Geographic distribution of ecosystem functions and services in territorial management of urban municipalities. Case study: La Presidenta Watershed (Medellin, Colombia)

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ABSTRACT

Current trends in the processes associated with territorial management show specific needs aimed at strengthening the decision-making oriented to development and investments in regions and localities. One of the main drawbacks is the lack of models that allow the characterization and mapping of ecosystem functions and services that can be implemented in the scope of land management and planning processes. In this work, a model of ecosystem service *stability of hillsides* in a hydrographic basin of Medellin City, Colombia, was carried out, trying to determine the geographically distributed behavior of the associated ecosystem functions and the mapping of the flow of the aforementioned service. Erosion control, morphodynamic activity and surface water runoff were considered as relevant ecosystem functions. One of the most important results of the project consisted of a software application development that allow the decision makers to carry out such modeling in a practical and efficient way.

Keywords: Ecosystem, Environmental Services, Territorial Management and planning, High Mountain Slopes, Water Runoff.

TERRITORIAL PLANNING TODAY: WORLD CONTEXT AND LOCAL CHALLENGES

Projections made by United Nations Department of Economic and Social Affairs (*U.N., 2017*, see Figure 1) show a clear tendency for the world population to grow, at least, until year 2060. Even when some continents – Africa and Asia - demostrate this behaviour in a more pronounced way (see Figure 2), the whole planet is exposed - in different rates of change according to its geographic location - to a future ammount of people that carry the environmental capacities to their sustainability limits.

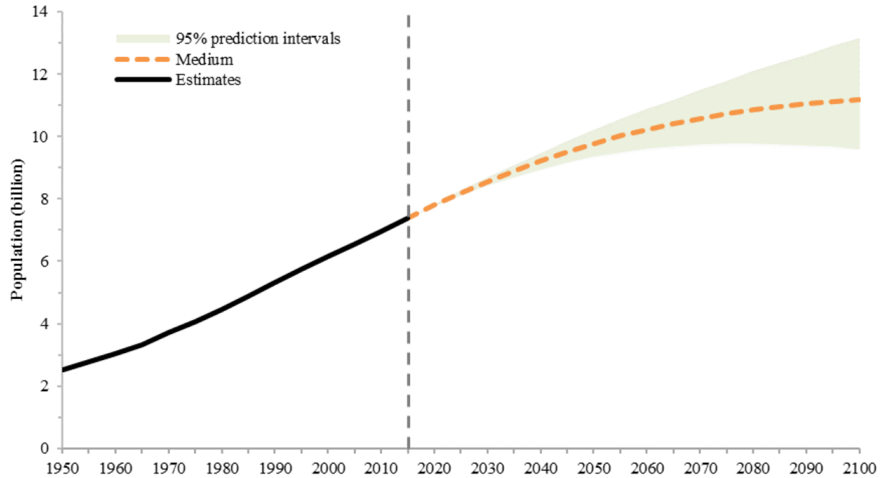

Figure 1. Population of the world: Estimates, 1950-2015, and medium-variant projection with 95 per cent prediction intervals, 2015-2100. Source: Source: United Nations, Department of Economic and Social Affairs, Population Division (2017). World Population Prospects: The 2017 Revision. New York: United Nations.

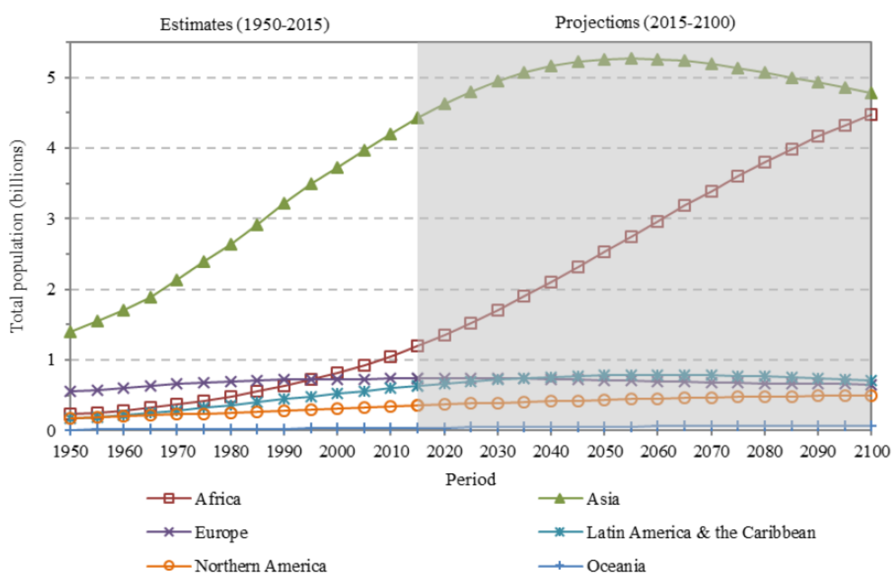

Figure 2. Population by region: estimates, 1950-2015, and medium-variant projection, 2015-2100. Source: United Nations, Department of Economic and Social Affairs, Population Division (2017). World Population Prospects: The 2017 Revision. New York: United Nations.

