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Flood and drought assessment with dam infrastructure: A case study of the Ba River basin, Fiji

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Abstract: In Fiji, frequent flood and drought events require implementation of preventive infrastructure and planning measures to reduce potential damages that may be caused by these events. The Ba River basin, which is located in the Western part of the main island, Viti Levu, has experienced severe floods and droughts. The flood record of the Ba River extends from 1871 to 2009 and reports flooding of about 127 times with the most disastrous floods in 1931, 1956, 1993, 1999 and 2009 (McGree et al., 2010). For example, the 1993 flood damages amounted to about 8 million USD. For the past droughts, the rain fed sugar cane agriculture is affected by shortages of precipitation with the most severe drought in 1998. In the Ba River basin, the sugar cane agriculture recorded a loss of 21.80 km^2 at the Rarawai Mill during the 1998 drought. For the flood hazard reduction, a dry dam infrastructure is proposed upstream of the Ba Town allowing for natural river flows while only reducing flood peaks. In addition, two multipurpose dams are proposed for the water supply during droughts as well as flood reduction.

In our approach, we utilize numerical models to investigate the effectiveness of dam infrastructure for flood control and water supply, and standardized indices to characterize historical droughts. For the standardized indices, the precipitation record of the Ba River basin has been investigated with the use of Standardized Precipitation Index (SPI) from 1960 to 2009 and the Standardized Precipitation Evapotranspiration Index (SPEI) was obtained from global datasets. The 3-arcsecond (about 90-m) grid block-wise TOP (BTOP) and 15-arcsecond (about 450-m) grid rainfall-runoff-inundation (RRI) models were constructed for the Ba river basin of 957 km^2 to simulate flood river flows and inundation. For the BTOP model, monthly potential evapotranspiration and Normalized Difference Vegetation Index (NDVI) were obtained using climate forcing data CRU TS3.1. Both BTOP and RRI models with short- and long-term local precipitation data were calibrated and validated with the local available data at two river gauging stations. Using the simulated discharges of the calibrated BTOP model, we estimated flood discharges of the selected return periods with flood frequency analysis and conducted flood inundation simulations with Flood Inundation Model (FID) model. The estimated flood inundation area and flood exposure with and without infrastructure are utilized for the flood risk estimation. For flood risk, we estimated the number of flood affected people and agriculture and found a satisfactory comparison with the record of the 1993 flood. For the historical drought assessment, both SPI and SPEI demonstrated the most extreme drought conditions of the 1998 drought and are consistent with the affected agriculture record during the 1998 drought. These preliminary results indicate the usefulness of our approach and suggest it could be used for selecting effective counter-measures for flood and drought risk reduction in Ba River basin.

Keywords: *BTOP model, RRI model, flood inundation, standardized indices*

1. INTRODUCTION

Flooding has been a common problem in Fiji, happening almost on annual basis. In the Ba River basin, the flood record extends from 1871 to 2009 and reports about 127 floods with the most disastrous flooding in 1931, 1956, 1993, 1999 and 2009 (McGree et al., 2010). For example, the 1993 flood damages amounted to about 8 million USD. In addition, droughts occur frequently in Fiji and are closely associated with the El Niño events. The worst drought recorded in Fiji's history was experienced during the El Niño event of 1997/1998 with many parts of the country recording 20% to 50% below average rainfall (Lightfoot, 1999). For example, the most severe 1998 drought affected the population of Ba Town and caused losses of sugarcane production area of 21.80 km^2 in the Ba River basin (Kaloumaira and Rokovada, 1998).

Over the years, the government of Fiji has implemented flood and drought disaster risk reduction measures such as river dredging, construction of small check dams, early flood warning system for flood and supply of water and food rations, ENSO monthly outlook and supply of rainwater tanks for drought (Nawai, 2015). Recently, the focus has been on construction of water infrastructure. For example, the construction of two dry dams is proposed as countermeasures for flood risk reduction in the Ba River basin. In addition, a study by JICA (1998) also proposed two multipurpose dams for flood reduction as well as providing water supply during drought period. However, there have been no numerical simulations investigating the effectiveness of these proposed dry and multi-purpose dams. Therefore, the main objective of this study is to investigate the effectiveness for proposed infrastructure in reducing flood and drought hazards.

