GIS SURVEYING OF DAM SITE SELECTION AS FLOOD MITIGATION PLAN FOR WIVENHOE DAM

A Thesis submitted by

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ABSTRACT

Climate change poses a global challenge, marked by rising temperatures and increasing the frequency and intensity of extreme weather events such as heavy rainfall and flooding. Addressing the need for effective flood disaster management, this study explores the utilization of flexible mitigation plans, particularly through the construction of supplementary dams. Focusing on the potential overtopping failure of the Wivenhoe Dam in Brisbane, Australia, due to severe flooding events, this research employs a methodology that integrates Remote Sensing (RS) and Geographic Information System (GIS) techniques to select an optimal site for a supplementary dam. The objective is to identify a site that could protect an estimated 300,000 lives and $100 billion in assets, while also maximizing water harvesting and power generation benefits. By leveraging 'Google Earth Pro' and satellite imagery, alongside detailed analysis using QGIS software, potential dam sites near Linville, Brisbane, were assessed. Utilizing Digital Elevation Models (DEM) obtained from the Queensland Spatial Catalogue, various parameters including watershed volume (the total volume of water collected and stored in the catchment area), water harvesting efficiency, and dam wall construction cost were evaluated to determine the most suitable location. The results highlight the feasibility of supplementary dam construction in mitigating flood risks while emphasizing the importance of rigorous site selection criteria. Recommendations for future research include further refining the methodology and expanding the scope to address broader challenges in flood management practices.

CERTIFICATION OF THESIS

I Aseel Zytoon declare that the master Thesis entitled *GIS Surveying of Dam Site Selection as Flood Mitigation Plan for Wivenhoe Dam* is not more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes.

This Thesis is the work of Aseel Zytoon except where otherwise acknowledged, with the majority of the contribution to the paper presented as a Thesis by Publication undertaken by the student. The work is original and has not previously been submitted for any other award, except where acknowledged.

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STATEMENT OF CONTRIBUTION

The article produced from this study was a joint contribution of the authors. The details of the scientific contribution of each author are provided below:

PAPER 1: Aseel Zytoon, Zahra Gharineiat, Omar Alajarmeh (2024). Supplementary Dam Site Selection Using a Geospatial Approach: A Case Study of Wivenhoe Dam. ISPRS International Journal of Geo-Information, 13(6), 180. https://doi.org/10.3390/ijgi13060180

The overall contribution of Aseel Zytoon was 75% related to the data collection, critical review of related literature, analysis and interpretation of data, drafting and revising the final submission. Zahra Gharineiat and Omar Alajarmeh contributed to the structuring of the manuscript, analysis and interpretation of data, editing and providing important technical inputs.

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ABBREVIATIONS

A:	Reservoir surface area
AUD:	Australian Dollar
BOM:	Bureau Of Metrology
DEM:	Digital Elevation Model
E:	Evaporation
EAV :	Elevation–Area–Volume
GIS:	Geographic Information System
km2:	kilometre square
LiDAR:	Light Detection and Ranging
m:	metre
MML:	Million Megalitre
P:	Precipitation
Q:	Water flow of a full year
QGIS:	Quantum Geographic Information System
RS:	Remote Sensing
S:	Storage
PAR:	Population at Risk
PLL:	Potential Loss of Life

CHAPTER 1: INTRODUCTION

1.1 Flooding Mitigation: Wivenhoe dam case study

Climate change is usually described as the long-term, average change in temperature or precipitation levels that that impacts human life (Alley et al., 2007). Greenhouse gases that accumulate in the atmosphere and absorb sunlight and solar radiation are the main culprits behind global warming. Yoro and Daramola (2020) stated that, the severe consequences of climate change will continue to affect Earth, and the average surface temperature of the Earth is likely to exceed 3°C in this century. Furthermore, the Climate Report from CSIRO and Bureau of Meteorology (BOM) in Australia highlights that Australia is already experiencing the effects of climate change, with the country's climate having warmed by approximately 1.4°C since 1910 (Bureau of Meteorology, 2020). AS Alley et al. (2007) note, These changes, characterized by increased evaporation levels, can intensify the water cycle, potentially leading to extreme precipitation events and catastrophic flooding in many areas. Conversely, some regions may experience prolonged dry spells and drought due to shifts in precipitation patterns. Furthermore, by the end of this century, these changes are predicted to increase the frequency of extreme sea level events, which are currently expected to occur once every 100 years(Masson-Delmotte et al., 2021).Therefore, it is crucial to mitigate the overflow of excessive rainfall and control potential disaster occurrences.. The need for flood mitigation measures is expected to grow in certain countries due to climate change's impact, as it may increase the annual probability of precipitation by 10% or 20%, leading to a more than 20% increase in related floods (Lempérière, 2017). In fact, devastating once-in-100-year flood events may occur as often as once every 10 years (Lempérière, 2017). Consequently, climate model projections indicate a concerning trend of increased flooding across various regions in Australia, particularly in southeastern Australia(Smith & McAlpine, 2014).

Flood mitigation is a complex challenge, as plans must adapt to changing conditions such as climate change, population growth, and land use. One of the most effective measures for mitigating peak floods is a system of detention basins (Manfreda et al., 2021). Dams are constructed to halt the flow of water, allowing it to accumulate over time and create a reservoir for water storage (Ajayi et al., 2018). This process serves the primary purpose of holding water for drinking, domestic use, and flood management by mitigating or preventing flood events. A dam's design and operating regulations determine how excess water is regularly discharged through spillways or gates, which can reduce the threat of floods. However, retaining large amounts of water increases pressure on dam walls, posing a potential risk of failure. Ingles (1984) stated that dam failures in Australia fall into major categories: piping, 26%; overtopping, 20%; slope failures, 20%; foundation failures, 17%; other reasons, 17%. Overtopping can be considered a natural hazard (primarily due to flooding events), but in some cases, it can result from design errors, such as insufficient freeboard. Other failure types, such as piping and slope foundation failures, are attributed to design and engineering errors, which can be mitigated through proper construction.

Wivenhoe Dam (Figure 1) is the largest dam in southeast Queensland, with a full supply capacity of 1.165 million megalitres (supplying 45.3% of Queensland's water; see Figure 2) and a flood mitigation capacity of 1.967 million megalitres. According to a fact sheet published by SeqWater (2019b), the dam is located upstream of the Brisbane River (80 kilometres from Brisbane City) with a wall length of 2300 m. Wivenhoe Dam is an earth and rock embankment with a concrete spillway containing five massive steel gates that measure 12.0 m in width and 16.6 m in height (Figure 1). In the event of high-intensity localized rain in the catchment, these five steel gates are opened to release excess water and maintain a safe level in the reservoir. Thus, the main purpose of this dam is to provide Brisbane and the surrounding areas with a stable water supply (see Figure 3) and to play a major role in flood mitigation and power generation. According to Shaw (2011) "Wivenhoe has a clay core and an earthen wall which is lined on the outside with rocks”. Consequently, Wivenhoe Dam dose not have the required structural reinforcement to withstand the pressure from overtopping—water flowing over the dam wall—unlike the concrete wall in Somerset Dam (Shaw, 2011).

Additionally, in fact, water from the upper Brisbane River and Somerset Dam flows into Wivenhoe Dam. During continuous heavy rainfall, the dam wall may experience significant pressure due to rising reservoir levels, which increases the risk of failure. Gates are thus opened to release water and lower the reservoir volume. However, this action increases water flow into Brisbane City, creating flooding challenges downstream of Wivenhoe Dam. Where major creeks beneath the dam converge with the Brisbane River, further escalating the river's flow and making water management in these areas difficult. This has led to intense flooding in Brisbane, posing risks to human life and causing significant damage.

On the other hand, reducing water inflow from the Brisbane River by retaining water within the dam is considered unsafe, as it may cause additional pressure on the dam wall.

A dam failure could place an estimated population at risk (PAR) of over 300,000 people downstream, with a potential loss of life (PLL) of up to 400 fatalities and infrastructure damage valued at up to $100 billion (ABC News, 2017). Therefore, this study aims to identify a suitable location for a supplementary dam that can share the water load from the Wivenhoe catchment area and mitigate the pressure on the dam wall. This suggestion will reduce the amount of water fed into Wivenhoe Dam by ceasing the flow upstream of the Brisbane River somewhere to mitigate the flood before reaching Wivenhoe Dam.

Figure 1. Wivenhoe Dam (ABC News, 2014).

