Dynamic model for the management of water resource and water aptitude for irrigation of the Togllahuayco gorge in the Guangopolo micro-basin

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Abstract. Water management is one of the fundamental principles for comprehensive management and water security and is affected in various ways by the degradation of watersheds, mainly the agriculture sector due to the reduction of water resources and soil erosion. The objective of this research was to implement a dynamic model for the water management of the Quebrada de Togllahuayco as a modeling and dynamic prediction tool and thus determine the quantity of water available for a sustainable quinoa crop and the adaptation to future conditions. This work involves the use of dynamic modeling applied to water supply for irrigation with a general model and the application for the ancestral population of La Toglla. A trend model with incidence of climate change and a current one under the initial variables is proposed. The Vensim 7.3.4 free software was used, determining a positive water balance to satisfy the needs of water, both to preserve the ecological flow and to use water for irrigation, since approximately 10,500 m³ is needed for cultivation, which is favorable for the use of water.

1. Introduction
Nearly half of the world's population is affected in various ways by the degradation of watersheds. In general, all these basins present serious problems of ecological deterioration and in fact soil erosion can have devastating effects for the numerous inhabitants of rural areas who depend on agriculture [1]. Thus, the volumes of available fresh water for agricultural use and urban-industrial worldwide have declined considerably, this is a consequence of the excessive use of surface and groundwater for agricultural irrigation for the production of food from a growing population [2]. Currently, available water sources cannot meet the growing demand. Water scarcity is deeply linked to food security, therefore, the irrigation system can play an important role for food security and sustainable income, specifically in developing countries [3].

1.1. Initial diagnosis
Currently due to the deterioration of vegetation, deforestation, the introduction of exotic species, the
use of water springs as livestock water troughs and seasonal availability of the river bed do not make it feasible [4]. For this reason, the water circulating in this micro-basin is not used by the 7,000 people that make up the community ancestral of the Toglla located to the skirts of the Hill Ilaló whose volcanic past has originated edaphological formations with physical and chemical characteristics that impede its tillage [5].

1.2. Type of soil and need for water for irrigation
The cangahua, a Quechua word meaning “hard sterile earth” is a geological formation derived from the quaternary pyroclasts, which is found on the surface of the soil with a high degree of hardening, usually found on the middle and lower flanks of a volcano [5]. This is how irrigation water is either diverted from the streams or pumped from the wells of the tubes, contains appreciable amounts of harmful substances in solution that can reduce crop yields and impair soil fertility [6].

1.3. Type of crop to be implemented
Given the high nutritional quality of quinoa and its ability to withstand extreme environmental conditions, FAO has selected quinoa as one of the crops destined to offer food security in the 21st century. In addition, in the last decade, quinoa has gained a place in international consumer markets, which opens economic opportunities for Andean producers in Ecuador [7]. The quinoa crop prefers a loamy soil, with good drainage and high content of organic matter, with moderate slopes and an average content of nutrients, since the plant is demanding in nitrogen and calcium, moderately in phosphorus and little in potassium [8].

1.4. Dynamic model
They are necessary, models capable of reproducing the temporal evolution of the states of the system, that is, dynamic models that adapt to changing conditions. Complex systems are subject to high uncertainty, so one of the most used techniques for modeling are simulators, which allow studying and predicting the behavior of the system under different scenarios and initial conditions. In this way, the systems approach and the dynamic modeling applied to water management is one of the most active fields of research and technological development [9,10].

The main problem is the lack of use of water resources and ignorance of the quality and quantity of water available for agricultural use. The objective of this study was the implementation of a dynamic model for the water management of the Togllahuayco stream and thus determines the amount of water available for cultivation and the future trend under conditions of climate change and growth of water demand.

2. Materials and methods
2.1. Determination of the study area
The area of study of the Togllahuayco gorge (figure 1) located in the parish of Guangopolo Quito Canton, which occupies 551 ha on the slopes of Ilaló, limited by the parishes of Tumbaco, Alangasi and La Merced, the altitude of the Togllahuayco gorge presents a range of 2370 to 2785 meters above sea level. Its climate is temperate and humid, oscillates from 16 Celsius degrees on average and sometimes it is hot on sunny days, reaching to mark the 23°C of temperature, as well as at night it goes down to 8°C. It is subject to two seasons, winter is rainy season and summer is dry season [11]. The hot season is shown during the months of June to September and is characterized by a somewhat prolonged drought and strong winds increasing the temperature, while the months of increased rainfall increase the humidity being these torrential and continuous [12].

