# GROUNDWATER FLOW MODELING USING iMOD FOR BARVA AND COLIMA AQUIFERS IN THE CENTRAL VALLEY OF COSTA RICA: VALIDATION OF A CONCEPTUAL MODEL USING TRACER DATA

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## Abstract

A stationary numerical model of groundwater flow was developed using iMOD to better understand the recharge processes within Barva and Colima aquifers (BCS), located in the northwestern region of the Central Valley of Costa Rica. Lithological information was used to develop a conceptual model representing the complexity of the system, defined as high transmissivities, low storage capacity, and steep hydraulic gradients.

Due to the lack of more detailed lithological and hydrometric data to perform robust calibrations, the system was studied by analyzing water flux dynamics using the iMOD particle tracer and water balance tools.

The validation process was done by comparing the results of each simulation with the potential recharge elevation (PRE) derived from the ages of existing noble gases (tritium/helium) at different wells and springs in the system. Tracer estimations indicate a groundwater age (GWA) ranging from 2.3 to 71 years.

Based on the tracer information, two hypotheses of PRE were evaluated. The first scenario (H01), with a PRE between 1,500 to 2,500 m a.s.l., and a second one (H02), with a PRE between 1,300 to 1,500 m a.s.l. Results from H01 were the most reliable: 77% of the particles dropped in the PRE were captured by the Lower Colima aquifer, with a GWA ranging from 1 to 45 years.

Although the results reflect the dynamic-complex fluxes, more information is needed to understand the influence of surface water and recharge rates on groundwater levels in order to improve and calibrate the model as a reliable water management tool.

**Keywords:** Costa Rica; iMOD; groundwater age and modelling; tracer data; water resources management.

## Resumen

Se desarrolló un modelo numérico estacionario de agua subterránea utilizando iMOD, para comprender la recarga del acuífero Barva y Colima (BCS), ubicados en el noroeste del Valle Central de Costa Rica. Con base en litología, se desarrolló un modelo conceptual que representa la complejidad del sistema, altas transmisividades, baja capacidad de almacenamiento y gradientes hidráulicos abruptos.

A falta de datos litológicos e hidrométricos para una adecuada calibración, el sistema se estudió analizando la dinámica del flujo de agua, mediante el uso del trazador de partículas y balance hídrico de iMOD. La validación se realizó comparando los resultados con la elevación de recarga potencial (PRE) derivada de las edades de gases nobles existentes (tritio/helio) en diferentes pozos y manantiales del sistema. Los trazadores indican una edad del agua subterránea (GWA) que varía de 2.3 a 71 años.

Basado en los trazadores, se evaluaron dos hipótesis de PRE. El primer escenario (H01), con un PRE entre 1,500 a 2,500 m.s.n.m y el segundo (H02), con un PRE entre 1,300 a 1,500 m.s.n.m.

H01, género resultados más confiables: 77% de las partículas depositadas en el PRE fueron capturadas por el acuífero Colima Inferior, con un GWA que varía de 1 a 45 años.

Aunque los resultados reflejan la compleja dinámica del flujo de agua, se requiere más información para comprender la influencia de las aguas superficiales y las tasas de recarga en los niveles de agua subterránea, con el fin de mejorar y calibrar el modelo para ser una herramienta confiable de gestión.

**Palabras claves:** Costa Rica; iMOD; edad del agua subterránea y modelado; datos de trazador; gestión de recurso hídrico.

## INTRODUCTION

The central region (CR) of Costa Rica is the most developed portion of the country, with a population of ~3,500,000 inhabitants and 80% of the industrial activity. The CR is bounded to the north by the Central Volcanic Range (CVR), to the south by the Escazú, Tablazo, Cedral, and Candelaria mountain ranges, to the west by the Aguacate formation, and to the east by the Talamanca Mountain Range. There are two valleys in the CR: the East Central Valley (ECV) and West Central Valley (WCV).