2. DATA OF THE BA RIVER BASIN

Fiji, which comprises of over 320 islands with a total land area of approximately 18,333 km2, lies at the heart of the Pacific Ocean with the two largest islands, Viti Levu and Vanua Levu. The Ba River basin is situated on the north western part of Viti Levu and drains an area of 957 km^2 (Figure 1). The main river, Ba River, flows in a northwesterly direction, originating from the central mountainous parts of Viti Levu and discharging into the South Pacific, about 15 km downstream of Ba Town (Figure 1). The Ba River basin is home to approximately 18,500 inhabitants where 37 percent of the population are living in urban areas (i.e. Ba Town area) and the other 63 percent in the peri-urban areas, mostly settlements and villages (FBS, 2015). For the flood hazard reduction, a dry dam infrastructure is proposed upstream of the Ba Town allowing for natural river flows while reducing flood peaks. In addition, the location of the Ba River basin, in the leeward side of Viti Levu, makes it susceptible to meteorological drought events affecting rain fed agriculture by a prolonged dry period. For drought reduction, two multipurpose dams proposed by JICA (1998) at the same locations are considered as a possible alternative design, with the multi-purpose operation of flood control as well as maintaining river flows during droughts.

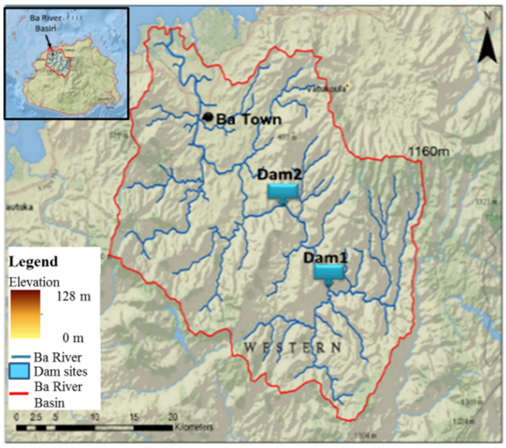

Figure 1. Locality of the Ba River basin.

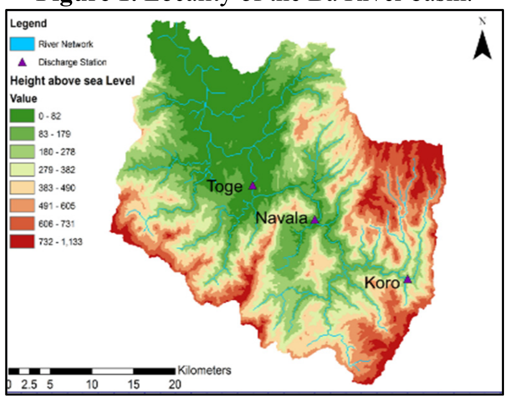

Figure 2. The Ba River Basin features.

In this study, we collected global and local data of the Ba River basin. For the global datasets, the topographical data of the Ba River basin was obtained from HydroSHEDS digital elevation model (DEM) data set (Lehner et al., 2008) (Figure 2). The land cover and soil classification were extracted from the Global Land Cover Characterization (GLCC) and Food and Agriculture Organization (FAO) global soil database, respectively. For the local data, the daily precipitation was obtained from seven rain gauge stations. The observed daily river discharges were obtained from Toge and Navala stations, see Figure 2. The Landsat image was used in this study for verification of the 1993 flood inundation extent (USGS, 2011). To estimate flood affected people, the population dataset was downloaded from the Fiji Bureau of Statistics website and is based on the 2007 population census (FBS, 2015).

3. METHODOLOGY

We utilized numerical models to investigate the effectiveness of dam infrastructure for flood control and water supply, and standardized indices to characterize historical droughts. The methodology was divided into flood and drought assessment parts (Figure 3). In the flood assessment, the block-wise TOP (BTOP) model was used to simulate long-term discharges in the Ba River basin, while rainfall-runoff-inundation (RRI) and Flood Inundation Depth (FID) models were used for flood inundation simulations. Using these models we estimated flood peak discharge and inundation with and without dry dam infrastructure and calculated affected people during the 1993 flood. For drought assessment, the monthly historical rainfall record at Ba Filter station, which is located in Ba Town, was utilised to estimate the Standard Precipitation Index (SPI). The computed SPI was compared with the Standardized Precipitation Evapotranspiration Index (SPEI) obtained from global dataset. The SPI and SPEI quantify the risk of precipitation deficit, which correspond to the affected rain fed agriculture in the Ba River basin during droughts. For the BTOP simulations, the multi-purpose dams were also investigated for maintaining low flow during drought.

