

HYDROLOGIC MODELLING WITH SWAT AND BIVARIATE RISK ANALYSIS BASED FLOODPLAIN MAPPING OF RIVER AWASH, ETHIOPIA

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**Hydrologic Modelling with SWAT and Bivariate Risk Analysis based
Floodplain Mapping of River Awash, Ethiopia**

by

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This thesis is devoted to my family, I would say

Certificate

This is to certify that we have examined the thesis titled *"Hydrologic Modelling with SWAT and Bivariate Risk Analysis based Floodplain Mapping of River Awash, Ethiopia"* submitted by **Teklay Gebreagziabhier Hagos** (Entry Number: **2015CEZ8293**) to the Indian Institute of Technology Delhi, New Delhi (India), is worthy of consideration for the award of the degree, **Doctor of Philosophy**.

This thesis is a record of the original research work carried out by this student under our joint supervision. We hereby certify that the results contained in this thesis, which may have been previously communicated in the form of manuscripts, conference presentations or patent filings, have not been submitted in part or full to any other university or institute for the award of any academic degree or diploma.

We certify our approval of it as a study carried out and presented in a manner required for its acceptance as per the regulations of the Institute and has reached the standard needed for submission.



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Abstract

In river basins, high flow periods cause rivers to reach peak water levels, creating challenges with excess water, while low flow periods lead to water shortages, stressing the system. These hydrological extremes result in floods during high flows and droughts during low flows. In basins with highly variable precipitation, such as those in developing economies like Ethiopia, floods and droughts severely affect communities and their assets due to limited funding for water infrastructure and poor coordinated water management. The Awash River basin, for example, frequently faces significant flood and drought challenges. Nowadays flood is a serious problem in most areas of the world including the Awash River basin. A flood occurs when river flow surpasses a threshold, which is an arbitrary value varying by context. Robust estimation and prediction of flood risk and flood hazard is so important. Hydrological extremes comprise of several interrelated variables. For instance, flood comprises of variables such as flood peak, flood volume and flood duration. For more accuracy of probability and return period estimations, taking into consideration of multiple thresholds and annual maximum series as compared to single threshold or the annual maximum series alone is essential. Bivariate models, which account for multiple variables, provide more precise flood risk assessments and better infrastructure design compared to univariate models that focus on a single variable. Design of water structures such as spillway based on univariate flood risk analysis may be faulty and it may not have the capacity to convey safely the excess flood coming into a reservoir. The flood volume is an important variable as equally as the flood peak in describing the flood situation. Bivariate flood risk modelling by comparing various copulas and bivariate distributions for flood risk analysis, flood hazard assessment and for design of structures such as spillways is so vital. Estimation of natural flows using a hydrological model such as SWAT is required in order to study the univariate and bivariate nature of floods. Besides, addressing the problems associated within the SWAT model is essential. Thus, analyzing both univariate and bivariate aspects of floods is vital for evaluating their severity, risks, and hazards, and for enhancing integrated water resource management in the Awash River basin. Additionally, estimating flood variables like extent, depth, and velocity with reasonable accuracy requires hydrodynamic models such as HEC-RAS and iRIC, where selecting an appropriate grid size is critical for reliable results. Hydrologic models are expected to be streamlined representations of the actual system. They serve for research purposes of boosting knowledge and comprehension of