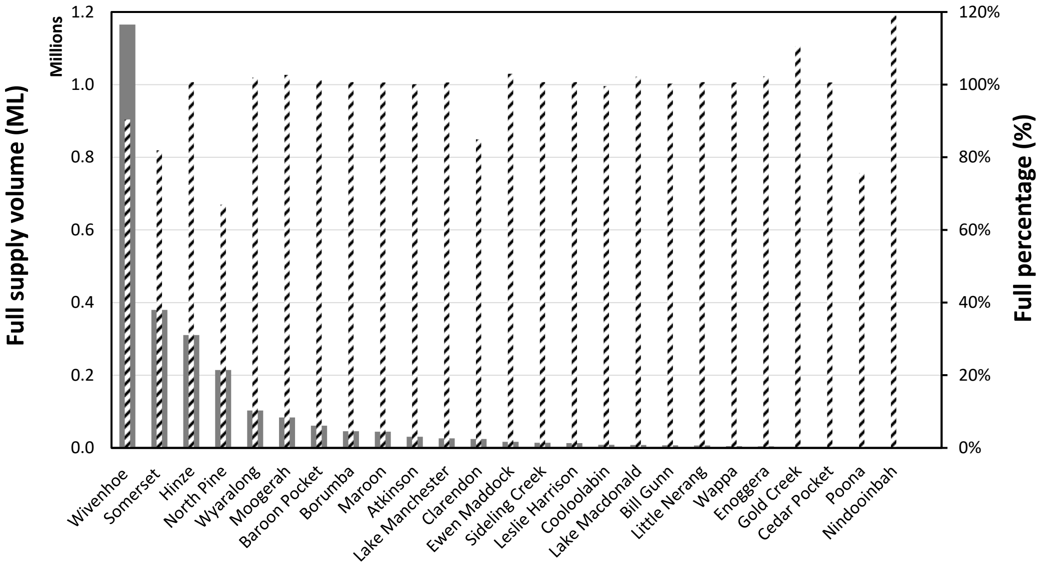

Figure 2. Water storage capacity of the major dams in Queensland-Australia (8 May 2022)

According to Petheram et al. (2017), Dam is a massive infrastructure project that requires planning and analysis of critical data, which generally takes between 2 to 10 years to ensure the right decisions are made. Moreover, a pre-feasibility assessment is necessary for the construction of a potential dam due to the significant costs and time involved in building such large-scale infrastructure (Petheram et al., 2017). This pre-feasibility assessment involves extensive initial investigations that thoroughly examine all potential dam construction sites, considering factors such as topography, morphology, geological structure, catchment area size, and cost efficiency.

This pre-feasibility assessment can be accelerated using remote sensing and geographic information systems (GIS) techniques, in contrast to the time-consuming nature of traditional ground surveying methods (Abushandi & Alatawi, 2015). GIS is a powerful geographical analytic tool with an intuitive interface that captures, stores, queries, analyses, displays, and exports geographic data, facilitating the identification of appropriate dam construction sites in conjunction with other strategies. (Rikalovic et al., 2014). While satellite imagery provides valuable data for dam site selection—such as topography, land use, catchment boundaries, and grid delineation (Abushandi & Alatawi, 2015), geotechnical and soil studies are also fundamental for assessing site suitability. Since these factors were not covered in this document, they are acknowledged as limitations. In general, digital elevation models (DEMs) obtained from satellite images can provide slope data, a critical factor in determining flood behaviour and stream flow direction (Abushandi & Alatawi, 2015). DEMs are also essential for realistic terrain simulation, as they provide key information on reservoir size, flow direction, and velocity (Li et al., 2021). This study aims to identify an optimal site for constructing a supplementary dam in Brisbane, Australia, which will manage a certain volumes of water during sudden flood events and heavy localized rain while providing an additional water resource near the Wivenhoe and Somerset dams.. Site selection will utilize DEM and open-access software ‘QGIS,’ which will offer essential data to evaluate potential locations based on factors like catchment area, water yield, topography, morphology, and proximity to residential areas.. This analysis will determine an optimal position, size, and height of the proposed dam wall to mitigate the current threat to Wivenhoe Dam. Additionally, the study will calculate the initial reservoir capacity and construction costs of the proposed dam. The findings aim to streamline the initial assessment phase for decision-makers and researchers involved in selecting suitable dam sites in the future.

1.2 Research Objectives

The proposed work aims to choose an ideal location for a supplementary dam near Wivenhoe Dam using GIS and remote sensing techniques. The specific objectives are as follows:

1. Enhance flood mitigation efforts and improve water management infrastructure within the Brisbane River catchment area.
2. Identify an optimal site for a new supplementary dam that can help alleviate water pressure on Wivenhoe Dam, reduce the risk of Overtopping and Dam wall failure, and minimize future flooding in Brisbane and surrounding areas.
3. Utilize a GIS and remote sensing approach to efficiently collect and analyse freely available spatial data for developing dam site selection criteria, demonstrating an effective and cost-efficient methodology.

1.3 Study area

The study area of this research is Linville, a rural town located in the Somerset Region of Brisbane (Figure 3). The area covers approximately 145.0 km², with a population of 133 individuals, according to the Australian Bureau of Statistics (ABS, 2021).

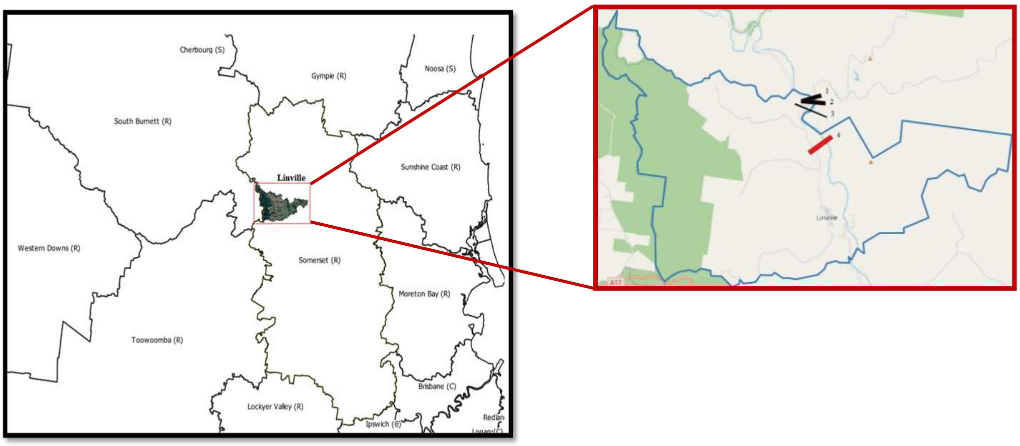

Figure 3. Linville site and potential dam wall locations

The Upper Brisbane River passes through Linville on its way to Wivenhoe Dam. Satellite imagery analysis suggests that the topography around Linville is suitable for a potential dam wall due to natural mountain-restricted zones and its distance from populated areas. Preliminary GIS analysis and contour line mapping identified four potential sites for further investigation, each designated by a number (Figure 3). Three of these sites, numbered 1 through 3, share a ground level of 120 meters, with one to be selected based on established comparison criteria, while the fourth site has a ground level of 105 meters. Details of further investigations will be covered in the methodology section. In contrast, the densely populated areas downstream along the Brisbane River make the construction of a dam in those areas highly risky.

This study proposes the construction of a supplementary dam upstream of Wivenhoe Dam. The target is to distribute water storage more effectively during heavy rainfall, relieving pressure on the Wivenhoe Dam wall and reducing or preventing flooding in Brisbane city. It is important to note that an ideal location for a potential supplementary dam will depend on various factors, including the number and size of streams, the expected water capacity of the reservoir, terrain parameters, morphology, and proximity to residential areas.

1.4 Study limitations

A Digital Elevation Model (DEM) is a valuable input for GIS software used in terrain analysis and modeling. However, the resolution of the DEM significantly impacts the accuracy of the results. It is important to note that the DEM used in this study has a spatial resolution of 25 meters, making it the most accurate DEM available from free sources. Digital representations of terrain may lose detail or fine-scale topographic features when captured at low resolutions. To enhance accuracy, a high-resolution DEM of up to 0.5m is preferred, which was not feasible in this study. Furthermore, on-site investigation into the geotechnical and soil conditions is recommended as part of future work to ensure the site's safety and viability for construction. This was not feasible in this study due to a lack of technical equipment.

