Assessing and Quantifying Impacts of Land Use and Climate Changes on Hydrological Processes: Review

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Abstract
Land use and climate changes have become prominent drivers of changes in hydrologic responses. Understanding impacts of land use and climate changes on hydrology is vital for water resources management. Many studies have used computer models to examine the linkages and interactions between land use, climate and hydrologic responses. The objective of this paper is to summarize these studies and provide critical review of limitations of the methodologies. Approaches used to analyze the impacts of land use and climate changes on hydrologic responses can be grouped as (i) the impacts of climate changes, (ii) the impacts of land use changes, and (iii) the combined and separate impacts of land use and climate changes. Findings of this review include (i) the combined effects of land use and climate changes are different from the separate impacts, (ii) effects of land use and climate changes on hydrologic responses vary from basin to basin depending on the basin's physical characteristics, climate condition, and the scope of climate change and land use change. These findings imply that basin specific impact analysis using integrated modeling approach that examines the combined effects of land use and climate changes is decisive for planning and management of water resources.
Keywords: land use change; climate change; integrated watershed modeling; combined and separate impacts; hydrologic impacts of land use change; hydrologic impacts of climate change.

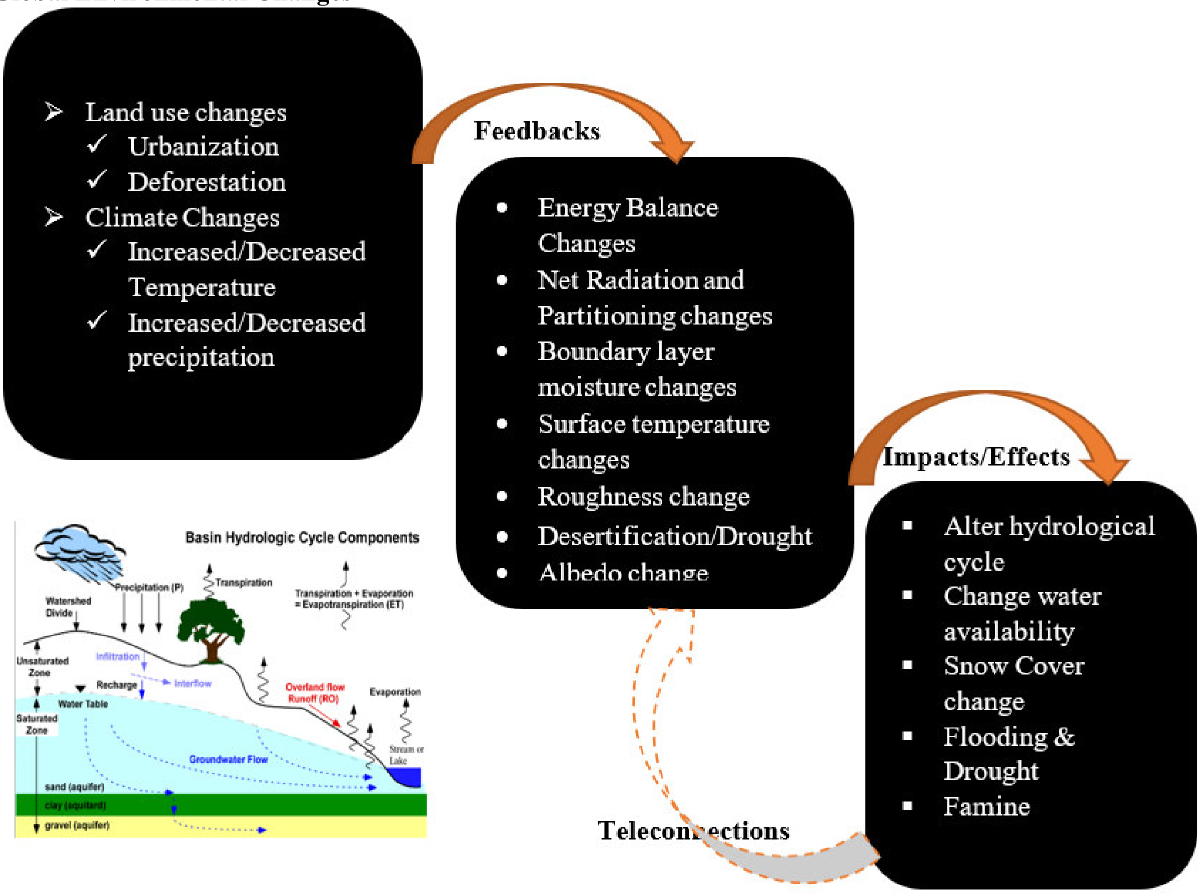
1. Introduction

Land use change and climate change are active components and drivers of global environmental changes (Chen et al. 2012; Molina-Navarro et al. 2014; Wang et al. 2014; Zhang et al. 2016). Human induced land use change modify biophysical, biogeochemistry and biogeography of the terrestrial surface and the atmosphere (Kabat et al. 2004; National Research Council 2005). Modification of the Earth's material and energy flows have resulted in climate and ecosystem changes (Yang et al. 2014). Land use change along with the climate forcing influences atmospheric temperature (Feddema et al. 2005; Christy et al. 2006; Ezber et al. 2007; Nuñez et al. 2008). Besides, several studies have found that land use and climate changes can influence hydrological processes (e.g., Chen & Li 2004; Wang et al. 2006; Brath et al. 2006; Zhang et al. 2014). As a result, land use change and climate change impact analysis has been a major research topic in the past two decades (e.g., Legesse et al. 2003; Guo et al. 2008; Ma et al. 2010; Mango et al. 2011; Setegn et al. 2011; Xu & Luo 2015; Pau et al. 2016; Yin et al. 2017).