the hydrological processes governing the actual system and are used as instruments for streamflow prediction and modelling. In order to characterize the real-world system as well as to understand the hydrological processes governing the actual system the parameters of the system are required to be assigned with the correct values. The parameters' values vary as detail watershed characteristics vary. For a process-based model, the default parameter values have to vary as the detail catchment physiognomies vary. Employing the SWAT, modeling hydrology of the Awash River Basin has been done by considering different resolutions of DEM for various user defined threshold levels. The model default values for numerous parameters, especially groundwater parameters, were not varying as the catchment characteristics varied. Keeping other parameters at their default values, a change in curve number value alone has not been found improving the model Nash-Sutcliffe efficiency. Equifinality has been observed while calibrating and validating the model even with small number of parameters. Number of HRUs, number of parameters and range of values of the parameters have been found affecting the quotient of equifinality and the Nash-Sutcliffe efficiency value. Assigning appropriate optimal values to the physical parameters for the Awash River Basin have been found impossible with the SWAT hydrological modelling platform. Based on the calibration and validation results of the Nash-Sutcliffe efficiency values, the natural flows have been simulated using the SWAT model in the presence of equifinality, system non-identifiability and with the assumption that the basin characteristic details do not change. The simulated natural flows have been used for univariate and bivariate flood risk modelling as well as hydrodynamic modelling of the Awash River. Bivariate flood risk modelling has been done using copulas and bivariate distributions at different gauge stations of the Awash River by employing new methodological approach to estimate the unconditional probabilities and return periods by considering different threshold levels and the annual maximum series as prior information. Hydrodynamic modelling in Awash River Basin with special focus on variation of grid size and centerline using iRIC and HEC-RAS models have been studied for a given bivariate return period of flood. Parameters' values for the different copulas were approximated by maximum likelihood method using the Markov Chain Monte Carlo and local optimization algorithms. For some of the copulas when there has been found dissimilarity between the estimated copula parameters using the two optimization algorithms, the Root Mean Square Error for the Markov Chain Monte Carlo optimization algorithm has been found smaller than that of the local optimization algorithm. There were not found significant changes in Nash-Sutcliffe efficiency

values among most of the copulas. The Nash-Sutcliffe efficiency may not be a good criterion for selection of copulas. The Bayesian Information Criteria has been used as goodness of fit criteria to select marginal distributions and copulas to the flood peaks and flood volumes at different gauge stations of the Awash River. A substantial difference in magnitude flood as well as in extent of inundation have been observed among the different grid sizes in both the hydrodynamic models. The output results of the Nays2D Flood of iRIC model have been found varying as the centerline was changed. As the grid size is smaller the variation of the magnitude of flood and the extent of inundation variation due to the centerline has been found to reduce. Similar results of flood magnitude and inundation extent for both the models i.e., iRIC and HEC-RAS have been found when the grid size is smaller. The maximum depth of flow was found directly linked to the flood peak magnitude provided that the flow at the outlet is free outflow. While the flow depth at the finale of the flood has found related not only to the flood peak magnitude but also to the flood volume.

Keywords: Hydrologic Modelling, SWAT, Equifinality, System Non-identifiability, Univariate Flood Risk Analysis, Bivariate Flood Risk Analysis, Hydrodynamic Modelling, iRIC, HEC-RAS

सारांश

नदी बेसिनों में, उच्च प्रवाह की अवधि के दौरान नदियों का जलस्तर चरम पर पहुँच जाता है, जिससे अतिरिक्त पानी की समस्या उत्पन्न होती है, जबकि निम्न प्रवाह की अवधि में जल की कमी हो जाती है, जिससे प्रणाली पर दबाव पड़ता है। ये जलविज्ञान संबंधी चरम स्थितियाँ उच्च प्रवाह के समय बाढ़ और निम्न प्रवाह के समय सूखे का कारण बनती हैं। अत्यधिक परिवर्तनशील वर्षा वाले बेसिनों में, जैसे विकासशील अर्थव्यवस्थाओं उदा., इथियोपिया में, बाढ़ और सूखा समुदायों और उनकी संपत्तियों को गंभीर रूप से प्रभावित करते हैं क्योंकि जल अवसंरचना के लिए धन की कमी और समन्वित जल प्रबंधन कमजोर होता है। उदाहरण के लिए, अवाश नदी बेसिन अक्सर गंभीर बाढ़ और सूखे की समस्याओं का सामना करता है। वर्तमान में, बाढ़ दुनिया के अधिकांश क्षेत्रों सहित अवाश नदी बेसिन में एक गंभीर समस्या है। जब नदी का प्रवाह किसी सीमा से अधिक हो जाता है (जो संदर्भ के अनुसार अलग-अलग हो सकती है), तब बाढ़ आती है। बाढ़ जोखिम और बाढ़ खतरों का सटीक अनुमान और पूर्वानुमान अत्यंत महत्वपूर्ण है। जलविज्ञान संबंधी चरम स्थितियाँ कई परस्पर संबंधित चर से बनी होती हैं। उदाहरण के लिए, बाढ़ में बाढ़ की चोटी (फ्लड पीक), बाढ़ की मात्रा और बाढ़ की अवधि जैसी चर शामिल होती हैं। संभावना और पुनरावृत्ति अवधि के सटीक अनुमान के लिए एकल सीमा या वार्षिक अधिकतम श्रृंखला के बजाय बहु-सीमाओं और वार्षिक अधिकतम श्रृंखला को ध्यान में रखना आवश्यक है। बहु-चर (बाइवेरिएट) मॉडल, जो कई चरों को ध्यान में रखते हैं, एकल-चर (यूनिवेरिएट) मॉडल की तुलना में अधिक सटीक बाढ़ जोखिम मूल्यांकन और बेहतर अवसंरचना डिज़ाइन प्रदान करते हैं। केवल एकल-चर आधारित बाढ़ जोखिम विश्लेषण पर स्पिलवे जैसी जल संरचनाओं का डिज़ाइन दोषपूर्ण हो सकता है और इसमें आने वाली अतिरिक्त बाढ़ को सुरक्षित रूप से निकालने की क्षमता नहीं हो सकती। बाढ़ की मात्रा, बाढ़ की चोटी के समान ही, बाढ़ की स्थिति का वर्णन करने में एक महत्वपूर्ण चर है। इसलिए, बाढ़ जोखिम विश्लेषण, बाढ़ खतरे का मूल्यांकन और स्पिलवे जैसी संरचनाओं के डिज़ाइन के लिए विभिन्न कॉपुला और बाइवेरिएट वितरणों की तुलना करके द्विवेरीय बाढ़ जोखिम मॉडलिंग करना अत्यंत आवश्यक है। प्राकृतिक प्रवाह का अनुमान लगाने के लिए SWAT जैसे जलविज्ञान मॉडल की आवश्यकता होती है ताकि बाढ़ की एकल और द्विवेरीय प्रकृति का

