Dam Sustainability Assessment and Flood Volume Estimation Using Remote Sensing and GIS

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Abstract –

In recent years, an increasing number of unprecedented rainfall events around the world brought about devastating floods that have been a challenge for urban planners and decision-makers. Numerous studies addressed these floods to climate change and investigated its trends at different time scales. In face of many uncertainties caused by environmental phenomena, considering the current magnitude of extreme events is a crucial step towards preventing disasters. In this study, the Dez dam, which is an arch dam on the Dez River in the southwestern province of Khuzestan, Iran, is selected to study if it could be operated more efficiently to store a larger fraction of the feeding river flow. Remote sensing provides means to monitor hydrological and environmental changes over large areas. In addition, it enables researchers to detect vulnerabilities in civil infrastructures. Satellite images are used to estimate the reservoir area of the dam and then to estimate the height and volume of the water behind the dam. The results show a spike in the height and volume of the water behind the dam to 94% of the dam's capacity, which can endanger the dam itself, and downstream urban infrastructure. Therefore, better flood management strategies are required to minimize the risk and destruction created by these flood events. An online Cyber-Physical System should be in place to monitor the dam condition and integrate the data to the runoff stormwater downstream to get a fully functional prediction and prevention framework for extreme floods.

Keywords –

Satellite images; Remote sensing; Flood; Dam sustainability; Volume estimation; Infrastructure monitoring;

1 Introduction

In recent decades, the increasing number of natural and manmade threats are endangering the civil infrastructures that are crucial to the functionality of societies. The vulnerability of critical infrastructures, which generally form 10-15% of the built environment, has been one of the main concerns for scientists and decision-makers. Thus, considering the aftermath of a disaster and its effect on the welfare of the public, overall safety, security, and impacts on economical markets are of great importance [1].

With the growing need for freshwater, constructing dams became a vital part of the survival of modern societies and a key contributor to the better management of water resources under climate change and water scarcity. However, critics of dams point out that benefits have been overvalued and socio-environmental aspects of them are getting neglected [2]. Secondly, the hydropower projects, which are clean and environmentally friendly sources of energy, may not have enough capacity to overcome the tensions caused by deterioration, population growth, climate change, and extreme events. Thus, accurate estimation of inflow to a dam reservoir has significant importance to the management and operation of reservoirs, hydroelectric energy generation, and control infrastructures [3].

New sensing and geospatial technologies such as the Internet of Things, Geographical Information System (GIS), and remote sensing proved to be great tools for smart infrastructure control and monitoring under severe loading conditions [1], [4], [5]. Remote sensing provides means for environmental monitoring over large areas. It is the process of inferring reflected or emitted electromagnetic radiation from the land surface [6]. The availability of high-resolution satellite images provides a new data source for capturing environmental and urban changes. For instance, GIS and image processing approaches, enable aerial and satellite images to be used for object detection, which has an important role for a wide range of applications [7] such as vehicle detection, building extraction [8], air quality, and traffic monitoring.

Over the 2018-2020 period, Iran has fortunately experienced wet seasons after years of struggling with drought. However, this has brought about devastating consequences such as floods that took place across the northern and western regions. One particular region of significance was the Khuzestan Province, which is the home of some largest dams in the country such as Dez, Karkheh, and Karoon. During the first month of spring (referred to as the month of "Farvardin", spanning from March 21st to April 20th), Iran was hit by devastating floods in 26 of its 31 provinces. These floods cost about $3.5 billion U.S. dollars to the economy and caused 78 fatalities [9], [10].

With the recent challenges in water resources management of Khuzestan Province, Dez dam as one of the critical infrastructures located in the middle peaks of Zagros finds socio-environmental importance. The range of the Dez basin is 32˚35´ to 34˚07´ North latitude and 48˚20´ to 50˚20´ east longitude [3]. Since data collection is still a difficult task, using remote sensing for flood analysis is a common approach that can be helpful for hazard management [11].

Remotely-sensed data have provided information that can help us uncover many aspects of environmental challenges with an eagle eye. One of which is volume estimation of floods and consequently investigating dam sustainability based on several digital images that have been gathered in a certain period. This can help us plan for the next extreme events, monitor the current state of civil infrastructures based on the experienced load, and prevent possible disasters. However, the control actions (e.g. Dez dam height control) at a given site cannot necessarily guarantee the stability of a complex system [12]. This is why a GIS-based monitoring system coupled with remotely sensed data is necessary to control the flows across the scale of the entire stormwater system.