CHAPTER 2: LITERATURE REVIEW

2.1 DAMS AND FLOODS

2.1.1 Flood's Impact and Failure of Dams

According to the Queensland Reconstruction Authority (QRA) flood management report (QRA, 2021), flooding causes more damage in Queensland than any other natural disaster. The authority administers funding of more than $16.4 billion for disaster recovery, with 85% of the total funding dedicated to flood recovery. Floods occurs frequently in southeast Queensland. Kron (2002) stated that "flooding as a temporary covering of land by water as a result of surface waters escaping from their normal confines or as a result of heavy precipitation". However, understanding the type of flood plays a major role in effective planning, flood monitoring, mitigation, and management, as well as in developing early warning systems and assessing flood damage (Opolot, 2013). The type of flood is identified by physical characteristics such as water depth and flow velocity, which help determine the severity of the impact. Most studies classify floods into coastal floods, river floods, drainage-related floods (such as those due to high precipitation or tsunamis), and flash floods (Younis & Thielen, 2008). Flash floods are considered a life-threatening type of flood, as they occur suddenly due to high-intensity localised rainfall, leaving short time for forecasting and issuing warnings (Younis & Thielen, 2008). Moreover, the high rate of rise and flow speed of flash floods makes it not only dangerous to human life but also capable of causing serious damage to dam walls and infrastructure (see Figure 2 a and b). Frequent flooding events in the Brisbane River due to heavy rainfall in the catchment area are a part of city life, with major floods occurred in 1893, 1974, 2011, 2013, and 2022 (Queensland Reconstruction Authority, 2018). The Brisbane River has a well-documented history of flooding, with records dating back to 1824.

a) Failure of Sanford Dam-Michigan, USA (WION Web Team, 2020)

b) Failure of the Tokwe-Mukosi Dam-Zimbabwe (Lempérière, 2017)

Figure 4. Typical overtopping dam wall failure

2.1.2 Wivenhoe dam: A Case Study

The construction of the Wivenhoe Dam was a response to the 1974 flood event (Kearney et al., 2011). The dam is recognized as the primary water resource for Brisbane and the greater Ipswich area, providing water supply to the region and playing a crucial role in mitigating and preventing further flooding. A study conducted by the Queensland Department of Energy and Water Supply (QDEWS, 2014) on the optimization of Wivenhoe and Somerset dams revealed that, in addition to their primary functions of mitigating floods and storing water, both dams have a larger capacity for flood storage compared to water supply storage. The study highlighted that, for safety reasons, both dams are maintained below their total capacities even when the water supply storage in the reservoir is full. It's important to note that dams are typically considered 'full' when the water supply compartments reach capacity, but not when the flood mitigation storage space is occupied. This flood mitigation space must remain completely empty and should not be used for storing water supply. During flood events, the dam functions to mitigate the flood by slowing down the water flow in a controlled and safe manner. This is achieved by temporarily storing the excess water in designated flood relief compartments within the dam, which is then released gradually with careful control to manage river levels downstream of the dam.

However, during the 2011 flood event, dam operators were forced to open dam gates to maintain a certain level in the reservoir, to avoid overtopping and protect the dam structure (Kearney et al., 2011). According to Maslen and Hayes (2014), increasing the flow into the swollen Brisbane River contributed to downstream flood damage and caused severe harm to the previously unaffected city. I. In fact, a report published by the Queensland Floods Commission of Inquiry authored by Shaw (4 April 2011) , stated that Wivenhoe Dam is a rock and earth-fill embankment dam; it has a clay core and an earthen wall lined on the outside with rocks. Additionally, this structure makes the dam unable to resist the force of the water flowing on its wall. Therefore, retaining a large amount of water in the dam reservoir is considered unsafe..

In the case of overtopping, the earthen dam wall would collapse, and the consequences of its failure would be disastrous for all downstream communities. To avoid such a disaster in the future, 'Seqwater' planned to upgrade Wivenhoe Dam by raising the dam's wall up to 4 meters (News, 2017). However, engineering studies conducted by 'GHD Engineering Consultants' predicted that this upgrade might lead to a major collapse of Wivenhoe Dam, posing a threat to 300,000 people, resulting in the deaths of at least 400 individuals, and causing up to $100 billion in asset damage in the areas behind the dam's wall (ABC News, 2017). More concerning, the same news report also revealed that Wivenhoe Dam, completed in 1984, has not met the National Safety Guidelines for large dams since 2002. Therefore, an additional spillway was constructed at Wivenhoe Dam in 2005, designed to function as a giant rain and flood event pressure valve. This infrastructure serves to safeguard the dam wall and downstream residents from potential threats (SeqWater, 2019c). This step is to prepare the Dam from 1 to 100 years flood event. However, living in an era of climate change and extreme events encourages preparedness. Moreover, long term actions need to be taken to reduce the risks in the Wivenhoe dam area.

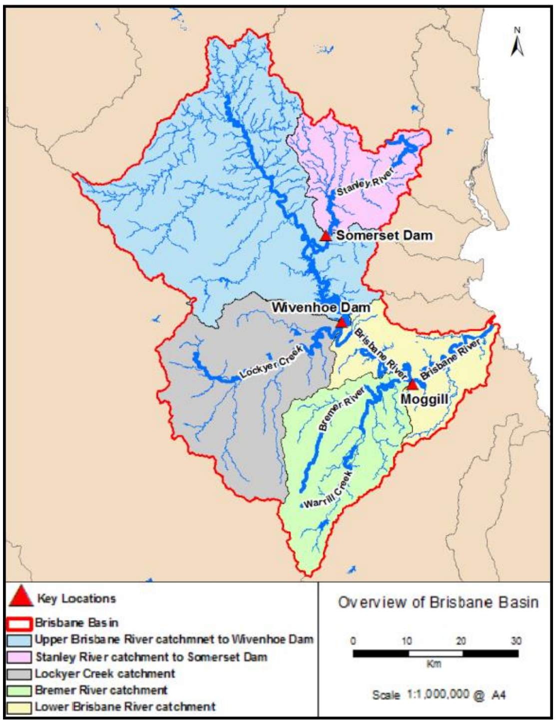

Figure 5. Brisbane River Basin (SEQWATER, 2019a)

2.2 SUPPLEMENTARY DAM AND SITE SELECION CRITERIA

2.2.1 Wivenhoe Dam: Background and Case for a Supplementary Dam

Wivenhoe Dam was designed to provide water supply and flood mitigation benefits during flood events. However, approximately half of the Brisbane River's catchments, including the Bremer River and Locker Creek, lie below the Wivenhoe Dam (see Figure 5). As a result, their flow cannot be controlled. Therefore, in heavy rain events, when there is a need to release water from Wivenhoe Dam to avoid overtopping, a massive amount of water from both the dam and the catchments below will be released towards Brisbane city, potentially causing a new disaster.

According to a report published on the Australia Bureau of Meteorology website, (BOM, 2017), about flood history for Brisbane and Ipswich, during the 1974 flood event, both Brisbane River and Bremer River reached their highest levels since 1893, causing extensive damage; the damage was estimated at about $200 million in 1974, and 14 lives were lost. Meanwhile, in 2011, a massive rain event caused flash floods in Toowoomba and the Lockyer Valley, initiating major river flooding in the Brisbane and Bremer rivers. River levels upstream of Somerset and Wivenhoe dams exceeded the heights of the floods in 1974 and reached all-time highs in some locations (more than 1000mm). The inflows into Somerset and Wivenhoe dams were nearly double that of 1974. Both the Bremer and Brisbane Rivers produced the largest flood heights since the 1974 floods, necessitating the release of excess water to protect the dam wall. Nevertheless, nearly 75% of the state was affected, leading to thousands of evacuations, and the damage was estimated at $15.9 billion (Maslen et al., 2014).

In February 2022, in a shocking event, a major flood occurred with a record higher than the 1974 event, causing more damage than any previous similar events; almost 91% of Brisbane suburbs were affected, with 13 lives lost and a $2.5 billion property damage bill as claimed by the insurance(ABCNews, 2022). This heavy rain event triggered flash floods and increased the inflows into Somerset and Wivenhoe dams. The total dams' storage reached 148.0% and 183.9%, respectively, recording the highest water storage capacity in the history of both dams, which caused the third major flood to hit Brisbane in less than 50 years. The storage history of Wivenhoe Dam showed that a significant amount of water entered the flood mitigation capacity of the dam (183.9% - 100% = 83.9%) on 27 February 2022 (see Figure 6), which then decreased to 91.1% in ten days (7 March 2022) with a massive release at a flow rate of 1251 cubic meters per second (see Figure 7). Reducing such a large volume of water in a short period prompts us to consider where to store this immense amount and how much the dam can withstand in the event of another sudden heavy rain or flood. Additionally, it raises questions about the implications for flooding in the Brisbane area.

