

Article

# Planting Waterscapes: Green Infrastructures, Landscape and Hydrological Modeling for the Future of Santa Cruz de la Sierra, Bolivia

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Abstract: The expansion of cities is an emerging and critical issue for the future of the planet. Water is one of the most important resources provided by urban and peri-urban landscapes, as it is directly or indirectly connected with the quality of the environment and life. Santa Cruz de la Sierra is the leading city in Bolivia (and the second in Latin America) in regard to population growth and soil sealing. Water is available to the city mostly from the Piraí River basin, and is expected to be totally inadequate to support such powerful urban development. The project Aguacruz, which is financed by the Italian Agency for Cooperation and Development, aimed to (1) restructure and harmonize existing data on the landscape ecology, hydrological features, and functional aspects of the Piraí River; (2) build hydrological scenarios for the future of the basin by introducing a landscape ecology approach, and (3) involve stakeholders and local actors in decision-making processes oriented to increase the resilience of the urban-rural landscape of the Piraì River and the city of Santa Cruz. SWAT (Soil and Water Assessment Tools) tested five scenarios through simulating different landscape settings, from the current previsions for urban expansion to a sound implementation of green infrastructures, agroforestry, and regreening. The results indicate that integrated actions in rural-urban systems can lead to a substantial reversal of the trend toward a decline in water supply for the city. From a governance and planning perspective, the proposed actions have been configured as to induce (i) integrated waterscape ecological planning; and (ii) the preparation and approval of departmental regulations for the incorporation of green infrastructures in the municipalities.

Keywords: SWAT; ecohydrology; ecosystem services; land use change; landscape scenarios; hydrological modeling; green-blue infrastructure; agroforestry; rural-urban governance; naturebased solutions

## 1. Introduction

Cities and their residents depend on peri-urban and rural landscapes for ecosystem services, economic and social benefits, and ultimately, health and quality of life [1–3]. On the other hand, it is increasingly evident both in the world of science as well as for the actors of city governance, that urban environments need a green infrastructure approach in order to mitigate the critical state of the environment, particularly in the fast-growing cities of developing and industrialising countries [1,4,5].



The process of heavy urbanization is responsible for the degradation of ecosystem services and the loss of some benefits induced by urban nature [6,7]. The "ecology in the city" [8], including semi-natural areas such as forests, rivers, and wetlands, is starting to be compromised by urban sprawl. Water is one of the most important resources provided by the urban and peri-urban landscapes, as it is directly or indirectly connected with the quality of the environment and life. Water resources sustainability depends on dynamic interactions among infrastructure systems (natural, urban, social), and water resource planning and management should be based on the evaluation of the adaptations among these systems [9–11]. Changes in land use/land cover (LULC) in the upstream portion of a basin can change the hydrological response to precipitation events, heavily affecting the downstream areas [12–15]. The urbanization of headwaters and peri-urban areas of a catchment may lead to increased peak flows [16–18], while forest cover, especially in the Southern Hemisphere, can provide ecosystem services such as soil protection, climate regulation, and water supply [19–21].

Santa Cruz de la Sierra (hereafter denoted as Santa Cruz) is leading Bolivia (and is the second city in Latin America) in regard to population growth and soil sealing. At the global level, it has been ranked the world's 14th fastest-growing city, with a presumed average annual growth rate of 3.98% between 2006 and 2020 based on past growth/decline according to the Bolivian National Statistical Institute (INE). It is estimated that over the next five years, the current 2.6 million inhabitants (registered in 2015) could double [22]; food, energy, and water requirements will be completely altered by this change. In particular, water available to the city, mostly from the Piraí River basin, is expected to be totally inadequate to support such powerful urban development. In addition to the urban expansion, the forests of the Pirai River catchment are the object of a deforestation project mainly driven by the *quemas* slash-and-burn techniques of local farmers, which are used for reclaiming new agricultural lands and pastures from forests [23].

