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Exploration of land-use scenarios for flood hazard modeling – the case of Santiago de Chile

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Abstract

Urban expansion leads to modifications in land use and land cover and to the loss of vegetated areas. These developments are in some regions of the world accelerated by a changing regional climate. As a consequence, major changes in the amount of green spaces can be observed in many urban regions. Amongst other dependences the amount of green spaces determines the availability of retention areas in a watershed. The goal of this research is to develop possible land-use and land-cover scenarios for a watershed and to explore the influence of land-use and land-cover changes on its runoff behavior using the distributed hydrological model HEC-HMS. The study area for this research is a small peri-urban watershed in the eastern area of Santiago de Chile.

Three spatially explicit exploratory land-use/land-cover scenario alternatives were developed based on the analysis of previous land-use developments using high resolution satellite data, on the analysis of urban planning laws, on the analysis of climate change predictions, and on expert interviews. Modeling the resulting changes in runoff allows making predictions about the changes in flood hazard which the adjacent urban areas are facing after heavy winter precipitation events. The paper shows how HEC-HMS was used applying a distributed event modeling approach. The derived runoff values are combined with existing flood hazard maps and can be regarded as important source of information for the adaptation to changing conditions in the study area. The most significant finding is that the land-use changes that have to be expected after long drought periods pose the highest risk with respect to floods.

1 Introduction

Processes visible in a large number of urban agglomerations are changes in land use in the urban area and towards the urban periphery. The first important determinants of land-use and land-cover (LULC) changes in this context are population growth and urban planning decisions that influence the expansion of built-up areas towards the periphery. The second factor is a changing local and regional climate that is currently observable in vast parts of the world and that is predicted to be further intensified in the future. That results in modified ecosystem conditions: Extended drought periods as one example of future climate change provide less favorable growth conditions for plants and thus diminish the amount of green vegetation. Higher irrigation efforts or cooler climate would lead to an increase in green spaces.

This study takes Santiago de Chile as an example as this fast-growing urban environment was subject to the Helmholtz-funded project *Risk Habitat Megacity* in which this research is embedded. This area is currently further investigated upon in the scope of the project ClimateAdaptationSantiago funded by the German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety.

Previous studies showed that land use and land cover significantly influence the runoff behavior in a watershed (Naef et al., 2002; Niehoff et al., 2002). The smaller the basin area, the more important the spatial pattern of these land-use changes with respect to the generation of runoff (Poelmans et al., 2010). If transferred to practice, model results can form a valuable decision making aid in the context of urban planning and flood risk management. Changes in LULC that are currently taking place in Santiago de Chile and that are expected to continue occurring in the future were so far only evaluated by Fuentes and Romero (2007). Even though this study delivers valuable insights into the changes taking place in the urban part of the catchment, this study does primarily focus on current runoff coefficients and does not yet make any predictions about the future. Planning decisions in Santiago de Chile in fact require some type of environmental impact analysis, but these assessments are performed on a large scale and do focus on the analysis of single lots rather than considering the system behavior of an entire watershed. This study overcomes this gap for a specific study area and proposes a scenario-based modeling approach to analyze the impacts of possible future land-use changes on flood hazard.

A variety of hydrological and hydraulic models are being used for flood hazard assessment in the framework of urban expansion (Knebl et al., 2005; Breuer et al., 2009; Im et al., 2009). However, no quantitative and spatially explicit studies about the impact of urban expansion and climate change in a peri-urban South American area were encountered that can be used as a decision making base for urban planners. It is shown in the scope of this study that the hydrologic model HEC-HMS with the standardized hydrological grid that was developed especially for the conterminous United States can also be transferred into other regions of the world. That enables the application of a freely available distributed hydrological modeling approach to model future land-use scenarios in a South American country and to quantify the impacts of ongoing urbanization and climate change on the flood hazard in a small peri-urban basin.

2 Description of the study area

2.1 Location and urban development in Santiago de Chile

Santiago de Chile is located in the central part of Chile between 32°55′ and 34°19′ S and 69°46′ and 71°43′ W. With approximately 6.7 million inhabitants (40% of the total population) it is the largest urban agglomeration of Chile (INE, 2008) and its capital city. From 1940 to 2002, the urban built-up body grew from 11 017 ha to 64 140 ha (Galetovic and Jordán, 2006). Urban expansion took place towards the natural areas of the Andean foothills but also in areas that had previously been used agriculturally, e.g. for the cultivation of vine and crops. Areas open for construction are defined by the Regional Development Plan of the Metropolitan Region of Santiago de Chile (PRMS). Thereby, it has to be distinguished between the normative limit set by the PRMS of which 69% is currently built-up area and the total physical built-up area (Galetovic and Poduje, 2006). Construction outside the normative limit can be permitted for housing and commercial projects with a maximum density of 150 inhabitants/ha in the Metropolitan Area. For that reason, the physical boundary, e.g. the area already covered with buildings and urban infrastructure has a larger extent than the official limits as defined by the PRMS. It is under debate whether or not the currently valid maximum elevation for construction should be set higher than 1000 m. That would result in another spatial extension and in a loss of biodiversity and retention areas amongst others. As expected, the main driver for that discourse is the pressure on the land market and profitable land prices (Reyes Paecke, 2003). Construction is already possible above the 1000 m limit (*cota mil*) if the usage is neither residential nor industrial. The protection of ecologically valuable areas is legally being ignored in such cases.