This study aims to estimate Farvardin's flood inflow to the Dez dam using remote sensing and evaluate if the dam could be operated more efficiently to store a larger fraction of the feeding river flow. To this purpose, the authors used satellite imagery to estimate water volume stored in the Dez dam before and after Farvardin's flood.

2 Background

Using remote sensing for predicting potential areas of flash flood hazards is one of the substantial topics that have an enormous impact on sustainability and future developments. Hussein et.al. (2019) used an active microwave and visible/Near-IR (VNIR) remote sensing coupled with land use data and showed that most of the southern Quseir city is in danger of flash floods. Also, several dams are required to minimize the predicted hazards in that region [13]. Andre (2012) presents a preliminary analysis of the concept of sustainability assessment in the context of dam development [14]. Furthermore, Karami and Karami (2020) suggested that for investigating the sustainability of a dam there should be a framework consisting of social dimensions, environmental dimensions, and economic dimensions [2]. In addition, selecting a suitable site for a dam in the first place can prevent decades of mismanagement in the future. Current trends show a tendency to use new technologies for sustainability purposes. Figure 1 presents an overview of new technologies that are being used for smart flood monitoring systems.

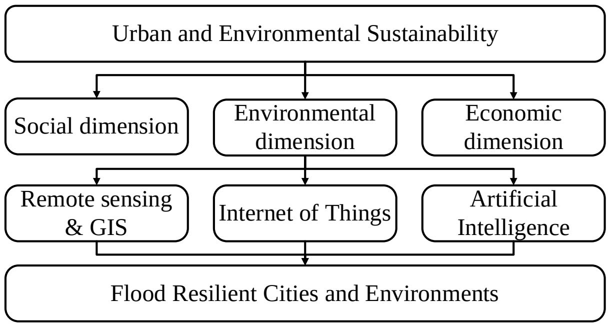

Figure 1. An overview of new technologies being used for smart flood monitoring systems

One of the primary focuses of remote sensing in hydrology is estimating hydrometeorological states and fluxes such as land surface temperature and evapotranspiration [6]. Noori et.al. (2019) used remote sensing, GIS, and multi-criteria decision-making techniques to show the suitable dam site between four potential locations [15]. Capolongo et.al. (2019) investigated the long-term monitoring of a flood event in the Strymonas dammed river basin, Bulgaria, based on a multi-temporal dataset of high-resolution X-band COSMOSkyMed, C-band Sentinel-1 SAR, and optical Landsat-8 images of the region [11]. Mixing Machine Learning techniques and GIS is one of the new approaches that Motta et.al. (2021) used to establish sensible factors and risk indices for urban floods. This new method can be outlined as a long-term flood management strategy for Smart Cities [16]. Also, Mourato et.al. (2021) developed an interactive Web-GIS fluvial flood forecast and alert system that integrates: i) a rainfall forecasting model (WRF), ii) a hydrological model (HEC-HMS), iii) a hydraulic model (HEC-RAS 2D), and iv) a Web-GIS platform to provide responsiveness to disasters and timely decision making [17]. By installing wireless sensor networks for rainfall monitoring, developing an alerts system that can predict flood events is a reachable goal. Ortega-Gonzalez et.al. (2021) evaluated the best options of wireless communication protocols that are suitable in a rainfall-monitoring device [18]. Flood events are natural disasters that consist of natural risks and vulnerabilities. For preventing infrastructural damages, distresses, revenue losses, injuries, and fatalities, researchers are proposing new solutions based on the Internet of Things (IoT), Big Data (BD), and Neural Networks. Anbarasan et.al. (2020) presented a flood disaster detection system using IoT, BD, and Convolutional Neural Network that gives a very accurate result compared to other methods such as Artificial Neural Network (ANN) and Deep Learning Neural Network (DNN) [19]. Although having IoT devices gather data in larger areas can be challenging, lack of data is a bigger problem that can justify the large-scale installation of IoT. Using remote sensing can give a bigger picture in many cases of flood disasters. Figure 2 presents the architecture for an integrated flood monitoring system.