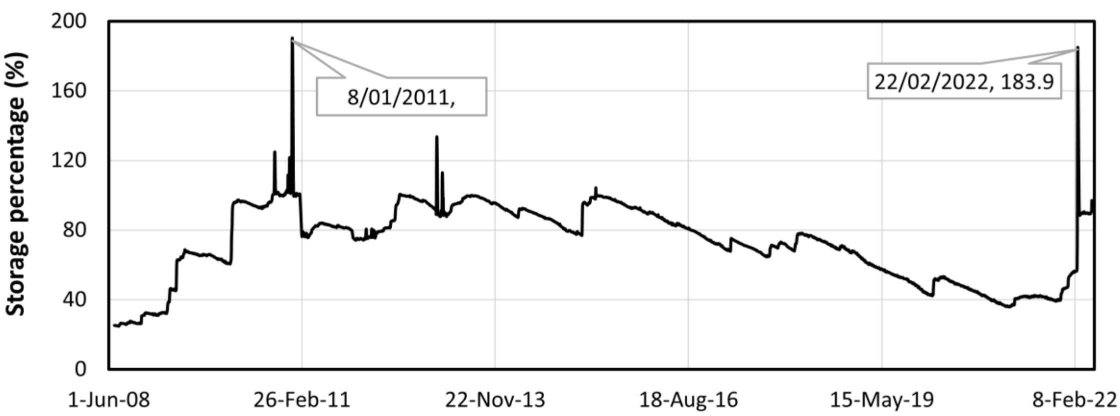

Figure 6: Wivenhoe Dam storage History 2008-2022

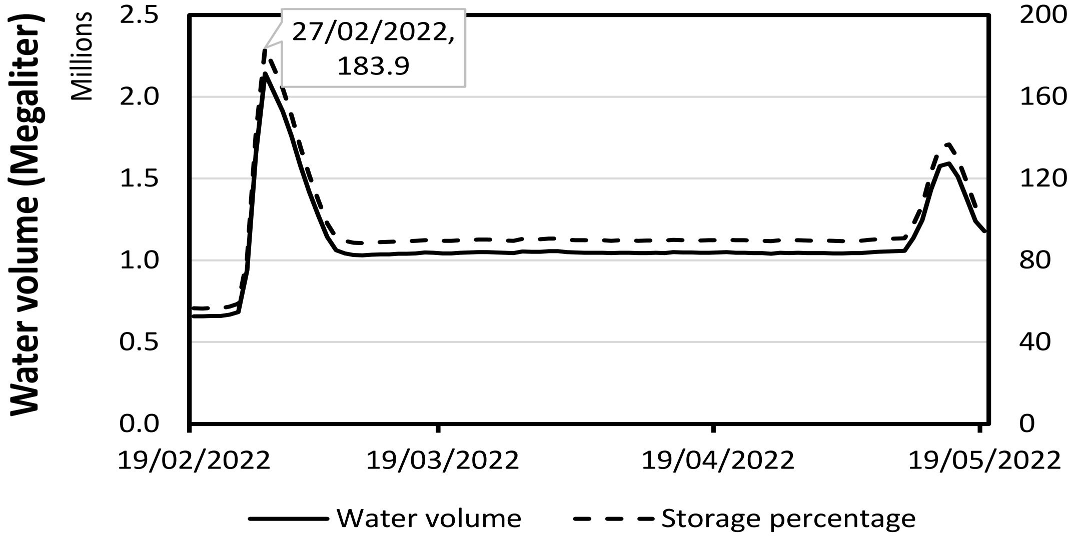

Figure 7: Wivenhoe Dam storage History February to May 2022

Understanding the reasons for the flooding phenomena in the Brisbane area and the inability to control it requires studying the area's topography and hydrostatic nature. The Department of Energy and Water Supply(QDEWS, 2014) stated that water spilled from Wivenhoe Dam takes 26 hours to reach Brisbane city, where downstream it meets Locker Creek along the way. After 16 hours, the combined flow of the Brisbane River and Locker Creek joins the Bremer River near Moggill (see Figure 8). Since there is no control over the water flow downstream of Wivenhoe Dam, these rivers can flood the Brisbane and Ipswich areas. During flood events, dam operators rely on flow measurements from the gauging station at Moggill, where all streams combine, to determine the appropriate amount of water released from Wivenhoe Dam and to reduce the risk of flooding in the Brisbane area. In recent floods, it was observed that significant damage to homes and buildings increased when the combined streams at Moggill exceeded 4,000 cubic meters per second. Severe damage occurs when floodwaters exceed 6,000 cubic meters per second, though damage has been recorded even at 2,000 cubic meters per second. Therefore, dam operators work to minimize flood streams at Moggill by reducing the water released from Wivenhoe Dam, aiming to maintain flood streams at around 4,000 cubic meters per second or less, unless it is unavoidable.

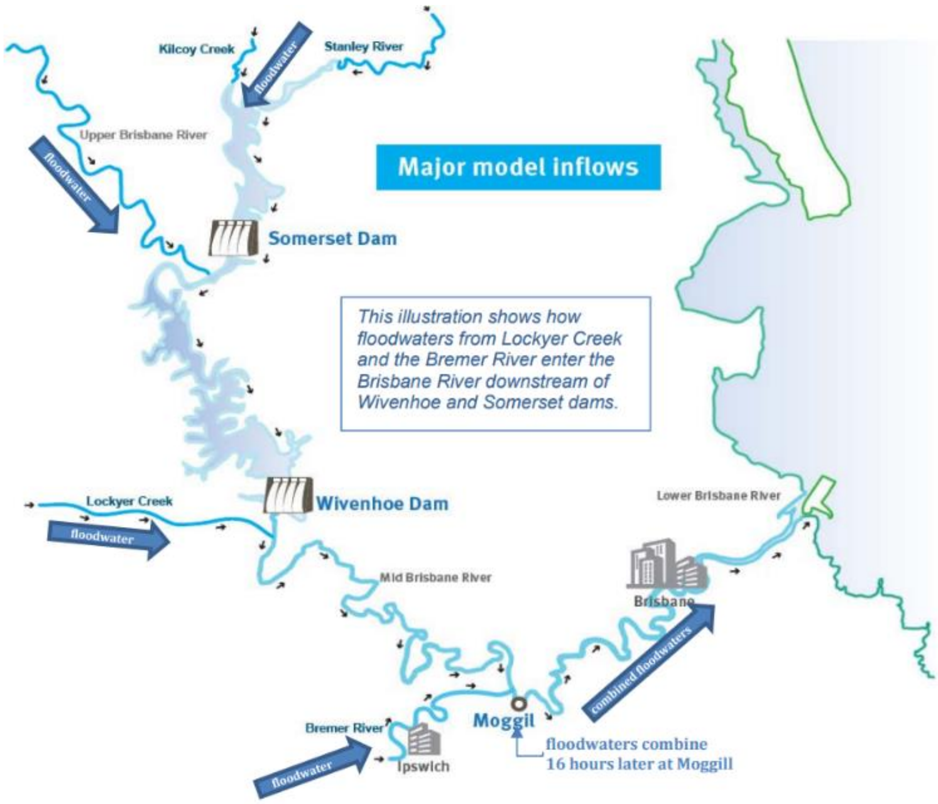

Figure 8: Flow model in Brisbane area (DEWS, 2014)

Controlling the amount of released water might not be feasible during heavy rain events, which puts pressure on the dam wall. Furthermore, an investigation conducted by Maslin, Hayes et al. (2014) showed that the downstream flood would be lower, and damage reduced if the water level at Wivenhoe Dam had been lower at the start of the 2011 flood event. Reducing the water level at Wivenhoe Dam would involve either releasing water from the dam, which would increase the flow into the city. Additionally, it is not possible to build a dam near residential areas for safety purposes (see Appendix A, Study Area).

A second suggestion is to reduce the amount of water entering Wivenhoe Dam by halting the flow upstream of the Brisbane River to mitigate the flood before it reaches Wivenhoe Dam. This location should be distant from residential areas and have sufficient water resources to support the new reservoir (see Appendix A, Study Area).

2.2.2 Dam site selection and criteria decision making

The Geographic Information System (GIS) is an innovative and powerful tool that offers functionality for managing, storing, querying, extracting, and visualizing spatial data across various applications, especially in the context of water resource management(Sayl et al., 2016). According to Abushandi and Alatawi (2015), many data required for dam site selection, such as topography, land use, catchment boundaries, and grid delineation, can be obtained from satellite images. Generally, the Digital Elevation Model (DEM) generated from satellite images can provide slope data—a critical factor in determining flood behavior based on stream flow direction—which serves as input data for GIS. However, it is important to note that the accuracy of the generated DEM can be affected by the low resolution of satellite images (mainly from free-access resources) (Abushandi & Alatawi, 2015). Nevertheless, studies on dam site selection indicate that DEM from free sources can provide a representative simulation of topography (Al-Ruzouq et al., 2019). Over the last two decades, much research has focused on the physical and hydrological aspects of water harvesting using GIS. The effective utilization of Remote Sensing (RS) and GIS based on DEM has facilitated the delineation and selection of potential zones for rainwater harvesting structures(Sayl et al., 2016). For instance, a study conducted in northwest Saudi Arabia in 2015 focused on dam site selection using GIS and remote sensing techniques. The criteria for selecting the best location included catchment slope, land cover type, soil type, and soil infiltration rate (Abushandi & Alatawi, 2015). Furthermore, studies on dam site selection for flood mitigation using RS and GIS combined with decision-making processes have proven to be powerful and valuable tools for finding the optimal dam location, as demonstrated by studies conducted in Surat, India(Raaj et al., 2022), and in the Far Eastern region of Russia(Fedorov et al., 2019). These approaches facilitate the integration of spatial data and offer fundamental perspectives on dam site suitability. Through GIS and remote sensing, specialists can evaluate elements like topography, geology, and terrain features(Al-Ruzouq et al., 2019). In this study, an investigation was carried out in the Upper Brisbane River catchment area using tools like Google Earth Pro, satellite images, and maps from the Brisbane City Council to identify residential areas, flood-prone zones, water sources such as rivers and streams, and areas with narrow terrain. The purpose of this investigation is to determine the best site for the dam wall. Each site was thoroughly examined using QGIS by creating cross-sections of each location for further investigation. Additionally, software-based analysis was used to determine the "Elevation-Volume-Area" relationship, which is necessary to calculate the reservoir's area and volume and to further analyze the dam's efficiency. This method has proven effective in other studies. . It is noteworthy that a study conducted in the western desert of Iraq by Sayl et al. (2016) aimed to choose the location of the dam using the "Elevation-volume-area" method, and the results indicated a remarkable level of accuracy.