2.2 Physical characteristics

The in-depth study area for this research is the catchment of the Ramón River (Fig. 1) with a size of around 36.72 km^2 and a river length of 12.60 km. The highest point in the catchment is the Cerro San Ramón with an elevation of 3253 m; the medium elevation is 1400 m (AC Ingenieros, 2008). At an elevation between 1450 and 1650 m material from a quaternary mass movement is deposited, resulting in a very flat slope in that area. Slopes outside that part vary between 10° and 30°. Mass movements and erosion have previously been and still are frequent phenomena in the study area. That results in patches with accumulated material (Stumpf, 2009) (Fig. 1).

Only little information and no maps about the soils in the San Ramón catchment are available (Stumpf, 2009). Field studies showed that the soils in the catchment are to a large part just developing and do not yet show distinct horizons. Therefore, the main soil information is directly taken from the geomorphologic map.

The Metropolitan Region of Santiago de Chile has a subtropical climate with hot and dry summers (November to March) and heavy periodic rainfalls during the colder winter months (May to August) (Weischet, 1970). The average rainfall at a central station located at 560 m is 332.3 mm compared to 442.9 mm at a peri-urban station located in the eastern part of the city at 920 m a.s.l. (own calculations of rainfall statistics between 1979 and 2007). Almost every longer or intense rainfall event leads to floods in at least some parts of the city. Precipitation from above 1500 m is likely to fall as snow (Dirección Meteorológica, 2009). However, that might change with a rising snowline.

2.3 The role of climate change in the study area

Climate change studies based on the scenarios A2 and B2 developed by the Intergovernmental Panel on Climate Change (IPCC, 2007) predict a general reduction of precipitation and increase in temperatures in the central region of Chile (Bárcena et al., 2009). At the same time, the probability of hydro-meteorological extreme events, droughts as well as floods, increases clearly. Even though the total number of extreme precipitation events will decrease, respective events will become more threatening as the amount of rainfall will increase with an increasing height of the 0 °C-isotherm (Bárcena et al., 2009; Perez, 2009).

3 Data base and data preparation

Table 1 provides an overview about available data sets for the study.

Runoff [m^3 s^{-1}] and precipitation [mm] values are required as input for the application of the hydrological model HEC-HMS. Available runoff data however are not considered being reliable and have therefore been omitted for the analysis. Rainfall data at a temporal resolution of 1 h were available from a station closed to the Ramón basin. HEC-HMS requires input data without data gaps. For the modeling process, only periods with significant precipitation (above 65 mm per event) are being considered as the focus is laid on simulating runoff after extreme events. Thus, events were selected both after amount of rainfall and data availability.

To derive information about LULC, ASTER satellite data were pre-processed and interpreted using a supervised pixel-based image classification approach (Richards, 1999). The result of the image analysis are tables and maps for 2002, 2005, and 2009 containing the amount and spatial distribution of the seven hydrologically relevant LULC classes in the San Ramón basin (Table 2).

4 Hydrological modeling

The hydrological model HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) is a conceptual deterministic basin model that was developed by the hydrologic engineers of the US Army Corps of Engineers (USACE). It has mainly been applied for urban flooding studies, flood-frequency studies, flood-loss reduction studies, flood-warning system planning studies, reservoir design studies, and environmental studies in the USA (Ford, 2008, p.vii). In this study it is applied to simulate the relationship between precipitation and runoff in the catchment of the San Ramón River. Figure 2 provides an overview about the basin area and the derived subbasins.

4.1 Selection of methods

The analysis of the influence of LULC changes on runoff generation clearly requires an approach with a spatial reference that is as explicit as possible (compare Poelmans et al., 2010). Thus, a distributed or semi-distributed modeling approach was found to be most appropriate. HEC-HMS is a lumped basin model but has one component that supports a distributed approach: The empirical and distributed gridded Soil Conservation Service (SCS) curve number (CN) loss method that works on a grid basis. The CN method was developed by the Natural Resources Conservation Service (NRCS, formerly known as Soil Conservation Service SCS) and is a quantitative descriptor of the land-cover/soil complex. This information can be derived from remote sensing data (Tekeli et al., 2007; Slack and Welch, 1980) in combination with soil or geology data. The CN values take the land-cover type, treatment (especially relevant for agricultural studies), the hydrologic conditions, antecedent runoff conditions and the Hydrological Soil Groups (HSG) into consideration (USDA, 1986). While only few input data are required, one of the limitations is that it does not consider time and rainfall duration or intensity (USDA, 1986). The resulting excess precipitation is transformed into runoff using the empirical ModClark method (Kull and Feldman, 1998). ModClark is a method based on the Clark hydrograph method that considers translation (movement of the

excess rainfall from origin to outlet) as well as attenuation (storage effects of excess rainfall) processes (Feldman, 2000, p.60). It is the only available option to be used for a distributed modeling approach in HEC-HMS. The Recession Baseflow model was chosen to simulate baseflow and the Muskingum Routing method was selected for the routing of the stream elements because it is the most accurate method that can be used with regard to data availability. No loss/gain method was defined.

