Linguistic and Philosophical Investigations
ISSN: 1841-2394, e-ISSN: 2471-0881
Vol 23 (1), 2024
pp.3308-3321

Spatial modeling of climate change in watersheds: Systematic review

Juan David Herrera Galviz[1], Olga Lucía Ocampo López[2], Juan Carlos Hernández Criado[3]
[1]Universidad Autónoma de Manizales, Manizales – Colombia.
[2]Universidad Autónoma de Manizales, Manizales Colombia.
[3]Universidad Francisco de Paula Santander Ocaña, Ocaña – Colombia.
DOI: https://doi.org/10.5281/zenodo.17066800

Abastract

Climate change modeling in watersheds is part of the technical inputs that enable land-use planning processes to be developed from an environmental perspective. In these modeling processes, techniques that combine the use of mathematical methods and software are a clear trend in new methodologies, which are constantly being optimized. Spatial modeling techniques are widely used in the modeling of environmental systems, as they relate the representation of these systems to mathematical models. Based on this principle, dynamics in environmental systems such as land use changes, forest fires, water quality, deforestation, and even land urbanization processes have been modeled. In this regard, there is particular interest in understanding the applicability of spatial modeling techniques in climate change modeling processes in watersheds, considering watersheds as environmental systems in which the dynamics of different phenomena are present. Thus, the objective of this systematic review is to establish the state of the art regarding the aforementioned interest. To this end, basic bibliometric analysis techniques were used, combining the usability of scientific and academic information databases with software tools such as VosViewer, which allowed us to identify clusters of topics related to the subject addressed in this review.The review of hydrological modeling in basins under climate change showed a predominance of the Markov technique, models such as SWAT and GCM, and advanced statistical methods, revealing gaps in uncertainty analysis, spatial and temporal resolution, and studies applied to Colombia.

Keywords:climate change, spatial modeling, systematic review, VosViewer, watersheds.

1. Introduction

Knowledge of climate risk is a pillar of management at the international and national levels (Bastidas Pacheco et al., 2019). Climate change is articulated with disaster risk management in the reduction of the vulnerability of ecosystems and communities by virtue of the knowledge of threats and the definition of adaptation strategies such as early warning systems and sectoral actions, considering the dynamics of climate variability and its intensification associated with climate change (Intergovernmental Panel on Climate Change - IPCC, 2022). The Disaster Risk Management System (Congreso de La República, 2012), the climate action law (Congreso de La República, 2021) and the climate change policy (Ministerio de Ambiente y Desarrollo Sostenible, 2016), establish the need for studies that can be articulated in territorial planning instruments. For their part, the comprehensive climate change management plans of the mining and energy (Ministio de Minas y Energía, 2018), agriculture (Ministerio de Agricultura y Desarrollo Rural, 2021), Housing and Territory sectors prioritize knowledge of climate risk as a sectoral and territorial need.

Knowledge of climate risk suggests the need for technical studies at the territorial unit level, with river basins being the most appropriate territorial units for such studies, since it is easier to visualize the impacts of climate change on hydrological dynamics and their relationship with changes in land use. In these studies at the watershed level, modeling processes are usually developed with technological tools that facilitate the understanding of the dynamics of the phenomenon and make it possible to project prospective scenarios to understand the future behavior of the phenomenon under study.

This is the main motivation for establishing the state of knowledge on the use of the spatial variable in climate change modeling studies in watersheds. In other words, there is an interest in knowing how much geographic information has been used in climate change scenario modeling processes in territorial units such as watersheds, and what type of techniques are most used in these processes.

2. Methodology

In order to carry out the review process, inclusion criteria were established for all studies developed in river basins that included processes of analysis of climate change dynamics and methodologically described the use of some spatial modeling technique. The studies could be developed in any river basin of any continent. In this sense, the main exclusion criterion corresponded to studies not developed in river basins, such as studies developed in urban areas or in other units of territory. The studies were grouped by continent, i.e., studies from Asia were grouped together, as were studies from Europe, Africa, North America (Canada and the United States) and Latin America.

For the development of the review, Scopus was used as the main database for the search. This database was considered because of the amount of high impact information available, the ease of access through available subscription, and the robustness in the deployment of filtering tools and basic analysis of bibliographic information metrics. As for open access databases, google scholar was considered, since other databases were reviewed, such as Reference, which has very little information available and records found in scholar, while in the case of Microsoft Academic, it is no longer available for consultation. In addition, Scholar is linked to different repositories such as Scielo, Redalyc, DOAJ, institutional repositories of Universities, among others.

Initially, it was decided to use Elsevier's Topics thesaurus to define the keywords that would integrate each search equation. In this thesaurus, it was decided to start with an equation that would yield denser results, which was made up of the following keywords in English: climate change AND watershed AND Spatial Modeling; in Spanish: cambioclimático AND cuencahidrográfica AND Modelaciónespacial.

Both Scopus and Google Scholar used these search equations. In Scopus, the only filter used was the publication date filter and the language filter, establishing the search filter for studies from the last five years in English, as in Scholar, where in addition to this filter, only works published in Spanish were activated.

Once the resulting metrics and some of these studies obtained in the search process were verified, it was established to filter studies from the last five years, with special interest in studies published in the years 2020 to 2022.

The search equation visualized results that were not so abundant, especially in scopus, which were reduced by applying the publication temporality filters. By developing the above, a smaller number of results were displayed from which the previously described eligibility criteria could be applied. As an automation tool, the VosViewer software was used to review the clusters obtained in concurrence with the search equation used, identifying some clear research trends.

In each selected study, data on methodology, results and conclusions were collected, initially reviewing their summaries and going deeper into each section respectively. As mentioned above, VosViewer was used as an automation tool where csv format data obtained from Scopus were loaded to visualize concurrence clusters and co-authorship maps. These clusters made it possible to identify the studies with the greatest affinity to the established eligibility criteria and, in this way, the data were cleaned. It is important to note that the clusters were corrected by incorporating a thesaurus to replace duplicate records in keywords that were synonyms.