International migrations, as well as internal population movements, are being recognized as powerful motors for ecomomies, and as the same time, considered as planning paradigms that involve multi-risk scenarios. Main cities of developing countries are experiencing unprecedented threats due to new hubs of demographic concentrations located in sites that are unsuitable for safe living, with insufficient infrastructure, avoided by local law, or exposed to natural risks.

Taken as a whole, this situation represents a challenge for municipal decisors, which must manage with a desirable economic, social and intercultural growth, even with a new and unexpected tax incoming, but facing a rapid change in the local land use, altering the hydrologic cycle by creating extended areas of impermeable surface, diminishing the controlled infiltration, increasing surface runoff, modifying maximum flows and base time of hydrographs, concentration times in the networks, and in most cases, creating inssuficiency for many hydraulic infrastructures.

The scenario mentioned above, is even more pronounced in cases when social conflict is presented in rural areas. Violence and abscense of goverment authority, estimulate migration from the field to the city. New companies (some locals, others foreigns) settle down to intend satisfy product and service necessities for all the population.

As a result of that, In the city of Medellín, the Comuna (a geographical district - set of neighboorhoods - with economic, social and physical characteristics relatively homogeneous) of El Poblado, inside of which, La Presidenta watershed is located, presents the highest Multidimensional Indicator of Life Conditions (MILC) over the analysed time lapse 2010-2017 (see Figure 3). MILC comprises 15 different dimensions: public services access, housing quality, natural environment, schooling, movility, liberty and security, health access, work opportunities, to say some of them (*AMCV, 2018*).

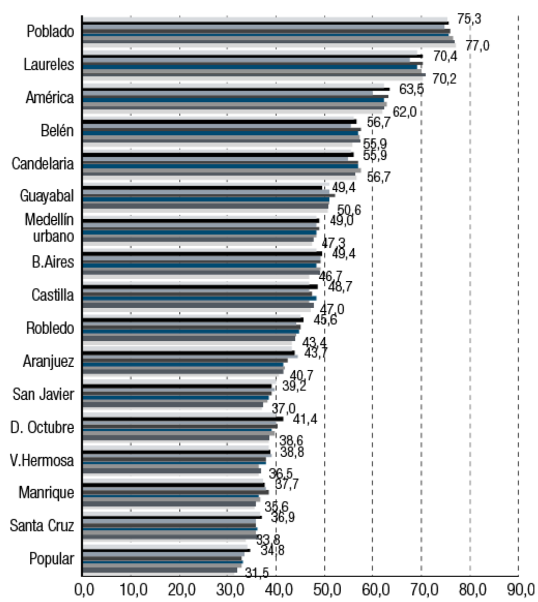

Figure 3. Urban Medellín: Multidimensional Indicator of Life Conditions, 2010-2017. Source: 2017 Medellín Quality of Living Report. Information Sub-Direction. Administrative Department of Municipal Planning. Medellín City Hall, 2018.

The dynamics of growth and assembling of El Poblado Comuna, and the La Presidenta watershed in specific, can be explained as the result of the occurrence of the same flows - in diverse intensities

- identified among the Valley of Aburrá, the lower Valley of Cauca River and the upper Valley of San Nicolás in the last 10 years. These flows encompass 12 different kinds: population, investment resources, education services, water, energy and environmental ecosystem services, to mention some. The strong integration between the Valley of Aburrá and the Valley of San Nicolás, crossing La Presidenta watershed with one of the most relevant highway in the city-region "is confirmed by the numbers" (*Medellín City Hall, 2011*) making reference to the public and private frecuency related to multimodal transport.

Nevertheless, how the City of Medellín expands its limits (as much as the long and narrow Valley of Aburrá allows), accommodates new habitants coming from Venezuela and from internal regions as Urabá and Chocó, and adopts new land uses, strongly contrasts with the emerging urban and peri-urban planning strategies, the slow velocity as the territory widens the physical infrastructure and the way it brings up to date its integrated risk management system, then conditioning the city for the requirements of a multicultural society that demands living quality standards according to those of the top South American metropolis.

Clearly, the expanding tendency brings a high environmental unbalance (in regional and local scale) between the surface required to mitigate the greenhouse effect due to new hard covers which produce microclimates, and the existing protected areas responsible for this action. The last indicates some challenges in the territorial order, already recognized for prior administrations: "to define concrete use and management policies for lands under protection with high environmental and ecosystem value, for those ecosystems defined to be recovered or restored to prior conditions, in order to guarantee the proper functioning of the main ecological structure of the region" (*Medellín City Hall, 2011*).