4.2 Data processing using HEC-GeoHMS

In combination with the ESRI Spatial Analyst extension the modeling extension HEC-GeoHMS supports the development and derivation of hydrological and terrain data that can directly be used as input for HEC-HMS. Its functions and features comprise the visualization and storage of data, the terrain, and hydrological pre-processing of the digital terrain data.

Since a distributed modeling approach is used for this analysis, the elevation, LULC, and soil/geology data are required in grid format. The application of gridded data is based on the spatial reference of the standard hydrological grid (SHG). This is a predefined grid by the USACE for the conterminous United States with various cell sizes. In order to apply HEC-HMS outside this area all projection information associated with the available raster data (elevation data, land-use data, etc.) have to be deleted and replaced by Albers projection which is also used for the SHG (Universidad Politecnica de Catalunya, n.a.).

4.3 Delineation of Hydrological Soil Groups (HSG)

To estimate the surface runoff based on a certain LULC pattern in the basin, the gridded CN method was applied (USACE, 2003). That means that hydrological classes are defined through the concept of Hydrological Soil Groups (HSG). The groups are based on the minimum infiltration rate of the barren soil after prolonged wetting (Mockus et al., 2007; USDA, 1986). Four different types of HSGs exist (HSG A, HSG B, HSG C, HSG D), whereby the proportion of each of the four HSGs has to be defined for each land-use and soil class (Mockus et al., 2007). The main characteristics of the HSGs are:

- HSG Type A: Soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist of deep, well to excessively drained sand or gravel, and have a high rate of water transmission (greater than 0.30 in h^{-1}).
- HSG Type B : Soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (0.15–0.30 in h^{-1}).
- HSG Type C: Soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission (0.05–0.15 in h^{-1}).
- HSG Type D: Soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0–0.05 in h^{-1}) (Mockus et al., 2007).

Soil data are not available for the study area but a geologic/geomorphologic map was compiled by Stumpf (2009), compare Fig. 1. Based on the description of the geologic formations, the proportions of each hydrological soil group were estimated (Table 3).

A very low infiltration capacity, i.e. high runoff potential (HSG D = 90) is assigned to the class Rigid Bedrock Abanico Formation. Faults where rainfall is captured and stored are accounted for by setting the value for HSG A (high infiltration potential) to 10. Active and old alluvial deposits contain gravel and sand and in the eastern part of the basin they also contain sand, silt, and clay (Stumpf, 2009). They are therewith

highly to moderately permeable. The process of consolidation of the older deposits was accounted for by setting the HSG A value to 30 instead of 70 for active deposits.

The HSG B value was defined accordingly to reach 100 in sum (compare Table 3). The values for HSG A and B of the young alluvial deposits were set to 50 as this formation represents an intermediate stage of the two classes described beforehand. Old landslide deposits show a high proportion of sandy gravels with volcanic ashes and do therewith get a higher HSG A value of 70 and a complementary HSG B value of 30. The quaternary deposits in the Santiago basin show according to Stumpf (2009) a high proportion of alluvial, fluvial, lacrustine, and evaporitic deposits. The deformed quaternary deposits in the western part of the basin are therefore described with HSG A and B values of 50.

The HSG values for each LULC class were taken from literature (USDA, 1986). Table 4 describes the contents of each of the seven LULC classes derived from the ASTER satellite data with their hydrological properties expressed through the HSGs.

Based on these data, a CN theme in raster format can automatically be created using HEC-GeoHMS and the information as defined in Tables 3 and 4 (Atkinson, 2001).

A grid spatially matching the SHG has to be defined as a spatial reference for the further grid-based analysis using HEC-HMS. A cell size of 50 m was selected for the present analysis to generalize land-use information as little as possible and to still enable acceptable computing times.

4.4 Model parameterization

Before the provided model can be used for runoff estimation, its parameters need to be specified to fit the model to the local conditions of the watershed (Ford et al., 2008). The main model parameters were the different land-use scenarios, the elevation information and several physical basin and subbasin characteristics that were taken from literature or that were derived during the pre-processing steps.

4.5 Simulation

The simulation time frame covers the duration of the rainfall event and ends after the runoff values return to normal level. The model is run for eight precipitation events.

The events were initially selected based on the total amount of precipitation and the proximity to the dates for which LULC information was available. However, most important is the intensity of the rainfall. The time interval for the simulation runs is set to 1 h.