The following is a part of the data list used for the visualization process of concurrence and co-authorship maps in the Vosviewer tool, based on Scopus:

Table 1. List of references analyzed

Authors	Author(s) ID	Title	Year	Source title
Naulleau A., Gary C., Prévot L., Vinatier F., Hossard L.	57220090691;7006855206;7006604024;32267700800;26532629200;	How can winegrowers adapt to climate change? A participatory modeling approach in southern France	2022	Agricultural Systems
Menna B.Y., Waktola D.K.	57299637400;55337475200;	Extreme temperature trend and return period mapping in a changing climate in Upper Tekeze river basin, Northern Ethiopia	2022	Physics and Chemistry of the Earth
Fox J.T., Magoulick D.D.	57198663634;6602343673;	Hydrologic and environmental thresholds in stream fish assemblage structure across flow regimes	2022	Ecological Indicators
Aieb A., Kadri I., Lefsih K., Madani K.	57206270756;57425817400;54400264100;25923554600;	Spatiotemporal trend analysis of runoff and actual evapotranspiration in Northern Algeria between 1901 and 2020	2022	Modeling Earth Systems and Environment
Hachemaoui A., Elouissi A., Benzater B., Fellah S.	57695342100;57188669118;57209021345;57694123400;	Assessment of the hydrological impact of land use/cover changes in a semi-arid basin using the SWAT model (case of the Oued Saïda basin in western Algeria)	2022	Modeling Earth Systems and Environment
Soomro A.G., Shah S.A., Memon A.H., Alharabi R.S., Memon D., Panhwar S., Keerio H.A.	57205656484;57216730761;57949397100;57948541800;57949274200;57196185567;57214450708;	Cascade Reservoirs: An Exploration of Spatial Runoff Storage Sites for Water Harvesting and Mitigation of Climate Change Impacts, Using an Integrated Approach of GIS and Hydrological Modeling	2022	Sustainability (Switzerland)
[No author name available]	[No author id available]	Corrigendum to "A review of spatial statistical approaches to modeling water quality"(Progress in Physical Geography: Earth and Environment, (2022), 10.1177/03091333221118363)	2022	Progress in Physical Geography
Sun J., Hu L., Liu X., Sun K.	57226157323;14012430500;57200535392;57195681004;	Enhanced Understanding of Groundwater Storage Changes under the Influence of River Basin Governance Using GRACE Data and Downscaling Model	2022	Remote Sensing
Al-Chokhachy R., Letcher B.H., Muhlfeld C.C., Dunham J.B., Cline T., Hitt N.P., Roberts J.J., Schmetterling D.	11440640300;6701770364;6602958349;7004856985;41561110800;6602303849;8625928700;6602570834;	Stream size, temperature, and density explain body sizes of freshwater salmonids across a range of climate conditions	2022	Canadian Journal of Fisheries and Aquatic Sciences
Ferreira Filho D.F., Pessoa F.C.L.	57561807700;56105109300;	Identification of homogeneous regions based on rainfall in the Amazon River basin	2022	International Journal of Climatology
Girma R., Fürst C., Moges A.	57241893400;55971391700;35611913600;	Performance evaluation of CORDEX-Africa regional climate models in simulating climate variables over Ethiopian main rift valley: Evidence from Gidabo river basin for impact modeling studies	2022	Dynamics of Atmospheres and Oceans

Authors	Author(s) ID	Title	Year	Source title
Ren Y., Zhang F., Li J., Zhao C., Jiang Q., Cheng Z.	57340462900;57217293570;57340357400;56718861100;57813962000;57813962100;	Ecosystem health assessment based on AHP-DPSR model and impacts of climate change and human disturbances: A case study of Liaohe River Basin in Jilin Province, China	2022	Ecological Indicators
Amponsah W., Dallan E., Nikolopoulos E.I., Marra F.	56968147600;57200622200;25228997600;56256597400;	Climatic and altitudinal controls on rainfall extremes and their temporal changes in data-sparse tropical regions	2022	Journal of Hydrology
Ray A., Pandey V.P., Thapa B.R.	57733179900;35325070000;57189466751;	An assessment of climate change impacts on water sufficiency: The case of Extended East Rapti watershed, Nepal	2022	Environmental Research
Hao X., Ouyang W., Zhang K., Wan X., Cui X., Zhu W.	57194649493;8945084300;57703340800;57211683742;57208664994;35108598300;	Enhanced release, export, and transport of diffuse nutrients from litter in forested watersheds with climate warming	2022	Science of the Total Environment
Anselmetto N., Sibona E.M., Meloni F., Gagliardi L., Bocca M., Garbarino M.	57297784800;55857742000;50961407000;57298386100;16686510700;26039059300;	Land Use Modeling Predicts Divergent Patterns of Change Between Upper and Lower Elevations in a Subalpine Watershed of the Alps	2022	Ecosystems
Kluver D.B., Robertson W.	25927156100;55480611900;	Validation and Projections of Climate Characteristics in the Saginaw Bay Watershed, MI, for Hydrologic Modeling Applications	2021	Frontiers in Water
Caro A., Condom T., Rabatel A.	57218627169;6506678027;9276067100;	Climatic and Morphometric Explanatory Variables of Glacier Changes in the Andes (8–55°S): New Insights From Machine Learning Approaches	2021	Frontiers in Earth Science
Baccour S., Albiac J., Kahil T., Esteban E., Crespo D., Dinar A.	57209102770;6507537454;57225204351;42061376100;57209096218;7004108044;	Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the Ebro River Basin, Spain	2021	Journal of Cleaner Production
Wallace C.D., Tonina D., McGarr J.T., de Barros F.P.J., Soltanian M.R.	56344124800;16029924900;57275165200;13408651800;56496948000;	Spatiotemporal Dynamics of Nitrous Oxide Emission Hotspots in Heterogeneous Riparian Sediments	2021	Water Resources Research
Akstinas V., Virbickas T., Kriaučiūnienė J., Šarauskienė D., Jakimavičius D., Rakauskas V., Negro G., Vezza P.	57190686572;23020433800;6507007542;6506514917;36499261100;30567709200;57223203794;35306061800;	The combined impact of hydropower plants and climate change on river runoff and fish habitats in lowland watersheds	2021	Water (Switzerland)

It is important to note that the above list shows the result of all the studies obtained from the application of the search equation, corresponding to Climate change AND Watershed AND Spatial modeling. These results correspond only to scopus, because google scholar results cannot be grouped and exported in this way, taking into account that this database has a very basic interface.