Land use change, climate change and hydrological processes are linked via complex feedback mechanisms. In addition, variations in hydro-meteorological variables and basin characteristics at different spatio-temporal scales makes analyzing the impacts of land use and climate change on hydrological responses challenging (Figure 1). On the other hand, reliable and current estimates of the impacts are essential for planning and management of water resources (Vorosmarty et al. 2000). As such, computer modeling has been widely used to quantify the impacts of land use and climate changes on hydrological responses. Most of the studies, however, focused either on land use change or climate change impacts despite findings that combined impacts of land use and climate changes are more reliable for water resource management (Dwarakish & Ganasri 2015; Chawla & Mujumdar 2015). The combined impacts could be substantially different from the impacts of only land use change or climate change (Guo et al. 2008). Regardless of this fact, relatively few studies considered both land use change and climate change impacts (Table 1 and Figure 2).

Findings of those studies are contradictory in many cases making it difficult to have consistent information regarding the combined and separate impacts of land use and climate changes on hydrological responses. The objective of this review is to (i) review studies reported on the impacts of land use and climate changes on hydrological processes and summarize their findings, (ii) provide critical review of the methodologies and limitations of the studies.

Global Environmental Changes



Source: Google
Figure 1. The complex linkage via feedback mechanisms.

2. Impacts of climate change on hydrology

Several studies have examined the impacts of climate change on hydrologic responses for various regions of the world since 1990s (e.g., Ezber et al. 2007; Chen et al. 2012; Gebre et al. 2015). While many different methods and models have been used, as of 2010, over 226 peer-review articles that used SWAT model for such analysis were published (SWAT peer-review publication database, https://www.card.iastate.edu/swat_articles). The studies used Global Circulation Models (GCMs) and Regional Climate Models (for studies conducted at regional scales) to project future climate temperature and precipitation. Whereas most of the studies used the IPCC AR4 based GCMs, the current generation GCMs that are based on IPCC AR5 are believed to project temperature and precipitation more accurately (Knutti & Sedlacek 2012; Flato et al. 2013). With this caveat, the consensus is that temperature will continue to increase during the next century in all regions of the world while precipitation projections showed inconsistency among regions and GCMs.