अध्ययन किया जा सके। इसके अलावा, SWAT मॉडल से संबंधित समस्याओं का समाधान करना भी आवश्यक है। इस प्रकार, बाढ़ के एकल और द्विवेरीय दोनों पहलुओं का विश्लेषण करना उनकी गंभीरता, जोखिम और खतरों का मूल्यांकन करने और अवाश नदी बेसिन में एकीकृत जल संसाधन प्रबंधन को बेहतर बनाने के लिए महत्वपूर्ण है। बाढ़ के चर जैसे विस्तार, गहराई और वेग का सटीक अनुमान लगाने के लिए HEC-RAS और iRIC जैसे हाइड्रोडायनामिक मॉडल आवश्यक हैं, जहाँ उपयुक्त ग्रिड आकार का चयन विश्वसनीय परिणामों के लिए महत्वपूर्ण है। जलविज्ञान मॉडल वास्तविक प्रणाली के सरलीकृत प्रतिनिधित्व होने चाहिए। ये अनुसंधान उद्देश्यों के लिए काम करते हैं ताकि वास्तविक प्रणाली को नियंत्रित करने वाली जलविज्ञान प्रक्रियाओं के ज्ञान और समझ को बढ़ावा दिया जा सके और प्रवाह पूर्वानुमान और मॉडलिंग के उपकरण के रूप में उपयोग किए जा सकें। वास्तविक प्रणाली का वर्णन करने और जलविज्ञान प्रक्रियाओं को समझने के लिए प्रणाली के मानकों को सही मानों के साथ निर्दिष्ट करना आवश्यक है। ये मान विस्तृत जलग्रहण विशेषताओं के अनुसार बदलते हैं। प्रक्रिया-आधारित मॉडल के लिए, डिफ़ॉल्ट पैरामीटर मानों को भी कैचमेंट की विशेषताओं के अनुसार बदलना चाहिए। SWAT का उपयोग करके अवाश नदी बेसिन की जलविज्ञान मॉडलिंग विभिन्न उपयोगकर्ता-परिभाषित थ्रेशोल्ड स्तरों के लिए DEM के विभिन्न रिज़ॉल्यूशन को ध्यान में रखते हुए की गई है। कई पैरामीटर, विशेष रूप से भूजल पैरामीटर, कैचमेंट विशेषताओं के बदलने के बावजूद डिफ़ॉल्ट मानों पर स्थिर रहे। अन्य पैरामीटर को डिफ़ॉल्ट मानों पर रखते हुए केवल कर्व संख्या के मान में परिवर्तन करने से मॉडल की नैश-सटक्लिफ दक्षता में सुधार नहीं पाया गया। पैरामीटरों की कम संख्या के बावजूद मॉडल को कैलिब्रेट और सत्यापित करते समय इक्विफिनेलिटी देखी गई। पैरामीटरों की संख्या, HRU की संख्या और मानों की सीमा ने इक्विफिनेलिटी और नैश-सटक्लिफ दक्षता को प्रभावित किया। SWAT प्लेटफ़ॉर्म के साथ अवाश नदी बेसिन के भौतिक पैरामीटरों को उचित इष्टतम मान सौंपना असंभव पाया गया। कैलिब्रेशन और सत्यापन के परिणामों के आधार पर, इक्विफिनेलिटी, सिस्टम नॉन-आइडेंटिफ़िएबिलिटी और यह मानते हुए कि बेसिन की विशेषताओं में कोई बदलाव नहीं होता, SWAT मॉडल का उपयोग करके प्राकृतिक प्रवाह का अनुकरण किया गया। द्विवेरीय बाढ़ जोखिम मॉडलिंग विभिन्न कॉपुला और बाइवेरिएट वितरणों का उपयोग करके अवाश नदी के विभिन्न गेज

