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Article

Supplementary Dam Site Selection Using a Geospatial Approach: A Case Study of Wivenhoe Dam

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Abstract: Flooding, exacerbated by climate change, poses a significant threat to certain areas, increasing in frequency and severity. In response, the construction of supplementary dams has emerged as a reliable solution for flood management. This study employs a geospatial approach to assess the feasibility of constructing a supplementary dam near Linville, Brisbane, Australia, with the aim of mitigating floods and preventing overtopping failure at Wivenhoe Dam. Using QGIS software and a 25 m resolution DEM from the Queensland Spatial Catalogue 'QSpatial' website, four potential dam sites were analysed, considering cross-sections, watershed characteristics, and water volume calculations. Systematic selection criteria were applied on several dam wall options to identify the cost-effective and optimal one based on the dam wall dimensions, volume-to-area, and volume-to-cost ratios. The selected option was further assessed against predefined criteria yielding the optimal choice. The study provides insights into the feasibility and effectiveness of supplementary dam construction for flood mitigation in the region, with recommendations for future research and implementation plans for the asset owners.

Keywords: climate change; flooding; surveying; GIS; DEM; selection criteria

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1. Introduction

Climate change is the long-term shift in temperature and precipitation that affects human life [1]. According to Yoro and Daramola [2], the severe consequences of climate change will continue to affect the Earth, and the average surface temperature of the Earth is likely to exceed 3 °C in this century. A climate report from CSIRO and the Bureau of Meteorology [3] highlighted that Australia's climate has warmed by about 1.4 °C since 1910. This warming trend is expected to increase the evaporation rates and intensify the water cycle, causing extreme precipitation and flooding [1]. Lempérière [4] suggests that a 10% to 20% increase in annual precipitation could result in a corresponding 20% increase in floods' occurrence. In fact, climate model projections for Australia indicated a concerning trend of increased flooding across various regions, particularly in south-eastern areas, where once-in-a-hundred-year flood events may occur as frequently as once every ten years [4,5]. Queensland Reconstruction Authority highlighted that floods cause more damage in Queensland than any other natural disaster, with frequent occurrences in the Brisbane River basin due to heavy rainfall events [6]. This represents a significant challenge for disaster management, saving lives and protecting infrastructure.

Establishing a reservoir can effectively control excessive rainfall, reduce downstream flow, and mitigate the effect of floods [7,8]. This approach has been adopted as a flood mitigation solution. For instance, the construction of Wivenhoe Dam, Brisbane, was prompted by the devastating flood event of 1974 which resulted in widespread damage and loss of life [9]. It should be highlighted that dams are erected to stop or restrict the natural flow of water, allowing it to accumulate in a reservoir [10]. This process serves the primary purpose of holding water for drinking, domestic use, and flood management. However, selecting an optimal dam location is crucial, considering financial, population, and environmental factors [11]. Proper planning of dam construction can prevent or mitigate flooding, improving rainwater use efficiency.

The geographic information system (GIS) is a robust technique for tracking and monitoring environmental changes and disasters resulted from climate change, offering a wide-ranging multi-temporal database. For instance, it has been previously utilised to monitor the Muringato catchment in Kenya [12], and to monitor environmental pollution in Surakarta [13]. Furthermore, over the last two decades, much research has focused on the physical and hydrological aspects of water harvesting using GIS and remote sensing. These studies showcase the effectiveness of GIS in identifying optimal locations for dams as part of flood mitigation plans in various locations and environments, such as Surat, India [14], and the Far Eastern region of Russia [7]. These studies indicate the reliability of the geospatial approach to be utilised for optimal dam site selection as a risk management plan for a flooding crisis.

The following chapter outlines the background of the problem and the objectives of this research as a case study. Then, the chapter closes up with the role of the GIS approach and analysis in effectively addressing relevant issues. Following that, the bases for selecting the study area are highlighted, with support from the GIS data. Test results are then reported, and a discussion is conducted based on the critical criteria for selecting the optimal dam wall location. The last section encompasses conclusions, concluding with recommendations for possible further improvements.

2. Statement of Problem

2.1. Wivenhoe Dam: Case Study

Wivenhoe Dam (Figure 1), the largest in southeast Queensland, has a full supply capacity of 1.165 million megalitres (constituting 45.3% of Queensland's water, Figure 2) and a flood mitigation capacity of 1.967 million megalitres. The dam is located upstream of the Brisbane River (80 km from Brisbane City) with a wall length of 2300 m. Wivenhoe Dam is an earth and rock embankment with a concrete spillway contains five massive steel gates 12.0 m in width and 16.6 m in height [15]. During intense local rain, the dam's five steel gates open to release excess water, maintaining a controllable reservoir level. The dam primarily serves to supply essential water to Brisbane and the surrounding areas (see Figure 3) and plays a crucial role in flood mitigation and power generation.

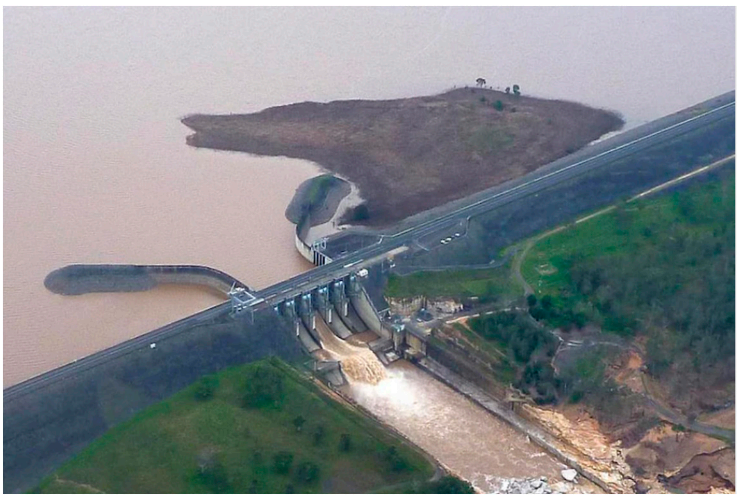


Figure 1. Wivenhoe Dam [16].

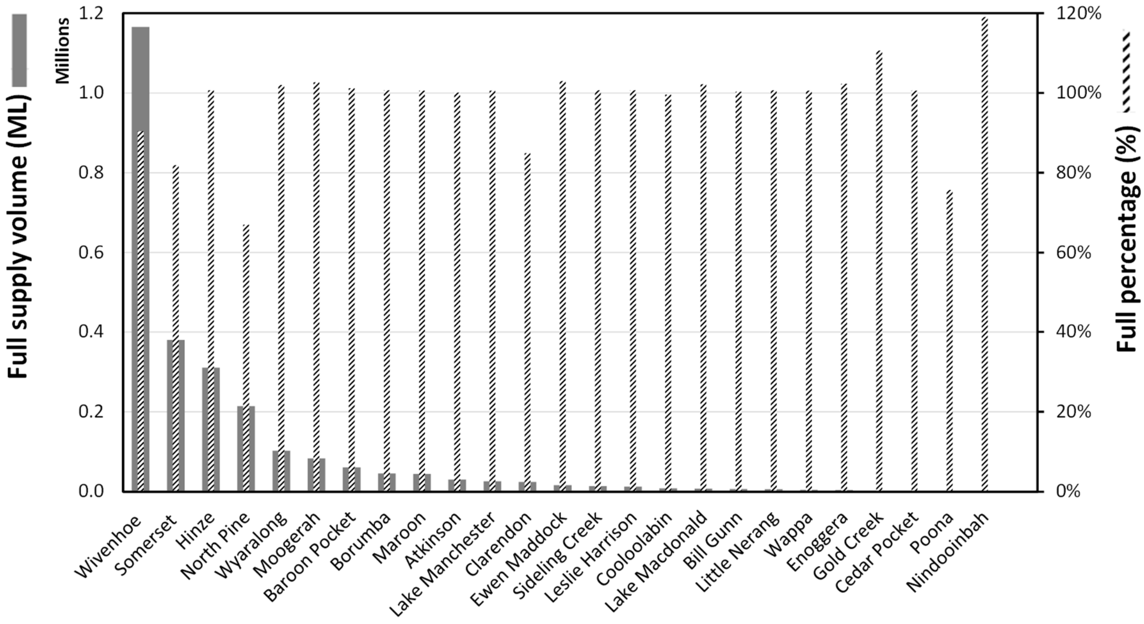


Figure 2. Water storage capacity of major dams in Queensland, Australia (by 8 May 2022).

