow patterns considering the meteorological variables like mean value or minimum and maximum values as input.

In this research we focused on the built-in interpolation function of SWAT with the different sources of climate data taken from the PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects) project. PRUDENCE (Christensen et al. 2002), whose aim was to test the capacity of a suite of RCMs to reproduce current European Climate and to compare model projections for a "greenhouse climate" by 2100. Outputs from this project have been used for various impact studies, such as discharge estimations (Beniston 2010) and hydropower potential (Schaefli et al. 2007). The SWAT model (Arnold et al. 1998) uses a simplified way of inserting climatic model inputs from the nearest station, i.e., for instance the closest to the centroid of the sub catchment is used for that sub catchment (Neitsch et al. 2005). This may lead to a certain inaccuracy due to spatial heterogeneity linked to meteriological data, especially in mountainous terrain. This can have significant implications on the runoff produced by the hydrological model used. Input uncertainty reduction is often a challenging task for hydrological models. Given the large uncertainity encountered when RCM are used as input data for SWAT, this study tested a number of RCMs at two different spatial resolutions by comparing simulated and observed runoff. Therefore the objective of this research is to assess the variability of the meteorological inputs generated from different RCMs for reproducing streamflow using SWAT hydrological model and performance evaluation of individual RCM.

2 Study area

The upper Rhone River is located in the south-western part of Switzerland; it originates in the Rhone glacier (Fette et al. 2007) and completes its alpine course in Lake Geneva. This segment is 167.5 km in length with a drainage basin of 5220 km^2. Approximately 14 % of its surface is covered with glaciers (Meile et al. 2010) and 46 % is covered with forest. The runoff behavior is characterized by two important regimes, namely the high flow period that occurs in the summer due to snow and ice melt, and the low flow period that occurs during the winter. The average observed precipitation of the basin is 1435 mm/year. The upper Rhone is considered a seven order tributary; lower orders are illustrated in Fig.1. Two major modifications were undertaken in 1930 and 1960 for flood protection for which 91% of its length was affected. This channeling reduced its original length from 424 km to 251 km (Meile et al. 2010). In total 11 high head hydropower plants are located in the upper Rhone and most of them started functioning between 1951 and 1975. Therefore a shift of natural behavior has been observed since the construction of these dams due in both high flow and low flow periods because of controlled storage or release of water for hydropower operations. The river represents a very important source of water for the cantons of Valais and Vaud in Switzerland.

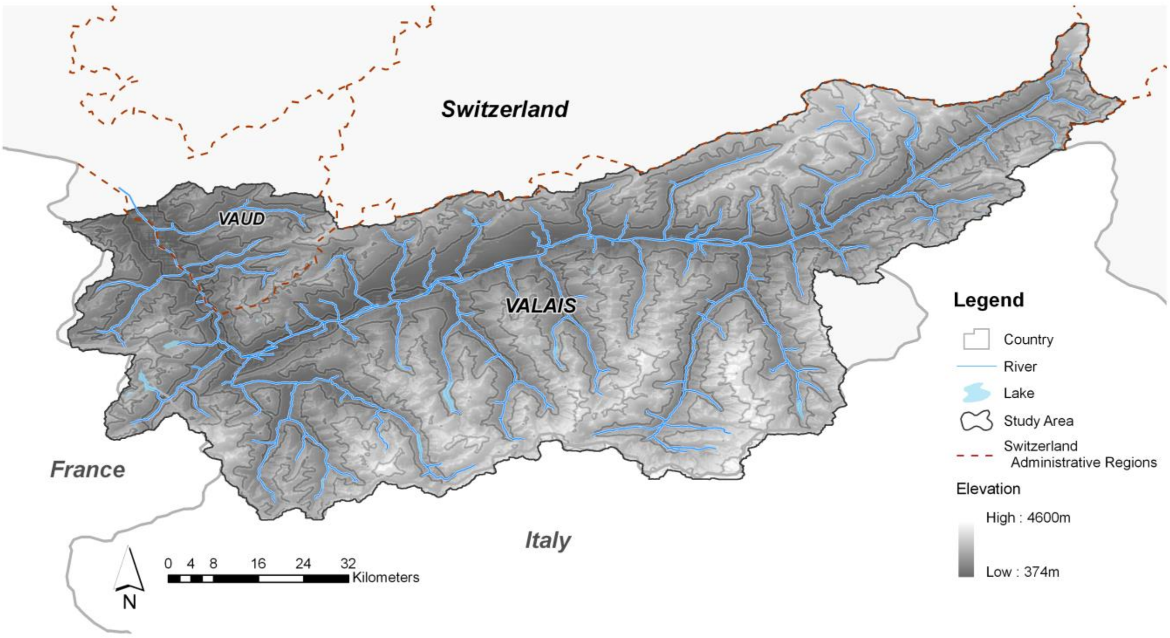

Fig.1: Upper Rhone river catchment located in Valais (Switzerland)

Elevation ranges from 400 m MSL at the floodplain part of the valley and 4634 m MSL at the top of the Dufourspitze, the highest peak of Switzerland. Variability of precipitation is large due to its complex topography, the lowland is one of the most driest place in Switzerland with annual precipitation less than 600 mm and highest is at alpine part generally greater than 2100 mm (Bordoy and Burlando 2012).

3 Methodology

3.1 Soil and Water Assessment Tool (SWAT)

SWAT (Arnold et al., 1998) is a process-based distributed parameter watershed scale simulation model. It subdivides the watershed into numerous sub watersheds connected with the river network and smaller units called Hydrological Response Units (HRU). Each HRU represents unique combination of land use, soil type and slope values. HRUs are non-spatially distributed assuming that there is no interaction or spatial dependency (Neitsch, 2005). SWAT has been successfully applied in different parts of the world but relatively less often in snow and glacier dominated mountainous terrain. However, several studies have been performed or are ongoing to explore hydrological fluxes in mountain regions (Fontaine et al. 2002; Morid 2004; Wang and Melesse 2005; Abbaspour et al. 2007; Ahl et al. 2008; Zhang et al. 2008; Debele et al. 2010; Pradhanang et al. 2011). The meteorological variables needed to run the model include precipitation, temperature, wind speed, solar radiation, and relative humidity on daily or sub daily time steps. SWAT simulates energy, hydrology, soil temperature, mass transport and land management at the sub basin and HRU levels. For this specific study, variables related to discharge and snow melt in mountainous terrain will be addressed; more detailed information about the other processes can be obtained from Neitsch (2005). Geographic and climatic data used for this study and their sources are listed in table 1.

Table 1 Data used and sources

Data Type	Data Sources	Scale	Description
DEM	Swiss-topo	(Grid cell: 25 m · 25 m)	Elevation
Land use	Swiss Federal Statistical Office	(Grid cell: 100 m · 100 m)	Classified land use such as crop, urban forest water etc.
Soil	Swiss Federal Statistical Office	1:200000	Classified soil and physical properties as sand silt clay bulk density etc
Hydro network	Swiss-topo	1:25000	River network-diversion
River flow	FOEN	-	River discharge at daily time step

Weather	Meteo Swiss	-	Precipitation Temperature Wind Speed Solar radiation
Hydropower Discharge	Alpiq, KW Mattmark	-	Inflow and outflow, lake level

The hydrological routine of SWAT consists of discharge, snow melt, and both actual and potential evapotranspiration. The soil conservation services SCS curve number method from USDA was used for the surface runoff volume estimation. SWAT evaluates evapotranspiration through various approaches, such as FAO Penman–Monteith, Hargreaves, and Priestley-Taylor. For this study Penman–Monteith was found suitable based on the results obtained in the initial model performance before calibration. Since the hydrology of the Rhone watershed is driven by snow and glacier melt the we focused on the snow and glacier melt algorithms. For the detail description of the individual process of SWAT, readers are referred to the documentation (Neitsch et al. 2005).

Temperature is considered as driving factor for snow melt in the temperature index method (Hock 2003). The snow melt in SWAT is calculated as a linear function of the difference between the average snow pack-maximum air temperature and the base or threshold temperature for snow melt

$$SNO_{mlt} = b_{mlt} \,.\, sno_{cov} \,.\left[\frac{T_{snow} + T_{mx}}{2} - T_{mlt}\right] \qquad \textbf{1}$$

SNO_{mlt} is the amount of snow melt on a given day (mm H_2O), b_{mlt} is the melt factor for the day (mm H_2O/day-^oC), sno_{cov} is the fraction of HRU area covered by snow, T_{snow} is the snow pack temperature on a given day (^oC), T_{mx} maximum air temperature on a given day (^oC), T_{mlt} base temperature above which snow melt is allowed (^oC).The melt factor is allowed seasonal variation with maximum and minimum values occurring on summer and winter solstices

$$b_{mlt} = \left(\frac{b_{mlt6} + b_{mlt12}}{2}\right) + \left(\frac{b_{mlt6} - b_{mlt12}}{2}\right) \times \sin\left(\frac{2\pi}{365}(d_n - 81)\right) \qquad \textbf{2}$$

Where, b_{mlt} is the melt factor for the day (mm H_2O/day-^oC), b_{mlt6} is the melt factor for June 21 (mm H_2O/day-^oC), b_{mlt12} is the melt factor for December 21 (mm H_2O/day-^oC), d_n is the day number of the year. This melt factors are parameterized for June (SMFMX) and for December (SMFMN) in the SWAT code. The glaciers are simulated as multi reservoir approach and melt rate is calculated as a function of daily air temperature (Rahman et al. 2013).

3.2 PRUDENCE project

The PRUDENCE project consists of numerous regional climate models that were applied to Europe to assess a number of key climate variables, and to investigate eventual shifts of their mean values in a changing climate (Christensen et al., 2002). We analyzed four RCMs generated variables they are from DMI (Danish Meteorological Institute), SMHI (Swedish Meteorological and Hydrological Institute) METNO (Norwegian Meteorological Institute) and ICPT from the International Center for Theoretical Physics from Italy. It is to be mentioned that several other RCMs output are available in the PRUDENCE web portal but we choose this four based on the availability of the input parameters. The inputs are: precipitation, minimum and maximum temperature, and wind speed. All the models used in this European project have been applied to two series of 30-year simulations, for the 1961-1990 period regarded as the control period, and for the last 30 years of the 21st century 2071-2100, is considered as simulation period. All models have roughly the same spatial scale resolution, with grid sizes varying between 0.44 and 0.5 degrees, which correspond to approximately 50 km. Moreover, some models have been tested at finer resolutions, with grid sizes as small as 0.22 degrees (SMHI and DMI) or even 0.11 degrees (DMI).

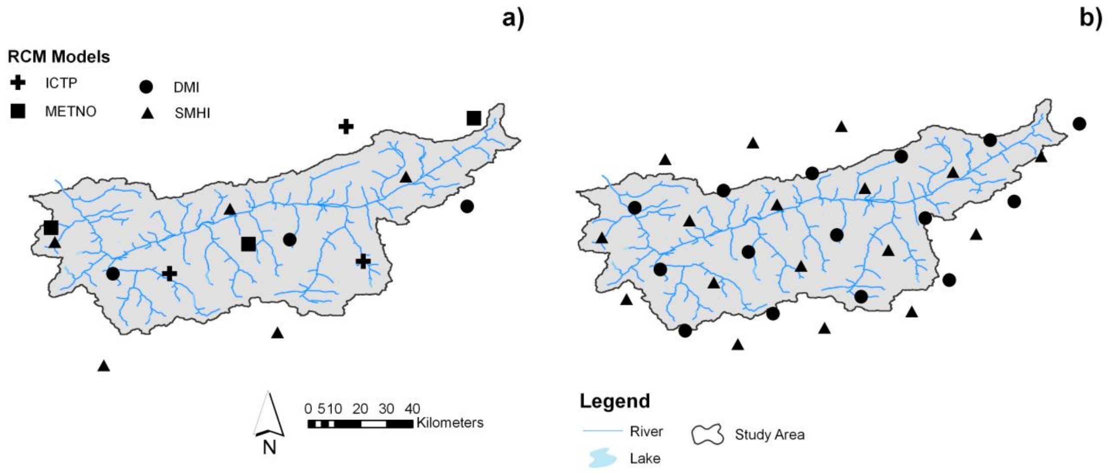

Fig.2: Grid points from different PRUDENCE models that were used in this study. (a) points of models at 50km grid size, (b) points at 25 km.

The models within the PRUDENCE project provide daily, monthly or seasonal outputs; in this study, only the daily outputs were used. Details regarding all the models used in this study are listed in table 2.

Table 2 Climate models and grid size.

Model	Acronym	Scale	Number of grid points in the watershed	Variables	References
DMI	HC1 F25	50km 25km	3 15	Tmin, Tmax, Wm, Precip	(Christensen et al., 1998)
SMHI	HCCTL HCCTL_22	50km 22km	3 17	Tmin, Tmax, Wm, Precip	(Doscher et al., 2002)
METNO	HADCN	50km	3	Tmin, Tmax, Wm, Precip	(Christensen et al., 1998)
ICTP	ref	50km	3	Tmin, Tmax, Precip	(Giorgi et al., 1993a;Giorgi et al., 1993b;Pal et al., 2000)

To assess the quality of the PRUDENCE simulations for the Rhone watershed, the daily outputs from the listed models for the four climatic variables of interest for this study (tmin, tmax, precipitation and mean wind speed), were extracted for the model grid points that are located in the watershed (figure 3), for the control period (1961-1990). The extraction of meteorological variables was done specifying the geographic location of the watershed considering the min and max latitude and longitude [45.82 47.46; 5.3 7.68]. All the conversion from NetCDF to time series has been done with MATLAB and the scripts are provided as supplementary document with this paper. The purpose is to assess the quality of these output variables regarding their orders of magnitude and their variability compared to observations provided by the eight MeteoSwiss meteorological stations located inside the study area. Knowing that the statistical records of observations are fully available only since 1981, the comparisons were merely investigated for the 10-year matching period from 1981 to 1990. For all the daily datasets (PRUDENCE outputs and meteorological observations), yearly means of all points located in the watershed were calculated from 1981 to 1990 in order to compare the profiles of the different models. The correlation between the different simulated outputs from RCMs with the observed meteorological data using tailor diagrams (Taylor, 2001) are represented by figure 4.

3.3 Hydrological model performance evaluation

Various statistics used for hydrological model performance analysis frequently employ Nash and Sutcliffe efficiency (NSE), Mean Square Error (MSE) approaches. The Percent bias (PBIAS) and Root Mean Square Error (RMSE) are also used for hydrological time series analysis. For this study we followed NSE, PBIAS and R^2 as model evaluation statistics (Moriasi et al. 2007). The model performance were considered satisfactory if NSE > 0.5 and PBIAS = ± 25%.

$$\mathbf{NSE} = \mathbf{1} - \frac{\sum_{t=1}^{T}\left(Q_{m,t} - Q_{s,t}\right)^2}{\sum_{t=1}^{T}\left(Q_{m,t} - \bar{Q}_m\right)^2} \qquad 3$$

$$\mathbf{PBIAS} = \left[\frac{\sum_{t=1}^{T}\left(Q_{s,t} - Q_{m,t}\right)}{\sum_{t=1}^{T} Q_{m,t}}\right] \times \mathbf{100} \qquad 4$$

$$\mathbf{R^2} = \left[\frac{\sum_{t=1}^{T}\left(Q_{m,t} - \bar{Q}_m\right)\left(Q_{s,t} - \bar{Q}_s\right)}{\sum_{t=1}^{T}\left[\left(Q_{m,t} - \bar{Q}_m\right)^2\right]^{0.5} \sum_{t=1}^{T}\left[\left(Q_{s,t} - \bar{Q}_s\right)^2\right]^{0.5}}\right]^2 \qquad 5$$

NSE indicates the strength of the relationship of observed and simulated values where $Q_{m,t}$ is the observed data value at time t and $Q_{s,t}$ is the simulated data value at time t. NSE values lie between -∞ to +1, (Nash and Sutcliffe 1970). Values close to +1 indicates the better model performance.

The PBIAS indicates the average tendency of the simulated data to be larger or smaller than their observed values. According to Gupta et al. (1999), the PBIAS can be utilized as an indicator of under- or over-estimation. Negative PBIAS indicates the underestimation of model-generated values with respect to the measured values. The square of Pearson's product moment correlation is indicated by R^2 which represent the proportions of total variance of the measured data that can be explained by the simulated data. Higher values of R^2 for simulated data close to 1 represent better model performance.

4 Results and Discussion

This part of the paper contains five sections. In the first section meteorological variables were represented with the observed variables and in the second section comparison with the observed value were plotted with tailor diagram. In the third section, the calibration of the hydrological model based on the local data and the list of parameters responsible were described. In the fourth section, the performance test of climatic variables for reproducing runoff is represented. Finally the impact of grid resolution of reproducing the observed hydrograph is assessed in the fifth section.

4.1 Profiles analysis of SWAT input variables

The results obtained for the comparison between the simulated and observed values for the four climate variables for the watershed are shown in figure 3. All graphs plot the yearly mean values from 1981 to 1990 for the various PRUDENCE models and for the meteorological observations (bold lines). Apart from the wind speeds, the graphs indicate that all PRUDENCE models either overestimate or underestimate the observed values. For precipitation (Fig. 3a), the PRUDENCE models overestimate the observed precipitation amounts. The two DMI simulations provided the best results. The grid resolution seems to have less influence on the effectiveness of the outputs, as the HC1 run seem to be better matching observations than the F25 runs. Overall, simulations and observations seem to indicate a slight decrease of precipitation in the Rhone watershed.

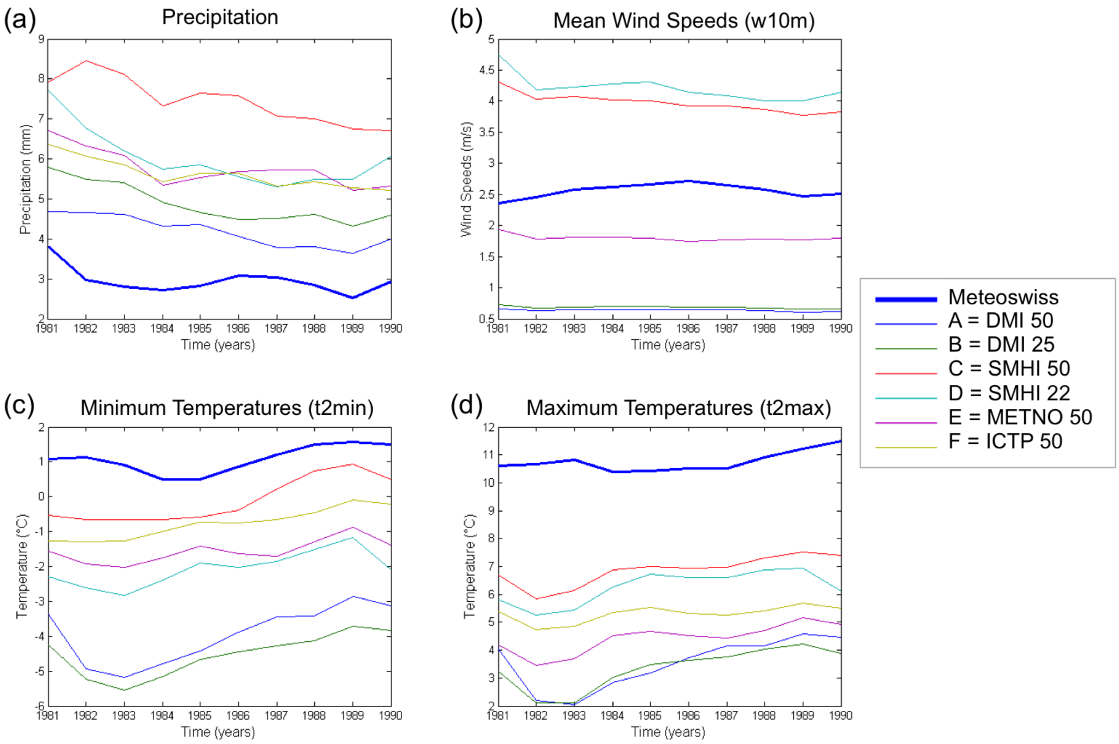

Fig.3: Profiles for the 1981-1990 Periods of yearly means of PRUDENCE simulations and MeteoSwiss observations and of daily values of 4 climatic variables: precipitation (a), mean wind speeds (b), minimum (c) and maximum temperatures (d).

For the two temperature graphs (Fig. 3c and 3d), the SMHI HCCTL outputs are the closest to the meteorological observations. Nevertheless, although they differ in their orders of magnitude, all PRUDENCE runs have similar trends for both the minimum and maximum temperatures. The DMI values are very close to each other (especially for the t2max values), but rather far away from the observations. Trends can be observed on both temperature graphs for the 1981-1990 decade: figure 3c shows an increase of the minimum temperatures, whereas the maximum temperatures seem to be gently decreasing. These trends need to be investigated for longer periods before making any concluding remarks regarding the climate of Rhone watershed. The wind graph (Fig. 3b) reveals little variability in the mean wind speeds during the 1981-1990 periods for all datasets. This is particularly the case for the two DMI runs, which show a constant close to zero wind speed. The METNO outputs provide values just below 2 m/s that are the closest to the observations.

4.2 Taylor Diagrams of SWAT input variables

After having assessed the orders of magnitude of the simulated variables compared to the meteorological observations, one needs to investigate the correlation between datasets. These are shown in figure 4 in the form of Taylor diagrams (Taylor, 2001) for each of the four climatic variables. These diagrams are very useful when assessing the performance of many models as they graphically summarize their patterns into a single plot and allow comparing them to the observed data. The models performances are expressed in terms of their correlation, their centered root-mean-square difference and their standard deviations compared to observations. These diagrams have been widely used in the past to assess the quality of various simulated outputs (Maurer et al., 2002; Covey et al., 2003; Davies et al., 2005). The radial coordinate gives the standard deviation and the angular coordinate provides the correlation with the observations. Furthermore, the distance between the observation point and the models' point is proportional to the r.m.s. model error.

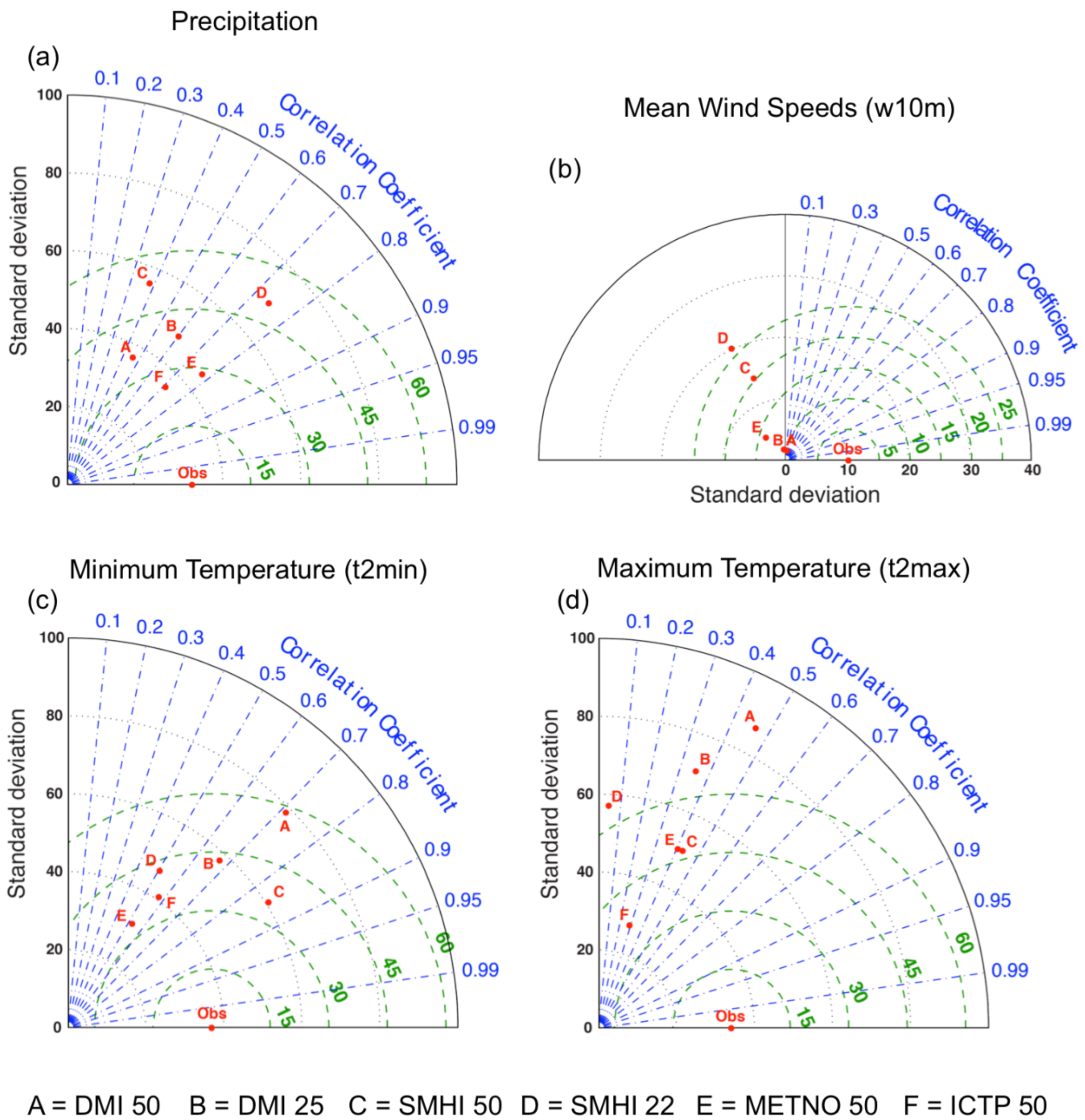

Fig.4: Taylor diagrams plotting the MeteoSwiss data versus the simulation outputs for seven PRUDENCE models. Graphs show 3 axis, the R^2 correlation coefficients (in blue), the standard deviation (x and y axis, in black) and the centered root-mean-square errors (in green). Observations are intersecting the x-axis.(a) precipitation, (b) mean wind speeds at 10m elevation, (c) minimum (d) maximum temperatures are given.