The map was prepared in ArcGIS software, which is licensed 10.3.1 in the Computer Lab of the Faculty of Engineering in Geology, Mines, Petroleum and Environmental.
2.2. Description of the dynamic model developed

To analyze the problem regarding the availability of water resource applied for irrigation in the Togllahuayco gorge, a dynamic modeling was carried out with Vensim free software 7.3.4 The general scheme of the model presents a complex network of diverse variables, which are interrelated carrying out a complex analysis of data in a realistic scenario, this in turn generates a balance between the availability of water in the micro-basin and the demand for irrigation water potential. It is important to mention that the model was adjusted to the reality of the micro basin and data provided by the residents of the Ancestral Community of La Toglla were taken, both for the cultivation area and for the type of crop.

2.2.1. Hydric balance. The "Thorhwaite" method was used to estimate the water balance, in which the variables of rainfall, evapotranspiration, surface runoff and infiltration intervene \[13\]. For the determination of rainfall, data provided by INAMHI was used \[11\] of the variables rainfall and temperature of the La Tola M002 station. Meteorological data from a period of 27 years were used and the average annual rainfall was obtained, according to the rainfall. The value of the runoff was obtained from the research carried out by \[14\] the result obtained is the average annual volume of runoff applied to the Togllahuayco ravine.

2.2.2. Climate change and ecological flow. The rate of decrease in rainfall due to the effects of climate change is a reduction of 0.6% per year for the city of Quito, calculated until the year 2040, this produces a decrease due to the same factor of the infiltration variable and in the amount of water that drains through the micro-basin and in the same period there is a temperature increase of 1°C according to the modeling methodology TL959, producing an annual evapotranspiration increase of 1 mm \[15\].

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**Figure 1.** The Togllahuayco gorge.
data that will serve for the scenario of future modeling.

2.2.3. Crop. In an interview with the villagers, Paul Dehausse is their representative [16]. He said that the area designated for the recovery of the land for cultivation is 2.5 ha, also live barriers and fruit trees will be installed. The main crop to be made corresponds to a quinoa plantation [8]. This crop is suitable for geographical areas ranging from sea level to 4000 m.s.n.m., in areas with rainfall from 0 mm to 1000 mm. In soils of different textures and with a pH range that fluctuates between 4 and 9 [17]. The harvest time of quinoa is 7 to 8 months and each plant occupy 0.1 m$^2$. It requires 1000 m$^3$ of water per hectare for the production of quinoa, being one of the most efficient to use water and resists a large amount of chlorides [18]. Based on all the characteristics described above, quinoa cultivation is considered as a feasible alternative to develop in the field.

3. Results and discussion

3.1. Dynamic model

The dynamic model in detail was carried out annually with a simulation period until the year 2040, determining the annual average variables as shown in figure 2 and it shows a complex network of different variables, which are interrelated to carry out a complex analysis with linear and exponential relationships. It is observed that there are data that converge, and the collection of information is distinguished in:

- Hydric balance with the variables of evapotranspiration, runoff, rainfall and infiltration.
- The ecological flow and the availability of water
- Agricultural use

![Figure 2. Dynamic model.](image)

The variables used in dynamic modeling can be found in the table 1.

From the introduced variables, the amount of water needed for irrigation of quinoa for cultivation period of 8 months is 10500 m$^3$ for the 2.5 ha planned for cultivation and the micro-basin, it receives 777263 m$^3$ annual, and so the availability of water is quite good and can be used for irrigation in the crop proposed by the community.
Table 1. Data for the simulation model for water management in the Togllahuayco and sources of information consulted.