According to the flood history study conducted by Queensland Reconstruction Authority [17], Brisbane River has experienced frequent flooding documented since 1824 due to heavy rainfall in the catchment, becoming an integral part of city life. For instance, the 1974 flood caused AUD 200 million in damage and the loss of 14 lives, served as the main impetus to construct Wivenhoe Dam. While in the 2011, instant rainfall triggered flash floods in Toowoomba and Lockyer Valley, resulting major river flooding in Brisbane and Ipswich, resulting in AUD 15.9 billion in damage. The February 2022 flood event affected 91% of Brisbane suburbs, causing AUD 2.5 billion in property damage [18]. Furthermore, Wivenhoe and Somerset Dams (see Figure 3) reached unprecedented levels at 183.9% and 148.0%, respectively, marking the highest water storage in their history. Notably, three major floods occurred in less than 50 years, emphasising the need of flood management plans. However, Wivenhoe Dam is a rock and earth-filled embankment dam; it has a clay core and an earthen wall lined on the outside with rocks [19]. Unlike Somerset Dam's concrete wall, Wivenhoe Dam lacks a structure to tolerate the pressure of water flowing over the wall [19]. Water from Somerset Dam and the upper Brisbane River feed Wivenhoe Dam (see Figure 3). During intense rainfall periods, the water level in the reservoir rises, creating substantial pressure, making the dam wall vulnerable to failure. Gates are consequently opened to release water and reduce pressure. However, this solution raises the volume of water flowing into Brisbane City, creating a new challenge for downstream areas of Wivenhoe Dam, especially in flooding events. Additionally, major creeks beneath the dam combine with the Brisbane River, escalating the river's enlarged flow already resulting in difficult water control in these locations (see Figure 3). This terrific flooding in Brisbane poses a crucial risk to human life and causes widespread infrastructure damage. On the other hand, reducing the water inflow from the Brisbane River by retaining water within the dam is considered dangerous and may cause extra pressure on the dam wall. Wivenhoe Dam failure could expose more than 300,000 people downstream to danger and destroy infrastructure worth AUD 100 billion [20]. In fact, the Queensland Government has suggested constructing a supplementary dam or raising the Wivenhoe Dam wall to protect communities in Brisbane and Ipswich [21]. However, no final decision has been made. Nevertheless, raising the dam wall increases the potential failure risk due to the significant increase in the pressure from the dead load of the wall as well as the ceased water [20]. Therefore, this study aims to find a suitable location for a supplementary dam that can share a significant amount of water from the Wivenhoe catchment area, alleviate the pressure on the dam wall, and provide an additional source of water.

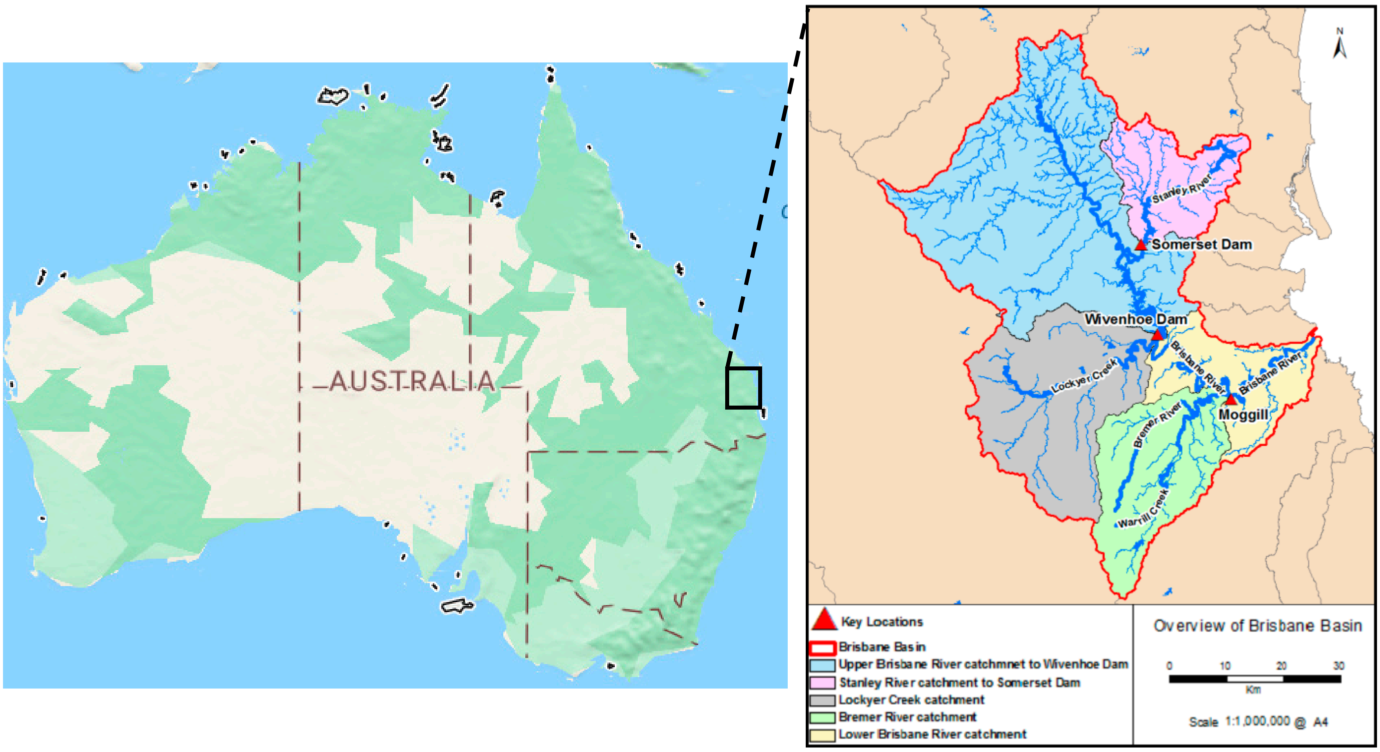


Figure 3. Brisbane City, Australia, and Brisbane Basin [22].

2.2. Pre-Feasibility Study for New Dam Development

A dam is a huge piece of infrastructure that requires planning and analysis of critical data which usually takes a period of 2 to 10 years to ensure taking the right decision [23]. According to Petheram et al. [23], a pre-feasibility assessment is required for the construction of a potential dam due to the significant costs and time involved in the construction associated with such huge infrastructure. This pre-feasibility assessment requires extensive initial investigations that comprehensively examine all potential dam construction sites considering the topography, morphology, geological structure, size of the catchment area, and the cost efficiency.

2.3. Scope of the Work and Study Objectives

The proposed work aims to identify an optimal site selection of a supplementary dam in Brisbane, QLD, Australia. This dam would serve the purpose of managing large volumes of water during sudden flood events and heavy localised rain, while also providing an additional water resource near Wivenhoe and Somerset Dams. The selection of the new dam site will be achieved through the utilisation of a geospatial approach. This approach will provide the necessary data to evaluate potential locations based on factors such as the catchment area, water yield, topography, morphology, and proximity to residential areas. Furthermore, it will help to determine the best position, size, and height for a potential dam wall as a case study to address the current threat to Wivenhoe Dam. It will also calculate the initial reservoir capacity and construction cost of the proposed dam. By conducting this study, moreover, decision-makers can significantly reduce the time and cost of the initial analysis phase when selecting suitable locations for future dams.