As the same time as the covers are conserved or restored, looking for climate balance, soil degradation diminishes or keep steady its rate of occurrence, and the ecosystem service *hillside stability* is preserved or increased. This is particularly important for basins where the values of slope are significantly high, and scarps are frequent. In the other hand, when natural cover disappears in relative short lapses, transforming green areas to pavement and concrete surfaces, and this joined to an insufficient or wrong management of water runoff and percolation, risk of mass movement or risk flooding materialize in disasters. La Presidenta watershed is an example of these environmental cause-effect cases. This is a major concern for the authorities, not only for the zone mentioned, but for several Comunas. Municipality public policies related to risk management in 2017 were oriented to "reduction of flood risk in zones adjacent to streams…and the realization of interventions to manage disasters", and for the same year, compared to the prior "the number of emergencies assisted by the local office of risk management increased from 12064 to 17357" (*AMCV, 2018*). The same source confirms that in 2017, deaths caused by natural disasters increased.

Evidently, the proactive key role of local and national government consists, partially, in assisting communities involved in risk situations by means of a robust structure to prevent disasters through reduction of the vulnerability and supporting scientific research looking for the increase of the level of knowledge related to natural hazards.

Furthermore, national and regional entities must understand and reconsider the prevailing economic model, intentionally to secure sustainability levels in the utilization of natural resources and ecosystem services. This marks the construction – and discussion - of a series of laws that identify and regulate permitted and avoided land uses based on soil capacities and resilience levels, restrict geographic growth by considering geomorphology aspects, and stimulate economic activities assimilable by the environment.

ECOSYSTEM SERVICES, INTEGRATED WATER RESOURCES MANAGEMENT (IWRM) AND TERRITORIAL PLANNING

As water is one of the most relevant resources on the Earth (for both positive and negative scenarios), the concept of IWRM become fundamental to a modern Territorial Planning. The principle of this approach is that interdependency of many water uses occurs (*Global Water Partnership, 2005*), thus, conditioning the quantity, quality and accessibility - the three milestones - of water in the present and in the future over a region.

In 2010, Colombian government published the National Policy for the Integrated Management of Water Resource, which stablishes objectives, strategies, indicators and strategic action lines over a 12-year horizon (*Ministry of Environment, Housing and Territorial Development, 2010*). In its concept frame, the Policy acknowledge and embrace the definition of IWRM made by The Global Water Partnership. This Policy become the legal basis for all the national, regional and local plans, and therefore, for all the territorial planning initiatives and actions over every single jurisdiction.

The document lists the main postulates of the IWRM, highlighting for the present work the postulate #7: “The integration of water and land management and other natural resources and related ecosystems”. The postulate above mentioned is fully loaded of implications, as recognizes that environmental issues where water is involved, require a holistic and strategic vision to deal with, as not only water but other resources are present, and beyond, many other elements of the whole ecosystems can be part of those issues.

But even when the Colombian National Policy for the Integrated Management of Water Resource, addresses - indirectly - the environmental services as resources belonging to the economic and productive structure of the country (using the figure of *payment for environmental services*), and also mention them in the list of problems related to the water resource management (this, exposed as “insufficient knowledge about environmental services related with water, that the ecosystems and the same water resource offer”), the interpretation of ecosystem services that the Policy adopts is strongly narrow, scarce of scope, and not much detailed in its intentions.

As the ecosystems constitute the support for the application of the IWRM, ecosystem services must be part of the IWRM plans. The development of IWRM plans can be understood as a cycle (see Figure 4):