Killeen [24] explains that no single social or economic factor is the primary cause of this habitat change, but four categories can be accused: non-mechanized or low mechanized (indigenous) farming, highly mechanized (non-indigenous) farming, cattle ranching, and forest use and conservation approaches on protected areas. Slash-and-burn agriculture is the major production system, but established settlers have also invested in intensive cropping systems and started using trucks, tractors, harvesting machines, and other implements. Historically, settlement and the resulting deforestation was limited to landscapes near the city of Santa Cruz, but the dynamic of land cover change in all of the study area has changed over the last half century. During the 1986–1991 period, an increase in land-use change happened as a consequence of the establishment of agro-industrial corporations in the alluvial plain east of the Río Grande River [25].

The project Aguacruz, financed by the Italian Agency for Cooperation and Development, is an action research project oriented to investigate the current state of landscape conservation of the Piraì River basin, and how the latest changes are affecting the availability of water intended as an ecosystem service for the city of Santa Cruz. The study deals with two major issues: understanding the pattern of landscape and land-cover changes in recent decades, and retracing the hydrological pattern of the basin as related to land cover aspects. The results of the research are expected to deliver guidelines to promote concrete and effective nature-based solutions (NBS) to counteract the progressive impoverishment of the water supply.

The objectives of Aguacruz project, which is part of the Support Program for the natural area of integrated management of Rio Grande, Santa Cruz, Bolivia (ANGIRG)funding of the Italian Agency for Cooperation and Development (AICS), were selected through a collaborative process between the government of Santa Cruz, the non-governmental organisations (NGOs) Institute de Capacitacion de Oriente (ICO) based in Bolivia, and Istituto per la Cooperazione Universitaria (ICU), based in Italy, the local municipalities, and the University of Florence. Main objectives were: (1) restructure and harmonize the existing data on the landscape ecology, hydrological features, and functional aspects of the Piraí River; (2) build hydrological scenarios for the future of the basin by introducing a landscape ecology approach, and (3) involve stakeholders and local actors in decision-making processes oriented to increase the resilience of the urban–rural landscape of the Pirai River and the city of Santa Cruz.

Data collection and field surveys have been realized to build an appropriate SWAT (Soil and Water Assessment Tool) hydrological model. The model was used to simulate five scenarios, representing different landscape settings, from the current previsions for urban expansion to a sound implementation of green infrastructures, agroforestry, and regreening. Simulated results have been utilized to inform a planning proposal that will be implemented at the regional level for reversing the trend of water resources depletion.

### 2. Study Area

Hydrological and landscape ecology modeling have been elaborated on the Piraí River basin area (Figure 1), which is the main water source for the almost three million people living in Santa Cruz. The outlet of the catchment was located at the Eisenhower bridge, for a total area of 3955 km<sup>2</sup>.



Figure 1. Study Area.

The landscape is wavy, with steep slopes in some places, and the flat lower basin area is mainly characterized by strongly developed agriculture. The vegetation is scarce and little, and is influenced by wind and moderate to high water erosion [26]. The elevation ranges between 200 and 2700 m above sea level. An altitude gradient constrains plant species distributions on the eastern slope of the Andes, whereas a latitudinal gradient defines vegetation structure in the lowlands, where seasonality considerably increases with a decrease of precipitation. Humid Amazonian species in the northern

plains develop through the seasonally dry forests of *Chiquitania* into the semi-arid woodlands of *Gran Chaco* to the south [27]. According to the Köppen and Geiger classification, the climate in the investigation area goes from warm and temperate (Cwb) in the South to tropical (Am), with significant rainfall in most months, with a short dry season (Figure 2).



Figure 2. Climatology of the Pirai River watershed: (a) Downstream area; (b) Upstream area.

Geomorphology influences the distribution of habitat types across the latitudinal gradient: from seasonally flooded savanna wetland in the alluvial western plain to the *Cerrado* savannas predominating on weathered upland soils and rocky landscapes.

Nonetheless, most of the Piraí River basin area remains as natural coverage (forest, wood land, grassland, wetland); deforestation has been the predominant type of habitat conversion.

The trend in habitat conversion changed radically after 1991 with intensive cattle ranchers experienced a 10-fold increase in the clearing of Chiquitania cerrado and Gran Chaco woodlands [24] and agro-industrial corporations expanded exponentially. During recent years, the growth in deforestation rates leveled off for agro-industrial corporations and intensive cattle ranchers.

