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Editorial

This Volume 46 Number 1 is a Special issue published for the 7th Water Efficiency Conference (WATEF 2022), that was held at the Faculty of Engineering, The University of the West Indies, Saint Augustine Campus, Trinidad and Tobago on 14th-16th December 2022. The conference proceedings included invited keynote and feature speeches, scheduled professional/technical presentations, and panel discussions, all addressing various topics and areas associated with the conference theme, "Water Resources Resilience for Small Island Developing States (SIDS)". After a rigorous peer review process, published in this issue are seven (7) manuscripts that demonstrate a set of quality contributions originated from the Conference. Besides, an excerpt of abstracts of the presentations are included. The articles included in this issue are summarised below.

J. Gibberd, "School Rainwater Harvesting Decision Support Tool", explored how rainwater harvesting system could help address water shortages by providing a safe alternative source of water in schools. A simple modelling tool called the School Water and Rainwater Use Modeller (SWARUM) was developed. The tool was applied to case study schools in water-scarce areas of Southern Africa. It could generate graphs of water consumption and rainwater harvesting over a year, and enable interventions such as more efficient use of water, increasing rainwater collection surfaces and the use of dry sanitation. Results showed that the modeller could support increased awareness and enable decision-making about water and rainwater harvesting systems by schools and the department of education. Besides, a simple manual could be developed.

In their article, "Advanced Photo-Oxidation Process for Treatment of River Water Pollutants and Pathogens", **R. Ramkissoon** et al., employed two techniques, photocatalytic semiconductor, and photo Fenton, as an enhanced oxidation process to get rid of diverse water impurities and offer a reliable water treatment approach. A test on samples of river water was undertaken, the analysis of number of parameters was used to determine the removal of contaminants and pathogens. The physiochemical criteria were used to evaluate the reaction using both approaches. The two techniques effectively eliminated between 80 and 100 percent of the contaminants that were detected in the river sampled. Variations in Titanium Dioxide concentration correlated with changes in reactivity and degradation rates. Besides, the rate of degradation was directly correlated with light intensity.

R. Ragoobir and **R. Bachoo**, "Cumulative Fatigue Damage of Small-Bore Piping Subjected to Flow Induced Vibration", investigated the structural fatigue of a vertically oriented small-bore connection due to flow induced turbulence emanating from an upstream piping manifold. From the experimental analysis for single phase water, the largest bending stresses were due to the out-of-plane vibration of the small-bore piping. The pulsating characteristics of the single-phase air and multiphase flow resulted in significantly larger in-plane bending stresses. Results also showed that through a series of parametric analysis, there existed a minimum support stiffness for which the fatigue life of a small-bore connection excited by flow induced vibration, achieves its upper bound value.

P.N. Felix, "Potential Impact of Oil Spills in Coastal Waters on Water Supply", investigated a seawater surface oil spill using numerical mathematical modelling to model the spill's movement underwater in the Gulf of Paria, south-west coast of Trinidad. Depending on key parameters of the oil and the current ambient conditions, an oil plume could travel significantly long horizontal distances underwater before destabilising. Inferences suggested that oily underwater and existing ambient conditions could potentially affect the desalination equipment. It was advocated that oil spill modelling is necessary to determine oil trajectory and further inform the decision-making process in determining the best location for constructing desalination plant.

In the fifth article, "The Impact of Climate Change on the Upper Navet Reservoir, Trinidad", **R. Baboolal** and **V. Cooper** evaluated the potential impacts of climate change on the Navet Reservoir using the Soil Moisture Accounting algorithm in Hydrologic Engineering Centre Hydrologic Modelling System with continuous simulations. The selection of model parameters was based on previous work on the nearby hydrologically Nariva catchment. The model was subject to a split-sample test with a calibration period of 24 months (2003-2004) on a daily time-step followed by validation over a period of 60 months (2005-2009). The validated model was used to evaluate the system's response to climate change. The results of simulations conducted for the period 2030-2096 showed that for continuous operation, production rates at the Navet reservoir would require a 40% reduction of present values for two of these scenarios and 30% for the most optimistic scenario.

V. Maraj et al., "Optimal Design Storm Frequency for Flood Mitigation in the North Valsayn Community of Trinidad", investigated two (2) economic approaches to determine the level of protection for flood mitigation works within the North Valsayn community of Trinidad. For both the Cost per Inhabitant (CPI) approach and the Hydroeconomic Analysis (HEA) approach, work was done to (i) Identify flood hazards using a calibrated 2D hydraulic model, (ii) Assess the community's vulnerability by developing a Flood Damage curve, (iii) Identify flood mitigation works for various design storm frequencies, and (iv) Determine the life cycle cost for implementing the design various design solutions. The study showed a disparity in defining a project's budget and the Optimal Design Storm Frequency in the industry.

Challenges in the water supply are a consequence of obsolete pipelines, numerous leaks, failure of mechanical equipment and a shortened duration of supply. **G. Davis**, "Water Distribution Challenges in Northeast Trinidad and Tobago", identified the inefficiencies and challenges of the water distribution system in the areas. She simulated flow through crucial transmission and distribution pipelines using ANSYS Fluent simulation. The Hazen-Williams equation was used to calculate frictional pressure loss in the respective crucial pipelines. Using the results from both analyses, prospective solutions to alleviate and eliminate the inadequate water supply experiences faced by customers in these areas were advocated.

Moreover, **K. Adeyeye** and **K. Tota-Maharaj,** excerpted abstracts of the 28 papers/presentations of the WATEF 2022 Conference that provided a forum of authors and presenters from various universities, research centres and industry to showcase their projects, share their ideas, knowledge and experiences on pertinent issues on water and the environment. Academics and professionals across the water, wastewater and environmental industries and various sectors need to stay on the cutting edge to face the challenges of the future.

On behalf of the Editorial Office, we gratefully acknowledge all authors who have made this issue possible with their research work. We greatly appreciate the voluntary contributions and unfailing support that our reviewers give to the Journal. Our reviewer panel is composed of academia, and practicing engineers and professionals from industry and other organisations as listed below:

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Lastly, this current issue includes a 'Call for Papers' for *The Caribbean Academy of Sciences 23rd Biennial Conference 2023* (CAS23-2023) that is to be held at The University of the West Indies - St. Augustine Campus, Trinidad and Tobago, on 24th-25th November 2023. With the theme, "Sustainability and Development Initiatives of the Caribbean", the Conference aims to revive, establish, and sustain knowledge production, sharing, and collaboration around sustainability and development in the region and beyond. Original abstracts and papers relevant to the Conference theme are invited. Deadlines for submissions have been extended.

The conference's sustainable development theme is in line with the WIJE's Editorial Aim and Policy. The UWI-Faculty of Engineering, via the Industrial Engineering Office, serves as a co-organiser of the CAS23-2023 Conference. Strong papers from the conference would be recommended for a fast-track publication in WIJE, subject to its review process.

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School Rainwater Harvesting Decision Support Tool

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Abstract: *Climate change has meant that many schools in hot and dry areas are increasingly experiencing water shortages. This can affect the health of students and teachers, disrupt education and in the worst case, lead to school closures. Rainwater harvesting can help address water shortages by providing a safe alternative source of water. However, there is limited guidance on how rainwater harvesting systems can be applied to schools resulting in schools not being aware of the potential of rainwater harvesting systems. There is a need, therefore, for a simple tool that can be used by schools to understand rainwater harvesting systems. This study aims to address this gap by developing and testing a simple modelling tool called the School Water and Rainwater Use Modeller (SWARUM). The tool is presented and applied to case study schools in water-scarce areas of Southern Africa and the findings are critically evaluated. The study finds that the modeller can be used to support decision-making about rainwater harvesting systems at schools and makes recommendations for the improvement of the tool.*

Keywords: *Schools, rainwater harvesting, School Water and Rainwater Use Modeller*

1. Introduction

Climate change is resulting in increased temperatures, long dry spells and the occurrence of droughts and water scarcity in many areas (Diedhiou et al., 2018; Makki, 2015; IPCC, 2022). Rapid urbanisation exacerbates this problem by placing additional demands on existing water supplies that are already struggling to meet demands (UN-Habitat and IHS-Erasmus University, 2018). Limited capacity and resources in water utilities and municipalities mean that water infrastructure may not be maintained resulting in increased leakage and unreliable supplies (Wensley and Mackintosh, 2015; SACN, 2014). This combination is leading to unreliable water supplies and shortages in many areas.

A lack of water in schools has severe consequences and can lead to closure as they cannot function without drinking water, water for cleaning and water for flushing toilets (Jasper and Bartram, 2012). The closure of schools, even for a short time, has negative impacts on teaching and learning and the ability to achieve required education outcomes. Prolonged closures can affect whole communities as poor education achievement negatively affects students' access to employment opportunities.

Large-scale interventions can be carried out to improve the resilience of municipal water supplies, such as increasing locally stored water (Gibberd, 2017). However, these interventions require significant resources and capacity and may take a considerable time to implement. It is, therefore, important that schools investigate what they can do themselves to improve the reliability and resilience of their water supplies. While water efficiency measures and greywater systems can radically reduce water consumption at schools, a reliable water source is still required. Boreholes can be used as an alternative water source but are often expensive to drill and maintain and usually require statutory permission. Onsite water storage and rainwater harvesting are therefore one of the few effective ways that schools can address unreliable water supplies. Rainwater harvesting systems can be used to reduce the reliance of the school on external water supplies and enables the school to run for a part, or all, of the school year, on their supply.

However, there is limited guidance on rainwater harvesting at schools. Many schools are not aware of rainwater harvesting systems as a potential solution to water problems they have such as unreliable supplies and rapidly escalating water costs. Schools do not have ready access to tools that enable them to ascertain the impact that rainwater harvesting systems can have. This study addresses this gap by developing, presenting and testing a simple rainwater use modeller for schools. The modeller is designed to enable a school to understand key characteristics of water consumption and rainwater harvesting at a school and try out different options to improve the sustainability of their water systems. To test the proposed modeller, it is applied to two case study schools and the results are analysed to ascertain the value of the tool and approach.

2. Literature Review

Climate change, combined with rapid urbanisation and limited resources and capacity has meant that water

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supplies in many cities are becoming increasingly constrained and unreliable. For example, urbanisation in Africa is likely to result in average urban growth rates of 3.9% to 2050 (Bahri et al., 2016). This growth will largely happen in smaller towns with limited infrastructure where new water supplies will be required (Bahri et al., 2016; South African Cities Network, 2014). At the same time, increased densities and populations in existing suburbs, as well as changing lifestyles, will lead to increased water consumption rates (Popkin, 2006).

Water utility companies and municipalities already struggling to keep up with this demand are also faced with ageing infrastructure and significant losses through leakage (South African Cities Network, 2014; Wensley and Mackintosh, 2015; Bahri et al., 2016). These pressures mean that water supplies, especially in drier areas, will continue to be severely constrained and may be unreliable for the foreseeable future. It is therefore important that local water supply systems such as rainwater harvesting are developed to reduce the pressure on mains water supply systems and to improve the reliability of water supply to users.

2.1 Rainwater Harvesting Systems

Rainwater harvesting systems appear to offer a valuable way of addressing many of the pressing water problems that are being faced by households, organisations and cities. Ghaffarian Hoseini et al. (2016) argue that rainwater harvesting could make a very significant impact on housing and that these systems could meet 80–90% of overall household water consumption globally. Similarly, work by Steffen et al., 2012 confirms that the widespread installation of rainwater harvesting systems in cities can be used to avoid the need to construct new centralised water supply systems.

Despite the clear benefits that can be derived from rainwater harvesting systems, these systems have not been widely adopted and used to address unreliable water supply systems. The slow uptake of rainwater harvesting systems has been attributed to the following factors. First, there may be little awareness of rainwater harvesting systems and how effective they can be in addressing water problems, which has affected their uptake (Akuffobea-Essilfie et al., 2020; Sheikh, 2020). Second, where there is awareness, there may be perceptions that rainwater harvesting systems are expensive and unaffordable (Rahman et al, 2014; Campisano et al., 2017; Akuffobea-Essilfie et al., 2020). Third, there are concerns about the quality and safety of water from rainwater harvesting systems (Rahman et al, 2014; Fewtrell and Kay, 2007). Four, concerns about building regulations and the maintenance of rainwater harvesting systems may deter adoption (Campisano et al., 2017).

Once rainwater harvesting systems have been installed, research indicates that users tend to be strongly supportive of the technology (Gould,1997; Fuentes-Galván et al., 2018; Sunkemo and Essa, 2022). There are distinct differences in the way rainwater harvesting systems are used in different countries (Cook, et al., 2013). In ‘water-rich’ developed countries, rainwater harvesting systems tend to be used as a backup to mains systems. In dry developing countries, rainwater harvesting systems are more often the primary supply as there may not be an alternative supply (Cook, et al., 2013). There are also differences in the way organisations use rainwater harvesting systems. Kerlin et al. (2015), for instance, show how schools use rainwater harvesting systems as a learning resource.

2.2 Rainwater Harvesting Guidance, Tools and Modellers

The adoption of rainwater harvesting systems can be enhanced by guidance, modelling tools and supportive regulations (Domenech and Saurí, 2011; Campisano et al., 2017). These aim to ensure that rainwater harvesting systems are correctly designed and are safe and easy to use.

Rainwater harvesting modellers tend to be based on the following four components (Campisano et al., 2017). First, a behavioural model is developed based on water demand. This model is used to project water flows out of the system over time (water used patterns) and may be based on water consumption benchmarks and norms, manufacturers’ data sheets as well as metered data.

Second, a rainwater model is developed to represent rainwater captured over time from catchment surfaces. Flows are based on climate data or local rainfall records as well as the size and type of catchment area and the design of the system and take into account losses due to runoff, filtration and overflows.

Third, a calculation module simulates volumes of water in the rainwater tank. This indicates the balance between the water used and rainwater captured over time and is used to represent the volume of water in the tank.

Fourth, data from the three components are presented so that water inflow and outflow patterns can be discerned and understood. Ideally, modellers enable different options, such as increasing catchment areas or reducing water consumption can make, to be tested and their impact ascertained (Campisano et al., 2017).

3. Methodology

The methodology developed for the study addresses the following research questions:

1) How can a school rainwater harvesting modeller be developed?
2) What can a school rainwater harvesting modeller be used for?
3) Is a school rainwater harvesting modeller useful in supporting decision-making in schools?

To answer the first question an integrative literature review is undertaken. This is used to develop the school rainwater harvesting modeller, called the School Water and Rainwater Use Model (SWARUM). Integrative literature reviews are used to analyse empirical findings from previous research to develop new models (Tranfield et al., 2003). An integrative approach is used as this enables literature and data from a range of sources to be used to develop new models (Snyder, 2019). The keywords 'rainwater water harvesting' and 'schools' were used to identify journal articles relevant to the study and were used to develop a specification for a school rainwater harvesting modeller and a tool that met this specification. The proposed modeller was developed in Microsoft Excel as this tool supports rapid development and testing. This software is also available in most schools who can also open Excel files in open-source software.

To answer the second question, the SWARUM is applied to case study schools in different climate regions. The following criteria are used to determine the case study schools; a) the school must be in an area that experiences water shortages b) the schools must be in different climatic zones and c) data on the climate and schools must be available and accessible. The schools selected are in the Eastern Cape and Gauteng, South Africa. Both areas while in different climatic zones that have experienced significant water shortages in the last 5 years. Data on local climate and schools was gathered through online databases and tools (such as Google Maps) and visits. To test what the modeller can be used for, 4 interventions were identified and developed for each school. These interventions represent practical measures that could be adopted by a school facing water shortages and go from the simple (do nothing) to the more complex and expensive interventions which include large-scale rainwater harvesting systems and water-less toilets. Interventions have also been designed so that they can be progressively adopted to enable a school, over time, to use these to become off-grid for water. The interventions are outlined below.

- *Intervention 1*: Use the existing school roofs for rainwater harvesting.
- *Intervention 2*: Use existing school roofs for rainwater harvesting, and reduce water consumption through increased efficiency including reducing washing water per occupant from 6 to 4 litres and reducing WC flush rates from 6 to 4 litres and urinal flush rates from 2 to 1 litre.
- *Intervention 3*: Use existing school roofs for rainwater harvesting, reduce water consumption through more efficient fittings, and increase the rainwater harvesting collection area by 50% by including yard hard surfaces.
- *Intervention 4:* Use existing school roofs and hard surfaces for rainwater harvesting, reduce water consumption through more efficient fittings, and install waterless sanitation. This means that all water associated with water-borne sanitation is reduced to zero.

To answer the third question, the modeller was used to determine the impact of these interventions and the extent to which data generated could be used to support school decision-making. A critical review is used to identify the advantages and disadvantages of the modeller and makes recommendations for further development.

4. School Water and Rainwater Use Modeller (SWARUM)

The literature review was used to develop specifications for the modeller. These are outlined in Table 1 with the specifications on the right and the source on the right. The School Water Use Rainwater Modeller (SWARUM) was developed to respond to this specification and is shown in Figure 1. It has three parts: the input section, the table report and the graphic report.

To use the modeller, inputs are required in the light blue areas. These elements as well as outputs, shown in Figure 1, are explained below.

- *School name*: The name of the school is entered here.
- *School address*: The address of the school is entered here.
- *The number of female and male occupants*: The number of female and male occupants at the school is entered. This includes students, teachers and school staff, such as administrators.
- *School year*: This is the number of days the school is occupied by students and staff over a year. This is the sum of the days occupied each month which is shown in the table section.
- *Drinking water per occupant*: The amount of drinking water used per occupant is indicated here. This can be based on studies at the school or a norm, such as 2 litres per day per person (Meinders and Meinders, 2010).
- *Cleaning and washing water per occupant*: The amount of cleaning and washing water used per occupant is indicated here. This can be based on

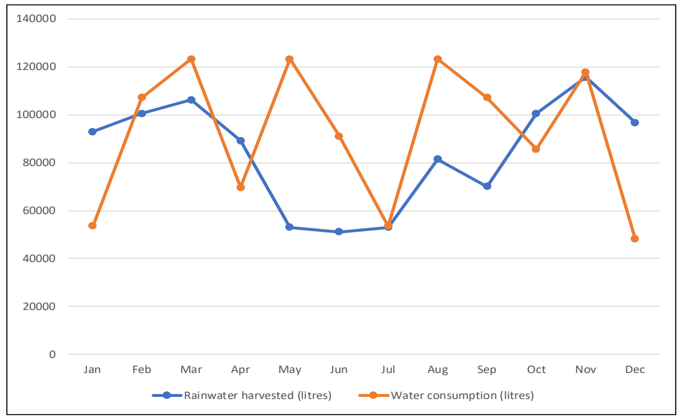
Table 1. Modeller Specifications Derived from Literature

Specification	Sources
1. The modeller must be very simple to use and be readily understandable by teachers, students and school governing bodies	Akuffobea-Essilfie et al., 2020; Sheikh, 2020
2. Data used in the modeller must be readily accessible and easy to input.	Campisano et al., 2017; Kerlin et al. (2015)
3. The modeller should enable users to model: a) A simple rainwater harvesting system at a school and understanding the patterns of rainwater production over a year. b) How different factors including behaviour, management and efficient fittings within water use and catchment area within rainwater harvesting systems can be used to improve performance.	Akuffobea-Essilfie et al., 2020; Sheikh, 2020; Campisano et al., 2017; Domenech and Saurí, 2011;

School Water and Rainwater Use Modeller

School name	Case Study School
Address	Loerie, Eastern Cape, South Africa

Female occupants	105	number
Male occupants	105	number
School year	206	days
Drinking water per occupant	3	litres
Washing water per occupant	6	litres
Water consumption per WC flush	6	litres
Water consumption per urinal flush	2	litres
Collection surface area for rainwater harvesting	2106	m2
Collection surface runoff factor	0.9	
Water consumption per occupant per year	5,253	litres/yr
Water consumption per occupant per day	26	litres/day/person
Water consumption per occupant per day		
Rainwater harvested per collection surface m2	480	litres/year
Volume of water deficit (figures in orange)	-214,922	litres/year
Percentage of water needs met from rainwater	84	%



Month	Rainwater harvesting				Balance	School water consumption							
Month	Rainfall (mm/month)	Collection surface (m2)	Runoff factor	Rainwater harvested (litres)	Surplus/deficit (litres)	Consumption (litres)	Days (premises occupied)	Female (staff and students)	Male (staff and students)	Drinking (litres per person)	Washing (litres per person)	WC (litres per flush)	Urinal (litres per flush)
Jan	49	2106	0.9	**92,875**	39,325	**53,550**	10	105	105	3	6	6	2
Feb	53	2106	0.9	**100,456**	-6,644	**107,100**	20	105	105	3	6	6	2
Mar	56	2106	0.9	**106,142**	-17,023	**123,165**	23	105	105	3	6	6	2
Apr	47	2106	0.9	**89,084**	19,469	**69,615**	13	105	105	3	6	6	2
May	28	2106	0.9	**53,071**	-70,094	**123,165**	23	105	105	3	6	6	2
Jun	27	2106	0.9	**51,176**	-39,859	**91,035**	17	105	105	3	6	6	2
Jul	28	2106	0.9	**53,071**	-479	**53,550**	10	105	105	3	6	6	2
Aug	43	2106	0.9	**81,502**	-41,663	**123,165**	23	105	105	3	6	6	2
Sep	37	2106	0.9	**70,130**	-36,970	**107,100**	20	105	105	3	6	6	2
Oct	53	2106	0.9	**100,456**	14,776	**85,680**	16	105	105	3	6	6	2
Nov	61	2106	0.9	**115,619**	-2,191	**117,810**	22	105	105	3	6	6	2
Dec	51	2106	0.9	**96,665**	48,470	**48,195**	9	105	105	3	6	6	2
	533			**1,010,248**	**-92,882**	**1,103,130**	**206**						

Figure 1. School Water and Rainwater Use Modeller (SWARUM)

studies at the school and would include washing hands after using the toilet and meals, cleaning cooking and eating utensils, as well as building cleaning (such as mopping floors). A guideline of 2-5 litres in water-restricted areas can be used.

- *Water consumption per WC flush*: The amount of water each time the toilet at the school is flushed that is indicated here. Flush rates can be obtained from the manufacturer or physically measured by measuring the amount of water required to fill a toilet cistern after a flush. Flush rates vary between 9 and 3 litres per flush, with most modern toilets having a flush rate of 6 litres per flush (Aurelien et al., 2013).
- *Water consumption per urinal flush*: This can be obtained from the manufacturer or measured by placing a container under the flushing mechanism and measuring the amount of water per flush. Urinal flushes vary between 1 and 2 litres per flush (Aurelien et al., 2013)
- *Rainwater collection surface*: The rainwater collection surface is the area used to collect rainwater. This may include roof surfaces and hard surfaces such as tennis and netball courts.
- Runoff factor of rainwater collection surface: The runoff factor relates to the type of material of the collection surface. As the school buildings have sloping corrugated metal roofs, a factor of 0.9 is used (Farreny et al., 2020; Goel, 2011).
- *Water consumption per occupant per year*: This provides the amount of water consumed at the school by each occupant over a year. It is calculated by dividing the total amount of water consumed by the school divided by the number of occupants.
- *Water consumption per occupant per day*: This provides the average amount of water consumed at the school by each occupant per school day. It is obtained by dividing water consumption at the school by the number of occupants and the number of school days.
- *Rainwater harvested per collection surface m^2*: This provides the amount of rainwater captured by each square metre of the collection surface.
- *The volume of water deficit* (figures in orange): This provides water volume of the water deficit which is the volume of water consumed minus the volume of water captured and indicates the amount of water that will be needed to operate the school over the amount harvested from rain.
- *Percentage of water needs met from rainwater*: This indicates the percentage of water consumed at the school that has been harvested from rain.

As depicted in Figure 1, the modeller presents input and output data. Areas in light blue require data to be entered, while other data is generated by the modeller. Monthly rainfall for the site should be entered in the light blue column on the left. This data is readily available for most sites. The light blue column on the right requires the days the school is occupied by month to be entered.

5. Case Studies

Case Study One

The first case study school is near Loerie in the Eastern Cape, in South Africa. Figure 2 shows photographs of the school indicating the large roof and hard surface areas available as collection surfaces.

Figure 2. Photographs of Case Study School near Loerie

Figure 3 shows a plan of the school with the main collection surfaces shown in dark grey (roofs). The roofs of the building are corrugated iron and can be used as collection surfaces. From Table 1, the collection surfaces have a runoff coefficient of 0.9. The collection surface area available for rainwater harvesting is 2,160 m^2 on a school site of 67,500 m^2.

Figure 3. A Plan of the Case-1 School Site and the Roof Collection Surface

Figure 4 shows rainfall patterns for the case study site over a year. This indicates that most rain falls in the summer months (November-March) when there are between 70 and 80 mm^3 per month. This decreases between April and October when rainfall is between 60 and 70 mm^3. This indicates that rainfall is fairly regular throughout the year and there are no long dry periods. The average annual rainfall is 533 mm^3.

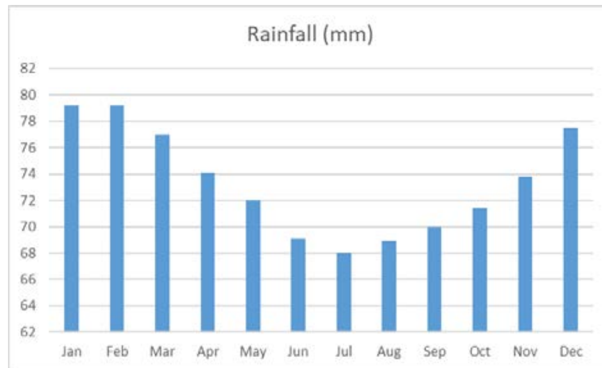


Figure 4. Monthly Rainfall in Loerie, Eastern Cape, South Africa

The school has 202 learners and 8 full-time staff equivalents and therefore has 210 occupants on site. As gender ratios vary over time, for this exercise the number of male and female occupants was made equal at 105 females and 105 males. The number of days the school is occupied is entered per month and is determined by the school calendar which remains broadly the same from one year to the next.

Case Study Two

The second case study school is in Pretoria, in Gauteng, South Africa. Figure 5 shows photographs of the school indicating the large roof areas and sports courts where rainwater can be harvested.

Figure 5. Photographs of Case Study School in Pretoria, Gauteng

Figure 6 shows a plan of the school with the main collection surfaces shown in dark grey (roofs). The roofs of the building are corrugated iron and can be used as collection surfaces. From Table 1 the collection surfaces have a runoff coefficient of 0.9. The collection surface area available for rainwater harvesting is 5,970m^2 from school roofs within school grounds of 3.33ha.