2.2.3 Dam wall dimensions and cost analytical process

Dams are major infrastructure projects that incur significant costs. Selecting suitable locations for dam construction depends on several factors, including average water flow, rainfall rates, reservoir surface area and volume, and dam wall type. Additionally, Becue et al. (2002), stated that reservoir storage is one of the main factors influencing the overall dam design, with other important factors including climate, geological, and geotechnical conditions. Becue and colleagues also highlighted that the cost of a primary dam can be significantly impacted by the construction of supplementary structures, such as secondary dams, to enhance reservoir efficiency. These secondary structures, known as saddle dams, are built to support the main dam's reservoir by allowing additional water storage or by limiting the reservoir's expansion.

Constructing a dam is time-dependent on its size and the type of terrain. Steeper terrains are preferable, as they allow dam walls to be perpendicular to river flow. It is essential to reduce the reservoir's surface area and increase its depth to minimize evaporation. According to Becue et al. (2002), the ideal and financially efficient dam location is a narrow site where the valley widens upstream, provided that the dam abutments are sound (i.e., a narrowing without zones prone to rockfalls or landslides). To maximize the benefits of a dam, the volume of water inflow should exceed water loss from sources such as evaporation and seepage.

Petheram et al. (2017) stated that reducing the subsequent calculations assumed at each DEM cell dam, the dam height and width should be restricted to Equation (1), representing the envelope of largest dam construction feasibility.

$$Dams\ side\ area = height \times width < 180000 \qquad \text{Eq. (1)}$$

The Australian National Council on Large Dams (ANCOLD) database showed that Equation (1) was used to calculate the height and length of 560 large dams in Australia and can be adjusted to suit different locations. Moreover, Petheram et al. (2017) highlighted that the cost of 80 large dams were calculated using the equation (2).

$$Dam\ Contruction\ Cost = 0.0039 \times height^{1.5681} \times Width^{0.6148} \qquad \text{Eq. (2)}$$

Where cost in Australian Dollars and both dam height width is in (meters).

To select the best location for a Dam, two main criteria should be considered: the volume of water to the construction cost ratio (GL “gallon” storage per $M) and the yield amount of water to the construction cost ratio (GL yield per $M). River channel and valley size determine the construction cost and water volume. Therefore, an optimised location has to be selected to achieve the highest possible benefit. This process requires accurate surveying for the location.

2.3 SUMMARY

Floods are the most damaging disaster in Queensland, typically occurring in southeastern Queensland. Additionally, the Brisbane River has experienced frequent floods, with records dating back to 1824. Several large flood events have caused severe damage in Brisbane city, notably the 1974 flood event. In response to this event, Wivenhoe Dam, the largest dam in Brisbane, was constructed.The dam is considered the main water supplier for Brisbane city and the greater Ipswich area. However, during the flood events of 2011 and 2022, caused by heavy rain in the catchment area of Wivenhoe Dam, the dam demonstrated limited capacity to contain and mitigate water, revealing its vulnerability to overtopping failure. To reduce the devastating impact of floods in the region, understanding the occurrence of floods is key. The slope of the natural terrain and major water channels in the area contribute to increased flooding toward Brisbane city. A proposal to increase the capacity of Wivenhoe Dam has been rejected due to concerns about potential structural failure. Hence, this study recommends the construction of a supplementary dam to Wivenhoe Dam to share the water load, relieve water pressure on the dam wall, and mitigate flood risk in Brisbane city.

GIS has played a major role in dam site selection in several studies conducted at different sites, demonstrating the effectiveness of GIS and remote sensing in decision-making processes. The integration of GIS with remote sensing (RS) enables effective management, visualization, and analysis of spatial data. While the open-access DEM model provided a good topographic simulation, the Elevation-Volume-Area relationship was used to evaluate the area and volume of the reservoir, proving to be an effective method supported by previous successful applications in other studies, such as the study conducted in the Western Desert of IraqSayl et al. (2016) . The side area of the dam was calculated using equations employed to determine the height and length of 560 large dams in Australia. Meanwhile, the cost of building dams can be calculated based on the equations used to estimate the cost of building 80 large dams in Australia.

CHAPTER 3: SUPPLEMENTARY DAM SITE SELECTION USING GIS-REMOTE SENSING APPROACH: A CASE STUDY OF WIVENHOE DAM

3.1 Introduction

Climate change is the main reason for the increasing intensity and frequency of natural disasters. Flash floods, considered one of the most dangerous natural disasters, occur suddenly due to cyclones or heavy rainfall events, leaving no time for emergency planning. The threat posed by this natural disaster phenomenon to the lives and infrastructure in Brisbane, Queensland, makes developing strategic solutions a priority to reduce recurring damage. Furthermore, dams are considered reliable solutions to mitigate flood events in the catchment area and store excess water for use in drought seasons or to meet increasing water demands.

Determining the right location for dam construction is key for successful flood management planning. In this context, Geographical Information Systems (GIS) technology and Remote Sensing can provide the necessary data and tools for analysis to determine the best location as well as the initial calculations for reservoir yield and suitable dimensions for the dam. The open-access DEM and software like QGIS and Google Earth Pro can demonstrate good results for the initial reservoir capacity and construction cost assessment. While the selection criteria based on the dam wall dimensions, volume-to-area, and volume-to-cost ratios can notably reduce the time and cost of the initial analysis phase when selecting suitable dam locations in the future.

3.2 Submitted paper

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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.

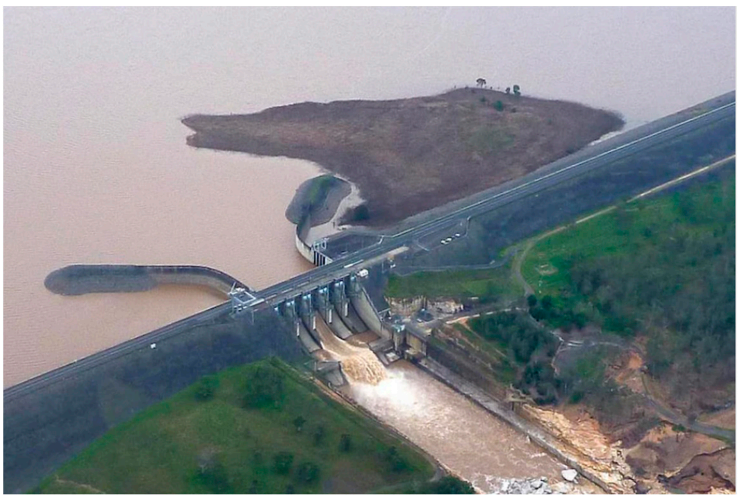


Figure 1. Wivenhoe Dam [16].

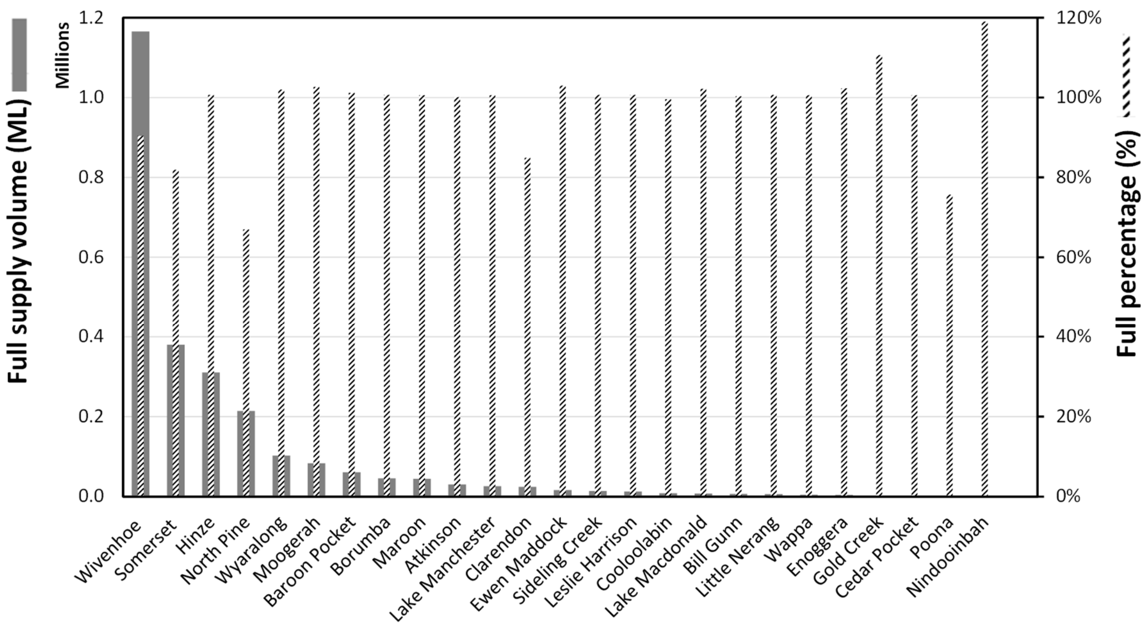


Figure 2. Water storage capacity of major dams in Queensland, Australia (by 8 May 2022).