Furthermore, even though, extents of the changes vary from region to region, the studies revealed that hydrologic responses (e.g., streamflow and evapotranspiration) are impacted either positively or negatively by the changing climate. The studies described below were selected to highlight implications of climate change for various regions of the world. The selected studies are sample studies on Africa and China as the regions are susceptible to climate change.

For example, Setegn et al. (2011) studied sensitivity of future water resources to climate change in Lake Tana watershed located in Ethiopia. Global Circulation Models (GCMs) were used to project future climate variables including temperature and rainfall. The study revealed potential increase in temperature but inconsistent precipitation trend in the watershed that could alter the water balance during the next century. The direction of the change in water balance (i.e., increase or decrease) was not predicted with confidence due to output uncertainty caused by course spatial resolution of the GCMs. Faramarzi et al. (2013) analyzed the impacts of climate change on freshwater availability for the entire Africa as well as at watershed scale. The study projected future climate (2020-2040) of Africa using five GCMs. The study revealed that while temperature will increase in all regions of Africa, precipitation will increase during the wet months in humid and semi-humid regions and will decrease during the wet months of hyper-arid and arid regions. The impacts of the climate change on fresh water availability were also analyzed using SWAT model. The result revealed that mean annual quantity of water resources is likely to increase for the entire Africa with considerable variations for individual watersheds and countries.

The study conducted by Dile et al. (2013) for Gilgay Abay River basin located in Ethiopia found different results. The climate projections made for the river basin using GCMs and Statistical Downscaling Tool (SDSM) found that mean annual precipitation will decrease by 30% during the 2010-2040 period resulting in 40% to 50% decrease in mean monthly flow volumes. However, precipitation was projected to increase by 30% in the following 30-year period (i.e., 2070-2100) increasing mean monthly flow volume by more than double (i.e., 135%). The study further revealed that climate change appears to have insignificant impact on low flow conditions of the river basin. However, seasonal mean flow volume may increase by more than double (i.e., 136%) and 30% to 40% during spring (semi-rainy season) and summer (main rainy season), respectively. The study concluded that climate change will increase annual flow volume for the Gilgay Abay River basin which is consistent with the study conducted for Dhidhessa River basin by Gebre et al. (2015).

Xu & Luo (2015) quantified impacts of climate change on hydrological processes by simulating streamflow using SWAT for two basins in China. The study revealed that annual discharge in the basins will increase in response to wetter and warmer conditions projected for the basins. The authors also reported variability in impacts of climate change on hydrological processes for different hydro-climatic regions. Semi-arid regions will experience more warming and wetting subtropical humid regions. The authors also stressed the need to consider uncertainty analysis in such studies to improved reliability of the results.

Yao et al. (2015) investigated effects for Lushi basin in China using SWAT model. Future precipitation and temperature were projected using GCMs. The study showed that both temperature and precipitation will increase in all seasons; evapotranspiration (ET) will increase in winter and spring, but decrease in summer and autumn; and streamflow will increase throughout the year. The increased streamflow would improve water availability in winter and spring but exacerbate flooding and soil erosion in summer.

Likewise, Piras et al. (2014) analyzed the impacts of climate change on runoff for Rio Mannu basin in Italy using a physically based distributed hydrological model. The study result showed that runoff from the basin would be significantly decrease leading to hydrological drought. Similarly, Islam et al. (2014) examined the impacts of climate change on hydrological processes for Murray-Hotham catchment in Australia. The study projected 2.3% reduction in mean annual rainfall and 14% decline in mean annual runoff.