3. Results

For the search equation: Climate Change AND Watershed AND Spatial Modeling, the results with the filters applied and described in the search strategy section were:
Scopus: 595 documents
Google Scholar: 5,320 documents
In order to address the review, it was decided that the minimum number of manuscripts to be included in the consolidation of results would be fifty articles.
From Scopus, two studies met many criteria but were excluded due to duplicate publication, i.e., they were studies that were published in conference proceedings and at the same time in a journal.
The documents found in Google Scholar were also excluded because they did not meet the eligibility criteria, i.e., some addressed the issue of climate change in a watershed but did not include spatial modeling. Others included spatial modeling studies but did not include anything related to watersheds or climate change.
When performing the analysis with VosViewer, it can be deduced that studies focused on the use of the spatial component in climate change modeling and analysis processes in watersheds project the use of techniques such as Markov, Mann–Kendall trends, coefficient of determination, correlation coefficient, among others, results that are articulated with the simulation of climate change scenarios. However, very few studies show the use of spatial modeling in the analysis of climate change impact in Latin American watersheds, which reinforces the premise of knowledge gaps and the need to address these studies from a scientific research perspective.
One limitation in the development of the study is the lack of information on the applicability of spatial modeling techniques in Latin American basins. This highlights the fact that there is considerable dispersion among the different clusters identified, as shown in the following figure:

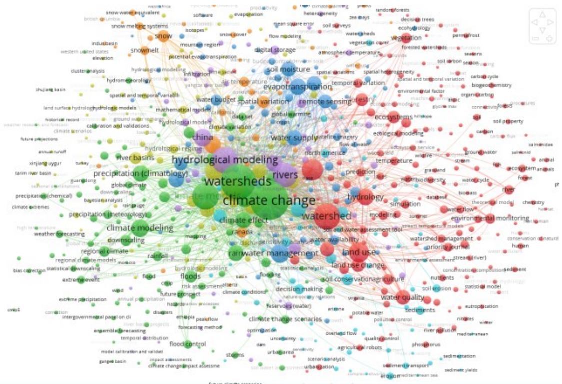

Figure 1. Concurrency analysis in VosViewer.

In the image above, there is a main cluster corresponding to climate change, another cluster corresponding to river basins, and a cluster corresponding to climate models. There are many relationships between clusters due to the density of information consulted and the number of keywords outlined in the articles taken for analysis in the VosViewer tool.
Another very important point to highlight is the small number of authors who have published on this topic, as shown in the following map, most of whom are from China and the United States.

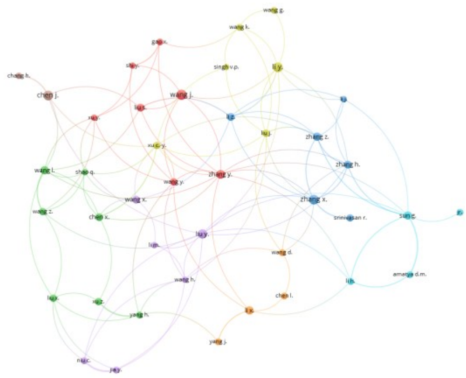

Figure 2. Co-authorship analysis in VosViewer.

It is important to note that a significant number of the studies included were conducted in Asia and the United States, and therefore most of the authors who make up these co-authorship networks come from that geographical location, which also greatly limits the number of studies included in the review. A final issue to highlight is that some of the studies were conducted in the same area or river basin under study, which reduces the geographical diversity of the selected studies.

3.1. State-of-the-art findings in climate change modeling in watersheds

Climate change modeling studies in watersheds take various approaches that integrate the spatial component using different modeling techniques to understand the dynamics of the environmental system based on multiple indicators related to climate change, hydrometeorological variables, land use, and other variables at the watershed scale. Various studies have been conducted internationally, as described below:

In Asia, Ray, Pandey, and Thapa (2022) evaluated the spatial-temporal distribution of water availability in the Greater East of the Rapti basin in Nepal; specifically, they focused on the "Palika" (local government unit) as a spatial scale and future seasons and periods as a temporal scale. Water availability was assessed based on the relationship between water supply and the water stress index. The results showed a projected decrease in water availability by mid-century of 40% in relation to water supply and 61% in relation to the water stress index. Despite the projected decrease, annually available water resources are projected to be sufficient to meet demand until mid-century; however, seasonal variability and future scarcity were established in the basin.

Park et al. (2008) conducted a study in the Presa Basin, South Korea, using the SWAT-K model and data series for the period 1990–2006 to establish the behavior of hydrological components, evapotranspiration, soil moisture content, groundwater recharge, dam inflow, and land use. This study used the Markov technique to identify land use dynamics from Landsat satellite images. On the other hand, Park et al. (2008) applied the SLURP model to agricultural reservoirs in Geumgwang and Gosam, South Korea, to assess the impacts of climate change; they used the Markov technique to analyze land cover scenarios based on time series of Landsat images. Similar to the previous study, the SLURP model was used in an urbanized basin in South Korea to determine the future impact of climate change on water flow and recharge (So-Ra et al., 2008). The Markov technique was also used to model land use.

In the case of Adnan et al. (2022) investigated the spatiotemporal variations in runoff and runoff components in response to the impacts of climate change on the flows of the Gilgit River in China from 1981 to 2020 using a basin model proposed by the University of British Columbia (BCU-MW). They used three statistical indices—Nash-Sutcliffe efficiency, correlation coefficient, and coefficient of determination—to evaluate the model's performance in simulating flows. Based on trend analysis, they found a significant increase in all runoff components with interannual variations in their relative contributions to flows for the analysis period.