2.4. Geospatial Analysis for Supplementary Dam Planning

The geographic information system (GIS) is a powerful tool for managing, storing, querying, extracting, and visualising spatial data for a variety of applications especially in the context of water resource management [11]. Furthermore, satellite images provide information on topography, land use, catchments boundaries, and grid delineation which is a key data source for dam site selection [24]. Generally, a Digital Elevation Model (DEM) generated from satellite images provides vital slope data for flood behaviour prediction based on the flow direction of streams in GIS [24]. It is important to note that the accuracy of generated DEM can be affected by the low resolution of the satellite images, however studies on dam site selection showed that free sources DEM can provide representative simulation of the topography [25].

The effective utilisation of the available satellite images and GIS, based on Digital Elevation Models (DEMs), has facilitated the delineation and selection of potential zones for rainwater harvesting structures [11]. Additionally, these technologies are employed to calculate the elevation–area–volume (EAV) curve, enabling the estimation of optimal depth, surface area, and volume at various height increments of the dam. This approach proves to be efficient in dam site selection, offering optimal water harvesting modelling, planning, and management [26]. The method has proved to be efficient in other studies. For instance, a study aimed to optimally select a location for dam using the "elevation–volume–area" method conducted in the western desert of Iraq by Sayl et al. [11], and the results indicated a remarkable level of accuracy. Thus, this manuscript utilises GIS to efficiently choose a cost-effective site for a supplementary dam, serving as a flood risk management strategy for a large existing dam in Brisbane, Australia. This existing dam is susceptible to the risk of failure due to flooding.

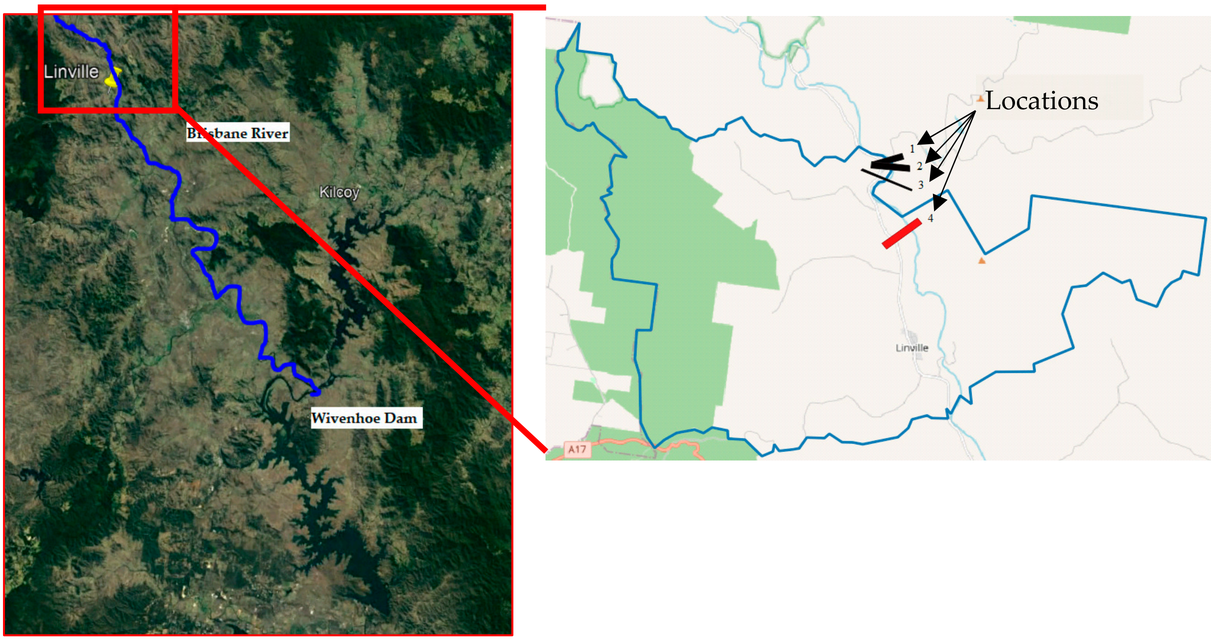
The investigation specifically targeted main streamlines, narrow terrain, and distances from urban centres. Each potential site underwent thorough examination using QGIS software, including the creation of cross-sections for further analysis. Additionally, the EAV curve was developed from a software-based process to determine the reservoir's area and volume, supporting further analysis to evaluate dam efficiency. A selection criteria assessment was also established to examine potential options.

3. Area Selection for the Supplementary Dam

3.1. Study Area Selection

In the process of finding the optimal location for a supplementary dam, this study initiated by outlining the flooding regions in Brisbane City, and determining the flow direction for main rivers and creeks, particularly those that feed into Brisbane City (upstream and downstream of Wivenhoe Dam). These results were verified through DEM analysis using QGIS software (version 3.16). This pilot investigation revealed a potential area close to Linville with a broad catchment, relatively narrow terrain, and major streams like the Brisbane River (see Figure 4a), potentially serving as a dependable water source for damming and as an ideal location for effectively managing water resources.

As shown in Figure 4, the upper Brisbane River flows through Linville on route to Wivenhoe Dam. Satellite imagery indicates that the topography above the Linville area is conducive to the construction of a potential dam wall. This location is also strategically distanced from densely populated areas. Conversely, downstream areas along the Brisbane River are characterised by a high population density, rendering the notion of constructing a dam infeasible. As a primary terrain analysis, four potential dam wall locations have been identified and numbered (1 to 4 in Figure 4b). It is important to note that Locations 1 to 3 (referred to as Potential Point 1 later) will share the same watershed and water volume calculations as they all fall within the same catchment area and have almost similar ground-level elevation (only difference is dam wall side area), whereas Location 4 is Point 2, with different watershed area and volume.



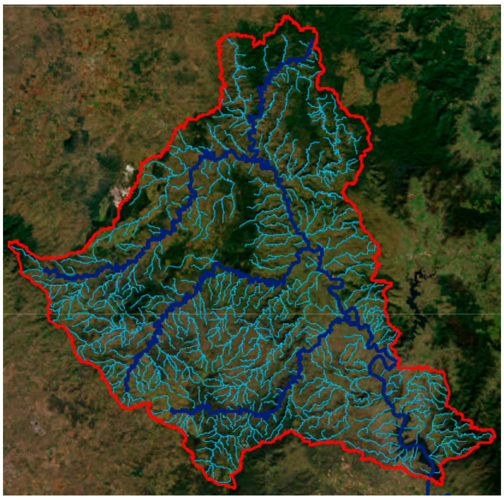
(**a**) (**b**)

Figure 4. Brisbane River through Linville to Wivenhoe Dam. (**a**) Upper Brisbane River passing through Linville. (**b**) Potential dam wall locations.

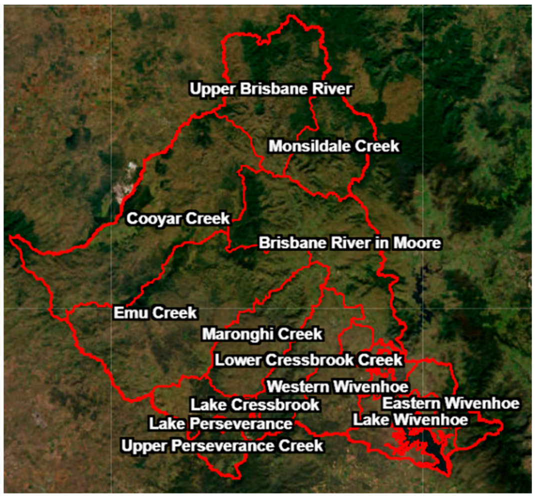
Linville is a rural town located southeast Queensland, within the Somerset Region, which covers an approximate area of 145.0 km^2 and has a population of 133 individuals as of 2021 [27]. The area is known for its sub-tropical climate, characterised by rainfall influenced by various weather systems, including cyclones, east coast lows, monsoonal depressions, and extra-tropical systems. Rainfall peaks during the summer months and reaches its lowest point during winter [5]. According to data sourced from the Australian Bureau of Meteorology (BOM), Brisbane experiences an average annual evaporation level of around 1600 mm, alongside a minimum temperature of 16.6 °C and a maximum temperature of 26.6 °C. In addition to these climatic attributes, there is an average annual rainfall of approximately 1200 mm. This unique combination of high temperatures, significant evaporation rates, and huge annual rainfall emphasises how crucial it is to establish efficient water management measures in the area. Therefore, constructing dams, reservoirs, and water storage facilities becomes paramount to harness and store rainfall during the wet seasons, thereby ensuring a consistent water supply for various industries and the burgeoning population of the city. For the study area's water sources, it is important to understand the involvement of the upper Brisbane sub-catchments.