While the studies previously discussed focused on surface water responses such as streamflow, Mechal et al. (2015) examined spatial and temporal variability of groundwater recharge and its sensitivity to climate change for Gidabo River basin located in Ethiopian using SWAT model. The study reported that average annual recharge for the 1998-2010 period varies from 410 mm/year for the highland area to 25 mm/year for the lowland areas in the rift valley. They also found that annual recharge is very sensitive to variability in precipitation and moderately sensitive to changes in temperature.

In summary, temperature would increase in all regions while precipitation pattern varies from region to region as well as from season to season. For example, precipitation decreases in arid regions and increases in humid regions. Moreover, precipitation is expected to increase in summer season and decrease in dry season for most regions. In a similar way, hydrologic responses to the climate change also vary with regions and seasons. For example, wetting and warming climate will increase streamflow while dry and warm condition will reduce streamflow of most basins. However, all the studies under this category does not consider land use change impact on hydrology. In general, even though, the extent and the direction of climate change varies from region to region, all studies indicated that hydrological responses and water resource availability are affected either positively or negatively by the changing climate.

3. Impacts of land use changes on hydrology

Several studies have analyzed the impacts of land use change on hydrological responses in various regions of the world. The extent of land use changes and the corresponding impacts on hydrologic responses vary from region to region. Some of the findings are contradicting perhaps because of the models used, intensity and types of the land use changes, basin characteristics, and variation in climatic conditions of the basins. It should be emphasized that the studies described in this section examined the impacts of land use change on hydrologic responses but ignored the impacts of climate change. Some sample studies are described below to highlight the findings of land use change impact on hydrology. Most of the studies are from Africa and China as the regions are reported to undergone extensive land use change as well as its significant hydrologic impacts.

Brook et al. (2011) quantified the impacts of human induced land use change for Angar watershed located in Ethiopia using SWAT model. The study reported changes in hydrological variables in response to considerable land use change in the watershed due to deforestation, and increased agriculture and urbanization. The study concluded that mean annual evapotranspiration, percolation and base-flow declined whereas surface runoff and sediment yield increased. The study further showed that streamflow increased during wet season by about 41% and declined during dry season by about 22%.

Likewise, Baker et al. (2013) assessed the impacts of land use change on water resources using SWAT model for the Njoro watershed located in Kenya's Rift Valley. The study reported that land use changes resulted in increased surface runoff and decreased groundwater recharge. Getahun et al. (2015) evaluated the impacts of historical land use change on hydrology of the Melka Kuntrie watershed located in Ethiopia using semi-distributed hydrological model (i.e., HBV). The study showed that deforestation and associated increase in agricultural activities reduced evapotranspiration and increased streamflow during the main rainy season. Their finding was inconclusive, however, for the dry season.

Nobert and Jeremian (2012) examined the impacts of land use change on Wami River located in Tanzania using SWAT model. The study reported decreased average streamflow, increased runoff, and decreased base-flow in response to land use changes driven by deforestation and increased agriculture and urbanization from 1987 to 2000. Similar study was completed for Angereb watershed located in Ethiopia using SWAT model (Haile & Assefa 2012). The study revealed mean monthly streamflow for the wet months increased by 39% and declined by 46% for the dry mean months. The land use changes were due to increased farmland and urbanization, deforestation, and loss of grass lands. Likewise, Tadesse et al. (2015) analyzed the hydrological response (i.e., streamflow and sediment yield) of a watershed to land use change in USA using SWAT model. The study reported that land use change (especially urbanization) can alter hydrologic conditions over various temporal and spatial scales.

Ahn & Merwade (2017) investigated the effects of land use change on the duration and severity of high and low flows by integrating SWAT, Bayesian model averaging and Consulas. The study reported that land use changes affect both duration and severity of high and low flows. They found that land use change leads to more severe high and low flow events that last longer. The study concluded that high and low flows are more sensitive to land use change than average flows which implies that land use change could intensify extreme hydrologic events such as flooding and droughts.