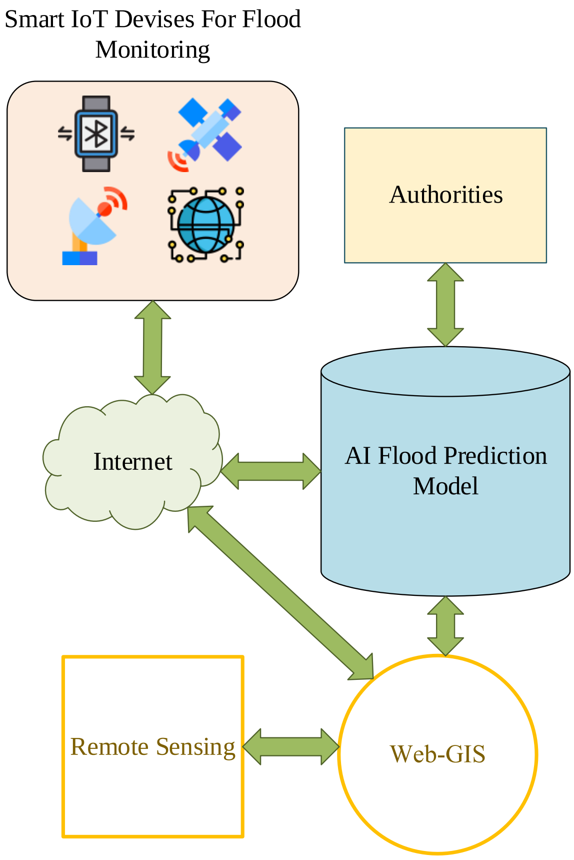

Figure 2. The architecture of Flood Monitoring Systems

Yuan et.al. (2021) used Sentinel-1 data to monitor flood disasters in China [20]. Research on flood disasters using remote sensing and GIS is trending because of its little cost and huge benefits. FloodStroem is a fast dynamic GIS-based urban flood and damage model that can generate a surface network of depressions and flow paths alongside flood depth maps and associated damage costs [21]. As an application of GIS in determining dam storage volume, İRvem (2011) estimated the reservoir storage volume for the Buyuk Karacay Dam using the Ripple method [22].

Learning from previous studies and integrating them with the recent surveys of the Dez dam one can obtain suitable answers to the sustainability problem. The impacts of climate change in the Dez basin have been investigated by Norouzi (2020), which shows that this basin faces discharge reduction, and modified water management strategies are required to adapt to climate change in this area [23].

3 Research Framework

The Dez River Basin, as a third-order basin, is a subset of the Greater Karun Basin and is located in a larger subdivision of the Persian Gulf and the Sea of Oman. Dez dam is a concrete hydroelectric dam that was built on the Dez River (Figure 3).

The dam irrigates 125,000 hectares of downstream land and plays an important role in controlling upstream floods. The lake of this dam is 65 kilometers long and has an area of about 60 square kilometers and its final capacity is 3.3 billion cubic meters. This dam, with a height of 203 meters, at the time of its construction was known as one of the highest dams in the world.

This research aims to use satellite imagery to estimate the water volume stored in the Dez Dam before and after March's flood. First off, ArcMap was used to extract the underlying river network of the basin draining into the Dez dam. The location of the Dez dam was applied as the outlet of the delineating basin.

One of the principal inputs of the above process is defining the minimum area (A_{th}). A_{th} is applied to determine the initiation point of the first-order channels. The extracted river network from airborne imagery was applied to compare and validate the chosen A_{th}. For this task, Google Earth images were digitized and used. Also, drainage density was calculated to analyze the river networks.

In the next step, multiple river networks were extracted from different A_{th}'s to determine the best A_{th} resulting in the most realistic river network.

For satellite imagery analysis, the number of Sentinel satellites images were downloaded. Downloaded images were digitized for the aim of delineating the boundary of the water storage behind the dam. ArcMap tools were utilized for calculating the area of the polygons obtained in the previous step.