In the WCV are the urban centers of the counties of San Jose, the capital of Costa Rica, Heredia and Alajuela. These correspond to the upper and middle Virilla River watershed (part of the Tárcoles basin), and contains the largest aquifer system in the basin: the Barva-Colima aquifer system (BCS). The WCV is important regionally for groundwater recharge, and also provides drinking water supply to approximately 20% (1,000,000 inhabitants) of Costa Rica's population. In the WCV, there are 5,198 well extractions (2013), corresponding to 42% of the total of well extractions registered with the National Service of Groundwater, Irrigation, and Drainage (Servicio Nacional de Agua Subterráneas, Riego y Avenamiento – SENARA).

During the 2013 and 2014 dry seasons, surface water discharged from the Barva and Colima groundwater springs decreased by up to 65%, resulting in severe water shortages to roughly 65,000 inhabitants (Sánchez-Murillo, 2015). A decrease of 18% of the annual precipitation for the CV has been predicted through the end of the century (MINAE et al, 2008), increasing the vulnerability of drinking water availability in the region.

In order to improve the understanding of the BCS, an initiative was developed in 2014 by the National University of Costa Rica's (Universidad Nacional – UNA) Stable Isotope Research Group (UNA-SIL), the public drinking water company of the province of Heredia (Empresa de Servicios Públicos de Heredia – ESPH), and FUNDECOR. The project titled "Ensuring Sustainability and Water Security in the Central Valley of Costa Rica (COS7005)" was sponsored by the International Atomic Energy Agency (IAEA).

To accomplish the overall objective of the project, a hydrological and meteorological long-term monitoring network was established to collect stable isotope and noble gas data from a variety of water samples (wells, springs, rivers, and rainfall). The main outputs from the project were: i) water balances improvement, ii) mean transit time estimations in spring systems, and iii) a better understanding of groundwater and surface water interactions. The results provide the scientific background for future water resource plans and regulation within the Central Valley of Costa Rica (Sánchez-Murillo, 2015).

### Study site

The northern part of the WCV is a quaternary volcanic system formed by emissions from the craters of the Barva volcano, and other influences from the Poás and Irazú volcanoes. The study area is located between 1087000-1124000 N and 445500--527500 E (CRTM05) (Figure 1) and has an area of 473 $km^2$. The lithography is characterized by a high permeability in the layers of fragmented and igneous lava (Astorga et al., 2007).

To the north the area presents a variety of microclimates and an irregular topography that allows air masses to pass from the Caribbean Sea to Pacific Ocean the between the mountains and hills (Reynolds et al, 2009).

Precipitation patterns are defined by two seasons: the dry season, from December to April, and the rainy season, from May to November. The mean annual precipitation (MAP) for the area varies from 1,498 mm/year in the lowlands to 7,775 mm/year in the highlands near the Zurquí formation (CVR). The minimum value of the actual evapotranspiration (AET) is 458 mm/year, with a maximum of 1,439 mm/year. The minimum value of the potential evapotranspiration (PET) is 50 mm/year, with a maximum of 117 mm/year (Sanchez and Birkel, 2016).

The area is drained by both infiltration and surface runoff to a large number of rivers, with long, narrow catchments that exhibit complex influent-effluent relationships with the underlying aquifers (Foster, 1985). The soil is classified as silty-loam with a moderate water transmission ranges from 0.38 cm/hr up to 0.72 cm/hr (USDA, 1989).