Figure 6. A Plan of the Case-2 School Site and the Roof Collection Surface

Figure 7 shows rainfall patterns for Pretoria over a year. It shows that most rain falls in summer (November-March). It shows that there are 5 months of low rainfall over May, June, July, August and September. The average annual rainfall is 661 mm^3.

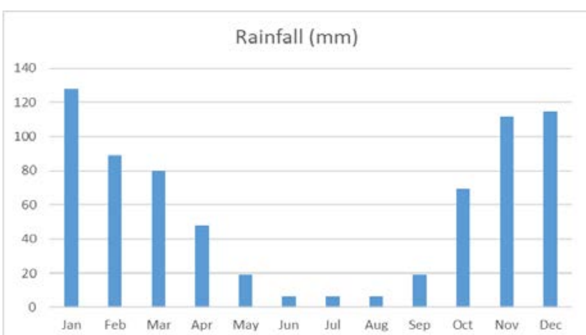


Figure 7. Monthly Rainfall in Pretoria, Gauteng, South Africa

The school have 987 learners and 42 staff, resulting in an overall number of 1,029 occupants on site. As gender ratios vary over time, for this exercise the number of male and female occupants was made equal at 115 female and 115 male. The number of days the school is occupied is entered per month and is determined by the school calendar which remains broadly the same from one year to the next.

6. Results

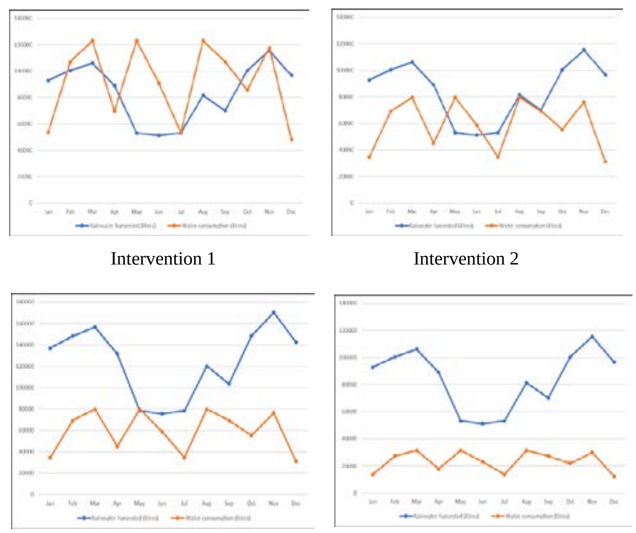
Case Study 1

The results of undertaking the interventions listed in the methodology and applying this to the case-1 school are depicted in Figure 8. Results for Intervention 1 show that water consumption at the school generally exceeded the amount of rainwater harvested. The modeller indicates that the rainwater harvesting system could meet about 84% of the school's water requirements.

Results for Intervention 2 indicate that water consumption has dropped at the school resulting in more months where rainwater harvested water exceeds water consumed. This results in 95% of the school's water needs being met from rainwater harvesting.

Results for Intervention 3 indicate that rainwater harvesting exceeds the amount required at the school and that 100% of the school's needs are met. An exception is in May when the consumption of water is equal to the amount of rainwater harvested.

Results for Intervention 4 indicate that rainwater harvesting far exceeds the amount of water required at the school and that the school could operate on 100% rainwater harvesting



Intervention 1 Intervention 2

Intervention 3 Intervention 4

Figure 8. Water Consumption (orange) and Rainwater Harvested (blue) at Case Study 1 School for Different Interventions

Case Study 2

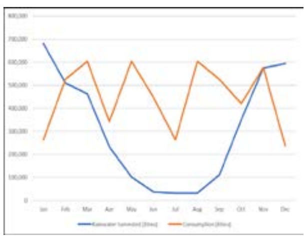
The results of Case Study 2 are shown in Figure 9. Intervention 1 results show that water consumption at the school generally exceeded the amount of rainwater harvested for all months except for January and December. The modeller indicates that the rainwater harvesting system could meet about 69% of the school's water requirements.

Results for Intervention 2, indicate that water consumption has dropped at the school resulting in more months where rainwater harvested water exceeds water consumed. It now shows that the school could meet all of its water consumption needs for January, February, March, October, November and December (i.e., 6 months, instead of just the 2 for Intervention 1). This results in

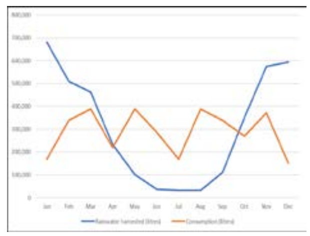
73% of the school's water needs being met from rainwater harvesting.

Results for Intervention 3, indicate that now rainwater harvesting exceeds the amount required by the school for all months except for May, June, July and August. It shows that 76% of the school's needs are met.

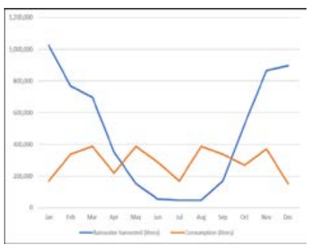
Results for Intervention 4 indicate that the rainwater harvesting systems still do not meet the school's water needs during May, June, July and August. It indicates that rainwater harvesting meets 82% of the school's needs.



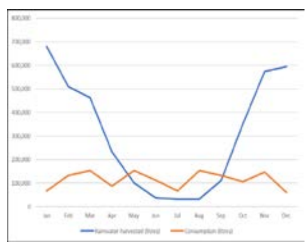
Intervention 1



Intervention 2



Intervention 3



Intervention 4

Figure 9. Water Consumption (orange) and Rainwater Harvested (blue) at Case Study 2 School for Different Interventions

6. Discussion

The results are discussed in terms of the research questions and have an emphasis on the nature of the data provided by the modeller and whether this is useful for schools interested in making decisions about rainwater harvesting.

The modeller enables patterns of water use over a year to be understood as these are presented as the orange line on graphs and relate directly to the number of days the school premises were occupied. When school premises are fully occupied, for instance for 23 days in May and August, it is more difficult for rainwater harvesting systems to match consumption as shown in Case Study 1, Intervention 1. Similarly, when occupancies are lower, for instance during January and December, it is much easier for rainwater harvesting systems to meet needs. This is shown in Case Study 1, Intervention 1. This finding would be interesting for schools and departments of education because it highlights the possibility of matching occupancy with rainwater harvesting patterns. Thus, there could be more days of school during months of high rainwater harvesting volume and reduced occupancy during drier months. This alignment of water consumption to rainwater harvesting production would reduce reliance on external water supplies and improve a school's water resilience.

The graphs also enable schools to visualise rainwater harvesting patterns and show how water harvesting in Case Study 1 is fairly even over the year compared to Case Study 2 when little water is harvested during the 4-5 month dry period. This information and the percentage of water met from rainwater is useful for decision-makers as it indicates that rainwater harvesting systems are more effective in areas where there is less variation in rainfall over the year, such as in Case Study 1 area. Effectiveness is measured as the percentage of water met from rainwater harvesting generated by an intervention.

The results show that even the most simple intervention, which is to have a rainwater harvesting system linked to roofs, has a very significant impact in both cases, with Intervention 1 in Case Study 1 reducing water consumption by 84% and this reduced by 69% in Case Study 2. This type of information is useful for decision-makers at schools as it illustrates the significant impact that can be achieved with simple rainwater harvesting systems. It also provides sufficient data for business case calculations to be made to support decision-making on rainwater harvesting system investments.

The results show that the impacts of interventions 2, 3 and 4 in Case Study 1 are more significant than in Case Study 2. In Case Study 1, these interventions enable the school to totally meet its own water needs and effectively be off-grid. However, in Case Study 2, all of the additional interventions only enable up to 82% of the water needs of the school to be met from rainwater harvesting and are insufficient to enable the school to be off-grid for water. This finding is useful for departments of education as it shows that for some climates, such as the climate in Case Study 1 it is possible to achieve off-grid schools relatively easily, while with schools in Case Study 2 areas, this is much more difficult.

The findings confirm that the modeller is easy to use and enables the implications of different interventions to be readily ascertained. However, it also shows that the modeller may not provide an accurate basis for the detailed design of a rainwater harvesting system for the following reasons. Firstly, only one flush rate for toilets and urinals is provided. Schools with many toilets may have toilets and urinals with different flush rates and this diversity is not captured. Secondly, the modeller only allows for one collection surface runoff factor to be entered. Schools may have different collection surfaces with different runoff factors. Thirdly, schools may have other water uses, such as irrigation, that currently are not included in the modeller. Fourthly, the 'lag' effect of large rainwater tanks is not considered (Gibberd, 2020). Thus, water harvested, but not consumed entirely in a month, such as during January, is not reflected as a ''credit'' to the following month, as would happen in an actual rainwater harvesting system. Fifthly, the modeller assumes regular rainwater patterns with limited variation between years. Data from climate change projections indicate that rainwater patterns are likely to change and therefore this should be considered (Maúre et al., 2018).

A review of the original specification of the modeller indicates that the SWARUM appears to meet the defined requirements. The tool is easy to use and understand, the data used by the modeller is easy to access, and the modeller provides an indication of water use and rainwater harvesting over a year and enables the implications of interventions to the water and rainwater harvesting system to be understood.

The modeller can therefore be said to support increased knowledge and understanding and contribute to "responsible decision-making" by the school governing body and staff (Williamson, 2010). Achieving a high degree of accuracy was not part of the specification and the complexity associated with achieving this may result in a tool that is complex and difficult to use (Borgstein, et al., 2016). However, Williamson (2010), notes that while achieving a high degree of accuracy in modelling tools may not be necessary, tools should indicate the levels of accuracy achieved, so this is understood. This recommendation should be incorporated into the SWARUM.

7. Conclusions and Recommendations

The study develops a school water use and rainwater harvesting modeller and applies this to case study schools in water-scarce areas of South Africa. Specifications developed for the modeller require that it can be easily used by school staff to model different interventions which explore the potential of rainwater harvesting to contribute to improved water resilience. Applying the modeller to the case study schools indicates that it can generate graphs of water consumption and rainwater harvesting over a year. It also shows that the modeller enables the implications of interventions such as more efficient use of water, increasing rainwater collection surfaces and the use of dry sanitation to be determined. Thus, the tool contributes to an understanding of how rainwater harvesting and associated water-efficiency measures can contribute to improved water resilience in schools.

While the modeller provides valuable insights into rainwater harvesting and water consumption in schools, other guidance and tools are required. This includes guidance on ensuring harvested water is as clean as possible through first flush mechanisms, filters and maintenance, modellers that enable rainwater tank sizes to be sized correctly, calculators that can be used to cost rainwater harvesting systems and ascertain their return on investment (ROI) and if water is to be used for drinking, water testing methodologies to ensure this is safe and healthy. Additional research is also required to compare daily rainfall and consumption with monthly figures to understand how the granularity of data affects results and therefore effective decision support.

The study suggests that the modeller has the potential to support increased awareness and enable decision-making about water and rainwater harvesting systems by schools and the department of education and therefore make a valuable contribution to improving water resilience at schools. A recommendation from this study is that the modeller is tested more widely with school decision-makers, such as school management teams and governing bodies and department of education officials. A simple manual should also be developed to show how the tool could be used and its limitations.

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Advanced Photo-Oxidation Process for Treatment of River Water Pollutants and Pathogens

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Abstract: *Water is a fundamental resource for human civilisation, yet there is a critical water shortage happening all across the world in the twenty-first century. In some areas of underdeveloped nations, people drink water that has been extensively polluted and comes from rivers that are home to deadly diseases. Microbial infections in drinking water can cause illness and increase the prevalence of disease. There are several treatment methods available to remove microorganisms from drinking water. This study suggests employing two techniques, photocatalytic semiconductor and photo Fenton, as an enhanced oxidation process to get rid of diverse water impurities and offer a reliable water treatment approach. A test on samples of river water was undertaken, and the analysis of a number of parameters was used to determine how well the test had removed contaminants and pathogens. The physiochemical criteria were used to evaluate the reaction and determine the properties of safe water using both approaches. The two techniques effectively eliminated between 80 and 100 percent of the contaminants that were detected in the river sampled. Variations in Titanium Dioxide concentration correlated with changes in reactivity and degradation rates. Results showed that light absorption was reduced dramatically as titanium dioxide concentration rose to saturation. Besides, the rate of degradation was directly correlated with light intensity.*

Keywords: *Photo Fenton, Photocatalytic Semiconductor, Advanced Oxidation Process, Water Disinfection*

1. Introduction

Despite the fact that the globe has greatly evolved thanks to new technologies, there are still some nations in modern society where the demand for water is great. Water is essential for all forms of life, from industry to agriculture, but it is also essential for the health of the natural world. Therefore, it is crucial that the water be pure and devoid of impurities. A clean water supply has historically been a successful means of eradicating many different diseases. Due to factors including industrial and agricultural expansion, population growth, an increase in the average lifespan, and the long-lasting drought brought on by global warming, clean water sources are becoming increasingly scarce while demand is rising sharply in many parts of the world. One example of a short-term remedy being employed at the time to address this issue is an increase in the capacity for rainwater harvesting.

Unfortunately, both humanity and changing nature greatly pollute water. The food chain is impacted by contaminated water in a number of ways. Pollutants like lead and cadmium, which are frequently consumed by small animals, are then consumed by fish, disrupting the food chain at subsequent levels.

Point-source pollutants and non-point-source pollutants are two different categories of water contaminants. Non-point sources are the indirect releases of toxic substances into the environment, typically as a result of environmental changes, while point sources are the direct releases of poisonous substances into water bodies. Technology makes it simpler to monitor and manage point source pollution, whereas non-point source pollution is far more difficult to manage, for example, using ozone or UV treatment of water. The majority of the undesirable components in lakes and streams are caused by non-point sources of pollution.

2. Literature Review

2.1 Solar Photo-catalyst Properties

The development of advanced oxidation processes (AOPs) and substantial advances in wastewater technology are the results of various investigations. Due to their capacity to produce hydroxyl radicals (OH), AOPs are processes that allow the oxidation and breakdown of organic chemical compounds in a hydrous solution. Non-

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photochemical and photochemical processes are the two categories under which advanced oxidation processes (AOPs) fall. They can be utilised individually or in combination with many other types of conventional wastewater.

There are many types of AOPs, but the best one so far is photocatalytic oxidation (PCO), which involves the destruction of organic compounds by the shining of ultraviolet light or sun light onto a catalyst (for example Titanium Dioxide (TiO_2), Zinc Oxide (ZnO), Iron Oxide (FeO_3)) while at the same time avoiding the introduction of other chemicals. In this context, it could be said that a brand-new material should be used to destroy the unwanted constituents (fungus and bacteria) into non-harmful products with the help of solar light and UV lamps which will be used to excite the catalyst. Among the different types of catalyst, Titanium Dioxide (TiO_2) is by far the best for water treatment at present. TiO_2 is stable, affordable, environmentally-friendly, sustainable and nontoxic.

Titanium dioxide is advantageous for usage in locations like schools, restaurants, clinics, and hospitals because it produces hydroxyl radicals when exposed to light, which eliminate germs like bacteria and fungi. This catalyst greatly accelerates the photocatalytic reaction without producing an end product, which is a key component of its appeal (Wubbels, 1983). Additives are unneeded and help a wide range of pollutants that foul water at room temperature to photodegrade. Titanium dioxide has some drawbacks, including post-recovery particles or the inability to separate particles, as well as a limited adsorption capacity (Chekir et al., 2012). TiO_2 has been the most promising catalyst due to the following reasons:

- TiO_2 catalyst does not output any toxic products unlike other semiconductor catalysts.
- TiO_2 operates at ambient pressure and temperature.
- The mineralisation of parents is complete leaving no secondary pollution.
- Low operation cost.

Figure 1 depicts the TiO_2 photocatalytic degradation cycle. Through this interaction, different chemical compounds in contact with the titanium dioxide continuously degrade until they become harmless. Photo catalysis has a nearly permanent impact.

2.2.1 TiO_2 Water Disinfection Processes

Titanium dioxide (TiO_2), a compound semiconductor, naturally becomes a potent oxidant when exposed to any type of light, including UV rays or the sun (see Figure 2). The majority of naturally occurring or artificial substances can degrade with titanium dioxide (TiO_2), even at low concentrations, according to its peak oxidation properties (Castellote and Bengtsson, 2001).

Many electrons are concentrated in the bound region of semiconducting composites or compounds. To excite these electrons, a level of energy of at least 3.2 electron volts (*eV*) must be created. A quantum of light (*hv*) having a wavelength of less than or equal to 390 mm can provide the energy (3.2 eV). TiO_2 catalyst particles generate a hole (h^+) and charged linked electrons that are dissociated from the ion when exposed to UV radiation and sunshine. Free electrons (e^-) are what these are known.

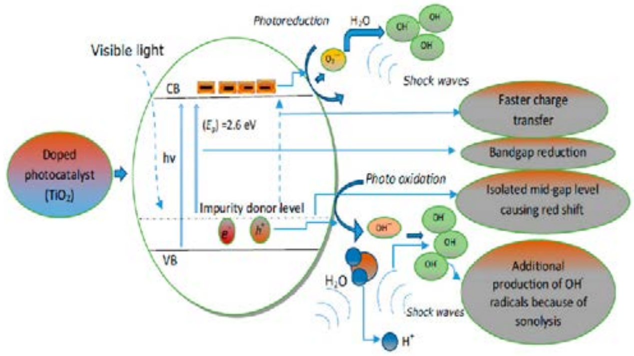

Figure 1. Light Radiating onto TiO_2 Causing Decomposition
Source: Adopted from Panda and Manickam (2017)

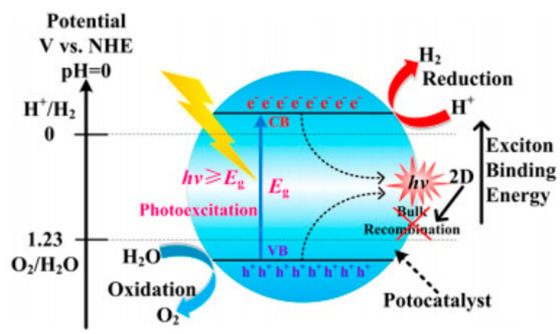

Figure 2. Photo Catalysis Operation on the Surface TiO_2
Source: Adopted from Su et al. (2018)

Once exposed to ultraviolet light (UV), TiO_2 valence band (*vb*) electrons (e^-) get excited and make their way to the conduction band (*cb*), thereby abandoning the hole (h^+), which has a positive charge (Mills et al., 1997). The excitement of valence band electrons under UV light, causing their movement from the hole to the conduction band, is termed photo-excitation and can be expressed as this reaction

$$TiO_2 + hv \gg TiO_2 + e^- + h^+ \quad (1)$$

Coupled e^- and h^+ from the process can join again to reseal the energy soaked in as heat. Holes (h^+) get into reactions with water (H_2O), forming hydroxyl radicals (OH), and simultaneously, natural compounds are oxidised. In the meantime, electrons also react with oxygen (O_2) to generate superoxide radicals (O_2) and carry out oxidation and the breakdown of organic matter reactions (Kang et al., 2007).

The reactions that form TiO_2 superoxide and hydroxyl radicals are as follows:

$$TiO_2(h + vb) + H_2O \gg OH^- + H^+ \quad (2)$$

$$TiO_2(h + vb) + OH^- \gg OH \quad (3)$$

$$TiO_2(e - cb) + O_2 \gg O_2^- \quad (4)$$

Where: *vb* is the valence band and *cb* is the conduction band.

According to Legrini et al. (1993), additional superoxide and hydroxyl radicals are produced, interact with contaminants, and experience oxidation, which causes them to decompose into water (H_2O) and carbon dioxide (CO_2). Due to the potent oxidising agents generated throughout the process, the TiO_2 photo catalytic process is an effective method for removing microorganisms and dissolving organic contaminants. TiO_2 is a much better and faster way to reduce microorganisms in wastewater because it has an excessively large surface area overall for the reaction. The main issue with this method, which adds to its complexity and time requirements, is the requirement to filter out more TiO_2 particles from the water, but this could easily be accomplished (Benjamin et al., 2013).

2.2 Solar Photo Fenton (SPF) Properties

2.2.1 Levels of Fe^{2+}

Prior research looked at the ideal iron concentrations required for a more efficient SPF response. The investigations examined the amounts of iron in pesticide-containing industrial wastewater. The tests were conducted using different dosages of the substance $7H_2O.FeSO_4$. The outcomes of these tests showed that increasing the concentration of Fe^{2+} to 2.4 mg/L was the ideal dose with a hydrogen peroxide concentration of 10:1 (Alalm et al., 2013).

2.2.2 Hydrogen Peroxide and the Fenton Process

A study looked at the various outcomes of the degrading activity when hydrogen peroxide was added to the sample. The pollutant samples received additions ranging in dosage from 30 mg to 180 mg. The greatest substantial removal activity occurred at a 10:1 ratio, when most contaminants were eliminated in 90 minutes by a dosage of 120 mg.

Too much water would prevent the reaction from proceeding. No additional water was needed. By using hydrogen peroxide, this study has the advantage of lowering the amount of water required for the reaction, which is very helpful when trying to be more affordable (Samet et al., 2012). However, there are many conditions where hydrogen peroxide has not been practical under UV conditions. Water has a very low molar extinction coefficient, and increasing the depth of the water quickly decreases the activity of the UV light energy.

The quantity of pollutants in the water generally affects the degradation. In a UV environment, hydrogen peroxide will be regarded as effective if the pollutants' concentration levels are low (Binnie, 2013).

2.2.2 Time

One study compares the degradation of the contaminants using sunlight against churning the sample to see which is more effective. The results showed that when stirring, 85% of COD was removed in less than half an hour; however, solar energy achieved a greater 91% COD removal rate, but the process took four times as long, or 120 minutes. In addition, churning was less efficient at removing chloropyrifos than solar light, with clearance rates only reaching 83% after 180 minutes of solar exposure compared to 60% after an hour of stirring (Ogier et al., 2008).

2.2.4 Solar Light Compared to UV Light

Previous research seems to suggest that when performing the SPF reaction, the effectiveness of each light source varies. They discovered parallel efficiency in both light forms when examining how the SPF reaction was utilised to discolour liquid tea. However, solar energy was favoured over ultraviolet light since it was less expensive to operate. Since the goal is to conduct the contact in the most cost-effective way possible, this is a crucial factor to take into account. The amount of energy was delivered to the polluted sample over time that was more significant than the reaction time (Sekine et al., 2012).

2.2.5 Improving the SPF Process Reaction

Titanium dioxide could improve the pace at which pollutants degrade in a sample after research into the impacts of adding specific compounds was conducted. The application of TiO_2 enhanced chloropyrifos degradation in the sample water by 27%, an improvement of 10% over the normal SPF response. It was discovered after testing several catalyst concentrations that 1.5-2.0 mg/l of titanium dioxide was the ideal amount (Alalm et al., 2013).

2.2.6 Cost-effective

In developing countries, significant expenditure on water treatment processes is not an option. This reaction needs to be extremely cost-effective. Previous studies have carried out a cost evaluation of the entire reaction and found ways to cut the expenditure. The results of these studies were extremely promising, as a reduction of 83.33% in reagent costs was achieved (Trivedy et al., 2009).

It would be expensive to treat water with advanced oxidation processes (AOPs) alone if the level of pollution is high. The SPF reaction would be adopted to decrease costs in the initial stage of the degradation process. Biological treatments would remove the remaining pollutants. In the preliminary oxidative procedure, the non-biodegradable and toxic compounds in the water would be removed. Subsequently, the remaining intermediates need to be removed with biological treatments (Trivedy et al., 2009).

3. Methodology

3.1 Experiment Procedure

Figure 3 shows the experimental setup for a solar photochemical reactor for both water and wastewater treatment. The setup was to record the photo-fenton reaction's performance when exposed to sunlight through the solar reactor's flowrates. The experiment procedure is as follows:

1) Compare the outcomes based on the levels of iron and sulphates,
2) Using TiO_2 to perform photocatalytic reactions in the presence of solar light,
3) Determine which approach is most efficient by measuring the rate at which contaminants are removed from the surface water system, and
4) Put improvements into practice to boost productivity.

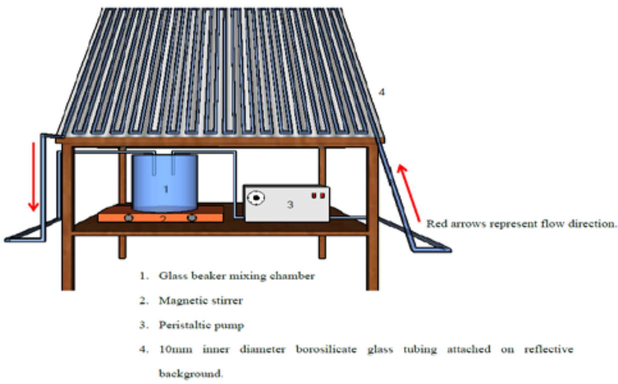

Figure 3. Experimental Setup for Solar Photochemical Reactor for Water and Wastewater Treatment

3.2 River Water Collection and Sampling

The Couva River in Trinidad was sampled twice a week for river water. Utilising technology and contrasting the water collected over a longer period of time are important issues. Any imaginable external effect can result in unexpected readings that can be corrected. For instance, certain pollutants released upstream may alter the water's properties.

3.3 Water Parameters

There are specific parameters that needs to be calculated to show how effective the reaction has been in removing the pollutants and to assess the integrity of the sample against standards established by the authorities. These parameters measure different elements of the sample to examine if there are any problems in the sample compared to the standardised water.

3.3.1 Phosphates

Phosphate is a crucial element that affects the growth of living things such as plants and animals and is essential for nutrition. It is important to moderate these physiochemical parameters since a high concentration of phosphate can lead to an increase in mineral and organic nutrients, which in turn leads to a reduction in the amount of dissolved oxygen in the water.

3.3.2 *Turbidity*

Turbidity is a measurement of a water sample's ability to transmit light. These tests evaluate the water discharge's quality in terms of residual and colloidal suspension problems. Colloidal matter absorbs light, making the difference in water samples under the same circumstances. Studying the amount of light scattered on a water sample reveals the presence of any colloidal matter.

3.3.3 Colour

The sample water taken from the two water sources can be coloured to identify its age. Specific properties relating to the age of the water would determine the smell and colour of the water sample. Fresh wastewater exhibits a pale grey hue when sampled.