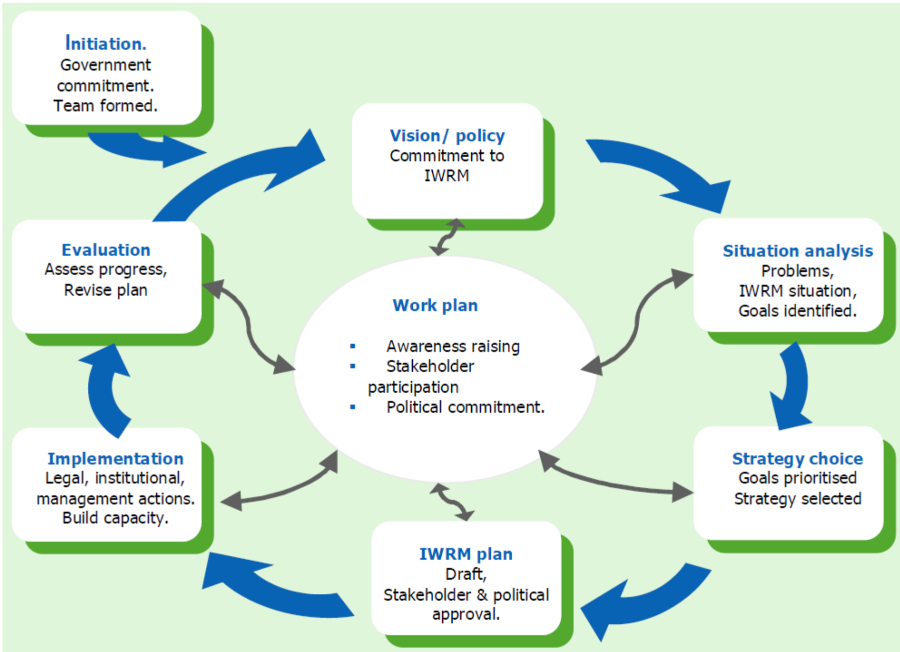

Figure 4. The cycle for developing and adjusting an IWRM plan. Source: Integrated Water Resources Management Plans. Training Manual and Operational Guide. Global Water Partnership, International Network for Capacity Building in Integrated Water Resources Management, United Nations Development Program, 2005.

In this structure, the accoupling of ecosystem services supply and protection to the IWRM should start from the *Construction of the Vision (Stablish the Strategic*) phase: recognizing a future when environment can absorb a fraction of the anthropic impacts, and in the same intensity, the need to protect them from direct or indirect human actions, will help to prioritize goals associated to the opportunities and threatens identified in the *Situation Analysis* phase.

After this, in the *Water Management Strategy* phase, some key question about ecosystem services must be answered in order to concrete their real impact. Carrying the ecosystem service role from the top, will ease to confront the key phase of *Making the Action Plan*. Identification of legal necessary actions and relevant actors also become crucial.

In this Action Plan, the activities, physical and human resources, supplies and results needed and expected to protect and to take advantage of the defined ecosystem services, can be structured through the figure of one or several *Strategies*. Some *Operational Actions* can be needed to achieve the expected results.

METODOLOGY AND CASE OF ANALYSIS

The area of study selected for this research is located at the south-east of the Valley of Aburrá (see Figure 5). This watershed presents a mixing of different urban and rural environments in a surface of 1500 Ha. The length of the main channel is 7.17 km, with a terrain average slope of 17.68%, and a channel slope of 18.33%. The upper part of the watershed is located in the rural zone of El Plan (Santa Elena) over altitude of 2700 m, and the lower zone, where the main channel tributes to the Río Medellín, reaches 1488 m.

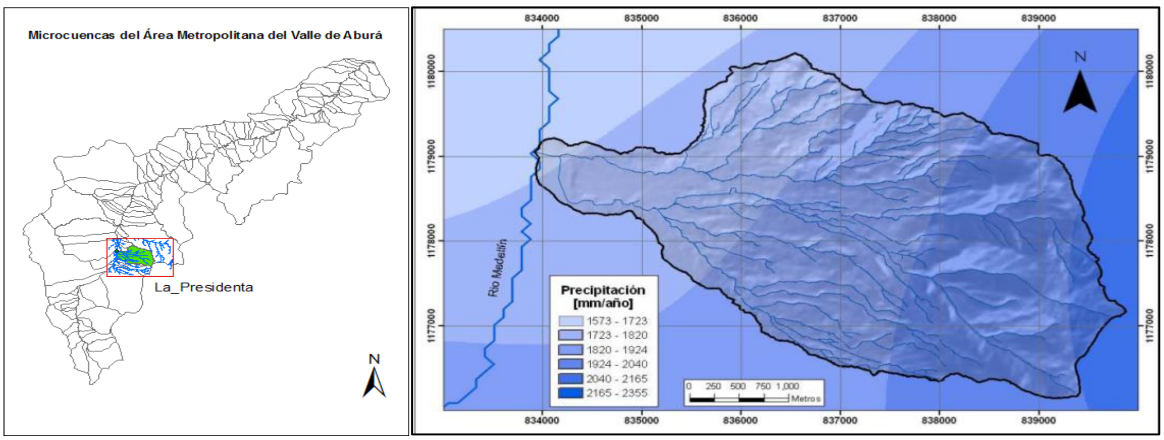

Figure 5. La Presidenta watershed inside Valley of Aburrá. Spatial distribution of annual mean precipitation. Source: Área Metropolitana del Valle de Aburrá, 2007.