3.2. Linville Catchment

The upper Brisbane catchment (Figure 5) is located to the north of Brisbane City and form around 40% of Brisbane River catchments with an estimated area of around 5493 km^2. It functions as the primary area of runoff for Brisbane's water supply to Wivenhoe Lake [28]. The upper Brisbane catchment contains 12 sub-catchments that can be seen in Figure 5b. The main water channels that feed in the proposed dam at Linville include the upper Brisbane River, Monsildale Creek, and Cooyar Creek sub-catchments (see Figure 5b). As each location has different characteristics, the water flow will be different [29].



(a)



(b)

Figure 5. The upper Brisbane catchment. (**a**) Upper Brisbane River catchments. (**b**) Sub-catchments for the upper Brisbane River.

According to the Department of Environment and Science [29], the upper Brisbane River sub-catchment receive a good annual rainfall of about 1001 mm in the upper north-east of the sub-catchments; with a low porosity of metamorphic geologies, they do not facilitate efficient groundwater recharge, while the runoff rate is high. When combined with steep slopes and abundant rainfall, this can lead to rapid creek flows. While the lower Brisbane River annual rainfall is around 751 mm in the middle to the lower areas of the sub-catchments. The high rainfall and low porosity of the upper sub-catchment indicate that the middle and lower sub-catchment remain vulnerable to flash flooding during heavy rainfall events. The mid-upper Brisbane sub-catchment is characterized by steep to undulating terrain. The lower sections of the sub-catchments exhibit a series of terraces and benches composed of quaternary alluvium, which are resistant to erosion. This geological feature contributes to the stability of the area, particularly during periods of increased water flow and potential flooding.

The Monsildale Creek sub-catchment (Figure 5b) contains three main creeks, where the upper sub-catchment area receives good rainfall, and the combination of steep to undulating slopes, combined with metamorphic geology and low-porosity sandstone, results in rapid creek flow during heavy rainfall and limited potential for groundwater recharge. The last sub-catchment is the Cooyar creek that encompasses seven main creeks [29]. Compared to the other sub-catchments (upper Brisbane river and Monsildale), it shows a highly variable geology. The upper sub-catchments have good filtration rates, whereas the lower areas have a lower porosity and maintain a more sustained water flow. Moreover, the flow is almost permanent in the middle of the sub-catchments.

3.3. Geospatial Methodology in Dam Site Determination

The DEM used in this research was obtained from Queensland Spatial Catalogue 'QSpatial' website with a ground resolution of 25 m [30]. Subsequently, the DEM was processed afterwards using QGIS software. Figure 6 illustrates the workflow for processing the DEM.

The downloaded DEM was reprojected to the coordinate system (World_Cylindrical_Equal_Area) and filled to avoid depression in the digital representation of the landscape and interruption in the flow network using the processing SAGA toolbox in QGIS (see Figure 7a). To visualise the streams in the study area, channel networks were delineated showing the flow direction of these channels at selected potential points (representing the proposed dam wall locations, as mentioned previously) (see Figure 7b). Furthermore, defining the catchment area behind the selected points (using the Upslope function in

QGIS), which provides an information on the size of this catchment, terrains, number of streams and the contribution of runoff water (see Figure 7c), and the reservoir area and volume. In Figure 7, the upslope function was applied on two points on the DEM, where the first one represents Locations 1 to 3 in Figure 4b due to no change in the watershed and volume values, while Point 2 represents Location 4 as it has different properties than the former locations.

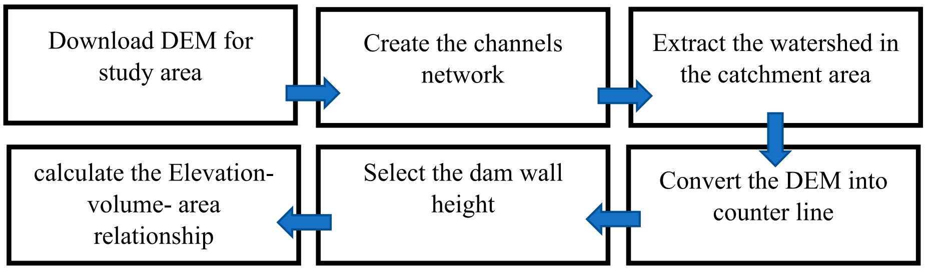


Figure 6. DEM workflow process.

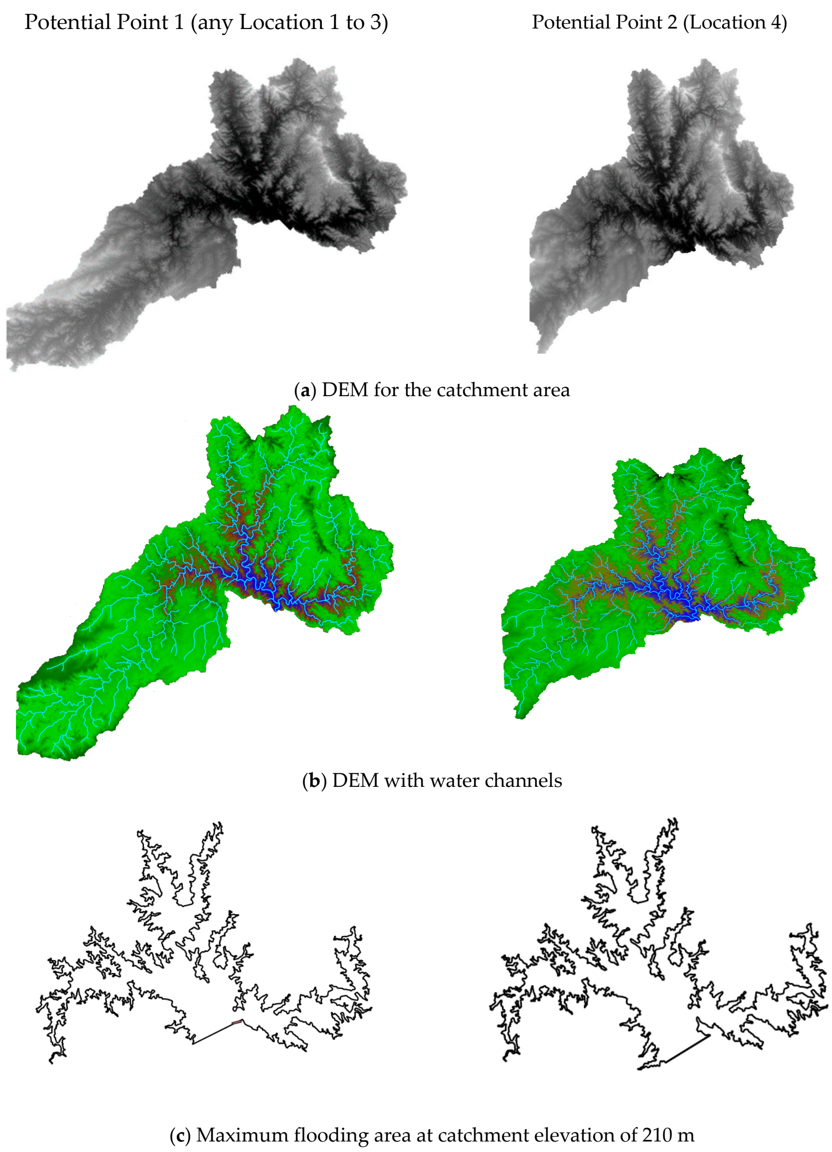


Figure 7. Illustrations of proposed dam wall locations.

