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FLOOD INUNDATION ANALYSES AND THREE-DIMENSIONAL HAZARD MAPPING APPROACHES FOR SMALL-SIZED RIVERS

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ABSTRACT: As global warming accelerates, the frequency and severity of heavy rainfall events have increased dramatically. Although a range of mitigation strategies exists, disaster-management specialists consistently emphasize that evacuation remains the most effective means of protecting human life. Accordingly, accurate and reliable flood-inundation information is essential for enabling timely and effective evacuations. In Japan, flood hazard maps grounded in detailed inundation analyses have been developed, disseminated, and widely utilized for major river basins. However, in small river basins, flood behavior is often influenced by backwater effects and runoff interactions with larger downstream rivers, and the development of comprehensive watershed databases has lagged. Consequently, high-precision flood-inundation analyses are difficult to perform, and reliable hazard maps are frequently lacking. In this study, we employ the iRIC (International River Interface Cooperative) model to analyze the hydraulic behavior of small river basins and to generate detailed three-dimensional hazard maps. Validation of the simulation results and the derived hazard maps confirms their reliability. The proposed methodology for flood-inundation analysis and hazard-map development is expected to provide a practical and effective framework for supporting evacuation planning and reducing casualties during flood events.

Keywords: Global Warming, Inundation Analyses, Evacuation Planning, Hazard Map, iRIC (International River Interface Cooperative)

1. INTRODUCTION

In recent decades, Japan has witnessed increasingly severe extreme weather events attributed to climate change, including record-breaking heavy rainfall occurring almost annually [1]. These events have caused widespread flooding and inundation exceeding urban flood control standards, as well as serious landslides, resulting in substantial economic losses and human casualties [2].

To mitigate damage from flood inundation, the reinforcement of hard infrastructure flood control measures is essential. However, such developments require significant financial investment and extended timelines, limiting their immediate effectiveness. Consequently, evacuation strategies have gained increased attention. Numerous cases demonstrate that timely evacuation can prevent fatalities, whereas delays or failures in evacuation exacerbate harm, highlighting the critical role of effective evacuation planning [2]. However, Japan is facing a pronounced demographic challenge, with individuals aged 65 and older constituting 29.1% of the population in 2023, projected to rise to 40% by 2050 [3]. This unprecedented aging population presents considerable obstacles to rapid evacuation.

To ensure efficient and reliable evacuation, local governments have developed evacuation plans supported by hazard maps that provide essential information such as inundation depths and extents, possible evacuation facilities and routes for various flood scenarios. While hazard map development is advanced in major river basins and metropolitan areas, smaller river basins have lagged behind. Often, disaster prevention plans for tributaries depend on finalized plans for downstream major rivers, resulting in numerous basins without adequate hazard maps [4].

Many small-sized river basins are treated merely as a collection of grid cells in regional hazard maps, where only the average inundation depth for each cell is displayed. As a result, the detailed information necessary for evacuation is often insufficient. Moreover, these river basins are typically located in mountainous upstream areas of major rivers, where steep topography and limited evacuation routes are common. In such settings, average inundation depth for each cell alone is often inadequate for assessing the safety of evacuation routes.

This study aims to present a systematic procedure for creating hazard maps that provide more detailed inundation information for such regions, with particular emphasis on establishing a method for developing three-dimensional hazard maps that can be used in evacuation drills.

This study employs the reliable and user-friendly iRIC (International River Interface Cooperative) flood simulation model to analyze inundation in small river basins [5]. Using the simulation results, we develop a three-dimensional flood hazard map aimed at securing smooth and rapid evacuation routes during floods. Finally, evacuation scenarios are simulated to enable virtual pre-experience of evacuation routes, thereby assessing the feasibility of prompt evacuation behavior.

