Streamflow and Runoff Responses to Climate Change in High Elevation Watersheds

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論 文 内 容 要 旨

The dissertation investigates the runoff and streamflow generation responses to climate change in mountainous regions at high elevation in the tropics (Latitudes 30° North to 30° South), with high emphasis in the region dominated by the Eastern Cordillera (Central Andes), in the upper Beni River basin, headwaters of the Amazon basin in Bolivia (15.8° to 16.7° South Latitude). The objectives are accomplished through visual, statistical, mathematical analysis of the trends drawn by historical ground observations recorded in gauging stations, historical observations from satellite platforms, outputs from global circulation models (GCMs). The tools employed in the analysis are: distributed representations of the spatial saturation patterns relying essentially in topographic information, a semi-distributed water balance model, a semi-distributed glacier melting model, and a thoroughly investigation of the predictive uncertainty of a distributed hydrological model.

The work developed demonstrates that the impacts of climate change are observable along the tropics, discarding the local or regional character of the phenomena. The latter statement is investigated through two climate change indicators: the trends in the glacier ice caps and the trends in the vegetation cover, both evaluated in East Africa, in the Puncak Jaya in Indonesia, and in the Central Andes, at decadal resolution, and 30-m spatial resolution. Results show that the trends of glacier ice cover are an adequate indicator of regional climate change impacts; on the other hand, the investigation of the vegetation trends is found to be an adequate indicator for local scale studies because it is highly influenced by the topographic characteristics of a region. Specifically, the results demonstrate that the most sensitive region to climate change are the areas dominated by the plateau glaciers of the Puncak Jaya in Indonesia, where glacier ice loss rates of 0.45 km^2 per year are observed during the period 1974-1976, in response to a historical decrease in total precipitation of 1.02 mm per year and a rise in air temperature of 0.01 °C per year for the same period. In reference to the changes observed in the trends of the vegetation dynamics, the only region where variations are observed is the Kilimanjaro, in East Africa, on slope faces oriented towards the direction where winds from the north-west bring higher precipitation than to the other slope faces. In the Western Cordillera, Central Andes of Bolivia, some changes in the biomass are observed; however, vegetation succession is not evidenced. The inability to observe vegetation succession in other regions is attributed to the low spatial resolution of the remotely-sensed imagery employed to monitor the changes.

In reference to the climate change impacts in the water resources availability, the regions in East Africa and in the Central Andes are the zones were the most relevant impacts of climate change are likely to be observed, because of the notorious decrease in total precipitation (-8.45 mm per year in the Central Andes, according to the CCSM 3.0 GCM) and the notorious increase in the air temperature (+0.03 °C per year in the Central Andes, according to the CCSM 3.0 GCM) during the period 1960-2000. As a result, the aridity is likely to increase in both regions. The results are representative indicators of climate change impacts in the tropics, with exception of the Himalayas where local conditions are highly influential.

At the regional scale, in the area dominated by the formations of the Eastern Cordillera (15.8° to 16.7° South Latitude) (Central Andes), analysis of ground observations and remotely-sensed imagery at 30-m ground resolution demonstrate that the impacts of climate change are more relevant in regions with poor vegetation cover, shallow soils, and glacier covered areas. In general, an apparent high sensitivity of the catchment response to climate change in regions with upstream contributing areas between 4507 km^2 and 10835 km^2 is unlikely to have a negative impact on the water resources availability, due to the high volumetric discharges recorded. In small catchments that have upstream contributing areas smaller than 4507 km^2, an apparent rising trend in the discharge records is uncertain because of the specific discharge values recorded have high variability. In the region dominated by the formations of the Eastern Cordillera, the analysis of climatic variables described by the MIROC Hi-res 3.2 and the CCSM 3.0 GCMs draw an average rising rate of 0.035 °C per year in the air temperature information downscaled at an average altitude of 1700 m a.s.l.; the congruence observed in the predictions of both models suggest that their inferences are reliable; on the other hand, the decadal trends observed in the total precipitation predicted by the two latter mentioned GCMs, suggest that to prediction a trend towards drier or wetter conditions is uncertain.