Figure 3. Dez dam study area

For calculating the water levels and volumes from the estimated water surface areas, we employed the data of the Iran Dam Organization, which includes water level and corresponding areas and volumes. In the final step, the changes in the time series of water level and water volume behind the dam were analyzed. Figure 4 shows the data provided by the Iran Dam Organization on the various conditions that the Dez dam has been, in terms of volume, area, and height.

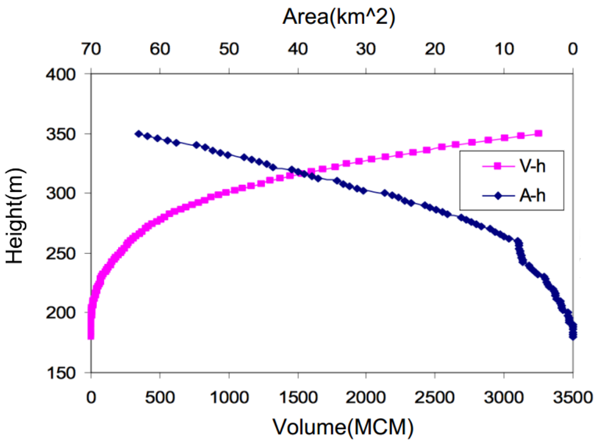

Figure 4. Relationship between Volume-Area-Height of Dez dam

Based on the calculated area and matching it with the Iran Dam Organization Area-Volume-Height chart (Figure 4), the respective height and volume are estimated and presented in Table 1.

Table 1. Respective height and volume for the different areas calculated by the digitization of the Dez dam water reservoir

Date	Area (km^2)	Height (m)	Volume (MCM)
12/27/2018	51.1729	333.403	2301.047
1/11/2019	56.2901	341.049	2665.295
1/26/2019	57.2388	341.906	2710.071
2/5/2019	58.524	343.558	2783.809
2/20/2019	54.8043	340.315	2609.719
2/25/2019	53.8039	338.724	2531.548
3/2/2019	53.2809	337.99	2490.254
3/7/2019	52.2428	335.36	2391.425
3/12/2019	52.8602	336.889	2447.872
3/22/2019	53.8482	338.846	2541.588
4/8/2019	62.5709	348.759	3140.691
4/21/2019	61.7841	347.718	3089.148

4 Real-case Application of Remote Sensing in Dez Dam

In this study, the Dez River network was evaluated using GIS and network samples were drawn for the study area with different minimum areas (A_{th}). To select the best A_{th} from satellite images, authors analyzed local rivers and selected those A_{th} that are most compatible with the existing rivers. In the second stage, images related to the Dez dam were received from the Sentinel satellite with a cloud cover of less than 10% from 11 Jen 2019 to 21 Apr 2019. After performing radiometric and atmospheric corrections in ENVI software, the lake area was calculated in ArcMap software at different times. In the first part, the sub-basin of Dez dam lake was estimated through the 2nd-degree sub-basins of Iran, and the digital elevation model (DEM) of the sub-basin was downloaded from the NASA website.

In order to fill the gap points in the DEM and drawing the flow lines and flow accumulation, tools such as fill, flow direction, and flow accumulation have been used. The type of flow lines and flow accumulation in ArcMap was set to D8. To draw the flow lines, first, the coordinates of the outlet point of the Dez dam were found and applied to the flow accumulation. The point closest to the dam's outlet, which is located on the flow accumulation lines, was selected as the main outlet of the flow lines. Then, the raster calculator tool was used to apply the A_{th} in the ArcMap. In this study, the A_{th} is calculated from 500 to 4000 with intervals of 500.

Authors reached the best A_{th} by comparing several tributaries with satellite images. Finally, radiometric and atmospheric corrections were performed on the Sentinel images with less than 10% cloud cover.

5 Results

When it comes to the Farvardin's floods, one of the hurtful mismanagements in the Dez dam was not releasing water from the reservoir in a timely manner. As it is shown in Figure 5 the dam reservoir was not emptied in the last three months of the year and with the increase in rainfall, the volume of water in the reservoir has increased from 65% to 85% in just 38 days.