2. RESEARCH SIGNIFICANCE

This study applies a comprehensive methodology for developing three-dimensional hazard maps for small- to medium-sized river basins, where obtaining reliable and detailed flood information for evacuations is particularly challenging. The three-dimensional hazard maps produced through this process enable users to identify suitable evacuation shelters, determine optimal evacuation routes, and estimate required evacuation time, thereby supporting the development of feasible and effective evacuation plans. Moreover, the application of these three- dimensional hazard maps facilitates the

Table 1. The major research items required by the standard hazard mapping procedure for inundation analyses

Items Related to River Basin	Item Related to River Channel	Items Related to Management Facilities
➢ Assessment of the maintenance status of levees and related river embankment structures ➢ Identification of water levels that allow safe conveyance of flood flows at each location ➢ Identification of flood-initiation discharge at each location ➢ Identification of locations with potential flood or overflow risk ➢ Determination of the target inundation area ➢ Survey of ground elevation and drainage conditions within the target inundation zone ➢ Setting of drainage conditions and parameters for inundation analysis ➢ Inundation analysis ➢ Determination of inundation duration and related conditions ➢ Setting of inundation areas and water depths caused by external forces other than river flooding	➢ Assessment of current river-channel topography ➢ Understanding water-level transitions within the river channel using calculation methods employed in river planning ➢ Setting of initial river water levels ➢ Calculation of overflow discharge, inundation discharge, and related flow components ➢ Setting of flood-hazard zones for building collapse due to riverbank erosion ➢	➢ Assessment of current conditions of flood-control facilities and river-management structures (e.g., levees, flood-control installations) ➢ Setting of assumed maximum-scale rainfall ➢ Estimation of possible discharge hydrographs under crisis-management rainfall, considering upstream flooding and related factors ➢ Setting of inundation-analysis parameters for hydraulic-force calculations ➢ Inundation analysis ➢ Setting of judgement criteria for building collapse ➢ Setting of flood-hazard zones for building collapse caused by flooding
➢ Display of flood-inundation hazard maps and related datasets ➢ Storage and publication of analysis data		

(Note: Produced based on the guidelines of the River Flood Hazard Map Generation Manual [4,6].)

implementation of online evacuation drills, which are expected to make a significant contribution to reducing human casualties in the event of flooding. Furthermore, Combining the traditional inundation analysis model with the three-dimensional mapping technology makes the hazard map generation procedure more reliable and easier.

3. INUNDATION ANALYSES

3.1 General Inundation Analysis Procedure

In Japan, the preparation and dissemination of hazard maps are mandated by law for river administrators. Corresponding to this legal obligation, the procedures for developing such maps have been standardized [4,6], and river administrators are required to adhere strictly to these manuals. Table 1. summarizes the principal items related to flood-inundation analysis prescribed in the manual for hazard-map development; the level of technical detail and procedural complexity is extraordinarily high.

The present study will not follow the manual strictly because it does not seek to produce hazard maps on behalf of river administrators, but rather aims to propose methodologies for improving their development. Within this framework, and while maintaining consistency with the structure of the existing manual, we present below a series of methodological steps for producing hazard maps for small- and medium-sized river basins.

3.2 Inundation Analysis Model iRIC

iRIC (International River Interface Cooperative) is a free software platform designed for inundation analysis and numerical simulation of rainfall-runoff processes. Developed by the International River Interface Cooperative [5], iRIC supports a diverse range of computational solvers addressing various problems in water science and engineering [7]. Originally created as a tool for river flow and morpho-dynamic analysis, the software has since evolved to encompass a broad spectrum of applications, including flood prediction, rainfall-runoff modeling, tsunami propagation, debris flow simulation, habitat assessment, and other hydrological and hydraulic phenomena.

iRIC is widely used in Japan, and its reliability, flexibility, and user-friendly interface have been demonstrated through numerous reported case studies [8]. It is currently recognized by the Japanese government as one of the approved inundation analysis models that can be utilized in the formulation of river management plans [4,6]. Therefore, this study adopts the iRIC model for inundation analyses.

The specific hydrological and hydraulic details implemented within iRIC model are omitted here; readers are referred to the official iRIC manual for further information. The manual is available for download from the iRIC official website [5,7].

3.3 The Watershed for Inundation Analyses

This study has chosen the Oiwagawa River watershed located in Toyama Prefecture, Japan for inundation analyses. The location of the Oiwagawa watershed is shown in Fig.1. This river is a tributary of the Shiraiwa River and is a small river with a total length of 12 kilometers. Originating from Takamine Mountain, which stands at an elevation of 958 meters, the river descends while forming deep V-shaped valleys and large waterfalls, eventually converging with the Shiraiwa River. Several settlements have developed around the basin areas along the river. Repeated flooding of this river poses significant threats to the lives and properties of these inhabitants [9]. The Oiwagawa basin was selected for the analysis with the aim of providing essential information for the evacuation of residents.