3.3.4 Temperature

Temperature is an important factor when taking hygiene into account. In terms of biochemical reactions, a rise in temperature of 10 degrees Celsius can approximately double the reaction rate of bacteria with the uptake of oxygen, while cooling to low temperatures will destroy living bacteria as, without heat, the bacteria cannot survive. A key factor of temperature in water is that specific constituents (such as the concentration of dissolved oxygen) can be changed at different temperatures due to the ionisation of ammonia elements (Afgan et al., 2007).

3.3.5 Ammonia NH_3

Ammonia is typically found in modest amounts in natural water, but large amounts are extremely damaging to freshwater aquatic life.

3.3.6 Biochemical Oxygen Demand

The Biochemical Oxygen Demand (BOD) is a parameter that is routinely used in various forms of containment for surface and wastewater. This parameter measures the amount of dissolved oxygen to be consumed by the microorganisms within the wastewater sample. This occurs when the organic matter within the sample has undergone biochemical oxidation (Pizzi, 2011).

3.3.7 Chemical Oxygen Demand

The Chemical Oxygen Demand (COD) represents the amount of organic matter within a pollutant sample, which is very sensitive to the oxidation process when undergoing the SPF process. The definition of COD is the 'total quantity of oxygen required to chemically oxidise the non-biodegradable and biodegradable organic matter'. The organic matter within the sample should be eliminated and transformed into water and carbon dioxide (Gautam, 2015).

3.3.8 pH Value

When determining whether a liquid is acidic or alkaline, the negative logarithm of the hydrogen ion concentration is employed to classify the pH (Letterman, 1999).

3.4 Experimental Methods and Results

3.4.1 River Water Collection

The given equipment was tested to ensure the safety of all those involved in the river water collection, and a risk assessment of the water collected was done in the beginning to account for any potential risks.

3.4.2 Solar Photo Fenton Experiment

All testing was done with 2.4 grams of iron and 12 litres of river water sample. Specifically, Tests 1, 2, 3 and 4 used 24 ml of 30% Hydrogen Peroxide. The piping system for Test 1 was flat, while all the other tests were done at an angle of 45 degrees. Other settings and conditions per test are described as follows:

- Test 1: Sunlight test: Flat piping system with 10:1 ratio.
- Test 2: Sunlight test: 10:1 ratio.
- Test 3: Sunlight test: 5:1 ratio. The difference in the lighting situation has had a substantial influence on the quantity of pollutants.
- Test 4: Sunlight test: 20:1 ratio.
- Test 5: Sunlight test: 10:1 ratio; Hydrogen Peroxide (6%): 24ml. The variation in concentration has dramatically reduced the reaction’s abilities to remove the pollutants in comparison with 30% hydrogen peroxide.
- Test 6: Sunlight test: 5:1 ratio; Hydrogen Peroxide (6%): 12ml.
- Test 7: Sunlight test: 20:1 ratio; Hydrogen Peroxide (6%): 48ml.
- Test 8: Sunlight test: 2:1 ratio (Iron: Alum); Hydrogen Peroxide (6%): 48ml
- Test 9: Sunlight test: 5:1 ratio (Iron: Alum); Aluminium Sulphate: 12g Hydrogen Peroxide (6%): 48ml

The results of the tests 1 to 9 are summarised in Table 1, after 120 minutes. The percentage removal of parameters is depicted in Figure 4, with 10:1 ratio of 6% sunlight and 30% sunlight.

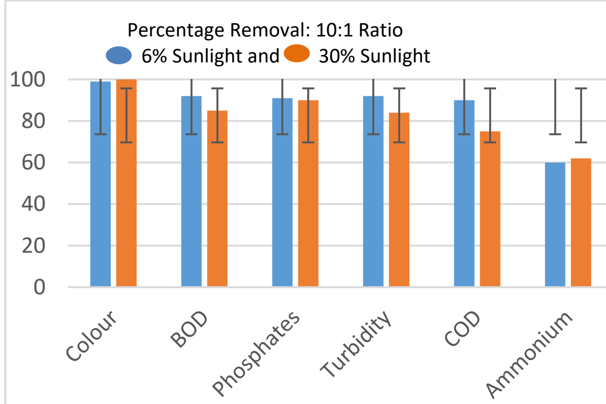

Figure 4. Percentage Removal of Parameters Using 10:1 Ratio of 6% Sunlight and 30% Sunlight

3.4.3 Solar Photocatalytic Semiconductor Experiment

The testing was done using 10 litres of river water sample with varying Titanium Dioxide concentration. Results for Tests 1-4 are depicted in Tables 2-5, respectively.

Table 2. Test 1 Mean Results from Sunlight + 0. 2g/L TiO_2 Test

Minutes	0	60	120	180	240
Colour	500	197	155	45	35
BOD	42.00				1.52
Turbidity	61.35	36.27	28.29	23.95	17.42
PH	7.20	7.40	7.50	7.60	7.70
Phosphates	0.41	0.17	0.12	0.09	0.05
COD	82.41	14.31	5.69	5.51	4.47
Nitrite (NO_3)	0.87	0.12	0.13	0.09	0.07
TDS (ppm)	935.00	881.00	875.00	868.00	860.00

Table 3. Test 2 Mean Results from Sunlight + 0. 5g/L TiO_2 Test

Minutes	0	60	120	180	240
Colour	500	135	32	25	15
BOD	43.00				1.63
Turbidity	61.35	18.27	16.29	14.95	11.22
PH	7.20	7.50	7.80	7.90	7.90
Phosphates	0.41	0.16	0.12	0.09	0.05
COD	82.41	12.31	11.69	9.51	6.47
Nitrite (NO_3)	0.87	0.76	0.62	0.59	0.47
TDS (ppm)	935.00	929.00	910.00	901.00	814.00

Table 1. Average Results for Test 1 to 9 after 120 Minutes

Test #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Colour	5	3	12	16	2	28	26	4	8
BOD	4.81	4.55	5.95	5.15	6.35	8.32	9.32	2.52	3.52
Turbidity	2.64	7.10	3.44	0.42	2.42	8.42	6.42	0.72	8.72
PH	6.90	7.10	7.20	6.80	6.40	6.40	6.40	7.00	7.00
Phosphates	0.08	0.04	0.14	0.05	0.09	0.22	0.15	0.06	0.06
COD	4.74	4.74	5.74	11.77	12.77	19.77	11.77	0.47	0.87
Ammonium	3.64	3.61	3.21	3.41	3.11	5.11	4.11	5.16	5.06

Table 4. Test 3 Mean Results from Sunlight + 1g/L TiO_2 Test

Minutes	0	60	120	180	240
Colour	500	85	18	16	7
BOD	43.00				1.68
Turbidity	61.35	16.28	15.25	11.95	7.50
PH	7.20	7.60	7.80	7.90	7.90
Phosphates	0.41	0.36	0.31	0.28	0.26
COD	82.41	16.38	14.69	12.51	10.17
Nitrite (NO_3)	0.87	0.72	0.65	0.58	0.36
TDS (ppm)	935.00	852.00	848.00	785.00	630.00

. **Table 5.** Test 4 Mean Results from Sunlight + 2g/L TiO_2 Test

Minutes	0	60	120	180	240
Colour	500	16	12	10	8
BOD	43.00				2.23
Turbidity	61.35	13.68	11.25	8.75	6.50
PH	7.20	7.60	7.70	7.90	7.90
Phosphates	0.41	0.38	0.35	0.31	0.29
COD	82.41	16.23	14.29	10.41	9.13
Nitrite (NO_3)	0.87	0.52	0.45	0.38	0.25
TDS (ppm)	935.00	710.00	667.00	645.00	607.00

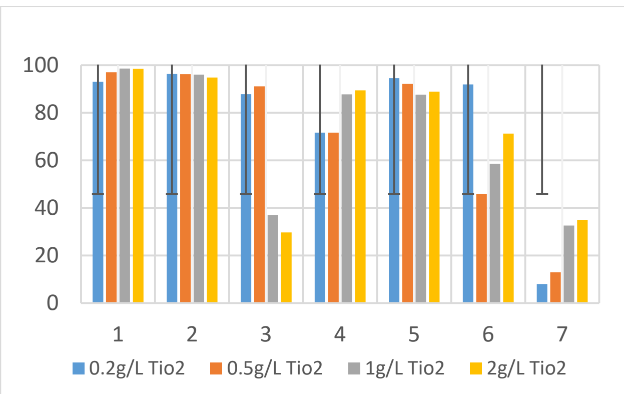

Figure 5. Percentage Removal with Different Concentrations of TiO_2

4. Analysis

4.1 Solar Photo Fenton Kinetics

The main presumption is that a 30% concentration of hydrogen peroxide would be sufficient to remove the contaminants in accordance with the literature review. Even in the climate that was present, the sample yielded the expected results. The effectiveness of the reaction, however, was significantly influenced by the light source.As revealed by earlier studies, the 10:1 ratio proved to be the most effective during testing for eliminating the degradants. When used in conditions with sunlight, hydrogen peroxide at a 30% concentration can eliminate the bulk of contaminants. However, when the experiment was repeated with hydrogen peroxide at a 6% concentration, it was less successful and significant amounts of physiochemical parameters were still present in the sample.

The optimum concentration of hydrogen peroxide cost more than twice as much as the 6% concentration when the price differential is taken into consideration. This puts a lot of pressure on the technology's ability to be both economical and useful. Therefore, the goal was to achieve the same effects at 30% concentration utilising only 6% hydrogen peroxide. The elimination of degradants between 30% and 6% with aluminium sulphate is comparable with particular physiochemical characteristics, as indicated in Table 6. When comparing the original 6% and the 6% with aluminum sulfate, the coagulant's impact on the peak findings was highly noticeable. When the concentration of iron sulfate to aluminium sulfate was increased from the 2:1 concentration, it seemed to be less active. Pollutant reduction is significantly hampered by dosage increases of 5:1 and 10:1. The findings of coagulation supplementation demonstrated high elimination activity despite the varying amounts of sun exposure that were seen during testing in external settings. Another element that needs to be taken into account is the experiment's overall settlement term. This happens because iron is a reaction by-product. It is necessary to separate the sample from the iron that has impurities attached.

4.2 Solar Photocatalytic

4.2.1 Effect of Initial Concentration

Concentration photo degradation of the river water was implemented at different concentrations ranging from 0.2, 0.5, 1.0, and 2.0 g/L. The results show that the rate of deterioration increased with increased concentration until it reached the plateau stage.

From the first test, turbidity was very bad even after 240 minutes, and colour was not good either, but this sample, which was collected from the river, contained a high level of colour and turbidity to begin with. Despite the poor turbidity and colour, there was a rapid decrease in COD from 82.41 mg/L to 14.31 mg/L during one hour; hence, an 82.6% reduction in COD was achieved. Although the water was clearly non-toxic after treatment, it was not aesthetically pleasing.

The second test showed turbidity and colour were partially improved but still well below the maximum WHO drinking water guidelines. Generally, this experiment was better than the first test (0.2 mg/L concentration).

The third experiment was very positive and produced the best solar results. The water was cloudy, and the BOD and COD reductions were worse than in the previous concentration of the experiment. Turbidity and colour were partly better, proving the hypothesis that colour and turbidity decrease when permitted to settle over a period of time.

The results for the fourth experiment indicated that the first hour of the test saw a slight degradation rate, and after 3 hours, most of the values obtained were higher than the 0.1 mg/L concentration.

Overall, it can be inferred from the tests that the Titanium Dioxide amount was proportional to the reaction

Table 6. Optimal Results with Mean Water Quality Parameters from Experimental Tests

	Physiochemical Parameters	Time (Minutes)				
		0	30	60	90	120
1	Ammonium 6%	8.31	7.95	5.82	4.91	3.11
	pH	6.2	6.2	6.3	6.3	6.4
	COD 6%	50.71	35.32	24.69	17.51	12.77
	Phosphates 6%	0.574	0.213	0.180	0.146	0.089
	Turbidity 6%	27.35	13.27	8.21	4.43	2.42
	Colour	314	32	13	8	2
2	Ammonium 30%	9.21	7.15	5.32	4.11	3.61
	pH	6.1	6.3	6.7	7.1	7.1
	COD 30%	51.31	25.35	18.69	8.51	4.74
	Phosphates 30%	0.474	0.233	0.212	0.176	0.039
	Turbidity 6%	29.25	12.61	6.54	4.43	2.24
	Colour	290	38	12	6	3
3	Ammonium 6% with Al	9.31	8.93	7.25	5.91	5.16
	pH	6.3	6.4	6.7	7.0	7.0
	COD 6% with Al	52.71	16.31	9.69	2.51	0.47
	Phosphates 6% with Al	0.474	0.263	0.118	0.046	0.059
	Turbidity 6% with Al	28.35	12.27	7.29	2.41	0.72
	Colour	343	24	15	7	4
4	Ammonium 6%	8.31	7.95	5.82	4.91	3.11
	pH	6.2	6.2	6.3	6.3	6.4
	COD 6%	50.71	35.32	24.69	17.51	12.77
	Phosphates 6%	0.574	0.213	0.180	0.146	0.089
	Turbidity 6%	27.35	13.27	8.21	4.43	2.42
	Colour	314	32	13	8	2
5	Ammonium 30%	9.21	7.15	5.32	4.11	3.61
	pH	6.1	6.3	6.7	7.1	7.1
	COD 30%	51.31	25.35	18.69	8.51	4.74
	Phosphates 30%	0.474	0.233	0.212	0.176	0.039
	Turbidity 6%	29.25	12.61	6.54	4.43	2.24
	Colour	290	38	12	6	3
6	Ammonium 6% with Al	9.31	8.93	7.25	5.91	5.16
	pH	6.3	6.4	6.7	7.0	7.0
	COD 6% with Al	52.71	16.31	9.69	2.51	0.47
	Phosphates 6% with Al	0.474	0.263	0.118	0.046	0.059
	Turbidity 6% with Al	28.35	12.27	7.29	2.41	0.72
	Colour	343	24	15	7	4

and degradation rate until it got to the point when the latter became constant and then started to significantly decline. The absorption of light (photons) coefficient often falls dramatically as the Titanium Dioxide amount increases up to saturation point (creating a high turbidity scenario). A reactor's surface area exposed to the photo catalyst is decreased when too much Titanium Dioxide is added because excess titanium dioxide particles have a tendency to shade the reactors.

This problem can be resolved by operating the photo reactors below the saturation point of the photo catalyst and combining the Titanium Dioxide with a sample of wastewater that must be processed to make a solution before introducing it to the reactors.

4.2.2 Effect of Light Intensities

Intensity of light has an inverse relationship with rate of deterioration. Although the difference in degradation rates became exceedingly minor after a certain point, greater light intensities did produce increased degradation rates. At increasing light intensity, electron holes are created.

More electron holes were produced as light intensity rose from noticeably lower levels. However, this grew more steady and gradual when the light intensity peaked, with little change in the rate of disintegration. Due to the collisions and recombination of electron holes with the separation of electron holes, the resulting light intensity and rate of deterioration decreased (Chong et al., 2010).

5. Conclusion

According to the solar fenton test results, a 10:1 ratio is the most effective for eliminating the degradants. When used in conditions with sunlight, hydrogen peroxide at a 30% concentration can eliminate the bulk of contaminants. However, when the experiment was repeated with hydrogen peroxide at a 6% concentration, it was less successful and significant amounts of physiochemical parameters were still present in the sample. On particular physiochemical criteria, the elimination of degradants by aluminium sulphate ranges between 30% and 6%. It appeared less active when the ratio of Iron Sulphate to Aluminium Sulphate was increased compared to the 2:1 concentration. The solar photo fenton experiments managed to remove within 80-

100 percent of pollutants measured from the river samples.

It was evident from the findings that the rate of degradation accelerated with rising Titanium Dioxide concentrations until it reached the plateau stage. The absorption of light (photons) coefficient often falls very dramatically as the Titanium Dioxide amount increases up to saturation point (creating a high turbidity scenario). The rate of deterioration is inversely related to light intensity. Increased light intensities caused increased degradation rates, although after a certain point, the difference in degradation rates would become small. On the other hand, solar photocatalytic semiconductors have their disadvantages. However, their positives are greater than their negatives.

Another issue with the climate was the temperature; as previous studies have indicated a higher temperature assists the degradation rate, which was absent when conducting the external tests under solar radiation. Therefore, when implementing this technology in the targeted countries, the outcome will be either improved, or somewhat similar but achieved in less time.

Moreover, compact procedures, very low chemical doses that result in fewer chemical residues and quicker reaction times are some of the benefits. Operational costs, the non-specific reactivity of hydroxyl radicals, and the production of biodegradable dissolved organic carbon (BDOC) are drawbacks. Utilising titanium dioxide for photo catalysis is a successful method of treating wastewater. For this technology to work as intended, intense light must be present constantly.

The study of solar photo fenton and photocatalytic semiconductors has proved to be effective by achieving the targets that were originally set. The reaction has been improved and made more affordable, which is crucial in restoring river water in developing countries to remove the threat that more than 500 million people suffer in these countries.

Graphene-based photo catalysts have gained significant attention in the wastewater treatment process due to their exceptional physical, chemical, and mechanical capabilities. This is a topic for further study. Since graphene exhibits exceptional electron conductivity, there are a wide range of light absorption, a large surface area, and a high adsorption capacity in the graphene-based photo catalyst. It would significantly increase the photocatalytic activity toward the photo degradation of pollutants when integrated into metals, metal-containing nanocomposites, semiconductor nanocomposites, polymers, MXene, and other compounds.

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Cumulative Fatigue Damage of Small-Bore Piping Subjected to Flow Induced Vibration

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Abstract: *The structural fatigue of a vertically oriented small-bore connection due to flow induced turbulence emanating from an upstream piping manifold is experimentally investigated. Dynamic strain measurements are taken at two perpendicular locations on a small-bore connection and the method of rainflow counting is used to determine the cumulative damage incurred. A number of factors is investigated and their influences on the cumulative damage are explained. These include the effects of (1) single phase and multiphase flow, (2) the upstream flow path through the manifold, and (3) steady-state and transient conditions. From the experimental analysis, key observations that may be useful to piping designers and engineers are reported. For instance, for single-phase water, the largest bending stresses are due to the out-of-plane vibration of the small-bore piping, whereas the pulsating characteristics of the single-phase air and multiphase flow result in significantly larger in-plane bending stresses. It is also observed that under certain manifold outlet conditions, transient effects upon pump start-up can produce more than 300 times the cumulative fatigue damage compared to steady-state operation. As part of this study, the finite element method is also used to investigate the influence of piping support stiffness on the fatigue life of a small-bore connection. Through a series of parametric analysis, it is demonstrated that there exists a minimum support stiffness for which the fatigue life of a small-bore connection excited by flow-induced vibration, achieves its upper bound value.*

Keywords: *Cumulative damage, Dirlik's method, Fatigue, Flow induced vibration, Rainflow counting, Small bore connection*

1. Introduction

Piping networks are major assets for utility and industrial process plants in the Caribbean region and beyond. Depending on the application, piping systems can vary in geometric configuration, layout, material construction and operating conditions. Maintaining the integrity of piping systems is a key component in managing safety, business and environmental risks. Historically, it has been well documented that excessive vibration and fatigue in piping systems can lead to premature failure, often with disastrous consequences (Garrison, 1988). With respect to water supply and utility systems, piping fatigue can introduce cracks that result in leakage and service reduction (Barton et al., 2019). Bradshaw et al. (2011) identified 406 recorded incidents in a UK-based regional water supply system between 1997 to 2006. It was shown that the second largest number of incidents were directly associated with material fatigue.

A major source of vibration in water and other utility piping systems transporting high velocity flow streams, is flow induced turbulence. The excitation that arises from flow induced turbulence becomes significant in piping systems with geometric discontinuities such as mitre bends, 90° bends, and tee junctions (Bull and Norton, 1981; Hambric et al., 2010)). Small bore connections (SBCs) are branched connections that protrude off the mainline piping. The nominal diameter of SBCs is typically 2 inches (50.8 mm) or less, and it is particularly prone to vibration induced fatigue failure (Pewkliang et al., 2017).

A common approach to designing SBCs is to use the screening procedure proposed by the Energy Institute's (EI) Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework (Energy Institute, 2008). The procedure determines a likelihood of failure, giving ranges of values for which the SBC passes or fails the screening. If the initial design fails the screening process, the guidelines provides the analyst with two options; (1) redesign or resupport the SBC or (2) conduct detailed experimental or finite element based assessments. Although the EI guidelines (Energy Institute, 2008) do not propose a finite element procedure, they do provide a vibration chart that allows analysts to use measured vibration levels to determine if the probability of failure is high.

Several researchers have expanded on the EI

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Guidelines (Energy Institute, 2008) and proposed both experimental and numerical methods to analyse the vibrations and fatigue of SBCs. For instance, Hamblin (2003) proposed an empirical method to determine the dynamic bending stresses of cantilevered small bore connections. Application of the method was illustrated using laboratory and onsite field testing. Xue et al. (2010) used a hybrid empirical and numerical approach to determine the cumulative damage of a simply supported small bore piping connection in a nuclear power plant. Moussou (2003) proposed a root velocity experimental criterion to evaluate the risk of vibration-induced fatigue of small bore pipes.

This paper investigates the cumulative fatigue damage incurred by a small bore cantilevered connection located downstream from a piping manifold. The problem is important since piping manifolds can generate large flow disturbances (Bachoo and Bridge, 2021), which can result in downstream SBCs being susceptible to vibration induced fatigue. An experimental test rig that includes a manifold and a downstream SBC is used to perform the analysis. Dynamic strain measurements are taken for single phase air flow, single phase water flow and a multiphase mixture of air and water. A rainflow cycle counting algorithm is then used to determine the cumulative damage for a fixed period of time. The effect of transient (start-up) conditions compared to steady state operation is considered and discussed. The piping manifold used in this study, divides the inlet flow into three separate legs. By using ball valves to control the flow through the manifold, the influence of the flow path on the cumulative damage of the SBC is investigated.

The study also presents a finite element methodology to study the influence of support stiffness on both the resonant characteristics of a piping system and the fatigue life of the small bore connection. It is demonstrated that there are two unique minimum stiffness values for which the natural frequency and fatigue life can be maximised. The results are particularly profound since, from a design point-of-view, it is often desirable to have piping supports that are rigid enough to reduce vibration levels, but are flexible enough to accommodate the effects for thermal expansion. It follows, therefore, that designers and engineers can use the methodology and results presented in this work to design small bore connections that mitigate structural fatigue.

2. Description of the Experimental Piping Test Rig

Consider the schematic of the test rig shown in Figure 1. A 600-gallon polyethylene tank (A) situated on top of a metal frame (C) feeds the single impeller Aurora 1070 centrifugal pump (B). A GPI TM-300F turbine metre (D) measures the volumetric flowrate whilst a globe valve (G) is used to manually throttle the flow. Multiple piping supports (such as EF in Figure 1) are placed at different points along the length of the piping system. A Kellog 452TV compressor located far upstream the mainline pipe, supplies pressurised air through a branched connection (H). The inlet air-pressure and flowrate are measured using a Wika pressure gauge and Hedland H771A-150 air flowmeter, respectively.

Figure 1. Components of the experimental piping system

Downstream the air inlet (H), a piping manifold (I) is introduced into the system. The manifold consists of one inlet and three outlets as depicted in Figure 2. The inlet of the manifold has an inner diameter and thickness of 77.93 mm and 5.49 mm respectively, which is similar to the mainline piping upstream of the manifold. The ends of the manifold are closed using two hemispherical caps, each having a nominal diameter of 76.2 mm. The caps are designed in accordance with ASME B16.9 (ASME 2003). The outlet of the manifold splits into three separate channels, each having an internal diameter of 52.5 mm and thickness 3.91 mm. Threaded ball valves (BV1-BV3 shown in Figure 2) are installed to control the flow in each of the three legs of the manifold. Flow travelling through the legs of the manifold merges through a cross tee-fitting (O in Figure 2) and subsequently returns to tank A via the piping span KL (see Figure 1). Additional details of the general features of the piping test rig may be found in (Bachoo and Bridge, 2021).

Figure 2. Manifold and Ball Valve Configuration

The small bore connection (SBC) that will be investigated in this work is located directly downstream 'O' as shown in (Figures 2 and 3). The SBC has a ball valve connected at its free end and is placed vertically upright. The outer diameter and thickness of the SBC are 33.40 mm and 1.65 mm, respectively. A 3000-class threadolet having a nominal diameter of 25.4 mm is used to connect the SBC to the mainline piping. The mainline piping on which the SBC is connected has an inner diameter and thickness of 52.55 mm and 1.65 mm respectively. The lengthwise dimensions of the SBC inclusive of the threadolet and valve are also shown in Figure 3. The pipe material for the SBC connection is cold drawn galvanised steel.

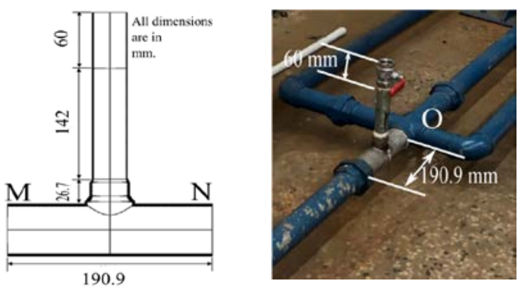


Figure 3. Sketch and Location of Vertical Small Bore Connection

2.1 Experimental Methodology

Axial strain measurements were taken at the base of the SBC using a PCB RHM240403 dynamic strain gauge having a sensitivity of 10 mV/$\mu\epsilon$. Strain measurements were taken at two perpendicular positions (Location 1 and Location 2) as shown in Figure 4 for both single phase and multiphase fluid flow. Location 1 measures the out-of-plane strain whilst Location 2 measures the in-plane strain. The strain gauge was connected to a laboratory charge amplifier and data acquisition unit (Kistler Type 5165A4). A sample rate of 62500 Hz was selected and a low pass antialiasing filter with a cut-off frequency of 10 KHz was utilised. For each individual measurement taken; data was collected for a total of 60 seconds. It was observed that a sample time of 60 seconds consistently led to a well-defined asymptotic mean square strain value.

Figure 4. Position of the strain gauge on the SBC; Location 1 (left) and Location 2 (right)

The first set of experimental measurements was conducted for single phase water (that is the air inlet was closed and the compressor taken offline). Both transient and steady state conditions are considered. In the transient case, the effects of pump start-up are included whilst in the steady state case, measurements were only taken after the transient effects became negligible. Consequently, steady state measurements were only taken after the pump was operational for at least five minutes after start-up. The strain produced by the fluctuating excitation forces was recorded for the six ball valve combinations shown in Table 1.