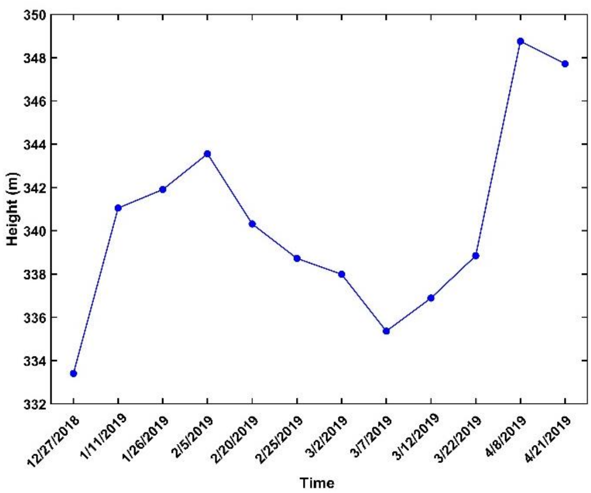

Figure 5. Dez dam water height in different times

In addition, the estimated water volume shown in Figure 6 indicates that not emptying the water was a hard decision for the authorities. The danger threatening downstream cities is that they may face floods after releasing this volume of water in the river and eventually reaching cities such as Dezful. In this case, there should be sensor networks that can monitor the rainfall status, stormwater runoff, and capacity of the urban sewer systems to get a sense of the consequences of releasing the water behind the dam. Integrating IoT and remote sensing can provide a framework for these situations and minimize uncertainties of extreme flood events. Such devices are already developed and can be used on a large scale. For instance, Chaduvula et.al. (2021) developed an IoT device for flood alert monitoring systems using microcontroller 8051 [24].

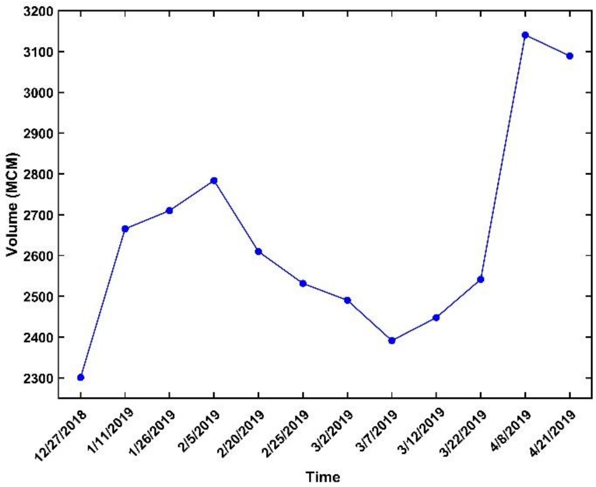

Figure 6. Dez dam water volume in different times

As the country has faced a wet season at the end of 2018 and the beginning of 2019, the Dez dam has contained a number of floods in the last months of 2018. With the increase in rainfall in March and April 2018, a critical situation has been created for this dam and the volume of water in the reservoir in April 2018 reached its maximum capacity with 3.14 billion cubic meters, equivalent to 94% of the total capacity of the reservoir. Any action during a crisis must be planned in the pre-crisis time. The most important executive-managerial damage for controlling recent floods is the lack of a flood management program. Because of the high probability of flooding in March and early April, measures should be taken to reduce future risks and damages. The most important steps that could be taken in this regard are as follows:

1. Predicting the inflow to the dam and then planning on releasing it based on the input and downstream capacity
2. Keeping the volume of flood in control
3. Having a releasing framework and flood

management program before and after the crisis

4. Establishment of flood warning system in reservoirs of dams and downstream rivers

The lack of images from satellites in some periods and cloudy days made some of the critical times to be considered as missed data. According to our analysis, the critical state happens on the 8th of April 2019. Therefore, the higher the number of photos, the more accurate the results will be. Also, Low resolution of the satellite images makes it very hard to digitize them manually, and this made errors in the final calculation of the area of the reservoir. Therefore, using machine learning techniques to automatically detect the water of the reservoir and calculated the area can be a very good step towards automating the digitization process.

6 Conclusions

Constructing dams is regarded as one of the major contributors to water resources management techniques across the world, especially in arid and semi-arid regions. Despite the significance, there is a lack of comprehensive investigations in regards to impacts of climate change and extreme events on critical infrastructures and appropriate approaches to automatically monitor and control them.