Also at catchment scale, the trends drawn by remotely-sensed surface temperatures (Ts) and surface albedo (α), are found to be the dominant factors in the energy balance equation. Specifically, the decreasing trends in the instantaneous α in response to the rising trends in the air and surface temperatures (Ts), suggest that changes on the land surface in regions characterized by a poor vegetation cover and granitic formations are more notorious than the changes observed in regions covered with close vegetation. The decreasing trends in α and the rising trends in Ts suggest an increase in the soil moisture, whose source is likely to be found on the increase in the melting water from frozen soil during night hours (considering that there is no permafrost beyond the regions where ice caps are found). The potential implications are: an enhancement in the erosive processes, and the increase in the infiltration and evaporation losses. Downstream the poorly vegetated areas are situated areas covered by close forests. In that region, the increase in the air temperature caused by climate change has low impacts on the trends of Ts and α, whose change rates suggest a trend towards stagnation. In conclusion, the basins situated at high elevation are more sensitive to climate change than the forested parts of the catchments situated downstream. The relevant role of forests in the mitigation of the climate change impacts demand the protection of those areas.

The idea of the hydrologically-sensitive areas (HSAs) is a concept considered to propose an alternative to bridge the gap between research and application. From a research perspective, the results from the investigation demonstrate that the integrative character of the lumped catchment response is representative at ungauged locations for most states of the catchment. The highest predictive uncertainties are expected when the catchment is at dry state, when the interactions of internal processes are small, demanding case-specific representations of the systems being studied such as lumped or semi-distributed representations.

From a practical perspective, the assessment of the model predictive uncertainty is fundamental in the modeling process, which is demonstrated through the investigation of the streamflow source areas concept and the HSAs idea. Among the major findings, it is demonstrated that for analysis at day time resolution, in mountainous watersheds where surface runoff is originated from areas with gentle topographic slopes (slope gradients up to 23%, until an average altitude of 350 m a.s.l. in the Natori basin as model basin), the topographic slope is important in the analysis of the streamflow source areas, but it is likely to be the second in relevance after the topology of the area where runoff is generated. Results also suggest that the latter mentioned observation is confirmed in mountainous watersheds dominated by river channel processes, where the topology of the region where surface runoff is generated is likely to have a role that is more important than topographic slope of a region. On the contrary, in steeped mountainous watersheds (topographic slopes up to 47% in the Zongo River basin), that are dominated by processes other than river channel processes, the topographic slope is the first aspect to consider in the inference of the relevance of land surface changes in the watershed response analyzed at monthly resolution. The latter mentioned observations lead to infer that high altitude watersheds in the Andes are likely to have a response originated from a terrace-like configuration, where the relevancy of the terraces on the uppermost region of the catchment grows not only according to the intensity of the input rainfall, but also according to the retention capacity of permanently saturated areas likely to be influenced by the health of the aquatic vegetation.

The investigation of the HSAs on the streamflow generation responses to climate change is carried during the dry season (May-September) in the Andes, through the application of topographic models, a semi-distributed water balance, and a glacier melting model. During the wet and transitional season (October-May), the analysis of the HSAs is carried through a distributed hydrological model. The results of the investigation suggest high sensitivity to glacier depletion in regions above 3000 m a.s.l. at all the basins modeled; the regions with high sensitivity to glacier depletion have partial upstream contributing areas that vary from 693 km^2 to 202 km^2. Only the lower part of the Zongo River basin (situated at an altitude below 2500 m a.s.l.) is identified to have very low sensitivity to glacier depletion due to the high volumetric catchment discharge.