4.6 Sensitivity analysis

The sensitivity analysis is carried out to investigate the performance of the model under the condition of changing parameter values. That means that single parameters of the model are altered in a realistic range and that the resulting changes of the simulated runoff values are analyzed. The output of the model (discharge values) is in many cases evaluated using the Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970). However, as measured runoff values are not available at a reliable quality level, the output values are solely compared with modeling results from other studies in this catchment (AC Ingenieros, 2008; Perez, 2009). It was found that the model results are very well in line with the results obtained during the two recent reference studies.

This sensitivity analysis focuses on the parameters “Initial abstraction ratio” (I_a), “Retention scale factor”, and “CN grid” (input raster data) as changes in all other parameters are not considered being realistic and comprehensible. First, I_a was tested. A general finding is that the parameter influences the amount of the total and the peak discharge but not its time of occurrence. Changing the retention scale factor was considered being a potential parameter to improve the model performance but did not yield realistic results. The impact on the resulting runoff values is evaluated to be too high.

Finally, the sensitivity of the applied CN grid was tested. The CN grid values result from the same soil and geology information combined with different land-use patterns depending on the year of investigation. The test was carried out for the rainfall event on 22–23 May 2008 with a maximum precipitation of 46.75 mm. Table 5 shows the resulting differences in peak and total runoff for the same precipitation event under different LULC conditions.

This parameter is a very important variable as the land-use/land-cover scenarios are represented through changing LULC maps and consequently through updated CN grids. Thus, the obvious sensitivity of the model regarding this parameter is very well suited to fulfil the purpose of this investigation.

To optimize the model results, solely the initial abstraction ratio was modified as all other factors but the retention scale factor were physically defined or did yield credible results. This is supported by the fact that most discussion in literature focuses on the proper selection of values for I_a (Scharffenberg and Fleming, 2008; Mockus, 1972; Woodward et al., 2003).

5 Scenario development

Two main types of scenarios can be distinguished: Exploratory and normative scenarios (van Notten et al., 2003). In the current project, the aim is to show how flood risk-related conditions might change under certain (varying) circumstances, to ponder which development directions are possible and what implications they bring. Therefore, exploratory, forecasting scenarios are applied (van Notten et al., 2003). Scenarios can either be created intuitively or formal (van Notten et al., 2003). While the formal approach often uses quantitative knowledge or computer simulations as prediction method, the intuitive approach is more creative, based on discussions and qualitative knowledge (van Notten et al., 2003). Several interviews were conducted during field work to obtain expert knowledge from different perspectives about possible future urban development and relevant planning regulations were revised as the intuitive approach is meant to be used for this study.

Three different possible LULC scenarios (Scenario I to III) were developed for the San Ramón basin (Fig. 3). The spatial LULC patterns do thereby not follow an urban growth model or mathematical equations; they are rather pictures of possible developments that arose from field surveys, the analysis of the physiogeographic setting (aspect, slope, and elevation), conversations with the local population, and the analysis of the regulatory planning framework. The scenario alternatives were all developed with the intention to represent consequences of different types and intensities of urban expansion and regional climate change.

The envisaged time horizon for the scenarios is the year 2030. Scenario I refers to the impacts of the projected climate change in the study area that is regarded being a very realistic future development. Scenario II refers to the ongoing afforestation activities that could be observed during field stays. Even though afforestation in the study area requires substantial irrigation activities and the seedlings need special protection as they are otherwise destroyed by fauna living in the basin it is very relevant to qualitatively assess the possible impact of an increase in shrub and tree coverage. Scenario III finally assumes that the construction restrictions are lifted and that leisure or residential areas would develop in the central parts of the basin that are characterized by flat slopes. This is an alternative that is for legal restrictions not officially being discussed. However, interviews proofed that this option is regarded being realistic to a certain degree if the neo-liberal economy system and low ecological awareness are maintained.

Figure 3 illustrates the mentioned alternatives and provides quantitative information about the amount of LULC changes.

6 Results

6.1 Modeling the past events

As a reference, selected precipitation events from the past were simulated using HEC-HMS. The modelling results for these events are shown in Table 6.

6.2 Modeling alternative LULC scenarios

The simulation runs using the alternative LULC scenarios were carried out for the same precipitation events as listed in Table 6. All model parameters were left as initially defined, only the CN grid and consequently the initial abstraction ratio, both representing the new LULC pattern, were changed according to the new land-use patterns.

Table 7 summarizes the original model outputs based on the CN grids of the respective years and the results of the modeling process for Scenario I (dry conditions), Scenario II (afforestation), and Scenario III (construction).