Surface runoff annual mean flow for the watershed in its discharge point to the Medellín River was calculated through a hydrologic long-term balance based on rain and evaporation maps with a value of 0.978m3/s (Ministry of Environment, Housing and Territorial Development, 2006). Also by means of balances and regionalization methods, maximum and minimum stream flows for different return periods are known (*Table 1*):

Table 1. Minimum and maximum (m3/s) flows associated to typical return periods for La Presidenta watershed. Source: Valley of Aburrá Early Alert System (SIATA, 2018).

Tr	Qmin	Qmax
2.33	0.153	3.535
5	0.106	4.296
10	0.080	4.916
25	0.056	5.699
50	0.042	6.280
100	0.030	6.856

Based on the hydraulic modelling provided by the Plan of Environmental Management of La Presidenta Watershed (*Área Metropolitana del Valle de Aburrá, 2007*), some aspects were defined:

the modelling for return periods of 100 and 500 years, in the lower zone of the watershed, generated floods due to lack of hydraulic capacity in the channels, which are partially blocked by an important number of crossing infrastructure works (most of them, box culverts) that constitute strong hydraulic controls upstream, generating overflows over the flood plain. Streams lead to hard covers, realignments, invasion of flood zones and urban processes which constrict the hydrologic network, cause the loss of natural zones suitable for swelling control.

Due to the available information, but also pretending to increase the knowledge relevant to relationship between ecosystem services and risk management in high slope mountain systems, the ecosystem service stability of hillsides has been modelled. From the set (see Figure 6) of ecosystem functions and services associated to hydraulic and geotechnical variables, some of them take especial importance in the Andean mountain system. In this way, *Stability of hillsides* service is directly referred to the capacity of ecosystems to minimize landslides.

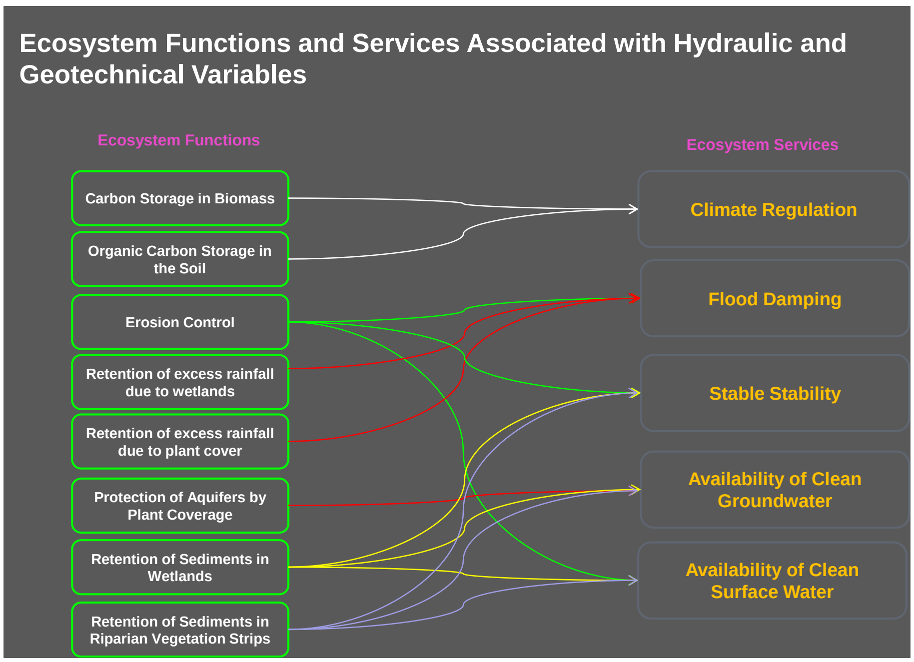

Figure 6. Ecosystem functions and services associated to hydraulic and geotechnical variables.

The role of Stability of Hillsides as ecosystem service

Hillsides stable for years can fail suddenly due to topography changes, seismicity, subsurface flows, variations in soil resistance, weathering, anthropogenic or natural factors which modify its original stability state (Suárez, 1998). To evaluate the ecosystem service Stability of Hillsides, in this methodologic approach ecosystem functions erosion control, morphodynamical activity and surface runoff are considered.

The stability of a hill can be deducted according to its dynamical behavior, as well as according to its geological and geomorphological characteristics, resulting at the end a semi-quantitative assessment of stability related to mass movements or morphodynamical processes. According to this, one ecosystem function related to morphodynamical activity is included in the approach. Surface Runoff must be included in the general scenario, as water is probed to be trigger of many landslides in Andean basins. Another ecosystem function, Erosion Control, is taking into account trying to catch the effects of soil losses and put them in the final result.

In Figure 7, the methodology proposed for mapping the ecosystem service Stability of Hillsides is graphically described. The path to transfer the effects of this ecosystem service over a territory where different dimensions of vulnerability are present, and the final consequences in the levels of risks, are also shown.