Fig.1 The location of the Oiwagawa River watershed

Fig.2 illustrates the specific inundation analysis area within the Oiwagawa watershed. The inundation analysis region encompasses a rectangular area measuring 1.3 kilometers in width and 8.0 kilometers in length, covering nearly the entire upstream watershed from the confluence with the Shiraiwa River to the exit of the Takamine Mountain valley.

The rectangular analysis area does not include four tributaries of the Oiwagawa River (Shioya River, Kakenana River, Futaguchi River, and Suyama River) and the very upstream segment of the Oiwagawa River that flows down the Takamine Mountain valley. The inflows from all the five rivers are inputted directly into the corresponding segments of Oiwagawa River with careful considerations of the runoff time in each river segment. Also shortened names of the five rivers are used for simplicity in this paper as Shio, Kake, Futa, Suya and Oiwa, respectively.

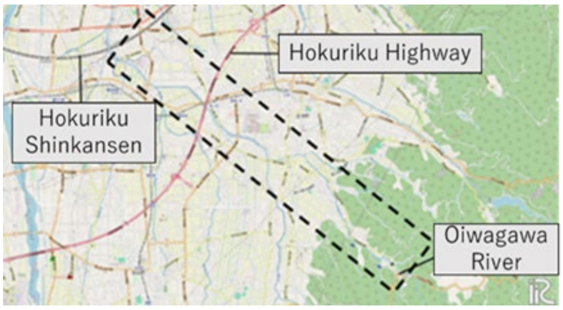

Fig.2 The inundation analysis area within the Oiwagawa River watershed

3.4 Setting Up the Analysis Conditions

To apply the iRIC model to the target river basin, it is essential to define both the basin conditions and the analysis parameters in advance.

First, topographic data of the study area is required. For this purpose, data provided by the Geospatial Information Authority of Japan (GSI) through its GPS system was utilized [10]. The GSI data was selected due to its high reliability.

Next, the river basin was discretized into a rectangular grid (cells) based on the topographic data described above. The grid comprises 200 cells along the river flow direction and 50 cells across the river width, resulting in individual cell dimensions of approximately 40.3 meters in length and 26 meters in width. This grid resolution was chosen in consideration of the trade-offs among topographic data accuracy, analysis duration, and computational cost.

A key parameter used to represent the hydrological characteristics of the river channel is Manning's roughness coefficient. The values adopted here are those traditionally used by Toyama Prefecture in previous flood analyses of the Oiwagawa River [11]. This choice allows for direct comparison and validation against prior results.

Furthermore, rainfall intensity must be specified as input for the flood inundation model. In the flood mitigation planning for this basin, Toyama Prefecture has already established standard design rainfall based on a 1-in-50-year return period. The rainfall intensity associated with this probability rainfall is defined by the following equation [12]:

$$\mathbf{r} = \frac{2019.92}{t^{0.76} + 7.680} \tag{1}$$

where t is time in minutes and r is the rainfall intensity in mm/hr. The corresponding hyetograph for this design rainfall is presented in Fig. 3.

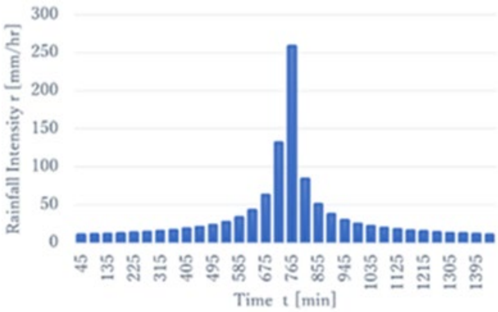

Fig.3 The hyetograph of the design rainfall

Finally, the study area receives inflows from several tributaries, including the upstream portion of the Oiwagawa River (see Fig.4). The inflows from these tributaries must be predefined as input for the iRIC model. To estimate these inflows, the well-known Rational Method was employed:

$$\mathbf{Q} = \frac{1}{3.6} frA \tag{2}$$

In this equation, Q represents the flow rate from a tributary (in m^3/s), f is the runoff coefficient (dimensionless), r is the rainfall intensity (mm/hr) as defined in Eq.(1), and A is the drainage area of the tributary (in hectares).