6.3 The influence of runoff changes on flood hazard

It was lined out above that extreme precipitation events lead to floods in large part of the city. One of the most hazard-prone areas in Santiago de Chile is the San Ramón River in its lower regions where it has been canalized. The final step of the research is to relate the changing runoff levels to simulated flood hazard maps. Six specific flood hazard maps of the San Ramón channel available from a previous study were generated based on the following runoff volumes: 27.3 $\mathrm{m^3\,s^{-1}}$, 35.1 $\mathrm{m^3\,s^{-1}}$, 38.2 $\mathrm{m^3\,s^{-1}}$, 47.4 $\mathrm{m^3\,s^{-1}}$, 50.9 $\mathrm{m^3\,s^{-1}}$ and 64.6 $\mathrm{m^3\,s^{-1}}$ (Perez, 2009). To investigate the influence of changes in the runoff on the flood hazard, the existing hazard maps were related to the newly calculated runoff volumes. As a matter of fact, the new runoff values do not exactly match the runoff values on which the calculations of Perez (2009) were based. Nevertheless, a combination of both data sets delivers an insightful output. With an increase of the runoff values from 27.3 to 35.1 to 38.2 $\mathrm{m^3\,s^{-1}}$ the affected area changes from 188 to 214 ha (runoff + 7.8 $\mathrm{m^3\,s^{-1}}$) and from 214 to 217 ha (runoff + 3.1 $\mathrm{m^3\,s^{-1}}$) (Perez, 2009). Assuming higher discharge values the changes are accordingly: With an increase from 47.4 to 50.9 to 64.6 $\mathrm{m^3\,s^{-1}}$ the flooded areas (only outlines) would increase from 230 to 243 (runoff + 3.5 $\mathrm{m^3\,s^{-1}}$) and from 243 to 396 ha (runoff + 13.7 $\mathrm{m^3\,s^{-1}}$) (Perez, 2009). In addition, the water depth changes with an increasing amount of overflow (Perez, 2009). The changes are not linear but indicate that in that dense urban environment the damage would increase notably. The higher the absolute peak discharge values the higher the absolute changes in the spatial extent of the hazard zones with the same absolute increase in discharge. That means that the absolute changes are higher for high runoff values, i.e. low frequency events. The runoff volumes calculated for a changing land-use pattern are shown in Table 7. Taking the rainfall event from August 2005 as an example shows that the runoff would increase from 45.6 $m^3 s^{-1}$ to 49.2 $m^3 s^{-1}$ in Scenario I. That means an absolute increase of approximately 3.6 $m^3 s^{-1}$ and the areas affected only by the San Ramón channel would increase by approximately 13 ha. Even though this number seems not to be threatening at the first sight it is considerably high when referring back to the research area, i.e. a dense urban environment with a high density of people and values. In addition to the increase of the spatial extent of the affected areas, most of the flooded areas would face a higher water depth which requires more investments in measures to reduce the physical exposure and most likely results in longer duration of the floods. Furthermore, additional regions of Santiago de Chile are stronger affected by river floods from other creeks or by urban floods.

The impact is less for events with a lower return period, e.g. for the example of May 2008 (a) with a return period of two years. The runoff would increase from around 21.7 to 23.3 $m^3 s^{-1}$, i.e., by 1.6 m^3 s6−1. This would also increase the size of the affected areas and the water depths, but to a lower degree. The projected increase in precipitation intensity for the extreme events is in this analysis not yet incorporated.

7 Discussion

The application of the precipitation-runoff model HEC-HMS using a distributed modeling approach does for the first time in that study area quantitatively show how previous and possible future changes in land use and land cover influence the flood hazard. The chosen grid cell size of 50 m is small enough to account for a very good spatial representation of the current, previous, and future land-use patterns. Remote sensing

data from the ASTER sensor proofed to be a valuable data base for the time efficient and semi-automatic derivation of LULC information covering the entire catchment at various points in time. ASTER data and the meteorological data are low-cost data, the elevation and geologic data are available to most decision makers in the city.

The applied methodology can (i) be repeated at low costs if new data become available and can (ii) be comparatively easily be transferred to other regions of interest. The sensitivity analysis showed that the model reacts sensitive to changing LULC data. Consequently, the influence of LULC changes on the peak runoff volume can be explored and the new knowledge obtained can be regarded as a valuable and new aid in decision making for planners.

However, it has to be kept in mind that the modeling process remains a simulation of the reality. The main drawback of the applied modeling process is that the resulting data cannot be validated as no measured runoff data are available for that area at a sufficient level of quality. That means that the modeling error remains unknown. Assessing the results from the sensitivity analysis shows that the range of values varies by ±3%. The precipitation data used as model input have a temporal resolution of one hour, which is acceptable. Another deficit however is that the location of the snow line is not explicitly incorporated in the modeling process. Rather, significantly higher retention capacities are assigned to the two uppermost subbasins to account for snow storage. When precipitation falls as rain it directly infiltrates or runs off. If temperatures are low and the precipitation falls as snow above the 0 °C isotherm it behaves differently, i.e. it is stored on the surface and infiltrates or runs off with a temporal delay. The basin area contributing to the runoff is thus smaller during cold weather conditions. For further modeling processes in that area it should be included explicitly in the modeling process as the exact location of the snow line in combination with the precipitation intensity again influences the amount of runoff generated (Perez, 2009). The LULC pattern is incorporated in the model using the SCS CN method. This is a rather simple method and can thus be applied almost readily but it was developed for the use in the United States of America. A systematic investigation to adapt this method on the Chilean conditions is not known. The modeling results show that the calculated discharge values are well within a plausible range and comparable with other investigations. However, this research is not capable of certifying the validity of the approach in areas outside the United States as a proper validation of the runoff data could not be done. The results thus rely on the assumption that the CNs developed for the certain LULC types in the US are also valid for the LULC types in Chile.