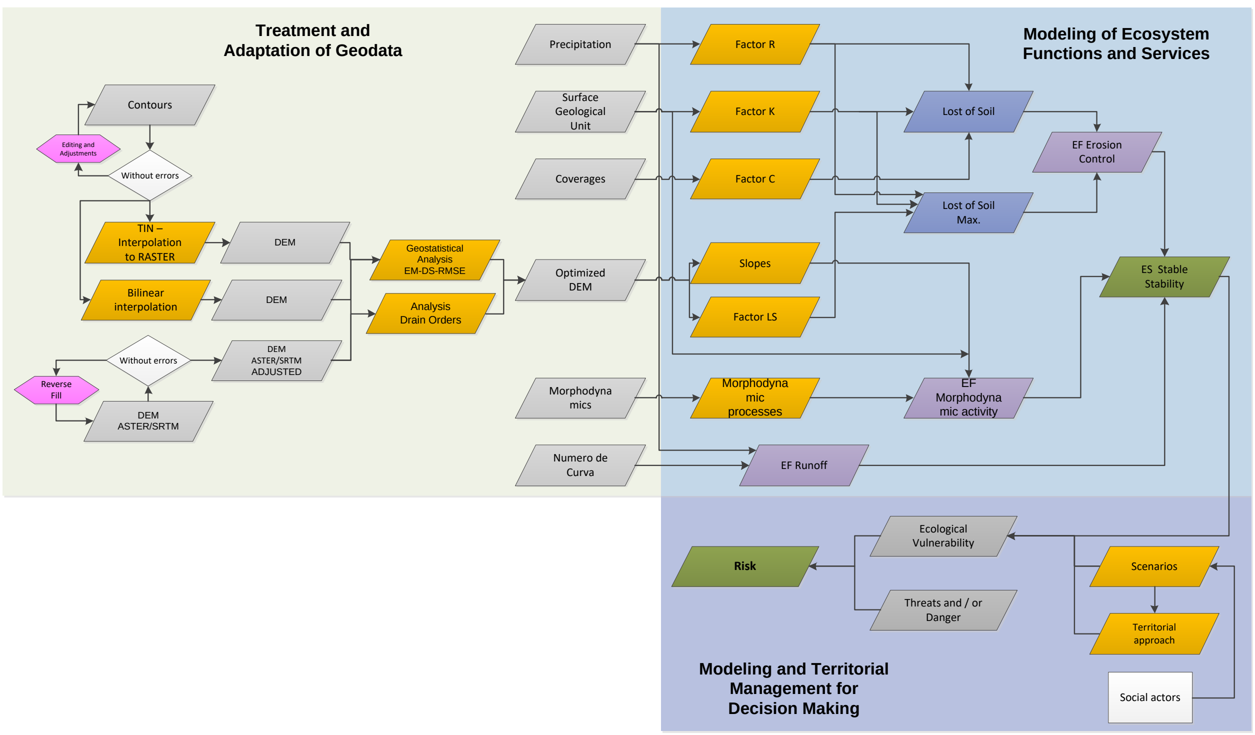

Figure 7. Methodology for mapping the ecosystem service Stability of Hillsides.

The Matrix of Saaty (*Saaty, 2000*) was implemented in the ecosystem service assessment, to obtain weights that affected every single function, thus generating the following equation:

$$SH = 0{,}35 \times \text{Erosion Control} + 0{,}49 \times \text{Morphodynamical Activity} + 0{,}16 \times \text{Surface Runoff}$$

In this process, to weigh the functions, expert knowledge was considered in the construction of the matrices. Table 2 shows different valuations given by experts to every function.

Table 2. Average weighting of ecosystem functions form expert knowledge.

	Erosion control	Morphodynamical activity	Surface Runoff
Erosion control	1,000	5,000	3,000
Morphodynamical activity	1/5	1,000	5,000
Surface Runoff	1/3	1/5	1,000

After following the procedure to compute the matrix, the final weights are obtained (as shown in Table 3).

Table 3. Final weights for ecosystem functions.

Function	Weight (%)
Erosion control	35
Morphodynamical activity	49
Surface Runoff	16

In Figure 8, it can be observed the result of modelling the ecosystem service Stability of Hillsides using the methodology above described.