Using Eq. (2), the flow rates for five tributaries—Oiwa, Futa, Suya, Shio, and Kake—were calculated with the same design rainfall as defined by Eq.(1). The resulting hydrographs are presented in Fig. 5, and will be used for the inundation analysis.

3.5 Inundation Analysis Results

Using the analysis conditions established in the previous section, including the design rainfall and the

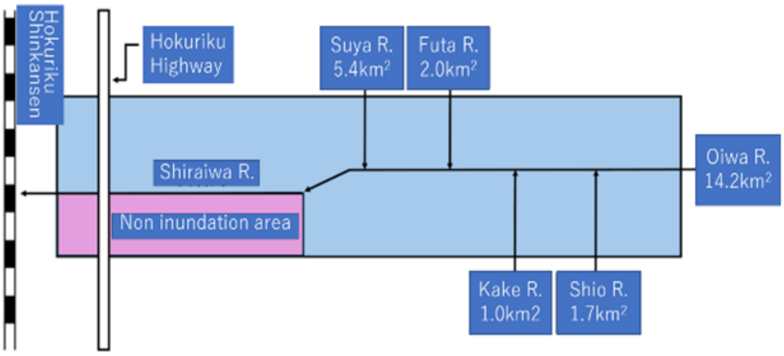

Fig.4 The Oiwagawa River watershed and its tributaries

inflow hydrographs of the five tributaries, the iRIC model was applied to the target watershed. As a result, the extent and depth of inundation caused by the design rainfall were obtained.

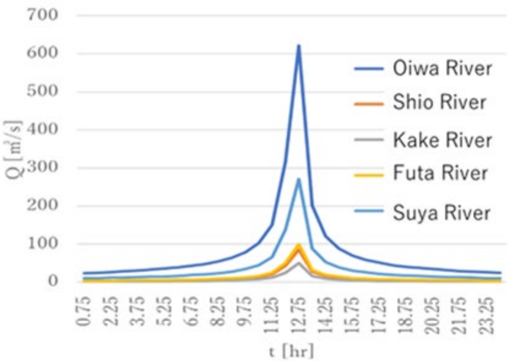

Fig.5 The hydrographs of the five inflowing tributaries based on the design rainfall.

Fig.6 illustrates the inundation depth at the time of peak discharge (t=46,800 seconds) at the downstream end of the simulation domain. The areas where inundation water depths are less than 0.01m are not shown in this figure because these water depths are considered will not cause any more problems for evacuation activities than the heavy rainfall itself.

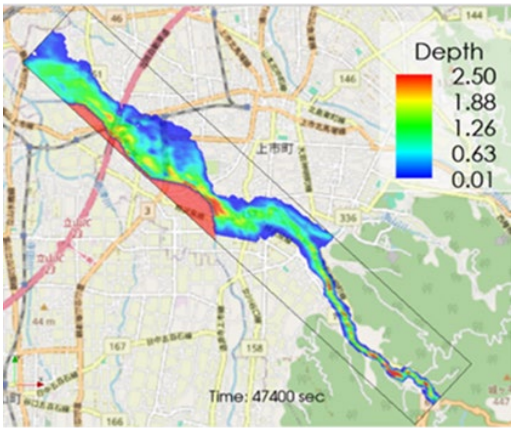

Fig.6 The inundation depth(m) when the downstream discharge reached the maximum

Fig.7 shows the maximum inundation depth recorded in each computational cell during the whole design rainfall event. It should be noted that the timing of these peak depths varies across cells. Nevertheless, the maximum inundation depth is particularly important when considering evacuation planning.

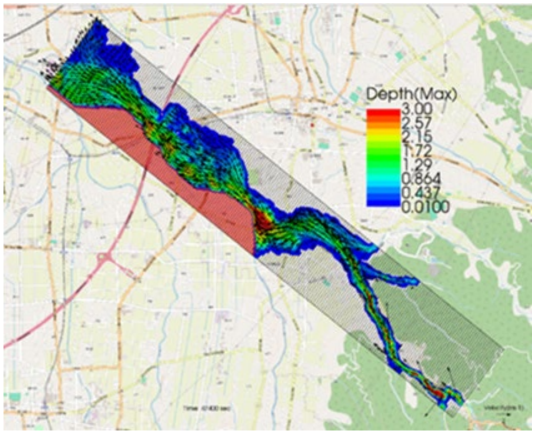

Fig.7 The maximum inundation depth(m) during the whole runoff process

Fig.8 shows the planned inundation scenario for the target river basin currently published by Toyama Prefecture [13]. It has already been confirmed that this published scenario contains calculation errors [14], and a reassessment is currently being conducted by the prefectural authorities to evaluate the impact of those errors. In comparison, the flood assessment conducted in the present study reveals a wider inundation extent and greater inundation depths, indicating a more severe flood scenario than previously reported.