Specifically, Coulthard et al. (2008) analyzed the two-dimensional CAESAR model, which simulates the geomorphological response of basins and rivers to changes in climate and land cover at different scales; they simulated the presence of hydraulic works interfering with the channel, flow, and transport of sediments and the effect on the riverbed.

Akhtar et al. (2022) evaluated the performance of the SWAT soil and water assessment model using statistical indicators including Kling-Gupta efficiency (KGE), Nash-Sutcliffe efficiency (NSE), and the coefficient of determination (R^2) in the Kabul River basin in Afghanistan, where they also analyzed streamflow under climate change scenarios, considering representative concentration pathways (RCP) 4.5 and 8.5 for the period 2020-2045. They found that, due to the heterogeneous nature of the basin, only the Kling-Gupta efficiency index performed well.

Cai & Wang (2010) used cellular automata through artificial neural networks to model existing behavior and project future behavior of vegetation cover in the Yellow River basin in China. They included Geographic Information Systems and Remote Sensing in this modeling, with optimal results for decision-making in local governments.

Tian et al. (2020) evaluated runoff dynamics from the impact of projected climate variability in the Hanjiang River basin in China. They analyzed land use using the Markov technique and modeled the hydrological process with SWAT using climate change scenarios. They estimated the increase in forest cover and land for construction in the period from 2010 to 2050, and the decrease in agricultural land and grassland cover. Chanapathi&Thatikonda (2020) also used Markov chains to model changes in land use in the Krishna River basin in India, and thus assess the combined impact of climate change and land use change, with and without water storage structures, on water balance components; they conclude that simulated land use changes can influence streamflow compensation by 20 to 30% with reference to observed flow.

Limbong et al. (2021) analyzed precipitation using a CSIRO Mk3.5 general circulation model in the upper reaches of the Kelara River basin; They considered the analysis of estimated land cover change using a combination of geographic information systems, remote sensing, and the Markov chain method with Landsat images, and the prediction of erosion rates using the Universal Soil Loss Equation method. They found that land use changes are insignificant in the period 2006–2016 but significant by 2026.

Rasoolzadeh-Darzi et al. (2021) developed a soil erosion risk simulation under climate change and land use scenarios in northern Iran in the Kasilian basin; They used the Long Ashton Research Station Weather Generator (LARS-WG) model to estimate daily precipitation and predict future changes in precipitation. They integrated a multi-criteria assessment with the Markov technique to study land use in 2011 and project it to 2030. Andaryani et al. (2019) also worked in Iran, in the Zilbier basin, where they determined the effects of land use and climate change on the hydrological regime; They used the Markov technique to analyze land use based on satellite images and found that the hydrological regime would decrease by 2030, with a climate tending to be hot and dry and an increase in land uses with high water consumption.

Zeshan, Mustafa, &Baig (2021) conducted a study on land use changes in the Perak River basin in Malaysia. To do this, they used spatial information obtained from remote sensors, processed with neural networks using the cellular automaton technique. They estimated a prediction of the expansion of arid and urban lands by 2030, 2040, and 2050, as well as the actual loss of dense forest cover over the last 20 years.

Wu et al. (2022) developed a multi-scenario joint prediction method (MSEP) in the Naryn River basin to explore the impacts of climate and land use changes on runoff. The method integrated multiple climate models, the Markov technique, and the Soil and Water Assessment Tool (SWAT) model. They considered 96 scenarios to analyze runoff trends, and the technique used was only used for the analysis of land use changes.

Yang, Long & Bai (2019) used the Markov technique to analyze land use changes and their subsequent impact, combined with climate change, on surface runoff in the Luanhe River Basin in China. They found an increase in forest land use and a decrease in agricultural land use, with effects on average annual runoff, which increases in summer and decreases in other seasons.

Liu, Bi &Lv (2018) determined the impact of future land use and climate change on four ecosystem services in the Taihu Basin in China. They used the Markov technique to analyze land use, a downscaling method to analyze ecosystem services, and projected RCP and combined climate change scenarios. They found that future land use changes would improve nitrogen purification in the basin and decrease phosphorus purification, while climate change scenarios would have effects on water supply and soil retention, and the combined scenario would generate effects on all services, with a particular impact on nitrogen purification.

Alilou et al. (2018) worked in the Khoy basin in Iran to implement a robust water quality monitoring network to overcome the cost and time constraints this generates. They used the Markov technique to simulate future changes in non-point sources during the period 2026-2036, which allowed them to conclude that the changes identified would not affect the location of the seven sampling points they established in the research process.

Rani et al. (2018) developed a study and assessment of scenarios for the future spatial plan in the catchment area, which is part of a research project on flood risk in the Bandung basin in Indonesia. They used the LCM (Land Change Modeler) model, which applies a combined technique of Markov chain and a multilayer perceptron neural network. With this model, they simulated all scenarios, with a special focus on the use of the Markov chain to predict urban growth, results that were integrated into the flood risk scenarios, which the authors suggest analyzing in future work, with the aim of determining their hydrological impacts.

Zare, Mohammady& Pradhan (2017) used a method to estimate soil loss rates under the effects of future land use change and climate change scenarios in the Kasilian Basin in Iran. A regional downscaling process was applied, and the Markov technique was used for characterization based on two future land use scenarios that were designed using suitability maps. They found that future changes in land use could induce major changes in the erosion process in the basin. The above study was complemented by another study conducted in the same basin by Zare, Panagopoulos &Loures (2017), who predicted land use patterns and soil erosion scenarios using the revised universal loss equation and Markov chains. They found that the potential for erosion would increase by 45%, and that the change in land use from forest to human settlement would have a greater effect on soil loss due to erosion.

Ramachandra et al. (2017) worked in the Western Ghats basin in insular India, with the aim of analyzing changes in land cover and its relationship with water availability and climate change. The analysis was carried out for the periods 2004–2007, 2007–2010, and 2010–2013, and scenarios were projected using Markov chains for the year 2022. This revealed losses of vegetation cover between 56% and 66% in the coastal area of the basin, while in the Sahyadri area the losses ranged from 55% to 65%, due to the construction of dams, hydroelectric projects, and monoculture plantations.