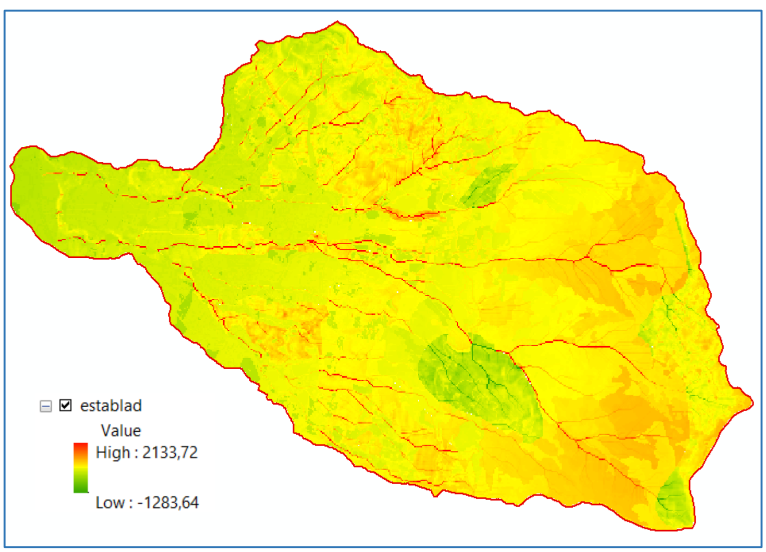

Figure 8. Geographical distribution of Ecosystem Service Stability of Hillsides in La Presidenta watershed.

Ecosystem Function Surface Runoff and its importance in Stability of Hillsides ecosystem service

Surface runoff encompasses the excess of rain that stay after a significant event and move freely over the surface of a terrain, as well as the runoff of a stream that can be formed by the excess of precipitation and for subsurface flows (*Forero, 2015*). The runoff generated by rain, can be calculated as:

$$Q = \frac{(I-0,2S)^2}{(I+0,8S)}$$

$$S = \frac{25400}{(N)} - 254$$

Where:

- Q: Surface runoff, in mm
- I: Precipitation (rain) in mm
- S: Maximum potential difference between total rain and surface runoff
- N: Curve number

The Curve Number is a methodology developed by the United States Department of Agriculture to calculate runoff and considers the probability that the rain can be transformed in runoff as a result of the kind of cover and its interaction with soil properties. Graphic representation of rain depth (P) and excess of precipitation depth (Q), allows to build a family or curves standardized through a non-dimensional number CN, meaning when CN reaches 100, that all the rain becomes runoff (*Lavao, 2014*). Then, high curve numbers imply low infiltrations, which could be associated to eroded hillsides, while low curve numbers represent low surface runoff and limited hydric erosion.

In this methodology, a rain raster matrix for a lapse of one year is provided. This lapse can vary according to the scale of data and the information available. To compute de curve number, tables made for different surface covers and vegetation classes can be used.

The factors that affect the curve number are (*Barral, 2014*):

- Use of land and vegetal cover: due to de capacity of the plant to absorb water in wet periods.
- Hydrologic group: in terms of type of soil and subsurface infiltration conditions. There exists four categories. From Group A (low potential of runoff) to Group D (high potential of runoff).

- Antecedent Moisture Condition (AMC): it is function of the rain fallen 5 days before. AMC I for dry soils, AMC II for average hydrologic conditions and AMCIII for soils close to its saturation point.

For this case, tables for CN from different authors were analized: Lavao (2014), Juárez-Méndez, Ibáñez-Castillo, Pérez-Nieto and Arellano-Monterrosas (2009). Once analized the available information, hydrologic group B and AMCII were determined as the closest elections to represent the reality of the watershed. To estimate runoff Q, a value of CN was assigned to the vector element of covers according to every specific kind of cover presented in the watershed. Then, a raster matrix is obtained and subsequently analyzed with the Model Builder Simulator (see Figure 9)

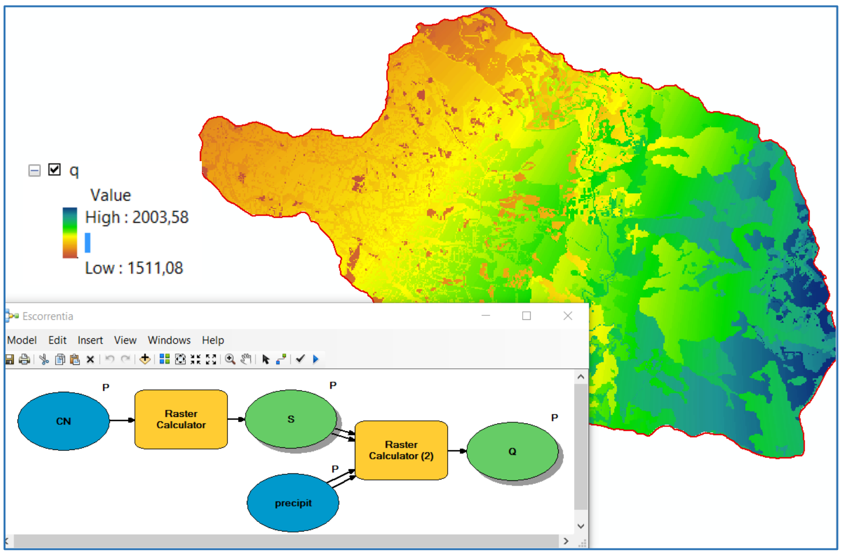

Figure 9. Geographical distribution of Ecosystem Function Surface Runoff for La Presidenta watershed.