4. GENERATE INUNDATION HAZARD MAPS

4.1 Two-Dimensional Hazard Map

By overlaying the inundation depth results obtained from the flood simulation described in the previous section with various digital maps, it is

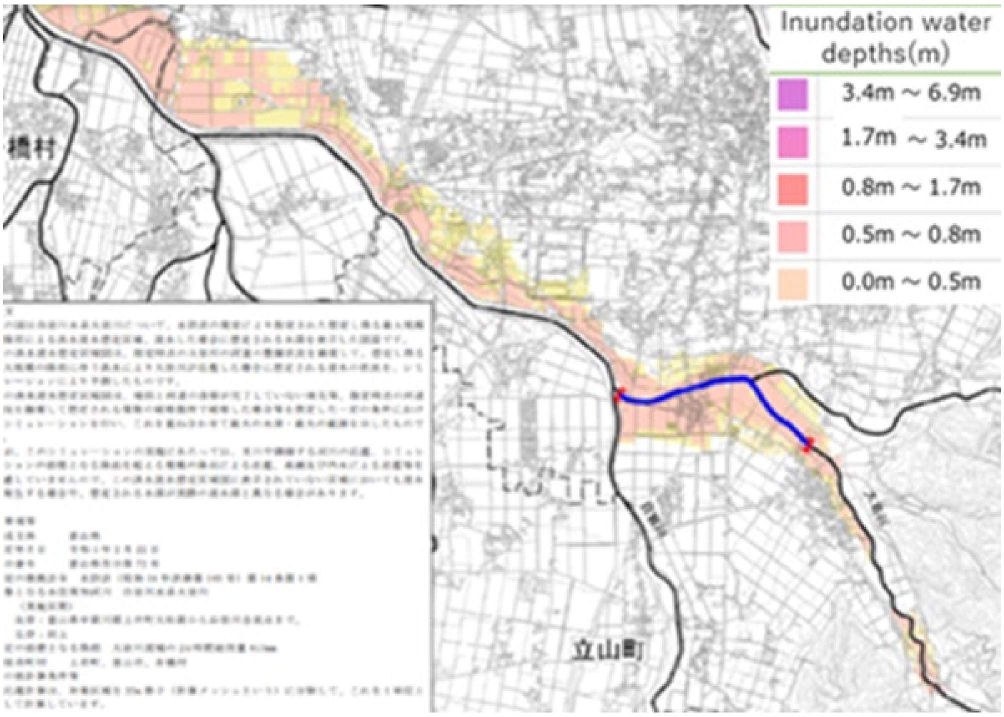

Fig.8 The current inundation scenario for Oiwagawa watershed published by Toyama Prefecture [13]
(The analysis river segment for this study is between the two red dots.)

possible to generate different types of hazard maps tailored to specific purposes.

First, a two-dimensional hazard map was created by superimposing the maximum inundation depths during the design rainfall event (as shown in Fig.9) onto Google Maps. Fig.10 presents an image illustrating the overlay process, and Fig.9 shows the base version of the resulting two-dimensional hazard map. Naturally, to complete this hazard map, additional information—such as the locations of evacuation facilities—should be overlaid as well. However, such information is already well-maintained by local governments in Japan, and thus that step is omitted in this discussion.


Fig. 9 Generate two-dimensional hazard map

4.2 Three-Dimensional Hazard Map

Next, the creation of a three-dimensional hazard map is described. Regarding the construction of three-dimensional hazard maps, the Government of Japan has prepared and published a highly detailed manual [15]. Since the present study fundamentally follows this manual, readers are referred to it for the specific procedures involved. Below, we outline the general process used in this study for creating three-dimensional hazard maps.