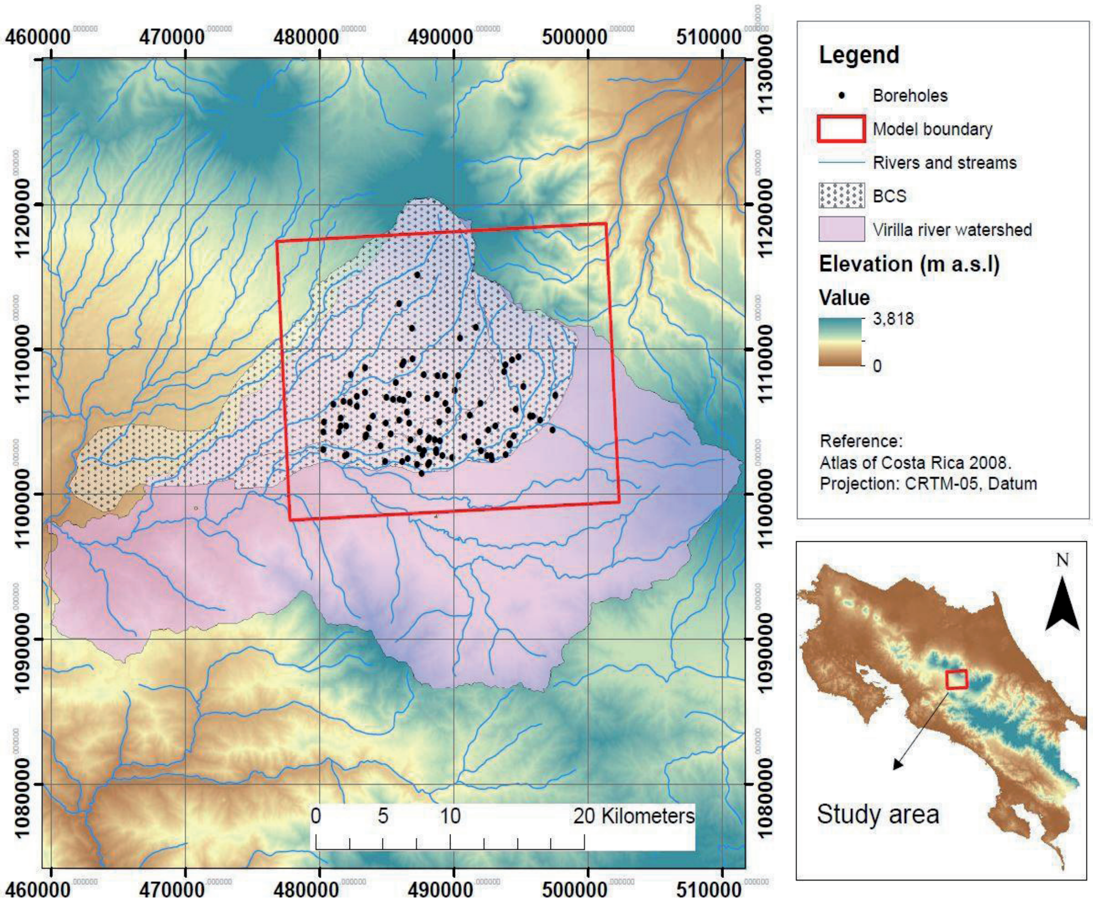


Figure1. Study area location.

## METHOD

A groundwater numerical model was developed for the BCS using iMOD. The numerical model relies on the conceptual model of the BCS, constructed from several previous studies in the area. The first part of the research was focused on transferring the lithological information into iMOD format to develop the different layers of the groundwater system. A steady-state approach was implemented.

During the running of the models, several limitations were encountered: a) the hydraulic parameter of the different units have a wide range of values assigned, depending on the author and the research performed, b) there was no information available to validate the conductance parameter between the rivers, the drainage systems, and the groundwater system, and c) there was only one inactive production well from the ESPH that could be used as an observation borehole. Due to the uncertainties in the amount of water entering and leaving the system, the system was studied by means of the behavior of the fluxes dynamic (using the particle tracker simulation tools and the water balance).

The results from the particle tracker were compared against the noble gas and tritium analyses performed, at different wells (N=15) and springs (N=3) in the system by UNA-SIL in collaboration with IAEA. This section describes the more relevant concepts of the BSC.

- Model boundaries: The boundary of the model was defined using the delineation of the BCS from the geological map of the CR (BGS-SENARA, 1985). The lowlands of the model range from 800 to 2,900 m a.s.l.
- Conceptual model: The conceptual model was built using the information of deep boreholes with sufficient information to explain the deep stratigraphy of the BCS. In the study area, there are 682 registered wells, of which only 15% of them had reliable information with core recovery. The majority of the boreholes are located in the eastern part of the BCS. This is due to the fact that in this area the deeper lavas formations have resulted in the most prolific aquifers from the WCV. The BCS is divided into three formations: Barva Formation (BF), Tiribi Formation (TF), and Colima Formation (CF). The BF and the CF are also divided in two aquifer units separated by an aquitard unit (Table 1).