Similar processes are implemented in GIS for Erosion Control and Morphodynamic Activity Ecosystem Functions.

CONCLUSIONS

This research pretends to expose a set of criteria and tools for the establishment of a methodology to map ecosystem functions and services, aiming to broad the alternatives heading to a subsequent assessment of vulnerability. At the end, a more reliable risk management is expected to reach, as the territorial planners have more robust elements to support their decisions, and also, to enhance the public policies in permanent construction.

To accomplish the former, technologic tools for modelling ecological processes and flows of ecosystem functions and services are needed. These new tools not only filter the relationship between ecosystem services and risk management in the geographic plane, but also help to build solid frames to support decisions about territorial planning.

This was the main reason to drive part of this research to a development of a geoinformatics interactive software, which allows the manager/planner-user to take decisions about processes and to consider diverse future scenarios, even in situations where data are scarce.

The software was developed and supported in Python language, and a register licence over the final product was obtained, emitted by the Ministry of Interior Affairs (Author Rights Administrative Direction Office). The software (see Figure 10) was called "Geoinformatics Python-GIS Tool For Simulating And Analyzing Soil Erosion With Focus On Ecosystems – modelv2jc". In this first phase, the package only considers parameters for the ecosystem service Stability of Hillsides.

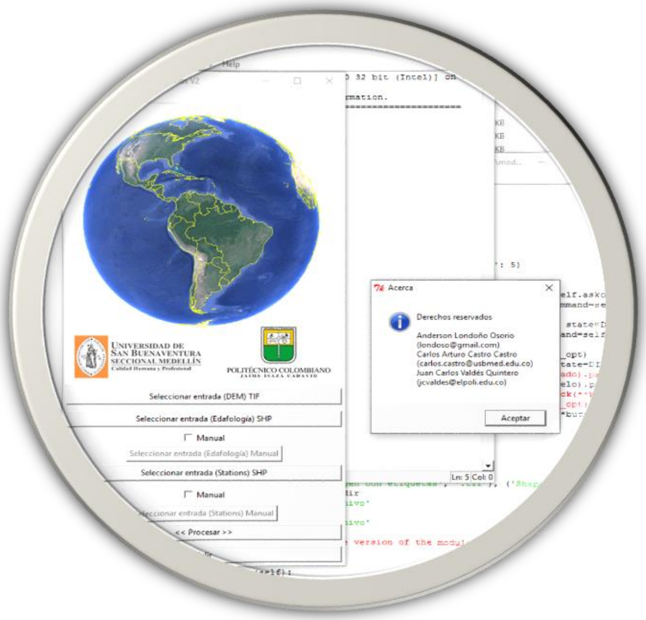

Figure 10. Geoinformatics Python-GIS Tool For Simulating And Analyzing Soil Erosion With Focus On Ecosystems.

For the labor of software design, a group of informatics and GIS experts participate, following a flexible Agile Unified Development (see Figure 11) Methodology, comprising 8 stages.

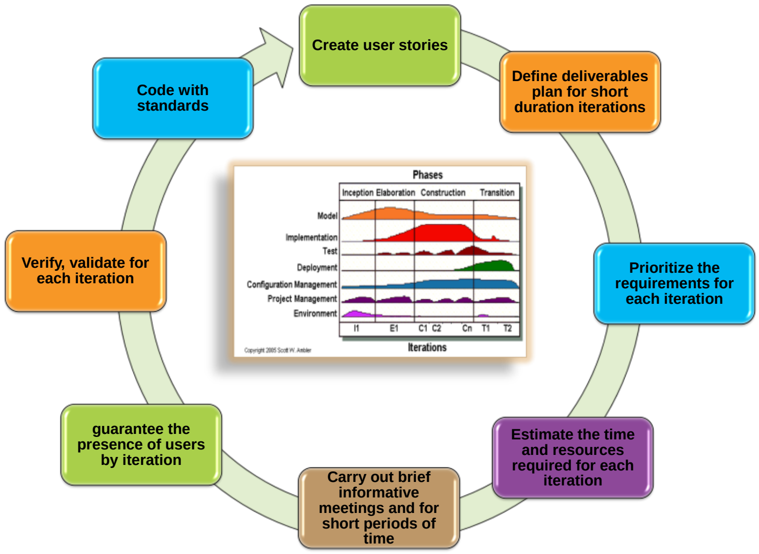

Figure 11. Agile Methodology applied to creation of Geoinformatics Python-GIS software.

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