The measured strain data was subsequently converted to dynamic stress and a rainflow cycle counting algorithm was used to determine the cumulative damage that occurred over the 60 second period. The rainflow counting algorithm, which adheres to ASTME 1049-85 (ASTM, 2005), was executed in Matlab 2022a (Irvine, 2018). The second and third set of experiments were conducted by repeating the above procedure for single phase air and a multiphase combination of air and water.

Table 1. Ball valve configurations and flow path control

Ball valve configuration	Valve settings
1	BV1 opened, BV2 opened, BV3 opened
2	BV1 closed, BV2 opened, BV3 opened
3	BV1 closed, BV2 closed, BV3 opened
4	BV1 opened, BV2 closed, BV3 closed
5	BV1 closed, BV2 opened, BV3 closed
6	BV1 opened, BV2 closed, BV3 opened

3. Experimental Results and Discussion

3.1 Single Phase Water and Single Phase Air

In this study, the manifold inlet velocity for single phase water is 1.94 m/s, which corresponds to a Reynolds number of 163000, thereby indicating turbulent flow. For Location 1 of the strain gauge, the average cumulative damage for all ball valve combinations at transient and steady state conditions is shown in Figure 5. In Figure 6, similar data is presented for Location 2.

It can be observed Location 1 had a larger cumulative fatigue damage compared to Location 2. For steady state and transient conditions, it is shown that certain Ball-Valve-Configurations can lead to greater fatigue damage compared to others. It is also observed that the transient effects of pump start-up results in the cumulative damage being significantly larger than the steady state conditions. In Ball Valve Configurations 1 and 2, the transient cumulative damage is 177% and 337% greater than the steady state damage.

In general, when all three ball valves are opened, the cumulative damage of the SBC is the smallest. Closing either one or two of the valves results in a marked increase in cumulative fatigue damage to the SBC. This can be explained by considering that there is an increase in the amplitude of the underlying excitation pressure as the

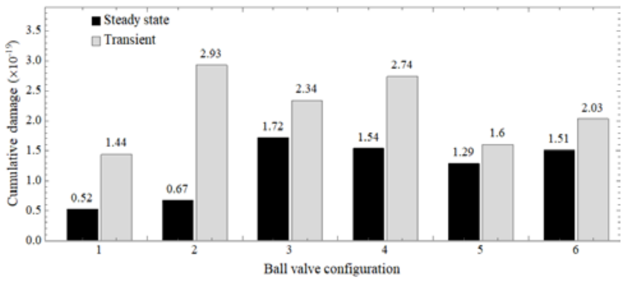


Figure 5. Cumulative Damage of the SBC at Location 1 for Single Phase Water

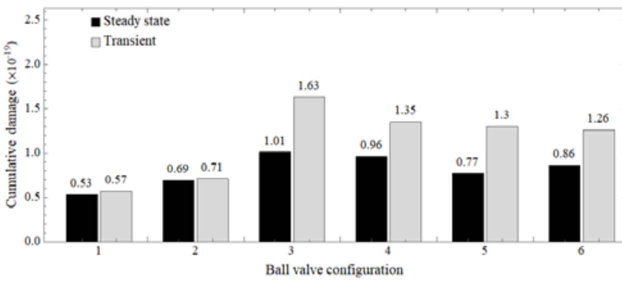


Figure 6. Cumulative Damage of the SBC at Location 2 for Single Phase Water

already turbulent flow is restricted to pass through only certain valves at a higher speed. Interestingly, the combinations where BV2 is closed and flow passes through BV1 and/or BV3, a higher cumulative damage is generally observed compared to when BV2 is open. This can be explained due to the flow separation and turbulence associated with the 90° bends located upstream of the BV1 and BV3 valves.

The mechanisms accompanying turbulent flow around a bend are shown in Figure 7. The turbulent boundary layer between the fluid and the inner piping walls produces a strong pressure gradient. Due to the random nature of the flow, this encourages wall pressure fluctuations to develop, producing high levels of localised kinetic energy, which causes the piping to vibrate. Transverse plane waves propagating throughout the piping system can also be present, although the induced vibration is restricted to low frequencies (Norton and Bull, 1984).

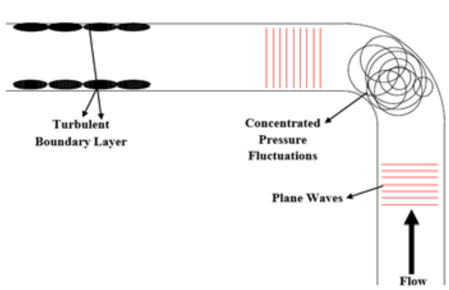


Figure 7. Mechanisms Producing Wall Pressure Fluctuation from Flow Induced Vibration

Single phase air was allowed to flow through the system with an inlet velocity of 3 m/s, and a Reynold's number of 15844. The cumulative damage for all valve combinations at steady state and transient conditions are shown in Figures 8 and 9 for Location 1 and Location 2 respectively. It can be observed that across both plots, the trend is reversed compared to single phase water as the in-plane stresses now dominate. The effect of the transient conditions still, however, produce significant damage compared to the steady state condition. The results for both water and air emphasise the influence that both start-up conditions and flow path have on the cumulative damage induced by single phase flow.

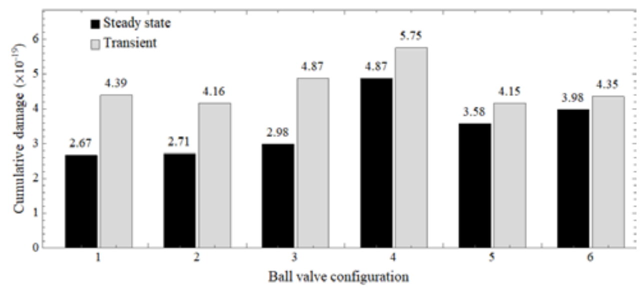


Figure 8. Cumulative Damage of the SBC at Location 1 for Single Phase Air Flow

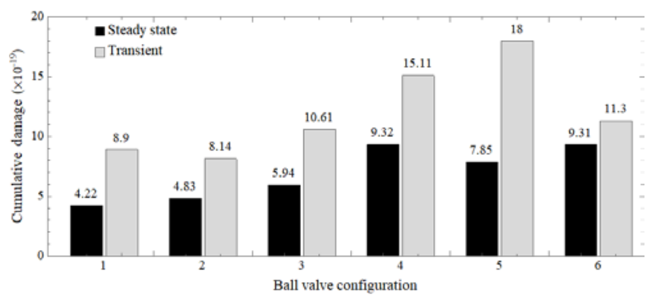


Figure 9. Cumulative Damage of the SBC at Location 2 for Single Phase Air Flow

3.2 Multiphase Air-water Flow

In the experimental study, the multi-phase air-water mixture had a manifold inlet velocity of 0.99 m/s for water and 3 m/s for air. The cumulative damage for all valve combinations at steady state and transient conditions is shown in Figures 10 and 11 for Location 1 and Location 2, respectively. Two key differences are observed upon comparing the results with single phase flow. The first is that the amount of cumulative damage in the 60 second period is significantly greater across all ball valve configurations, despite the flow rate of the water being less than the single phase case. The second major difference is that the strain gauge at Location 2 records higher strain response levels compared to Location 1. These changes are due to the pulsations associated with the alternating periods of air followed by water.

The pulsations cause the underlying pressure fluctuations at pipe walls to have larger magnitudes and therefore induces greater vibration and stress levels. Additionally, the pulsations occur along the longitudinal axis of the mainline piping. It follows this excitation induces larger in-plane deflections of the SBC (Location 2) compared to the out-of-plane motion (Location 1).

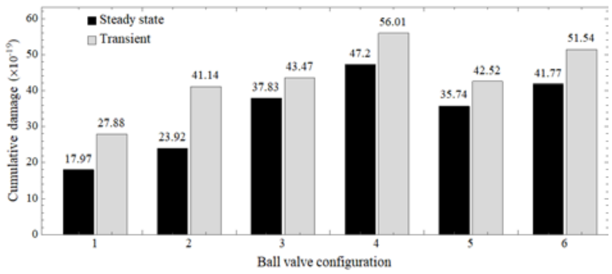


Figure 10. Cumulative Damage of the SBC at Location 1 for Multiphase Air/Water Flow

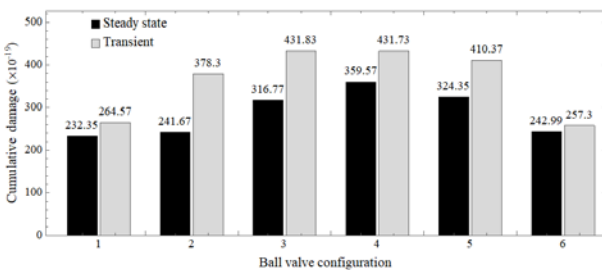


Figure 11. Cumulative Damage of the SBC at Location 2 for Multiphase Air/Water Flow

4. Numerical Fatigue Analysis of a Small Bore Connection

4.1 Description of the system

In this section of the paper, the influence of piping support stiffness on the stress response and fatigue life of a SBC are analysed. The system considered, is a flowline with a single mitre bend and a SBC as shown in Figure 12. As the fluid flows through the mitre bend, strong pressure gradients are created, which causes the entire structure to vibrate in three planes. Fluctuating stresses at the root of the cantilevered SBC are capable of inducing failure due to fatigue.

The internal diameters for the mainline piping and SBC are 78 mm and 26.7 mm, respectively. The piping thickness for both the mainline and SBC is 5.49 mm. At the free end of the SBC a valve of mass 1 kg is included. The lengthwise dimensions are shown in Figure 12. Two identical piping supports are placed on either side of the SBC at an equal distance. The piping supports are assumed to only having a stiffness in the vertical direction.

The fluid flowing through the pipe is single-phase gas with a density of $\rho_f = 4$ kg/m^3, dynamic viscosity $\mu = 10^{-5}$ Pa.s, and velocity U_o= 170m/s. The power spectral density due to flow induced turbulence within the vicinity of the mitre bend is obtained from Bull and Norton (1981). Figure 13 shows the variation of the dimensionless power spectral density with dimensionless frequency for four different regions downstream the bend. The amplitude of the power spectral density when $z > 2.31a$, where a is the internal diameter of the mainline, has been shown to be negligible (Bachoo and Bridge, 2021).

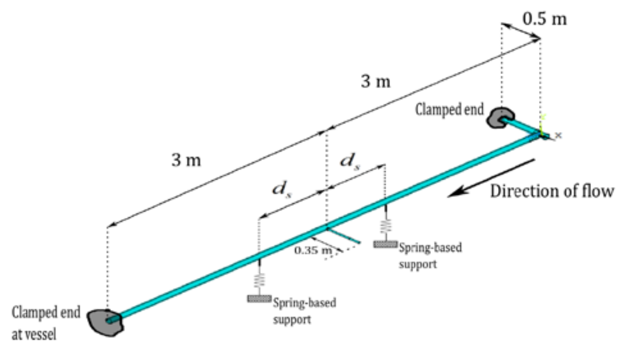


Figure 12. Spring Supported Flow Line with a Horizontal SBC

Applying the scaling rules in Bull and Norton (1981), the power spectral density functions for the specified operating conditions may be obtained from the following expressions:

$$\Phi = \frac{4\phi}{\rho_f^2 U_o^3 a} \tag{1a}$$

$$\Omega = \frac{\omega a}{U_o} \tag{1b}$$

where Φ is the dimensionless power spectral density, ϕ is dimensional equivalent, Ω is the dimensionless frequency and ω is the circular frequency in radians per second.

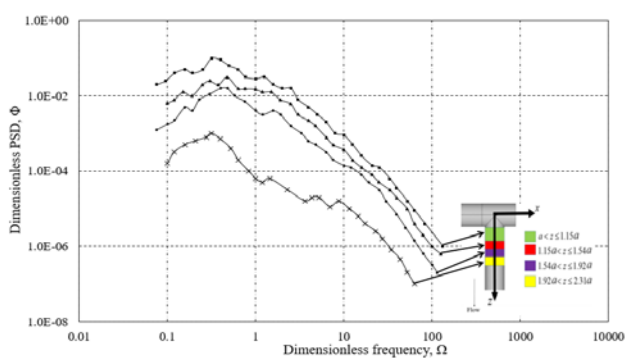


Figure 13. Dimensionless Power Spectral Density (PSD) of the Pressure Fluctuations Downstream the Mitre Bend

4.2 Finite Element Model

A finite element model of the system (see Figure 12) is generated using the software Ansys® Academic Research Mechanical APDL, Release 2022 R2. To undertake the analysis, 18938 SHELL181 elements were used to model the piping structure and 500 MATRIX27 elements were used to model the support stiffness. Specifically, SHELL181 is a four node element with six degrees of freedom (DOF) at each node, whilst the MATRIX27 element directly relates the stiffness between two nodes. The meshed model is shown in Figure 14.

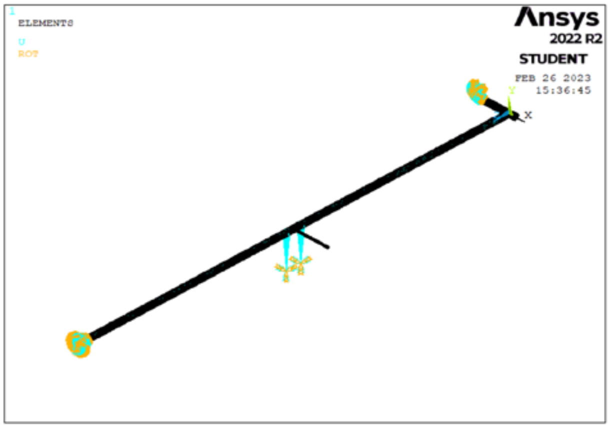


Figure 14. ANSYS® Model of Piping System

The natural frequencies and mode shapes of the piping system in the desired frequency range were obtained by using the Block Lanczos solver. The spectral analysis toolbox in ANSYS® was then used to perform the random vibration analysis. An in-house script in ANSYS® was written to apply the power spectral density functions within the regions downstream from the mitre bend (Fig. 13). Upon solving for the response of the piping system due to the excitation power spectral density, the frequency response function for the stresses at the root of the SBC can be obtained. Figure 15 shows an example of the bending stress power spectral density obtained at the root of the SBC when the stiffness is set to zero.

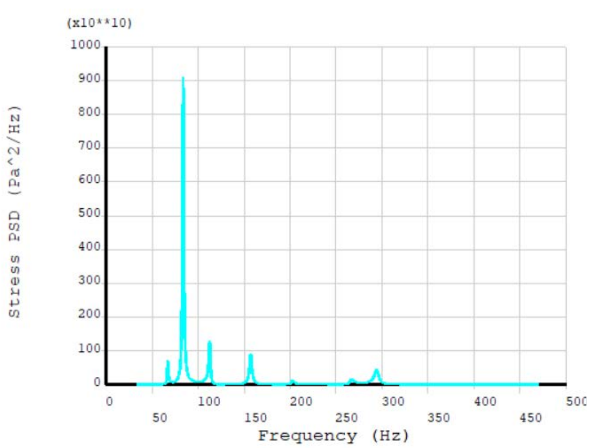


Figure 15. Power Spectral Density of the Bending Stress of the SBC from ANSYS®

4.3 Fatigue Life Calculation

In this study, the connection between the SBC and mainline piping is assumed to be a full penetration butt weld between steel components. The SN curve for the piping material is given by:

$$N_F S^m = K, \tag{2}$$

where N_F is the number of cycles to failure when a constant amplitude stress range S is applied. The variables K and m are the fatigue strength coefficient and fatigue strength exponent, respectively. For steel welded butt joints, the parameters $K = 1.08(10^{14})$ and $m = 3.5$ (Bachoo and Bridge, 2021).

The fatigue life of the SBC is obtained by using Miner's cumulative damage rule in conjunction with Dirlik's spectral fatigue method. According to Miner's rule the damage fraction is determined using the expression

$$D = \frac{1}{K}\sum_{i}^{M} n_i S_i^m \tag{3}$$

where n_i is the number of cycles of the stress range S_i, and M is the number of stress ranges in the spectrum. Dirlik's analytical method is then used to determine the damage fraction D, by analysing the power spectral density of the bending stress as obtained from the ANSYS® model.

Dirlik's method combines two Rayleigh and one exponential distribution function to describe the probability distribution function of the stress range $p(S)$ obtained from the stress spectrum. The distribution function is given by (Bachoo and Bridge, 2021)

$$p(S) = \frac{\frac{D_1}{Q} e^{-Z/Q} + \frac{D_2 Z}{R^2} e^{-\left(Z^2/2R^2\right)} + D_2 Z e^{-\left(Z^2/2\right)}}{2\sqrt{m_o}} \tag{4}$$

The functions in Eq. (4) are evaluated using the following expressions,

$$D_1 = \frac{2\left(x_m - \gamma^2\right)}{1+\gamma^2}, \quad D_2 = \frac{1-\gamma-D_1+D_1^2}{1-R}, \quad D_3 = 1 - D_1 - D_2,$$

$$Q = \frac{1.25\left(\gamma - D_3 - D_2 R\right)}{D_1}, \quad R = \frac{\gamma - x_m - D_1^2}{1-\gamma-D_1+D_1^2}, \quad Z = \frac{S}{2\sqrt{m_0}},$$

$$x_m = \frac{m_1}{m_0}\sqrt{\frac{m_2}{m_4}} \text{ and } \gamma = \frac{m_2}{\sqrt{m_0 m_4}}.$$

The n^{th} moment of the spectral density is given by $m_n = \int_0^\infty f^n P_s(f)\mathrm{d}f$, where P_s is the power spectral density of the bending stress. The statistical expectation (E) of the fractional damage after time T seconds has elapsed that is given by,

$$E[D] = \frac{T}{K} E\left[P\right].E\left[S^m\right] \tag{5}$$

where $E\left[S^m\right] = \int_0^\infty S^m p\left(S\right)\mathrm{d}S$, and $E\left[P\right] = \sqrt{\frac{m_4}{m_2}}$ is the expected number of peaks in the spectrum. It follows, therefore, that the time T when E[D] approaches unity represents the time taken for failure to occur. A program, based in Matlab, is used to import the stress power spectral density from ANSYS® and apply Dirlik's method to obtain the estimated fatigue life of the small bore connection.

4.4 Dynamic Response and Fatigue Life of the SBC

Figure 16 shows the variation of the natural frequencies of the first ten modes with spring stiffness. Interestingly, it is observed that for each mode there exists a minimum spring stiffness for which the natural frequency achieves its upper bound value. Here, upper bound refers to the natural frequencies obtained when the springs are infinitely stiff. For instance, when $k_s > 10^4$ N/m the natural frequency of the first mode is independent of the stiffness. It is also observed that the frequency spacing between modes can be dependent on the spring stiffness. For example, when $k_s = 1$ N/m the first two natural frequencies are 12.01 Hz and 12.82 Hz, respectively, whereas for $k_s = 10^7$ N/m, the corresponding first and second modes become 12.82 Hz and 36.79 Hz, respectively.

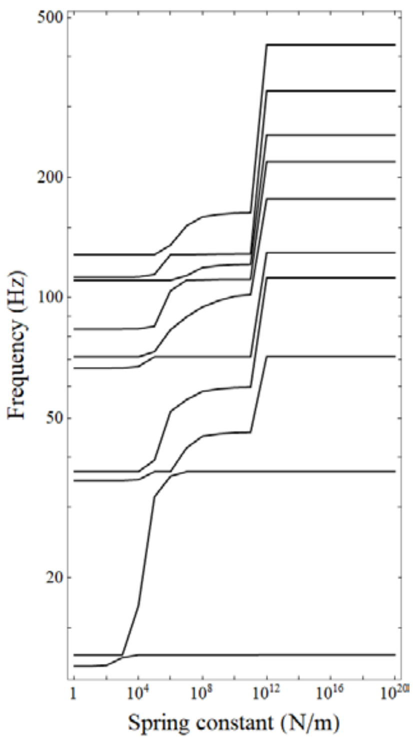
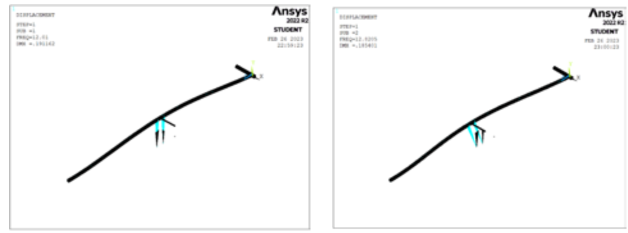


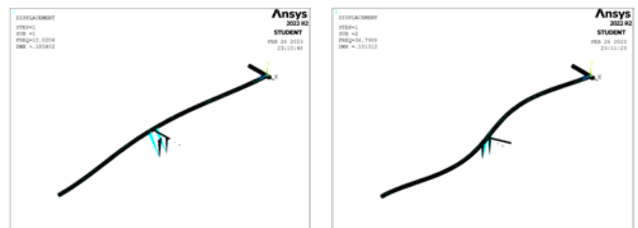
Figure 16. Frequency Locus for the First 10 Modes of the Piping System

The mode shapes for these specified frequencies are shown in Figures 17 and 18. The ability to tailor the natural frequencies based on the stiffness (k_s) is an important design tool, which may be used to avoid harmful resonant conditions.



(a) (b)

Figure 17. The First 2 Modes of the Piping System when (a) First Mode and (b) Second Mode.



(a) (b)

Figure 18. The First 2 Modes of the Piping System when (a) First Mode and (b) Second Mode

The flow induced turbulence at the mitre bend results in the root of the SBC being the most stressed location along the entire piping span. This position is shown in Figure 19, and the associated the fatigue life is calculated. Figure 20 shows the influence of spring stiffness on the fatigue life of the SBC. In general, it is observed that as the spring stiffness increases, the fatigue life of the SBC also increases. Notably between the stiffness range $10^7 < k_s < 10^{14}$, the fatigue life increases rapidly. Moreover, it is observed that, analogous to the behaviour of the natural frequencies, there is also a minimum stiffness at which the fatigue life is maximised. In the case of this system when $k_s > 10^{14}$, the fatigue life is independent of the stiffness value.

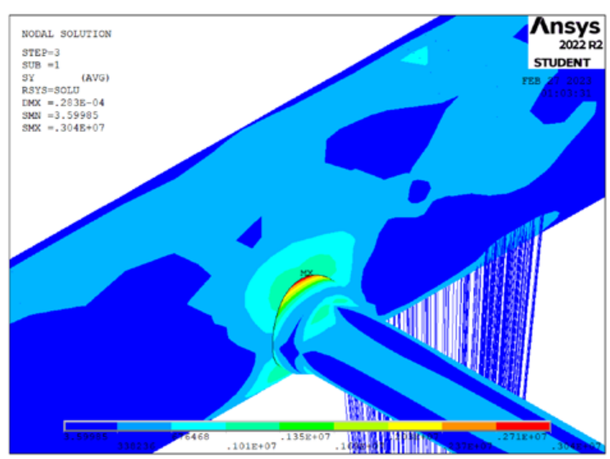


Figure 19. Location of Maximum Stress on the SBC

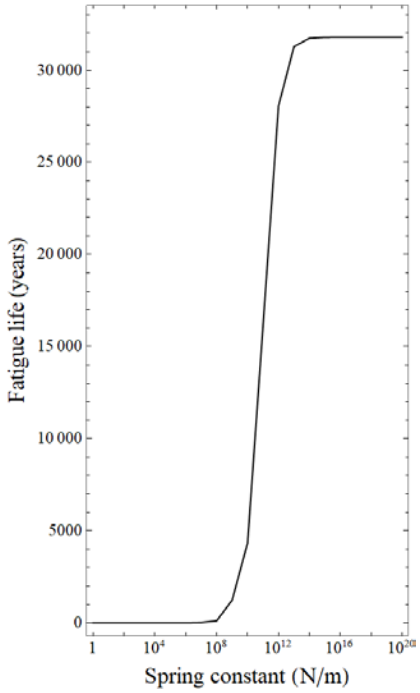


Figure 20. Variation of fatigue life with spring stiffness

5. Conclusions

Experimental and numerical analyses are used to study the fatigue life and dynamic characteristics of small bore piping connections. Specifically, in-plane and out-of-plane dynamic strain measurements are taken on a small bore connection located downstream a complex piping manifold. The method of rainflow counting is applied to determine the cumulative damage for both single phase and multiphase flow. In the case of the single phase flow of water, it is observed that the out-of-plane bending stresses are largest whilst for single phase air and the multiphase flow, the in-plane bending stresses dominate. The flow path through the manifold is controlled by manipulating the on and off position of ball-valves located at the outlet. It is shown that the flow path can significantly influence the magnitude of the cumulative damage. The effect of transient start-up conditions compared to steady state operating conditions is also investigated. It is observed that the latter can result in significantly larger amounts of cumulative damage.

Finite element simulations are conducted to determine the influence of mainline support stiffness on the fatigue life of the SBC and the resonant characteristics of the piping system. By applying Dirlik's spectral fatigue method, it is shown that there exists a minimum stiffness value for which the maximum fatigue life is obtained. Analogously, it is also observed that there is also a minimum stiffness value that optimises the fundamental natural frequency of the piping system. The work presented herein can be used in conjunction with other available methods, such as those available in the EI Guidelines (Energy Institute, 2008), to design SBCs that are resistant to cyclical fatigue.

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The Potential Impact of Oil Spills in Coastal Waters on Water Supply in Trinidad

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Abstract: *Oil exploration poses an inherent risk to water resources and water quality, exemplified by oil spills resulting from broken pipelines, underwater blowouts and oil transport vessel accidents. In these instances, as vulnerable to spilled oil, water is usually the first casualty, resulting in oil contaminated water. In an effort to ensure the sustainability of freshwater resources resilience in Small Island Developing States, (SIDS), desalination is increasingly used to provide potable water. Thus, oceanic oil spills are of significant relevance to the provision of a guaranteed supply of potable water. Trinidad and Tobago, an oil-producing (SIDS), with considerable oil and gas activities on land and in shallow coastal waters; can become increasingly stressed from oil spills, possibly leading to halting seawater intakes in the desalination process. A real-life seawater surface oil spill in the Gulf of Paria, south-west coast of Trinidad, not far from the largest desalination plant in the Caribbean, is investigated using numerical mathematical modelling to model the spill's movement underwater. The trajectory plots produced and analysed, indicated that depending on key parameters of the oil and the current ambient conditions, an oil plume can travel significantly long horizontal distances underwater before destabilising. Inferences suggested that oily underwater and existing ambient conditions can potentially affect the desalination equipment. Hence, oil spill modelling is necessary to determine oil trajectory and further inform the decision-making process in determining the best location for constructing desalination plants so as to minimise disruption to the island's domestic freshwater supply in oil spill events.*

Keywords: *SIDS, Gulf of Paria, Trinidad, oil spill, numerical mathematical modelling, trajectory plots, effect of oil spill on desalination plant and freshwater supply*

1. Introduction

Despite the global thrust towards renewable energy, reputable global energy online and print reports, including (Raimi et al., 2023; Gordon and Weber, 2021; Tan, 2021; IEA, 2018, 2021) have indicated in different ways that the increase in renewable energy is less than the overall increase in global energy demand. This implies that renewable energy is not yet keeping abreast with rising energy demand. This point was further expressed by the Canadian Association of Petroleum Producers (CAPP, 2023) in which it includes projections from the International Energy Agency (IEA), namely: increasing use of renewables, improved energy efficiency and a shift towards electric vehicles. However, the report also states that oil and natural gas will continue to meet rising demand for petrochemicals (which are used to make everyday products ranging from smartphones to running shoes) and to fuel transportation by land, sea and air, and this global increase in the use of oil and natural gas is shown in Figure 1.