The DEM of the resulting watershed at each proposed point was converted into a contour map at 5 m intervals representing the surface topography. Accordingly, using a contour filter at various selected heights (with 5 m increments) made it possible to identify the area susceptible to flooding (watershed area) and the reservoir size (watershed volume) at a specific dam wall height. It is worth mentioning that each potential dam wall location has a known ground level (zero watershed area and volume), which allows for the calculation of the height of the dam wall for volume estimations based on the contour in order to establish an elevation–volume–area (EAV) relationship. Determining the watershed area and volume below any specific height was achieved using the "count only below base level" function from processing toolbox. The height increments were gradually increased until reaching the potential spillway rather than the dam wall location (this will be discussed in the coming sections). This approach, even if the contour line is above the dam and spillway elevation, ensures preparedness should the dam wall height need to be increased in the future. Proactive data collection enables a seamless response to potential changes.

4. Results and Discussion

In this section, the results of the aforementioned methodology will be reported and discussed for all potential locations selected in this study. A comparison between the proposed location was based on the catchment properties considering parameters like elevation, watershed area, maximum flooding area and volume, dam wall height, and volume-to-area ratio. Following this, a cross-sectional analysis for each location was conducted to determine the size of the dam in potential locations. Afterwards, the new potential supplementary dam was compared to Wivenhoe Dam in terms with the dam side area (m^2), watershed volume (MML), volume-to-area ratio (MML/km^2), and cost. Lastly, a systematic decision matrix was established to select the optimal dam wall size for the selected site.

4.1. Catchment Properties at Potential Dam Points

According to Figure 7, the catchment properties at both potential points were determined and reported in Table 1 for a catchment elevation of 210 m representing the first spillway occurring at Point 2. It should be mentioned that a spillway was not observed when selecting a dam wall at Point 1 until reaching a catchment elevation at 270 m. This explains the reason behind the bigger catchment area shown when selecting a dam wall at Point 1 compared to Point 2 (Figure 7a,b). The dam wall at Potential Point 2 (with a catchment elevation of 210 m) showed a higher maximum flooding area and volume compared to any dam wall at Potential Point 1 (Figure 7c). This occurred because a new channel stream was included at Point 2 in addition to the catchment at Point 1. However, constructing a dam wall at Point 2 results in a higher dam wall at Point 1 due to the lower ground elevation, making the decision challenging until more evidence supports the selection. Thus, dam wall size, reflecting the construction cost of the new supplementary dam, will be used to reduce the available options.

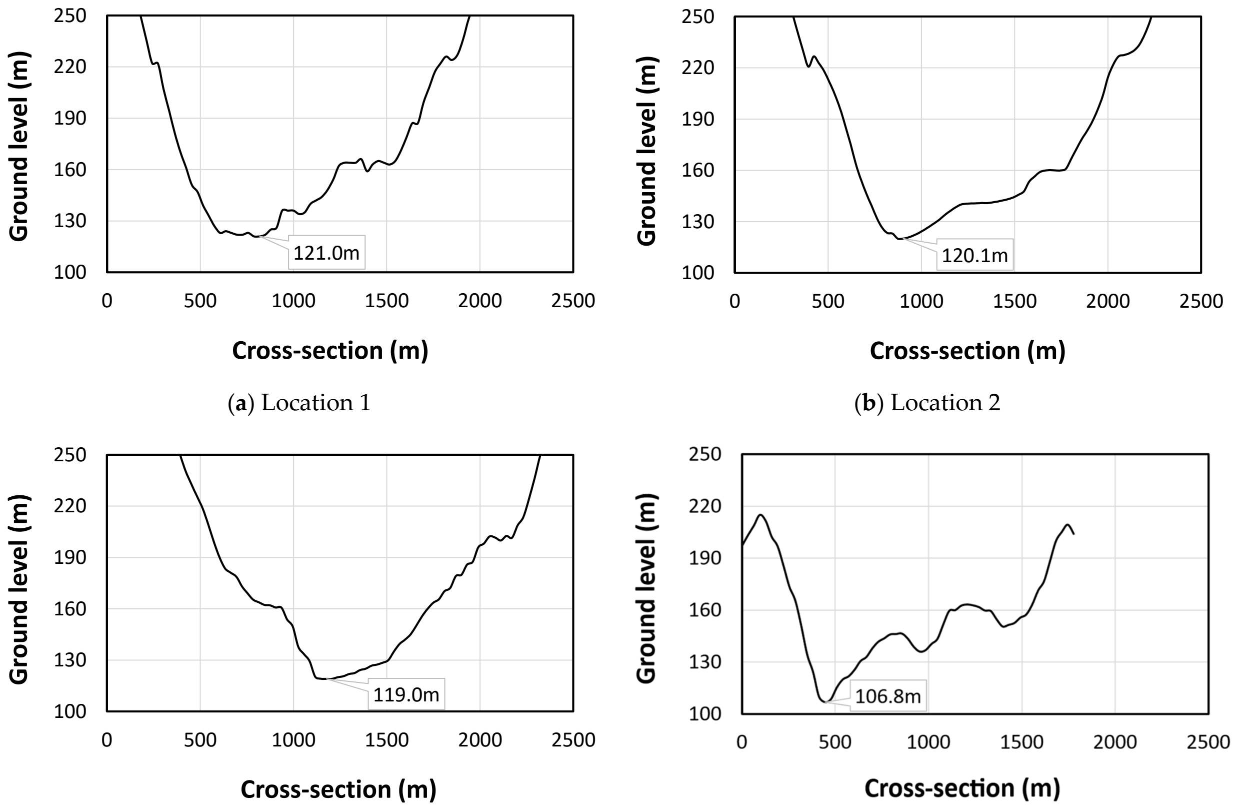
Table 1. Catchment properties of the new supplementary dam at the potential points.

	Potential Point 1	**Potential Point 2**
Ground-level elevation (m)	120.0 ± 1.0	106.8
Catchment elevation (m)	270	210
Catchment area (km^2)	1828	1586
Maximum flooding area (km^2) at 210	126.6	137.3
Dam wall height (m)	80.0 ± 1.0	93.2
Maximum flooding volume (MML) at 210 m	3.67	4.32
Volume-to-area ratio (MML/km^2)	0.0290	0.0315

4.2. Topographical Analysis

4.2.1. Optimal Dam Wall Location

Dam wall size can be used for the optimal selection of the new supplementary dam wall location. Thus, QGIS was relied upon to extract the topographical cross-section of the proposed dam walls at both Potential Points 1 and 2. Figure 8 shows the cross-section of the proposed dam wall Locations 1 to 4 for further optimising the selection of the best option. The cross-section at Potential Point 1 (including Locations 1 to 3, see Figure 8a–c) appears to have similar properties with no significant difference in the topographical features. In contrast, at Potential Point 2, the topography is not uniform, indicating that preconstruction preparations should be taken place to build a safe and quality dam wall. Additionally, it can be observed that the maximum dam wall height in Location 4 (Figure 8d) is around 103 m (this maximum height is normally applied to reduction factors to obtain road facilities and avoid any over-flooding risks). At Potential Locations 1 to 3, it can be noticed that the topography extends up to 150 m (with a ground level of 120 m and first spillway at 270 m) which allows for the flexibility to construct a mega dam wall. Building a dam wall of 150 m leads to having the biggest dam in Australia in terms of collected watershed volume and the second tallest dam wall after Talbingo Dam in New South Wales. Excluding Location 4 as an option is further supported by the higher construction cost of the dam wall in Location 4 (at least 93.6 m in height) compared to Locations 1 to 3 (80 m in height) (see Table 1 and Figure 8) for the same catchment elevation. Therefore, Potential Location 2 is suggested to be excluded from further analysis.