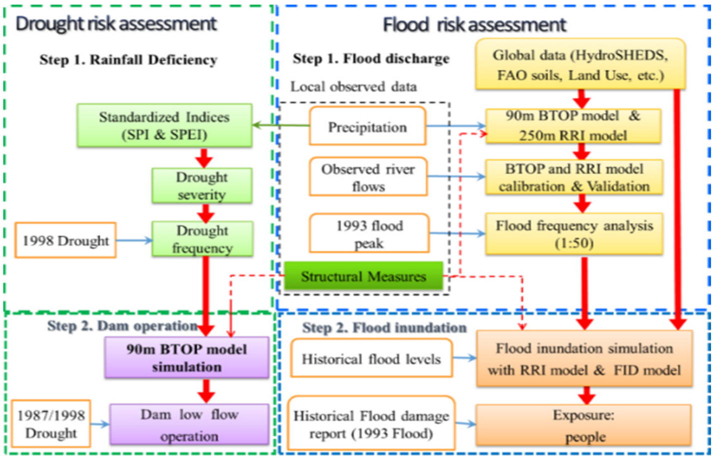

Figure 3. Methodology for flood and drought risk assessment.

3.1. Numerical Models

The BTOP and RRI models were utilized for the Ba River basin to perform simulations of runoff, soil moisture and river discharge processes. The BTOP model uses a redefined topographical index by Takeuchi et al. (2008) for river discharge simulations and has been applied for the investigation of dam infrastructure for flood and drought assessment in various river basins (Gusyev et al., 2015a,c; Navarathinam et al., 2015). The RRI model is a two-dimensional distributed model that can simulate runoff and flood inundation concurrently (Sayama, 2014). The Flood Inundation Depth (FID) model is a simple process for computing potential flood inundation depths by using HYDROSHEDs data with BTOP simulated flood peak discharges (Kwak et al., 2012; Gusyev et al., 2015a). For the BTOP model, monthly potential evapotranspiration and Normalized Difference Vegetation Index (NDVI) were obtained using climate forcing data CRU TS3.1 (Harris et al., 2014). The detailed description of BTOP, RRI and FID models setup is provided by Nawai (2015). Both BTOP and RRI models were run with short- and long-term local precipitation data and were calibrated with the available daily river discharge data at Toge river gauging station. The performance of the BTOP and RRI models was evaluated by using efficiency criteria such as Nash-Sutcliffe efficiency (NSE), root mean square error (RMSE), coefficient of determination (r^2) and the index of agreement (IoA) (Nawai, 2015). Using the simulated discharges of the calibrated BTOP model, the flood frequency analysis (the Gumbel distribution with L-moments) was used to estimate the flood peak discharges of 10-, 25-, 50-, 100-, 200-, 500-, and 1000-year return periods. These flood peak discharges were used by the FID model for the inundation simulations.

3.2. Standardized Drought Indices

For the study basin, we selected SPI and SPEI for characterizing meteorological and agricultural droughts. Standardized indices are quantitative measures that can characterize multiple droughts (Gusyev et al., 2015b) and are more useful to drought planners than raw data (Zargar et al., 2011). The SPI was calculated from local rainfall data of monthly totals using the WMO (2012) tool and SPEI was obtained from the global SPEI database (Vicente-Serrano et al., 2010). The SPEI requires both rainfall and evapotranspiration data as an input and is able to indicate agricultural droughts (Vicente-Serrano et al., 2010). These standardized indices (SPI and SPEI) have the same range of values indicating wet climates with positive values and dry climates with negative values: “near normal” up to -0.99, “moderate drought” from -1.0 to -1.49, “severe drought” from -1.50 to -1.99, and “extreme drought” from -2.0 (McKee et al.,1993). Therefore, both SPI estimated with local precipitation data and SPEI with global data were used in this study.

4. RESULTS

4.1. Simulation of flood event

In Figure 4, we demonstrate the BTOP and RRI daily simulated discharges for the 1984 and 1986 flood events at Toge station. The statistical performance of both models at Toge station is satisfactory. The 1984 flood is selected for model calibration and the statistical performance of BTOP and RRI models is NSE=0.79 and NSE=0.78, respectively. Both BTOP and RRI models have IoA of 0.9 and r^2 values of 0.86 and 0.97, respectively. In Navala station, both the BTOP and RRI simulated discharges have a better fit with the 1984 flood peak (not shown). For the 1984 flood event, the BTOP model has NSE of 0.95 and the RRI model has NSE of 0.85. For the validation of the 1986 flood, the BTOP model demonstrates NSE of 0.4 while the RRI model has NSE of 0.6 (Figure 4). Therefore, both models demonstrate a satisfactory performance in reproducing past flood events during calibration and validation periods.