| Variable                                      | Units           | Description and information source                                                                 | Value model |
|-----------------------------------------------|-----------------|-----------------------------------------------------------------------------------------------------|-------------|
| Rate of decline due to climate change         | Year            | [15] Report the reduction of climate change for the city of Quito in 15% annual rainfall and increase of 1°C to 2040. | 0.6%        |
| Annual average infiltration                   | $m^3 \text{ } m^{-2} \text{ } year^{-1}$ | Estimating infiltration was used by the method reported by [19] and method Thorhwaite [13]. The infiltration coefficient for the cangahua of [20] as well as data from INAMHI [11] | 0.398       |
| Annual average evapotranspiration             | $m^3 \text{ } m^{-2} \text{ } year^{-1}$ | For evapotranspiration, the Thorhwaite method reported in [13] and the interannual average temperature of INAMHI were used [11] | 0.28        |
| Annual rainfall                               | $m^3 \text{ } m^{-2} \text{ } year^{-1}$ | The average annual publication was obtained from INAMHI [11] of a series of 27 years at La Tola station | 0.846       |
| Average annual runoff                         | $m^3 \text{ } m^{-2} \text{ } year^{-1}$ | The average annual runoff by indirect methods in the Togllahuayco ravine [14] | 0.168       |
| Infiltration in the watershed                 | $m^3 \text{ } m^{-2}$ | Infiltración en la microcuenca que resulta de la multiplicación de la infiltración media anual por la superficie | 2189000     |
| Evapotranspiration in the watershed           | $m^3$           | Evapotranspiración en la microcuenca que resulta de la multiplicación de la evapotranspiración promedio anual por la superficie. | 1540000     |
| Rainfall in the watershed                     | $m^3$           | Rainfall in the micro-basin that results from the multiplication of the annual average rainfall per area. | $4.7 \times 10^6 \text{ }$a |
| Runoff in the watershed                       | $m^3$           | Infiltration in the micro basin that results from the multiplication of the average annual infiltration by the surface. | $9.2 \times 10^5 \text{ }$a |
| Catchment                                      | $m^2$           | Value obtained through geographic information system software reported in [14] | $5.5 \times 10^3 \text{ }$a |
| Ecological flow                               | $m^3$           | The minimum flow for the preservation of the biodiversity of the area, was calculated with the equation obtained from [21] | $1 \times 10^5 \text{ }$a |
| Water supply for cultivation                  | $m^3$           | Amount of water that can be used for the crop after subtracting the ecological flow | $7.7 \times 10^5 \text{ }$a |
| Harvest time                                  | $\text{year}$   | Quinoa harvest time [17] | 0.7         |
| Crop area                                     | $m^2 \text{ } plant^{-1} \text{ } year^{-1}$ | Space used by a quinoa plant [17] | 0.1         |
| Cultivated area                               | $m^2 \text{ } año^{-1}$ | Cultivated area resulting from the multiplication of the number of plants per crop per area [16] | 25000       |
| Number of floors                              | plant           | Number of plants needed for the cultivated area [17] | 250000      |
| Water requirement                             | $m^3/m^2$       | Amount of water required for cultivation of quinoa [18] | 0.6         |
| Total water volume                            | $m^3$           | Total volume of water that gets broken the Togllahuayco | $9.2 \times 10^5 \text{ }$a |
| Unused water available                        | $m^3$           | Water that drains and is not used | $7.7 \times 10^5 \text{ }$a |
| Increase agricultural                         | año             | Possible increase of agricultural activity, auxiliary variable for modeling | 10%         |

*aInitial value before modeling*
The model complies with an annual design that is not considered periods of rain and drought, so it is advisable to develop a system to capture and collect water for the dry period as proposed [14].

3.2. Simulation model 2040
Variable climate change causes a reduction in rainfall, runoff and infiltration affecting the availability of water in the basin in the future also evapotranspiration is affected increasing 1 mm annually due to possible temperature increase 1°C expected 2040 and the model calculates annually the variations that exist in the micro-basin the same before the availability of water. For the simulation, the most representative variables were considered, among them the supply of water for irrigation (figure 3), the demand for water for cultivation (figure 4).

![Figure 3. Water supply for cultivation.](image1)

![Figure 4. Crop water demand.](image2)

The figure 3 presents the graph of water supply for the crop which is influenced by climate change, with a fall of 12.9% for 2040. figure 4 shows the volume of water for the crop required for 2040, for the simulation it was considered a 10% annual growth of cultivated areas. The reduction of the ecological flow and surface runoff are directly influenced by climate change, reducing its volumes by 13%, which directly affects the biodiversity that depends on the river bed, so measures must be taken to mitigate and increase resilience to this projection.

4. Conclusions
The modeling of adaptive dynamic systems for water management is useful for creating scenarios and making decisions in the future. The model for water management is a complex system due to the influence of many variables, but an alternative is presented in time with the simulation. The dynamic model applied to the Togllahuayco gorges presents a positive water balance to satisfy the needs of water both to preserve the ecological flow and for the use of water for irrigation since it is needed approximately 10500 m³ for the cultivation of quinoa for its entire cycle of production in the 2.5 ha destined for it and there is a surplus of 766000 m³ of water to be used in a future expansion of the cultivation area. The possible trend effect due to climate change was analyzed, demonstrating the reduction of resource availability in the future, so the agricultural project to be implemented must consider resilient systems for adaptation to climate change and with an adequate management and improvement of the soil can improve infiltration of water preventing erosion by solving the biggest problems of the study area and increasing the availability of the resource.