Within the foreseeable future, this continued growth in global oil demand will continue to require more oil and gas activities such as exploration, production, refining and transportation. This gives more reason to believe that the associated environmental risks can intensify, with the coastal marine environment being a common locality for this to occur, as water is oftentimes the first casualty of oil

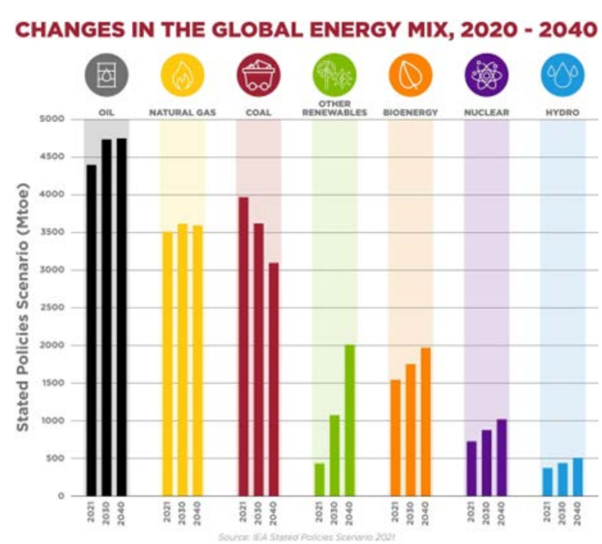

Figure 1. Predicted Changes in the Global Energy Mix
Source: Abstracted from CAPP (2023)

exploration related accidents or faulty operations causing

https://doi.org/10.47412/SETW8054

marine pollution such as oil spills which impacts the quality of the coastal waters. Small island developing states (SIDS) face threats to their freshwater resources from different forms of anthropogenic pollution that can lead to freshwater scarcity (Gheuens et al., 2019; Karnauskas et al., 2018; UNEP, 2014; Guduru, 2020).

One such pollution is oil spills, which are likely to occur in oil-producing SIDS. Trinidad and Tobago is an oil exporting SIDS (Scobie, 2017) with considerable oil and gas exploration and production activities along its coasts, especially along the south-west coast in the Gulf of Paria. These oil and gas industrial activities consume a lot of water, which is usually sourced from freshwater resources, such as groundwater, aquifers, reservoirs or rivers (Allison and Mandler, 2018), which are already in high demand in the residential, agricultural and other industrial sectors of the island. This competition for freshwater resources can engender water scarcity and further increase the demand for fresh, potable water, and so in an effort to provide a solution to this problem while relieving the pressure of the natural freshwater resources for the island’s domestic use, a 50 MIGD (Million Imperial Gallons per Day) desalination plant was installed on the central west coast of Trinidad (https://desalcott.com/) to provide, as well as augment the supply of fresh potable water to the island.

Broadly speaking, desalination produces freshwater from seawater (Kress, 2019; Tahir, 2020). It is the process of removing salts from seawater to obtain freshwater suitable for human consumption and other uses (Asadollahi et al., 2017). The frequency and severity of any underwater and near-surface oil spills can cause stress to the island’s coastal seawaters due to oil contamination that adversely impacts its quality (Kostianoy et al., 2022). This high oil content in the seawater can have a significant impact on the operational capability of a desalination plant, which rely on the intake of seawater (Ogunbiyi et al., 2023). Also, (Ogunbiyi et al., 2023) stated that seawater intake portals are typically located in shallow water, thereby highlighting the possibility of damage to the intake equipment used for desalination when a spill occurs in that area, as is the case in this study. Further, (Ogunbiyi et al., 2023) mentioned that spilled oil can find its way into the intake filter lines, causing biofouling of screen filters, membranes and heat exchangers due to the hydrocarbons. Therefore, the overall efficacy of a desalination plant infiltrated by spilled oil will be severely compromised. Hence, it is clear that oil spills pose a risk to equipment failure in desalination plants. Therein lies the possibility of disruption to the supply of freshwater to the island’s main state-owned public utility water supply, as well as other areas of Trinidad, if an oil spill occurs in the Gulf of Paria. This paper therefore identifies and discusses the potential impacts of a near surface oil spill due to a broken jetty pipeline in the Gulf of Paria on potable water supply in Trinidad.

On 17th December 2013, an oil spill occurred at a loading jetty at Trinidad’s largest state-owned oil refinery company (PETROTRIN), in which over 7,000 barrels of oil were released into the Gulf of Paria (FFOS, 2018; Cummings et al., 2015). The loading pipeline broke at a flange joint falling to an angle of approximately 15 degrees to the water surface, resulting in the injection of heavy bunker C fuel No. 6 oil into the shallow coastal waters of the Gulf of Paria. An aerial reconnaissance survey was conducted, and the oil was observed to be trapped underwater at a shallow water depth and travelling horizontally in the direction of the prevailing current before eventually resurfacing at some distance away from the spill site (Cummings et al., 2015).

Figure 2 encapsulates this entire the oil spill flow behaviour in flow field regions. In the near-field region, the oil is being discharged from the pipeline, the oil is suspended in the water column at a shallow water depth in the intermediate field region, and the far-field region, the oil re-surfaces. Note, the encircled area is the focus of the research.

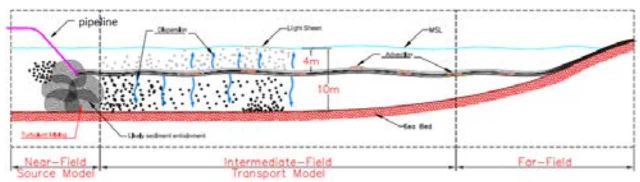

Figure 2. The Entire Oil Spill Behaviour Studied
Source: Abstracted from Felix (2020)

This oil spill behaviour posed great interest because its behaviour fitted none of the two expected main types of oil spills, according to existing literature. The first type, water surface oil spills occurs when oil is spilled directly on the water surface primarily due to oil vessel accidents and leakages. Oil spilled on the water surface forms a surface slick, which is acted upon by a number of oil weathering processes that transform the oil over time and determine its fate. Figure 3 shows the typical configuration of a water surface oil spill and the different oil weathering processes.

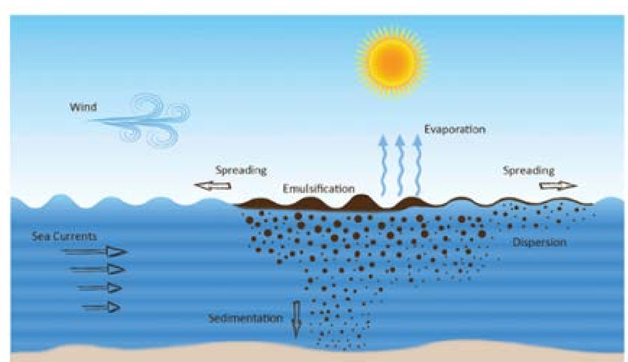

Figure 3. Typical Water Surface Oil Spill Flow Configuration
Source: Based on Zodiatis et al. (2017)

Hence, most water surface oil spill models are designed to simulate these processes, as well as to determine the transport of the oil (Keramea et al., 2021; Zodiatis et al., 2017; Mishra, 2015; Berry et al., 2012; Zelenke et al., 2012; Lardner et al., 2006; Annika et al., 2001; Reed et al., 2004; Daniel et al., 2003; Lehr, 2002; Lardner et al., 1999). The second type, underwater oil spills, occur due to blowouts and underwater ruptured pipelines. These oil spills usually possess a near-field jet flow which is a flow behaviour driven by momentum and a far-field plume flow which is a flow behaviour driven by buoyancy. Hence, underwater oil spill models are developed to simulate both the jet and plume flow behaviours (Lardner and Zodiatis, 2017; Yapa et al., 2012; Yapa and Li, 1997; Yapa et al., 1999).

Figure 4 shows the configuration of the common form of an underwater oil spill, consisting essentially of the formation of two plumes. The first plume is due to momentum of the initial oil jet very near the source and also the buoyancy of the oil and gas plume mixture since in underwater blowouts, gas usually comes out with the oil forming a mixture of gas hydrates and oil. Therefore, in the near-field area, the oil shows a jet and plume behaviour. The other plume is due to the buoyancy of the individual oil droplets separating from the first plume, this plume moves in the direction of the prevailing current. The more buoyant oil droplets rise to the water surface, allowing the underwater oil spill to become obvious to the public.

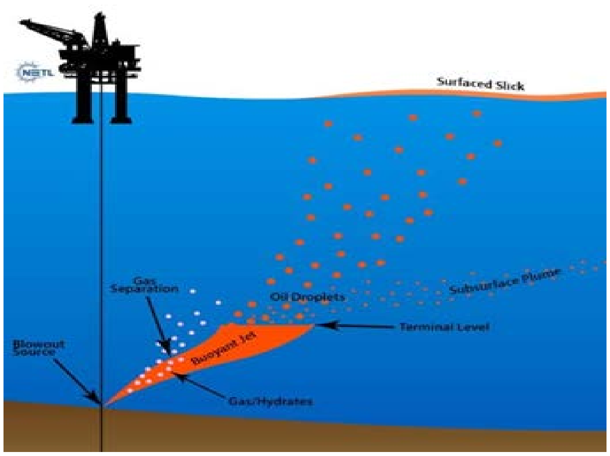

Figure 4. Typical Underwater Oil Spill Flow Configuration
Source: Abstracted from Sim et al., (2015)

The configuration of the oil spill under study does not conform to typical water surface oil spills that are usually spilled directly on the water surface. Figure 5 shows a jet and plume behaviour which are characteristics of underwater oil spills. This limited the use of existing water surface oil spill models. Therefore, it was necessary to determine the mechanism that allows the oil to become suspended underwater at a shallow water depth and travelled a significant distance before seemingly precipitously re-surfacing on the beach. A different approach had to be employed to capture the features of this oil spill.

This study investigated the oil spill behaviour by developing a novel water surface oil plume model. The model was based on integral bubble plume theory (Milgram, 1983; MacDougall, 1978; Socolofsky and Adams, 2002) and numerical mathematical modelling techniques (Lardner and Zodiatis, 2017) to produce trajectory plots of the oil movement underwater for different values. The three important dimensionless parameters included the entrainment of seawater into the plume, the detrainment of the plume fluid into the seawater and the drag coefficient to determine the force on the lateral boundaries of the plume as it moves through the seawater (Felix, 2020). This expansion in the range of modelling techniques allows for the determination of the fate and transport of an oil spill exhibiting such features.

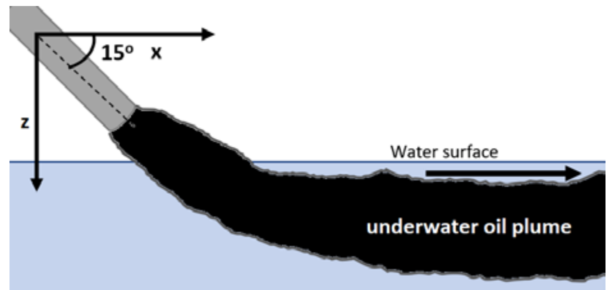

Figure 5. The configuration of Oil Spill Behaviour Studied
Source: Abstracted from Felix (2020)

Having tools to predict such a phenomenon will be an important aid for quantifying the threat to the desalination plant and perhaps help in developing operational procedures to monitoring water quality and modifying plant operation. This paper infers the results of the model to the potential possible impacts of the suspended underwater oil plume due to a long residence time in shallow water depths of the Gulf of Paria on the island's water supply.

2. Methodology

Existing water surface oil spill models are not sufficient to handle the water surface oil spill described in this research. Therefore, it was useful to consider the modelling behaviour of underwater/subsurface oil spills, since the oil spill research problem herein, can be conceptualised as an underwater spill turned on its head, and more importantly, it involves oil jet and plume behaviours.

2.1 Mathematical Modelling

The mathematical modelling methodology involved three main modelling steps. The first step involved the derivation of the single-phase plume flow in a cross-flow current, with the effect of the entrainment of the ambient seawater fluid into the buoyant oil jet. Single-phase plume flows involve the dynamics of the same phase, for example, sewage water discharge from outfall discharges or heated water plumes from cooling plants.

In single-phase plumes, the buoyancy is mixed with the bulk fluid (North et al., 2011; Socolofsky, 2001). The advection of buoyancy is controlled by the motion of the fluid. The equations derived were the continuity equation, the horizontal and vertical momentum equations and the buoyancy flux equation, the spread equation, the x-direction geometric equation and the z-direction geometric equation. These equations form the basic mathematical model which incorporates the two-phase plume flow. For this single-phase plume flow step, the research followed the work of Wood (1993) and Gaskin (1995).

The second step involved the modification of the equations in Step 1 to introduce the two-phase oil plume flow. The two-phase bubble flow is a flow of gas and liquid. Now, the main feature of two-phase bubble plume models is the separation of the dispersed phase from the continuous phase. This is due to an important variable called the slip velocity (Milgram, 1983). The slip velocity is the rise velocity of the dispersed phase relative to that of the surrounding liquid oil phase.

This research is focused on an oil spill that involved an oil plume in seawater, so the existing two-phase bubble plume model of an oil and gas mixture in seawater was to guide the derivation of the equations to make the research model equations suitable and novel to handle the research problem. First, in the work done by Milgram (1983), there was a slip velocity, however, for the research model, the slip velocity was set to zero, thereby making the oil plume fluid a homogeneous mixture. According to Milgram (1983), ambient cross-flow was not included and vertical density variation was in the gas fluid and not in the seawater. However, for this model, vertical density variation was implemented in the seawater, and ambient cross-flow current was included.

Moreover, the model did not cater for an inclined jet, so the jet angle of 15^o to the water surface was included. Another significant difference of existing two-phase bubble plumes is that they are usually vertical flows since they stem from underwater blowouts. The oil spill flow studied herein is predominantly a horizontal flow. To capture the behaviour of the oil flow plume under study, a mixture of both the water and oil densities were incorporated into the momentum equations, with the water density being a function of depth, thereby making the model an acceptable model for the research problem. The two-phase set of equations that were derived included water mass volume flux equation, oil mass volume flux equation, horizontal momentum equation, vertical momentum equation, buoyancy flux equation, x-horizontal geometric equation, the z-vertical geometric equation and the spread equation.

2.2 Two-fluid Oil Plume Flow Model Equations

Step 3 involve the introduction of the two-fluid oil plume flow model. Interestingly, because of the complexity of the equations derived in Step 2, an equivalent set of equations were further derived with equal rigor and robustness of the original set of equations in Step 2. The recent work of Lardner and Zodiatis (2017) was used to guide the derivation of the two-fluid oil plume. Although their work focused on subsurface spills, they used integral theory for the derivation of the governing oil spill flow equations of mass, momentum and buoyancy and treat the oil spill as a plume model under similar key conditions to the flow studied herein. These conditions stated in (Lardner and Zodiatis, 2017) included: the absence of a slip velocity (i.e., a homogeneous system), it can allow for jet angle inclination and the effects of entrainment of seawater into the plume and detrainment of oil into the seawater are considered and the ambient water density is a function of depth (i.e., vertical ambient stratification). Based on the work of (Lardner and Zodiatis, 2017), the final equations were developed to solve the oil spill flow problem. These equations are listed as follows:

The mean vertical velocity profile,

$$u_{eg}(r, s_{eg}) = U_{eg}(s_{eg})e^{-\frac{r^2}{b^2(s_{eg})}} \tag{1}$$

The local mean oil fraction,

$$f(r, s_{eg}) = c(s_{eg})e^{-\frac{r^2}{\lambda^2 b^2(s_{eg})}} \tag{2}$$

$$\rho(r, s_{eg}) = f(r, s_{eg})\rho_o + \left(1 - f(r, s_{eg})\rho_w(z)\right) \tag{3}$$

The total mass flux equation,

$$\varphi(s_{eg}) = \int_0^\infty \rho(r, s_{eg})u_{eg}(r, s_{eg})2\pi r dr \tag{4}$$

The oil mass flux equation

$$\varphi_o(s_{eg}) = \rho_o \int_0^\infty u_{eg}(r, s_{eg})f(r, s_{eg})2\pi r dr \tag{5}$$

The total momentum flux equation,

$$M(s_{eg}) = \int_0^\infty \rho(r, s_{eg})u_{eg}^2(r, s_{eg})2\pi r dr \tag{6}$$

The total buoyancy flux equation,

$$B(s_{eg}) = g\int_0^\infty [\rho_w(z) - \rho(r, s_{eg})]2\pi r dr \tag{7}$$

The conservation of total mass in the plume,

$$\frac{d\varphi(s_{eg})}{ds_{eg}} = 2\pi b(s_{eg})[U_{eg}(s_{eg}) - U_\infty \cos\alpha_r(s_{eg})](\alpha\rho_w(z) - \beta\rho_o) + 2\pi b(s_{eg})U_{eg}(s_{eg})U_\infty \sin\alpha_r(s_{eg}) \tag{8}$$

The conservation of the oil in the plume,

$$\frac{d\varphi_o(s_{eg})}{ds_{eg}} = -2\pi b(s_{eg})c(s_{eg})[U_{eg}(s_{eg}) - U_\infty \cos\alpha r(s_{eg})]\beta\rho_o \tag{9}$$

The horizontal momentum equation in cross-flow,

$$\frac{dM(s_{eg})}{ds_{eg}} = -C_d\rho_w(z)2\pi b(s_{eg})U_{eg}^2(s_{eg}) + B(s_{eg})\sin\alpha_r(s_{eg}) + U_\infty \cos\alpha_r(s_{eg})\frac{d\varphi(s_{eg})}{ds_{eg}} \tag{10}$$

The vertical momentum equation in cross-flow,

$$M(s_{eg})\frac{d\alpha_r(s_{eg})}{ds_{eg}} = B(s_{eg})\cos\alpha_r(s_{eg}) - U_\infty \sin\alpha_r(s_{eg})\frac{d\varphi(s_{eg})}{ds_{eg}} \tag{11}$$

The spatial x-coordinate,

$$\partial_{seg} z\left[s_{eg}\right] = \sin\alpha_r\left[s_{eg}\right] \tag{12}$$

The spatial z-coordinate,

$$\partial_{seg} x\left[s_{eg}\right] = \cos\alpha_r\left[s_{eg}\right] \tag{13}$$

This integrated thirteen-equation approach, derived in (Felix, 2020) simulates the movement of the liquid oil in seawater. These equations were solved in MATHEMATICA. This two-fluid oil plume flow model caters for liquid oil (fluid 1) in seawater (fluid 2). It was developed to simulate the underwater behaviour of oil spills located at the sea surface that particularly behaves as a jet due to a protruding oil source (e.g., a broken pipe) into shallow ocean depth (< 10m) with slight vertical density variation and crossflow current.

3. Results

The model developed is a phenomenological type that considers parametric changes to observe a particular phenomenon or flow behaviour. A number of flow cases were set up under certain parametric conditions to observe the different flow behaviours (Felix, 2020). The results take the form of a set of trajectory graphical plots, in which the blue line represents the oil path. The following oil spill data was incorporated into the model:

- The angle of the discharge source (jet angle) is at 15 degrees to the water surface.
- The oil has an API gravity of 13.6, hence its specific gravity can be calculated to be 0.98.
- The density of the oil is 974.21kg/m^3.
- The discharge velocity of the oil is 1m/s
- while the seawater velocity is 0.2m/s.

The main parametric values are the drag coefficient, the rate of entrainment and the rate of detrainment. Table 1 shows the conditions that allow the oil to become neutrally buoyant, the trajectory plot associated with this condition is shown in Figure 6. Figures 7(a) and 7(b) are plots that show the suspended travelling a horizontal distance of 500m and 300m, respectively.

Table 1. Parametric Conditions for the Oil to Become Suspended/Neutrally Buoyant

Jet Angle, α_r	Drag Coefficient C_d	Rate of Entrainment, α	Rate of detrainment, β	Oil Velocity, U_o	Seawater Velocity, U_∞	Oil Density ρ_o
-15^0	0.00008	0.007128	0.00007	1m/s	0.2m/s	974.21kg/m^3

4. Discussion

The water surface oil plume model allows users to make the most appropriate values of the main parameters to determine the underwater trajectory of an oil plume. Figure 6 shows the results of the main model, as it depicts the oil becoming suspended in the water column. This plot

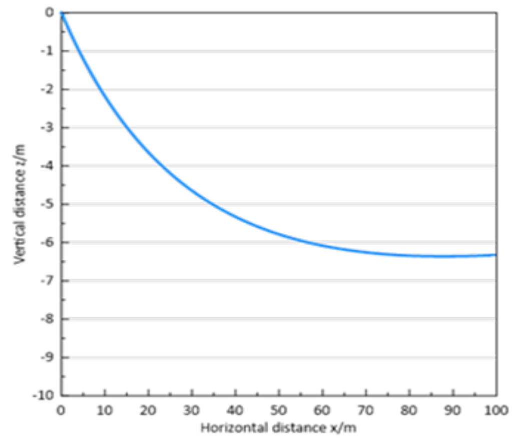

Figure 6. Trajectory Plot for Oil-water Plume Flow under Conditions for Oil to Become Suspended or Neutrally Buoyant

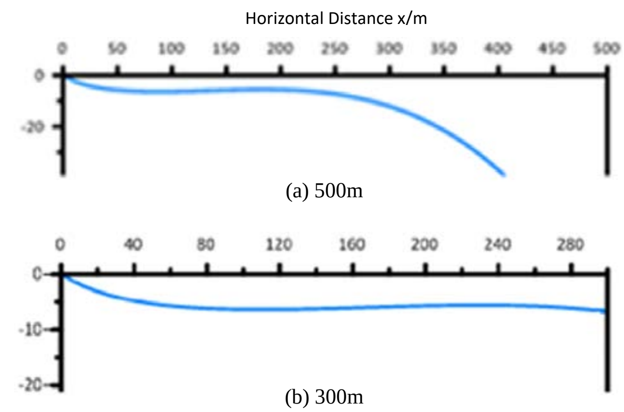

Figure 7. Trajectory Plot for Oil-water Plume Flow under Conditions for Oil to Become Suspended or Neutrally Buoyant at a Horizontal Distance of (a) 500m and (b) 300m

shows that as the oil plume drops below the water surface to a shallow depth between 6 and 7m, it begins to experience neutral buoyancy as the flow appears to be horizontal at a distance of about 70m, and seems to be moving downstream. The oil became suspended as a result of the low ambient velocity and the entrainment of the water into the plume becomes greater than the detrainment of the oil into the water, thereby forming a water-in-oil emulsion (Mishra, 2015). The emulsion is voluminous, viscous and stable over time, which means it can persist for some time after the spill has occurred (NASEM, 2022; Ulker et al., 2022).

The formation of the oil plume emulsion along with ambient stratification enable the oil to become trapped in the water column and be carried downstream by the ambient current due to its high viscosity. This main model result is verified by the observations of an aerial survey stated in the local unpublished oil report (Cummings et al., 2015). A long, narrow patch of oil appears to be trapped within the water column and hence under the water surface. Figure 7(a) shows the plot of the oil plume falling underwater, remaining suspended at a shallow water depth and travelling a horizontal distance of a little over 250m before moving downwards towards the seabed. This indicates that the water-in-oil emulsion form of the plume has travelled a significantly long distance, before eventually destabilising and in this case, falling onto the seabed. The results show the model's capability to capture the flow behaviour of the oil falling onto the seabed, since it was thought that the oil immediately resurfaced after being suspended and moving for a long distance (Cummings et al., 2015).

It can therefore be strongly inferred from this result that when the oil sank onto the seabed, it adhered to the sediments on the seabed, a weathering process referred to as sedimentation (NASEM, 2022) and then become acted upon by a wave-shoaling induced action/motion which eventually pushed it onto the beach in the form of black, thick tar balls as is described in Cummings et al. (2015). It is important to note that wave shoaling is the change in shape and behaviour as the wave propagate into water shallower water, resulting in increased wave height and decreased wave speed and wavelength (Bryan et al., 2020).

Figure 7(b) is another plot that shows the extent of the distance the oil travelled before destabilising. This plot indicates that the model can show that the oil can be suspended for a significant distance before becoming disrupted. Based on the water surface models seen throughout literature, this phenomenon has not been fully captured in this way (that is, the movement of an oil spill travelling at such long horizontal distance underwater) by existing oil spill plume models.

According to Tahir et al. (2020), oil spill in seawater causes changes in its thermos-physical properties such as density, pressure, temperature, thermal conductivity and dynamic viscosity. With the model results indicating that the oil plume travelled underwater for a significant horizontal distance, implying its high residency in the water column before destabilising, it can be deduced that the thermos-physical properties of the oil contaminated seawater may have been impacted in such a way that can cause increased difficulty in treating it to an acceptable quality for human consumption. From the model results, it can be inferred that the submerged emulsified oil can destroy the efficiency of the desalination plant by potentially coating the seawater intake equipment. Tahir et al. (2020) stated that oily seawater intake reduces the thermal performance of the heat exchangers, leading to a decrease in the productivity of distilled water. Another impact of the submerged oil is that it can lead to fouling of the heat transfer tubes and disruption in the heat transfer process, since in general oil adheres to heat transfer surfaces.

5. Conclusion

The results confirm that oil spills adversely impact coastal seawater quality and are indeed a threat to desalination plants. Oil in seawater makes the desalination process challenging. Since most types of oils do not get mixed with water, due to their lower density, they typically cannot be extracted via the desalination process. Hence, desalinated water containing oil would also affect the quality of the produced freshwater.

An oil spill can lead to the shutting down of the desalination plant which in turn can disrupt the production of freshwater supply for the island. The work done in this study shows that analysing the potential impacts of oil spills on desalination plants can aid in the policy-making decisions for informing suitable site selection for a desalination plant, as well as determining acceptable seawater quality to decrease the vulnerability to desalination plants allowing them to provide constant freshwater supply to the island.