The major expansion of urbanized area of the city of Santa Cruz is expected in the northwestern area of Porongo–Urubò, where new urbanization plots were evident at the moment of field surveys [28].

#### 3. Materials and Methods

The Soil and Water Assessment Tool (SWAT) is a physically-based, semi-distributed watershed model [29]. The model is widely applied for LULC change analysis and ecosystem services evaluation [30,31], and for the simulation of agroforestry [14] and reforestation interventions [32]. Input data required are represented by: meteorological data, topography, soil, and land use. SWAT divides the watershed into sub-basins that are further partitioned into hydrologic response units (HRU) characterized by unique land use, slope class, and soil. The scheme of the SWAT model is shown in Figure 3.



Deep aquifer

**Figure 3.** Water balance and flow partitioning in the Soil Water and Assessment Tool (SWAT) model. From [33], modified.

Meteorological data have been retrieved from the Santa Cruz department meteorological archive and the National Oceanic and Atmospheric Administration (NOAA) Global Surface Summary of the Day (GSOD). Solar radiation values have been simulated with the Climate Forecast System Reanalysis (CFSR) climatic model [34]. Missing climate data have been generated with a SWAT-embedded weather generator, and tables of weather generator input parameters were calculated with Boisramè's "wgnMaker" model [35], starting from available data.

A Shuttle Radar Topography Mission (SRTM) 90 m-resolution digital elevation model has been used for watershed delineation and topographic data. Soil information has been taken from the Santa Cruz department geographic database. A land cover map from the Noel Kempff Natural Museum [23] has been used for model set-up. The list of input data is presented in Table 1.

Data	Source	Description
Rainfall	Santa Cruz department meteorological archive	6 stations
Temperature	Santa Cruz department meteorological archive	3 stations
Wind speed	National Oceanic and Atmospheric Administration (NOAA) Global Surface Summary of the Day (GSOD) [36]	1 station
Relative humidity	National Oceanic and Atmospheric Administration (NOAA) Global Surface Summary of the Day (GSOD) [36]	1 station
Solar radiation	Climate Forecast System Reanalysis (CFSR)	Simulated data
Topography	Shuttle Radar Topography Mission (SRTM)	90 m resolution
Soil map	Santa Cruz department	
Land use map	Noel Kempff Natural Museum [23]	

Table 1. Input data for Soil and Water Assessment Tool (SWAT) hydrological model building.

The model was built for the period 1990–2013, considering two years as warm-up period (1990 and 1991), and 73 sub-basins were created using 5000 ha as threshold value for the area.

Calibration and validation of the model were not possible due to the lack of reliable discharge data for the simulated period. However, it has been proven that calibration is not necessary for the SWAT model to determine the direction of changes in streamflow due to LULC changes, and that only spatially distributed calibration procedures can improve model accuracy. There is also little difference between uncalibrated models and models calibrated with a single output in predicting relative changes in streamflow [37].

The SWAT watershed model (Scenario 1) was used to evaluate the spatial distribution of runoff generation, which is seen as a hazard for the city of Santa Cruz, and percolation to the shallow aquifer, which is seen as an ecosystem service of the Pirai River system that contributes to deep aquifer recharge and river discharge in dry periods as lateral flow or base flow.

The spatial analysis of runoff generation and percolation was realized by mapping a relative index of runoff ( $I_R$ ) and a relative index of percolation ( $I_P$ ) for each sub-basin, calculated as:

$$I_R = SURQ/R \tag{1}$$

$$I_P = PERC/R \tag{2}$$

where *SURQ*, *PERC*, and *R* are respectively the annual mean of surface runoff, percolation, and rainfall for the selected sub-basin.