Precipitation (4a): coefficients values are scaled from 0.4 to 0.8, with the SMHI HCCTL_22, the METNO and the ICTP models having the highest coefficients. However, when analyzing the standard deviations, fig 4a indicates that METNO and ICTP provide the patterns that are the most similar to the observations. This graph indicates that although the DMI precipitation outputs are of the same order of magnitude as the observations (Fig. 3a), other models can provide better performance in terms of their correlations and patterns. Concerning wind speeds (fig 4b): the graph indicates that correlations are very low, with values even being negative. The variability between all datasets are similar and close to zero. Minimum temperatures (fig 4c): the SMHI HCCTL model seems to provide the best results, with coefficients reaching 0.85, but with a more important variability compared to the observations. Moreover, as plotted in Fig. 3c, outputs are of similar values than the observed, indicating that SMHI HCCTL is providing satisfying results for minimum temperatures. All other models have coefficients that are between 0.4 and 0.7. Maximum temperatures (fig 4d): coefficients are lower than for the minimum temperatures as they are all below 0.5. Furthermore, except for the ICTP, standard deviations for simulations are higher than the observation data. One important signature of DMI can be noticed that the correlation is highest compared to other RCMs.

4.3 Hydrological model calibration and validation

The Hydrological model calibrations were done on daily simulations in order to satisfy the statistical performance listed in equations 3, 4 and 5. Comparing pre and post calibration (figure 5.(a) & figure 5.(b)) and the major problems identified were the overestimation of peak flow, the underestimation of low flow and the influence of secondary peaks. The sensitivity test was done using parasol (van Griensven et al. 2006), a built in sensitivity technique embedded in SWAT. The parameter adjustments were done by manual calibration. We tried to calibrate the model with a lower number of parameters in order to avoid the over parameterization problem. Both high flow and low flow parameters were tuned based on expert knowledge and existing literature (Klok et al. 2001). The surface water lag coefficient (SURLAG) was set to 1 instead of the default value of 4 considering the steep gradient of the mountainous terrain. The melt factor for June (SMFMX) was adjusted to 5.9 from the default value of 4.5. Similarly melt factor for December (SMFMN) was adjusted to 4.6. The snow parameter lag factor (TIMP) was adjusted to 0.572 within its range of 0 and 1. The threshold temperature for snow melt was adjusted to the value of 4.5 The overall precipitation lapse rate (PLAPS) value was kept as 10 mm/km, and temperature lapse rate was tuned to -3.920 ^{0}C/km following the results from the literature (Klok et al. 2001). Among the nine parameters TIMP was found most sensitive for model performance statistics because it is directly related to the melt process. We used 30 years measured daily discharges for our study at the downstream points of the watershed (Porte du seux) starting from 1981 to 2010. We split the time line for 3 slices, first 10 years for warming up the model, 10 years (1991-2000) for calibration and 10 years (2001-2010) was used for validation of the model illustrated in figure 5

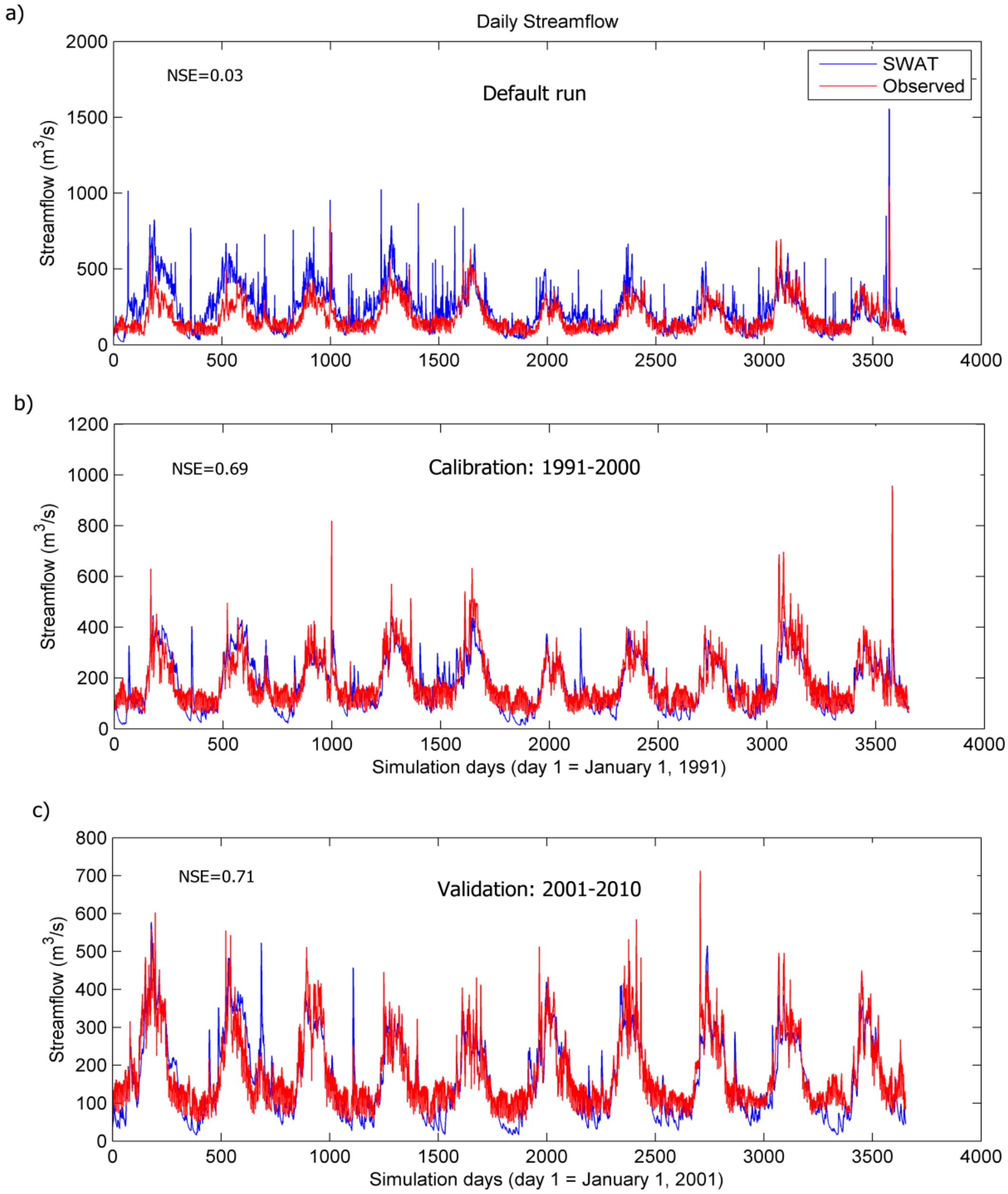

Fig.5: Observed and simulated relationship based on station data at the most downstream point of the watershed (a) before calibration; (b) after calibration; (c) validation.

4.4 Hydrograph generated from different RCMs

We compared the model-generated hydrographs with the observed hydrographs based on high flow period, low flow period, occurrence of high flow period and duration of high flow period. In figure 6 (blue colored) the bell-shaped hydrograph illustrates the monthly average discharge obtained from the observed data and the red the local station data. The high flow occurs in the summer time and the low flow period in winter time. The flow periods are highly correlated with the temperature and precipitation of the study area. Because the study area is located at a high altitude during the winter period it is covered with snow and ice, the snow accumulation process occurs during the winter therefore the flow is low compared with summer. Considering the shape of the hydrograph, only with the input from DMI could we produce a similar pattern, although there is a systematic over estimation during the high flow period, the peak flow is also overestimated. For instance, naturally, average peak flow occurs around 350 m^3/sec, whereas the DMI generated hydrograph 450 m^3/sec. None of the other climatic model generated output could reproduce a similar hydrograph pattern. Besides the DMI model, the output from ICTP has a similar pattern, but the peak flow is again highly over estimated; moreover there is an influence of the secondary peak during the recession limb of the hydrograph. The hydrograph generated from both SMHI and METNO models has a different shape and does not reproduce the similar time of occurrence of peak flow; the duration of high flow also does not match the natural flow. The hydrograph generated with the METNO model present a pattern that has less similarity with the natural flow regime.

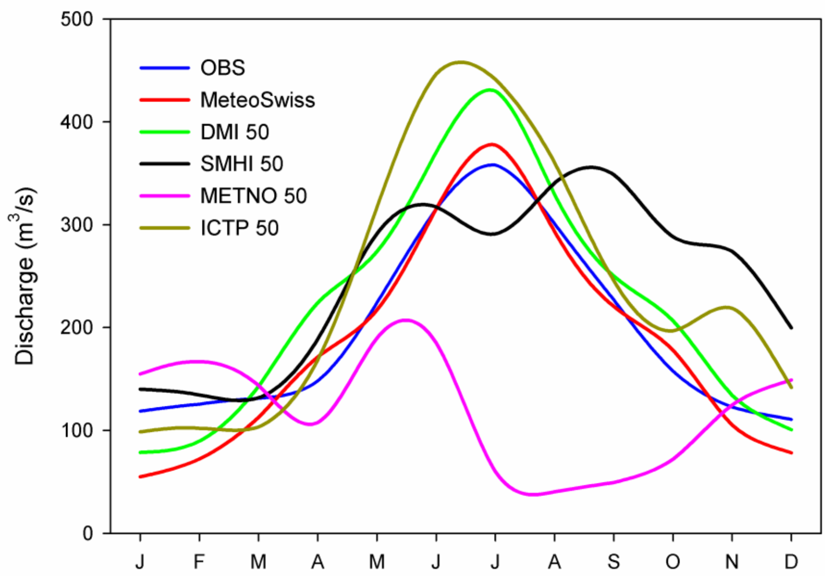

Fig.6: Monthly average hydrograph and outputs with regional climate models

Usually the discharge pattern of Switzerland is rather like a bell-shaped curve, which physically means that high flow periods are occurring during the summer and the low flow periods are occurring during the winter. This is due to the melting of snow and ice during summer. We therefore see, based on the discharge curves, that only the DMI output could produce a similar curve despite a sharper drop in the recession limb of the hydrograph.

4.5 Impact of grid resolution

In total three grid points fall within the watershed from the 50 x 50 km^2 grid of DMI as well as in the SMHI model (Figure 2). Whereas a total of 15 points fall within the 25 x 25 km^2 grid from DMI and 17 points from SMHI. The hydrograph generated from 25km x 25km and 50km x 50km grids exhibit similar peak flows, but in the low flow period 25x25 km^2 grids provided slightly improved statistical values, when comparing the observed hydrograph. For the DMI output, the main difference between the 50x50 and 25x25 km^2 grids is visible at the start of the high flow period (February to May). Whereas in the SMHI 22 x 22 km^2 grid the values better reproduce the results during the peak flow period. The duration of high flow period was highly overestimated for both grid sizes when compared to the observed value. For instance the observed peak flow reduction process starts in July-August whereas the model generated discharge still continues until September-October. Compared to the 50 and 22 km grid point resolutions, the 22 km grid produces better statistics (Table 3), changing the hydrograph to a more skewed shape.

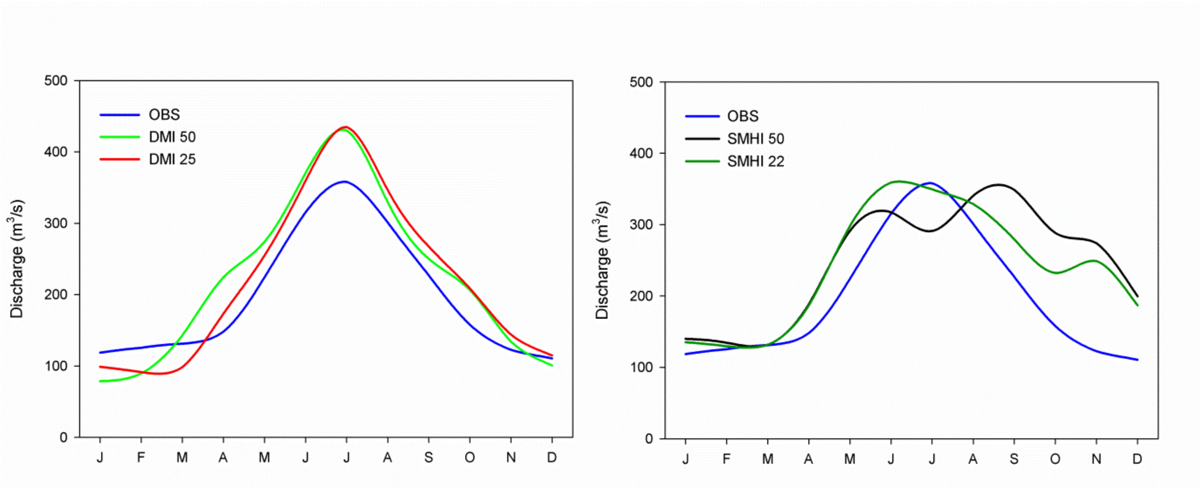

Fig.7: Hydrograph comparing the results obtained with (a) outputs from DMI (b) outputs of SMHI

4.6 Statistical performance

Streamflow simulation based on the model generated variables provided little correlation with the observed value. When considering the models' statistical performance (based on the equations 3 to 5), of the four models, the DMI with the higher resolution grid shows better results than the other models. Instead of using independent model results, ensemble multi-model means can also be used. However for performance analysis of specific application as discharge or return periods, the single model output can be more adequate than a multi-model ensemble mean. Similar results were reported by (Salzmann and Mearns 2012) that ensemble means do not necessarily provide better performance than single models. Therefore, after the sensitivity test of the RCMs with the observed data, it is important to apply an adjustment factor, e.g., the lapse rate for precipitation or temperature based on the physical characteristics of the watershed. These adjustment factors could be spatial or temporal, for spatial characteristics it can be elevation and slope of the region. For instance, Pepin and Losleben (2002) proposed the adjustment for the Colorado River basin with temporal adjustment, applying a monthly average lapse rate.

Table 3 Statistical performance of individual RCMs and local stations

Data Sources	NSE	R^2	PBIAS
MeteoSwiss	0.71	0.81	-5.27
DMI 25	0.37	0.63	-10.87
DMI 50	0.22	0.59	-12.52
SMHI 22	-0.47	0.25	-22.46
SMHI 50	-0.9	0.14	-25.82
METNO 50	-2.4	0.012	44.12
ICTP 50	-1.2	0.35	21.46

4.7 Discussion

The performance evaluation of global and regional climate model generated variables are analyzed in various ongoing studies, among the recent literatures, Jiang et al. (2013) examined the precipitation generated from 16 GCMs and 10 RCMs for four US cities and found the variability is quite significant. Their finding suggests current GCMs/RCMs tend to simulate longer storm duration and lower storm intensity comparing to observed records. Also, most GCMs/RCMs failed to produce the high-intensity summer storms when they are not bias corrected. Similar to our objective Hwang et al. (2013) focused streamflow response to dynamically-downscaled regional reanalysis data in central Tampa Bay region of Florida utilizing a hydrological model, where they noticed the reanalysis data provided better hydrological model generated streamflow then the raw data obtained from RCMs. Therefore, there is a need to focus on reanalysis techniques which in terms emphasizes the need of bias correction of meteorological variables. Not only for streamflow simulation, other variables like evapotranspiration (Obeysekera 2013) can also an important element that often utilize RCMs for future forecast using hydrological models.

Considering the performance evaluation criteria based on tailor diagram (fig.4) in connection with the streamflow (fig. 6) it is depicted that there is no strong harmonization of independent model generated variables with observation records. Especially the profile analysis illustration of maximum temperature (fig. 4d) DMI has highest correlation value (0.475) whereas SMHI has lowest (0.01). This is reflected in the hydrograph because the melt rate of snow and glaciers are significantly correlated with daily maximum temperature denoted in the denominator of the equation 1. Moreover, glacier melt uses the similar approach as temperature index, where melt rate is linear function of daily maximum air temperature, hence a significant percentage of streamflow is generated from glacier melt it is apparent that the daily maximum temperature will affect the model performance. It is visible that DMI generated variables provided streamflow with an overestimation of the entire period which is quite systematic. Our assumption is that this systematic overestimation can be resolved using the temperature lapse rate. Similarly the lapse rate of precipitation can also help providing significant improvement in bias correction techniques.

5 Conclusions

This study compared the gridded meteorological variables obtained from regional climate model outputs along with the local stations. As the hydrological models are driven by meteorological inputs such as precipitation and temperature we analyzed different climate models as input of the hydrological model. The variability found was quite significant compared to the local station that influences the model performance. The hydrological model (SWAT) was used for simulating discharge based on the climate inputs for reproducing runoff in the upper Rhone River watershed. At first we built the hydrological model based on the local station data and calibrated the model, later the meteorological inputs were replaced and simulated each time. We considered the hydrograph analysis both visually and statistically. Considerations were made for high flow period, low flow period, time of flow occurrence and duration of high flow period. We found temperature driven variables are more sensitive in the high altitude catchment as the melt processes are highly linked with the variability of temperature (min and max). Among the set of climate models driven hydrograph, the DMI model generated variables were able to reproduce similar patterns of high flows. Despite generating a similar pattern of hydrograph shape, the simulated hydrograph underestimated low flow and overestimated high flow. Apparently, a set of RCM driven variables could not produce similar pattern of hydrograph. Some of the climate models reproduced hydrographs with secondary peaks that have not been observed in reality. We analyzed 50 km and 25 km grid resolutions for the DMI model and the 50 km and 22 km scales for the SMHI model. The output from both resolutions reproduced similar patterns, but finer grids provided better performance with respect to the shape of the hydrograph and overall statistical performance (figure 7). Therefore, our conclusion is to test the acceptability of the RCM-generated variables before applying them to the decision making level especially for mountainous watershed emphasizing the temperature as a driving variable for bias correction studies. Our recommendation would be to use a correction factor for meteorological variables (ex. lapse rate along with elevation) before implementing them in complex terrain for impact modeling.

Acknowledgement

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Chapter: 3

Title: Quantification of daily dynamics of streamflow components in a small glacier-dominated alpine watershed using end member mixing analysis

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Abstract

There is a growing need to improve our understanding of catchment flow generation processes, especially in alpine watersheds where the aquatic biodiversity is dependent upon the types of water sources and their seasonal dynamics. In order to identify and quantity the potential sources that contribute to stream runoff, water samples were collected and discharge monitored in 6 different tributaries of a small (7 km^2) glacier dominated Swiss alpine catchment, 14% of which was glaciated. In situ measurements were done for temperature, electric conductivity and turbidity of water at different temporal scale. Mass spectrometry was done to analysed silica and sulfate along with chlorine. Three different water sources were identified based on their physio chemical characteristics: glacier melt water, quickly routed surface runoff, and slowly routed ground water. Principal component analysis was performed in order to reduce dimensionality of the chemistry data independently in two hydrological years. End member mixing analysis was carried out for morning and afternoon data to describe the daily variation of runoff components. Our study suggests that glacier melt component has a strong daily variation, which influence the magnitude and timing of peak flow. A sign of early melt and accumulation can be seen in this watershed based on the studied years.

Keywords: EMMA, PCA, Glacier melt, Snow melt, Alps

1 Introduction

In glacial streams, physical constraints have critical influences on biodiversity, and especially upon the diversity, distribution and composition of macroinvertebrate communities. Discharge from different water sources (glacier melt, snow melt and groundwater) also play a significant role in shaping the invertebrate communities (Brown et al. 2010; Milner et al. 2009). Difficulties of field sampling and seasonal inaccessibility often limit our understanding of hydrological and biogeochemical process occurring in high elevation watersheds (Bales et al. 2006; Barthold et al. 2010). Especially, discharge measurement is challenging due to the irregular geometry of the riverbed. However, glaciers are shrinking, especially in the Swiss Alps, 84 out of 85 glaciers are having negative mass balance (WGMS 2009), and the modification of their contribution to streamflow and environmental conditions is likely to alter running water biodiversity (Finn et al, 2010), prompting the need for a better understanding and modelling of water sources dynamics and streamflow generation.

End member mixing analysis (EMMA) (Christophersen et al. 1990; Hooper et al. 1990) is a multivariate analysis of catchment streamflow generation. EMMA is a widely accepted method for identifying water sources and their relative contribution to the stream discharge. It has been extensively applied for understanding streamflow generation process in small (Brown et al. 2006; Caine 1989; James and Roulet 2006; Liu et al. 2004) to large (Barthold et al. 2010) catchments and under various climatic conditions, including semi-arid seasonally snow-covered forested catchments (Liu et al. 2008). Studies reported about the applicability of end member mixing analysis in human influenced watersheds and discussed the limitations (Burns 2002). The application of EMMA depends on tracer selection, number of tracers and their conservative behaviour of end members (i.e sources) , Guidelines are provided for possible tracer selection, outliers (when stream samples do not bound properly with the end members) in mixing diagram were explained in some studies (Barthold et al. 2010; Hooper 2001; Liu et al. 2008). End member mixing results can differ depending on the selected tracers and their number (Liu et al. 2004). In a snow and glacier dominated high altitude catchment, Brown et al. (2006) used EMMA to differentiate "quick flow" (dilute, rapidly routed melt water), "distributed flow" (sulfate- enriched, slow routed subglacial waters), and "groundwater" (silica-enriched groundwater). Few other studies reported a seasonal quantification of glacier melt to the streamflow (Cable et al. 2011).

Most studies were conducted to quantify hydrograph components at a daily time scale. However, the sub-daily temporal variability might have substantial significance in high altitude / glacial catchments. During the melt season, strong variations in temperature, sheer stress, suspended solid concentration and water chemistry might indeed occur at a sub-daily time scale and represent determinant constraints for the biota (Brittain and Milner 2001; Uehlinger 2003; Uehlinger et al. 2003; Ward 2004). Therefore an attempt to quantify and model sub daily fluctuations of runoff contribution from various sources is a challenge for a better anticipation of biodiversity changes that might occur in glacier-fed streams. Temperature plays a very important role in melt process and the sub daily variation of temperature will determine the melt rate which has consequence with the potential contribution of snow and glacier melt.

Therefore, the objective of this research was to quantify the contributing sources of streamflow generation and of their dynamics in a small glacierized catchment (Mutt catchment, upper Rhône basin, Switzerland) at a sub daily time scale during the melt season. We focused on the applicability of EMMA technique for this watershed with relatively scarce data, because of limited accessibility during the year. We applied EMMA for two different time periods in order to assess relative changes between two hydrological years: 1997 and 2010. The specific research questions are: can end member mixing analysis be applied for such a watershed where the mixing dynamics is rapid due to steep slope. Can the contribution of each water source be quantified? If yes, which one has the most dominating contribution? Is there any temporal trend of flow components between the study years?