Table 1. Lithological information used to create the groundwater model.

| Formation | | Units | Lithology | Thickness |
|---|---|---|---|---|
| BCS | BF | Angeles and Bambinos Aquifers | Lavas | 0- 35m |
| | | Carbonal Aquitard | Tuffs and clays | 0-20 m |
| | | Bermudez Aquifer | Lavas | 0-85 m |
| | TF | Tiribi Aquitard | Tuffs and ignimbrites | 0-100 m |
| | CF | Superior Colima Aquifers | Lavas | 0-185m |
| | | Puente Mulas Aquitard | Tuffs and ignimbrites | 0-35m |
| | | Lower Colima Aquifer | Lavas | 20-190 m |

- Hydraulic properties: Table 2 shows a summary of the main properties used during the evaluation of the model. The groundwater simulation was performed using the transmissivity of the aquifers in combination with the vertical resistance of the aquitards, while the porosity was used for the particle tracker tool.

Table 2. Hydraulic properties, BCS.

| Units | Transmissivity ($m^2/d$) | Conductivity (m/d) | Porosity (%) |
|---|---|---|---|
| Angeles and Bambinos Aquifers | 100 - 500 (1) | 0.6 - 100 (3)<br>1 - 10 (1) | 0.05-0.25 (5) |
| Carbonal Aquitard | | 1 - 10 (1) | 0.45 - 0.60 (5) |
| Bermudez Aquifer | 400 (3) -1,000 (2) | 1 - 10 (1)<br>0.6 - 100 (3) | 0.05-0.25 (5) |
| Tiribi Aquitard | | $2.75x10^{-4}$ – 1.16 (6) | 0.45 - 0.60 (5) |
| Superior Colima Aquifer | 5,000 (3) – 20,000 (4) | 214 (3) | 0.05-0.25 (5) |
| Puente Mulas Aquitard | | 0.02-0.5 (5) | 0.45 - 0.60 (5) |
| Lower Colima Aquifer | 4,500 (3) – 16,000 (4) | 214 (3) | 0.05-0.25 (5) |
| [1]Ramírez & Alfaro (2002) cited by Sanchez-Murillo (2016). [2]ONU (1975) cited by Vasquez, 2010. [3]Gómez (1987) cited by Vasquez, 2010 and Reynolds (2006). [4]Echandi (1981) cited by Vasquez, 2010. [5]Foster, 1985. [6]Ramirez, 2007. | | | |

- Extraction wells: 114 wells were used in the simulation, where 72% corresponded to domestic use, 11% to industrial use, 10% to other uses, 5% to irrigation, and 2% to the agro-industry. Of the 114 wells, 32% have an extraction rate that is higher than 864$m^3$/day; in accordance with the depth of the well screens, the main extraction comes from the CF (units 3 and 4 in the model).
- Surface and Drainage systems: The main rivers that flow year-round were included as perennial rivers in the model. There are also a number of ephemeral streams in the region, which were included as drains. For the main river of the Virilla watershed, baseflow measurements showed that the discharge of the springs and infiltration of the CF are estimated to be ~ 8$m^3$/s (SENARA (1998) cited by Vasquez, 2010).
- Recharge: the recharge of the system was generated using the curve number methodology (USDA, 1989), the type and use of the land from the Atlas of Costa Rica 2008 (Malavasi, 2008), and meteorological information (mean annual precipitation, actual and potential evapotranspiration) from Sánchez-Murillo and Birkel, 2016. The recharge calculation includes different rooting depths depending on the type of plants (Grassi (1976) cited by Schosinsky, 2006) and the agronomic parameters of the soil. Following the diffuse recharge methodology applied by Faneca et. al., (2016), the recharge rate obtained represented approximately 40% of the precipitation rate.