Later, to provide and overview of the spatial runoff patterns, the spatial patterns of the topographic index weighted by gamma-type cumulative distribution frequencies are analyzed to improve the findings. Results demonstrate that sensitive areas *sensitive to glacier depletion* (areas HSG) are likely found on areas where flow velocity is slow, where in turn are allocated areas prone to saturate and wetlands. Then, combining the results from the semi-distributed approach and the spatial runoff patterns inferred through the modified topographic index, results show that the sensitive areas HSG have areal sizes that vary from 136 km^2 in the Zongo River basin to 501 km^2 in the Villa Barrientos basin; the latter mentioned basin has a larger area with gentle slopes likely to allocate saturated zones, for instance it is more sensitive to the depletion of glacier caps. Outside the dry season, the distributed model analyzed through uncertainty measures shows that the most sensitive areas HSG are in regions above 3500 m a.s.l.. Also during the rainy season, the impacts on regions below 3500 m a.s.l. are observed to be dependant on the storage capacity of the areas where wetlands are situated. The latter mentioned results show the differences between the capabilities of the semi-distributed approach and the capabilities of the distributed approach. In conclusion, the overall results obtained suggest that the most critical impacts of climate change are expected in areas with predominant bare soil. In that region, the conditions of the wetlands and the saturated zones (in the study area situated above 3700 m a.s.l.) are likely to define the magnitude of the impacts on the runoff and the streamflow generation in the areas situated downstream. Thus, the effects of glacier depletion are demonstrated to be beyond the direct threat to the streamflow.

Future research is aimed to cover the following areas: the comparison of various uncertainty techniques relying on statistical measures other than the variance, the verification of the remotely-sensed observations through intensive field work during the period 2011-2014, and the proposal of an effective synergy between remote sensing and hydrologic modeling.

論文審査結果の要旨

地球温暖化による氷河域の減少，降雨と蒸発散の変化が，高地流域環境にダメージを与えている．しかし，高地では十分な気象，水文観測が行われておらず，定量的な評価に至っていない問題がある．この解決のために，観測が十分に行われていない地域の水文モデルの構築を行い，モデル評価を通じてボリビア国氷河流域の気候変動の影響を考察したものが本論文である．

論文は全１０章よりなる．

第１章は序論である．

第２章は既往研研究との比較から独自性を記述している．

第３章は研究対象領域と利用データについて述べている．

第４章では，各地の氷河流域について衛星画像と降雨，気温データを解析し，各地の流域の抱える気候問題の違いを定量的に示した．

第５章では，全球気候モデル出力データのバイアス補正の後，高地流域の気候，水文データを解析した．その結果，標高の高い地域は，低い地域よりも降水，気温ともに時間変化が大きいこと，最大と最小降雨の差が大きくなることが定量的に把握された．これらは貴重な成果である．

第６章は，高地流域において地表面熱収支を標高別に時系列で求めた．植生限界より上では表面温度の上昇傾向とアルベドの減少が見られ，植生地帯では気候変動の緩衝作用のあることを把握し，高地流域の上下流の熱環境差を初めて定量的に評価した．

第７章では，感度分析手法を水文モデルに適用することによって最も感度の高い水文パラメータを分布データで導出する手法を提案した．この成果によって，気候変動による水資源問題について地域毎の対策案を考察することが可能になった．

第８章は，７章の手法によって河川流量の水源地域を判定することに成功した．この成果によって，下流任意地域の水資源確保のための上流の対策適地を特定できるようになった．

第９章では，氷河減少が下流域に与える影響を８章と９章の方法を用いて評価し，流域勾配，植生が乾季の低水流量に影響を与えることを定量的に初めて示した．

第１０章は結論である．

以上要するに本論文は，気候モデルと水文モデルを利用し，観測が未整備である高地氷河流域の水資源脆弱性を定量的に明らかにすると同時に，流出に対して最も敏感な水文過程を分布データとして導き出すことに成功した．本研究の成果は気候変動下の氷河を含む高地域の水資源管理さらには環境保全計画に大きく貢献できるものである．

よって，本論文は博士（工学）の学位論文として合格と認める．