2 Study Site

The Mutt watershed, one of the head water of the Rhone basin (46°62'N, 8°41'E), contains the Mutt glacier. It is located above the Gletsch hamlet in central Switzerland and contains both glaciated and unglaciated areas (Klok et al., 2001). The altitude ranges from 1757 m a.s.l. (gauging station Gletsch) to 3630 m a.s.l. (Dammastock) with a mean value of 2720 m a.s.l. The Mutt watershed covers an area of 7.06 km^2 where 14% is glaciated The high elevation areas are mostly covered by moraines and bare rock, whereas the lower areas are covered with prostrate vegetation (Lods-Crozet et al. 2001). This area has a significant importance because the River Rhone originates in this basin, and it is a nature reserve of national importance.

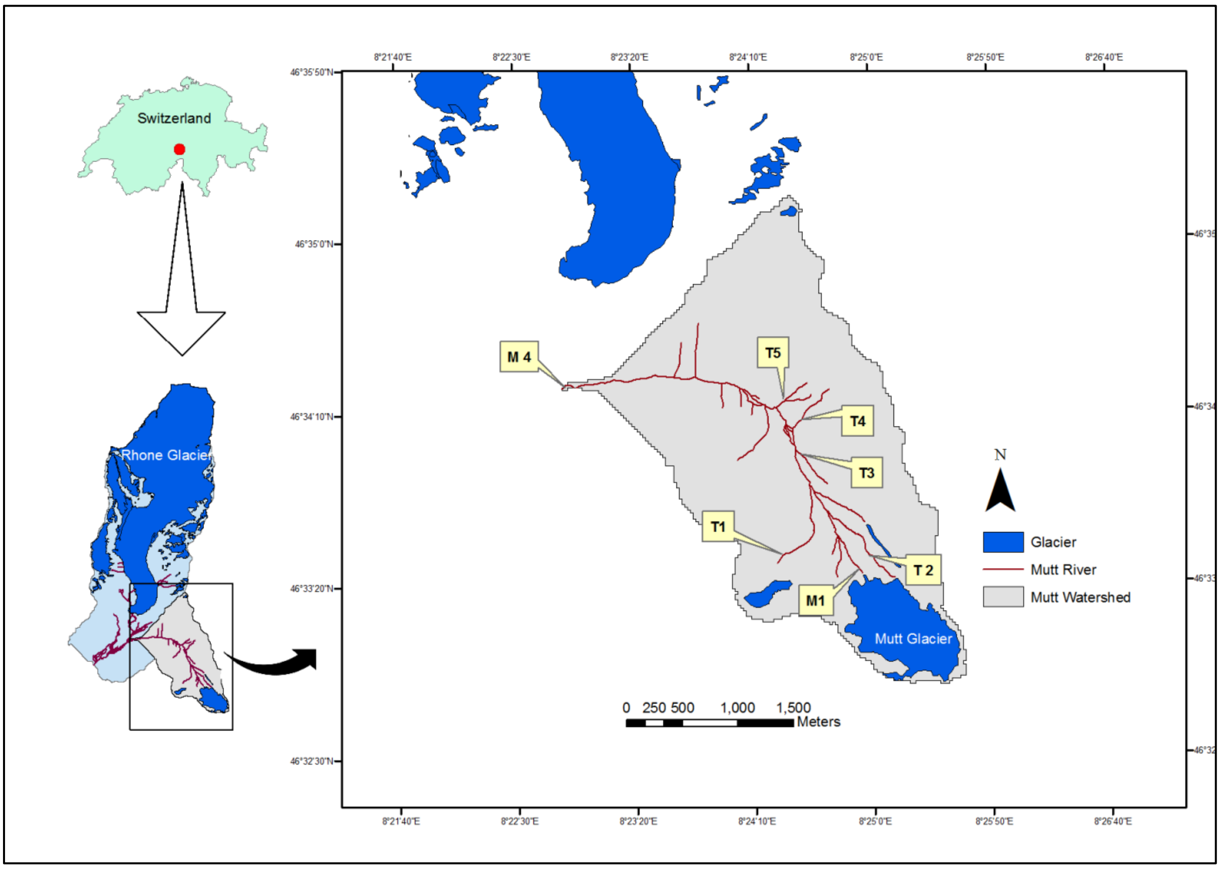

Figure 1 Study Area, showing the Mutt catchment. Yellow squares with codes indicate the sampling stations

The watershed is seasonally inaccessible. The reason of choosing this watershed is that it has a mixture of diverse water sources that generate stream runoff and it is not influenced by any dam of water diversion. Anthropogenic influences remain insignificant and the natural variability of flow can be depicted, moreover a meteorological station (Grimsel, Altitude 1980 m a.s.l., Longitude 8°19´60´´, Latitude 46°34´18´´) is located very close to the watershed and a continuous discharge measuring station (Gletsch Altitude 1716 m a.s.l., Longitude 8°39´08´´, Latitude 46°59´47´´) is located at its downstream point.

3 Materials and Methods

3.1 Hydrological and meteorological conditions

Discharge data were collected from Federal Office for the Environment (FOEN) for the nearest gauging station 'Gletsch' to have better understanding the relative changes in flow for the studied years (1997-2010). Together with discharge, precipitation and temperature data were collected to check for potential shifts between the studied years. Considering the melt season (April-October) a reduction in peak flow and a shift in his timing are visible (Figure 2). The major differences between the two years occurred between July and October. Important percentual decreases occurred from august to October, some being higher than 50%.

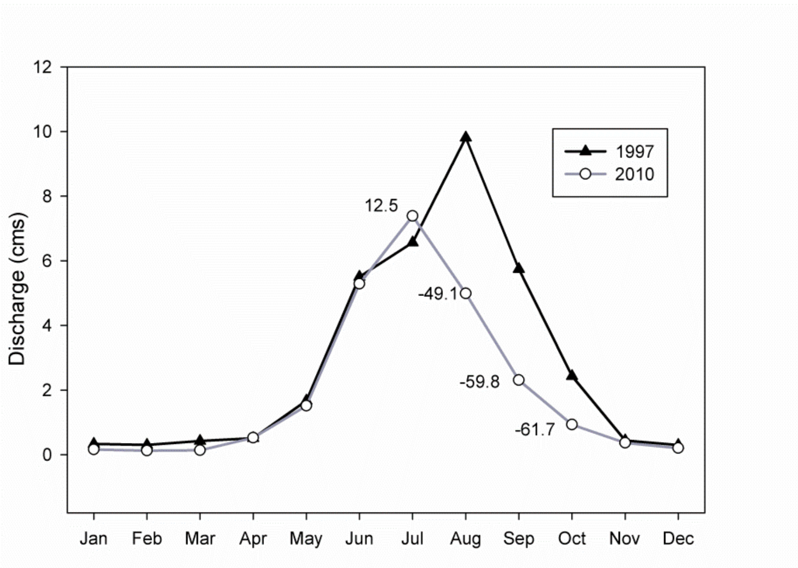

Figure 2 Discharge comparisons between two hydrological years 1997 and 2010 at Gletsch gauging station (Rhone River). Figures indicate the percentage change of the most significant shifts.

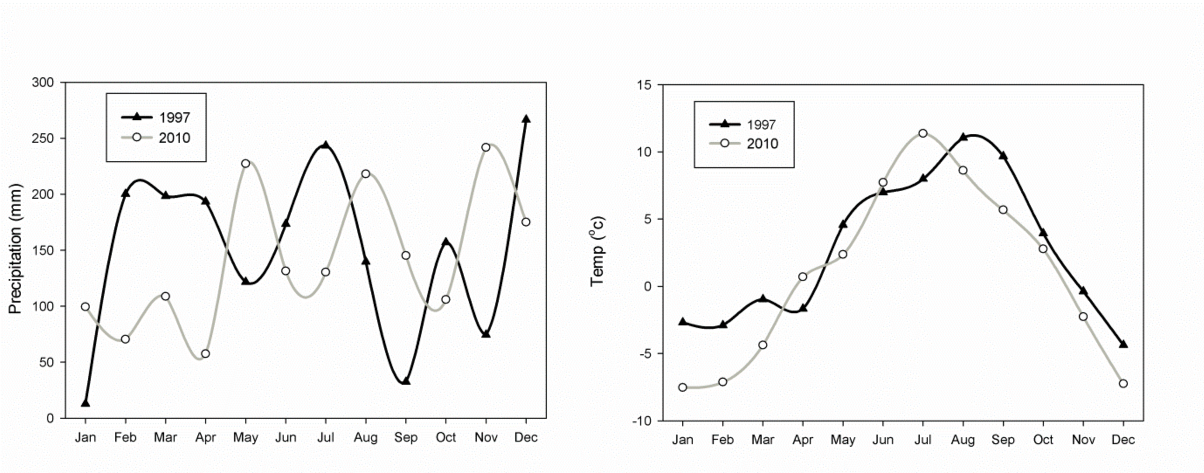

Figure 3 Precipitation (monthly sum) and temperature (monthly mean) at the Grimsel meteorological station for the years 1997 and 2010

This reduction of flow can be of various reasons and most apparently because of precipitation and temperature changes. Therefore precipitation and temperature data were analysed from the Grimsel station (Figure 3). Considering the correlation with discharge (Figure 2) it is apparent that the driving factor is temperature. Especially in July, despite of a reduction in precipitation, the flow is higher in 2010 compared to 1997. This also reveals that the runoff behaviour is dominated by temperature driven snow and glacier melt.

3.2 Sampling stations

Physical and chemical characteristics of water were measured at 7 stations in the Mutt catchment: M1 and M4 on the main Mutt stream, T1 to T5 in non-glacier-fed tributaries (Figure 1). M1 is the most upstream station in the catchment, and the closest from the glacier front. It was considered to express the highest proportion of glacier melt contribution. M4 was the lowest point of the catchment where the mixing processes were measured and the water sources contribution calculated. T1 to T5 tributaries were selected to depict various types of non-glacial water sources in the catchment. Snow samples were also collected to account for its contribution to the runoff.

3.3 Field measurements and chemical analyses.

Because of limitations imposed by snow cover, water samples could only be collected between June and September. There were three measurement periods in 1997 (27-28 June, 8-11 August, 20-22 September) and two in 2010 (18-18 july, 4-8 September). Water samples were taken, discharge, water temperature and electrical conductivity measured twice a day at low (morning) and high (afternoon) discharges, for two to four consecutive days). Discharges were measured with depth / velocity transects. The bucket method was used for some small tributaries.

Water sample were collected in plastic bottle and stored at 4°C until analysed. All water samples were filtered in the field through 0.45 µm filters. Chloride (Cl^-) and sulphate (SO_4^{2-}) were examined by capillary electrophoresis. Silica was examined with the Heteropoly Blue Method in a Hach spectrophotometer (Hach Company, Loveland, Colorado). Snowmelt (high chloride, low silica), icemelt (low chloride and silica) and groundwater (high silica and sulphate) were supposed to be separated on the basis of these three elements, as suggested by previous studies undertaken under the AASER project (Brittain & Milner, 2001; Brown et al., 2006).

3.4 Mixing model analysis

3.4.1 End member mixing analysis

End member mixing analysis is based on the assumption that stream water chemistry is composed of a set of end members that have distinct chemical signatures (Christophersen et al. 1990; Hooper et al. 1990; Liu et al. 2008). End members are basically sources that contributes to the streamflow (Neill et al. 2011). In the ideal condition the stream water samples should be bound by the median values of the end members (i.e. the median values of tracers of the end members). As a first step end members should be selected by their chemical signature. The chemical signature should be defined by a combination of tracers. Tracers are conservative, which means that no chemical reactions can occur that would modify their concentration All end members have significantly different concentrations for at least one tracer. End members are often considered as components by some authors (Liu et al. 2004) until the end member selection is not confirmed. The eligibility of end members will be confirmed with the mix diagram. Tracers (chemical signature of samples) plays important role in end member eligibility criteria section. Tracer concentrations in all components are considered temporally constant or having known variations. Tracer concentrations in all end members are considered spatially constant or treated as different components. Unmeasured components are regarded as having the same tracer concentrations or as contributing insignificantly. End members can be determined based on an eigen vector analysis, such as Principal Component Analysis (PCA). Based on the determined end members, their contributions can be calculated as a function of their chemical composition.

3.4.2 Hydrograph separation

A PCA was used to reduce the dimensionality of the water samples – by – tracer's data set and to determine the end members. PCA was used to identify 'lower dimensional' space often call U space. The so called U space, in which the stream water observations lies and which describes the variability of the data set. We followed the procedure described by (Barthold et al. 2011; Hooper et al. 1990; Neill et al. 2011), where the mixing point stream concentration values (n) for the solute (p) were standardized by centering them about their means and diving by the standard deviation. Similarly median of the concentration of end members were also standardized. After this transformation, both standardized stream data and end member medians were projected on to the m dimensional U space by the orthogonal projection

$U=XV^T$

Where U is the resultant data matrix of n*m, X is n*m standardized data matrix and V is the m*p matrix of retained Eigen vector obtain from PCA. The fraction of the identified end members in each stream water sample was then calculated by solving the following set of linear equations.

$1= x + y + z$ Eq.1

$SW_{U1}=xEM_{1U1}+yEM_{2U1}+zEM_{3U1}$ Eq.2

$SW_{U2}=xEM_{1U2}+yEM_{2U2}+zEM_{3U2}$ Eq.3

Where x, y, z are the unknown fraction of each end-member; SW_{U1} and SW_{U2} are projected stream water observation in U space, EM_{nU1} and EM_{nU2} are the nth end member coefficient in U space. This set of equations is an example for a three end member problem. It can be extended or reduced for larger or smaller sized end member problems. Table 3 presents the cumulative Eigen vector percentages for both the year studied.

Table 2 : Physico chemical characteristics of the Mutt water at station M4, where mixing components are calculated for the hydrological year 1997

Station	Date	Mor/Eve	Temp [DegC]	Cond [mg/l]	SO_4^{2}- [mg/l]	Cl [mg/l]	Si [mg/l]	Discharge [m3/sec]
M4	6/27/1997	Morning	3.60	144.00	22.32	0.39	1.18	NA
M4	6/27/1997	Evening	4.60	130.00	24.16	0.51	1.03	NA
M4	6/28/1997	Morning	4.50	132.00	24.03	0.47	1.41	0.75
M4	6/28/1997	Evening	5.80	115.00	21.62	0.35	1.13	NA
M4	8/8/1997	Evening	10.70	103.80	16.46	1.37	0.56	0.47
M4	8/9/1997	Morning	6.40	76.60	20.26	0.89	0.71	0.67
M4	8/9/1997	Evening	10.30	66.00	14.31	0.21	0.71	0.94
M4	8/10/1997	Morning	7.70	78.00	19.91	0.48	1.69	0.92
M4	8/10/1997	Evening	10.10	67.00	14.85	0.44	0.80	1.25
M4	8/11/1997	Morning	7.00	75.00	19.06	0.63	0.80	0.70
M4	9/20/1997	Morning	6.10	171.00	14.56	0.20	1.11	0.18
M4	9/20/1997	Evening	8.20	114.30	4.56	0.04	0.56	0.30
M4	9/21/1997	Morning	5.20	165.00	23.56	0.21	1.18	0.18
M4	9/21/1997	Evening	10.40	145.00	15.35	0.17	0.64	0.27
M4	9/22/1997	Morning	6.20	168.20	21.42	0.22	1.19	0.18
M4	9/22/1997	Evening	7.60	124.00	12.39	0.14	0.79	0.25

Table 3 : Physico chemical characteristics of the Mutt water at station M4, where mixing components are calculated for the hydrological year 2010

Station	Date	Mor/Eve	Temp [DegC]	Cond [mg/l]	SO_4^{2}- [mg/l]	Cl [mg/l]	Si [mg/l]	Discharge [m^3/sec]
M4	7/16/2010	Morning	11.90	121.70	24.00	0.19	27.50	0.57
M4	7/16/2010	Evening	13.30	110.00	20.00	0.19	79.60	0.72
M4	7/17/2010	Morning	9.90	120.00	21.00	0.20	47.40	0.57
M4	7/17/2010	Evening	12.50	111.10	21.00	0.19	64.60	0.67
M4	7/18/2010	Morning	5.90	130.10	18.00	0.23	15.20	0.70
M4	9/4/2010	Evening	12.40	194.40	41.00	0.94	4.50	0.29
M4	9/5/2010	Morning	7.30	192.60	22.00	0.90	4.20	0.39
M4	9/5/2010	Evening	11.70	193.90	44.00	1.26	7.80	0.38
M4	9/6/2010	Morning	6.50	193.00	43.00	0.64	4.00	0.42
M4	9/6/2010	Evening	9.40	188.00	42.00	1.11	8.60	0.50
M4	9/7/2010	Morning	6.90	174.00	NA	NA	11.10	0.47
M4	9/8/2010	Evening	8.10	153.10	NA	NA	36.30	0.69
M4	9/8/2010	Evening	7.70	158.90	NA	NA	26.00	NA

4 Results

4.1 Statistical analysis

Statistical analysis was done to characterize the water sources based on water sample collected from different sampling points with their chemical composition based on the hydro chemical characteristics, since temperature poses various energy gains and loss it was taken apart from the multivariate analysis. Together with temperature, turbidity and electric conductivity were not also considered as a variable in the principal component analysis because the conductance has influence on the total ions of the solution. PCA was done independently for both study years studied in order to understand changes happened due to different weather conditions. All the calculations were performed using MATLAB and cross checked with the statistical open source software package R version 2.13.1 (R Development Core Team, 2010) in Eigen vector calculation. Based on the site specific knowledge and physico chemical characteristics T5 and T4 were considered as ‘gradual flow’ occurring due to slow routed ground water. Together with the physical variable like temperature and conductivity T4 and T5 poses higher values of Si and SO_4^{2-} compared to the other sites (Figure 2 and 3). Whereas T1, T2, T3 were considered into slow routed gradual water flow coming mostly from snow melt and precipitation. M1 considered as glacier melt sources. T4 and T5 were considered as ground water fed tributaries since they have closer values of Si and SO_4^{2-} concentration (Figure 2 and 3) also reflected similar nature of electric conductivity.

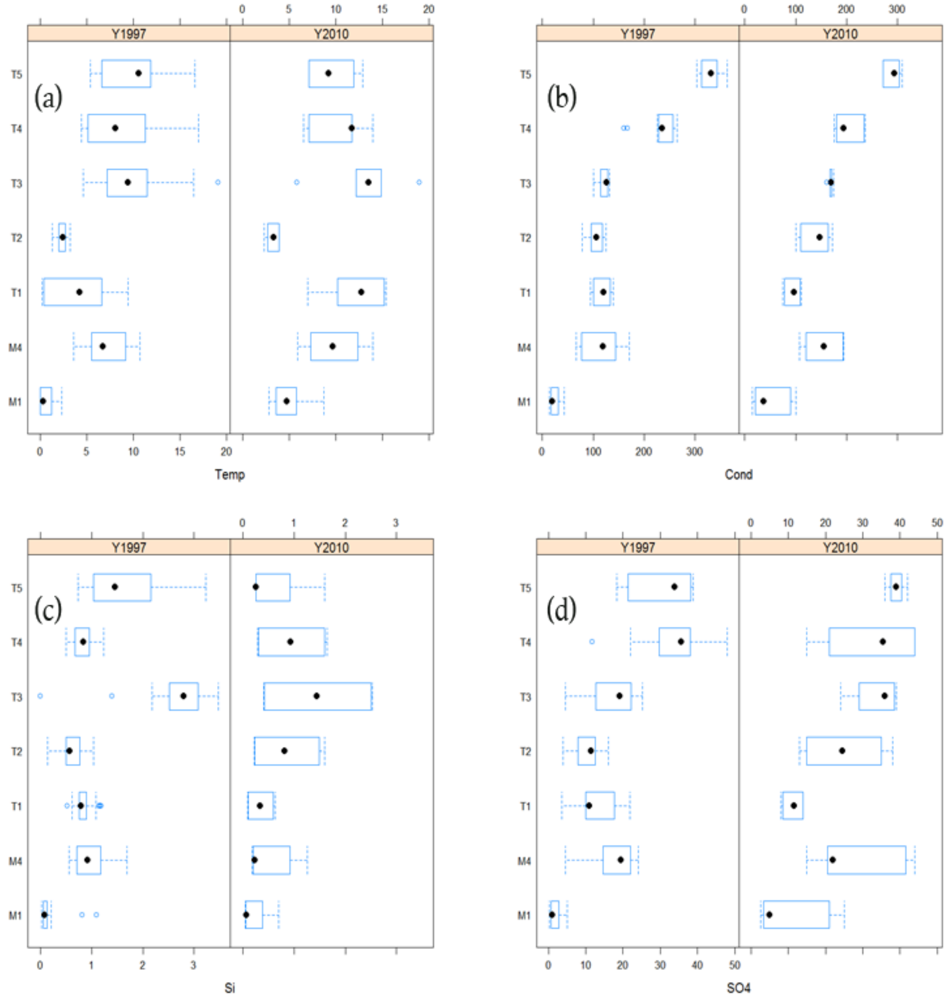

Figure 4: Variability of temperature (a) conductivity (b) silica (c) and SO_4^{2-} (d) in the Mutt and its tributaries for the hydrologic years 1997 and 2010.

4.2 Mixing model result

In figure 5, the stream samples collected at the downstream station M4 are represented together with the water sources selected within the catchment (i.e. the end-members). The dot points represents the stream water sample (at M4) and the error bars (±1 SD) represent the median concentration of end members. The error bars are significantly smaller in 1997 compared to 2010; however T3, T4 and M1 represent the best bound for the M4 stream samples. Water sample from M1 represents glacier melt with the lowest silica and SO_4^{2-}concentrations, whereas T4 and T5 have higher SO_4^{2-} and silica concentrations but their silica concentration differs slightly (based on table 2 and table 3). T3 contains the highest amount of silica. The T3 to T5 stations contain mineralized water (conductivity values above xx μScm^{-1}), reflecting the influence of a carbonated outcrop crossing the catchment in its central part (Lods-Crozet et al., 2001).

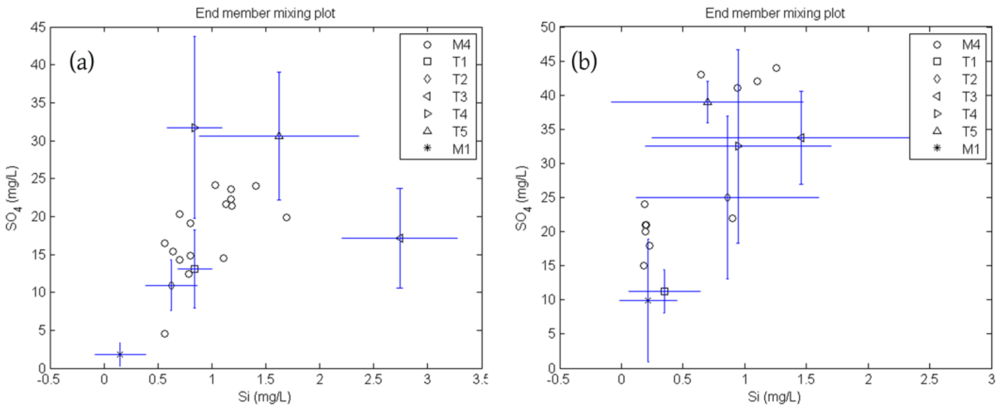

Figure 5: Si Vs SO_4^{2-} diagram showing the M4 downstream station and the other stations reflecting potential water sources for the hydrologic year 1997 (a) and 2010 (b).