It is important to mention that the land use is a significant variable when estimating the recharge rate and for the current research, the information used corresponded to the official land use from 2008 (Table 3); however, the study area has suffered some changes from coffee plantation to urban areas. Therefore, the calculation of the recharge can be affected, since nowadays there are less areas that allow infiltration and more impermeable areas due to construction.

Table 3. Land use distribution in the study area.

| Land use distribution | Percentage[1] |
|---|---|
| Coffee plantations | 5.00% |
| Urban areas | 2.10 % |
| Woods and secondary forest | 76.50% |
| Deforestation | 16.52% |
| [1] Generated from the Atlas of Costa Rica, 2008 (Malavasi, 2009). | |

## RESULTS

The results were first evaluated looking at the general water balance and then at the detailed water balance per unit (in terms of volume), as well as at the quantity of water extracted from the drinking water production wells. To evaluate the numerical model and the sensitivity to the different components, the following steps were performed:

i) In the first set of simulations, a sensitivity analysis was performed for three scenarios: using the lower, the mean, and the higher values of the transmissivity and permeability values of the units. The best results (percentage of difference in the water balance) were obtained using the higher values of the transmissivity and permeability.

ii) The second set of simulations was performed changing the resistance flow parameter, which relates the conductance value for the rivers and drainage packages to the layer below. The best results indicate that the rivers in the headwaters recharge the aquifer system and in the lowlands drain the aquifers system, which is consistent with the findings from previous studies. The conductance value is a sensitive parameter for this numerical model.

iii) In the third set of simulations, a general head boundary was introduced at the lower (southern) part of the model. Since the study area does not contain the entire extent of the BCS, the flow within the systems will continue in the direction of the slope, so this was represented by a general head boundary for all of the units.

Since there was not sufficient data to validate the water levels obtained from the model, an interactive particle tracking analysis was introduced. This tool can be essential in understanding how a hydrogeological system works. For this part, two hypothesis locations were used as starting points of PRE.

The particles were introduced in the mountains of Heredia, on the northern slope of the Virilla River watershed. From hypothesis H01, the particles were placed from 1,500 to 2,500 m a.s.l, and for hypothesis H02, from 1,400 to 1,700 m a.s.l. With this tool, we can determine the time and the flow path of the particles from the surface at certain elevations to the different aquifer units, and determine which wells or other drainage features they are captured by.

Preliminary results indicate a residence time of 1 to 45 years for hypothesis H01 and between 1 to 400 years for hypothesis H02. The residence time of the UNA-SIL analysis varies from 2.3 to 71 years. Based on this premise, hypothesis H01 is producing recharge scenarios in accordance to the tracer results; therefore, it is plausible to argue that the PRE is indeed located between 1,500 and 2,500 m a.s.l, since 77% of the particles released in the PRE region of hypothesis H01 were captured by Lower Colima aquifer (Figure 2).

## DISCUSSION AND CONCLUSIONS

The numerical model developed represents the complexity of the conceptual model of the BCS. Results showed that the model still needs to be improved in order to approximate the residence time to the field results, but that the preliminary results represent the situation well. The relationship between surface water and groundwater is a sensitive variable for the model, since there are a large quantity of rivers and streams that could act as discharge or recharge elements.

To further improve the model, piezometers and monitoring stations in the river system should be implemented in order to have more accurate information to calibrate and validate the model and use it operationally as a water resources management tool.

ESPH and UNA-SIL should continue their research program to expand the lithological database of the model, to understand the relationship between surface water and groundwater, to improve the recharge calculations, and to enhance the use of isotopic data. The isotope analysis has contributed so far to understanding the complexity of the BCS.

Once the model is ready to be used operationally, it will complement the hydro-meteorological and isotopic monitoring network implemented in the study area since 2014. The efforts of the ESPH and UNA to improve the knowledge of the BCS will provide a technical tool based on scientific knowledge to work towards an integrated water resources management. It may also be used in the future for mid- and long-term planning by analyzing different climate scenarios.