Starting from the analysis of Scenario 1, four future scenarios have been simulated with LULC changes:

- Scenario 2 (worst-case scenario): Porongo–Urubò area entirely urbanized.
- Scenario 3: Porongo–Urubò area entirely urbanized, with green infrastructures in the new urbanised areas (components: sustainable drainage systems, rain gardens, and green roofs).
- Scenario 4: Porongo–Urubò area entirely urbanized, with green infrastructures in the new urbanised areas and agroforestry—afforestation implemented in the degraded areas of the headwaters of the catchment.
- Scenario 5 (best-case scenario): Agroforestry—afforestation implemented in the degraded areas of the headwaters of the catchment.

Scenarios were realized by combining SWAT default available land uses and modifying the existent LULC map (Figure 4). The interventions simulated in the frame of SWAT modeling were implemented by using the module split land use by modifying the percentage of land cover.

Complete urbanization in the Porongo–Urubò (Scenario 2) area was modeled with URMD land use class (URban Medium Density); complete urbanization, including green infrastructures,

in Porongo–Urubò (Scenarios 3 and 4) was modeled with a 50% URMD and 50% GRSS (Grassland); Agroforestry (Scenarios 4 and 5) was modeled with a 50% CRWO (Cropland—Woodland), 30% CRIR (Irrigate Cropland and pastures) and 20% FRST (Mixed forest) in the degraded areas of the headwaters of the catchment.



Figure 4. Land use units modeled in Scenarios 2–5.

Variation in the water balance of the Pirai River for each scenario, and implications on watershed management, are analyzed and discussed in the following section.

## 4. Results

# 4.1. Results of Rio Pirai Watershed Model

Results of Scenario 1 modeling are presented in Table 2.

**Table 2.** Results of the Soil and Water Assessment Tool (SWAT) watershed model for Pirai River annual means for the period 1992–2013 (water balance) in mm (millimeters) and Mm<sup>3</sup> (millions of cubic meters) for the actual situation (Scenario 1).

Model Output	mm	Mm <sup>3</sup>		
Precipitation	974.7	3854.9		
Evapotranspiration	550.7	2178.0		
Revap from shallow aquifer	38.7	153.0		
Surface runoff	131.8	521.4		
Lateral flow	143.3	566.8		
Return flow	110.0	435.0		
Percolation to shallow aquifer	149.4	590.8		
Recharge to deep aquifer	7.5	29.5		

Spatial Distribution of Water Ecosystem Services

SWAT spatialized results were analyzed at a sub-basin level, and are shown in Figure 5.  $I_R$  and  $I_P$  distribution are shown in Figure 6.



**Figure 5.** Results of Scenario 1 Soil and Water Assessment Tool (SWAT) model (annual means for the period 1992–2013 in mm): (a) Precipitation; (b) Surface runoff; (c) Percolation.



**Figure 6.** Spatial distribution of watershed indices: (a)  $I_R$  and top 10 sub-basin for  $I_R$ ; (b)  $I_P$  and top 10 sub-basin for  $I_P$ .

Results show that most of the runoff produced is in the middle part of the watershed (Figure 6a), around the Santa Rita, El Torno, and La Angostura areas (sub-basins 63, 21, and 24, respectively). Here, most of the forest has been converted to agricultural land use in the last 20 years [23]. Forest degradation negatively affected water ecosystem services: the excess of runoff, and consequent increased peak river discharges, represents a potential hazard for the city of Santa Cruz, since despite high rainfall (Figure 5a), the percolation contribution to aquifer recharge and base flows is low (Figures 5c and 6b). Apart from the top 10 sub-basins,  $I_R$  analysis also show that some sub-basins in the headwaters of the Pirai River watershed, where land degradation related to *quemas* occurs, generate a high runoff contribution, and do not have a relevant impact on percolation.

The highest contribution to percolation is given by the Porongo–Urubò area in the tailwaters of the catchment (sub-basins 8, 9, 10, and 11—Figure 6b). Here, sandy soils and low slopes determine a hotspot for percolation, and thus shallow and deep aquifer recharge. Due to landscape characteristics, these areas are not generating excessive surface runoff (Figure 6a), allowing a reduction of flow peak discharges.

The relevant LULC changes that are envisioned for the Pirai River catchment, such as the complete urbanization of the Porongo–Urubò areas, will have an impact on the evolution of water flows for the city of Santa Cruz. Modeling of four future scenarios is discussed in Section 4.2.