In the Indus River basin (Nazeer, 2022), a doctoral thesis was developed focusing on the analysis of the hydroclimatic regime of the upper basin, covered by snow and glaciers under current and future climates. To this end, the ERA5-Land and JRA-55 reanalysis projects were used, in their coarsest resolutions, to obtain the respective calibration and validation data, and thus simulate the corrected land precipitation and observed flow using the GCM, DDD, and CMIP6 models. It was found that the highest precipitation in the study area falls between winter and spring, with higher precipitation at lower altitudes. In addition, the linear elevation precipitation gradient is inadequate for high-elevation areas.

In Europe, Pulido-Velásquez et al. (2015) conducted a study to identify the impacts of land use changes and climate change on groundwater dynamics in the Júcar River basin in Spain. They used a model integrated by SWAT, MODFLOW, and MT3DMS, to which they added Markov chains for the analysis of future scenarios of land use changes. They found that land use changes and climate change lead to a decrease in aquifer recharge and an increase in nitrate pollution.

In North America, Gädeke et al. (2022) applied the spatially distributed (10 m spatial resolution) process-based hydrological and thermal water balance simulation model to the 30 km^{2}Crea Creek watershed located on the Arctic coastal plain in Alaska. They found that even under current average climate conditions, water extraction from the lake is not compensated for by meltwater from the same year, as is currently assumed in land management regulations. Therefore, effective land management would benefit from considering the combined impact of climate change and industrial water extraction from the lake.

Straatman et al. (2011) coupled a cellular automaton model with the water resource management model in Alberta, Canada. The cellular automaton model simulated land use restrictions based on water availability in the Elbow River basin. They projected the simulation to the year 2031, with five-year intervals in two scenarios: extrapolation of historical data and land development limited by the water availability output of the water resource model for the area. In this same basin and its proximity to the city of Calgary, Farjad et al. (2017) applied an integrated framework to model the interactions between land use, climate, and hydrology along with stakeholder negotiation. This framework articulates a cellular automaton model of land use, an agent-based model used for automated stakeholder negotiation, and the MIKE SHE/MIKE 11 hydrological model. The framework functions as a kind of simulator, in which scenarios related to land development and water resource management can be obtained, and considers the influence of human and natural systems.The automaton technique used was not described in detail, although it is presumed to be Markovian based on the literature referenced in that work. Farjad et al. (2017) had already used a preliminary version of this framework in the same basin, integrating general circulation model scenarios and land use change scenarios for the 2020s and 2050s. They found that the impacts of climate change and land use are positively correlated with winter and spring flows, which intensifies their influence and leads to a significant increase in flow and, subsequently, increases the basin's vulnerability to flooding in spring.

Yong et al. (2012) modeled land use in the Little Miami River basin using the Markov technique;

they simulated five hypothetical climate change scenarios integrated into the FORTRAN hydrological model (HSPF), which simulates the transport and flow of nutrients; They found that changing land use in the basin could help reduce water scarcity pressure during dry years. Mitsova (2014) worked in the East Fork Little Miami River basin, Ohio. She developed an analysis of seasonal variability in mean discharge, 100-year flood, and 7Q10 low flow, and projected land cover and climate change scenarios for 2030. They also simulated future urban growth in the Cincinnati, Ohio metropolitan area to 2030. Markov chains were used in both land cover change and urban growth scenarios, which were then integrated into the calibrated BASINS-HSPF model. The author found that there is a higher probability of exceeding the 100-year flood during the fall and winter months and a probability of decreasing low summer flows.

In Africa, Mena and Waktola (2022) analyzed extreme temperature trends and mapped return periods in a changing climate for the upper Tekeze River basin in northern Ethiopia. To do this, they used the nonparametric Mann-Kendall (MK) statistical test and found that future extreme temperatures will increase by between 0.6 and 2.2 °C. In addition, future extreme temperatures showed a significantly increasing trend in most seasons (around 66.3%).

Getachew, Manjunatha& Bhat (2021) applied the Markov technique to model land use in the Lake Tana basin in Ethiopia; they used separate and combined impact assessments of water balance, climate change, and land use components; They identified that cropland, tree cover, and built-up areas are likely to increase in the 2020s, 2050s, and 2080s at the expense of grassland and shrub cover areas, leading to an increase in evapotranspiration conditions, base flow, and basin flow.

Samuel et al. (2022) evaluated the ability of the Coordinated Outcome for Regional Evaluations (CORE), initiated under the Coordinated Regional Experimental Downscaling Climate Program (CORDEX), to reproduce extreme summer precipitation indices over the Zambezi River Basin (ZRB) from 1983 to 2005. To do this, they used RCMs to spatially simulate the distribution of observed extreme precipitation. The results showed similarities in the spatial distribution of extreme precipitation between observations. However, there were considerable differences in the magnitude of extreme precipitation between observations.

Belay & Mengistu (2021) conducted a study of land use changes in the upper Blue Nile basin, their relationship to climate change, and the effect on soil erosion. To do this, they used the Markov technique, with which they determined an annual erosion rate of 15 t ha $^{-1}$ year $^{-1}$ in 1985 to 19 t ha $^{-1}$ year $^{-1}$ in 2002 and 19.7 t ha $^{-1}$ year $^{-1}$ in 2017; They estimated increases in this rate of more than 20 t ha $^{-1}$ year $^{-1}$ by 2033, while for 2050 they projected soil losses of 9.6% and 11.3% with climate change trajectories RCP4.5 and RCP8.5, respectively.

Jellouli&Bernoussi (2022) analyzed the impact of wind flow behavior on the spread of forest fires in a basin in Morocco, using cellular automata. They determined that climate change has an impact on wind variables, and although it is difficult to model the spread of fires, the results of this study made it possible to establish the accuracy of wind direction and speed based on topography and land use.