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.

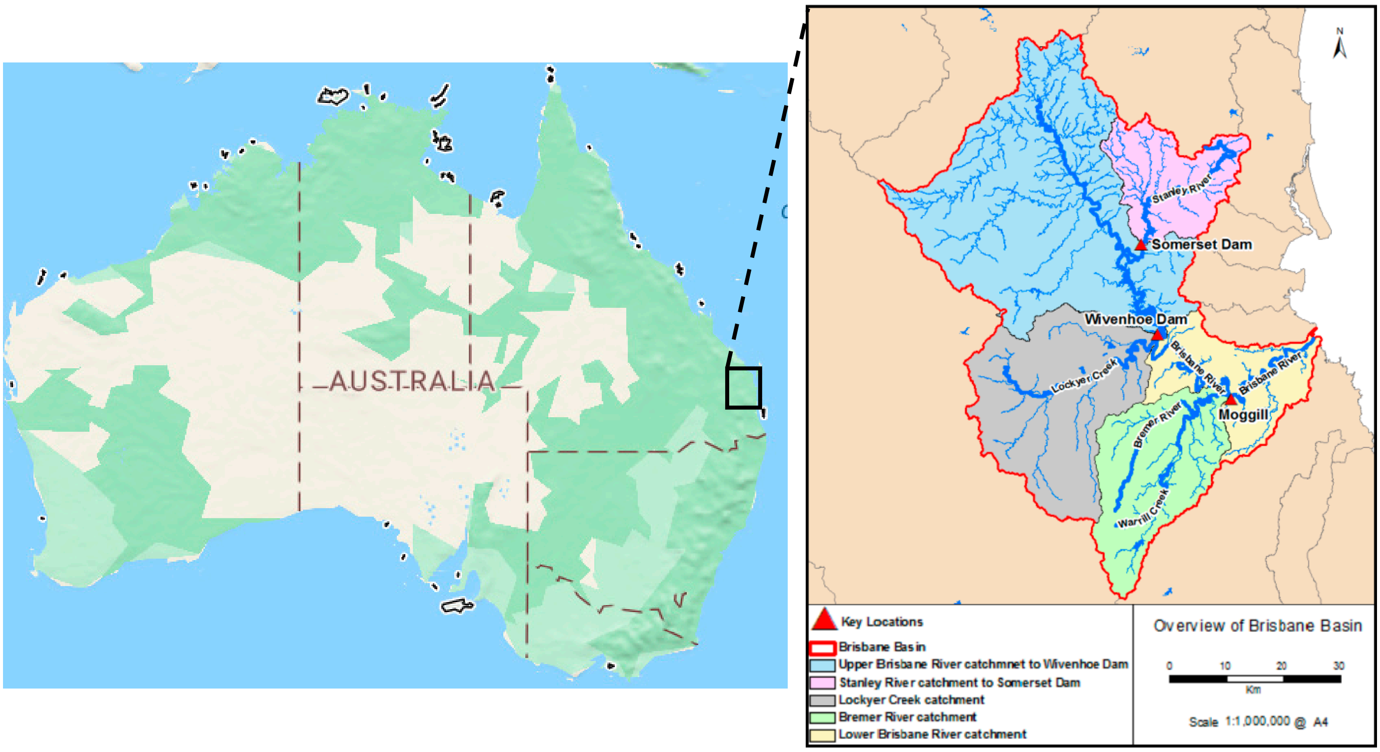


Figure 3. Brisbane City, Australia, and Brisbane Basin [22].

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.

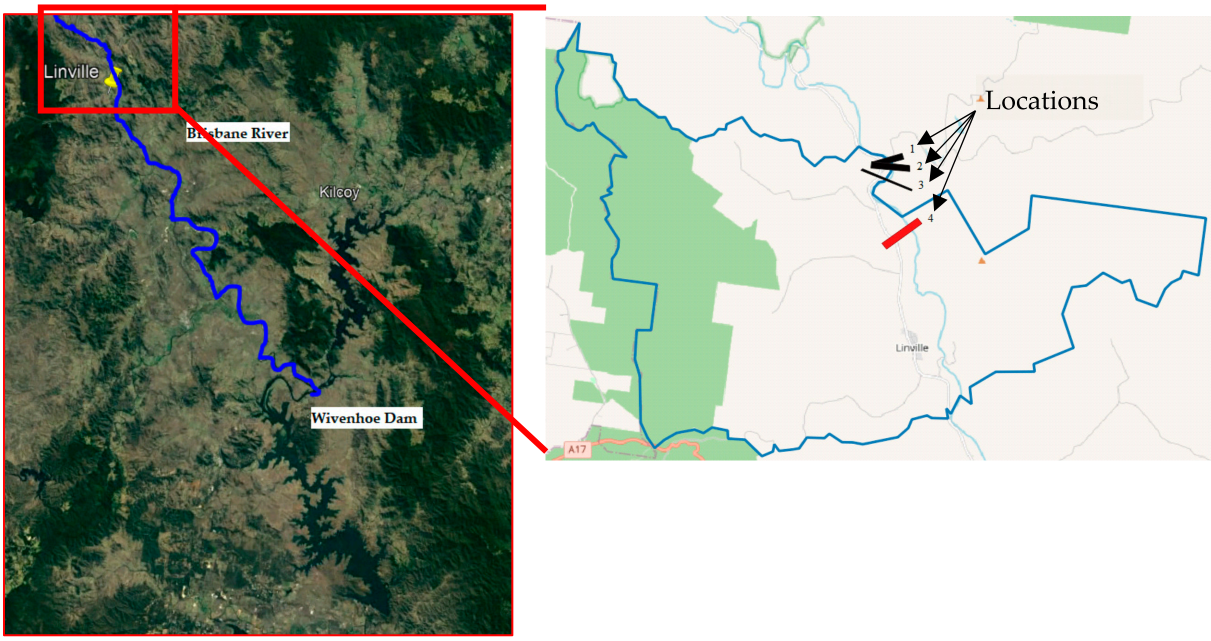
The investigation specifically targeted main streamlines, narrow terrain, and distances from urban centres. Each potential site underwent thorough examination using QGIS software, including the creation of cross-sections for further analysis. Additionally, the EAV curve was developed from a software-based 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.



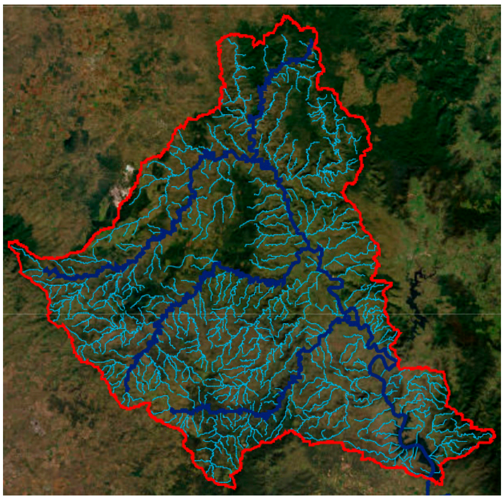
(**a**) (**b**)

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

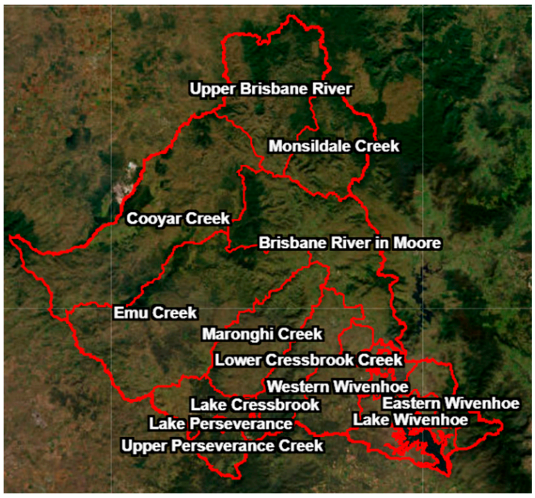
Linville is a rural town located southeast Queensland, within the Somerset Region, which covers an approximate area of 145.0 km^2 and has a population of 133 individuals as of 2021 [27]. The area is known for its sub-tropical climate, characterised by rainfall influenced by various weather systems, including 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.