Studies related to the impacts of land use change on hydrological processes are not limited to historical land use change. Several studies have looked at the impacts of future land use changes on hydrologic responses. For example, Wijesekara et al. (2012) assessed the impact of potential land use development over the next 20 years on the hydrology of Elbow River located in Canada by integrating a cellular automata model to predict future land use change and MIKE-SHE/MIKE-11 to predict associated hydrologic responses. The predicted land use changes were 34% decline in forestland, and increases in built-up area, range/park land and agricultural land by 65%, 20% and 1%, respectively. The corresponding hydrologic responses showed 7.3% increase in overland flow, and 1%, 13%, 4% and 2.3% decrease in evapotranspiration, base-flow, streamflow, and infiltration, respectively. In addition, Wanger et al. (2016) integrated land use projection model with hydrological model and analyzed potential future impacts of land use change on water resources at a watershed scale in India. The result showed changes in seasonal water balance components (i.e., increased water yield, and decreased evapotranspiration) in response to increased urban area, and decreased agricultural and semi-natural area.

Other similar studies conducted on the topic include Chen and Li. 2004; Wang et al. 2006; Brath et al. 2006; Yang et al. 2014 and Zhang et al. 2014. Overall, in the last few decades about 98 peer-reviewed articles were published related to impacts of land use change on hydrological responses (SWAT peer-review publication database, https://www.card.iastate.edu/swat_articles). Most of these studies focused on assessing the impacts of either past land use change or future land use change on hydrological responses by integrating land use change detection/land use projection models (e.g., CLUE-S) with hydrological models (e.g., SWAT). In some cases, scenario based land use projection were used to predict future land use change. The results of the studies, generally, showed that land use have been changing and will continuous to change in the future, and the changes have affected hydrologic responses.

4. Impacts of land use and climate change on hydrology

Analyzing the impacts of land use change and climate change on water resources has become one of the pressing research topic. Most of such studies examined the combined and separate impacts of historical and/or future land use and climate changes on major hydrologic responses. The studies reviewed in this section incompasses sample from different regions of the world.

Zhang et al. (2016) studied the separate as well as the combined hydrologic impacts of recent past (1995-2014) and near future (2015-2024) changes in land use and climate in China. The study integrated two land use models, one based on Markov chain processes and the other using Dyna-CLUE with SWAT model to analyze future impacts of land use change. The authors found that whereas land use change in the recent past has reduced surface runoff, groundwater discharge and streamflow, climate change has significantly increased these hydrologic responses. The joint impacts induced by land use and climate changes were identical to those caused by climate changes alone. The Authors concluded that the effect of climate change is more significant than that of land use change for both historic and future timeframes. However, they warned that impacts of land use change could be substantial if the climate becomes drier in the future.

Shrestha & Htut (2016) studied potential impacts of future land use and climate changes on hydrology of Bago River basin in Myanmar. Multiple tools and methods such as GCMs from CMIP5, CLUE-S, and SWAT were used to quantify the impacts. The study revealed that impacts of climate change on streamflow is greater than that of the land use change in the near future. However, the combined impacts of land use and climate changes showed greater impact compared to their separate impacts. The study further revealed that climate and land use changes would alter seasonal variability of streamflow in the basin but not the average annual streamflow. Likewise, Guo et al. (2008) examined the effects of climate and land use changes on hydrology for Xibjiang River basin located in China using SWAT model. The major finding is that annual streamflow is mainly affected by climate change while seasonal streamflow is more sensitive to land use change in the watershed. The results further showed that the combined effects of land use and climate changes could be quite different from the impacts of only land use change or climate change emphasizing the need to consider impacts of both for decision-makings.