Finally, it was shown that the model can be applied outside the conterminous US using a distributed approach despite the content-related challenges that are discussed above. In addition, there are some methodological challenges, i.e. the input data must fit into a standardized grid that is only defined and available for the conterminous United States. That means that the user needs to pretend to model a catchment located inside the United States. That does in no way affect the model output but it is cumbersome to transform all data (grid data as well as time series) in a way that they can be read by the model. In this scope it needs to be considered that HEC-HMS only accepts the DSS-format as input format which requires the application of specific data conversion software. This cannot directly be downloaded but can be requested by the HEC-HMS support team.

8 Conclusions

The changing land-use pattern in the basin – either man-made or resulting from a changing climate – impacts the runoff behavior in the basin after extreme precipitation events. An interpretation of the obtained results yields some interesting insights. The first modeled event, the rainfall event in July 2001, shows the lowest peak runoff values for the LULC pattern from 2002. As expected, increasingly dry conditions (Scenario I, compare Fig. 3) or construction activities in the basin (Scenario III) would increase the amount of surface runoff. But even Scenario II, representing the afforestation efforts currently going on in the basin, results in higher runoff values than during the original conditions from 2002. The reason is that – as a result of a changing environment –

Scenario II still contains less forested areas and bushland than it used to be present in the year 2002. Denser vegetation coverage than already contained in Scenario II, however, is not regarded being realistic with regard to the projected impact of climate change. The same conclusions apply for the rainfall events in May and June 2002 and for the storms in June and August 2005. Only for the events in 2008 and 2009, an improvement, i.e. a reduction of the total and peak runoff in comparison with the current conditions, could be achieved with Scenario II.

Another interesting finding is that the large-scale loss of vegetation due to increasing aridity would have an even more negative impact than construction activities in the central parts of the basin. The difference is not very large, but it can on this scale not be proven that potential future construction activities in the basin have a more negative impact on the runoff behavior than the expected impact of climate change. These results represent the negative impact of the ongoing changes in vegetation coverage in the basin. The types of construction assumed in Scenario III though are medium density residential areas with a large amount of private green spaces. The private green spaces associated with the potential building developments would be most likely irrigated and maintained thoroughly throughout the year. That offers a higher interception and infiltration potential than barren land as long as it compensates for the loss of infiltration capacities due to construction activities in the lots. Even though that seems at a first glance like a support for the development of settlements in the basin it should be clearly kept in mind which negative ecological consequences building development in that currently environmentally protected area would have.

To conclude, if precipitation events like the ones modeled in the scope of this research would reoccur, the maximum runoff value is in all scenario cases higher than in the original setting, partly as a result of changing land use and as a result of climate change. The influence of a changing LULC pattern will be further accelerated by a changing climate. As changing land-use patterns are - most obviously in Scenario I – strongly interlinked with a changing climate, the potential influence of a changing precipitation behavior should be explored in future studies. The increase predicted by

Perez (2009) in $P_{\max}$ is around 2% for a 2 year return period, 15% for a 5 year return period, 20% for a 10 year return period, 29% for a 50 year, and 31% for a 100 year return period in the case of B2. The changes are −3% for all return periods the scenario A2.

The conducted research makes clear that the peri-urban areas need to be strongly integrated into urban planning as they mainly influence the runoff regime of the rivers flowing into human settlements. The research makes clear that the main thread of land-use changes in the study area do not even result from human construction activities but from the expected impact of drier conditions. Thus, the planning activities should focus on afforestation and conservation of green spaces in the urban surrounding.

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Table 1. Overview about available data sets.

Content	Details
Precipitation data	Hourly precipitation data from Cerro Calán station, 2000–2010
Contour lines	1:50 000
Derived DEM	Derived from contour lines, resampled to 10 × 10 m
ASTER satellite data	Green, Red, and Near Infrared bands with 15 m geometric resolution, acquired on 2002/02/01, 2005/02/09, and 2009/02/04
Geologic map	Combination of geologic and geomorphologic information (Stumpf, 2009)

Table 2. Proportion of LULC classes in the San Ramón basin for February 2002, 2005, and 2009 as derived from the analysis of ASTER satellite data [km^2].

LULC class	2002	2005	2009
Dense built-up areas	0.01	0.01	0.01
Intermediate built-up areas	0.01	0.01	0.01
Water courses	0.22	0.23	0.22
Open rock	13.62	14.95	17.16
Barren land	7.83	7.88	10.07
Sparse vegetation	12.56	11.03	7.34
Woodland	1.56	1.70	1.00

Table 3. Geologic formations and hydrological soil groups. The columns PctA to PctD show the proportion of the four hydrological soil groups for each type of geologic formation accordingly.