Table 1 describes the cumulative Eigen vector percentage in two axes, since the total variability is explained more than 80 percent it is decent enough to take three end members

Table 1: Eigen vectors for the hydrological year 1997 and 2010

Year	Mor/Eve	U1	U2
1997	Morning	50.21	84.79
	Evening	51.48	93.38
2010	Morning	69.37	92.06
	Evening	98.124	99.95

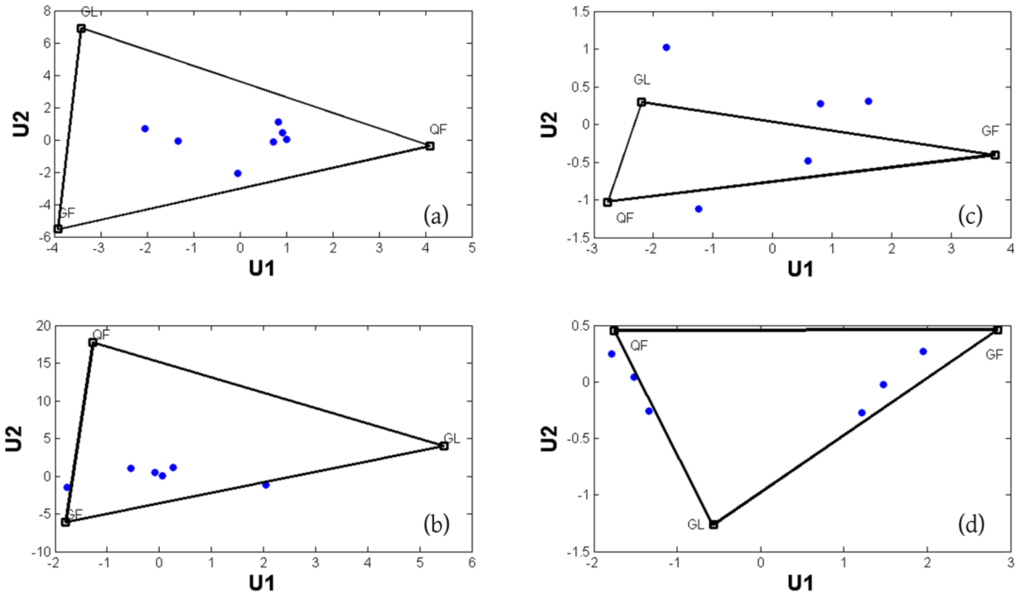

Figure 6: U space mix diagram for hydrological year 1997 and 2010. (a) Morning 1997 (b) Evening 1997 (c) Morning 2010 (d) Evening 2010. The blue dots represent the water samples taken at station M4, where corners of the triangles are the median value of end members.

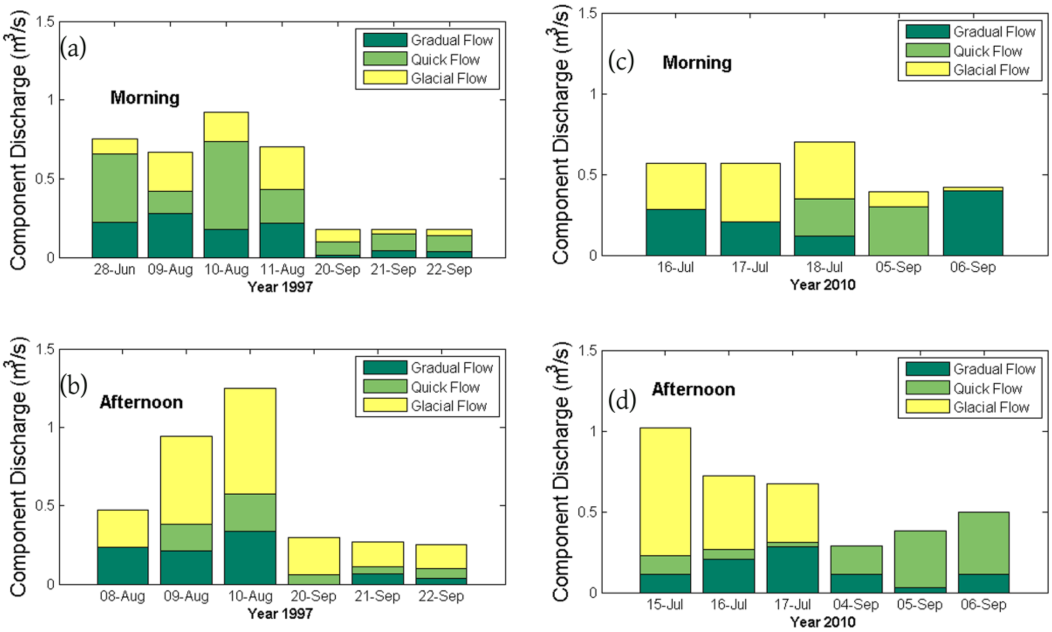

Figure 7 Flow components for the hydrological years 1997 and 2010, (a) morning 1997, (b) evening 1997 (c) morning 2010 (d) evening 2010.

4.3 Hydrological year 1997

In total 7 observations were taken in the morning and 6 were taken in the evening in the melt season of 1997. It is important to mention that the study site is seasonally inaccessible and some tributaries are located at high altitude where the vehicle facility is not available. The measured values of physical and chemical components are represented in the table 3. Considering the mix diagram, figure 6 (a) and (b) in the morning session it is clearly visible that the stream water sample (at M4) is properly bounded by the end members (or sources). Therefore, the end member selection can also be validated with this diagram. Considering the contributions of sources, there is a combination of all the sources that contributes stream runoff based on the observation days. It should be noted that the flow is relatively smaller in the September comparing to August in both morning and evening which is correlated with the mean temperature of nearest station (Figure 3). One important thing can be seen that the glacier melt component varies from morning to evening and the evening contribution is higher comparing to morning. This is possibly due to intensity of solar radiation.

4.4 Hydrological year 2010

5 observations were done in the morning and 6 observations were done in the afternoon in the hydrological year 2010. Some outliers are visible in the mix diagram of morning data which can be of various reasons. These outliers are mostly correlated with field sampling. Considering the contribution from the different sources the highest proportion is coming from glacier melt in the morning session. One important signal can be noticed with the comparison of morning and evening in the glacier melt contribution. The glacier melt contribution no longer exists in the evening session. This is probably because of early starts of snow accumulation process. There were two observations in the late summer for both morning and evening sessions (i.e 5^{th} and 6^{th} September) where the glacier melt has very little contribution in the morning comparing the other observations in the same period. This is a signal of melt process contribution reduces in the late summer. Also zero contribution in the evening reveals that in the late summer melt process occurs mostly in the morning.

4.5 Comparison between the two hydrological years

In the years studied, some similarities and discrepancy can be seen considering average discharge and contribution from individual end member contribution. The average discharge was higher in August and lower in September, which we can consider as raising and recession period. Similarities can be seen during the raising period of melt (until august) as the glacier melt component changes quickly. It is clearly visible that the glacier melt increases (yellow marked in fig.7) from morning to evening in both the studied years. However, quick flows are not present in all the events as they are linked with temperature and precipitation. Glacier melt flows also varies as we can see in the afternoon measurements of September 2010 where there is no noticeable contribution of glacier melt. This is probably due to snow accumulation process that starts earlier which is also apparent as the total discharge has a smaller values then the raising period considering raising period until August based on the figure 3.

4.6 Discussion

Our results show that contribution from end members varies along with time, even in the instantaneous day of a melting season the contribution can be different with morning and evening. This can be seen if we consider the melt season in two groups there is an increasing trend of glacier flow can be seen from morning to evening until August. The reason of choosing two different years is to address if there is any changes occurred in the catchment flow generation process. The variability can be observed in the glacier melt contribution, comparing 1997 and 2010 based on figure 6 we can see glacier melt decreases in September 2010 which physically means the snow accumulation process happen earlier then 1997.

However, several uncertainties arise due to sampling process. Precision and accuracy related to stream chemistry measurement has a significant importance in end member mixing analysis, if the chemical composition is not measured with proper precision it may lead to uncertainty which will affect the flow partitioning. In a study, Soulsby et al., (2003) calculated by mass balance that sub surface water contributed 6 % of total flow in a stream. The calculated contribution could however be as much as 17 % if the measured stream chemical compositions were adjusted by typical measurement error. Non conservative solute behavior, unidentified end members, and temporal variability of end members could also causes additional uncertainty. Beside these, more fundamental source of uncertainty in mass balance approaches to streamflow partitioning may arise from the trouble in reliably characterizing end member properties, even where the end members are appropriately identified. Several studies suggested solutions of application of EMMA such a situation have been described (Christophersen and Hooper 1992; Liu et al. 2008; Liu et al. 2004). Usually these ‘outliers’ causes systematic high and low estimation when calculating the contributions of the end members.

Another issue often discussed in the EMMA analysis about grouping of samples with respect to tracer selection. The first question may raise how many tracer do we need to perform EMMA analysis

(Barthold et al. 2011). What are the conditions that the tracers need to fulfill and what are the criteria we set for selecting the tracers. Studies conducted by Barthold et al.(2011) concluded that tracers are different with the different watershed, based on geology. Here we used silica and SO_4^{2-} as main chemical indicator following the literature by Brown et al., (2006) considering similar physiographic condition of mountainous watershed. Based on the solute vs solute diagram with silica and SO_4^{2-}we can see the variability is higher in 2010 comparing to 1997 that stream sample are well explained considering M4 as combined stream sample.

Some studies have been conducted in sub daily scale to understand the sediment flux in the mountainous basins with the objective of land conservation (Duvert et al. 2011). Sediments are important to understand nutrients transport, soil loss process, results obtained that sub daily fluctuations are highly correlated with the catchment size land-use type and gradient of the watershed. Similarly daily discharge fluctuation have been studied by Collins (1995) focusing discharge, solute content, and solute flux, in Findelengletscher and Gornergletscher, Kanton Wallis, Switzerland. Result suggests that net reaction rate is faster and that the rates of decrease of average transit time of melt water with discharge is less rapid beneath Findelengletscher. Also, the melt rate fluctuations are correlated with environmental variables like temperature, slope of watershed etc. Therefore, our results will provide an added value on sub daily dynamics of flow component contribution.

5 Conclusions

Mountanious glacier dominated stream poses a strong variability of dischare due to environmental varialbes like solar radition, wind speed, relative humidity the varialtion has a singnificiant influence for the invertibribate living in the diffrent type of water. Therefore, identification and quantification of discharge componet has important role of the living organisms. The overall objective was to analyze the streamflow component based on phisico chemical constrains using end member mixing analyis, and we found stream runoff can be explained as a function of end members. Based on the variability explained end member mixing analysis can be applicable to explain the identification of geographic runoff sources. According to the physical and chemical characteristics three major sources were identified provides stream runoff, they are glacier melt, quick routed surface runoff and slow routed ground water for the Gletsch watershed. Daily dynamics of the water reveals during rising period of the melt season glacier melt contribution is higher (until August) in the evening but slower in the late period. Our analysis was limited to summer melt due to in accessibility of the watershed, moreover the flow generation process has significantly important in the melting season which occurs during the summer period. Comparing two hydrological years 1997 and 2010 it can be concluded that the flow regime is changing based on the contribution of glacier melt water. Information gained form this study will be used to analyzed the ecological connectivity of specises living the the watershed their dependancy of the type of water as a future step.

Acknowledgement

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Chapter: 4

Title: Streamflow Response to Land-Use and Climate Change, Upper Rhone River Watershed, Switzerland

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Abstract:

Land-use and climate change play a significant role in hydrological processes. This study assesses the impact of land-use and climate change in a snow and glacier dominated high altitude watershed, located in the southwestern part of Switzerland. Climate projections until the middle of the 21st century were analyzed implying a Regional Climate Model for the IPCC A1B scenario. Land-use maps were generated using Idrisi TAIGA land change modeler, based on historical changes over two time periods and propagated for future forecasting. Logistic regression was used to generate maps containing the probability of change between two different land-use categories, and then the allocation of the land-use was based on a multi-objective land distribution. The semi-distributed hydrological model Soil and Water Assessment Tool (SWAT) was used for simulating streamflow. The analysis was done to assess impact of streamflow in three time periods where 1981-2010 is considered as the observed period and two other scenarios from 2011-2025 and 2026-2050. Flow Duration Curves (FDC) were constructed to assess the impact on low and high flow period. Our study shows a decrease in summer flow and the early high flow period. The major changes observed in this study are in the rising period of the hydrograph, i.e. in May and June an early shift is observed in discharge. Independent analysis from land-use change and climate change shows that the peak flow reduction occurs for land-use change, but the peak flow together with timing of peak flow occurrence is also influenced by climatic change. The combined effect suggests a reduction of peak flow and early melt driven streamflow for the future. Information obtained from this study can be useful for water managers, especially in the hydropower based energy production sector in the Rhone watershed.

Key words: Land-Use, Climate, Hydrological Model, Streamflow

1 Introduction

Watershed streamflow sensitivity is highly influenced by changes in land-use and climate (Mengistu 2012; Jin and Sridhar 2012; Beniston 2012; Immerzeel et al. 2010; Somura et al. 2009; Singh and Bengtsson 2004). This impact not only affects flow volume but also timing and duration. Due to human development, changes have taken place on a global scale as well as on regional scales (Barnett et al. 2005; Beniston 2012; Fowler 1999; Gain et al. 2011; Githui et al. 2009). Such influence can be manifold, but its impact on streamflow has elicited widespread concern (Barnett et al. 2005; Beniston 2012; Fowler 1999; Gain et al. 2011; Githui et al. 2009). In the context of a watershed, this influence can be quantified and various hydrological processes like evapotranspiration, surface runoff and ground water flow are closely related with ecosystems, the environment, and our economy. For example, changes in glacier cover can significantly change the inflow to a hydropower reservoir which subsequently influences the economy (Schaefli et al. 2007; Vicuna et al. 2008). In high attitude watersheds the changes in land-use are often insignificant because of irregular topography and relatively low anthropogenic influence. However, change in glacier cover makes a significant difference because the melted water is the main source of inflow to the reservoir. Therefore, reduction of the surface area of glaciers reduces the inflow to the reservoir (Schaefli et al. 2007; Fette et al. 2007).

Mountainous high altitude watersheds play a significant role in downstream processes like hydroelectricity generation, ecology and tourism activities (Miller et al. 2012; Viviroli et al. 2011; Viviroli et al. 2007; Woo and Thorne 2006). Changes in mountainous hydrological regimes affect downstream processes. To assess both long and short term changes, mathematical models are often used in hydrological studies. Hydrological models explain the physical processes with empirical equations. Therefore, there is a growing need to apply hydrological models for solving various environmental issues (Gassman et al. 2007). Hydrological modeling in mountainous watersheds is relatively challenging because of complex processes (e.g. snow melt, glacier melt and orographic precipitation). To understand these processes there is a strong need for a dense observation network, but in reality observation networks are sparse in these regions in comparison with floodplains. Different kinds of mathematical models exist based on their application, e.g. distributed, semi-distributed and conceptual (Beven and Binley 1992). Here we applied the semi-distributed physically based Soil and Water Assessment Tool (SWAT) to simulate streamflow and applied this for future forecasting based on Regional Climate Model (RCM) generated data.

The combined effects of land-use and climate change are often examined in various watersheds (Brovkin et al. 2004; Lopez-Moreno et al. 2011; Shi et al. 2013). Some studies considered the individual effect on climate considering that land-use values were constant (e.g. Mengistu 2012; Fischer et al. 2012; Chevallier et al. 2011; Immerzeel et al. 2010). Similarly, a large number of studies were conducted in which climate values were constant and those of land-use were changed (e.g.Qingqing et al. 2012; Moran-Tejeda et al. 2012; Dixon and Earls 2012; Britz et al. 2011; Petchprayoon et al. 2010). Most of the studies focus on vegetation change or urbanization, however, a relatively low number of studies focus on mountainous glacier dominated watersheds. The reason may involve the complexity of hydrological processes in mountainous watersheds as well as fewer observation networks.

Several studies were conducted in the Swiss Alps for runoff simulation using various hydrological models (Daniel Farinotti1 2011; Gurtz et al. 2003; Horton et al. 2006; Huss et al. 2008; Klok et al. 2001; Schaefli et al. 2005; Viviroli et al. 2009). Most of the models are object oriented (e.g. glacier melt model, snow melt model) and are focused on relatively small watersheds in order to understand runoff generation processes and quantification. Finger et al. (2012) assessed the impact of climate in the Vispa Valley, one of the major tributaries of the Rhone River located in the Rhone watershed, and observed flow reduction in the summer and early rising periods which is a consequence of climate change. The upper Rhone watershed is relatively important because it supplies the major inflow to Lake Geneva which in turn plays an important role in the economy as well as biodiversity. Therefore, a model could lead to a better understanding of the current inflow situation and scenario analysis could help in planning better downstream water management.

The major problem associated with the Rhone watershed is the strong influence of the hydropower network which impacts water storage in the summer and water release in the winter. This alteration process significantly changes the regular flow regime. The alteration process occurs by capturing the snow and glacier melted streamflow in temporary reservoirs and then storing them in large reservoirs. Therefore, extensive information is needed to implement all of the capturing points and flow routing processes in the hydrological model. Rahman et al. (2013) developed a distributed hydrological model using SWAT implementing the hydropower networks. This model has been used to assess climate and land-use scenarios testing with the extended data obtained from RCM and statistically built land cover model.

Therefore the objective of our study is to assess the impact of land-use and climate change in the entire upper Rhone River watershed considering all the changes due to climate, land-use and human influence (ex. hydropower network). We emphasize the changes in glacier and forest as a part of land-use change and precipitation and temperature as a component of meteorological input. With the objective we will answer some research question like; does land use change have impact on streamflow generation? If yes does the changes significant? Is the changes in streamflow will be all over the year or most significant in some specific season like summer and winter.

2 Study Area

2.1 Study area

The upper Rhone River is located in the southwestern part of Switzerland and originates from the Rhone glacier (Fette et al. 2007). It is 167.5 km long with a drainage basin of 5220 km^2. According to Meile et al. (2010) 14 % of its land area is covered with glaciers. Runoff behavior is characterized by two important regimes: the high flow period that occurs in summer due to snow and ice melt; and the low flow period that occurs during the winter.

The average precipitation of the basin is observed to be 1435 mm/year (Schaedler B and R 2001). The upper Rhone is considered as seven-order tributaries. Two main constructions were done in 1930 and 1960 for flood protection, for which 91% of its length were affected. This channeling reduced its original length from 424 km to 251 km (Meile et al. 2010). In total 11 high head hydropower plants are located in the upper Rhone and most of them started functioning between 1951 and 1975. Therefore a shift of natural behavior has been observed in high flow and low flow periods since the construction of these dams due to the long term storage of water. Long term discharge data were collected from Swiss meteorological office (FOEN) at six different outlets located in the study area for calibration. Notably, among the six outlets only one is undisturbed and all others were influenced by the hydropower activities. We used the continuous measured discharge from the upstream station 'Gletsch' for calibration in order to analyze the changes happened for natural change and Porte du Scex were chosen at the most downstream point where the discharge is combination of nature and human influence. The flow controlling in the Rhône valley is quite severe in the downstream which has correlation with the energy prices. When the energy price is high in the winter for higher energy consumption the discharge rate is high and low in the summer period. For this phenomenon the regular flow behavior is altered.

The important characteristic of this study area is that the Rhone river is one of the primary inflows and the only outflow of Lake Geneva, with a significant contribution in Swiss. Changes due to land-use and climate will affect the flow generation process which will impact the inflow and outflow of the lake (Loizeau and Dominik 2000). Therefore, a hydrological model can help providing better understanding the inflow process for current stage and predicted changes for future.

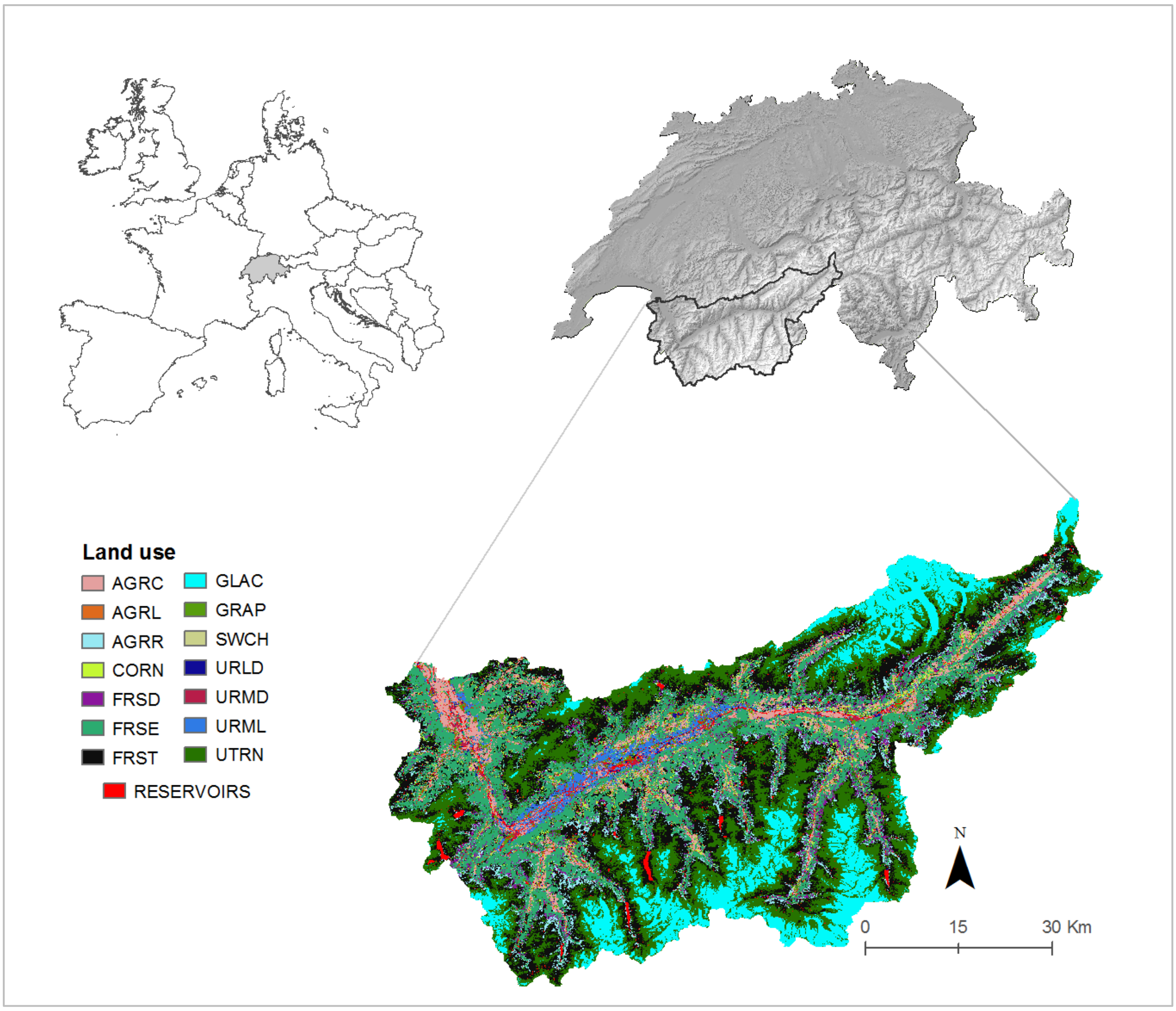

Figure: 1 Study area map

3 Methodology

3.1 Data used and sources

For a hydrological model development the data used can be subdivided in two major groups, spatial data and non-spatial data. In the spatial data group raster maps for digital elevation model land use and soil and for vector river geometry were used. For non-spatial data meteorological inputs like precipitation temperature were used. The data used for this study are listed in the table 1 below.

Table 1 Data used for this study

Data Type	Data Sources	Scale	Description
DEM	Swiss-topo	(Grid cell: 25 m · 25 m)	Elevation
Land use	Swiss Federal Statistical Office	(Grid cell: 100 m · 100 m)	Classified land use such as crop, urban forest water etc.
Soil	Swiss Federal Statistical Office	1:200000	Classified soil and physical properties as sand silt clay bulk density etc
Hydro network	Swiss-topo	1:25000	River network-diversion
River flow	FOEN	-	River discharge at daily time step
Weather	Meteo Swiss	-	Precipitation Temperature Wind Speed Solar radiation
Hydropower Discharge	Alpiq, KW Mattmark	-	Inflow and outflow, lake level

For model buildup and calibration data used are listed in this table beside the listed table scenario data were used from RCM generated variables like precipitation temperature (min and max).