Dibaba, Demissie, &Miegel (2020) used Markov techniques to model land use in the Finchaa watershed in Ethiopia and integrated these results into IDRISI software to establish future scenarios. They found that land use changes show an increase in surface runoff and water yield, but a decrease in available groundwater. These results were obtained from a combination of SWAT modeling of land use changes in the tools already described with climate change scenarios.

In Latin America, Brito, Rufino &Djordjević (2021) modeled future scenarios of land use or land cover using cellular automata through R software in a basin in Paraíba, Brazil. They used data series obtained from satellite images from 1985 to 2018 and obtained optimal large-scale modeling results, which demonstrate the wide possibilities of hydrological, urban, and social modeling in the Brazilian context.

The National University of Colombia has led, through its postgraduate programs, the development of various theses focused on modeling the problem of climate change in the country. Some, such as the Dynamics of extreme hydroclimatic events in the Chinchiná River basin due to climate variability (Marín Salazar, 2017), focused on characterizing the watershed under study to subsequently determine precipitation and flow extremes in the period from 1981 to 2012 using techniques such as trend analysis in RClimdex software, analysis of extreme value probability distribution curves, diurnal cycle and SPI, quarterly analysis, and flow duration curve. The main finding was the high influence of altitude and the El Niño Southern Oscillation on the intensity of rainfall and extreme flows, especially in the middle and lower areas of the basin.

Another study was Effect of Madden-Julian waves on precipitation over some regions of Colombia (Torres Pineda, 2012), which carried out a comparative analysis of the Madden-Julian Index (MJI) and a precipitation index (PI), estimating correlation coefficients and spectrum comparisons to estimate the relationship between the oscillation and seasonal precipitation variability. The results showed that the extreme phases of the oscillation have a direct relationship with precipitation anomalies, but the correlation coefficients are low, considering that the 30-day signal appears in both compared indices. It was also identified that under positive extremes of the Madden-Julian index, there is a decrease in pentadal precipitation in some regions of Colombia, while if the extreme values are positive, decadal precipitation increases in several regions.This allowed us to develop a climate prediction map that considers the effect of the Madden-Julian Oscillation. Other studies have been conducted by researchers Vélez-Upegui (Ocampo López, 2012)(Ocampo López, 2018)(Rincón-Castañeda, 2017) (Ramírez Carabalí, 2017) and Pabón (Alvarez Grueso, 2019)(Ruiz Cabarcas, 2012), who have used similar techniques in the analysis of data series to explain the incidence of climate change and variability in the territory, highlighting, for example, some research focused on the agricultural sector.

4. Conclusions

In summary, the review of studies focused on modeling phenomena in watersheds considering climate change scenarios shows the main use of the Markov technique, as well as the use of some models such as SWAT, the use of some climate models such as GCM, and above all the use of certain statistical techniques such as discrete-time Fourier transform (DTFT) and short-time Fourier transform (STFT), Nash and Sutcliffe model efficiency index, and the analysis of indices such as ONI, ENSO, and MJO. These studies present gaps in knowledge in relation to uncertainty analysis, simplification through the use of global models, spatial scales that are not very detailed in topographically heterogeneous regions, monthly time scales that do not allow inferences for risk analysis, and limited studies of water behavior with climate change scenarios in the case of Colombia.

References

Adnan, M., Liu, S., Saifullah, M., Iqbal, M., Ali, A. F., & Mukhtar, M. A. (2022). Spatiotemporal variations in runoff and runoff components in response to climate change in a glacierized subbasin of the Upper Indus Basin, Pakistan. Frontiers in Earth Science, 10. https://doi.org/10.3389/feart.2022.970349

Akhtar, F., Borgemeister, C., Tischbein, B., & Awan, U. K. (2022). Metrics Assessment and Streamflow Modeling under Changing Climate in a Data-Scarce Heterogeneous Region: A Case Study of the Kabul River Basin. Water (Switzerland), 14(11). https://doi.org/10.3390/w14111697

Alilou, H., Moghaddam Nia, A., Keshtkar, H., Han, D., & Bray, M. (2018). A cost-effective and efficient framework to determine water quality monitoring network locations. Science of the Total Environment, 624, 283–293. https://doi.org/10.1016/j.scitotenv.2017.12.121

Alvarez Grueso, E. (2019). Análisis de impactosasociados a la variabilidadclimáticaen los municipios de Guapi (Cauca) y Nuquí (Chocó) [Universidad Nacional de Colombia]. In Climatic Change (Vol. 47, Issue 4). https://doi.org/10.1023/A:1005627828199

Andaryani, S., Trolle, D., Nikjoo, M. R., Moghadam, M. H. R., & Mokhtari, D. (2019). Forecasting near-future impacts of land use and climate change on the Zilbier river hydrological regime, northwestern Iran. Environmental Earth Sciences, 78(6).

https://doi.org/10.1007/s12665-019-8193-4

Bastidas Pacheco, G. A., Hernández, R., Pacheco, G. A. B., & Hernández, R. (2019). Cambio climáticoalgunosaspectos a considerar para la supervivencia del ser vivo: revisiónsistemática de la literatura. RevistaCuidarte, 10(3). https://doi.org/10.15649/cuidarte.v10i3.664

Belay, T., & Mengistu, D. A. (2021). Impacts of land use/land cover and climate changes on soil erosion in Muga watershed, Upper Blue Nile basin (Abay), Ethiopia. Ecological Processes, 10(1). https://doi.org/10.1186/s13717-021-00339-9

Cai, Z., & Wang, X. (2010). Research on vegetation dynamic change simulation based on spatial data mining of ANN-CA model using time series of remote sensing images. In IFIP Advances in Information and Communication Technology (Vol. 317). https://doi.org/10.1007/978-3-642-12220-0_80

Chanapathi, T., &Thatikonda, S. (2020). Investigating the impact of climate and land-use land cover changes on hydrological predictions over the Krishna river basin under present and future scenarios. Science of the Total Environment, 721. https://doi.org/10.1016/j.scitotenv.2020.137736