स्टेशनों पर की गई, जिसमें विभिन्न थ्रेशोल्ड स्तरों और वार्षिक अधिकतम श्रृंखला को पूर्व सूचना के रूप में ध्यान में रखते हुए बिना शर्त संभावनाओं और पुनरावृत्ति अवधियों का अनुमान लगाने के लिए नई पद्धति अपनाई गई। हाइड्रोडायनामिक मॉडलिंग iRIC और HEC-RAS मॉडल का उपयोग करके की गई, जिसमें ग्रिड आकार और सेंटरलाइन में बदलाव का प्रभाव एक दिए गए द्विवेरीय पुनरावृत्ति अवधि पर अध्ययन किया गया। कॉपुला पैरामीटरों के मान अधिकतम संभावना विधि द्वारा मार्कोव चेन मोंटे कार्लो और स्थानीय अनुकूलन एल्गोरिदम का उपयोग करके अनुमानित किए गए। कुछ कॉपुलाओं के लिए जब दोनों एल्गोरिदम द्वारा अनुमानित कॉपुला पैरामीटरों में असमानता पाई गई, तो मार्कोव चेन मोंटे कार्लो एल्गोरिदम के लिए आरएमएसई स्थानीय एल्गोरिदम की तुलना में कम पाया गया। अधिकांश कॉपुलाओं के बीच नैश-सटक्लिफ दक्षता मूल्यों में महत्वपूर्ण बदलाव नहीं पाया गया। इसलिए, कॉपुला चयन के लिए नैश-सटक्लिफ दक्षता अच्छा मानदंड नहीं हो सकता। बेयेसियन सूचना मानदंड का उपयोग हाशिये के वितरण और कॉपुला चयन के लिए किया गया। विभिन्न ग्रिड आकारों में बाढ़ की तीव्रता और जलभराव के विस्तार में महत्वपूर्ण अंतर पाया गया। iRIC मॉडल के Nays2D Flood के आउटपुट परिणाम सेंटरलाइन बदलने के साथ बदलते पाए गए। छोटे ग्रिड आकार के साथ सेंटरलाइन के कारण बाढ़ की तीव्रता और जलभराव विस्तार में होने वाला अंतर कम पाया गया। दोनों मॉडलों (iRIC और HEC-RAS) के लिए समान परिणाम तब पाए गए जब ग्रिड आकार छोटा था। प्रवाह की अधिकतम गहराई आउटलेट पर मुक्त प्रवाह होने पर बाढ़ की चोटी की तीव्रता से सीधे जुड़ी पाई गई, जबकि बाढ़ के अंत में प्रवाह की गहराई बाढ़ की चोटी और बाढ़ की मात्रा दोनों से संबंधित पाई गई। कुंजी शब्द: जलविज्ञान मॉडलिंग, SWAT, इक्विफिनेलिटी, सिस्टम नॉन-आइडेंटिफ़िएबिलिटी, एकल-चर बाढ़ जोखिम विश्लेषण, द्विवेरीय बाढ़ जोखिम विश्लेषण, हाइड्रोडायनामिक मॉडलिंग, iRIC, HEC-RAS

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