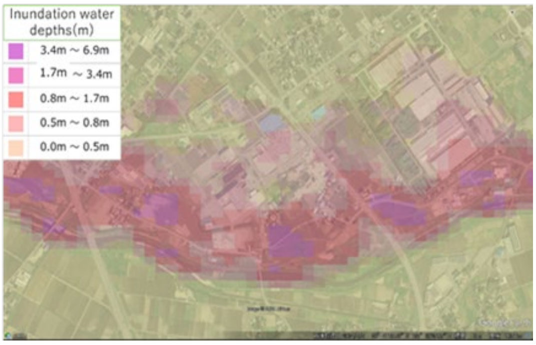

Fig.10 The two-dimensional inundation hazard map

Similar to the two-dimensional map, the three-dimensional hazard map is produced by overlaying the flood simulation results onto digital map data. In this case, however, Google Earth system [16] is used as the base platform, and Google Street View [17] is also incorporated to enhance the spatial context. Fig.11 and Fig.12 show examples of three-dimensional hazard maps for two different locations.

Fig.11 The Three-dimensional inundation hazard map at Street-A where the water depth is 1.68m

4.3 Results and Discussion

This three-dimensional hazard map generated above allows users to visually assess the extent of inundation in specific areas, including around evacuation facilities, offering an intuitive understanding of the flood situation at points of interest. Additionally, users can evaluate the inundation conditions along potential evacuation routes, which aids in selecting safer paths. Once the evacuation facilities and routes are identified, the three-dimensional hazard map can be used to estimate evacuation times, enabling the development of more realistic and effective evacuation plans [18].

Fig.12 The Three-dimensional inundation hazard map at Street-B where water depth is 1.21m

The primary advantage of this three-dimensional hazard map lies in its use of familiar platforms—Google Earth and Google Street View—which are widely used in daily life. While many disaster-specific systems have been developed, historical evidence has repeatedly shown that unfamiliar systems are often less effective during actual emergencies than the widely-used familiar platforms.

Moreover, the three-dimensional hazard map holds great promise as a tool for disaster education. Traditional two-dimensional hazard maps were typically used only for passive viewing. In contrast, the three-dimensional map, combined with Google Street View, offers high interactivity, allowing users to engage directly with the data and explore affected areas more actively. This interactivity is especially promising for engaging younger generations, who have consistently shown lower disaster awareness in various public surveys.

5. CONCLUSIONS

This study has been conducted to provide reliable and detailed flood hazard information for small- to medium-sized river basins. These basins are typically located upstream of major rivers and are often treated merely as tributaries within the broader flood management systems of major river basins. As a result, disaster-related information for these areas is frequently generalized, with data often presented as single-point or single-segment information. Such limited granularity makes it nearly impossible to formulate reliable and feasible evacuation plans. Consequently, preventable damages have occurred in many cases.

This study has also utilized the versatile runoff analysis model iRIC to simulate flood inundation extents and water depths under designed rainfall scenarios specifically for small- to medium-sized river basins. The simulation results were overlaid onto digital maps to enhance traditional two-dimensional hazard maps. Furthermore, we developed three-dimensional hazard maps by integrating these results with Google Earth and Google Street View, thereby offering a more immersive and spatially intuitive representation of flood risk.

These enhanced hazard maps provide residents living in small-sized river basins with more detailed and accessible flood risk information. This facilitates easier selection of evacuation shelters and routes, confirmation of evacuation timing, and ultimately supports the development of more reliable and actionable evacuation plans. The approach is expected to contribute significantly to the reduction of avoidable disaster damage.

The series of procedures adopted in this study is expected to make a significant contribution to establishing a methodology for developing hazard maps in small- and medium-sized river basins. The proposed method for creating three-dimensional hazard maps utilizes the Google Earth platform, a system with which many people are already familiar in their daily lives, thereby enhancing the accessibility and usability of the resulting maps.

Future work will involve collecting residents' feedback on the use of these hazard maps and identifying potential areas for improvement. Moreover, repeated practical applications are expected to clarify the educational value of employing three-dimensional hazard maps in disaster-prevention programs. In particular, by gathering and analyzing residents' opinions and related data obtained through evacuation drills that incorporate the three-dimensional hazard maps presented in this study, we aim to evaluate their effectiveness and explore further possibilities for their utilization.

6. ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to the International River Interface Cooperative for generously providing the iRIC runoff analysis software free of charge. Through the course of this study, the authors were able to confirm the reliability of the iRIC model and the user-friendliness of its interface.

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