Contrary to the studies described in the previous few paragraphs, Dong et al. (2013) reported that runoff is more sensitive to land use change than to climate change. The study quantified the effects of human activities and climate variability on runoff using SWAT model coupled with sequential cluster and separation approach. According to the study, about 86% reduction in runoff is attributed to human activities while only 14.3% reduction is caused by climate variability. Yin et al. (2017) applied SWAT model to quantify the combined and the separate impacts of land use and climate changes on surface runoff. The study indicated that land use and climate changes influence runoff differently in different decades but generally concluded that runoff fluctuations are more sensitive to land use change than climate change. Similarly, Paul et al. (2016) investigated the effects of land use and climate changes on hydrology of a watershed in South Dakota, USA using SWAT model. The study concluded that change in water balance is more closely associated to land use change than to climate change.

On the other hand, Ma et al. (2010) used scenario based land use change and climate change projections to investigate their future impacts on the hydrology of Kejie watershed located in eastern Himalayas using SWAT model. Results of the study indicated that land use change dominates the streamflow in the short and middle terms than climate change. Likewise, Legesse et al. (2003) studied the impacts of climate and land use changes on water resources in data scarce South Central Ethiopia using a distributed Precipitation-Runoff Modeling System (PRMS) model. The scenario-based simulation revealed that 10% decrease in rainfall would cause 30% reduction in streamflow while 1.5% increase in air temperature would result in 15% decrease in streamflow. On the other hand, converting the present day dominantly cultivated/grazing land in the Kater river basin by woodland would decrease streamflow at the outlet by about 8%. Mango et al. (2011) examined the response of headwater hydrology of Mara River, located in Kenya, to land use change and projected climate change scenarios using SWAT model. The study used satellite based rainfall data to improve accuracy of the study results. They found that conversion of forests to farmland and grassland in the basin headwaters could reduce dry season flows and increase peak flows leading to greater water scarcity and accelerated soil erosion at hillslopes. However, they found that runoff response to climate change scenarios (i.e., increased precipitation and temperature) were not linear.

Zheng et al. (2016) examined the separate and combined role of land use change and climate change to the historically decreasing trend inflow to Miyum Reservoir located in China. The study indicated that land use change was responsible for 64-92% of the decline in streamflow during 1984-1999 and 36-58% during 2000-2008. On the other hand, climate variability contributed 8-36% to the decline in streamflow during 1984-1999 but 42-64% during 2000-2008. The study further revealed that warming played dominant role in streamflow reduction in the most recent decade (i.e., 2000s). Yin et al. (2017) also reported that relative and absolute impacts of land use change and climate changes on runoff could vary from decade to decades.

Pan et al. (2015) studied impacts of land use and climate changes on water supply security for the Tibetan Plateau using Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model and Residual Trends (RESTREND) method. They showed that water availability significantly decreased from 1980 to 2005 and then increased from 2005 to 2008. They observed relative contributions of land use and climate changes on water quantity vary with decades. For example, climate change attributed 64% of the reduction during 1980 to 1995 while land use change contributed 58% to the reduction observed during 1995 to 2000. However, from 2000 to 2005, climate change increased water supply due to increased precipitation but land use change reduced water availability from 2000 to 2005. On the contrary, both climate and land use changes had positive impacts on water supply during 2005 to 2008 where 61% contribution was due to land use change.

In addition to the aforementioned studies, other researches were conducted on the topic (e.g., Nuñez et al. 2008). Table 1 and Figure 2 summarize peer-reviewed publications that used SWAT model and examined the impacts of land use change and climate change on water resources from 2010 to 2016 (SWAT peer-review publication database, https://www.card.iastate.edu/swat_articles). It is evident from the studies that both climate and land use changes influence hydrological responses and water resources (i.e., surface and groundwater).

However, relative contribution of land use and climate changes seem to vary with hydro-climatic regions and temporally (e.g., seasonally and from decade to decade). Most of the studies showed that hydrologic responses are more sensitive to climate change than to land use change while others reported that land use change is more significant than climate change. The discrepancy could be due to differences in physical characteristics and climate conditions of a basin, and to a degree due to uncertainties arising from data, and structure and parameters of the models (GCM and hydrology model) used for the study (Lopez-Moreno et al. 2011).