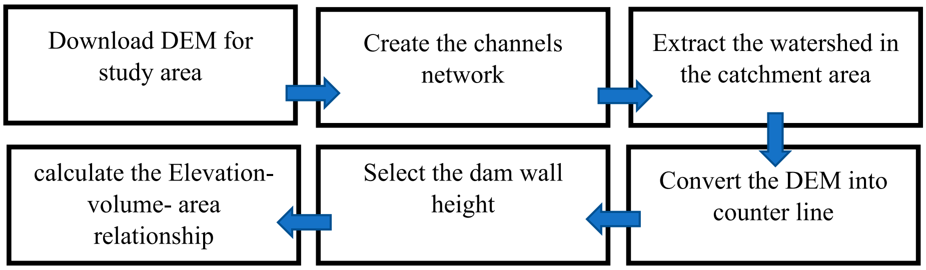


Figure 6. DEM workflow process.

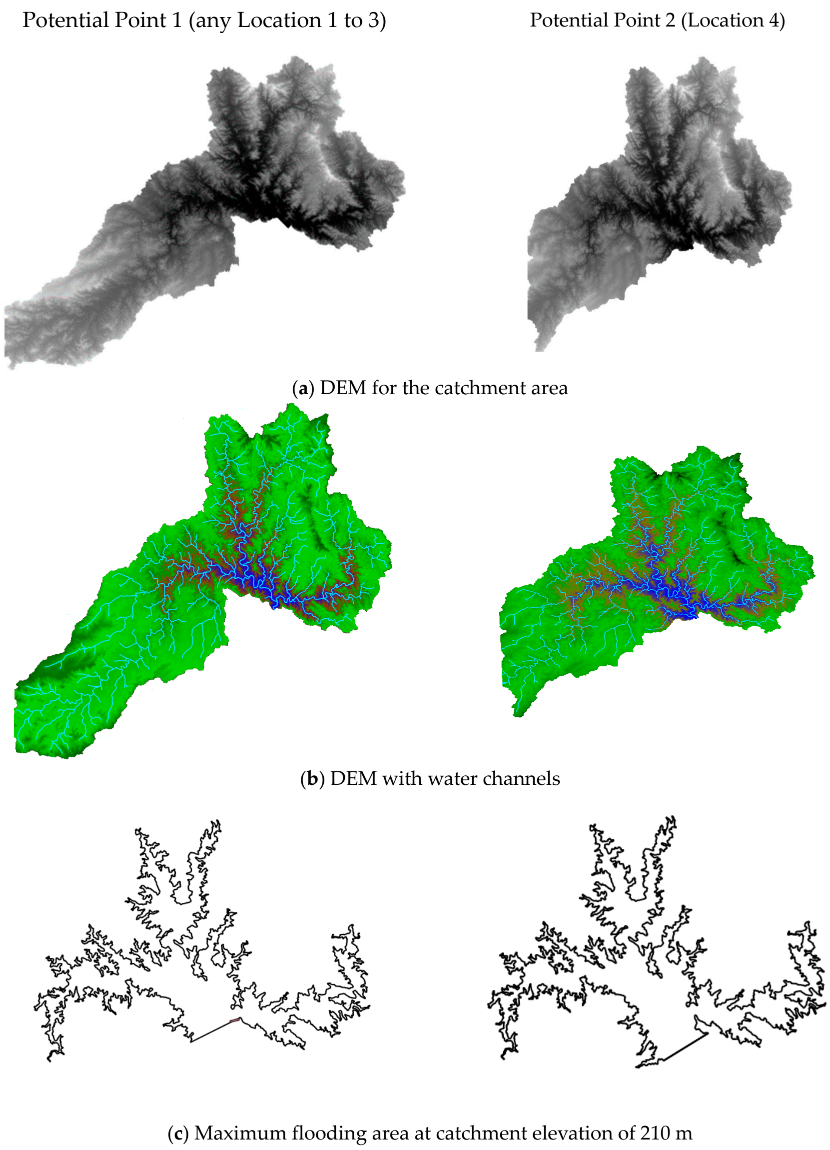


Figure 7. Illustrations of proposed dam wall locations.

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.

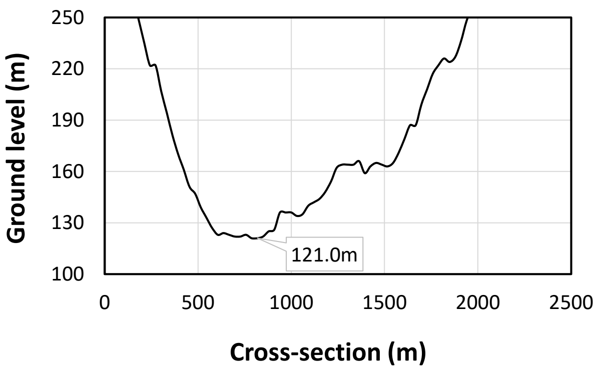
Table 1. Catchment properties of the new supplementary dam at the potential points.

	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

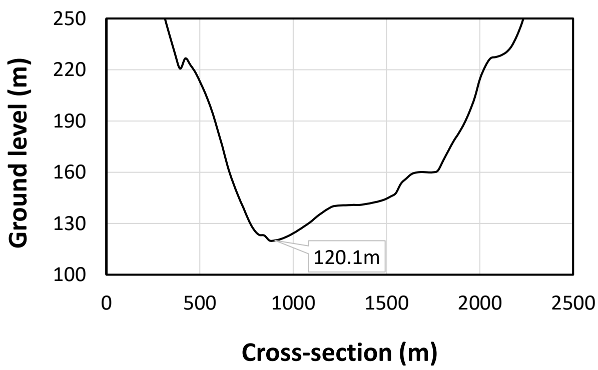
4.2. Topographical Analysis

4.2.1. Optimal Dam Wall Location

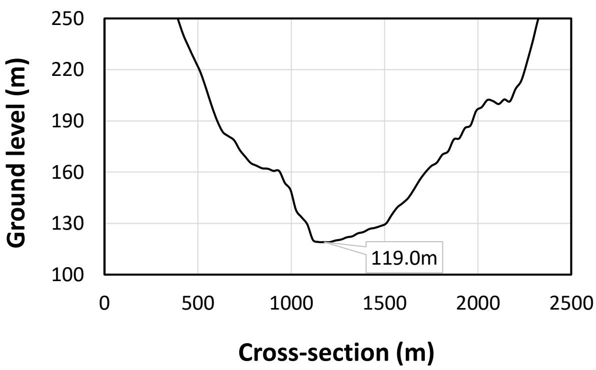
Dam wall size can be used for the optimal selection of the new supplementary dam wall location. Thus, QGIS was relied upon to extract the topographical cross-section of the proposed dam walls at both Potential Points 1 and 2. Figure 8 shows the cross-section of the proposed dam wall Locations 1 to 4 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.



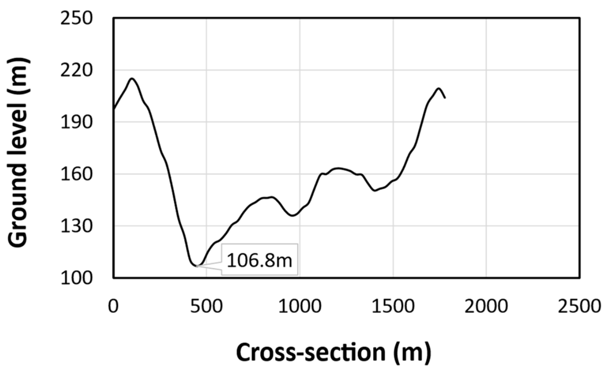
(**a**) Location 1



(**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.