3.2 Schematization of analysis

Both raster and vector data were used for building up the model. A Geographic Information System (GIS) support is needed to configure the basin delineation and flow routing direction, therefore, the model was developed in ArcGIS interface and calibration process was done in MATLAB. Since a number of iteration are needed to reach a better model performance the iteration process were done using the genetic algorithm AMALGAM (Vrugt and Robinson 2007). AMALGAM is a multi objective genetically adaptive algorithm that defines the ranges of parameter and their optimal values to get a better set of objective function. Here we use Nash and Suttclife Efficiency (NSE) as objective function.

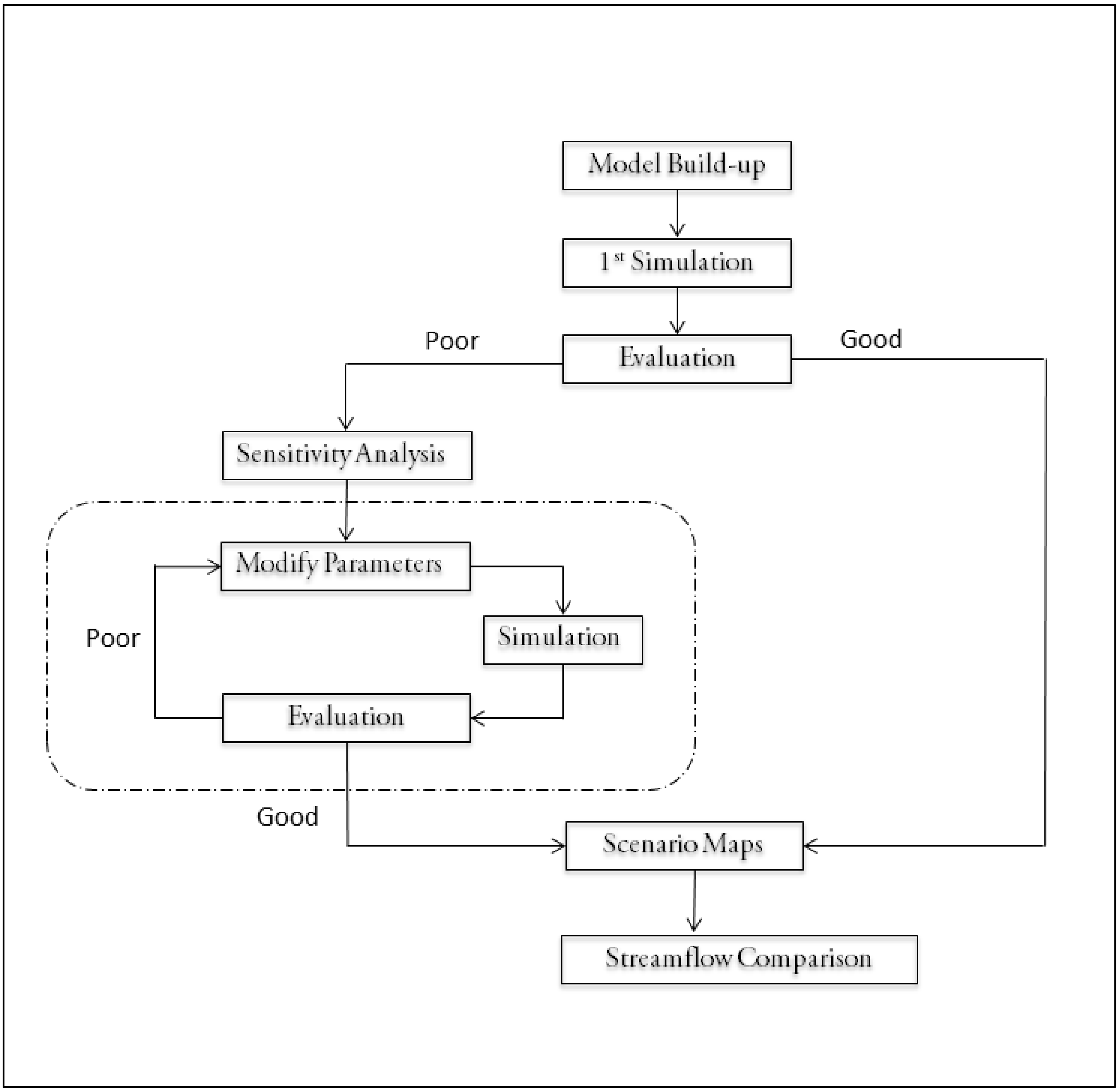

Figure 2: Schematization of workflow

After a satisfactory calibration based on the model performance statistics, we simulate the model separately to see the impact of land-use and climate.A 30 years [1980-2010] time period was used to see the sensitivity of the land-use changing the future predicated maps considering constant meteorological input. Current land-use maps were used to see the sensitivity of climate considering there time period 1981-2010 as observed and 2011-2025 as near future and 2026-2050 as far future. Combined impact was also simulated changing land-use maps and climate variables.

3.3 SWAT Model

Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) is a process-based distributed parameter that simulates watershed scale models. It partitions watersheds into sub-basins that are linked to the river network and into smaller units known as Hydrological Response Units (HRUs). Each HRU includes a combination of land use, soil and slope. Assuming that there is no interaction or dependency (Neitsch et al. 2005), HRUs are non-spatially distributed. SWAT has been successfully implemented all over the world in order to solve various environmental issues related to water quality and quantity studies – e.g. diffuse surface water pollution (Panagopoulos et al. 2011; Varanou et al. 2002). Although its use in snow and glacier dominated mountainous regions has been more limited, several studies have been conducted and a few continue to explore hydrological fluxes in mountain (Ahl et al. 2008; Debele et al. 2010; Fuka et al. 2012; Pradhanang et al. 2011; Rahman et al. 2013; Wang and Melesse 2005; Zhang et al. 2008). In order to run the model on daily or sub-daily time steps, meteorological variables such as precipitation, temperature, wind speed, solar radiation, and relative humidity are required. Subsequently, SWAT simulates hydrology, energy, soil temperature, mass transport and land management at the sub-basin and HRU levels. This particular study addresses variables related to snow melt and discharge in mountainous regions. Further information regarding the other processes is provided in the documentation of the model SWAT's hydrological routine is comprised of discharge, snow melt, and both actual as well as potential evapotranspiration. The USDA's SCS curve number method was applied for an estimation of surface runoff volume. Evapotranspiration is evaluated by SWAT using various methods including FAO Penman–Monteith, Hargreaves, and Priestley-Taylor. The Hargreaves method was found appropriate for this study based upon initial model performance before calibration.

3.4 Land-use change scenario development

In the Business as Usual (BAU) scenario, the future changes in the land use were estimated from the historical changes observed in the Swiss Land Use Statistics produced by the Swiss Federal Statistics Office (SFSO), and calculated in IDRISI TAIGA Land Change Modeler (LCM). The land use dataset used comprehends two sequential datasets for the periods 1979 to 1985 and 1992 to 1997 with a spatial resolution of 100m. While the recent dataset for the period 2004 to 2009 was used to validate the model. Each of the LU datasets contains 15 categories that were aggregated from the original 74 categories due to restrictions in LCM, which doesn't allow the processing of transitions for land use maps with more than 15 categories. The aggregation was done in such a way as to keep similar vegetation structures within the same new category. The drivers of LU change were chosen based on previous studies (Rutherford G. N. 2006.; Rutherford et al. 2007) . The different drivers were resampled to 100m, and tested to determine their strengths of association with the different LU transitions, using Cramer’s V as well as their correlation between themselves.

For this study local factors such as climate (Continental Index, Mean Annual Moisture Index and Annual average temperature), topography (Slope, Topographic Position Index, Topographic Wetness Index, West-East and South-North Gradients of Aspect), as well as distance variables between LU transitions were used. All the selected drivers have a Cramer’s V >= 5. The climate variables used in this study were obtained from (Zimmermann and Kienast 2009). From the possible transitions, a total of 16 were modelled empirically in separate sub-models by means of logistic regression using a 10% stratified random sampling. The following changes in the LU of the Rhone basin were modelled: deforestation (with the conversion of Forest into Agriculture areas); reforestation (Open Forest to Forest and Shrubland to Forest) and conversion of Open forest to Horticulture; the abandonment of Horticulture followed by afforestation (conversion to Open forest); abandonment of Horticulture with conversion to Agriculture areas, Urban buildings or Industrial buildings; afforestation due to agriculture abandonment; agriculture abandonment (conversion from agriculture to Shrubland); the conversion of Agriculture areas into Horticulture; the conversion of Shrubland to Agriculture areas; the decrease of Glaciers and perpetual snow with the increase of rock and sand.

In addition, the conversion of nonproductive areas (rock and sand) into Agriculture areas was also modelled. The model obtained was assessed by simulating the land use in the Rhone basin for 2009, and comparing with the observed land use dataset 2004-2009, using the Kappa Index of Agreement (KIA) on a pixel by pixel basis. The results obtained show an Overall Kappa of 0.86, while the majority of the modelled land use classes have high individual KIA higher values (Forest 0.88, Open Forest 0.96, Agriculture Areas 0.80, Glaciers 0.87, Rock and Sands 0.84 and Urban Buildings 0.78), with Shrubland and Clusters of Trees with low KIA values (0.35 and 0.44). The obtained overall Kappa coefficient was considered to be satisfying and the BAU scenario was run for 2025 and 2050.

The results obtained for the BAU until 2050 (Table 2) are characterised by the reduction of the Glaciers by 12169 ha, followed by the increase of Forest coverage of 6872 ha and non-productive land use (Rocks and sands) of 5887 ha. The BAU scenario is also characterised by the abandonment of Horticulture (4487 ha) with the increase of Agriculture areas (3418ha); in addition the area occupied by Urban and Industrial also increases (1599ha and 827ha).

Table 3: Gains & Losses 2009-2025 & 2025-2050 (ha)

Gain & Losses	Forest	Clusters of Trees	Horticulture	Agricultural areas	Glaciers	Rocks and sands	Urban Buildings	Industrial Buildings
2009 2025	3208	-387	-2206	892	-5339	2563	804	455
2025 2050	3667	-465	-2281	2526	-6830	3324	795	372

3.5 Simplification/Aggregation of land use classes

Table 3: Aggregation of land use classes

Land Use Categories	**Aggregated Categories**
Forested areas; Forest stripes, edges; Devastated forests; Brush forest and Normal dense forest	(1) Forest
Other woodsand and Open forest on unproductive areas	(2) Open Forest
Groves, hedges; Open forest on agriculture areas and Clusters of trees on agricultural areas	(3) Clusters of Trees
Regular vineyards; "Pergola" vineyards; Intensive orchards; Scattered fruit trees and Rows of fruit trees	(4) Vineyards and fruit trees
Horticulture; Other arable land and meadows; Favourable arable land and meadows and Extensive vines	(5) Horticulture
Farm pastures; Mountain meadows; Rocky alpine pastures; Favourable alpine pastures; Unproductive grass and shrubs; Remote and steep alpine meadows and pasture	(6) Agricultural areas
Brush meadows and farm pastures; Scrub vegetation and Brush and alpine pastures	(7) Shrubland
Wetlands and Water shore vegetation	(8) Wetlands

Glaciers and perpetual snow	(9) Glaciers
Rocks and sands	(10) Rocks and sands
Single or Multi-unit housing; Terraced houses; Apartment buildings; Unspecified buildings; Surroundings of single or multi-unit housing; Surroundings of terraced houses; Surroundings of apartment buildings and Surroundings of unspecified buildings	(11) Urban Buildings
Agricultural buildings and Surroundings of agriculture buildings	(12) Agriculture Buildings
Industrial buildings and Industrial grounds	(13) Industrial Buildings
Ruins; Buildings in recreational areas; Buildings in special urban areas; Sport grounds; Garden allotments; Camping, caravan sites; Golf courses; Construction sites; Cemeteries; Public parks; Other supply or waste treatment plants; Energy supply plants; Waste water ; Quarries and mines; Dumps and treatment plants	(14) Artificial surfaces
Motorway; Green motorwa; Roads and path; Parking areas; Railway station grounds; Railway lines; Airfields, green airport surroundings; Green railway surroundings; Green road surroundings; River shores; lakes; Rivers; Structure of protection againts floods	(15) Features

In the SWAT model the reclassification needs to be done with 4 digit codes, table 4 presents the final setup used for model development.

Table 4: Land-use classes and its coverage

ID	Land use	Pixel	% Coverage	SWAT Code
1	Agricultural Land-Generic	101963	19.20	AGRL
2	Agricultural Land-Row Crops	19472	3.67	AGRR
3	Corn	11061	2.08	CONR
4	Residential-Med/Low Density	9836	1.85	URML
5	Agricultural Land-Close-grown	24802	4.67	AGRC
6	Forest-Mixed	112704	21.22	FRST
7	Agricultural Land-Row Crops	21265	4.00	AGRR
8	Alamo Switch grass	238	0.04	SWCH
9	Glacier	70092	13.20	GLAC
10	Transportation	134230	25.27	UTRN
11	Vineyard	7940	1.49	GRAP
12	Agricultural Land-Generic	631	0.12	AGRL
13	Residential-Medium Density	1650	0.31	URMD
14	Residential-Low Density	2383	0.45	URLD
15	Water body-Reservoir	12867	2.42	WATR

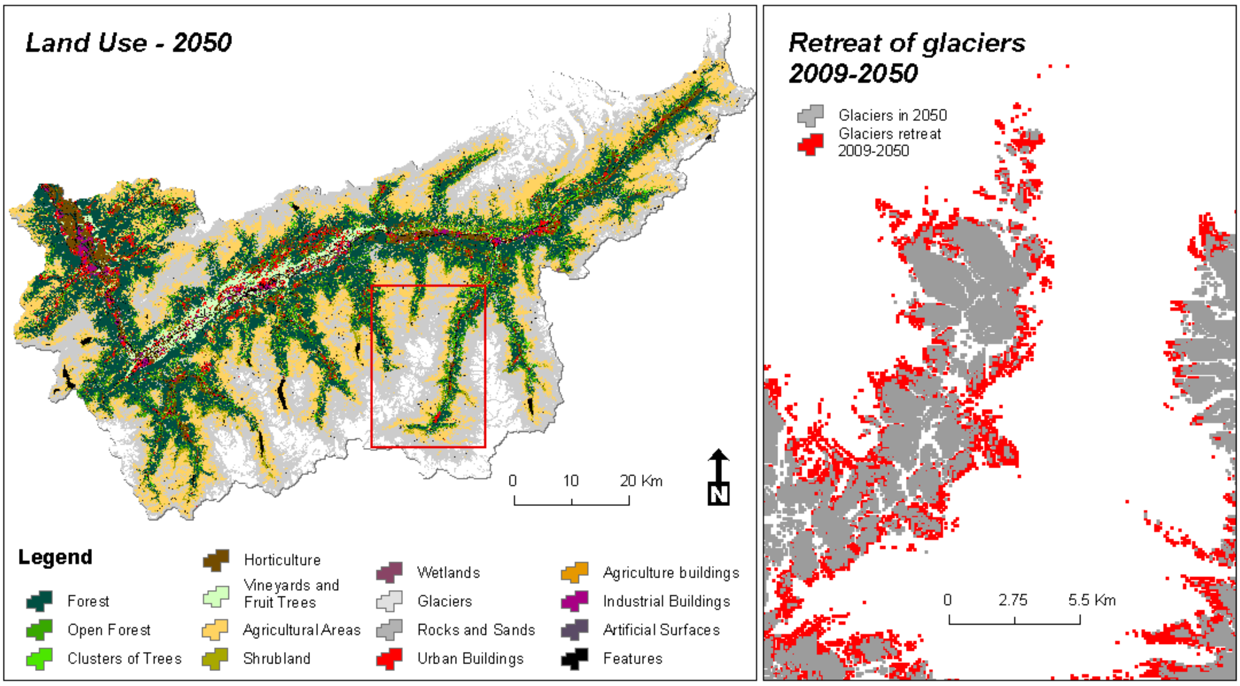

Figure 3 Scenario maps for year 2050 and glacier change between 2009 and 2050

3.6 Climate change scenario development

From the ENSEMBLES climate scenario database (www.ensembles-eu.org) a homogeneous set (in terms of starting date and available variables) of 16 regional climate simulations based on the A1B emission scenario (Nakicenovic et al., 2000) were selected. Among the 16 selected RCMs the best one is chosen considering the similar pattern of peak and low flow simulation in the mountainous watershed. 100-yr time series (1951 – 2050) for daily precipitation, 2-m air temperature, global radiation, relative humidity, wind, and atmospheric pressure were retrieved. As regional climate models (RCMs) are known to suffer from systematic errors, an empirical-statistical error correction method (quantile mapping, QM) was applied to adjust regional model results towards the local-scale observations, using daily observational data from the MeteoSwiss weather stations over the 29 year calibration period 1981 – 2009. Our implementation of QM is described in more detail by (e.g.Jakob Themeßl et al. 2011; Themeßl et al. 2012) for temperature and precipitation and by for further meteorological variables, and has already been applied in other climate change impact studies (Finger et al. 2012; Heinrich and Gobiet 2012).

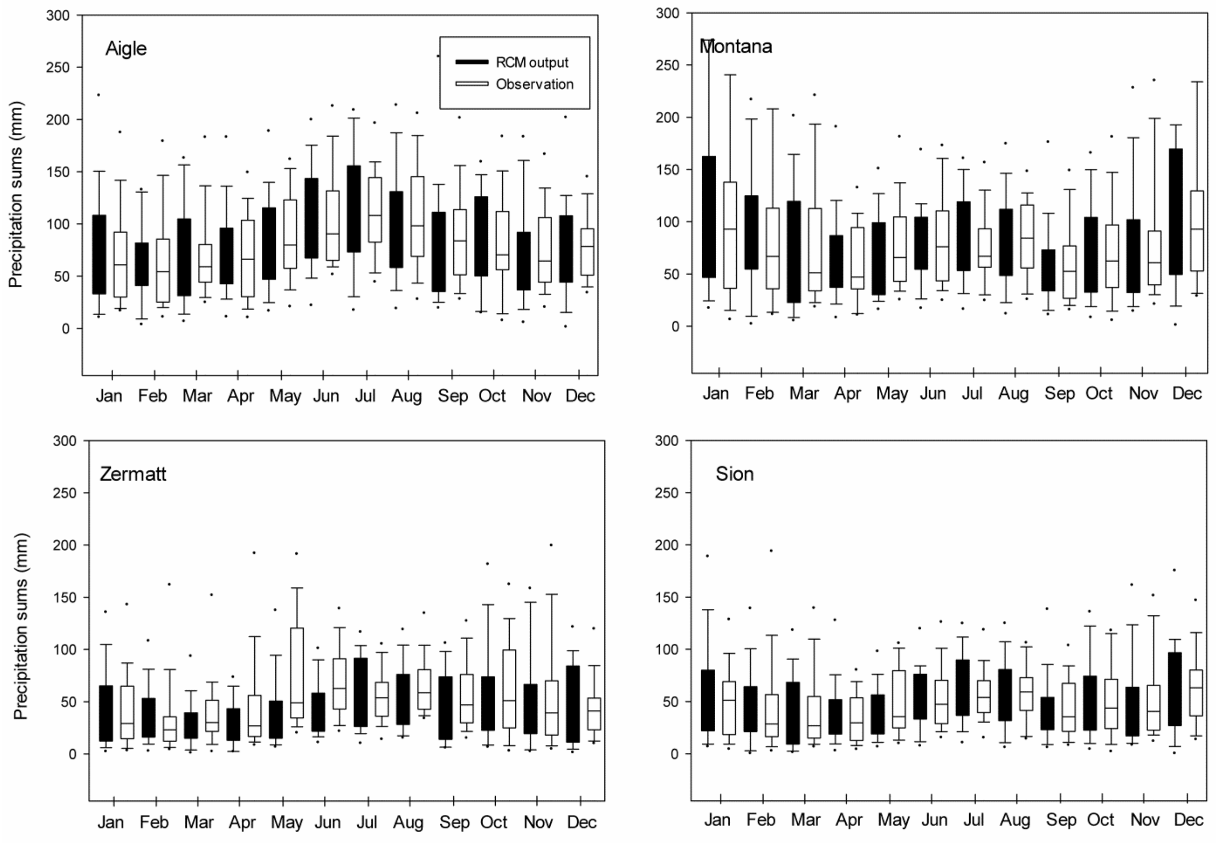

Figure 4 Consistency checking with 4 observation station

A comparison was made to the RCM generated input for precipitation along with the observed meteorological stations with the monthly sum of 29 years. It is apparent that the variability is higher with RCMs but there is a similar pattern of shape can be seen in the figure 4

3.7 Flow Duration Curves (FDC)

Flow duration curves summarize the likelihood of equaling or exceeding a given streamflow at a particular point on a river (Cole et al. 2003). It is similar to a cumulative distribution function. It is one of the important signals of changing magnitude of streamflow due to change of flow regime for atmospheric influence. FDC analyses are widely used in the hydrological studies like sensitivity of climate and land-use change (Lane et al. 2005; Shao et al. 2009) .The basic time unit used in preparing a flow-duration curve will greatly affect its appearance. For most studies, mean daily discharges are used for flow duration curve construction. These will generate a steep curve. When the mean flow over a long period is used (as example: mean monthly flow), the resulting curve will be flatter due to averaging of short-term peaks with intervening smaller flows during a month. Extreme values are averaged simultaneously, as the time period gets larger (e.g., for a flow duration curve based on annual flows at a long-record station). Flow duration curves can be designed daily or monthly time step, here our calibration is based on daily time step since the calibration is done is daily time step. The probability of exceedance can be calculated as P = 100 * [M / (n + 1)]

Where,

P = probability of exceedance (i.e. at a certain % of time the flow will be equal or exceed)
M = the ranked position on the listing (dimensionless)
n = number of observation in a given record (dimensionless)

3.8 Model performance statistics

Several studies have proposed a standard hydrological model performance criterion. For this study we followed NSE, PBIAS and R^2 as model evaluation statistics (Moriasi et al. 2007). NSE is the strength of the relationship of observed and simulated values where Qm,t is the observed data value at time t and Qs,t is the simulated data value at time t. NSE values lies between -∞ to +1, (Nash and Sutcliffe 1970). Values close to +1 indicates the better model performance.

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{T}\left(Q_{m,t} - Q_{s,t}\right)^2}{\sum_{t=1}^{T}\left(Q_{m,t} - \overline{Q}_m\right)^2} \qquad 2$$

$$\mathrm{PBIAS} = \left[\frac{\sum_{t=1}^{T}\left(Q_{s,t} - Q_{m,t}\right)}{\sum_{t=1}^{T} Q_{m,t}}\right] \times 100 \qquad 3$$

$$R^2 = \left[\frac{\sum_{t=1}^{T}\left(Q_{m,t} - \overline{Q}_m\right)\left(Q_{s,t} - \overline{Q}_s\right)}{\sum_{t=1}^{T}\left[\left(Q_{m,t} - \overline{Q}_m\right)^2\right]^{0.5} \sum_{t=1}^{T}\left[\left(Q_{s,t} - \overline{Q}_s\right)^2\right]^{0.5}}\right]^2 \qquad 4$$

PBIAS indicates the average tendency of the simulated data to be larger or smaller than their observed value's. According to Gupta et al. (1999), PBIAS can be utilized as an indicator of under- or over-estimation. Negative PBIAS indicates a slight underestimation of model generated values against the measured values. The square of Pearson's product moment correlation is indicated with R^2 which represents the proportions of total variance of measured data that can be explained by simulated data. Higher values of simulated data close to 1 represent better model performance.

In this work we considered that the model performance was satisfactory when we arrived to NSE > 0.5, PBIAS = ± 25%.

4 Results and Discussion:

4.1 Model calibration and validation with RCM output

The common period 1981-2010 was chosen for model calibration based on RCM generated input (e.g. Precipitation min temperature max temperature with daily time step) and the calibration results are presented with the figure 4. A total of nine parameters were tuned for model calibration based on the sensitivity analysis embedded in SWAT model. The LH-OAT (Latin hypercube one step at a time) technique was used to identify the most sensitive parameters for this watershed. Parameters mostly related to snow and glacier melt are found highly sensitive since the watershed is driven by the melt water of snow and glacier.