In summary, the studies described above show that the combined impacts of land use and climate changes on hydrological responses could be substantially different from the impacts caused by each factors alone. This underscore the need to examine the impacts of both land use change and climate change for sound decision-makings during planning, design and management of water resources systems.

Table 1. Peer reviewed publications on impacts of land use and climate changes on water resources using SWAT model.

LU & Climate changes		**Climate Change**		**Land use Change**	
Year	No of Articles	Year	No of Articles	Year	No of Articles
2010	0	2010	9	2010	1
2011	3	2011	18	2011	10
2012	3	2012	19	2012	19
2013	4	2013	24	2013	17
2014	9	2014	41	2014	13
2015	18	2015	40	2015	7
2016	12	2016	32	2016	6
2011-2016	**49**	2011-2016	**174**	2011-2016	**72**
2004-2016	**61**	1999-2016	**226**	1999-2016	**98**

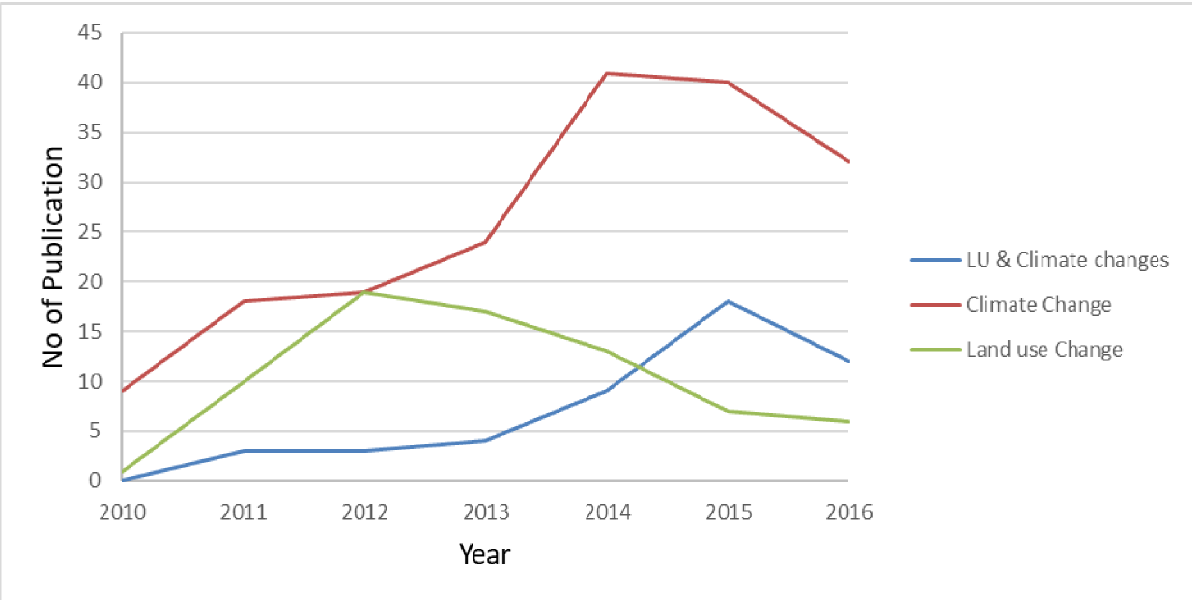


Figure 2. Yearly publications related to impact analysis using SWAT (2010-2016).

5. Methodologies Used

Modeling were used to study the impacts of land use and climate changes on water resources. Models were used for almost all studies conducted either on the combined or separate impacts of historical or future land use and climate changes on hydrology. Hydrology models along with long-term historical data from ground stations were often used to analyze the impacts of historical climate change on hydrologic responses. The future impacts of climate change on hydrological response, on the other hand, were analyzed using future climate projections derived using GCMs and RCMs for plausible emission scenarios.