#### 4.2. Analysis of Future Scenarios

Table 3 and Figure 7 show the results of Scenario 2–5 simulations. Scenario 2 shows an increase of runoff of 22% and a decrease of return flow, percolation, and recharge of 20%, 17%, and 17%, respectively. In Scenario 3, runoff increased by 13%, and return flows, percolation, and recharge decreased by 13%, 11%, and 11%, respectively. In Scenario 4, runoff increased by 2%, while the reduction of return flows, percolation, and recharge was 9%, 8%, and 8%, respectively. In Scenario 5, where no urbanization has been considered, runoff decreased by 11%, while return flows, percolation, and recharge increased by 4%, 3%, and 3%, respectively.



Figure 7. Relative changes in flow partitioning for Scenarios 2–5.

Model Output	Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	mm	Mm <sup>3</sup>						
Precipitation	974.7	3855	974.7	3855	974.7	3855	974.7	3855
Evapotranspiration	548.9	2171	550.7	2178	558.3	2208	559.4	2212
ap from shallow aquifer	37.34	148	37.93	150	38.12	151	38.87	154
Surface runoff	160.37	634	148.64	588	134.37	531	117.15	463
Lateral flow	141.82	561	142.45	563	143.79	569	144.67	572

95.92

133.62

6.68

379

528

26

99.97

138.03

6.9

395

546

27

**Table 3.** Water balance values—annual means for the period 1992–2013 in mm (millimeters) and Mm<sup>3</sup> (millions of cubic meters) for Scenarios 2–5.

#### 5. Discussion

Reva

Return flow

Percolation to shallow aquifer

Recharge to deep aquifer

Scenario 2, the worst-case scenario, shows how the effect of urbanization in the Porongo–Urubò area, where most of infiltration occurs, and thus baseflow and groundwater recharge are generated. Runoff increases, while the area cannot support the provision of groundwater as in Scenario 1.

87.78

124.33

6.22

347

492

25

The implementation of green infrastructures (Scenario 3) can considerably buffer the effect of the urbanization, but it does not fully restore the area. Results are in line with Feng et al. [38], who showed how green infrastructures can restore 82% of the antecedent water balance for the case study of a small urbanized catchment of Salt Lake City, Utah, in the United States. However, unlike the cited work, where the urbanization was located on a gravelly loam soil with low infiltration, new urbanization in Santa Cruz is going to alter the water balance in the Porongo–Urubò area, where most of the infiltration occurs. The area represents a hotspot for the generation of groundwater recharge ecosystem services, and green infrastructures cannot completely reduce the effect of soil impermeabilization.

Scenario 4 shows the additional effect of the implementation of agroforestry in the headwaters and degraded areas of the catchment. The runoff increase is almost eliminated because of additional tree cover, but negative effects on percolation, base flow, and groundwater recharge are still present, even if halved.

Scenario 5, the best-case situation, shows how agroforestry can contribute to reduce surface runoff and increase percolation, base flow, and groundwater recharge. It should be noticed how this effect is given only for the headwaters of the catchment, where  $I_P$  values are low (Figure 5b), while in this case, the critical areas to produce groundwater-related ecosystems services of the landscape are unaltered.

Model results of agroforestry impacts on runoff are in line with Mwangi et al. [14], while impacts on percolation, baseflow, and groundwater recharge (and lateral flow) are positive in the present study and negative in Mwangi et al.'s work [14]. This is due to the difference between case studies: (1) the present work simulates a water flow partitioning in an arid area of South America, while Mwangi et al. analyze the water balance of the Mara River, which is located in a humid area with rainfall exceeding 1800 mm in some areas of the catchment; (2) the present work simulates generic agroforestry implementation, while Mwangi's work simulates the implementation of productive woodlots; (3) agroforestry in the present work is intended to restore pasture areas and replace agricultural land reclaimed with slash-and-burn practices, while in Mwangi et al. [14], woodlots replace agricultural land use. Extensive modeling of agroforestry intervention for different climates, different agroforestry plot implementation.