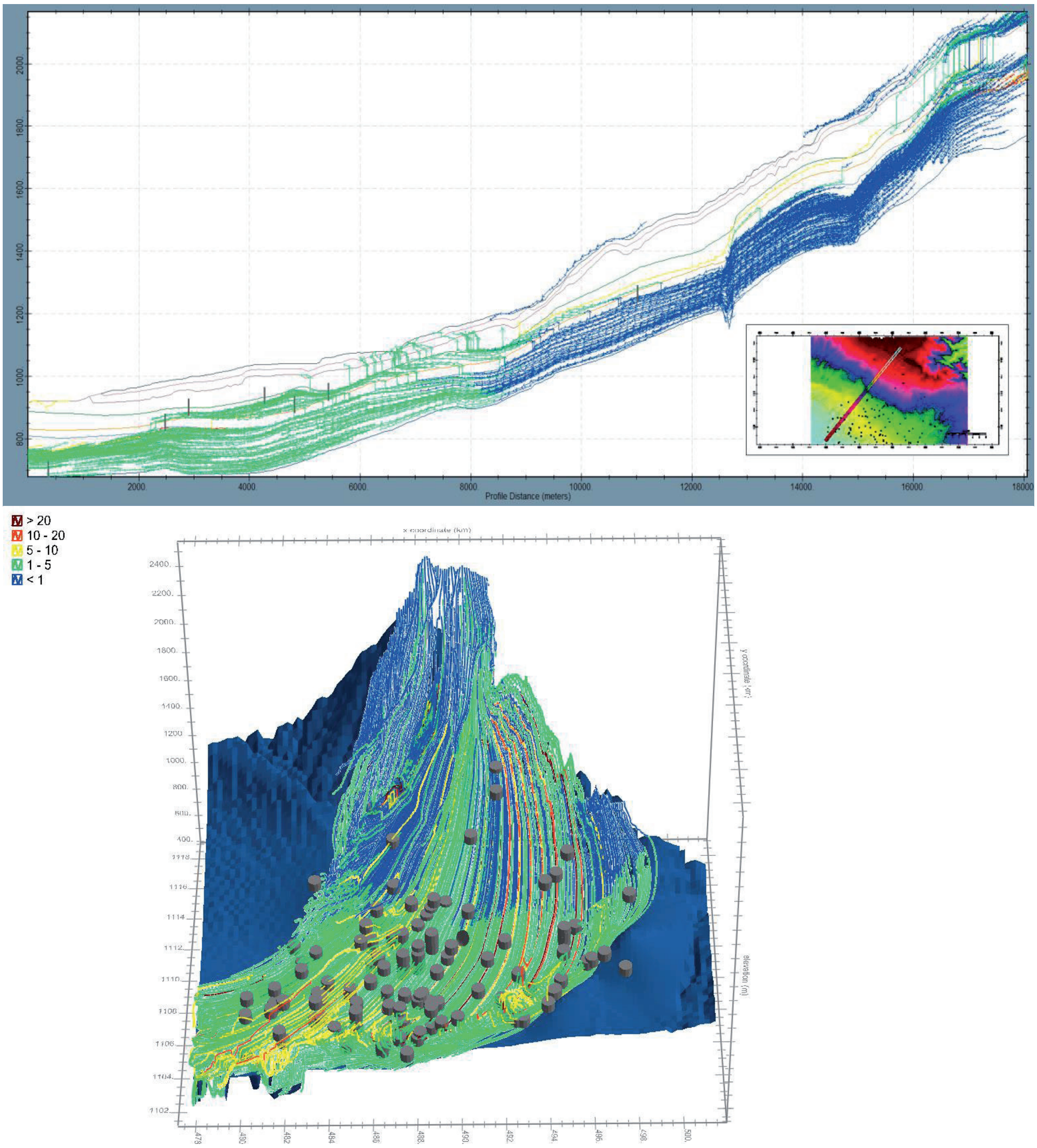


Figure 2. H01-simulated particles from the BCS model. Cross-section of the path lines of the particles (top) and 3D distribution of the particles in the BCS model (bottom).

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