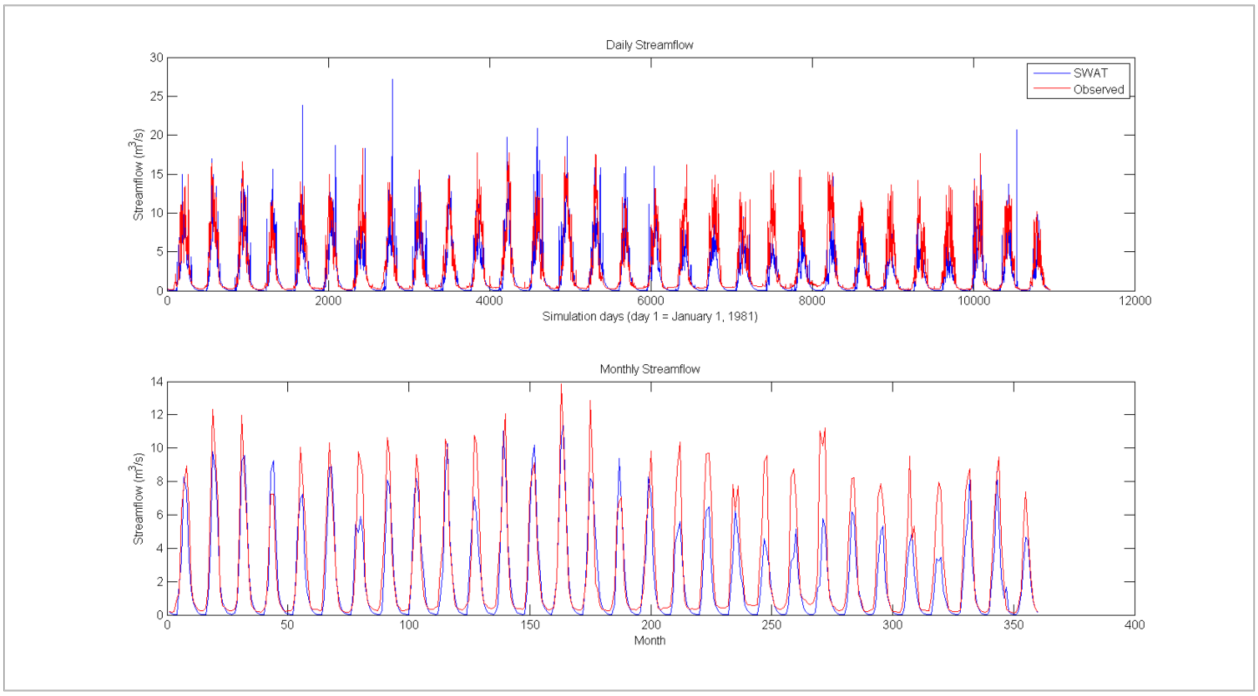

Figure 5 : Observed and simulated streamflow at upstream station (gletsch) (a) daily time step (b) monthly time step.

Comparison between observed and first simulated hydrograph revealed underestimation and overestimations of some periods, as well as the influence of secondary peaks. Those inconsistencies were removed by adjusting the parameters listed below. Table 5 describes the set of parameters their ranges and optimized values used for calibration.

Table 5 Lists of parameter and their optimal value used for calibration (based on best calibration)

Parameter	Description	Range	Optimized value
TLAPS	Temperature lapse rate [^{o}C/km]	0,-10	-2.8
PLAPS	Precipitation lapse rate [mm H_2O/km]	0,100	3.8
SFTMP	Snowfall temperature[^{o}C]	-5,+5	1.221
SMTMP	Snow melt base temperature [^{o}C]	-5,+5	2.1
SNOEB	Initial snow water content in elevation band [mm]	0,300	150
TIMP	Snow pack temperature lag factor	0.01,1	1
SMFMN	Melt factor for snow on December 21 [mm H_2O/ºC-day]	0,10	2.1
SMFMX	Melt factor for snow on June 21 [mm H_2O/ºC-day]	0,10	3.2
SURLAG	Surface runoff lag time [days]	1,4	1

4.2 Sensitivity of stremflow for land-use change

Figure 6 illustrates the observed and simulated hydrograph due to land-use change. For this analysis 30 years [1981-2010] were used keeping the climatic data constant. The major changes in the land use are the forest cover and glacier. Two major changes are apparent they are peak flow reduction and increase of low flow. There not many changes in the raising and recession limb of hydrograph which physically means the influences will be in specific time i.e melting period (June-July-August) and winter period (November-December-January-February) We observe that the mean monthly flow is decreasing than the current stage in the summer period. The figure 6(a) illustrated the downstream which combines the impact of all the sub basins and figure 6(b) illustrated the upstream sub basin. It is important o mention that the upstream basin has no anthropogenic influence that means the natural variable is reflected in this basin. However, the upstream basin covers most of it with glacier and solid rocks but the downstream basin are not all covered by glacier. Therefore the change in the upstream does not reflect the changes in forest cover.

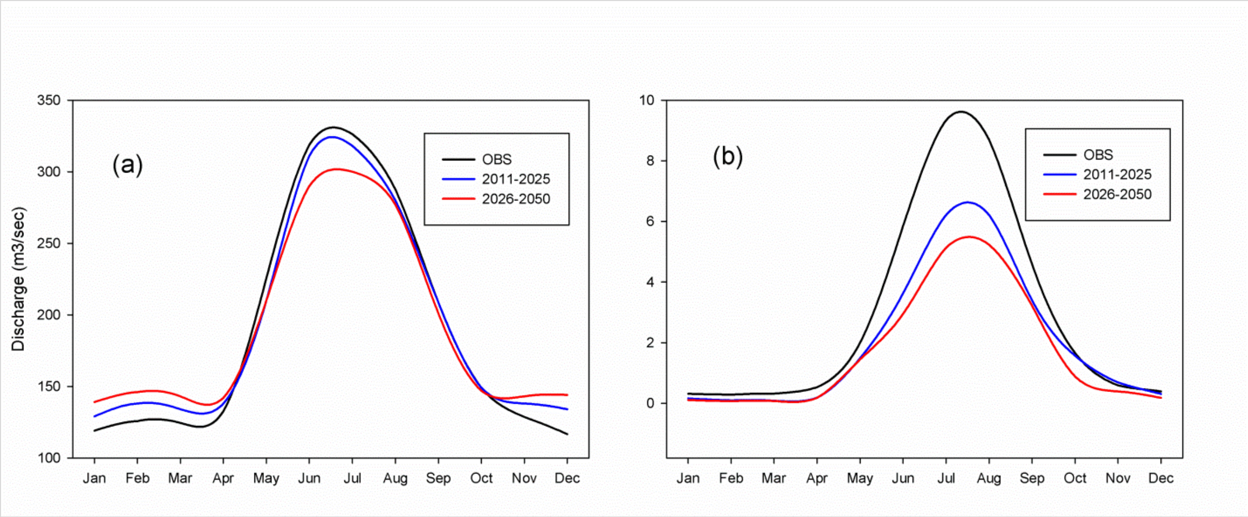

Figure 6: Discharge hydrograph at [a] upstream sub basin gletsch [b] downstream sub basin Porte du scex.

4.2 Sensitivity of stremflow for climatic change

Changes in streamflow due to climatic changes are illustrated by Figure 7. Likewise figure 7(a) describes the downstream and figure 7(b) describes the upstream. Two major signs are visible they are; peak flow reduction and early high flow occurrence. Similar to the changes of land-use but the difference is the timing of peak flow. In this analysis the current land use map was used and model simulated until 2050. The hydrograph was plotted slicing up three time period; observed i.e. (1981-2010) near future (2011-2025) far future (2026-2050). This early occurrence of peak flow has significance consequence in the reservoir operation.

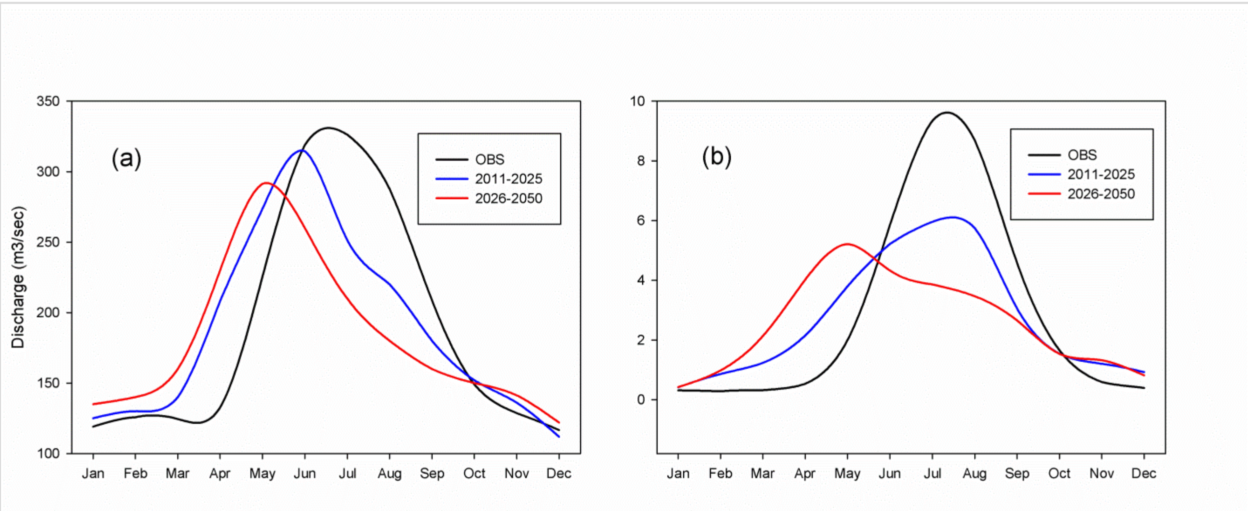

Figure 7: Discharge hydrograph at [a] upstream sub basin Gletsch [b] downstream sub basin Porte du scex.

Similarly considering June-July-August-September as a peak flow period the reduction will impact the hydrological regime of the river.

4.3 Combined impact

The combined impact is simulated based on the climate data series until 2050, along with the land-use map generated for 2025 and 2050. The changes due to climate are quite significant as it changes the flow regime. Two major changes can be seen, the peak flow reduction and the sign of earlier high-flow period. This has consequences with the climate simulations. The hydrographs below shows the mean average discharge of the two time period (2011-2025) and (2026-2050). It is apparent that in the combined impact the reflection of the impact of land-use and climate change will be replicated.

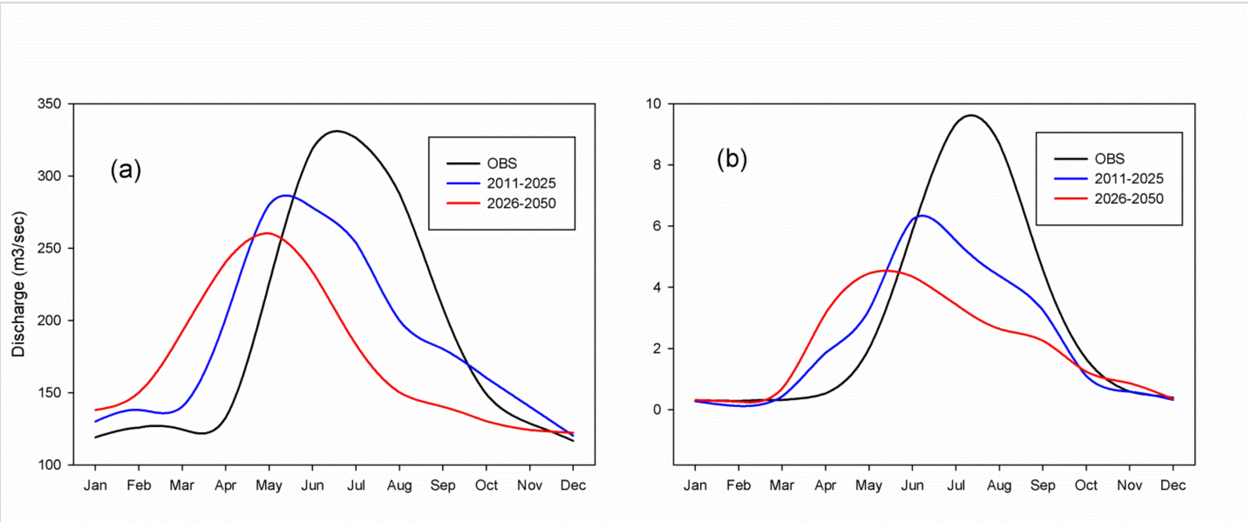

Figure 8: Discharge hydrograph at [a] upstream sub basin Gletsch [b] downstream sub basin Porte du Scex.

The severe reduction of summer flow starts from May and continues until October which is the period where the hydropower reservoirs are filled to generate energy in the winter. Therefore, a drop in peak flow will certainly reduce the inflow to the lake and disturb the regular phenomenon of energy production. Notably, the shift of peak flow period also have significant consequence especially in March and April which is often considered a reservoir emptying time, if the peak flow occurs in that time reservoir

4.4 Flow duration curve analysis

Flow duration curves are presented with the Figure 7. The impact in observed is quite significant in both low and high flow period. In the upstream catchment Fig. 7 (a) probability of exceedance increases in the low flow period and high flow high flow exceedance is decreasing.

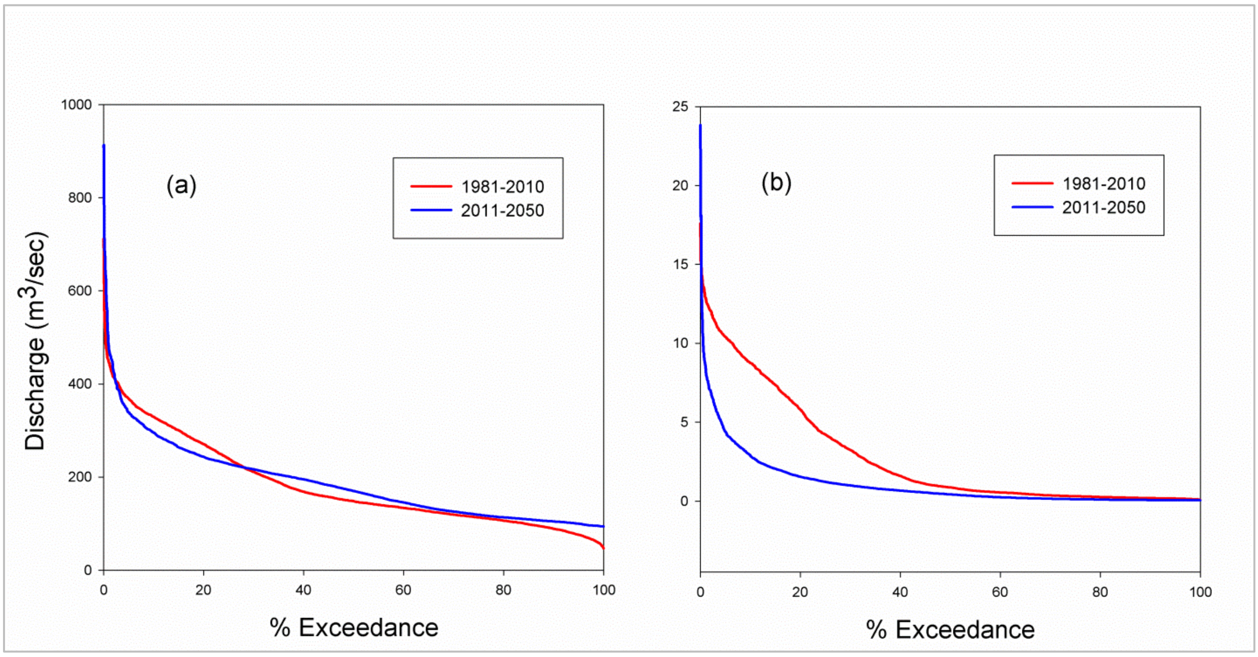

Figure 9: Flow duration curve [a] downstream station: 'Porte du Scex' [b] upstream station: 'Gletsch'

Considering 200m^3/sec as average flow inflection point the high flow period has lower trend of exceedance probability, which physically means the occurrence of high flow will be less in future, on the other hand, low flow occurrence will be more frequent. Similar trend can be seen in the upstream station (Fig.9 (b)) where the probability of exceedance is decreasing in the forecasted period. Considering 5 m^3/sec as average discharge which is often the starting of melt season will drop. It is apparent that the upstreamflow regime will not be replicated exactly because the upstream basin contains glacier but the downstream combines the snow and glacier and the forested sub basins as well. However a significant drop in the upstream sub basins has a consequence in hydropower production because the water is taken at the downstream hydropower reservoir.

4.6 Discussions

We investigated the streamflow response due to land-use and climate in the Rhone river watershed. Our experiment was limited to the upper part of the River which plays a significant role in hydropower generation as well as contributes for the water balance in the Lake Geneva. Moreover, downstream catchment is also linked with the upstream changes. We observed a change both in magnitude and timing of flow. Our analysis suggested that the magnitude reduction can happen both for land-use and climate change but the intensity of magnitude is different, i.e. difference between the flow reduction is smaller for land-use change than climatic change. Three major changes are apparent, peak flow reduction low flow increase and timing of peak flow occurrence, all of them have significant consequences in terms of hydropower production and biodiversity. Usually in the summer time water is stored in the reservoir and released in the winter based on the energy consumption. Since the summer required less energy snow and glacier melted water stored and in the winter higher energy is needed therefore the water released from the hydropower reservoirs. It may be relevant that a change in this phenomenon can change the energy planning strategy as example hydropower companies are committed to supply energy for small entrepreneurs if the production reduces the impact will also be faced by the small enterprises.

It is obvious from the analysis of the land-use change (Table 2), that a reduction of the streamflow is expected when considering a BAU scenario, instigate by the loss of glacier (6830 ha) and increased of forest (3667ha). The latter can affect the amount of precipitation will be absorbed by the trees and used in the evapotranspiration process. In addition the hydropower generation, like water use for agriculture, drinking water supply, and small to medium industries will also have impact due to changes of flow regime. Beniston (2010) explained the possible consequences of climatic changes on various section in the Rhone valley. Similar strategies observed by Finger et al. (2012) implementing hydrological model in the Vispa valley which is one of the major tributary the end century result shows a peak flow drop and early melt period. Recommendation's provided for adaptation of future hydropower production with possible uncertainties. Other studies (e.g.Horton et al. 2006) predicted the similar behavior with the RCM generated variable and a relative comparison in the Gletsch watershed with is also studied in this study. Their finding suggests an early melt.
There is one limitation is apparent; future energy consumption scenario should also be incorporated in such forecast analysis, because the decision on energy consumption is linked with type of energy generation sources (i.e. hydropower or nuclear) and their dependency based upon the future demand. As example if the future energy demand is inclined with nuclear based energy production, the hydropower operation rules will change; therefore an energy demand based scenario need to implement. However such scenario generation could lead uncertainties because this kind of forecast

analysis is highly dependent on large number of variables like demographic change and dependency of power sources.

Uncertainties of streamflow forecast studies can be of various folded, input, parameter uncertainty, model structure uncertainty. In this analysis the input was mostly taken from the 8 complete meteorological observation points with complete time series of precipitation and temperature, moreover an effort made to check the consistency and filtering of outliers were done before feeding into the model. Moreover the RCM generated inputs were also tested for homogeneity and plotted to see if there is any inconsistency. The plot is presented in figure 5.

The overall objective of this research was to test the sensitivity of streamflow due to change of land-use and climate, the analysis could also be performed with statistical approach making a correlation with the changes of variable (e.g. precipitation and temperature along with streamflow,) but a hydrological model can give better insight in various process as well as the simulation of peak and low flow period. We presented the result based upon the best simulation but a range of simulation could add an additional value to understand the ranges of uncertainty for better watershed planning.

Conclusions

The combined effect of land-use and climate change was assessed based on business as usual scenario (BAU) and changes observed in high flow and low flow periods. The climatic variables were tested before feeding into the model and performance test was done with quantile mapping approach. While building land-use scenario, the loss and gain pixels were validated with current observation to have accurate estimation two time period were chosen. Simulations were made keeping the current land use map and changing the climatic time series to see the climate change impact on streamflow, simultaneously climate variable were kept fixed (from 1981-2010) and simulation was done changing the land use map to examine the impact of land-use change. Individual effect analysis it is found that the land-use change has much lower effect than the climate change both upstream and downstream sub basins in reduction of the magnitude of peak flow. It is apparent that the changes in the mountains area are insignificant due to lake of living facility. While as in the flood plain the sensitivity is high for demographic features (i.e. increased population, afforestation), also climate change scenario is sensitive. This sensitivity is derived from the link between the increase of temperature and the melting process, for this reason SWAT uses temperature index method for snow and glacier melt process. In the temperature index method it is considered that the daily air temperature is proportional to the melt rate, therefore change in temperature can lead change in melt. Since the runoff in this watershed is driven by the snow and glacier melt the early melt could lead several consequences and most severe is the hydropower based energy production. Early melt will result in an early fill of the reservoirs and will result in a shortage during the peak flows. Therefore the result obtained from this study can be useful for water management in the Rhone Valley.

Acknowledgement

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Chapter 5

Breaking Walls Towards Fully Open Source Hydrological Modeling

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Abstract

Hydrological models are powerful mathematical tools to address environmental problems and are often used for watershed management and planning. Hydrological models are data driven and the availability of data often limits model development. In this paper, we address several challenges in building and running a hydrological model for stream flow simulation based solely on freely available data and open source software. The Soil and Water Assessment Tool (SWAT) hydrological modeling software has been used in the MapWindow Geographic Information System (GIS). Both spatial and non-spatial data used for this study were all obtained from various free of charge online sources. Model calibration and validation represent major challenges following the initial model construction since they involve several trial and error processes to reach acceptable model performances. These critical steps were programmed here as automated scripts in the R open source statistical package. The challenges of data extraction and processing are described step by step through video tutorials. Using a case study in the Mendoza watershed in Argentina, we show that model simulated stream flow exhibits sound agreement with the observed stream flow considering daily time steps. The workflow demonstrated in this study can be applied for other watersheds, especially in data-sparse regions.

Key words: SWAT Model, Open Source Software, Free Data, Hydrology

Supplements:

[1] R script for global climate data processing
[2] List of online videos
[3] R script for SWAT model calibration

Introduction

Managing water resources correctly should play a significant role for building a more sustainable world, especially in the face of several global changes such as climate, land cover and demography (UNESCO 2012). Applications of hydrological models for addressing various issues that are linked with water resources are under increasing demand (Arnold et al. 1998; Gassman et al. 2007; Santhi et al. 2001; Schuol et al. 2008a; Schuol et al. 2008b). Hydrological models are mostly data driven and easily accessing and efficiently using this data is of uttermost importance for tackling a number of water-related issues (e.g., pollutions, floods, biodiversity and ecosystems conservation, energy production, food security and water scarcity). Encouragingly, there are now various sources of spatial and non-spatial data available online for hydrological research, including NASA, USGS, FAO and others (Cantelaube and Terres 2005; Chen et al. 2012; El-Sadek et al. 2011; Liechti et al. 2012).

Different kinds of challenges often limit our ability to build and calibrate hydrological models. These mainly include data scarcity, software requirements and availability, and computational capacity. This complexity can be of various levels depending on the objectives of the study. For example, to model diffuse or heavy metal pollutions, rarely available observational data on these pollutions is needed to calibrate the model and evaluate its performance. Another important barrier can be software availability, which involves the discussion of the choice between open source and proprietary packages.

Several open source hydrological models are available now a days in online, the Soil and Water Assessment Tool (Arnold et al. 1998)[http://swat.tamu.edu/] is an open source hydrological model that is based typically on a daily simulation. SWAT has been extensively used in various regions around the world (for a review, see (Gassman et al. 2007) and benefits from a large worldwide user community. SWAT models are traditionally built on the ArcGIS proprietary platform (Winchell et al. 2007), but they can also be prepared on the MapWindow open source GIS interface (George and Leon 2007) using the MWSWAT extension [http://www.waterbase.org]. The major processes that SWAT simulate are water, sediment and nutrient flows. SWAT describes the hydrology of the selected catchment by estimating several processes: interception, evapotranspiration, surface runoff (SCS curve number method, USDA Soil Conservation Service, 1972), soil percolation, lateral and groundwater flows, and river routing (variable storage coefficient method, Williams, 1969). SWAT considers the catchment to be divided into sub-basins, river reaches, and further hydrological response units (HRUs). While the sub-basins can be delineated and located spatially, the further subdivision into HRUs is performed in a stochastic manner by considering the observed unique combinations of land use, soil, and slope, without any specified location in each sub-basin (Neitsch et al. 2005); hence it is considered to be a semi-distributed hydrological model.