(**a**) Location 1 (**b**) Location 2

(**c**) Location 3 (**d**) Location 4

Figure 8. Cross-section of the dam walls at the proposed locations.

At Potential Point 1, the streamlines (Locations 1 to 3 as seen in Figure 8a–c) appear similar; thus, the dam wall width will be the critical factor to determine the optimal selection. In Figure 9, the dam wall width was plotted against the catchment elevation for all possible dam wall options. It can be observed that the dam wall width of Location 3 is the smallest until a catchment elevation of 195 m, according to the topography. This catchment elevation indicates a wall height of 75 m which is higher than the Wivenhoe Dam wall (59 m). Thus, this option will be optimal if the target dam wall height mimics Wivenhoe Dam (which will be narrower than the other options). On the other hand, Location 1 will be optimal if the maximum wall height is considered (150 m), targeting the maximum watershed volume. This means that Location 2 can be excluded in both scenarios. However, more supporting statements need to be claimed and discussed in the next section to select the optimal option.

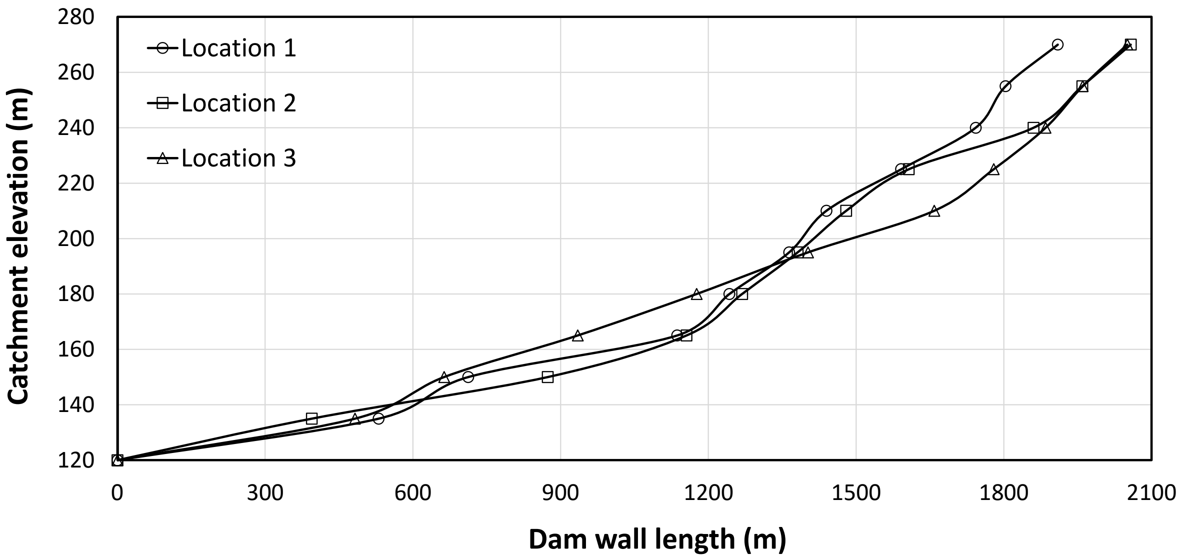


Figure 9. Dam wall dimensions at Locations 1 to 3.

4.2.2. Optimising the Proposed Dam Wall Dimensions

The catchment area of the proposed dam (Locations 1 to 3) represents 26.4% of the catchment area of Wivenhoe Dam since the proposed dam is located in its catchment area. This suggests that the proposed dam can share this amount of water percentage from the total water of Wivenhoe Dam, significantly reducing the risk of having over-flooding at Wivenhoe Dam during severe weather conditions.

To reduce the number of calculations at each DEM cell, a dam's height and width are restricted by Equation (1). This equation was used to calculate the height and length for 560 large dams in Australia, as mentioned in the Australian National Committee on Large Dams (ANCOLD) database [23]. Accordingly, the side area of the dam wall at Locations 1 (150 m × 1910 m) and 3 (150 m × 2050 m) exceeds 180,000. This indicates that the maximum side wall dimensions of Locations 1 and 3 will be 110 m × 1630 m and 102 m × 1745 m, respectively. The width was interpolated using Figure 9. It should be noted that the higher the dam, the greater the watershed volume that can be collected. It is also important to note that the dam wall height at Location 1 is slightly lower by almost 1 m as the ground level point at Location 1 is 121.0 while the dam wall height at Location 3 should be increased by 1 m as the ground-level point at Location 3 is 119.0 (see Figure 6a,c). Thus, Location 1 will be the optimal selection as a location of the new supplementary dam location.

For optimising the dam wall dimensions, several options were suggested by this study considering the watershed volume, dam side area, and cost of the dam wall construction comparing to Wivenhoe Dam as one of the largest dams in Queensland, Australia. For a more realistic comparison between Wivenhoe Dam and the proposed dam, Figure 10 shows the relationship between the dam wall height with the relative watershed area and volume as well as the dam wall length of the proposed dam.

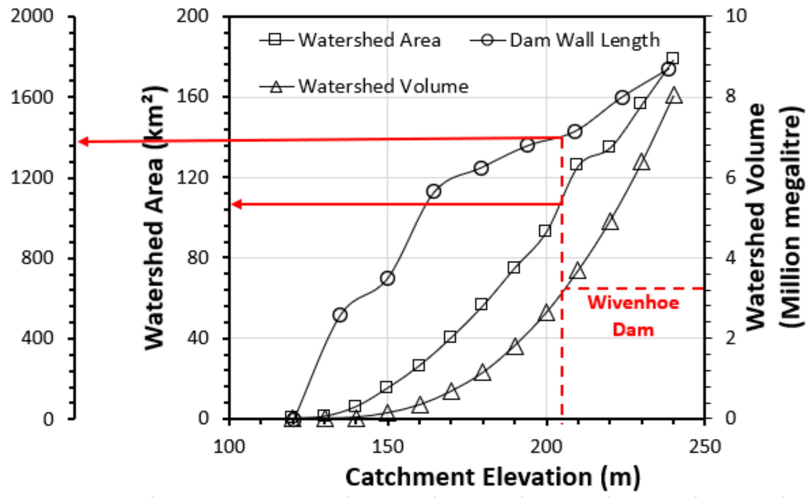


Figure 10. Dam wall length and watershed properties at Location 1.

Option 1: In this option, the maximum capacity of the new dam was suggested reflecting using the maximum allowable height of the dam wall (110 m) based on Equation (1). This option revealed a significantly higher volume-to-area ratio compared to Wivenhoe Dam (65%). Nevertheless, this increase in ratio efficiency accompanied a high construction cost but comparable volume-to-cost ratio to Wivenhoe Dam. Adopting this option results in having the largest dam in Queensland and the second largest dam in the whole of Australia after Gordon Dam (with a watershed volume of 12.4 MML).

Option 2: It was assumed that the wall height of the proposed dam was designed to collect the same watershed volume as Wivenhoe Dam. Figure 10 and Table 2 show that the new proposed dam wall height and length would be 85 m and 1360 m, respectively, with a little better volume-to-area ratio compared to Wivenhoe Dam. This implies that the small version of the proposed dam would have 85% of the dam side area of the Wivenhoe Dam wall. However, the construction cost will be more due to have a higher dam wall compared to the length with a 22% less volume-to-cost ratio as a result.

Table 2. Comparison between the proposed dam and Wivenhoe Dam.