This research focused on estimating flood volume associated with Farvardin's floods in the Dez river basin and consequently obtaining a sensible result on the sustainability of the Dez dam. In addition, using satellite imagery, this study evaluated if the Dez dam could be operated more efficiently to store a larger fraction of the feeding river flow. Having a clear picture of the past and present of an environmental system helps us prepare for similar anomalies that will happen in the future. This is now possible with remote sensing and GIS. Having these technologies coupled with IoT sensors enables us to have an all-in-one monitoring platform at the system scale. This study showed such a system is necessary for controlling future flood events.

One of the many problems in environmental monitoring is accessing real-time data. Most of the time, because of security reasons, governments and institutions do not provide scientists with the data that is required to develop prediction models. Authors suggest that decision-makers install wireless sensor networks in areas with the highest potential flood events as a monitoring system. Next, integrating it with remote sensing and Web-GIS systems to get a synchronized and online platform. This way scientists and urban planners can access data and develop real-time prediction models based on this cyber-physical system. Extreme flood events over the past decade showed an argent need for smart flood management systems based on IoT, BD, and remote sensing.

As a future study, this research aims to integrate meteorological data such as evapotranspiration, which needs various climatological and physical parameters, with sensors data, which are located in water systems of the urban regions. This can help to find new relationships and schemes of smart water management in the cities. In addition, the decision-makers can predict the consequences of heavy raining events and possible extreme floods and respond appropriately.

References

[1] M. Z. Naser and V. K. R. Kodur, "Cognitive infrastructure - a modern concept for resilient performance under extreme events," *Automation in Construction*, vol. 90, pp. 253–264, Jun. 2018, doi: 10.1016/j.autcon.2018.03.004.

[2] S. Karami and E. Karami, "Sustainability assessment of dams," *Environ Dev Sustain*, vol. 22, no. 4, pp. 2919–2940, Apr. 2020, doi: 10.1007/s10668-019-00326-3.

[3] M. Valipour, M. E. Banihabib, and S. M. R. Behbahani, "Comparison of the ARMA, ARIMA, and the autoregressive artificial neural network models in forecasting the monthly inflow of Dez dam reservoir," *Journal of Hydrology*, vol. 476, pp. 433–441, Jan. 2013, doi: 10.1016/j.jhydrol.2012.11.017.

[4] S. K. Singh, Y.-S. Jeong, and J. H. Park, "A deep learning-based IoT-oriented infrastructure for secure smart City," *Sustainable Cities and Society*, vol. 60, p. 102252, Sep. 2020, doi: 10.1016/j.scs.2020.102252.

[5] M. Marzouk and A. Othman, "Planning utility infrastructure requirements for smart cities using the integration between BIM and GIS," *Sustainable Cities and Society*, vol. 57, p. 102120, Jun. 2020, doi: 10.1016/j.scs.2020.102120.

[6] T. J. Schmugge, W. P. Kustas, J. C. Ritchie, T. J. Jackson, and A. Rango, "Remote sensing in hydrology," *Advances in Water Resources*, p. 19, 2002.

[7] G. Cheng and J. Han, "A survey on object detection in optical remote sensing images," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 117, pp. 11–28, Jul. 2016, doi: 10.1016/j.isprsjprs.2016.03.014.

[8] Q. Hu, L. Zhen, Y. Mao, X. Zhou, and G. Zhou, "Automated building extraction using satellite remote sensing imagery," *Automation in Construction*, vol. 123, p. 103509, Mar. 2021, doi: 10.1016/j.autcon.2020.103509.

[9] M. Sadeghi *et al.*, "Application of remote sensing precipitation data and the CONNECT algorithm to investigate spatiotemporal variations of heavy

precipitation: Case study of major floods across Iran (Spring 2019)," *Journal of Hydrology*, vol. 600, p. 126569, Sep. 2021, doi: 10.1016/j.jhydrol.2021.126569.

[10] S. Aminyavari, B. Saghafian, and E. Sharifi, "Assessment of Precipitation Estimation from the NWP Models and Satellite Products for the Spring 2019 Severe Floods in Iran," *Remote Sensing*, vol. 11, no. 23, Art. no. 23, Jan. 2019, doi: 10.3390/rs11232741.