The goal of this paper is to propose a methodology for efficiently assembling and preparing the minimum set of required input data to build a SWAT model for any watershed in the World. This methodology is based solely on freely available data and open source software solutions. The proposed methodology is presented in online videos on the technical steps required for data extraction and preparation, and for model calibration and validation. We illustrate our methodology through a case study in the Mendoza River watershed in Argentina. Finally, we discuss the limitations of our methodology and the implications of emerging environmental data sharing in the global context.

Data need and availability

Data requirement for SWAT model

Spatially distributed or semi-distributed hydrological models are data-driven; therefore the availability of data for building a model remains a major issue. Data requirement for building a hydrological model can be subdivided into three major categories: geographic, weather and hydrological data. These data are heterogeneous, typically structured according to several main data models such as tables, GIS raster, GIS vector or multi-dimensional arrays (e.g. NetCDF).

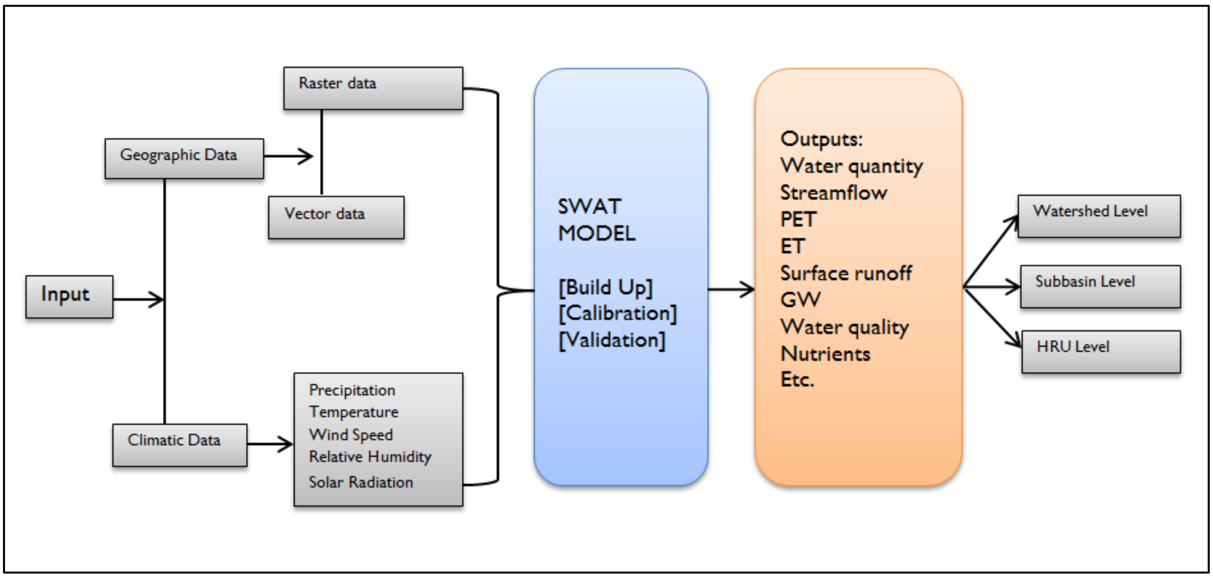

Figure1: Flow chart of data requirement for SWAT model preparation, calibration and validation.

Figure 1 summarizes the data requirements for SWAT inputs and its possible outputs. Digital Elevation Model (DEM), Land Use (LU) and soil maps are raster datasets, while river geometry comes typically in vector formats, hydrological and weather data as tables, and climatic data as arrays of points. Raster data are available in various resolutions ranging from several kilometers to a few meters per pixel. Similarly, the vector data are available at very different scales. For the weather data, the minimum requirements are for precipitation, with necessity to have minimum and maximum daily temperatures. Hydrological data concern essentially water flow, water quality and sediment loads. Both weather and hydrological data are generally made available as simple data tables. Finally, the outputs from global and regional climate models that can be used to predict the impacts of climate changes on the hydrological model are usually stored in NetCDF format. Table 1 presents the data used in the Mendoza catchment case study.

Table 1: Freely available data used for the Mendoza catchment in Argentina

Data Type	Data Sources	Scale/Resolution	Description-Web site
DEM	SRTM	90 m	Elevation http://srtm.csi.cgiar.org/
Land use	GlobCover	1,000 m	Classified land use such as crop, urban forest water etc. http://ionia1.esrin.esa.int/
Soil	FAO	1:5,000,000	Classified soil and physical properties such as sand, silt, clay, bulk density. http://www.fao.org/climatechange/54273/en/
Hydrological network	Hydroshed	1:25,000	River network http://hydrosheds.cr.usgs.gov/
River flow	GRDC	-	River discharge http://grdc.bafg.de
Weather	NCDC	-	Precipitation, Temperature, Wind Speed, Solar radiation http://www.ncdc.noaa.gov/

Mendoza watershed case study

The Mendoza River watershed covers 19553 km^2 . The peak flow occurs during summer due to snow and glacier melt. We focus on the upper portion of the watershed that covers 7291 km^2 (see Fig. 2). The major land covers are vegetation, bare rocks, shrubs, snow and glaciers. Detailed information of the watershed can be obtained from Girón et al. (2012). The flow variations are quite significant ranging from peak flow at 150-200 m^3/sec to low flow around 15-20 m^3/sec. The river plays an important role for domestic use at the downstream area of Mendoza city.

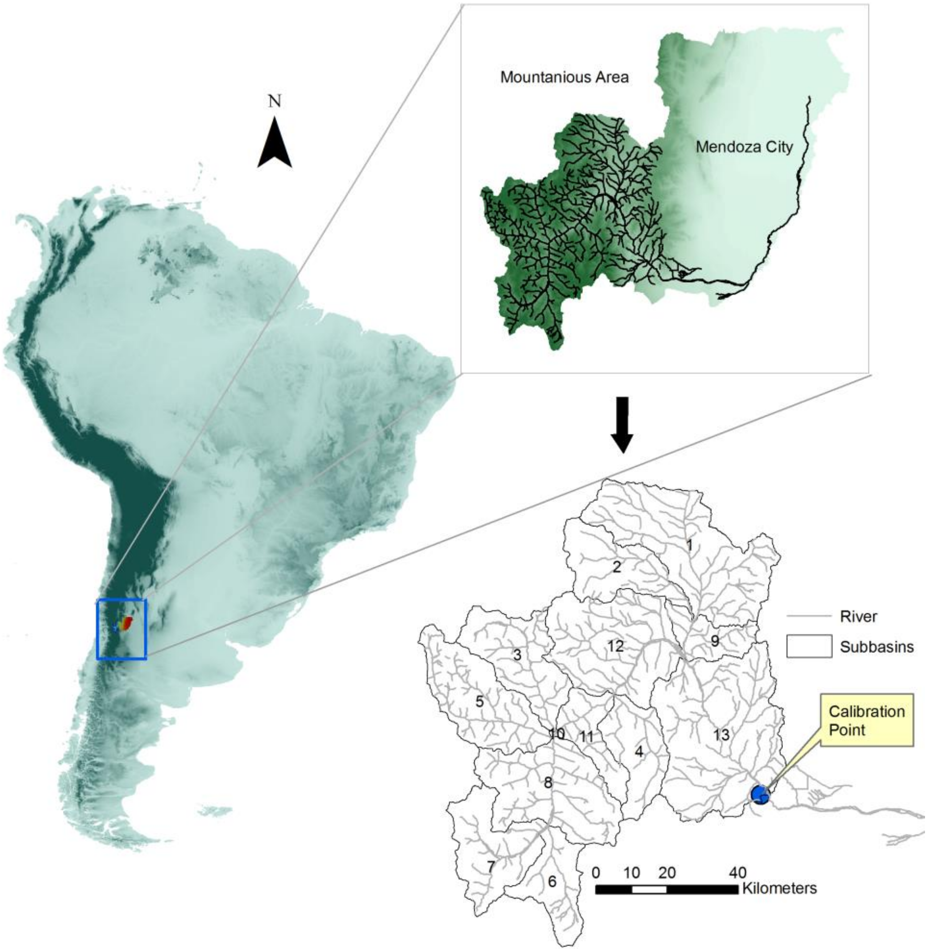

Figure 2: Study Area Map

Spatial Data

The Digital Elevation Model (DEM) was obtained from the shuttle radar topographic mission (SRTM) with a 90 m resolution. The SRTM produced the most complete, highest-resolution digital elevation model of the Earth (Farr et al. 2007). The land-use grid comes from the Global Land Cover Characterization with a 1 km resolution (GLCC, Version 2). The soil map was produced by UNESCO and FAO as the Soil Map of the World at a scale of 1:5,000,000 [FAO, 1995]. The soil and land-use associated characteristics were obtained from literature [Schuol et al., 2008a; Schuol et al., 2008b]. The Digital global stream network was obtained from the USGS public domain geographic database hydroshed. Table 1 summarizes data sources and their characteristics.

Weather Data

In this pilot study we used precipitation and temperature data from National Climatic Data Center of the United States of America along with the World Meteorological Organization. Various spatial and temporal issues arise with these data when building the SWAT model; four major problems are notified here: (1) discontinuity of time series, (2) scale differences, (3) unexpected characters, (4) changes of units (e.g. from Fahrenheit to Celsius degrees).We developed a set of scripts written in statistical package R version 2.13.1 (R Development Core Team, 2010) that correct all these issues and harmonize these weather data for correct input in SWAT. These scripts are available as a supplements to this article.

SWAT model building and calibration

At first, the model simulated with globally available data performed very poorly, which is typical of uncalibrated models. In order to optimize the default parameter settings, we developed a set of R scripts for continuous iterations and evaluation of model performance. This evaluation is based on three goodness-of-fit statistics: Nash Sutcliffe Efficiency (NSE) (Nash and Sutcliffe 1970), R^2 and Percent Bias (PB). Each stage of model building using online videos and calibration scripts is also provided as supplements.

Results and Discussion

Model Calibration:

Before model calibration (Fig 3a), three major problems were identified in the simulated discharge, which are (a) a systematic under estimation, (b) several high peaks, and (c) low flows highly under-estimated. Most of the problems were solved adjusting the snow and glacier melt related parameters. The list of sensitive parameters, their default values, and the calibrated values are presented in table 2. The calibrated model (Fig. 3b) resulted in the following evaluation statistics: NSE =0.69, R^2=0.72 and Percent bias =+9%, which are satisfactory according to the statistical performance criteria described by Moriasi et al (2007).

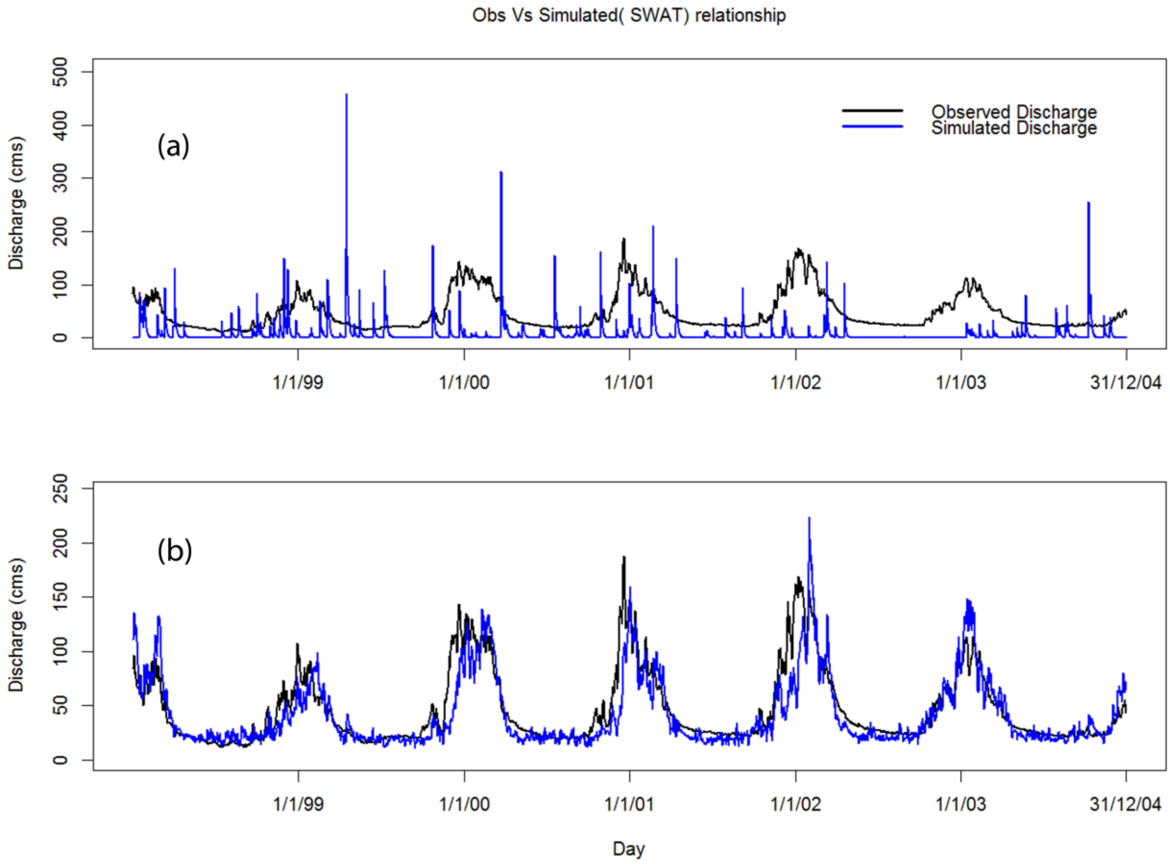

Figure 3: Mendoza catchment observed vs. simulated discharge (a) before and (b) after calibration.

Table 2: List of sensitive parameters and their optimized values

Parameter	Description	Range	Optimized value
TLAPS	Temperature lapse rate [^{o}C/km]	0,-10	-2.8
PLAPS	Precipitation lapse rate [mm H_2O/km]	0,100	3.8
SFTMP	Snowfall temperature[^{o}C]	-5,+5	1.221
SMTMP	Snow melt base temperature [^{o}C]	-5,+5	2.1
SNOEB	Initial snow water content in elevation band [mm]	0,300	150
TIMP	Snow pack temperature lag factor	0.01,1	1
SMFMN	Melt factor for snow on December 21 [mm H_2O/ºC-day]	0,10	2.1
SMFMX	Melt factor for snow on June 21 [mm H_2O/ºC-day]	0,10	3.2
SURLAG	Surface runoff lag time [days]	1,4	1

4.2 Discussion and conclusion

Although the SWAT model source code is freely available, the building up of a new hydrological model project needs some GIS analyses for subbasin delineation, flow accumulation and the flow direction process. Most often, the ArcSWAT (Winchell et al. 2007) interface is used for model development. ArcGIS is a proprietary software package with licensing costs that can now be avoided by using the MapWindow solution MWSWAT. Financial issues can be a hurdle for applying model in developing countries, and the open source solution is therefore a welcome alternative. Another advantage of using MWSWAT over ArcSWAT is that MWSWAT has a built-in window for the visualization of the hydrological model results through geospatial maps.

The third supplementary R code we provided for calibration can be helpful for formatting the meteorological data for multiple stations, especially in large watersheds with scarce data. Similarly, the second R code made available is useful for the trial and error processes. However, two major limitations to the workflow we presented must be mentioned. First, the minimum amount of data needed for model calibration and validation are difficult to get from all places around the world. Most countries are not making available hydrological data (e.g. discharge) on the web. In other countries, especially developed countries, online sources are more and more available. For this case study, freely available discharge data was obtained from the GRDC. However, in our case study we used daily data from local authority to improve the model calibration. Data from weather stations provided by NCDC are also less dense in the developing world. Second, computational capabilities can become a major challenge for working with high resolution models on large catchments. Research has been carried out for running SWAT on a distributed platforms such as grid infrastructures (Lecca et al. 2011; Yalew et al. 2012). Alternatively, SWAT and R codes can also run as web processes capable of remotely running all necessary steps of hydrological modeling: from data acquisition, basin delineation, model calibration, to spatial map representations. This promising way of chaining web processing services will be explored in a forthcoming study.

The overall objective of this work was to address the applicability of the freely available data and open source software for hydrological research. The conclusions drawn from our case study on the Mendoza catchment are that model generated runoff has a very close match with the measured runoff. Based on visual observations (Fig.3) and the statistical performance (NSE=0.69, R^2=0.72 and PB=9%) the open source SWAT model with globally available and freely accessible data can be utilized for addressing various environmental issues in Mendoza, especially those linked with river discharge. Making freely available data interoperable, as well as the outputs of developed models, would certainly represent an important step towards removing barriers to data availability, accessibility, and integration. This would greatly facilitate storage, diffusion and exchange of hydrological data, allowing faster and easier updates, fostering new collaboration and cooperation between various scientific disciplines, potentially allowing better understanding and interconnections of water-related processes. In this study, we demonstrated that data extraction and hydrological model implementation and calibration could be obtained from freely available data and open source packages. This methodology will be particularly important and useful in data sparse region or in large transboundary catchments to address for instance water sharing issues.

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6 Innovation and relevance, conclusions, limitations and recommendations for future research

Innovation and relevance

Due to the combined effects of natural variability and anthropogenic influence, it is often difficult to simulate streamflow in complex watersheds. The existing studies conducted in the Rhone basin typically focused only a certain portion of its area. The majority of the previous studies was conducted in small high altitude sub basins and was focusing on snow and glacier melt. To date, there were no model reported that integrated the entire range of complexity and simulate the flow until the downstream part of the watershed (Porte du Scex). Therefore, this research gave an added value to understand the flow simulation process of the entire watershed.

Furthermore, SWAT, being a very intensively used model worldwide, many possible extension of its used are being developed by other research groups. SWAT already include routines for water quality, agriculture practices and sediment transport. New extensions are being developed to connect it groundwater models or regional climate models. Thus, the SWAT calibrated model of the Rhone river is already providing a better understanding of the inflow into the Lake Geneva, since the upper Rhone is its major tributaries, with many possible extensions in the future. For instance, the evaluation of the flow components and their contribution will add value to the species distribution modeling. Based on the forecast studies, considering the uncertainty, it is validated that the flow regime will be changing in the Rhone River. There will be an early snow and ice melt, and a relative reduction of summer discharge. Therefore, the findings can help improving water management especially in the fields of hydropower, agriculture, tourism and drinking water supply.

Conclusions

Chapter: 1

Chapter 1 described the development of a hydrological model for the Rhone watershed and the complexities that arises due to both natural and anthropogenic influences.

High altitude watersheds possess complex hydrological behaviors. Among the various complexities, orographic precipitation and the lapse rate of precipitation and temperature are notable. Moreover, water transfer through pipeline networks makes hydrological modeling even more difficult. We need a dense network of observations to understand the physical processes, but in reality the observation network is much smaller compared to that of the floodplains. Obtaining information through hydrological modeling in mountainous watersheds requires detailed information. With this study, we succeeded in building a hydrological model which is capable to capture runoff patterns similar to that of observations. The major challenges were to implement the hydropower reservoirs and the water transfer issues in the model. Information obtained from the ALPIC Hydropower Company helped us to regenerate capturing points in the model. In addition to sufficient observation networks, calibration is an essential part of hydrological modeling. Without calibration, the model output is useless for decision making because the model can give ambiguous and misleading results. Calibration can be tedious since it requires an extensive trial and error process. It is important to select the important/sensitive parameters for calibration in order to minimize the trial and error process. We first tried to understand the sensitivity of the model performance by choosing parameters linked with snow and glacial melt processes. Since the hydrology of the Rhone watershed is driven by snow and glacier melts runoff, it is apparent that these parameters would be sensitive when reproducing the hydrograph. Together with manual calibration, we used a genetically adaptive search algorithm (AMALGAM) which determines the ranges of parameters that are responsible for simulated graph fitting with the observations. The close fit between the simulated and observed runoff can be seen in both the daily and monthly time steps. Nonetheless one limitation was that we could not capture the sub-daily peaks. The overall objective of this work was to build a hydrological model which would be used later for scenario analysis of streamflow changes due to land-use and climatic changes.

Therefore, we did not emphasize hourly peaks. The information obtained can be useful for reproduction of runoff in multiple outlets and thus for a better understanding in water management, for example, downstream hydropower production and drinking water supply or ecological modeling of river biodiversity.

Chapter 2

Chapter 2 analyzed the application of regional climate model variables and their performance in simulating streamflow in the Rhone River watershed.

Regional climate model outputs are often used in hydrological modeling for simulating streamflow, especially in forecast studies because they can extrapolate the climatic variables based on observation. It is important to analyze their performance because incorrect input can generate misleading results in hydrological model's output. Mountainous watersheds are quite complex because of multifarious topography and interaction between various processes such as orographic precipitation, snow and glacier melt. An attempt to test the performance of climate model generated variables, more specifically how well they can produce runoff in the Rhone River watershed was undertaken. The objective was to examine if there is any systematic under or over estimation that the climatic models yield. Four Regional Climate Models (RCMs) were chosen from the PRUDENCE project. A total of 30 years (1960-1990) of daily data was selected for the analysis. The PRUDENCE based data set mainly consisted of two time slices, one an observation that covers 1960 to1990 and the other a forecasted timeline from 2070 to2100. The data originates from the Danish Meteorological Institute (DMI), the Swedish Meteorological and Hydrological Institute (SMHI), the Norwegian Meteorological Institute (METNO) and the Italian Climate Model (ICTP). Precipitation, temperature (daily min and max) and wind speed were analyzed through a tailor-made diagram. First the hydrological model was calibrated with the observed meteorological data and later the climate model-generated variables were fed into the model. A daily time step was used to do the analysis since the observation occurred on a daily basis. Results suggest that variables generated by the DMI produce similar patterns of hydrographs, but the others (ex. METNO, SMHI) were not able to provide this. Therefore, our recommendation is to test the variability of climatic model outputs before implementing it into hydrological models for impact studies.

Chapter 3

Chapter 3 examined the quantification of streamflow contribution and its dynamics in a small, high altitude catchment in the Rhone River watershed.

It is particularly important to know the quantification of each of component in a hydrograph of a mountainous watershed because the downstream ecosystem is linked with the upstream discharge. we quantified streamflow components based on tracer analysis and field measurement of discharge. Considering hydropower based energy production it is more likely significant because the glacier melted water supplies the inflow in the reservoirs. If we can have a better understanding of the flow generation process we can have better plans for water management, especially in a changing climate. Together with the hydropower based energy production, biodiversity is also important since species distribution is also linked with the type of water and its chemical characteristics. Tracer based mixing analysis is a widely accepted method for flow component separation in time and space. We used End Member Mixing Analysis (EMMA) to better understand the sub-daily variation of flow components. At first, the flow samples were collected and their ion analysis was effectuated in order to characterize their chemical composition. Grouping was done to characterize the sources based upon the physical and chemical features (e.g. silica sulfate, electric conductivity and temperature). The analysis was based two hydrological years (1997 and 2010) and it is visible that the glacier melt component could vary dynamically in one day from the morning to the evening. Additionally, the amount of glacier melted water was less in the recession period of the melting season. In comparison with the monthly mean average discharge downstream it was discovered that the flow decreased at the end of melt season (August to September). Although two years of data is not statistically consistent, it allows us to have a better understanding of the flow process and its relative changes. Information obtained from this study can be useful for the species dependency of the type of water and their existence due to climatic change.