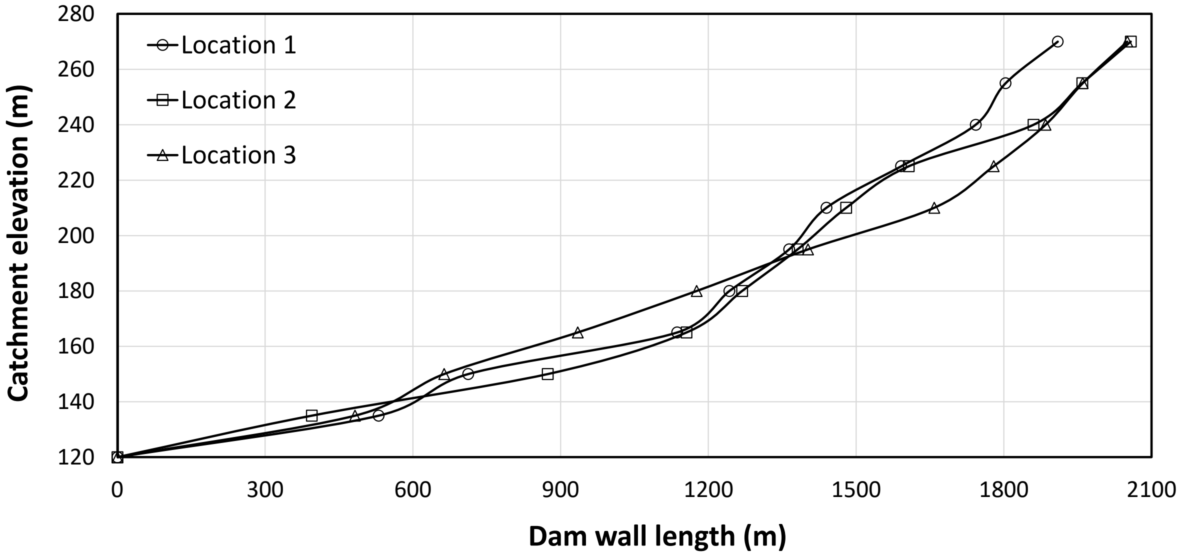


Figure 9. Dam wall dimensions at Locations 1 to 3.

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.

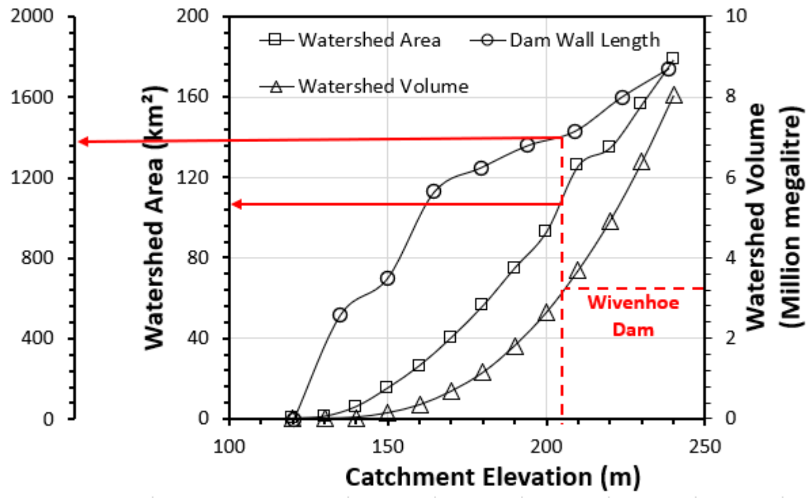


Figure 10. Dam wall length and watershed properties at Location 1.

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 ($\surd$) for satisfactory, ($\surd\surd$) for over satisfactory, and ($\times$) 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	$\surd\surd$	$\surd$	$\surd$	$\times$
Water harvesting efficiency	$\surd\surd$	$\surd$	$\surd$	$\surd$
Dam wall construction cost efficiency	$\surd$	$\surd$	$\surd$	$\surd$

($\surd$) for satisfactory, ($\surd\surd$) for over satisfactory, and ($\times$) 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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CHAPTER 4: CONCLUSIONS

3.1 Conclusions

In response to climatic changes, this study explores opportunities to mitigate flood events and prevent potential overtopping failure in Wivenhoe Dam, the largest dam in Brisbane, Queensland, Australia, where flood events have become frequent in southeast Queensland, mostly caused by heavy rainfall in the catchment area. This was achieved through optimal site selection for a new supplementary dam, assisted by satellite images, Google Earth Pro, QGIS, and DEM. The initial mapping used Google Earth Pro and data from governmental websites like Brisbane City Council, the Bureau of Meteorology, and the Queensland Reconstruction Authority to detect flooding areas and water streamlines, focusing on the Brisbane River and the area near Wivenhoe Dam. The results showed that the area upper Linville has the ideal topography for constructing the new supplementary dam, with four potential locations suitable for constructing the dam wall. All options had suitable narrow terrains and water streamlines, ensuring the best water harvesting. The proposed locations were examined 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 study area was cut and filled to avoid depression in the digital surface. The main streamlines were extracted, in addition to the watershed area. The maximum flooding area was determined, and the Elevation-Volume-Area curve was calculated. Furthermore, cross-sections of the potential dam walls were extracted. With the aid of watershed volume, dam side area, and the cost of dam wall construction, less feasible options were excluded. The selection criteria, based on parameters such as water volume, water harvesting efficiency, and dam wall construction cost efficiency, allowed for a comparison among different locations to determine the optimal one. Nevertheless, all proposed options revealed at least a 48% reduction in the new dam wall length at the same dam wall height compared to Wivenhoe Dam.

The study suggests the construction of a highly efficient and cost-effective dam, which would become the new largest dam in Queensland, with a 200% increase in the watershed volume compared to Wivenhoe Dam, and 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 that can aid decision-makers with sound evidence for the next steps towards constructing this supplementary dam as a precautionary plan to secure Wivenhoe Dam from potential failure risk.

3.2 Recommendations

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

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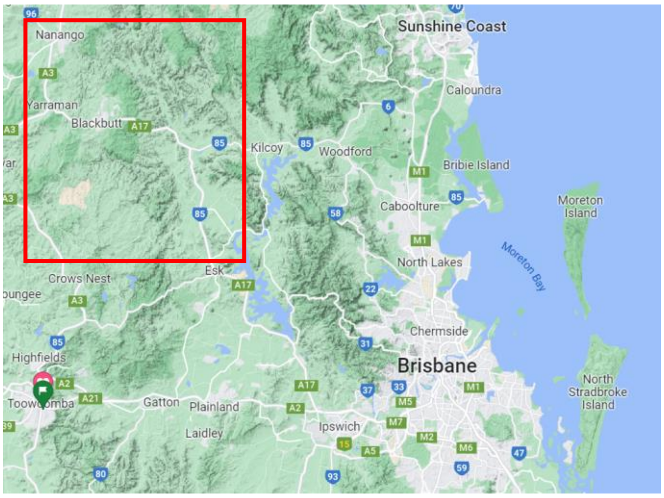
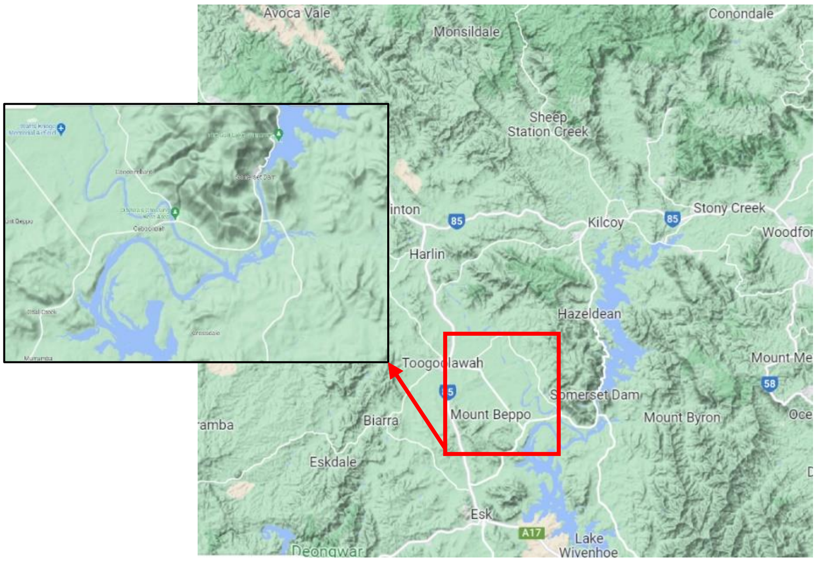
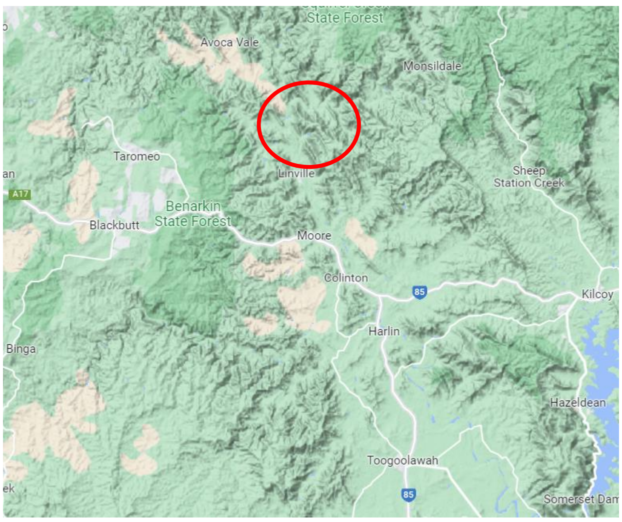
APPENDIX: A Satellite Images for study area



(a) Study area



(b) The upper stream of Brisbane River



(c) The reservoir area