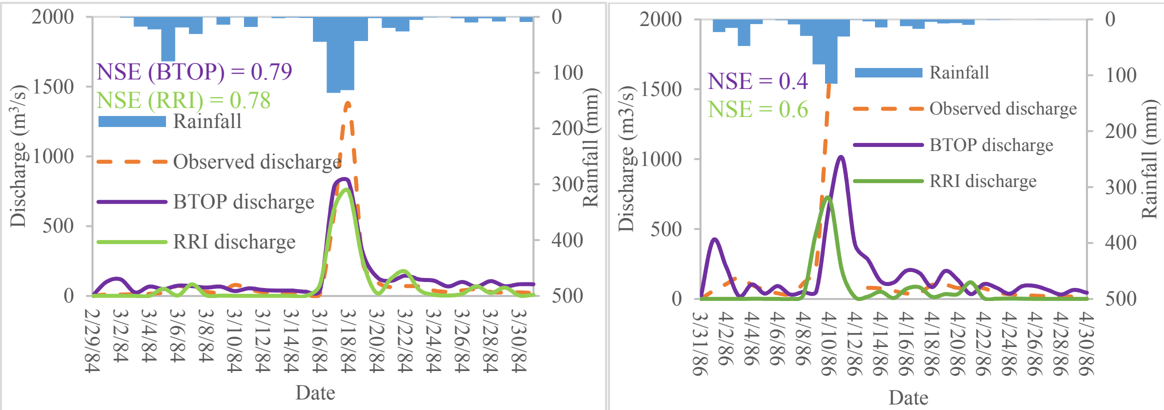

Figure 4. BTOP and RRI model simulations at Toge station of the 1984 flood (left) and 1986 flood (right).

4.2. Long-term River Discharge Simulation

In Figure 5, we demonstrate simulated daily discharges of the BTOP and RRI models for a period of 15 years from January 1984 to December 1999 at Toge station. Within this simulation period, the observed discharges were recorded from 1984 to 1992 and had missing data from 1988, especially for the past flood events. For the long-term daily simulations, the calibration period is selected only from 1984 to 1987 for both BTOP and RRI models.

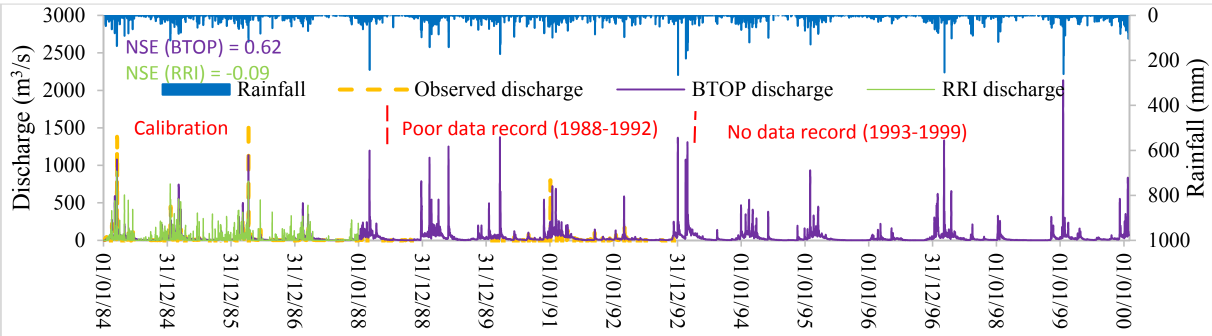

Figure 5. Long-term simulation of BTOP and RRI from 1984 to 1999 at Toge station.

The BTOP model is able to simulate both peak and low flow discharges during calibration period with NSE of 0.62. However, the RRI model performance is not unsatisfactory. This may be due to the missing groundwater component, which is not incorporated in the current version of the RRI model. From these long-term flood BTOP discharges, the flood peaks of 25-, 50-, 100-, 200-, 500- and 1000-year return periods are estimated in the Ba River basin. Table 1 summarized these flood peaks for three locations at Navala and Toge stations as well as Rarawai Mill located at the Ba Town. From these results, the simulated 1993 flood event, which does not have the observed record, is about 25-year return period flood (Table 1).

Table 1. Estimated flood peak discharges at Navala and Toge stations and Rarawai mill.