The approaches used to quantify the impacts of land use change on hydrology include (i) obtain historical land use change data (ii) project future land use maps either using land use change models or based on plausible scenarios, and (iii) force the land use information and other inputs through a hydrology model to predict watershed responses. Similar approaches were used to analyzed the combined and individual impacts of land use and climate changes.

Future climate projections were often made using IPCC AR4 based GCMs. Few studies used IPCC AR5 based GCMs that are generally considered more accurate. Commonly used land use change models include those that use Markov chain method and the Dyna-CLUE-S method. Popular hydrology models include Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), Precipitation-Runoff Modeling System (PRMS) model, Variable Infiltration Capacity (VIC) and Soil and Water Assessment Tool (SWAT). SWAT seems the most suitable model to analyze the hydrologic impacts of land use and climate changes, including separating the relative contributions of land and climate change. As such, most previous studies used SWAT.

6. Limitation of the studies

The impacts of land use and climate changes on hydrologic responses are the functions of physical characteristics, climate condition, and the type and intensity of land use in a basin. These make it challenging to generalize the impacts of land use and climate changes on water resources. Basin specific studies that incorporate uncertainty analysis are required to obtain reliable information that could be used for water resource management.

Most of the previous studies focused on either land use change or climate change impacts. Only few studies considered both climate and land use changes (Table 1). In addition, all the studies (except Mango et al. 2011) used historical climate data from only ground stations (i.e., rain-gauge data) as input for the hydrology models. Ground station data may lack the gauge density required to represent spatial variability of climate (especially precipitation)-thus limiting accuracy of the study results. Radar and satellite based rainfall products could supplement rain-gauge data.

The climate modeling approaches recommended by IPCC AR5 were rarely used for projecting future climate in the previous studies. Most studies used GCMs that are based on IPCC AR4 which is considered less certain. Likewise, land use change models (e.g., Markov Chain and Dyna-CLUE-S) used in the previous studies lack the capability to accommodate spatial and temporal dynamics of land use changes. The spatial and temporal transition between land use classes can only be analyzed on different platform which increases the likelihood of error to occur.

7. Conclusions and the way forward

Approaches used to analyze the impacts of land use and climate changes on hydrologic responses can be grouped as (i) those that focus on the impacts of climate changes only, (ii) those that focus on the impacts of land use changes only, and (iii) those that focus on the combined and separate impacts of land use and climate changes. More studies belong to the first two categories. However, the combined and separate impacts of land use change and climate change on hydrology are becoming hot research topic in the last two decades. The combined effects of climate and land use changes on hydrological responses are different from the separate impacts. Integrated modeling approach that consider the impacts of past, present and future land use and climate changes on hydrological processes should be followed to quantify the combined and separate impacts of land use and climate changes on hydrological responses in the changing environment.

The study results are inconsistent among studies. The reasons could be (i) uncertainty in the models, (ii) less representativeness of the input data (e.g., station data), (iii) difference in basin physical characteristics and climate condition, and (iv) differences in model used. Therefore, reliable and representative input data coupled with accurate models should be used at local scales. Moreover, the uncertainties in the models should be considered and accounted so as to use the information for decision makers. The state-of-the-art models for land use and climate projection should be used. Moreover, satellite based rainfall products should be used as an alternative and supportive input data for hydrological model than relying only on sparse station rainfall data, particularly in poorly gauged basins.

It is evident that both climate and land use changes highly affect hydrological processes and water resources (e.g., surface and ground). However, the extent of the impacts and the relative contribution of the two factors are not clearly known. Despite several studies, there is still limited knowledge about the relative contributions of land use and climate changes on hydrological processes. Therefore, basin specific studies should be conducted in an integrated modeling approach so as to provide detailed and accurate information for water resource planning and management. Moreover, reliable and accurate input data should be used for the modeling (e.g., satellite remote sensing products like land use/land cover, rainfall products).

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