Chapter 4

Chapter 4 investigated the sensitivity of streamflow due to land-use and climate changes in the upper Rhone River watershed

Analysis of flow regime changes is imperative for better water management planning. Land-use and climate play an important role in modifying the flow regime. In order to test the sensitivity of climate and land-use changes in the Rhone River watershed, scenario maps were generated based on two observation periods. The loss and gain of pixels was calculated considering the two of observation periods and the extrapolation was conducted based on the observation's relative changes. The business as usual scenario (A1B) was used to extrapolate changes for the future. The climate change scenario was generated based on a high resolution climate model (REMO) with a 25 km grid size. For bias correction of climatic data quantile mapping technique was used. An initial assessment was done to detect the outliers comparing with the observed precipitation and temperature. The sensitivity tests were done independently for land-use and climate changes. For the land use change the climatic data was kept constant [from 1981 to2010] and simulated simultaneously with land use maps generated for 2025 and 2050. A reduction of peak flow was forecasted due to land use change. Due to glacier loss and increased vegetation, the stream runoff was expected to reduce during the peak flow. While testing, the climate change impact assessment land-use map was kept constant. The model was simulated until 2050 and comparison was made for 2025 and 2050. A reduction in magnitude of peak flow along with a shift in peak flow could be predicted for climatic changes. The climate change variations were linked with temperature. Therefore, a rise in temperature will lead more melting. Finally, a combined effect predicted where the peak flow reduction in summer and a sign of early summer could be noticed. However, uncertainties are apparent due to the climate model output and reservoir operations. For the future forecast we kept the hydropower operation rules constant, as in the present-day, but due to change in energy demand scenarios the operational rules could be changed.

Chapter 5

Chapter 5 explores the possibility of building a hydrological model based upon freely available data and open source software.

Hydrological models are data driven. Based on the complexity of models the requirement of data can be of various types. Most often the data required for building a model can be grouped in two major groups, they are: spatial and non-spatial data, the spatial data can also be regrouped by two sub groups they are, raster and vector. In the raster group Digital Elevation Model (DEM) land use, soil map needed to build the model. In the vector group river geometry and other information like point sources, location of various infrastructures, etc. For non-spatial data, like meteorological inputs (e.g. precipitation, temperature) were also required to feed as in input. In this chapter an attempt was taken to build a hydrological model for Mendoza river watershed located in South America. The objective was to see how well the open source data can be utilized for simulating streamflow. The further objective is to see how we can calibrate the model. To ascertain the objectives, all the spatial and non-spatial data's were collected for various free available data sources. Since the calibration is a trial and error process, the iterations were done in open source programming tool 'R'. The lesson learned from this work is that we can build a model based on freely available data and open source software and reach to certain level of accuracy. However, some limitations are apparent they are: anthropogenic influence and heavy computation requirement. We need to provide information of the anthropogenic influences to have better calibration. The steps of model building were explained with online videos and the supplementary codes were given to utilize online resources. The information obtained from this wok can be useful in the data sparse region.

Limitations

- The glaciers were considered as reservoirs and the melt rate was correlated with temperature. Since this was a lumped way of converting glaciers into liquid water, a large uncertainty can arise.

- In the scenario analysis, a future energy-driven scenario should be added because energy consumption can change the hydropower operations based on future demand. This was not possible to include in this research work because generating a future energy scenario is highly uncertain.

- The End Member Mixing Analysis measurement was very limited because of limited access. Since the study site was only accessible during the summer, we could only acquire data during this season. Moreover, it was only possible to collect data from the upstream tributaries by going there in person. This was often difficult due to varying weather conditions. Therefore, our conclusions were mainly based upon the limited data that we could collect

- In the land-use change impact assessment, each component of the sensitivity analysis could give how significant is change due to change of each land use class (e.g. forest-glacier afforestation, - deforestation etc.)

- The best simulations are presented in the study, but a set of simulations with a certain extent of uncertainty could provide a better understating of flow behavior. This is especially the case in the high and low flow seasons.

- Some simplification was performed for water transfer issues. The secondary reservoir function was not implemented, but the exact information from this case could have led to a better model performance.

- The model was not able to simulate sub-daily functions since there was no hourly data from the hydropower reservoirs. Calibration performance improves with hourly data.

Recommendations for future research

- Computational requirements are very significant in detailed hydrological modeling. Therefore, faster and more efficient computation using High Performance Computing (HPC) could add value to the research by minimizing run time. For that, a parallel version of the script developed in this study could be designed for run time optimization.

- A detailed glacier subroutine could explain the glacier mass balance; therefore a new routine could be added with the source codes of SWAT focusing the accumulation and ablation of glacier melt.

- Snow melt and snow fall subroutine in SWAT need to be revised. In addition, a snow cover routine could help by providing information on the spatial extent of snow in the prevailing climate.

- Extensive discharge and chemical sampling could be done in the high altitude catchments (e.g. ‘Gletsch’) for the entire melt season in order to have better understanding of the flow generation process.

- The water temperature routine in SWAT was initially designed for tropical rivers which do not account for snow and glacier melt driven streams. The water temperature routine assumes that the temperature of water has linear relationship with air temperature, but for glacier melt driven streams there are other factors like the distance from the glacial rate of change and snow melt.

- Overall, there is a need for SWAT modeling in order to answer critical questions concerning mountainous watersheds. This could help to give a better understanding of the complex hydrological processes in high altitude catchments where an extensive modification of the source code is essential.

Appendix:

[A] SWAT calibration code in R environment

[B] PRUDENCE based netcdf data for climate scenario analysis

[C] MATLAB Script for flow separation

[D] MATLAB code for QDF curve preparation

[A] SWAT calibration code in R environment

```
#----------------------------------------------------------------------------------#
#                SWAT calibration in R Environment                #
#           EnviroSPACE Lab, University of Geneva            #
#                  Contact: kazi.rahman@unige.ch                  #
#----------------------------------------------------------------------------------#
```

 # Step 1: Execute SWAT2009

```
#system("swat2009.exe")
system("SWAT2012.exe")
```

 # Step 2: Read observed and simulated files

```
Qo<-read.table("obs7.txt")[,3]
Qs1<-read.table("output.rch",skip=9)
Qs<-Qs1[Qs1$V2==7,7]
```

 # Step 3: Calculate Model Performance Statistics

```
SSR<-sum((Qs-Qo)^2)
```

```
NS<-1-(SSR/(sum((Qo-mean(Qo))^2)))
PBIAS<-100*(sum(Qs)-sum(Qo))/sum(Qo)
SSR;NS;PBIAS
```

 # Step 4: Plotting Obs Vs Simulated relationship

```
Qo1<-Qo[c(1:2191)];
Qs1<-Qs[c(1:2191)];
vectory<-c(0,1.1*max(max(Qs1),max(Qo1)))
vectorx<-c(0,length(Qs1))
dates<-c("1/1/99","1/1/00","1/1/01","1/1/02","1/1/03","31/12/04")
date.ticks<-c(365,731,1096,1461,1826,2191)
plot(vectorx,vectory,type="n",xlab="Day",ylab="Discharge (cms)",axes=FALSE)
axis(1,at=date.ticks,labels=dates)
axis(2,at=NULL,labels=NULL)
#grid(nx=500,ny=100,col="lightgray",lty="solid")
lines(Qo1,lwd=2)
lines(Qs1,lwd=2,col='blue')
title("Obs Vs Simulated( SWAT) relationship",
    cex.main = 1,font.main=1,col.main= "black",)
legend(1500,450,"Observed Discharge",col='black',lwd=3,lty=1,bty="n")
legend(1500,420,"Simulated Discharge",col='blue',lwd=3,bty="n")
box(which='plot')
```

[B] PRUDENCE based netcdf data for climate scenario analysis

```
%--------------------------------------------------------------------%
%       NetCDF data extraction using MATLAB                          %
%       EnviroSPACE Lab, University of Geneva                        %
%       Contact: kazi.rahman@unige.ch                                %
%--------------------------------------------------------------------%
```

```
clear all;clc;
tic

LatLongRange = [45.82 47.46;5.3 7.68];% [min(latitude) min(longitude)]
StartYear = 1961;
EndYear = 1990;
DataDir = 'PRUDENCE_DMI_1961-1990_ZIPPED/HC1/UNZIPPED/';
%% Precipitation
ncid = netcdf.open([DataDir '/precip.DMI.HC1.nc'],'NC_NOWRITE');

[latlong latlongID] = GetLatLong(ncid,LatLongRange);
dlmwrite('ObsGrids.txt',latlong);
varID = netcdf.inqVarID(ncid,'precip');
data=netcdf.getVar(ncid,varID,'double');

for idx = 1:size(latlongID,1)
    iLatID = latlongID(idx,1);
    iLongID = latlongID(idx,2);
    for jdx = 1:size(data,3)
        t_PrecipData(jdx,idx) = data(iLatID,iLongID,jdx);
    end
end
PrecipData = [];
idx = 1;
jdx = 1;
NoData = -99;
for Yidx = StartYear:EndYear
    for Midx = 1:12
        ndays = eomday(Yidx,Midx);
```

```
        if ndays >= 30
            PrecipData(idx:idx+ndays-1,:) = ...
                NoData*(ones(ndays,size(latlongID,1)));
            PrecipData(idx:idx+30-1,:) = t_PrecipData((jdx-
1)*30+1:jdx*30,:);
        else
            PrecipData(idx:idx+ndays-1,:) = ...
                t_PrecipData((jdx-1)*30+1:(jdx-1)*30+ndays,:);
        end
        jdx = jdx + 1;
        idx = idx + ndays;
    end
end

        % WRite precipitation input files for each station
for idx = 1:size(PrecipData,2)
    fid = fopen(['pcpstn' num2str(idx) '.txt'],'w');
    fprintf(fid,'19610101\r\n');
    for jdx = 1:size(PrecipData,1)
        fprintf(fid,'%.1f\r\n',PrecipData(jdx,idx));
    end
    fclose(fid);

end
%% Temperature
clear data
ncid = netcdf.open([DataDir '/t2max.DMI.HC1.nc'],'NC_NOWRITE');

[latlong latlongID] = GetLatLong(ncid,LatLongRange);
varID = netcdf.inqVarID(ncid,'t2max');
data=netcdf.getVar(ncid,varID,'double');
data = data - 273.15;
for idx = 1:size(latlongID,1)
    iLatID = latlongID(idx,1);
    iLongID = latlongID(idx,2);
    for jdx = 1:size(data,4)
        t_TmaxData(jdx,idx) = data(iLatID,iLongID,jdx);
    end
end

clear data
ncid = netcdf.open([DataDir '/t2min.DMI.HC1.nc'],'NC_NOWRITE');

[latlong latlongID] = GetLatLong(ncid,LatLongRange);
varID = netcdf.inqVarID(ncid,'t2min');
data=netcdf.getVar(ncid,varID,'double');
data = data - 273.15;
for idx = 1:size(latlongID,1)
    iLatID = latlongID(idx,1);
    iLongID = latlongID(idx,2);
    for jdx = 1:size(data,4)
        t_TminData(jdx,idx) = data(iLatID,iLongID,jdx);
    end
end

TmaxData = [];
TminData = [];
idx = 1;
jdx = 1;
NoData = -99;
```

```
for Yidx = StartYear:EndYear
    for Midx = 1:12
        ndays = eomday(Yidx,Midx);
        if ndays >= 30
            TmaxData(idx:idx+ndays-1,:) = ...
                NoData*(ones(ndays,size(latlongID,1)));
            TmaxData(idx:idx+30-1,:) = t_TmaxData((jdx-1)*30+1:jdx*30,:);
            TminData(idx:idx+ndays-1,:) = ...
                NoData*(ones(ndays,size(latlongID,1)));
            TminData(idx:idx+30-1,:) = t_TminData((jdx-1)*30+1:jdx*30,:);
        else
            TmaxData(idx:idx+ndays-1,:) = ...
                t_TmaxData((jdx-1)*30+1:(jdx-1)*30+ndays,:);
            TminData(idx:idx+ndays-1,:) = ...
                t_TminData((jdx-1)*30+1:(jdx-1)*30+ndays,:);
        end
        jdx = jdx + 1;
        idx = idx + ndays;
    end
end
        % WRite temperature input files for each station
for idx = 1:size(TmaxData,2)
    fid = fopen(['tmpstn' num2str(idx) '.txt'],'w');
    fprintf(fid,'19610101\r\n');
    for jdx = 1:size(TmaxData,1)
        fprintf(fid,'%.1f,%.1f\r\n',TmaxData(jdx,idx),TminData(jdx,idx));
    end
    fclose(fid);
end
%% Wind Speed
clear data
ncid = netcdf.open([DataDir '/w10m.DMI.HC1.nc'],'NC_NOWRITE');

[latlong latlongID] = GetLatLong(ncid,LatLongRange);
varID = netcdf.inqVarID(ncid,'w10m');
data=netcdf.getVar(ncid,varID,'double');

for idx = 1:size(latlongID,1)
    iLatID = latlongID(idx,1);
    iLongID = latlongID(idx,2);
    for jdx = 1:size(data,4)
        t_WindData(jdx,idx) = data(iLatID,iLongID,jdx);
    end
end

WindData = [];
idx = 1;
jdx = 1;
NoData = -99;
for Yidx = StartYear:EndYear
    for Midx = 1:12
        ndays = eomday(Yidx,Midx);
        if ndays >= 30
            WindData(idx:idx+ndays-1,:) = ...
                NoData*(ones(ndays,size(latlongID,1)));
            WindData(idx:idx+30-1,:) = t_WindData((jdx-1)*30+1:jdx*30,:);
        else
            WindData(idx:idx+ndays-1,:) = ...
                t_WindData((jdx-1)*30+1:(jdx-1)*30+ndays,:);
        end
        jdx = jdx + 1;
```

```
        idx = idx + ndays;
    end
end

 % WRite Wind input files for each station
for idx = 1:size(WindData,2)
    fid = fopen(['wndstn' num2str(idx) '.txt'],'w');
    fprintf(fid,'19610101\r\n');
    for jdx = 1:size(WindData,1)
        fprintf(fid,'%.1f\r\n',WindData(jdx,idx));
    end
    fclose(fid);
end
%%
time=toc
```

```
function [latlong latlongID]= GetLatLong(ncid,LatLongRange)
latID = netcdf.inqVarID(ncid,'lat');
longID = netcdf.inqVarID(ncid,'lon');
lati = netcdf.getVar(ncid,latID,'double');
long = netcdf.getVar(ncid,longID,'double');
idx = 1;
LatRange = LatLongRange(1,:);
LongRange = LatLongRange(2,:);
for i = 1:size(lati,1)
    for j = 1:size(lati,2)
        if lati(i,j) > LatRange(1) && long(i,j) > LongRange(1) && ...
                lati(i,j) < LatRange(2) && long(i,j) < LongRange(2)
            latlongID(idx,:) = [i j];
            latlong(idx,:) = [lati(i,j) long(i,j)];
            idx = idx + 1;
        end
    end
end
```

[C] MATLAB Script for flow separation

%---%

% MATLAB Script for flow separation %

% EnviroSPACE Lab, University of Geneva %

% Contact: kazi.rahman@unige.ch %

%---%

```
% clear all;
clc;close all;
fclose all;
global InputFileName
InputFileName = 'DATA_26July11.csv';
% Load the complete data
[station year month code idate ampm temp cond no3 so4 cl si tur ss Q]...
    = textread(InputFileName,'%s%s%s%s%s%s%f%f%f%f%f%f%f%f%f',...
    'headerlines',2,'delimiter',',');

% Enter the year for which the analysis will be performed
indata.SimYr = 2010;

% Enter the station ID where the EMMA analysis will be performed
indata.MainStation = 'M4';

% Gradual flow station IDs
indata.GLStations = {'T4','T5'};%,'T2'};

% Quick flow station IDs
indata.QFStations = {'T3'};%,'T4','T5'};

% Glacial flow station IDs
indata.GFStations = {'M1'};

indata.AllStations = [indata.MainStation indata.GLStations ...
    indata.QFStations indata.GFStations];
% Time of the day
indata.TODList = {'mor','aft'};%mor or aft

% GL QF and GF string: string that stores the abbreviation to these
% different flows that will be used later in the analysis
indata.GQF = {'GL','QF','GF'};
indata.GQFLabel = {'Gradual Flow','Quick Flow','Glacial Flow'};

% Threshold percentage to select the eigenvectors for morning and afternoon
% separately
indata.ThresPerc = [80 99];%[morning afternoon]
```

```
for TODidx = 1:length(indata.TODList)
    [ProjData TData HydrSepData DateVector] = EMMAcalc(indata,TODidx);
    TOD = indata.TODList{TODidx};
    figure(1);

subplot(2,1,TODidx),plot(ProjData(:,1),ProjData(:,2),'bo','MarkerSize',5,'M
arkerFaceColor','b');
    hold on;
    plot(TData(:,1),TData(:,2),'k-s','MarkerSize',5,'LineWidth',2);
    for i = 1:size(TData,1)-1
        text(TData(i,1),TData(i,2)+1,indata.GQF{i});
    end
    xlabel('U1','FontWeight','bold','FontSize',16);
    ylabel('U2','FontWeight','bold','FontSize',16);

    figure(2);
    colormap summer;
    subplot(2,1,TODidx),bar(HydrSepData,'stacked')
    DateStr = [];
    xdates = cellstr(datestr(datenum(DateVector),'dd-mmm'));
    set(gca,'xticklabel',xdates,'YLim',[0 1.5]);
    xlabel(['Year ' num2str(indata.SimYr)],'FontWeight','bold');
    if TODidx == 1
    text(1,.5,'Morning','FontSize',12,'FontWeight','bold');
    elseif TODidx == 2
        text(1,.5,'Afternoon','FontSize',12,'FontWeight','bold');
    end
    legend(indata.GQFLabel)
    ylabel('Component Discharge (m^3/s)','FontSize',14)
    eval(['Fig2data.' TOD '= HydrSepData']);
    eval(['Fig2data.' TOD '= ProjData']);
end
```

```
function [ProjData TData HydrSepData DateVector] = EMMAcalc(indata,TODidx)
global InputFileName
% Load the complete data
[station year month code idate ampm temp cond no3 so4 cl si tur ss Q]...
    = textread(InputFileName,'%s%s%s%s%s%s%s%f%f%f%f%f%f%f%f',...
    'headerlines',2,'delimiter',',');

AllStations = indata.AllStations;
TODList = indata.TODList;
GQF = indata.GQF;
SimYr = indata.SimYr;
ThresPerc = indata.ThresPerc(TODidx);
MainStation = indata.MainStation;
GLStations = indata.GLStations;
QFStations = indata.QFStations;
GFStations = indata.GFStations;

TOD = TODList{TODidx};
dateflag = 0;
```

```
for sidx = 1:length(AllStations)
    tloc = strfind(station,AllStations{sidx});
    tidx = 1;
    for idx = 1:length(tloc)
        if tloc{idx}==1
            if SimYr == 1997
                tdata = [so4(idx) si(idx) cl(idx)];
            elseif SimYr == 2010
                tdata = [so4(idx) si(idx) tur(idx)];
            end

            CurrYr = strfind(year(idx),['Y' num2str(SimYr)]);
            TODfind = strfind(ampm{idx},TOD);
            if sum(isnan(tdata)) == 0 && size(CurrYr{1},1) == 1 && ...
                    size(TODfind,1) == 1
                if sidx == 1 && ~isnan(Q(idx)) == 1
                    Outdata(tidx,:) = tdata;
                    fdata(tidx,1) = Q(idx);
                    if dateflag == 0
                        DateVector = idate(idx);
                        dateflag = 1;
                    else
                        DateVector = [DateVector,idate(idx)];
                    end
                    tidx = tidx + 1;
                elseif sidx > 1
                    Outdata(tidx,:) = tdata;
                    tidx = tidx + 1;
                end

            end
        end
    end

    eval(['data.' AllStations{sidx} '=Outdata;']);
    clear Outdata;

end

% Club the data for gradual flow, quick flow, and glacial flow to calculate
% the median of these flow

for idx = 1:length(GQF)
    eval(['FData.' GQF{idx} ' = [];']);
    fstring = [GQF{idx} 'Stations'];
    for jdx = 1:length(eval(fstring));
        eval(['FData.' GQF{idx} ' = [FData.' GQF{idx} ';data.'
eval([fstring '{jdx}']) '];']);
    end
    sourcedata(idx,:)  = median(eval(['FData.' GQF{idx}]));
end


for i = 1:size(eval(['data.' MainStation]),1)
    tdata = eval(['data.' MainStation]);
    stddata(i,:) = (tdata(i,:)-mean(tdata))./std(tdata);
end

% Data from the sourcedata
```

```
% Load fiel with the source data information
% sourcedata = load('OrgHillGWHopper.txt');
for i = 1:size(sourcedata,1)
    stdsourcedata(i,:) = (sourcedata(i,:)-mean(eval(['data.'
MainStation]))./std(eval(['data.' MainStation]));
end

rhodata = corr(stddata);
[v,d] = eig(rhodata);

for i = 1:length(v)
    eigvalues(i) = d(length(v)+1-i,length(v)+1-i);
    eigvector(:,i) = v(:,length(v)+1-i);
end
eigperc = eigvalues./sum(eigvalues)*100;
cumeigperc = cumsum(eigperc)

teigvector = eigvector';

ProjEM = (teigvector*stdsourcedata')';

NumEigVectors =  find(cumeigperc > ThresPerc, 1 );
vselect=teigvector(1:NumEigVectors,:);

% EM slope and intercepts
ProjEMPick = ProjEM(:,1:NumEigVectors);
A = [ones(1,size(ProjEM,1));ProjEMPick'];
TData = [ProjEMPick;ProjEMPick(1,:)];
for i = 1:size(ProjEMPick,1)
    try
    y2 = TData(i+1,2);
    catch
        disp('error');
    end
    x2 = TData(i+1,1);
    y1 = TData(i,2);
    x1 = TData(i,1);
    Slope(i) = (y2-y1)/(x2-x1);
    Intercept(i) = (x2*y1-x1*y2)/(x2-x1);
end

% U1star modified so that it suits the order of projection during the
% process of Constrained proportions" below
Slope = [Slope(2:end) Slope(1)];
Intercept = [Intercept(2:end) Intercept(1)];

Ainv = inv(A);

ProjData = (teigvector*stddata')';

ProjData2 = [ones(size(ProjData,1),1) ProjData(:,1:NumEigVectors)];

% Unconstrained proportions
UncEMProp = (Ainv*ProjData2')';

% Projection of points onto Triangle
U1 = ProjData(:,1);
U2 = ProjData(:,2);
for i = 1:size(Slope,2)
```

```
    U1star(:,i) = (U1 + Slope(i)*(U2-Intercept(i)))/(1+Slope(i)^2);
end

% Constrainted proportions

for i = 1:size(UncEMProp,1)
    AllMat = 1:(NumEigVectors+1);
    negloc = find(UncEMProp(i,:)<0);
    AllMat(negloc) = [];

    if size(negloc,2) > 0
        ConsEMProp(i,negloc) = 0;
        for idx = 1:length(AllMat)
            if idx == 1
                tidx = 2;
            elseif idx == 2
                tidx = 1;
            end

            ConsEMProp(i,AllMat(idx)) = ...
                (ProjEM(AllMat(tidx))-U1star(i,negloc))/...
                (ProjEM(AllMat(tidx))-ProjEM(AllMat(idx)));


        end

    else
        ConsEMProp(i,:) = UncEMProp(i,:);
    end
end

for idx = 1:size(ConsEMProp,2)
    HydrSepData(:,idx) = ConsEMProp(:,idx).*fdata;
end
```

[D] MATLAB code for QDF curve preparation

```
%% Discharge Duration Frequency (QDF) curve
% Contact: kazi.rahman@unige.ch

% Equation
% P = 100 * [ M / (n + 1) ]

% P = the probability that a given flow will be equaled or exceeded (% of
time)
% M = the ranked position on the listing (dimensionless)
% n = the number of events for period of record (dimensionless)
```

```
%------------------------------------------------------

AllFlowDay=load('4Stations.txt');
SortAllFlow = sort(AllFlowDay,'descend');
figure(1)
for idx = 1:size(SortAllFlow,1)
    for jdx = 1:size(SortAllFlow,2)
        PercRankAllFlow(idx,jdx) = 100*idx/(size(SortAllFlow,1)+1);
    end
end
plot(PercRankAllFlow(:,1),SortAllFlow(:,1),'r-','LineWidth',1);
%plot(SortAllFlow(:,1),PercRankAllFlow(:,1),'r-','LineWidth',1);
xlabel('% Exceedance');
ylabel('Flow (m^3/s)');
hold on
%plot(SortAllFlow(:,2),PercRankAllFlow(:,2),'r-','LineWidth',2);
%plot(SortAllFlow(:,3),PercRankAllFlow(:,3),'b-','LineWidth',1);
%plot(SortAllFlow(:,4),PercRankAllFlow(:,4),'b-','LineWidth',2);
legend('QDF Curve');
```