Formation	Content	PctA	PctB	PctC	PctD
Rigid bedrock Abanico Formation	2000 m thick succession of basic to intermediate volcanic rocks	0	0	10	90
Old landslide deposits	Sandy gravels, volcanic ashes, and platy gravels	70	30	0	0
Active and old alluvial deposits	Stratified, moderately consolidated sediments	70	30	0	0
		30	70	0	0
Young alluvial deposits	Fluvial, colluvial, alluvial, and landslide deposits	50	50	0	0
Slope sediments	Dense, fine sand with clay	0	0	100	0
Intrusiva	Volcanic rock	0	0	0	100
Blockschutt	Blocks and gravel with finer soil material	100	0	0	0
Quaternary deformed	Alluvial, fluvial, lacustrine, evaporitic deposits	50	50	0	0

Table 4. Land-use/land-cover classes of ASTER classification results with their hydrological properties. The columns PctA to PctD show the proportion of the four hydrological soil groups for each LULC type accordingly.

Class	Content	PctA	PctB	PctC	PctD
Water bodies	Water courses, water bodies	100	100	100	100
Open rock	Barren surface without soil or vegetation coverage	98	98	98	98
Barren land	Barren surface with soil but without or minimal vegetation coverage	63	77	85	88
Sparse vegetation	Areas covered by shrubs, grasses, and small trees	55	72	81	86
Woodland	Forested areas with pine and eucalypt trees, little vegetation on soil	36	60	73	79
Dense built-up areas	Built-up areas with more than 70% imperviousness	81	88	91	93
Intermediate built-up areas	Built-up areas with more than 30% imperviousness	57	72	81	86

Table 5. The influence of the CN values on the model output at the example of the rainfall event on 22–23 May 2008.

Year	Total runoff [$m^3 s^{-1}$]	Peak runoff [$m^3 s^{-1}$]
CN grid 2002	23.95	19.6
CN grid 2005	24.75	20.3
CN grid 2009	26.25	21.7

Table 6. Modeling results for the San Ramón catchment.

			Input	Output		
Event	Dur. [h]	P_{max} [$mm\,h^{-1}$]	P_{max} [mm/24 h]	P_{total} [mm]	Q_{max} [$m^3 s^{-1}$]	Return Period
17–20 July 2001	47	6.75	75.00	104.50	38.50	10
25–28 May 2002	49	12.00	90.50	113.50	31.90	25
2–6 June 2002	51	13.25	161.25	243.00	73.50	100
27–29 June 2005	25	6.75	61.75	63.25	27.50	5
26–30 August 2005	48	10.25	89.25	148.00	45.60	25
22–23 May 2008	14	5.75	46.75	46.75	21.70	2
26–29 May 2008	38	4.50	38.25	55.00	14.70	2
5–8 September 2009	41	8.75	30.25	49.5	14.50	1

Table 7. Modeling results for the three LULC scenarios in the San Ramón catchment.

Event	$P_{\max}$ [mm/24 h]	Return period	Original Peak [$m^3 s^{-1}$]	Scenario I Peak [$m^3 s^{-1}$]	Scenario II Peak [$m^3 s^{-1}$]	Scenario III Peak [$m^3 s^{-1}$]
July 2001	75.00	10	38.5	41.5	39.6	41.3
May 2002	90.50	25	31.9	35.6	33.4	35.4
June 2002	161.25	100	73.5	78.5	75.4	78.2
June 2005	61.75	5	27.5	30.0	28.0	29.9
August 2005	89.25	25	45.6	49.2	46.2	49.0
May 2008 (a)	46.75	2	21.7	23.3	21.0	23.2
May 2008 (b)	38.25	2	14.7	15.4	14.3	15.3
September 2009	30.25	1	14.5	15.2	13.4	15.1

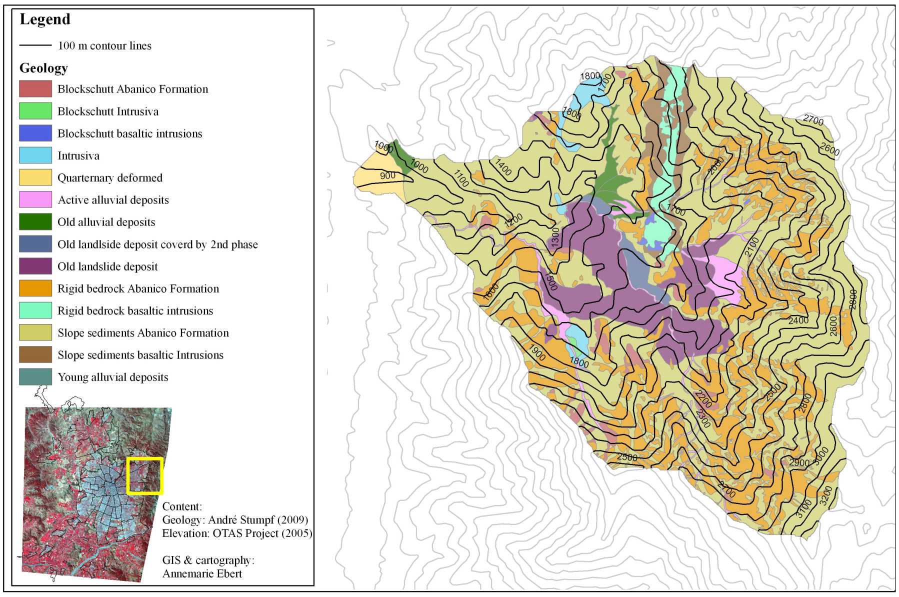


Fig. 1. Location (bright rectangle) and geologic-geomorphologic map of the study area (modified after Stumpf, 2009).