Considering the impact of new urbanizations located in the sandy area of Porongo–Urubò, the study makes evident the need for an ecosystem services-based perspective for planning landscape modification. In addition to this, the comparison of Scenarios 3 and 4 shows how it is not possible to restore ecosystem function with measures localized in the area of new urbanizations, and that catchment scale approach should be applied for water ecosystem services restoration in river systems.

451

608

30

114.03

153.79

7.69

#### 6. Aguacruz Project Outcomes

Considering the results of the study, the Aguacruz project formulated operational actions that were submitted to the city government through the project final reports.

Operational guidelines and a plan of action have been formulated to help decisionmakers and stakeholders adopt effective strategies and interventions to improve the hydrological budget, water availability, and water quality. The project Aguacruz suggested the adoption of two main operational policy items to governmental counterparts: (i) the adoption of a "waterscape" management plan for the Pirai River watershed, which was aimed to strengthen the provision of ecosystem services of the watershed to the city of Santa Cruz; and (ii) the adoption of a green–blue certification for new urbanization projects.

The "waterscape" management plan has been conceived as an instrument of waterscape ecological planning to evaluate possible management strategies that can improve ecosystem service provisions to Santa Cruz, and the other centers of the area, by acting on different areas of the catchment. At the level of proposal, the AGUACRUZ project advised to implement: (a) rainwater harvesting interventions [39] in the headwaters of the catchment; (b) agroforestry and reforestation in the central area of the catchment (Scenarios 4–5); and (c) green infrastructures for the new urbanizations in the tailwater areas around Santa Cruz (Scenarios 3–4).

In this sense, the green–blue certifications scheme for new urbanizations (AGUACRUZ-Green and AGUACRUZ-Blue) has been conceived as a voluntary certification for building enterprises, which will be assigned based on the environmental performance of new buildings. A list of the parameters to be adopted for the performance evaluation is currently under study. It will consider, for instance, the variation induced by urbanization on the hydraulic cycle, and the area and type of green infrastructures implemented. The action plan is based on three pillars: (1) a strategic section concerning thematic planning documents and governance tools, including the constitution of a water committee composed of the stakeholders and actors involved in the decision-making and implementation processes; (2) an operational section in which the technical aspects of the proposed actions are developed and coupled with their realistic feasibility in terms of space and time; (3) an education section for planning the capacity-building processes through institutional, technical, and community knowledge empowerment, proposed as a program of lifelong environmental learning.

#### 7. Conclusions

Water is an essential ecosystem service delivered to the cities by peri-urban landscapes. Understanding the hydrological dynamics associated with the ecological characteristics of the landscape and the dynamic processes of land use and land cover changes—experienced in the last three decades by the watershed that provides water to the growing city of Santa Cruz—has allowed the formulation of research hypotheses and consequent results oriented to give applicative guidance to the government of the city region.

Research has been configured as action research, and has had operational outputs through the production of five different scenarios, including sustainable interventions in planning and managing the Santa Cruz cityscape and its peri-urban landscape.

SWAT modeling has shown how complete urbanization may completely jeopardize Pirai River ecosystem service provisions in terms of water resources. Considering sustainable drainage systems, rain gardens and green roofs in new urbanizations may halve the impacts of the urbanization, but consistent mitigation of urbanization impacts can be achieved only with agroforestry implementation in the upstream part of the catchment. At last, the modeling of sole agroforestry implementation, without urbanization, showed a potential enhancement of water ecosystem services, such as the reduction of quick runoff, and the increase of baseflow and groundwater recharge.

The study outcomes have been used to support the Santa Cruz municipality to inform future policies for the implementation of a Waterscape Ecological Planning instrument, and the adoption of green infrastructures in new urbanizations.

Future research steps will need to address and investigate the performance of green infrastructure interventions at the municipality and community scales in greater detail. Consequently, this down-scale approach will provide the identification and evaluation of multiple ecosystem services of the Pirai River waterscape such as sediment production and nutrient cycling, but also recreational and cultural services. This process, through a deeper understanding of ecosystem services fluxes, will define the sustainability framework of water supply for the future of the region.

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