Return Period (years)	Estimated flood peak discharge (m^3/s)		
	Navala station	**Toge station**	**Rarawai Mill**
10	1041	1608	2325
25	1290	1983	2909
50	1475	2260	3341
100	1658	2573	3771
200	1841	2812	4200
500	2082	3176	4766
1000	2264	3451	5193

4.3. Flood Inundation and Exposure of 1993 flood

Using the BTOP simulated river discharges at Toge station as a boundary condition, the RRI model is used to simulate flood inundation for the 1993 flood (Figure 6a). These RRI results show a good match with the flood inundation extent obtained from Landsat image (Figure 6b). The RRI simulated flood inundation depth show a good match with the historical data at Rarawai mill (2.16 m) and Ba town (2.13 m), see zoom-in Figure 6b. The FID model with flood peaks of 25-year return period results in a similar flood inundation extent produced by RRI model (not shown). For the 1993 flood, the estimated flood exposure in terms of affected population (12,426 people) compares reasonably well with the past record of affected people (10,585 people) derived from the JICA study (1998). As a result, the RRI flood inundation is used for estimation of flood exposure in the Ba River basin and can be used for an additional cross-checking with historical data.

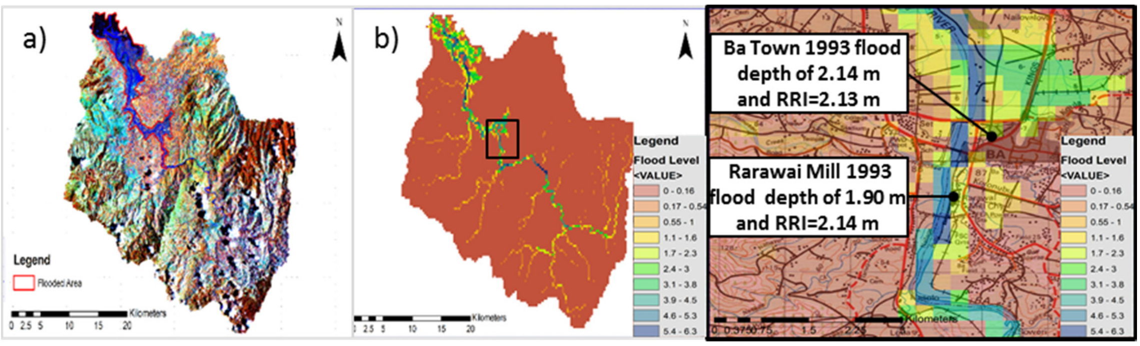

Figure 6. Landsat image inundation extent of the 1993 flood (a) and simulated 1993 flood depth with RRI model (b) and a zoom-in on at Rarawai mill and Ba Town locations.

4.4. Standardized indices

We demonstrate 3-month SPI estimated with local data and 3-month SPEI obtained from global dataset in Figure 7. Both SPI and SPEI have similar pattern from 1960 to 2009 matching historical drought period, especially during the 1998 drought. In Figure 7, the 3-month SPI and SPEI values are below < -2, which is categorized as an extreme drought with the 1 in 48 years return period (WMO, 2012). From these results, the 3-month SPI and SPEI values can be used for to identify both meteorological and agricultural droughts.

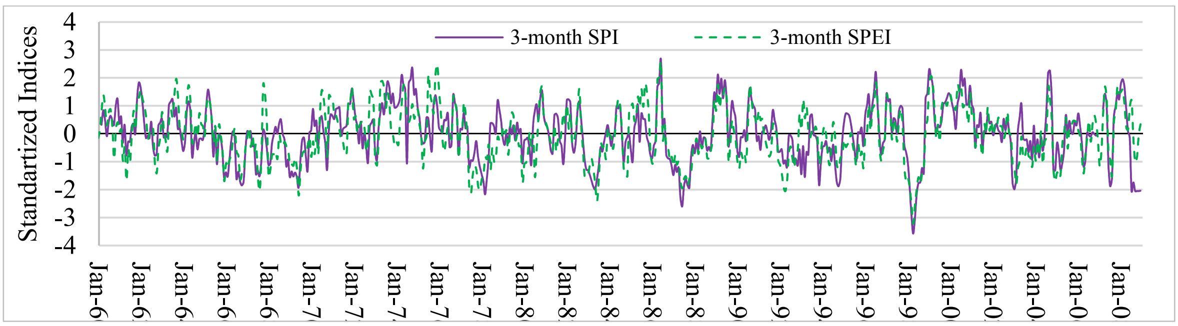

Figure 7. 3-month SPI and SPEI values at Ba Filter station.