The spill occurred in the Gulf of Paria, which is a semi-enclosed sea located between Venezuela and Trinidad in the southern Caribbean, known to experience significant current reversal along its coast. Hence, in this oil spill event, the results of the oil spill trajectory confirmed that the desalination plant was not threatened because it was located north of the spill location and the slow-moving prevailing current at the time of the spill carried the oil plume southward. Under these conditions, any desalination plant built south of the spill site or downstream of the prevailing current of the spill site will be under threat and may have interruption of its operations for supplying potable water to the island.

However, the situation could have been quite different if at the time of the spill, under certain climatic and ambient conditions, for example rain or wind and strong Orinoco river flow from the Venezuela mainland, the prevailing current was reversed and was instead northward. The application of the model under such circumstances would show movement of the oil plume northwards and in the direction of the desalination plant, this would have adversely threatened the operations of the desalination plant.

This research is concerned with the mechanism that enabled the suspension and horizontal underwater transport of an oil plume in the water column at shallow water depth, due to an oil spill originating from an acute-angled broken pipeline at the water surface, issuing heavy fuel oil into the near-shore coastal waters in the Gulf of Paria. The results provide useful insights for supporting informed decisions when developing spatial plans for sighting desalination plants in the event of accidental oil spills in coastal waters.

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The Impact of Climate Change on the Upper Navet Reservoir, Trinidad

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Abstract: *A hydrologic study of the Upper Navet Reservoir and its catchment was conducted to investigate and evaluate the potential impacts of climate change on it, using the soil moisture accounting algorithm in HEC-HMS to perform continuous simulations. The catchment is partially gauged, with a single rainfall gauge located within it. With the absence of a stream gauge, recorded stage data from the reservoir was used to evaluate catchment response. The selection of model parameters was based on previous work on the nearby Nariva catchment that was improved by a manual optimisation technique. The model was subject to a split-sample test with a calibration period of 24 months (2003-2004) on a daily time-step followed by validation over a period of 60 months (2005-2009). The validated model was used to evaluate the system's response to climate change. The meteorological data for this was generated by the PRECIS software for this region. The model was subject to three data sets based on the SRES A1B scenario. The results of simulations conducted for the period 2030-2096 showed that for continuous operation, production rates at the Navet reservoir require a 40% reduction of present values for two of these scenarios and 30% for the most optimistic scenario.*

Keywords: *Climate change, Hydrologic modelling, Water supply, Navet reservoir, Trinidad and Tobago*

Acronym	*Meaning*
WASA	*Water and Sewerage Authority*
WRA	*Water Resources Agency*
NWW	*Navet Water Works*
NRS	*Navet Reservoir System*
NRU	*Navet Reservoir Upper*
NRL	*Navet Reservoir Lower*
PRECIS	*Providing Regional Climates for Impact Studies*
HEC-HMS	*Hydrologic Engineering Centre Hydrologic Modelling System*
CROPWAT	*Crop Water Requirements*
CSGM	*Climate Studies Group Mona*
HadCM3	*Hadley Centre Coupled Model, version 3*
RCPs	*Representative Concentration Pathways*
SMA	*Soil Moisture Accounting*

1. Introduction

The Water and Sewerage Authority (WASA) of Trinidad and Tobago has the mandate to deliver a safe, reliable and efficient water supply to satisfy the demands of all sectors of its population. In recent decades, however, it may be perceived that the authority has faced an increasing challenge in meeting this mandate. This becomes particularly evident during the months of May to August each year when the islands' surface water reservoirs approach their minimum pool levels. Water management strategies such as rationing and use restrictions often result in constrained commercial activities, short-term closure of water dependent businesses and a general angst amongst citizens about short-term availability.

Regionally, there are predictions of more frequent and intense storm events and hurricanes. These effects can lead to changes in the total precipitation, its seasonal distribution, frequency and intensity. These conditions together with changes in evapotranspiration may affect the magnitude and timing of runoff, and subsequently, the intensity of floods and droughts (GORTT, 2017).

Historically, Caribbean territories have not been as severely impacted by droughts as other parts of the world and when they do occur, reactive responses have resulted in short-term solutions. However, the occurrence of droughts is a normal part of climate variability (Peters, 2015) and since there is evidence that both the duration and frequency of droughts are increasing, there is need for studies of the long term impacts and the development of strategies to improve resilience to future droughts.

A meteorological drought analysis performed by Beharry et al. in 2019 using 35 years (1980-2014) of monthly totals from fourteen rainfall stations across Trinidad identified drought variability between stations in the north and central regions of the island. The stations at the island's three major reservoirs, Arena, Hollis and Navet shown in Figure 1 were among those analysed. Over the study period, it was found that the frequency of

https://doi.org/10.47412/TUZH7133

meteorological droughts decreased at the Hollis Reservoir, while at the Navet Reservoir there was an increase, implying a drying pattern and possible adverse effects on the water resources of Trinidad (Beharry, et al., 2019).

Figure 1. Map of Trinidad showing the location of the Hollis, Arena and Navet Reservoirs
Source: Google Earth (2023)

With multiple authors such as Wilson and cooper (2017) identifying the need for further specific studies to understand the impact of climate change on our water resources, this research looked at the potential impacts of climate change on the hydrological response of the catchment of the Navet Reservoir. The method of approach involved the use of predicted hydro-meteorological data input to a hydrologic model of the catchment to gauge its future response.

The completed Upper Navet Dam and the Navet Water Works (NWW), an onsite water treatment plant, was commissioned in 1962 to service the southern capital of San Fernando and its suburbs. Since then the facility has undergone two major upgrades, firstly in 1966 when its original daily output of 27,500 m^3 was improved to 50,000 m^3. The second came with the completion of a second, lower dam in 1976 which increased output to 86,400 m^3 per day. The lower reservoir has a production capacity of 45,400 m^3/d (Phelps, 1981). At this time, it would have been the major water source on the island of Trinidad until the Caroni Arena project was completed in 1981.

The Navet Reservoir System (NRS) consists of interconnected dual reservoirs as shown in Figure 4, their catchments and the (NWW). The larger reservoir is the second largest of the three surface water impoundment facilities operated by the WASA on the island. For this article, the reservoirs will be referred to as the Navet Reservoir Upper (NRU) and the Navet Reservoir Lower (NRL). The NRU is the larger of the two reservoirs, with a storage capacity of 18.6 million cubic meters and was created by the damming of the Navet River and a major tributary. Its catchment is approximately 17.57 km^2. The NRL is downstream and intercepts the Navet River and a second tributary, it collects water from a lower catchment 9.13 km^2 in size and adds a further 4.3 million cubic meters of storage capacity to the NRS (Shrivastava, 1999). Overflow from the NRU continues along the Navet river which eventually enters the NRL. Water is pumped from the NRL to the NRU to supplement its storage capacity.

HEC-HMS, the hydrologic model used to simulate the response of the NRS, is categorised as a conceptual model. It uses a number of conceptual, interconnected reservoirs which represent the physical elements in a catchment as illustrated in Figure 2. These elements are recharged by rainfall, infiltration and percolation, and are emptied by evaporation, runoff, drainage and seepage. Semi-empirical equations describe how fluxes are transferred between the conceptual reservoirs. The values of the variables in these equations are determined from model calibration using observed hydrological data.

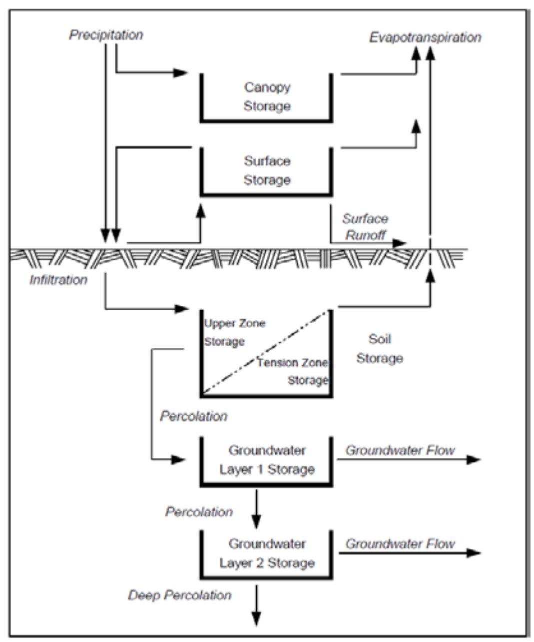


Figure 2. Conceptual Schematic Soil Moisture Accounting (SMA) Model
Source: Abstracted from Bennett and Peters (2000)

The challenge in using this type of model is that its parameters, although related to the physical features within the catchment are not measurable. This can lead to the selection of unrealistic parameter values while attempting to calibrate the model. Traditionally, this has made these types of models undesirable for use on ungauged catchments since calibration may be challenged. However, work by researchers such as Fleming and Neary in 2004 to relate the parameter values to physical measurable catchment properties has enabled the estimation of the major model parameters from its physical features, and observations of streamflow records.

Meteorological data on climate change were derived from outputs of the PRECIS (Providing Regional Climates for Impact Studies) software. PRECIS is a regional climate model used to downscale global circulation models to a regional level. This consisted of daily rainfall, maximum and minimum temperatures.

The hydrological model of the NRS was created within the Hydrologic Engineering Centre Hydrologic Modelling System (HEC-HMS) software. After successful calibration and validation stages, the meteorological data obtained from the regional climate model was used as input to the hydrological model. Model outputs gave an insight to the response of the catchment to possible future conditions. The results of this approach can become an effective tool in guiding water management strategies for the future. Therefore, the objectives of the study were (1) to calibrate, (2) to validate a hydrological model of the NRS, and (3) to evaluate the hydrologic response of the NRS to anticipated climate change.

2. Methodology

The HEC-HMS 4.4 software used to create the conceptual model of the NRS was designed to simulate the complete hydrologic processes of dendritic watershed systems (HEC, n.d.) and is a public-domain model which has been in existence since 1992. Modelling of the NRS was done in four phases. In the initial phase, a basin model of the NRS was configured where hydrologic elements were created and linked. Parameter values were then assigned to these elements and the processes linking them. There are four elements in the basin model, which are shown in Figure 3.

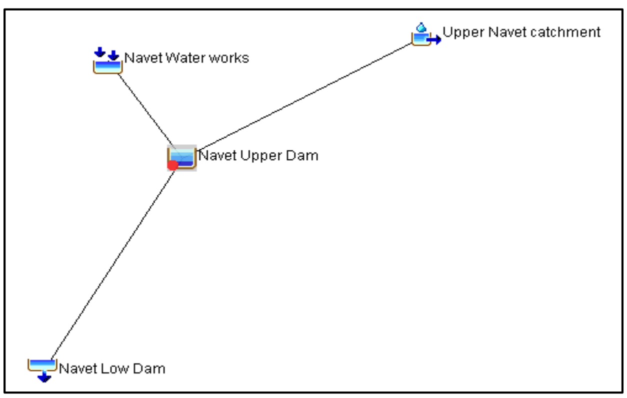


Figure 3. Basin Model of the NRS

The NWW element was created as a Sink, since it draws water from the NRU and, the NRL was created as a Source, as it supplies water to the upper reservoir. The catchment of the upper reservoir was created as a sub-basin element which allows its hydrologic processes to be simulated. This element inputs flows to the upper dam as a catchment output. The NRU was created as a reservoir element accepting inflows from both the low reservoir and upper catchment. Water leaves this element via pumping to the NWW and as overflow via the spillway. Water removal via the spillway is not shown in the basin model.

The second phase was a calibration process. This allowed the suitability of the model for representing the NRS to be determined. Observed meteorological data for a select period was input to the model and a comparison made between the modelled output and observed data for the same period. Each model parameter value assigned in the initial phase can vary within a realistic range, which is dependent on the physical properties of the catchment. During model calibration these parameter values are varied within their ranges until the model output is a good fit to observed values. An optimal combination of these parameter values is required for the modelled output to represent the catchment response. In HEC-HMS this parameter optimisation procedure can be automated where an algorithm continuously tries combinations of parameter values and compares its output to known outputs such as streamflow records. This approach could not have been used because of missing streamflow records for the catchment. Instead, catchment response was assessed using the daily water level records for the NRU. A manual trial-and-error method was used to find the best set of parameter values, with the goodness of fit between simulated and observed lake levels being checked with each iteration.

Model validation followed the calibration phase and was done using a split-sample test (SS). Refsgaard and Knudsen (1996) defined the process of validation as demonstrating that a site specific model can make accurate predictions outside of the calibration period. The model is considered validated when it produces results within an acceptable range of the observed condition. For this phase, meteorological data from a second period (outside of that used for calibration) is used to assess the modelled output by comparing it to observed lake levels for that period.

In the last phase, the validated model was used to simulate the response of the hydrologic system to hypothetical future conditions and so obtain a measure of its vulnerability to future climate. This phase used future rainfall and temperature predicted by the PRECIS model. A time-series for both rainfall and evapotranspiration for the period of 2030 to 2096 formed the meteorological data set used in this phase. Evapotranspiration was derived from the temperature time series using the Penman-Monteith Equation. For inputs from the lower reservoir, future values of course depend on the available rainfall as water in the lower reservoir is derived from runoff from surrounding lands.

It was assumed that the prevailing relation between lower reservoir withdrawal and rainfall would apply. With these inputs, a series of simulations was performed for each future scenario, as follows: The initial production was according to the existing values. The output lake level time series was examined to determine whether such a production rate could be sustained during the period, that is, the reservoir did not become empty. If such production could not be sustained, then a subsequent simulation was done, using 95% of the original production level. Subsequent simulations were performed each new one having a 5% reduction in production level from the previous one. Such continued until a production value that was able to maintain storage in the reservoir during the entire period was found.

3. Model Parameters

3.1 Catchment Characteristics

Information on the physical attributes of the NRS and its catchment was derived from digital shapefiles of land-use, soil types, contours and spot heights using a desktop GIS software. A watershed layer and a digital elevation model (DEM) were used to delineate the catchment boundary of the upper reservoir and other catchment properties such as area, slopes and length of flow paths (see Figure 4). The NRU catchment was represented as a sub-basin element in the basin model. Since its hydrologic response is an inflow to the NRU, its properties were needed for the model setup.

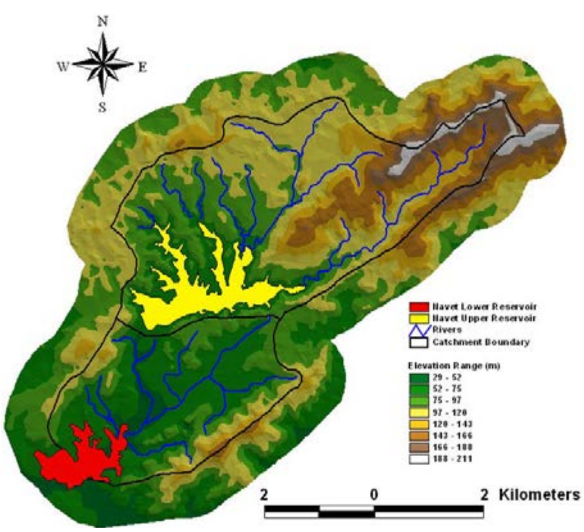


Figure 4. Digital Elevation Model of the NRS and Catchment

3.2 Meteorological Data

Meteorological data retrieved from the Water Resources Agency (WRA) consisted of daily rainfall and evaporation data recorded at the NWW. Daily production volumes from the water treatment plant and water levels in the upper reservoir were also provided. A seven-year period was identified from the year 2003 to 2009, as it was the longest period for which a complete record of daily rainfall was available. This rainfall was treated as being representative of the entire catchment because data from adjacent catchments for the same period was unavailable.

Measured daily evaporation data was limited to 2003-2004 and a few days at the start of 2005. Therefore, an alternate source of evapotranspiration data was sought. The reference crop evapotranspiration values reported by Ekwue et al. (2015) was considered as a possible alternative. The author computed these values for the Navet site by CROPWAT software (Crop Water Requirements) using the Penman-Monteith method. The values were reported as monthly average for the period 2001 to 2012 and are shown in Table 1.

3.3 Meteorological Data for Climate Change

The data used to simulate the hydrologic system response to climate change consisted of estimated daily rainfall totals and daily evapotranspiration values generated by the Climate Studies Group Mona (CSGM) of The University of the West Indies, Mona, Jamaica. These projected values were the results produced by a Regional Climate Model PRECIS (Providing Regional Climates for Impact Studies) which downscaled the global model HadCM3 (Hadley Centre Coupled Model, version 3) to a regional level. The global model was set up for Special Report on Emissions Scenarios (SRES) A1B scenario group. Although the SRES projections were superseded by Representative Concentration Pathways (RCPs) models for the IPCC's Fifth Assessment Report (2014), SRES may still be used for assessments since the underlying models are still applicable (Wilson and Cooper, 2017).

This scenario group develops from the A1 scenario family which describes a future world of very rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies (IPCC Working Group III, 2000). A1B is one of three A1 groups and is described as having a balanced technological emphasis, which is defined as " not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies."

For the NRS, three model simulations were used:

- AENWH which represents the standard unperturbed model for the A1B SRES scenario group (with original parameter settings)
- AEXSA and AEXSK which are based on the AENWH model but with two variations in parameters.

Table 1. Monthly Average Evapotranspiration at the Navet Reservoir

Navet Reservoir	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov	Dec.
ET (mm/mth)	112	106	135	128	116	99	114	124	120	115	89	103

The differences among these three scenarios are described by Wilson and Cooper (2017). By comparing the Intensity Duration Frequency (IDF) curves for all three models, it was noted that:

- AENWH: It shows decreases in intensity of events at most durations, with greater decreases shown for the most extreme events, ranging from decreases of ~30% (1-day, 100-year) to ~15% (10-day, 100-year).
- AEXSA: It shows increases in intensity for all events, with the largest proportional increases in smaller more frequent events (e.g. the 2-year, 4-day event shows an increase of ~80%).
- AEXSK: It shows increases in intensity for more frequent events (2, 5 and 10-year), but decreases in the less frequent, larger events (50 and 100-year) (Wilson and Cooper, 2017).

3.4 Reservoir Operations

Recorded daily water production values, reservoir levels and water extraction from the lower reservoir were used to represent the reservoir operations. The water removed from the upper reservoir for treatment at the NWW is taken as the main output from the system while lower reservoir production values represented the water pumped into the upper reservoir to maintain its storage capacity above the minimum pool level.

The spillway crest of the upper dam was modelled as a broad crested weir 10m wide (Errol Clarke Associates, 1999) using a coefficient of discharge of 1.6 (typical value used for this type of weir) with a crest elevation of 94.7m. This elevation represented the 100% storage capacity of the reservoir. An elevation-discharge curve was generated for the spillway using the general weir equation. The maximum elevation used on the spillway curve was 95.7m which is just above the maximum lake level observed for the study period. This equation also allowed spillage volumes to be evaluated by the model and simulate the filling and emptying of the reservoir. Water levels above the maximum storage elevation was removed from the reservoir as spillage. This water empties into the Navet River and contributes to the inflow to the lower reservoir.

The daily storage capacity of the upper reservoir was calculated, using the daily reservoir levels provided and its storage elevation curve. An elevation-surface curve was used to find the surface area of the reservoir and to estimate daily evaporation losses.

4. Model Setup

4.1 Basin Model

The basin model used to describe the NRS consists of the upper reservoir which collects runoff from the Upper Navet catchment as well as a pumped supply from the Navet low reservoir. Water is extracted from the upper reservoir to supply the Navet waterworks which in turn outputs potable water to WASA's distribution network. The lower reservoir is located downstream along the Navet River which was dammed to form the upper reservoir. This reservoir collects runoff from a separate downstream catchment as well as excess water whenever the upper reservoir spills.

4.2 Soil Moisture Accounting

The setup of the SMA within the HEC-HMS software requires the input of values for sixteen parameters. Wilson and Cooper (2017) compiled a range of parameters by examination of those listed in literature. Based on knowledge of the physical properties of the Nariva catchment, values of parameters were recommended. These parameters were used to model the hydrologic processes of interception, surface depression storage, infiltration, soil storage, percolation, and groundwater storage. The maximum depths of each storage zone, the percentage that each storage zone is filled at the beginning of a simulation. The transfer rates (such as the maximum infiltration rate) are required to simulate the movement of water through the storage zones. Besides precipitation, the only other input to the SMA algorithm is a potential evapotranspiration rate (Flemming and Neary, 2004).

4.3 Meteorological Models

A meteorologic model within the HEC-HMS tells the model how meteorological information is to be used. For continuous simulation of the hydrology of the catchment, evapotranspiration (ET) is a key component. This information is entered into the model as a time-series or alternatively an internal algorithm can model potential evapotranspiration using climatic data such as observed longwave and shortwave radiation.

For the NRS during the period of study from 2003 to 2009, there were two possible sources of evaporation data available for use in the meteorological model. These were:

- Measured daily pan evaporation at the Navet Dam site for the period of 2003-2004 (2 years), and
- Daily reference crop evapotranspiration generated by the CROPWAT and reported by (Ekwue, et al., 2015) for the period of 2001-2012.

5. Results and Discussion

5.1 Model Calibration and Validation

Model calibration on a daily time step was performed for a 24-month period from 01 January 2003 to 31 December 2004. The plots in Figure 6 show the comparison of observed water levels in the Navet Upper reservoir to those simulated by the model for the calibration. Inputs to the model for the calibration period were:

- Observed total daily rainfall in mm
- Total daily Evapotranspiration estimated from observed pan evaporation data in mm
- Recorded water transfer from the lower reservoir into the upper in m^3/s and
- Recorded raw water extraction from the upper reservoir in m^3/s (see Figure 5)

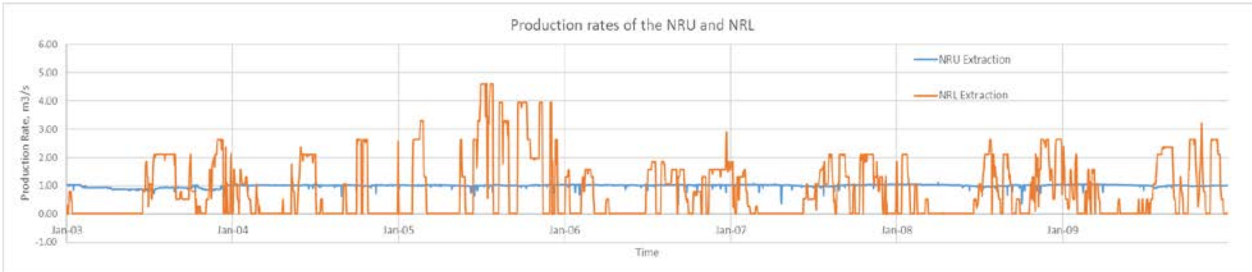


Figure 5. Recorded Water Extractions from the NRU and NRL

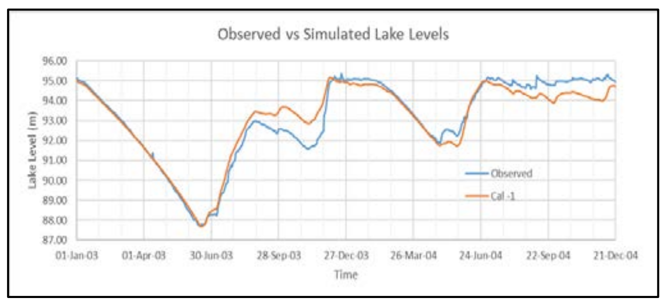
Table 2. Parameter ranges and Calibration values for the SMA

Storage Unit / Flow Component	Parameter	Lower range value	Upper range value	Typical	Values after Calibration
Canopy Storage	Max storage (mm)	1.6	2.2	2.0	2.0
	Crop coefficient	0	1	0.5	0.5
Surface Depression	Maximum storage (mm)	0.5	1.5	1.0	1.0
Soil Profile Storage	Maximum infiltration (mm/h)	4.13	8.13	6.13	**6.22**
	Soil storage (mm)	390	690	540	**450**
	Tension storage (mm)	390	540	470	**380**
	Soil percolation (mm/h)	0.75	1.16	0.89	**0.98**

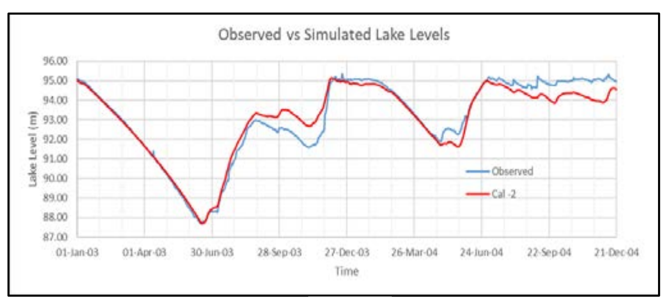
The parameter values of the SMA algorithm within the model was initially set at the recommended values. During the calibration phase, it was found that the model was sensitive to only the four parameters describing the soil storage reservoir as shown in Table 2. Within the SMA, this is called the Soil Profile storage and the model calibration was achieved by optimising the values of these parameters. The model was run multiple times, updating the parameter values until a good fit to the observed lake levels resulted. The range, typical values and the calibration values are shown in Table 2. The other parameter values were left unchanged at their typical values since varying their values within their ranges resulted in undetectable changes in the model output.

The lake level of the upper reservoir was used as the benchmark for the evaluation of the model performance. This data was the only recorded response of the catchment to rainfall input. The observed levels are represented by the blue lines on each of the plots in Figure 6 below. The calibration step used the observed evaporation data (2003, 2004) to create the meteorological model and the model output is shown as the Cal-1 plot in Figure 6 (a). To assess the suitability of the CROPWAT evapotranspiration data, it was used to create a second meteorological model. The hydrologic model was then run with this input. The output is shown as Cal-2 in Figure 6 (b).

The hydrologic model appears to give almost identical outputs to both meteorological models. This was confirmed by a correlation analysis performed on both model outputs, giving identical correlation coefficients of of 0.97, indicating high positive correlation between model outputs using observed evaporation and that generated by CROPWAT. It is for this reason, the CROPWAT data was considered suitable to supplement measured evaporation data for the validation period 2005-2009.



(a)



(b)

Figure 6. Observed Lake level vs Simulated levels for the Calibration Period using (a) measured pan evaporation data and (b) simulated ET from CROPWAT model

Model validation was performed for the 5-year period of 2005-2009. Figure 7 shows the observed levels represented by the blue line on the plot with Val-2 representing the model response during the validation period. This line has a 0.995 correlation coefficient. This high positive correlation for Val-2 indicates an almost perfect simulation of the validation period. This can be attributed to the input data on air temperature, wind speed, humidity, radiation and rainfall used in CROPWAT being collected at the Navet Dam site for a period (2001- 2012) which overlaps the period for this study. The model was successful in simulating the response of the catchment for the validation period. The model accurately simulated both the pattern of the filling and emptying of the reservoir, as well as the observed peaks and lows. It was validated.