[11] D. Capolongo *et al.*, "Coupling multitemporal remote sensing with geomorphology and hydrological modeling for post flood recovery in the Strymonas dammed river basin (Greece)," *Science of The Total Environment*, vol. 651, pp. 1958–1968, Feb. 2019, doi: 10.1016/j.scitotenv.2018.10.114.

[12] A. Mullapudi and B. Kerkez, "Autonomous Control of Urban Storm Water Networks Using Reinforcement Learning," pp. 1465–1459. doi: 10.29007/hx4d.

[13] S. Hussein, M. Abdelkareem, R. Hussein, and M. Askalany, "Using remote sensing data for predicting potential areas to flash flood hazards and water resources," *Remote Sensing Applications: Society and Environment*, vol. 16, p. 100254, Nov. 2019, doi: 10.1016/j.rsase.2019.100254.

[14] E. Andre, "Beyond hydrology in the sustainability assessment of dams: A planners perspective – The Sarawak experience," *Journal of Hydrology*, vol. 412–413, pp. 246–255, Jan. 2012, doi: 10.1016/j.jhydrol.2011.07.001.

[15] A. M. Noori, B. Pradhan, and Q. M. Ajaj, "Dam site suitability assessment at the Greater Zab River in northern Iraq using remote sensing data and GIS," *Journal of Hydrology*, vol. 574, pp. 964–979, Jul. 2019, doi: 10.1016/j.jhydrol.2019.05.001.

[16] M. Motta, M. de Castro Neto, and P. Sarmento, "A mixed approach for urban flood prediction using Machine Learning and GIS," *International Journal of Disaster Risk Reduction*, vol. 56, p. 102154, Apr. 2021, doi: 10.1016/j.ijdrr.2021.102154.

[17] S. Mourato, P. Fernandez, F. Marques, A. Rocha, and L. Pereira, "An interactive Web-GIS fluvial flood forecast and alert system in operation in Portugal," *International Journal of Disaster Risk Reduction*, vol. 58, p. 102201, May 2021, doi: 10.1016/j.ijdrr.2021.102201.

[18] L. Ortega-Gonzalez, M. Acosta-Coll, G. Piñeres-Espitia, and S. Aziz Butt, "Communication protocols evaluation for a wireless rainfall monitoring network in an urban area," *Heliyon*, vol. 7, no. 6, p. e07353, Jun. 2021, doi: 10.1016/j.heliyon.2021.e07353.

[19] M. Anbarasan *et al.*, "Detection of flood disaster system based on IoT, big data and convolutional deep neural network," *Computer Communications*, vol. 150, pp. 150–157, Jan. 2020, doi: 10.1016/j.comcom.2019.11.022.

[20] X. Yuan, X. Zhang, X. Wang, and Y. Zhang, "Flood disaster monitoring based on Sentinel-1 data: A case study of Sihu Basin and Huaibei Plain, China," *Water Science and Engineering*, vol. 14, no. 2, pp. 87–96, Jun. 2021, doi: 10.1016/j.wse.2021.06.001.

[21] C. Thrysøe, T. Balstrøm, M. Borup, R. Löwe, B. Jamali, and K. Arnbjerg-Nielsen, "FloodStroem: A fast dynamic GIS-based urban flood and damage model," *Journal of Hydrology*, vol. 600, p. 126521, Sep. 2021, doi: 10.1016/j.jhydrol.2021.126521.

[22] A. İrvem, "Application of GIS to Determine Storage Volume and Surface Area of Reservoirs: The Case Study of Buyuk Karacay Dam," *International Journal of Natural and Engineering Sciences*, vol. 5, no. 1, Art. no. 1, 2011.

[23] N. Norouzi, "Climate change impacts on the water flow to the reservoir of the Dez Dam basin," *Water Cycle*, vol. 1, pp. 113–120, 2020, doi: 10.1016/j.watcyc.2020.08.001.

[24] K. Chaduvula, K. kumar K., B. R. Markapudi, and Ch. Rathna Jyothi, "Design and Implementation of IoT based flood alert monitoring system using microcontroller 8051," *Materials Today: Proceedings*, p. S2214785321049002, Jul. 2021, doi: 10.1016/j.matpr.2021.07.048.