Congreso de La República. (2012). Ley 1523 "Por la cual se adopta la políticanacional de gestión del riesgo de desastres y se estableceel Sistema Nacional de Gestión del Riesgo de Desastres y se dictanotrasdisposiciones". https://www.funcionpublica.gov.co/eva/gestornormativo/norma.php?i=47141

Congreso de La República. (2021). Ley 2169 "POR MEDIO DE LA CUAL SE IMPULSA EL DESARROLLO BAlO EN CARBONO DEL PAÍS MEDIANTE EL ESTABLECIMIENTO DE METAS Y MEDIDAS MÍNIMAS EN MATERIA DE CARBONO NEU"RRALIDAD y RESILIENCIA CLIMÁTICA y SE DICTAN OTRAS DISPOSICIONES". https://dapre.presidencia.gov.co/normativa/normativa/LEY%202169%20DEL%2022%20DE%20DICIEMBRE%20DE%202021.pdf

Coulthard, T., de Rosa, P., & Marchesini, I. (2008). CAESAR: A model to simulate river dynamics | CAESAR: Un modello per la simulazionedelledinamiched'alveo. Alpine and Mediterranean Quaternary, 21(1), 207–214.

de Brito, H. C., Rufino, I. A. A., &Djordjević, S. (2021). Cellular automata predictive model for man-made environment growth in a Brazilian semi-arid watershed. Environmental Monitoring and Assessment, 193(6). https://doi.org/10.1007/s10661-021-09108-9

Dibaba, W. T., Demissie, T. A., &Miegel, K. (2020). Watershed hydrological response to combined land use/land cover and climate change in highland ethiopia: Finchaa catchment. Water (Switzerland), 12(6). https://doi.org/10.3390/w12061801

Farjad, B., Gupta, A., Razavi, S., Faramarzi, M., & Marceau, D. J. (2017). An integrated modelling system to predict hydrological processes under climate and land-use/cover change scenarios. Water (Switzerland), 9(10). https://doi.org/10.3390/w9100767

Farjad, B., Pooyandeh, M., Gupta, A., Motamedi, M., & Marceau, D. (2017). Modelling interactions between land use, climate, and hydrology along with stakeholders' negotiation for water resources management. Sustainability (Switzerland), 9(11). https://doi.org/10.3390/su9112022

Gädeke, A., Arp, C. D., Liljedahl, A. K., Daanen, R. P., Cai, L., Alexeev, V. A., Jones, B. M., Wipfli, M. S., &Schulla, J. (2022). Modeled Streamflow Response to Scenarios of Tundra Lake Water Withdrawal and Seasonal Climate Extremes, Arctic Coastal Plain, Alaska. Water Resources Research, 58(8). https://doi.org/10.1029/2022WR032119

Getachew, B., Manjunatha, B. R., & Bhat, H. G. (2021). Modeling projected impacts of climate and land use/land cover changes on hydrological responses in the Lake Tana

Basin, upper Blue Nile River Basin, Ethiopia. Journal of Hydrology, 595. https://doi.org/10.1016/j.jhydrol.2021.125974

Intergovernmental Panel on Climate Change - IPCC. (2022). Sixth Assessment Report, Climate Change 2022: Impacts, Adaptation and Vulnerability.

Jellouli, O., &Bernoussi, A. S. (2022). The impact of dynamic wind flow behavior on forest fire spread using cellular automata: Application to the watershed BOUKHALEF (Morocco). Ecological Modelling, 468. https://doi.org/10.1016/j.ecolmodel.2022.109938

Limbong, A., Barkey, R., Umar, A., Rijal, S., Nursaputra, M., &Chairil, A. (2021). Impact of climate and land use change on the erosion of the upstream Kelara Watershed. IOP Conference Series: Earth and Environmental Science, 807(2). https://doi.org/10.1088/1755-1315/807/2/022033

Liu, Y., Bi, J., &Lv, J. (2018). Future impacts of climate change and land use on multiple ecosystem services in a rapidly urbanizing agricultural Basin, China. Sustainability (Switzerland), 10(12). https://doi.org/10.3390/su10124575

Marín Salazar, J. P. (2017). Dinámica de los eventoshidroclimáticosextremosen la cuenca del ríoChinchiná por efecto de variabilidadclimática. Universidad Nacional de Colombia.

Menna, B. Y., &Waktola, D. K. (2022). Extreme temperature trend and return period mapping in a changing climate in Upper Tekeze river basin, Northern Ethiopia. Physics and Chemistry of the Earth, 128. https://doi.org/10.1016/j.pce.2022.103234

Ministerio de Agricultura y Desarrollo Rural. (2021). Resolución 355 "Por El Cual Se Adopta El Plan de Gestión Del Cambio Climático Del Sector Agropecuario,". https://www.minagricultura.gov.co/Normatividad/Resoluciones/RESOLUCI%C3%93N%20NO.%20000355%20DE%202021.pdf

Ministerio de Ambiente y Desarrollo Sostenible. (2016). Política Nacional de Cambio Climático.

Ministerio de Minas y Energías. (2018). Plan Integral de Gestión del Cambio Climático para el Sector MineroEnergético.

Mitsova, D. (2014). Coupling land use change modeling with climate projections to estimate seasonal variability in runoff from an urbanizing catchment near cincinnati, Ohio. ISPRS International Journal of Geo-Information, 3(4), 1256–1277. https://doi.org/10.3390/ijgi3041256

Nazeer, A. (2022). Analysis of the hydro-climatic regime of the snow covered and glacierised Upper Indus Basin under current and future climates. IHE Delft, Institute for Water Education.

Ocampo López, O. L. (2012). Análisis de vulnerabilidad de la cuenca del ríoChinchiná para condicionesestacionarias y de cambioclimático. Universidad Nacional de Colombia.

Ocampo López, O. L. (2018). Modelaciónhidrológica y agronómica de los efectos del cambio y la variabilidadclimáticaen la produccióncafetera de Caldas. DoctoradoenIngeniería - Automática .