	Wivenhoe Dam	Proposed Dam	Same Watershed Volume	Same Wall Surface Area	Same Cost
Catchment area (km^2)	7040	1828	1828	1828	1828
Dam wall height (m)	59	110	85	93	73
Dam wall length (m)	2300	1630	1360	1460	1330
Dam side area (m^2)	135,700	179,300	114,750	135,700	97,090
Watershed area (km^2)	110	137.3	106	131	82
Watershed volume (MML)	3.132	6.383	3.132	3.750	2.230
Volume-to-area ratio (MML/km^2)	0.0282	0.0465	0.0295	0.0286	0.0272
Dam wall construction cost (AUD M)	272.1	584.8	347.6	420.0	272.1
Volume-to-cost ratio (L/AUD)	11510	10915	9010	8929	8196

* The highlighted cells in one row take into account the assumptions made for the proposed dam wall option.

Option 3: The side area of the proposed dam in this option was assumed to be similar to the one at Wivenhoe Dam. This results in a wall dimension of 93 m × 1460 m (based on Figure 10) and an increase of 20% in the watershed volume capacity and similar volume-to-area ratio, respectively. Similar to the previous option, however, the dam wall height contributes significantly to the cost of the dam. Thus, a 23% reduction in volume-to-cost ratio is observed when compared to Wivenhoe Dam.

Option 4: This option assumes the construction of a dam having the same dam wall construction cost of Wivenhoe Dam, based on Equation (2). To identify economically efficient locations for dam walls, the optimal dimensions can be determined using Equation (2), which was derived using inflation-adjusted dam capital costs and data on dam attributes collected from 80 large dams in Australia [23] where cost is the dam capital cost in million Australian dollars and height and width are in meters. As a result, Option 4 results in a 30% lesser dam side area than Wivenhoe Dam but a 29% and 4% lesser watershed volume and volume-to-area ratio, respectively.

It has been observed that all options present both positive and negative aspects when compared to Wivenhoe Dam. Selecting the optimal option, therefore, three main parameters are suggested with proper ranking to come up with a decision. These parameters are the watershed volume (representing the amount of water that can be ceased), water harvesting efficiency (representing the volume-to-area ratio which indicates the water income considering the evaporation and seepage), and dam wall construction cost efficiency (representing the volume-to-cost ratio indicating the price of the collected litres without including the power benefits). It can be observed in Table 3 that the three parameters were marked by (√) for satisfactory, (√√) for over satisfactory, and (×) for unsatisfactory. Based on this marking approach, it can be concluded that Option 1 is the optimal selection among other options, making it the new proposed supplementary dam suggested in this study. However, the selection will be deemed invalid if it fails to achieve a satisfactory water yield within a specified timeframe. Therefore, the subsequent section is required to validate the optimal dam wall selection.

$$Dam\ side\ area = Height \times Width < 180,000 \tag{1}$$

$$Dam\ wall\ construction\ cost = 0.0039 \times (Height)^{1.5681} \times (Width)^{0.6148} \tag{2}$$

Table 3. Decision matrix for selecting the optimal dam wall size.

	Option 1	Option 2	Option 3	Option 4
Watershed volume	√√	√	√	×
Water harvesting efficiency	√√	√	√	√
Dam wall construction cost efficiency	√	√	√	√

(√) for satisfactory, (√√) for over satisfactory, and (×) for unsatisfactory.

4.3. Yeild Assessment of the Selected Dam

A number of techniques are available in the literature to predict the reservoir storage and its yield-reliability such as mainly carry-over storage yield and preliminary within-year yield methods. However, a significant discrepancy can be noticed when comparing between the two techniques. Nevertheless, the time-based yield analysis using the behaviour analysis model is considered a highly accurate technique to predict the reservoir storage with high yield-reliability. This technique requires a considerable daily data base along a range of years which is not available for our study area. Thus, rough feasibility calculations were conducted for the selected location of the dam based on annual records provided by governmental reports.

Data obtained from the hydraulic and hydrological models reported in the Brisbane River Catchment Flood Study [31] offer valuable insights. Hydraulic modelling offers a promising means of estimating water levels, providing reliable data when accurately implemented. The reliability of hydraulic models hinges on their physical and numerical representations, including boundary conditions and loss parameters. On the other hand, hydrological modelling simulates rainfall events to estimate discharge and link it to recorded measurement levels. For instance, within the Brisbane River catchment, a range of discharge values has been observed at Linville across different water levels:

- For the range of 0.7 to 2.7 m, the discharge ranges from 0.7 to 144 m^3/s, with 25 samples. The rating is based on the best fit of both gauging and model data.
- For the range of 2.7 to 7 m, the discharge varies from 144 to 1458 m^3/s, with 11 samples. The rating relies on the MIKE 21 model.

- For the range of 7 to 10 m, the discharge spans from 1458 to 3232 m^3/s, with 1 sample. The rating is also based on the MIKE 21 model.

Given that the proposed dam is primarily for flood mitigation, calculations prioritise the highest value within the 0.7 to 2.7 m range. Consequently, the average annual water flow in the Brisbane River at Linville is estimated at 144 m^3/s. Annual average precipitation for the reservoir (P) at the surface of reservoir (A) (922) mm, annual average evaporation is 800 mm from the reservoir (E) these data obtained by [32]. Using these inputs, it can be observed that Equation (3) reveals that the reservoir can store 4.56 MML in one full year or it can fill the full capacity of the dam in around a year and a half. This calculation did not consider the release of the dam to meet the demand which is something can be achieved or implemented by the decision-maker.

$$Storage = Water\ flow\ of\ a\ full\ year + reservoir\ surface\ area \times (Precipitation - Evaporation)$$

$$S = \sum_{0}^{full\ year} Q + A \times (P - E) \quad (3)$$

$$S = \left(144\frac{m^3}{sec} \times 60\frac{sec}{min} \times 60\frac{min}{hr} \times 24\frac{hr}{day} \times 365\frac{day}{year}\right) + 137,300,000 \times (0.922 - 0.800)$$

$$S = 4,557,934,600 \text{ Litres} = 4.56 \text{ MML}$$

5. Conclusions

This study investigated the opportunity to mitigate and prevent potential overtopping failure in Wivenhoe Dam, Queensland, Australia, caused by severe flooding. This was achieved through optimal site selection of a new supplementary dam wall with the aid of the national database and QGIS; the digital image model showed that Linville has the ideal topography to construct the new supplementary dam wall. In Linville, several options were proposed, discussed, and analysed to select the most optimal option based on systematic selection criteria considering the dam wall dimensions, volume-to-area, and volume-to-cost ratios. Utilising the predefined functions of the QGIS software, the cross-sections of the potential dam walls were extracted in addition to the watershed and water volume calculations, aiding in excluding some of the less feasible options. Nevertheless, all proposed options revealed a 48% reduction at least in the new dam wall length at the same dam wall height compared to Wivenhoe Dam. The outcome of this study suggests a high-efficiency and cost-effective dam which will be the new largest dam in Queensland at a 200% increase in the watershed volume compared to Wivenhoe Dam with only a 30% increase in the dam wall dimensions. Interestingly, the proposed dam will be the second biggest dam and the seventh tallest dam in Australia, indicating the cost-effectiveness of the new proposed supplementary dam. This study provides a case study on a real-life issue which can aid the decision-makers with sound evidence for approaching the next steps towards constructing this supplementary dam as a precaution plan securing Wivenhoe Dam from potential failure risk.

For further improvement of the current study, a more accurate DEM (up to 0.5 m accuracy) could be utilised, which would require significant financial support. Additionally, sophisticated surveying methods and techniques, like LiDAR-Drone, could be implemented to capture accurate surface measurements, which would positively affect the design and selection of the supplementary dam wall size and exact location. It would also be beneficial to complement this study with an environmental assessment to investigate the impact of the new supplementary dam on the environmental conditions of the new catchment area.