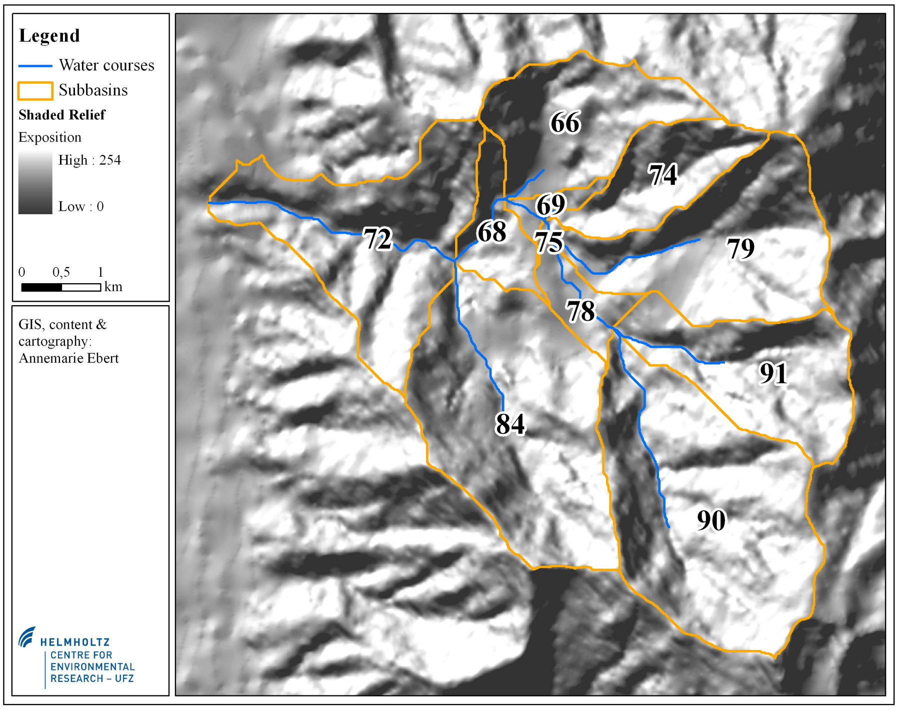
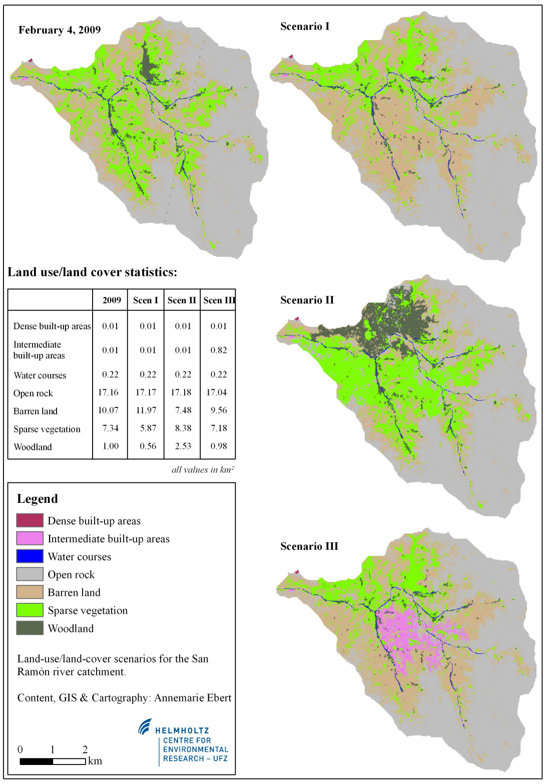


Fig. 2. Map showing the subbasins with names and shaded relief of the San Ramón basin.



Land use/land cover statistics:

	2009	Scen I	Scen II	Scen III
Dense built-up areas	0.01	0.01	0.01	0.01
Intermediate built-up areas	0.01	0.01	0.01	0.82
Water courses	0.22	0.22	0.22	0.22
Open rock	17.16	17.17	17.18	17.04
Barren land	10.07	11.97	7.48	9.56
Sparse vegetation	7.34	5.87	8.38	7.18
Woodland	1.00	0.56	2.53	0.98

all values in km²

Fig. 3. Land-use/land-cover data from 2009 as derived from the analysis of the ASTER data and LULC scenario alternatives.