References
[1] FAO 2007. La nueva generación de programas y proyectos de gestión de cuencas hidrográficas.
[2] Carrera-Villacrés D C 2011 Salinidad en suelos y aguas superficiales y subterráneas de la cuenca evaporítica de Río Verde-Matehuala, San Luis Potosí. Montecillo, México. doi:10.13140/RG.2.2.14037.73443.
[3] Irfan M, Arshad M, Shakoor A and Anjum L 2014 Impact of irrigation management practices and water quality on maize production and water use efficiency J Anim Plant Scis 24 1518-24
[4] Peña J 2017 Modelo de gestión de las tierras comunitarias para el pueblo ancestral La Toglla-Guangopolo con criterios de sostenibilidad. Universidad de las Fuerzas Armadas (ESPE)
[5] Palacios Orejuela I F, Ushiína Huera D P and Carrera Villacrés D V 2018 Identificación de Cangahuas para su recuperación mediante estudio multicriterio y constatación in situ en comunas del volcán Ilaló Congr Ciency Tecnol ESPE 13 10-3
[6] Arshad M and Shakoor A 2017 Irrigation water quality Fertilizer Guide, Faisalabad, Pakistan A Bakhsh and M R Choudhry eds. (Islamabad, Pakistan) pp 145-60
[7] Jacobsen S-E and Sherwood S 2002 Cultivo de granos andinos en Ecuador. Informe sobre los rubros de quinua, chocho y amaranto. Quito, Ecuador 45-16. ISBN: 9978-22-258-8
[8] Gómez L and Aguilar E 2016 Guia de cultivo para la quinua, segunda. Lima: Universidad Nacional Agraria La Molina doi:10.1109/JCSSE.2017.8025923.
[9] Martínez-Austria P F and Vargas-Hidalgo A 2016 Adaptive dynamic model for urban water management [Modelo dinámico adaptativo para la gestión del agua en el medio urbano] Tecnol y Ciencias Del Agua 7 139-54
[10] Giacomoni M H, Kanta L and Zechezian E M 2013 Complex adaptive systems approach to simulate the sustainability of water resources and urbanization J Water Resour. Plan. Manag. 139 554-64
[11] Instituto Nacional de Meteorología y Climatología INAMHI 2017. Boletines Climáticos y Agrícolas. Available at: http://www.serviciometeorologico.gob.ec/
[12] GAD Parroquial de Guangopolo 2014. Plan De Desarrollo Parroquial 2011-2025. Quito-Ecuador
[13] Ordoñez J 2011 Balance Hídrico superficial Glob Water Partnersh South Am 44-1
[14] Carrera-Villacrés D, Ayala J, Carmona C, Garofalo M, Mastián F, Moyón Á and Haro M 2018 Caracterización hídrica de la cuenca hidrográfica Toglla con fines de conservación de bosques y producción agrícola Memorias Del Congr REDU VI 2018 278
[15] Rosales M 2013 Análisis Básico sobre la posible variacion de la precipitacion y de la temperatura bajo la influencia del cambio climatico en la ciudad de Quito. Universidad Central del Ecuador
[16] Dehousse P 2018 Entrevista a la comuna ancestral La Toglla
[17] Cazar Bohórquez P D and Alava Ríofrío H F 2004 Escuela Superior Politécnica Del Litoral (Espol) “ Producción Y Comercialización De Quinua En El Ecuador.”
[18] Vinces H 2014 Gobierno lanza programa Proquinua para optimizar recurso hídrico. Andí Agencia Peru Not.
[19] Carvajal R 2015 Estudio de viabilidad de cosecha de agua de lluvia en Reserva Conchal para su utilización en riego del campo de golf. Universidad de Costa Rica.
[20] Janeau J L 2014 Thèse, Déterminants physiques et biologiques de l’infiltration : cas d’étude de sols tropicaux en Africa, en Asie et en Amérique Latine.
[21] Washington R, Ortiz S and Aguilera E P 2015 Determinación de Caudales en cuencas con poco información Hidrológica Cienc Unemi 7 100-10