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References

1. Alley, R.; Berntsen, T.; Bindoff, N.L.; Chen, Z.; Chidthaisong, A.; Friedlingstein, P.; Gregory, J.; Hegerl, G.; Heimann, M.; Hewitson, B. Climate change 2007: The physical science basis. *Agenda* **2007**, *6*, 333.
2. Yoro, K.O.; Daramola, M.O. CO_2 emission sources, greenhouse gases, and the global warming effect. In *Advances in Carbon Capture*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 3–28.
3. Bureau of Meteorology. *State of the Climate 2020*; Bureau of Meteorology: Docklands, Austrilia, 2020.
4. Lempérière, F.J.E. Dams and floods. *Engineering* **2017**, *3*, 144–149. [CrossRef]
5. Smith, I.; McAlpine, C. Estimating future changes in flood risk: Case study of the Brisbane river, Australia. *Clim. Risk Manag.* **2014**, *6*, 6–17. [CrossRef]
6. QRA. *Queensland Flood Risk Management Framework*; Queensland Government, Ed.; Queensland Reconstruction Authority: Brisbane City, Austrilia, 2021.
7. Fedorov, M.; Badenko, V.; Chusov, A.; Maslikov, V. GIS technologies for selecting location of dams in the flood control systems. In *E3S Web of Conferences*; EDP Sciences: Les Ulis, France, 2019.
8. Manfreda, S.; Miglino, D.; Albertini, C.J.H.; Sciences, E.S. Impact of detention dams on the probability distribution of floods. *Hydrol. Earth Syst. Sci.* **2021**, *25*, 4231–4242. [CrossRef]
9. BOM. *Known Floods in the Brisbane & Bremer River Basin*; Australia Bureau of Meteorology: Brisbane City, Austrilia, 2017.
10. Ajayi, O.G.; Palmer, M.; Salubi, A.A. Modelling farmland topography for suitable site selection of dam construction using unmanned aerial vehicle (UAV) photogrammetry. *Remote Sens. Appl. Soc. Environ.* **2018**, *11*, 220–230. [CrossRef]
11. Sayl, K.N.; Muhammad, N.S.; Yaseen, Z.M.; El-shafie, A. Estimation the physical variables of rainwater harvesting system using integrated GIS-based remote sensing approach. *Water Resour. Manag.* **2016**, *30*, 3299–3313. [CrossRef]
12. Kipkemboi, W.; Kuria, B.T.; Kuria, D.N.; Sichangi, A.W.; Mundia, C.N.; Wanjala, J.A.; Muthee, S.W.; Goebel, M.; Rienow, A. Development of a Web-GIS Platform for Environmental Monitoring and Conservation of the Muringato Catchment in Kenya. *J. Geovisualization Spat. Anal.* **2023**, *7*, 13. [CrossRef]
13. Anna, A.N.; Fikriyah, V.N. Environmental pollution monitoring using a Web-based GIS in Surakarta. In Proceedings of the IOP Conference Series: Earth and Environmental Science, West Sumatra, Indonesia, 15–16 November 2018; IOP Publishing: Bristol, UK, 2018; p. 012066.
14. Raaj, S.; Pathan, A.I.; Mohseni, U.; Agnihotri, P.G.; Patidar, N.; Islam, M.N.; Patidar, S.; Salihi, M. Dam site suitability analysis using geo-spatial technique and AHP: A case of flood mitigation measures at Lower Tapi Basin. *Model. Earth Syst. Environ.* **2022**, *8*, 5207–5223. [CrossRef]
15. SeqWater. Fact sheet Wivenhoe Dam. Available online: https://www.seqwater.com.au/sites/default/files/2019-09/Fact%20sheet%20-%20About%20Wivenhoe%20Dam.pdf (accessed on 1 September 2019).
16. ABC News. *State Government Proposes Eight New Dams for South-East Queensland*; ABC News: Sydney, Australia, 2014.
17. QAR. Brisbane River Catchment Flood Studies: A History of living with Flooding. Queensland Reconstruction Authority. 2018. Available online: https://www.qra.qld.gov.au/sites/default/files/2018-11/brisbane_river_catchment_historical_factsheet.pdf (accessed on 1 November 2018).
18. ABC News. How Brisbane Is Coping after the February Flood, the City's Third Major Inundation in 50 Years. ABC News: Sydney, Australia. 2022. Available online: https://www.abc.net.au/news/2022-05-17/the-february-2022-flood-marked-the-third-major/13885832 (accessed on 17 May 2022).
19. Shaw, K. Wivenhoe: A Dam Designed to Fail and Decimate Brisbane: With a Solution So That Won't Happen. Available online: http://www.floodcommission.qld.gov.au/__data/assets/file/0003/8463/Shaw_Ken.pdf (accessed on 4 April 2011).
20. ABC News. *Wivenhoe Dam $900 Million Safety Revamp Considered to Prevent Brisbane Flood Disaster*; ABC News Australia: Sydney, Australia, 2017.
21. QLD Government. Potential New Dams to Protect Brisbane and Ipswich. Available online: https://statements.qld.gov.au/statements/75474#:~:text=increasing%20the%20flood%20mitigation%20compartment%20of%20Wivenhoe%20Dam,dam%20on%20the%20Lower%20Warrill%20Creek%20near%20Willowbank. (accessed on 29 November 2023).
22. SEQWATER. Brisbane River Strategic Floodplain Management Plan. Available online: https://www.qra.qld.gov.au/sites/default/files/2019-04/Plan%20-%20Brisbane%20River%20Strategic%20Floodplain%20Management%20Plan%20(April%202019)_2.pdf (accessed on 1 February 2019).

23. Petheram, C.; Gallant, J.; Read, A. An automated and rapid method for identifying dam wall locations and estimating reservoir yield over large areas. *Environ. Model. Softw.* **2017**, *92*, 189–201. [CrossRef]
24. Abushandi, E.; Alatawi, S. Dam site selection using remote sensing techniques and geographical information system to control flood events in Tabuk City. *Hydrol. Curr. Res.* **2015**, *6*, 1000189.
25. Al-Ruzouq, R.; Shanableh, A.; Yilmaz, A.G.; Idris, A.; Mukherjee, S.; Khalil, M.A.; Gibril, M.B.A. Dam site suitability mapping and analysis using an integrated GIS and machine learning approach. *Water* **2019**, *11*, 1880. [CrossRef]
26. Sayl, K.N.; Muhammad, N.S.; El-Shafie, A.J.E.E.S. Optimization of area–volume–elevation curve using GIS–SRTM method for rainwater harvesting in arid areas. *Environ. Earth Sci.* **2017**, *76*, 1–10. [CrossRef]
27. Australian Bureau of Statistics. Linville, Census All persons QuickStats. 2021. Available online: https://abs.gov.au/census/find-census-data/quickstats/2021/SAL31666 (accessed on 1 January 2021).
28. Department of Environment, Science and Innovation, Queensland. South Eastern Queensland (SEQ) IBRA Bioregion—Facts and Maps, WetlandInfo Website. 2023. Available online: https://wetlandinfo.des.qld.gov.au/wetlands/facts-maps/ibra-bioregion-south-eastern-queensland-seq/ (accessed on 1 January 2023).
29. Department of Environment, Science and Innovation. Walking the Landscape—Upper Brisbane Map Journal v1.0 (2020), Presentation. 2020. Available online: https://wetlandinfo.des.qld.gov.au/wetlands/ecology/processes-systems/water/catchment-stories/transcript-upper-brisbane.html (accessed on 1 January 2020).
30. Queensland Government. Queensland Spatial Catalogue-QSpatial. 2022. Available online: https://qldspatial.information.qld.gov.au/catalogue/custom/index.page (accessed on 1 January 2022).
31. Aurecon Australasia. Brisbane River Catchment Flood Study–Comprehensive Hydrologic AssessmentData, Rating Curve and Historical Flood Review Report. Available online: https://www.qra.qld.gov.au/sites/default/files/2018-12/r.b20702.006.01.mr6_.brcfs_hydraulics_report.draftfinal.pdf (accessed on 1 December 2016).
32. Bioregional assessments, Surface water systems. Available online: https://www.bioregionalassessments.gov.au/assessments/11-context-statement-gwydir-subregion/1151-surface-water-systems (accessed on 5 January 2018).