Having passed the calibration and validation split sample test, the model was used for predicting the catchment response to climate change. This modelling stage required the generation of hypothetical data sets. The inputs of rainfall and evapotranspiration were available from the PRECIS model for three scenarios, AENWH favours a negative water balance while AEXSA and AEXSK would favour a positive water balance. Daily total rainfall and reference evapotranspiration values for all three scenarios were inputted directly into the model without changing the model parameter values found during calibration and validation.

The study period for using the climate change predictions was 2030-2096 (from 01 January 2030 to 31 December 2096). The extraction of raw water from the upper reservoir fluctuates slightly during the year which is expected because of seasonal changes in demand. Initially, for the purpose of future operation, it was taken to be 1.04 m^3/s which corresponds to the yearly average for the 2003-2009 period. Although an increase in demand can be determined from projected population growth for the future, these impacts were not factored in.

Similarly, a hypothetical time-series for extraction from the low dam was required. There is little information available about the operation of the lower reservoir other than the production values provided for the 2003-2009 period and the assumption that extraction is based on depletion of the upper reservoir. Information available on the WASA website indicates that extraction from the low dam is confined to the latter half of the year, a reasonable assumption since this would coincide with the time of year when the upper reservoir is approaching its low level. Having been depleted during the drier months of the year, water transfer from the lower reservoir is used to increase storage in the upper reservoir while the upper watershed begins to generate runoff during the rainy months.

An examination of production records showed that in addition to this, extraction from the low reservoir occurs during the earlier months of the year. This is seen in Figure 8 which was plotted for 2005. The blue line indicates the low reservoir extraction and the red line the water levels in the upper reservoir. A more reasonable operation scenario is that year round transfer of water to the upper reservoir is done in a manner to achieve the maximum combined storage capacity. If the low reservoir was only used in the latter months of the year, this would mean that it remains at maximum capacity and additional runoff from its catchment passes through the reservoir and empties via its spillway. It would be a more advantageous scenario to keep the lower reservoir below its maximum storage to be able to capture and store as much water as

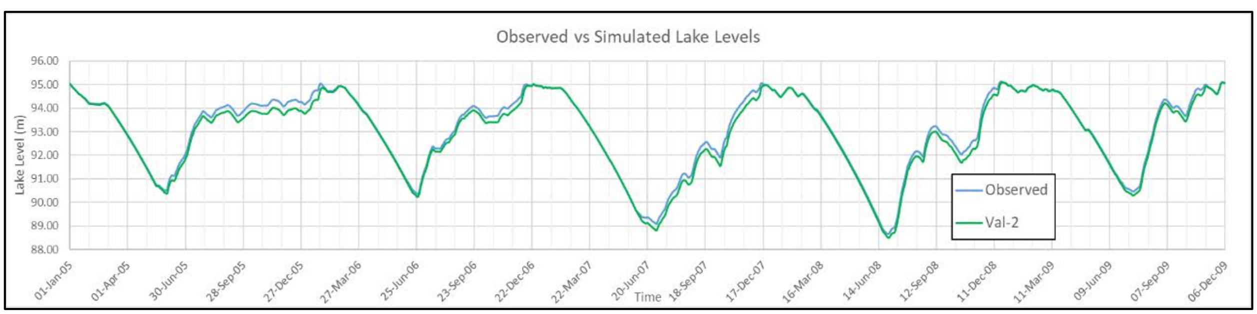


Figure 7. Observed Lake Level vs Simulated levels for the Validation Period

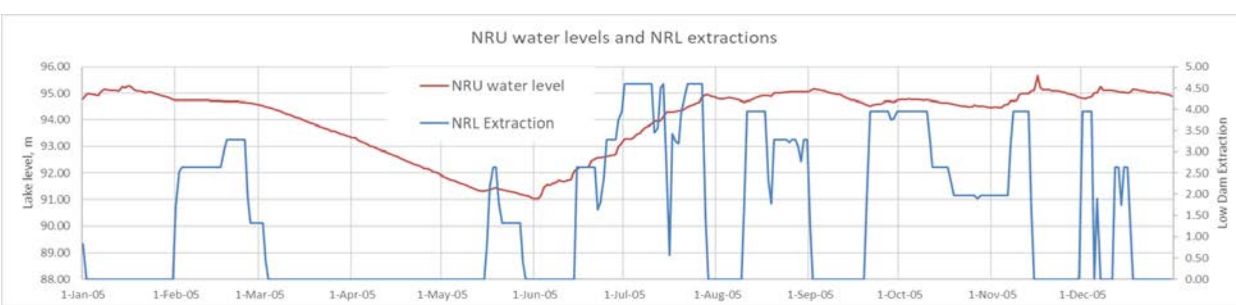


Figure 8. Low Reservoir Extraction and Upper Reservoir Levels 2005

possible. Pumping water to the upper reservoir during periods of significant rainfall during the year.

Assuming that the dam would keep at its maximum storage for periods when it is needed means that it would only be used when there is opportunity for it to be refilled. This suggests water extraction from the lower reservoir may be rainfall dependent. This relation between low reservoir usage and rainfall was examined. A plot of monthly average production from the low reservoir was compared with average total monthly rainfall in the catchment for the 2003-2009 period. There was an observable relationship between monthly rainfall and monthly extractions from the low reservoir, as seen in Figure 9. It suggests that water production from the dam follows the rainfall, with the peak extraction occurring approximately one month after the rainfall peak.

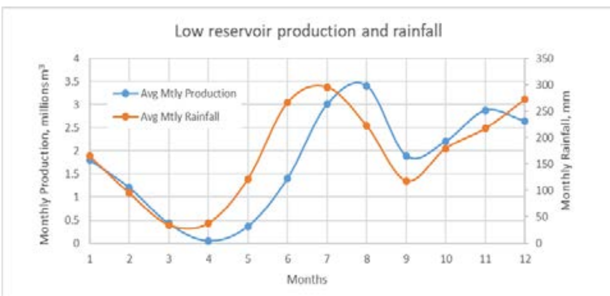


Figure 9. Monthly Low reservoir extraction and monthly rainfall 2003-2009

5.2 Future Operations of the NRS

Using the correlation described, a new time series was generated for the proposed low dam production for the period of 2030-2096. This was achieved by looking at the monthly rainfall for the period 2030 to 2096. The plot showed that the data collected at the Navet site (NWT) exhibits a peak total of 300 mm around July, while the corresponding peak of the predicted rainfall occurs much later on in the year around October. All three climate change models show a similar shift in peak rainfall and, a marked reduction in the total rainfall of approximately 60 mm.

The time series for the average monthly production for the low reservoir is assumed to repeat yearly. Therefore, a shift in the time scale was used to lag the rainfall peaks from the climate models by one month. Figure 10 shows the average monthly production for the period of record and the adjusted values used to generate the new time-series to be used for future operations. The expected reduction in rainfall will impact the available water in the catchment and in turn, that available for extraction from the lower reservoir. There is insufficient data available to model the lower reservoir, namely its storage elevation relationship, and its response to the reduced rainfall. For the purpose of this study, the time-series for use with simulating future operations assumes the low dam supplies water at the same rates however its temporal distribution has shifted.

Having adjusted the extractions from the low reservoir to occur with available rainfall as generated by the climate model, the hydrologic model was run for each of the climate change scenarios for the period 2030 to 2096 using the hypothetical hydrometeorological inputs. For all three scenarios, the upper reservoir was completely depleted before the end of the simulation period, which suggests that based on climate change predictions the NRS cannot supply water at its current rate of production.

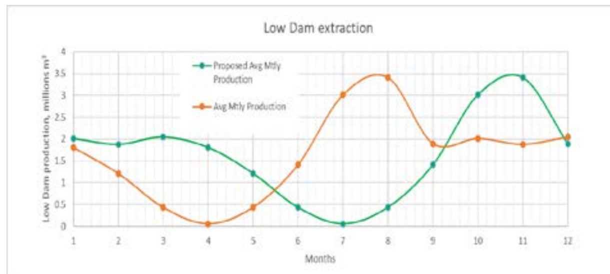


Figure 10. Observed Monthly Low Reservoir Extraction and Adjusted Extraction Used for 2030-2096

To simulate a reduction in raw water extraction from the upper dam, raw water extraction time series were generated with each successive year being 5% lower than the previous. Following this methodology, the raw water extraction was reduced to 95% of present capacity, which correspond to a rate of 0.99 m^3/s. The effect of this change was investigated for the AENWH climate scenario. At the current production rate, the reservoir was depleted before the end of the first year, 2030. Using the reduced production, the reservoir emptied by the end of 2031. Production rates were successively reduced by 5%, and the model run until a value was reached which allowed the model to run until the end of the simulation period. Table 3 shows the trial production rates used and their depletion years.

Table 3. Production Rates Used for the AENWH Scenario

AENWH Scenario		
Production Capacity, %	Production Rate, m^3/s	Reservoir Depleted
100	1.04	Dec-30
95	0.99	Dec-31
90	0.94	Dec-33
85	0.88	Dec-34
80	0.83	Dec-41
75	0.78	Dec-45
70	0.73	Dec-96

The model ran to completion for a drastically reduced production rate of 0.73 m^3/s corresponding to a reduction in production by 30%. A varying reduction in production rate was considered. However, the reservoir was still depleted over time because of the cumulative effect of a previous higher production rate.

A similar method was followed for both the AEXSA and AEXSK climate model scenarios. In both instances, the ultimate production rate was reduced to 0.63 m^3/s which corresponds to production rate which is 60% of present production. This is a simplified consideration of operational strategies. It is unlikely that production rates will remain constant over approximately 60 years and climate change predictions are likely to be more accurate over shorter time horizons.

Reductions in the smaller, more frequent events for the AENWH scenario meant longer dry periods between the less frequent larger events. This can be seen in the model response in Figure 11, with a larger difference between reservoir low-level and high-level elevations. This indicates possible longer periods between rainfall events and high evaporation loss.

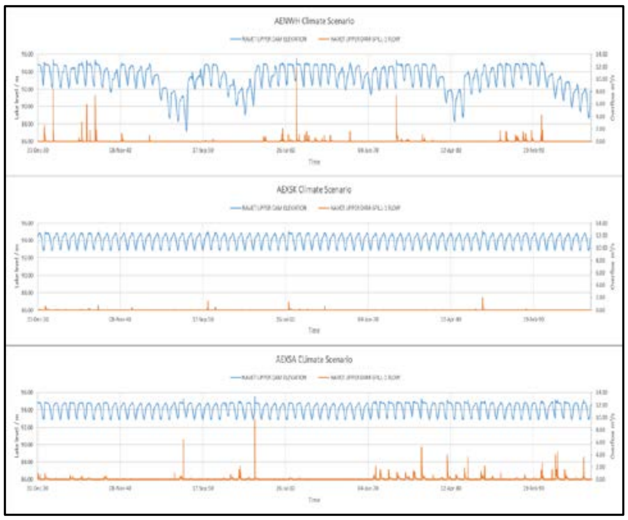


Figure 11. NRS responses to Climate Change Scenarios 2030-2096

The reservoir shows more frequent overflow events than the other two scenarios. These events continue for longer periods when they do occur. This occurs almost yearly for the period of 2059-2065 and can be seen as the horizontal sections of the lake level plot (blue line) in Figure 12. This volume of excess water will eventually be routed to the lower reservoir via the Navet river. The reservoir level reached very close to its low-level mark of 82 m in the years 2048, 2080, 2082 and 2096. It was also observed that these events occurred during periods when there were no overflow events for a number of years prior. These observations are consistent with a reduction in the more frequent smaller rainfall events and an increase in the less frequent larger events.

The AEXSA climate scenario showed the reservoir going through a very cyclic filling and emptying pattern. The range of level between the highs and lows is much smaller than those exhibited for the AENWH scenario. The reservoir under these conditions exhibited a lower sustained supply. This climate model showed an increase in both large and small events. The results of the simulation show that there are more frequent instances of reservoir overflow, although very small in the first 40 years of the simulation but more frequent, larger overflow events after 2071. The more frequent, smaller rainfall events were sufficient to refill the reservoir at a reduced rate of production prior to 2071. However, for post-2071, there would be larger and more frequent overflow events indicating a higher water availability and a possible larger production rate might be supported.

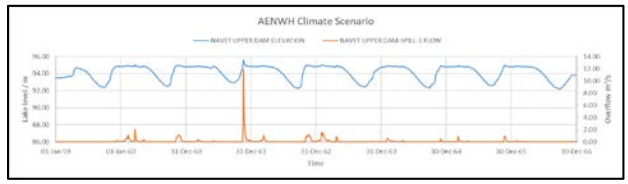


Figure 12. AENWN Overflow Periods, 2059-2065

The AEXSK climate scenario showed an increase in the more frequent smaller rainfall events and a decrease in the less frequent larger rainfall events. This scenario represents the most water scarce scenario of the three. The water levels simulated by the model showed a very cyclic filling and emptying of the reservoir with a very shallow elevation range. This, together with almost non-existent overflow events, indicated that the reservoir received sufficient water from small rainfall events to provide a reduced supply of 0.62 m^3/s, which is 60% of present production rates.

Of the three climate scenarios investigated, both the AEXSA and the AENSK show the largest reduction in continuous water production at Navet with the sustained production being reduced by 40% of present capacity. Although the overall reduction in reservoir production was the same for both, there was an increase in spillage of the reservoir after June 2070 (as seen in Figure 11). This suggests that a higher production rate can be sustained during this period. It is for this reason that the AEXSK can be regarded as the most water scarce scenario.

The AENWH appears to be the most favourable scenario with a comparatively smaller 30% reduction in long-term production. It may also appear that it is the most likely of the three since it is showing similar trends for drying as reported by Beharry et al. (2019). The 35-year meteorological drought analysis showed that there has been a tendency for drying at the Navet site with an increase in the frequency of dry events on the decadal scale, as well as a decrease in frequency of wet events on the 2-month, 7-month and 12-month scale. This shows a similar trend of drying as for the AENWH scenario as reported by Wilson and Cooper (2017). It was identified that there would be a decrease in intensity of rainfall events of most durations.

6. Conclusion

The HEC-HMS Soil Moisture Accounting algorithm (SMA) has been shown to adequately represent the continuous movement of moisture in the Navet catchment and to allow long-term simulation to be made. The simulated response of the catchment to predicted rainfall and climatic conditions has shown that the model can be used to make decisions on operational changes at the dam.

Based on predicted changes in climate, the Navet reservoir may not be able to adequately supply the water demands of its dependent populations in the near future. This can mean additional sources of water may need to be brought online to satisfy the increasing demands of a growing population. Additionally, it may signal the need for improved conservation practices, not the least of which is leak reduction along the water transmission network. The outcome of this study suggests that the future availability of water is threatened and present demands are unsustainable report based on recent climate change predictions of meteorological data. Although the AENWH scenario would likely occur, it still represents a 30% reduction in present production capacity.

The model has shown its suitability in predicting water levels in the upper reservoir. However, various approximations made would introduce various uncertainty that has not allowed inclusion of the dynamics of the lower reservoir subsystem. Future work would thus seek data to represent the catchment of the lower reservoir and so provide a sound basis for extraction to the upper reservoir. A rigorous treatment for determining production rates is required that considers various scenarios responding to how rainfall patterns change in the future.

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Optimal Design Storm Frequency for Flood Mitigation in the North Valsayn Community of Trinidad

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Abstract: *Determining the right amount of money or budget to be spent on flood mitigation works has always been a challenge in developing countries. This study investigates two (2) economic approaches that can be used to determine the level of protection or the optimal design storm frequency for flood mitigation works within the North Valsayn community of Trinidad. The economic approaches investigated can be described as (i) the Cost per Inhabitant (CPI) approach and (ii) the Hydroeconomic Analysis (HEA) approach. To facilitate these economic approaches, the following was done: (i) Identify flood hazards using a calibrated 2D hydraulic model, (ii) Assess the community's vulnerability by developing a Flood Damage curve, (iii) Identify flood mitigation works for various design storm frequencies, and (iv) Determine the life cycle cost for implementing the design various design solutions. Although both methods are acceptably used in the industry, the study shows a disparity in defining a project's budget and the Optimal Design Storm Frequency that is worth paying attention to by decision and policy makers, government agencies, practicing engineers, project managers and other stakeholders although both are acceptably used in the industry.*

Keywords: *Design Storm Frequency; Drainage Structures; Flood Hazard Mapping; Flood Risk Management; Hydro-Economic Analysis; Trinidad and Tobago*

1. Introduction

Over the years, countries have suffered many losses from floods which can be described as monetary and non-monetary or tangible and non-tangible (Thieken et al., 2008). Managing the risk of these losses is very important for economic stability of a community and by extension, a country. In doing so, decision makers are faced with determining the hydrologic design level (the design storm frequency) for which infrastructure, people and their properties are to be protected when implementing flood mitigation projects.

A hydrologic design level or hydrologic design storm frequency is the magnitude of the hydrologic event considered for a safe design of a hydraulic structure or project. It is not always economical to design such structures or projects for the worst case or limiting value (Chow et al., 1988, 8-9). Designing for the limiting value may render a high capital and life cycle cost for a project and may not provide equally or greater beneficial savings to the client or country's economy. Therefore, designing for an optimal design storm frequency is important for the execution of projects that make best use of public funds and promote sustainable growth of a country.

Recent reports such as the Rehabilitation and Improvement of Drainage Infrastructure in Trinidad done by Witteveen + Bros have justified budgets for flood mitigation works (Ravenstijn,2019)by comparing the cost of the recommended works to the value of same in the Netherlands (a developed country) using the cost per inhabitant per annum as the comparative measure. This approach gives a developing country such as Trinidad and Tobago (T&T) an idea of the acceptable amount of money to be spent on flood mitigation works. This identified budget can be correlated to the design storm frequency that yields the closest cost for mitigation works and therefore identifies the design storm frequency or level of protection that can be acceptably afforded.

This study compares the optimal design storm frequency that can be afforded from the Cost per Inhabitant (CPI) approach to which will be derived from executing a Hydroeconomic Analysis (HEA) for flood mitigation works within the North Valsayn community of Trinidad. According to Chow et al. (1988), the HEA is feasible for implementation of flood mitigation works if the probabilistic nature of a hydrologic event and the respective damage are known over a feasible range of

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hydrologic events. As the design storm frequency or level of protection for flood mitigation works increases, the cost of works (infrastructure) increases but the expected damage decreases. The total sum of the mitigation works and the expected damage cost for a particular design storm frequency can be defined as 'the total cost to the owner or to the country's economy'. Therefore, by estimating the total cost to the owner for each design storm frequency within a feasible range, the optimum design storm frequency having the lowest total cost can be found (Chow et al., 1988, 423-427).

For application of the HEA in this study, the costs of damage or damage cost referred is an association to flood risk. Flood risks can be defined in terms of hazard and vulnerability. Flood hazard assesses the intensity and the probability of flood scenarios and vulnerability assesses the direct impacts such as physical loss or damage to material and property. Vulnerability in other instances can include indirect impacts such as loss in production time in businesses and inflation of prices in the market (Thieken et al., 2008).

Quantifying these flood risks into cost of damage includes estimating both flood hazard and vulnerability. Flood hazards can be defined by representing the physical characteristics of flood events in terms of its frequency, depth and velocities, aided by flood maps developed from models (Cancado et al., 2008, 1-2). When using a modelling approach to estimate a flood's characteristic, one could either utilise one dimensional (1D) or two dimensional (2D) numerical models. The 1D numerical model can be used for simple rivers and streams in which flow is predominant in the downstream with limited lateral extent. The 2D numerical models can be used for more complex rivers and streams with multiple structure crossings, significant bends and meanderings with expected complicated flow patterns (FDOT, 2012, 38).

Vulnerability can be measured by assessing the potential damage or impacts that can occur and the recovery capacity of flood prone areas (Cancado et al., 2008, 1-2). However, the assessment of these damage and impacts carries many uncertainties as these are highly dependent on flood depths, velocities, contamination, building characteristics and even by the level of personal flood prevention measures used. Therefore, in most studies, not all of these are usually considered when assessing the damage and impacts of floods (Thieken et al., 2008).Flood depth for example is the only variable considered by some authors (Dutta et al. 2003). The loss estimation model was formulated based on stage-damage relationships for various flood inundation parameters and land use features.

Using similar practices, flood hazard maps using 2D hydraulic models for various designs storm frequencies, the associated damage costs, the mitigation works and their associated costs are identified to be used in the HEA and the CPI assessments in determining the optimal budget and design storm frequency. This has been done for flood mitigation works within the North Valsayn community of Trinidad. The flood mitigation works investigated in this study are: (i) increasing the hydraulic capacities of the adjacent segment of the St. Joseph River where it passes through the community with the introduction of vertical concrete levees, and (ii) increasing the hydraulic capacity of one (1) bridge located within the adjacent river segment.

The North Valsayn community is among several communities located on the foothills of the Northern Range of Trinidad within the St. Joseph River Catchment that experiences frequent riverine flooding. On 22nd November 2019, Trinidad and Tobago Weather Centre reported flooding on Prince Charles Avenue, one of the main entrances to the North Valsayn community. Based on the report of the Cable News Network (CNN) TV6 media station, residents within the North Valsayn community was marooned as stated by the Councillor for the area. Figure 1(a) and (b) depict the images of two (2) typical reports of recent flood events experienced by the North Valsayn community.

In addition to Valsayn North, there are several other communities affected by frequent riverine flooding that are also located within the St. Joseph River catchment. These communities are Bangladesh, South Valsayn, Bamboo No. 2 and Bamboo No.3. These areas are identified for ease of reference. As shown in Figure 2, these communities were developed along the banks of the lower river reach.

(a)

(b)

Figure 1: (a) Flooding on Prince Charles Avenue, Valsayn North (Source: Trinidad and Tobago Weather Centre, 2019)
(b) Residents Marooned in North Valsayn (Source: CNN TV6, 2022)

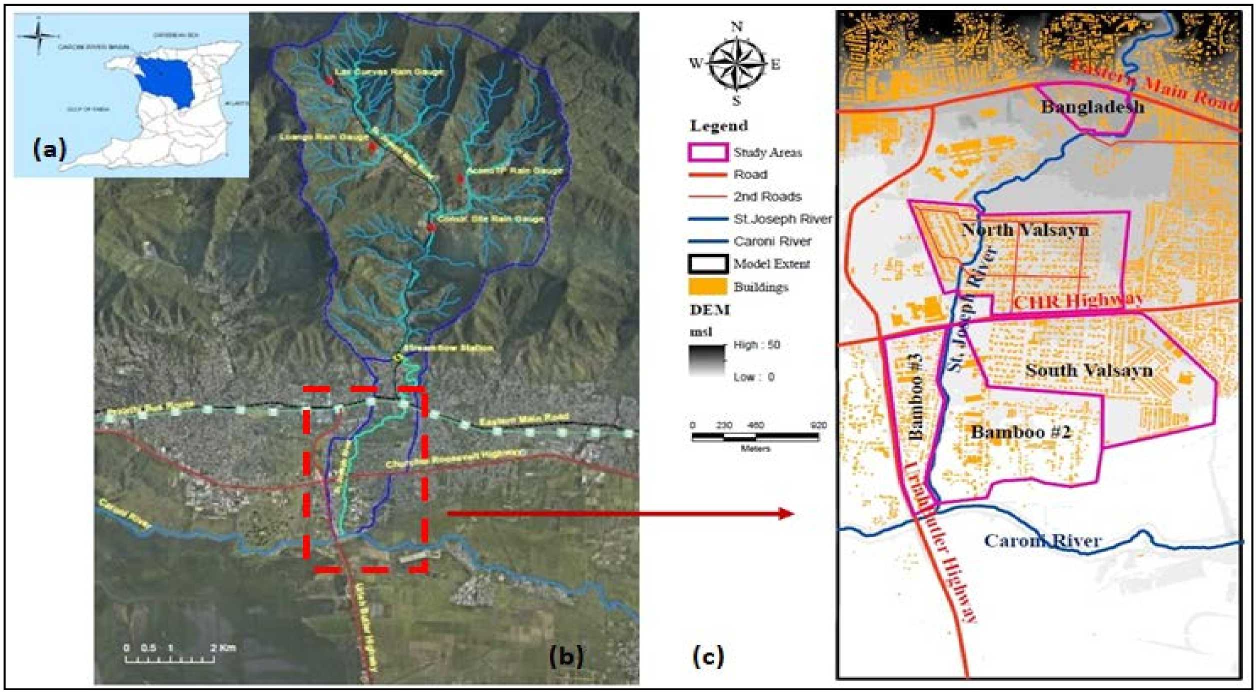

Figure 2: (a) Caroni Catchment within Trinidad, (b) St. Joseph River Catchment and (c) Map Showing Affected Communities within the Lower Reach of the St. Joseph River

The St. Joseph River is one of many tributaries to the Caroni River. The Caroni River watershed is the largest in Trinidad shown in Figure 2(a) and experiences spatially varied rainfall typically moving in a westerly direction, influenced by the North East Trade Winds. The St. Joseph River discharges into the lower reaches of the Caroni River before it enters the Caroni Swamp. As such, stream flow in the St. Joseph River frequently encounters high water levels at the Caroni River confluence. This frequently results in the St. Joseph River breaching its banks, and causes flooding in the areas and communities as there is inadequate capacity within the Caroni River to receive the discharge.

This study aims to determine the optimal design storm frequency for flood mitigation works for North Valsayn. It comprises three objectives to 1) perform hydrodynamic modelling to determine the extent of the flooding at various frequencies; 2) estimate the associated costs; and 3) apply the HEA and CPI analyses to determine the optimum design storm frequency.

2. Methodology

The HEA and CPI analyses require multiple studies, designs and analysis to be conducted as pre-requisite inputs into both economic approaches. A description of each work item is presented in the subsequent sections.

2.1 Conduct of Hydroeconomic Analysis (HEA)

The HEA was one of the economic approaches used to identify the optimal design storm frequency and budget(Chow et al. 1988). It relies on the determination of the total annual cost (TAC) of the flood mitigation works which represents the sum of the annual damage cost and the annual life cycle cost (LCC) of the mitigation works. The design storm frequency that yields the lowest TAC is identified to be the optimal level of protection for the works.

For this study, the HEA was modified to account for the LCC and not just the capital cost. This also accounts for the flood risk transferred downstream of the study area caused by the mitigation works and is termed the "Residual Damage." The modification for the residual damages/risks was made via the introduction of the columns highlighted within the original assessment table of HEA (see Table 1).