Park, G. A., Ahn, S. R., Lee, Y. J., & Kim, S. J. (2008). Assessment of climate change impact on the inflow to agricultural reservoir and the streamflow of a watershed in South Korea. American Society of Agricultural and Biological Engineers Annual International Meeting 2008, ASABE 2008, 4, 2231–2244.

Park, M.-J., Yong-Jun, L. E. E., Shin, H.-J., &Seong-Joon, K. I. M. (2008). Assessment of future climate and land use change impacts on hydrological behavior of dam watershed using SWAT-K Model. American Society of Agricultural and Biological Engineers Annual International Meeting 2008, ASABE 2008, 4, 2268–2278.

Pulido-Velazquez, M., Peña-Haro, S., García-Prats, A., Mocholi-Almudever, A. F., Henriquez-Dole, L., Macian-Sorribes, H., & Lopez-Nicolas, A. (2015). Integrated assessment of the impact of climate and land use changes on groundwater quantity and quality in the Mancha Oriental system (Spain). Hydrology and Earth System Sciences, 19(4), 1677–1693. https://doi.org/10.5194/hess-19-1677-2015

Ramachandra, T. V., Setturu, B., Rajan, K. S., & Subash Chandran, M. D. (2017). Modelling the forest transition in Central Western Ghats, India. Spatial Information Research, 25(1), 117–130. https://doi.org/10.1007/s41324-017-0084-8

Ramírez Carabalí, C. (2017). Modelo para la predicción de semanassecas o húmedasen la zona cafetera de Caldas para la planificación de laboresagrícolas. Universidad Nacional de Colombia.

Rani, M. S., Lange, E., Cameron, R., &Schroth, O. (2018). Future development scenarios for adaptation to climate change in the ci kapundung upper water catchment area, bandung basin, indonesia. Journal of Digital Landscape Architecture, 2018(3), 23–33. https://doi.org/10.14627/537642003

Rasoolzadeh-Darzi, N., Ahmad, H., Moeini, A., &Motamedvaziri, B. (2021). Simulating erosion hazard maps under climate change and land use change for the early twenty-first century in northern Iran. Arabian Journal of Geosciences, 14(15). https://doi.org/10.1007/s12517-021-07416-5

Ray, A., Pandey, V. P., & Thapa, B. R. (2022). An assessment of climate change impacts on water sufficiency: The case of Extended East Rapti watershed, Nepal. Environmental Research, 212. https://doi.org/10.1016/j.envres.2022.113434

Rincón-Castañeda, D. F. (2017). Índicesagroclimáticosen la cuenca del ríoChinchiná bajo efectos de variabilidadclimática. Universidad Nacional de Colombia.

Ruiz Cabarcas, A. del C. (2012). Análisis del impacto de los fenómenos El Niño y La Niña en la producciónagrícola del departamento del Atlántico. Universidad Nacional de Colombia .

Samuel, S., Wiston, M., Mphale, K., &Faka, D. N. (2022). Changes in extreme precipitation events in the Zambezi River basins based on CORDEX-CORE models: Part I—Evaluation of historical simulation. International Journal of Climatology, 42(13), 6807–6828. https://doi.org/10.1002/joc.7612

So-Ra, A. H. N., Geun-Ae, P., &Seong-Joon, K. I. M. (2008). Assessing future climate and land use change impact on streamflow and groundwater recharge of a stream watershed using SLURP hydrological model. American Society of Agricultural and Biological Engineers Annual International Meeting 2008, ASABE 2008, 4, 2305–2316.

Straatman, B., Hasbani, J.-G., Tang, T., Berg, K., Moreno, N., & Marceau, D. (2011). Linking a land-use cellular automata with a water allocation model to simulate land development constrained by water availability in the elbow river watershed in Southern Alberta. Geomatica, 65(4), 365–374. https://doi.org/10.5623/cig2011-059

Tian, J., Guo, S., Liu, D., Chen, Q., Wang, Q., Yin, J., Wu, X., & He, S. (2020). Impacts of climate and land use/cover changes on runoff in the Hanjiang River basin | 气候与土地利用变化对汉江流域径流的影响. Dili Xuebao/Acta GeographicaSinica, 75(11), 2307–2318. https://doi.org/10.11821/dlxb202011003

Tong, S. T. Y., Sun, Y., Ranatunga, T., He, J., & Yang, Y. J. (2012). Predicting plausible impacts of sets of climate and land use change scenarios on water resources. Applied Geography, 32(2), 477–489. https://doi.org/10.1016/j.apgeog.2011.06.014

Torres Pineda, C. (2012). Efecto de las ondas Madden-Julian en la precipitaciónsobrealgunasregiones del territoriocolombiano. Universidad Nacional de Colombia.

Wu, J. S., Li, Y. P., Sun, J., Gao, P. P., Huang, G. H., & Liu, J. (2022). Identifying the runoff variation in the Naryn River Basin under multiple climate and land-use change scenarios. Journal of Water and Climate Change, 13(2), 574–592. https://doi.org/10.2166/wcc.2021.422

Yang, W., Long, D., & Bai, P. (2019). Impacts of future land cover and climate changes on runoff in the mostly afforested river basin in North China. Journal of Hydrology, 570, 201–219. https://doi.org/10.1016/j.jhydrol.2018.12.055

Zare, M., Mohammady, M., & Pradhan, B. (2017). Modeling the effect of land use and climate change scenarios on future soil loss rate in Kasilian watershed of northern Iran. Environmental Earth Sciences, 76(8). https://doi.org/10.1007/s12665-017-6626-5

Zare, M., Panagopoulos, T., &Loures, L. (2017). Simulating the impacts of future land use change on soil erosion in the Kasilian watershed, Iran. Land Use Policy, 67, 558–572. https://doi.org/10.1016/j.landusepol.2017.06.028

Zeshan, M. T., Mustafa, M. R. U., &Baig, M. F. (2021). Article monitoring land use changes and their future prospects using gis and ann-ca for perak river basin, malaysia. Water (Switzerland), 13(16). https://doi.org/10.3390/w13162286