4.5. Effectiveness of Proposed Infrastructures

In Figure 8, the simulated dam inflow and outflow are shown from 1984 to 1999 at Toge station. For the proposed flood control infrastructure, the proposed 0.95 MCM capacity dams are able to reduce flood peaks of less than 2-year flood peak (Figure 8a). These results indicate that the proposed dry dam infrastructures may not be effective in reducing flood peak discharges of medium and low probability hazards at Toge station and downstream area of the Ba River basin.

For the two proposed multipurpose dams, the long-term BTOP simulation with dam operation indicates that the proposed dam by JICA (1998) may be a viable option at the same two locations (Figure 1). For the large dam infrastructure, the BTOP simulated dams with different water storage capacities and assumed outflow of 9.23 m^3/s are demonstrated in Figure 8b. In Figure 8b, dams with 200 MCM capacity are suitable for maintaining river flows during an extreme drought period similar to that of the 1998 drought in the Ba River Basin. Therefore, the two multipurpose dams can maintain river flows during droughts and also be utilized for the flood peak reduction with flood control operation.

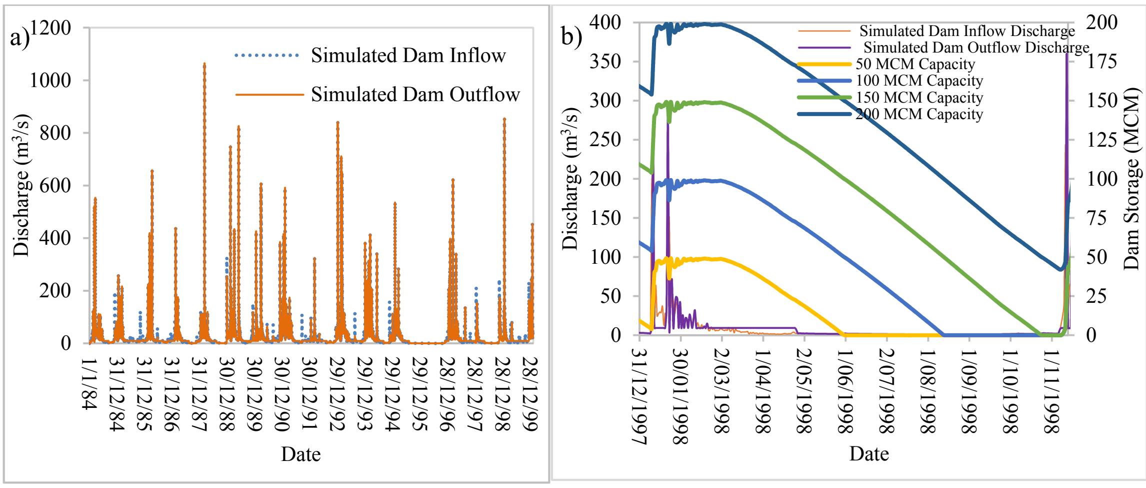

Figure 8. BTOP simulation of dry dam (a) and dam with water storage capacity for water supply (b).

5. DISCUSSION AND CONCLUSIONS

In this study, we utilized numerical models (BTOP, RRI and FID) to investigate the effectiveness of dam infrastructure for flood control and water supply, and standardized indices (SPI and SPEI) to characterize historical droughts. In the absence of historical data, numerical models provide a suitable alternative in quantifying flood hazards in the Ba River basin. From the numerical simulation, the two dry dams are only effective in reducing small flood peaks with about 2-year return period. The flood control capacity of 0.95 MCM/dam of the two dry dams is not effective for flood peak reduction in the downstream flood-prone and urban area of the Ba River basin. The two multi-purpose dams with 200 MCM capacity/dam are suitable for maintaining river flows during the 1998 drought period. Therefore, the numerical models are useful and cost-effective tools in assessing the effectiveness of proposed infrastructures for flood and drought risks reduction in the Ba River basin.

Further studies are required for assessing flood and drought risk with regards to damages to agriculture in the Ba River Basin, investigating the effectiveness of cascading small dams and analysis of other flood and drought countermeasures. The BTOP is suitable for flood discharge forecasting in the Ba River basin and the RRI model can be used for near real-time flood inundation simulation. Further applications of the FID model is also necessary for the delineation of static flood hazard and risk maps in the entire Fiji.

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