The Incremental Expected Damage (IED) is calculated, using the following equation:

$$\Delta D_1 = \left[\frac{D(x_{t1}) + D(x_{t2})}{2}\right][P(x \geq x_{t1}) - P(x \geq x_{t2})]$$

Where: t_1 is the Design Storm Frequency, $D(x_{t1})$ and(x_{t1}) are the damage cost and residual damage cost incurred from the respective storm frequency (*see Sub-section 2.1.1*), ΔD_1andΔDr_1 are the damage cost and residual damage cost reduced to annual values, and y_{t1} is the annual LCC for the flood mitigation works for the respective Design storm frequency (see *Sub-section 2.1.2*).

Besides, $P(x \geq x_{t1})$ and $P(x \geq x_{t2})$ are the annual exceedance probabilities for the t_1 year andt_2 year storm frequencies, respectively.

Table 1. HEA Assessment Format

1. Increment (i)	2. Return Period (T) /yrs	3. Annual Exceedance Probability (AEP)	4. Damage (US$)	5. Incremental Expected Damage per Year (US$)	6. Annual Damage (US$)	7. Residual Damage (US$)	8. Incremental Expected Residual Damage per Year (US$)	9. Total Annual Damage = Annual Residual Damage + Col.6 (US$)	10. LCC per Year (US$)	11. Total Cost per Year (US$)
1	t1	100/t1	D (x_{t1})			$D_r(x_{t1})$			y_{t1}	
2	t2	100/t2	D (x_{t2})	ΔD_1		$D_r(x_{t2})$	ΔDr_1		y_{t2}	
3	t3	100/t3	D (x_{t3})	ΔD_2		$D_r(x_{t3})$	ΔDr_2		y_{t3}	
4	t4	100/t4	D (x_{t4})	ΔD_3		$D_r(x_{t4})$	ΔDr_3		y_{t4}	
5	t5	100/t5	D (x_{t5})	ΔD_4		$D_r(x_{t5})$	ΔDr_4		y_{t5}	
Annual Damage (US$)					Annual Residual Damage (US$)					

Table 2. Bridges Included within the Hydraulic Model

Bridge ID	Bridge Location	Bridge Opening Width (m)	Bridge Opening Depth (m)	Invert Elev. from Dem (m, msl)	Soffit elev. (m,msl)
3	Farm Road Bridge	18.6	5	10.4	15.4
2	North Valsayn Bridge	23.2	5.05	5.01	10.06
1	Mayfield Road –Valsayn Bridge	10.7	4.2	3.8	8
0	CRH Bridge	29.5	6.6	3.29	9.89

2.1.1 Flood Risks or Damage Cost

The damage cost was estimated by correlating the expected flood depths at the affected homes within the North Valsayn community to a flood damage curve that correlates flood depths to monetary loss. This was done for each design storm frequency to obtain the corresponding damage costs. The flood depths and the number of homes affected were quantified using flood hazard maps developed (see *Sub-section 2.1.1.1*). The Flood Damage Curve was developed as a representation of the community's vulnerability to floods and the flood depth versus monetary loss correlation was defined (see *Sub-section 2.1.1.2*).

2.1.1.1 Flood Hazard Mapping

Flood hazard maps were developed for each design storm frequency (2yr, 5yr, 10yr, 25yr and 50yr), using a calibrated 2D hydraulic model. The hazard maps present the flood depths and flood extents within the affected communities, including North Valsayn. The 2D hydraulic model was developed using the sub-grid version of LISFLOOD-FP developed by Neal et al. (2012) primarily to account for the hydraulic effects of bridges.

A digital elevation model (DEM) was prepared using the 2012 LiDAR data for Trinidad with a 12m resolution to accurately represent the topography of the area under investigation. The DEM was processed such that the St. Joseph River, the Caroni River at the outfall, all road embankments, and all major drainage channels were included and accurately represented. Four bridges located within the study extent were also included using geometric surveys provided by Royal Haskoning DHV, consultants working in the study area (Mathijssen et al., 2013). Table 2 summarises the bridge sizes obtained.

Having defined the physical components of the model, the hydrologic and hydraulic boundary conditions were then defined. An inflow hydrograph for the 5th November, 2002 storm event within the St. Joseph River Catchment was used as the upstream boundary condition to calibrate the model. Figure 3 shows the hydrograph that was obtained from the hydrologic analysis report for the respective storm event done by The University of the West Indies (Cooper, 2003).

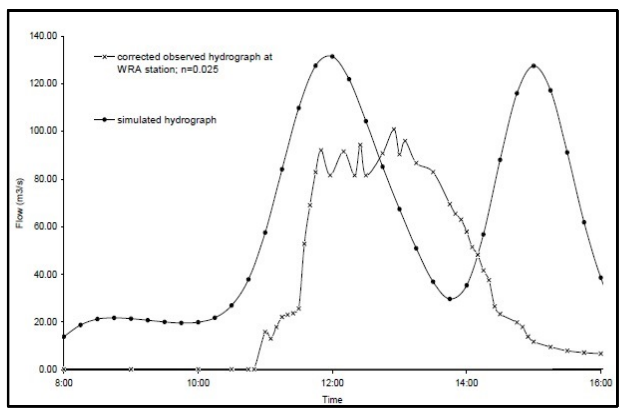

Figure 3. Simulated and Observed Hydrographs for the Flood Event of 5th November 2002
Source: Based on Cooper (2003, 16)

Once a calibrated model was defined, it was used to simulate flows from various design storm frequencies represented by "design storm hydrographs" obtained from the Royal Haskoning DHV 2013 study (see Figure 4).

The St. Joseph River is frequently encountered by high water levels at its discharge point into the Caroni River.This was reported to be the condition for the storm event that occurred on 5th November, 2002. Hence, the downstream boundary condition was set to represent a constant water level equivalent to a bank full condition of the Caroni River. This boundary condition was used for the calibration model and for the design models as it represents the general condition.

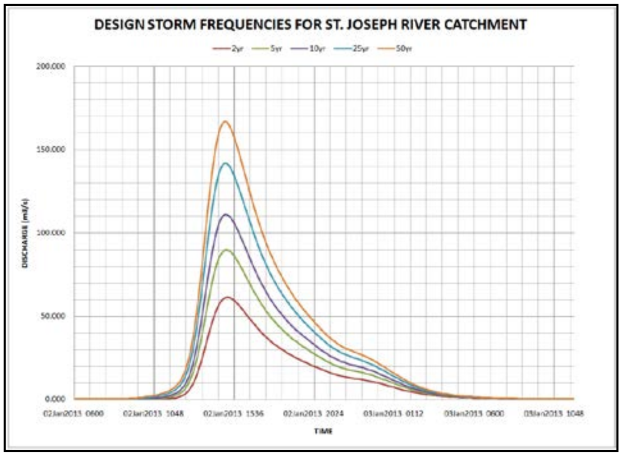

Figure 4. Hydrographs for Various Design Storm Frequencies
Source: Abstracted from Mathijssen et al. (2013)

The calibration of the hydraulic model was done by comparing the observed flood depths to the simulated flood depths for various floodplain and channel roughness coefficients. Observed flood depths were surveyed flood depths within and adjacent to the Nestle Compound, near the Cipriani Labour College and on Farm Road done post the 5th November 2002 event (see Figure 5).

The model was then validated using video footage provided by a local television station (TV6). This footage confirms a common area within the Grand Bazaar compound to be flooded. The validation was limited to flood extent only and not flood depth. Using this calibrated model, flood hazard maps were developed for various storm frequencies using the design hydrographs (see Figure4).

2.1.1.2 Community Vulnerability – Flood Damage Curve

A questionnaire was developed and a field survey was conducted within the flood prone communities in T&T. The survey gathered information on reported flood depths and reported flood damages experienced by each household. The data collected would have shown some disparity due to the individual level of protection adopted by each household, the home design and the valuables exposed to flood waters, and so the median damage cost was found for the flood depth ranges 0 to 0.3m, 0.3 to 0.1m and above 1m. These flood depth ranges were the most frequent ranges reported by the residences in the survey. The median of the damage cost for each flood depth range was plotted to develop the flood damage curve. This curve was then used to estimate the cost of damages required for input in Column 4 of the HEA as shown in Table 1.

2.1.2 Annual Life Cycle Cost

The HEA is focused on the capital cost of the flood mitigation works (Chow et al., 1988). This study however

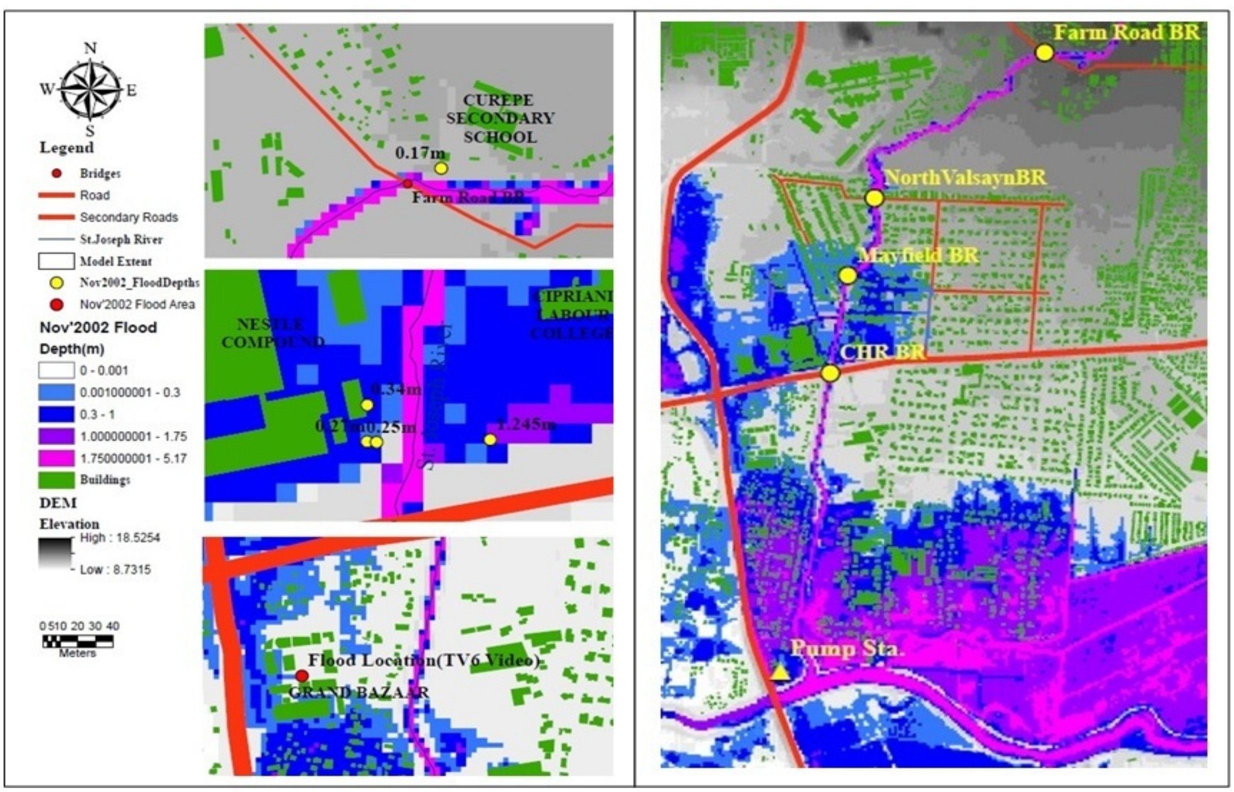

Figure 5: (a) Calibration and Validation Data (Observed) Point Locations, (b) Simulated Flood Map of 5th November 2002

considered the LCC of the works to capture the design and planning costs, construction costs and operational and maintenance costs. The construction costs were estimated using industry rates for the construction of bridges and concrete structures for the levees.

The design and planning costs were taken as 10% of the construction costs, as guided by the local engineering practice and associations in T&T (APETT, 2015). The operational and maintenance cost was taken to be 1% per annum of the construction cost (Zhang et al., 2008, 7). This LCC was then divided by 50 years (the expected life span of the structures) to obtain the Annual LCC. This was done for the flood mitigation works required for all the design storm frequencies and was input into Column 10 of the HEA table (see Table 1).

2.1.2.2 Engineering Designs of Flood Mitigation Works

The flood mitigation works investigated in this study were: (i) increasing the hydraulic capacities of the adjacent segment of the St. Joseph River with the introduction of vertical concrete levees, and (ii) increasing the hydraulic capacity of the one (1) bridge located within the adjacent river segment on Mayfield Road (Figure 5(b)). The calibrated hydraulic model was used as the design tool to determine the bridge size and the levee heights required to mitigate floods within the North Valsayn community for each design storm frequency.

2.2 Conduct of Cost per Inhabitant (CPI) Approach

This study utilises CPI approach to identify an acceptable project budget benchmarked to a developed country. A CPI per annum of US$90 was used as a benchmark for assessing an acceptable budget for flood mitigation works (Ravenstijn, 2019). This was the annual value per inhabitant for flood mitigation works within the Netherlands.

Since the flood mitigation works are effectively providing flood protection, an "acceptable or recommended budget" was identified using US$90 per inhabitant per year for the total estimated population of the community. The population of North Valsayn was taken as four (4) inhabitants per household identified.The budget obtained from this was developed independent of the design storm frequency or level of protection that the works can provide. However, the budget would dictate the type of works and the level of protection. This budget would then be compared with various annual LCCs for the flood mitigation works designed for various storm frequencies to identify the level of protection that the policyholder or decision-maker can afford.

3. Results and Discussion

3.1 Flood Model, Hazard Mapping and Mitigation Works

A calibrated hydraulic model was identified for the storm event of 5th November 2022, using a floodplain friction coefficient and a channel friction coefficient of 0.065 and 0.025, respectively.

Figure 5(a)(i)shows no flooding at one of the observed flood points located adjacent to the Farm Road bridge. This may have been caused by localised urban flooding which was different from the riverine flooding modelled in this study. This observed data point was located close to the upper boundary of the model extent and approximately 1km away from the site of interest, North Valsayn. The modelshowed good response when compared to the other four calibration points located north of the CRHBridge which are located within North Valsayn, as shown in Figure 5(a)(ii). The model also confirmed flooding at Grand Bazaar (see Figure 5(a)(iii)) and hence compared well with the TV6 television station's footage for the validation process.

This calibrated model was then used to simulate the flood hazard maps for the various design storm frequencies. Figure 6(a) shows an overlay of the flood extents for each design storm frequency. These maps were used to guide the designs for increasing the size of the bridge on Mayfield Road which was of inadequate hydraulic capacity for the design storms. The hydraulic capacity of the CRH Bridge was found to be adequate.

Moreover, the Mayfield and the CRH bridge heights and connecting roads were higher than the surrounding lands. This led to the river channel being breached prior to the full hydraulic depth of the bridges being realised. Therefore, levees were introduced along the riverbanks between these bridges as shown in Figure 6(b) to utilise the full hydraulic depth of the bridges. The levees were conceptualised as reinforced concrete and not earthen due to the limited space between the riverbanks and private properties. Table 2 shows a summary of the design structures for the mitigation works.

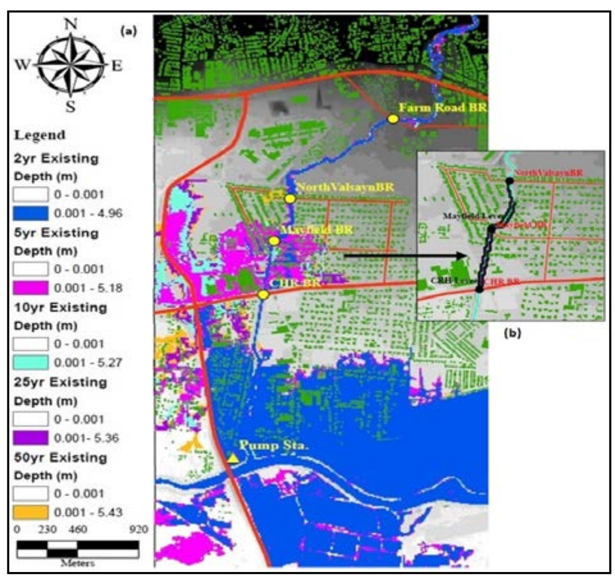

Figure 6: (a) An Overlay of the Flood Hazard Maps for various Design Storm Frequencies, and (b) Extent of Levee on Western and Eastern sides of the St. Joseph River Banks between the CHR Bridge and the Mayfield Bridge

Table 2. Summary of Design Works

	2yr	5yr	10yr	25yr	50yr
CRH Bridge Upstream Water Depth (m)	3.04	3.5	3.8	4.14	4.32
CRH Bridge Height (m)	Existing Bridge Span (29.5m) and Depth (6.6m) are adequate				
CRH Bridge Span (m)					
Western Levee Height (m)	3.42	3.96	4.27	4.5	4.55
Eastern-Levee Height (m)	4.2	4.2	4.4	4.6	4.7
Mayfield Bridge Upstream Water Depth (m)	3.42	3.96	4.27	4.5	4.55
Mayfield Bridge Height (m)	4.2	4.2	4.4	4.6	4.7
Mayfield Bridge Span (m)	13.5	22.6	22.6	22.6	22.6
Western Levee Height (m)	N/A	1.34	1.54	1.94	2.34
Eastern-Levee Height (m)	N/A	1.29	1.49	1.89	2.29

3.2 Community Vulnerability – Flood Damage Curve and Flood Damage Costs

Using the information collected from residents via the field interview and surveys, Figure 7 shows the spatial distribution of reported flood depths and the associated damage costs. The median of the reported damage costs was plotted against the flood depth ranges of 0-0.3m, 0.3-1.0m, and above 1m, to obtain a Flood Damage Curve as a mathematical representation of the community's vulnerability (see Figure 8).

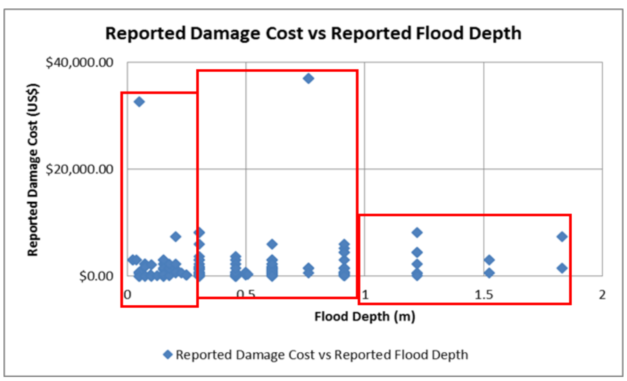

Figure 7. Reported Damage vs Flood Depth Data Plot

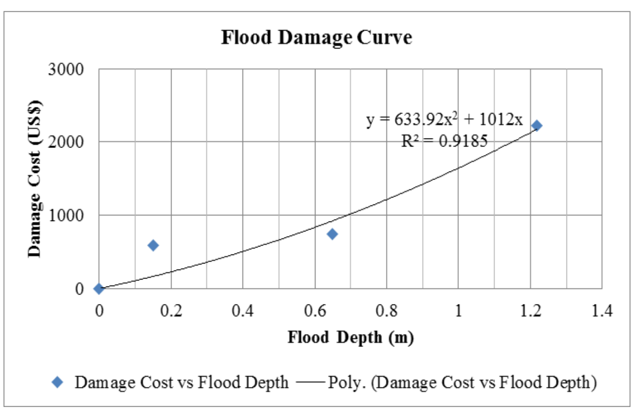

Figure 8. Flood Damage Curve

The function for the Flood Damage Curve was correlated to the design flood depths obtained from the flood hazard maps for each design storm frequency to obtain the projected damage costs, should no mitigation works be implemented. The LCC of the mitigation works and the damage cost for each design storm frequency are depicted in Table 3.

Once the models were adjusted to incorporate the mitigation works, the volume of water that is typically detained within the North Valsayn community has been conveyed downstream. This resulted in an increase in the flood risk and damages downstream. The increased cost in damages downstream was termed "Residual Damages" as presented in Table 4. Besides, these values were small as a significant volume of water was stored within the increased channel capacity.

Table 3. Life Cycle Cost of Flood Mitigation Works for each Design Storm Frequency

	COSTS PER DESIGN STORM FREQUENCY (US$)				
	2yr	**5yr**	**10yr**	**25yr**	**50yr**
CHR Bridge Constr. Cost	$0	$0	$0	$0	$0
Mayfield Bridge Constr. Cost	$1,040,661	$1,861,225	$1,861,225	$1,861,225	$2,157,521
Levees Constr. Cost	$0	$4,160,446	$5,193,184	$6,597,554	$7,781,552
Total Construction Cost	$1,040,661	$6,021,670	$7,054,409	$8,458,778	$9,939,073
Design Cost (10% * Constr. Cost)	$104,066	$602,167	$705,441	$845,878	$993,907
Maintenance Cost (1%*50yrs)	$520,330	$3,010,835	$3,527,204	$4,229,389	$4,969,536
Life Cycle Cost / LCC	**$1,665,057**	**$9,634,672**	**$11,287,054**	**$13,534,045**	**$15,902,517**
Annual LCC (LCC/50yrs)	**$33,301**	**$192,693**	**$225,741**	**$270,681**	**$318,050**

Table 4. Damage Cost and Residual Damage Cost

Design Storm Frequency	1 in 2yr	1 in 5yr	1 in 10yr	1 in 25yr	1 in 50yr
Damages in N.Valsayn (US$)	$3,653.92	$40,891.22	$72,258.09	$104,652.49	$112,673.51
Residual Flood Damages (US$)	$911.67	$2,546.35	$1,506.27	$4,263.35	$7,895.88

3.3Results of CPI Approach

The estimated population of North Valsayn was identified as 4,056 inhabitants. If the CPI approach is used, then an acceptable budget for flood defense works is obtained to be US$365,040 per annum. Table 5compares this budget to the Annual LCCs of the mitigation works designed for various design storm frequencies. Figure 9 shows the plot of the various components and highlights that the mitigation works designed for a 1 in 50 year design storm frequency can be afforded based on the recommended budget.

The study was restricted to the 1:50year storm due to limited data, however, it is expected that the absolute cost difference from the CPI budget would eventually increase as the design storm frequency increases resulting in a bell curve should the data become available. From Table 5 and Figure 9, the project budget recommended to a policyholder or decision maker is irrespective of the design storm frequency. However, when correlated to the annual LCC, the budget can afford the people of North Valsayn a level of protection against a 1 in 50 year storm event.

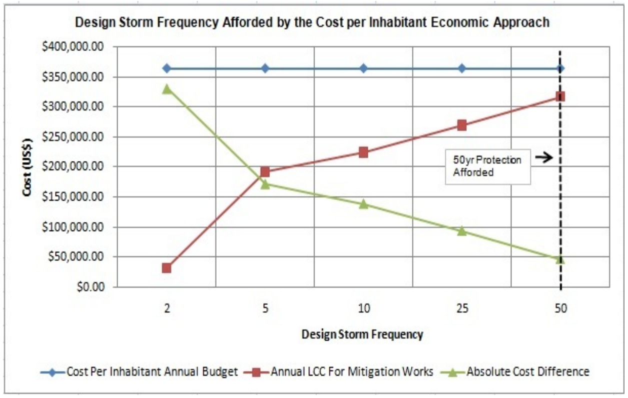

Figure 9. The Design Storm Frequency and the recommended Budget derived from the CPI Approach

Table 5. Comparison of an Acceptable Budget based on the Cost per Inhabitant Approach and the Annual LCC

Design Storm	1 in 2yr	1 in 5yr	1 in 10yr	1 in 25yr	1 in 50yr
Cost per Inhabitant per Annum	$365,040.00	$365,040.00	$365,040.00	$365,040.00	$365,040.00
Annual LCC	$104,931.80	$274,950.25	$307,997.88	$352,937.71	$390,825.65
Absolute Difference	$260,108.20	$90,089.75	$57,042.12	$12,102.29	$25,785.65

3.4From the Hydroeconomic Analysis

Using the annual LCC, damage costs and residual damage costs from Tables 2 and 3, respectively, the HEA was conducted. As presented in Figure 10, the HEA indicated that it is most economical to maintain the existing flood condition as the annual cost of mitigation works far outweighs the annual damage cost.

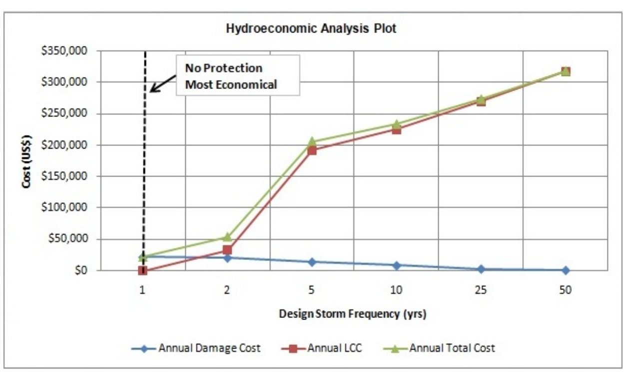

Figure 10. The Hydroeconomic Analysis (HEA) Plot

3.5 CPI versus HEA Analysis

Upon execution of both economic approaches, the HEA indicated that it is most economical to maintain the existing flood condition as the annual cost of mitigation works far outweighs the annual damage cost. On the contrary, when implementing the CPI approach, flood mitigation works performed for a design storm frequency of 1 in 50 years were found to be comparable to the recommended budget. The study shows a disparity in defining an acceptable budget and an optimal design storm frequency for decision/policy makers, and various stakeholders although both are acceptably used in the industry.

The HEA approach focuses on comparing the cost of the mitigation works to the direct and tangible impacts of flooding, namely the annual damage cost caused by floods (Chow et al., 1988). It does not account for simultaneous benefits outside of flood mitigation works that some hydraulic structures carry. In this case, while the total cost for the reconstruction of the Mayfield Bridge was used as part of the LCC to compare with the respective floods damages, in reality the bridge also serves as part of a road network and provides access and connectivity to the community.

In addition to the improvements made to the HEA in this study, it can be further improved by quantifying the portion of the total construction cost that can be realistically assigned to flood mitigation works or the hydraulic component versus what portion can be assigned to the road network component. However, the CPI is a more empirical approach determined from the cost estimates of the mitigation works accepted by developed countries (such as the Netherlands). The cost recommended by the CPI approach states a factor between direct and total cost of 1.7 (Ravenstijn, 2019, 7-8). It implies that this factor accounts for indirect and intangible impacts in addition to unforeseen costs or value. There is a possibility that the CPI approach may yield an uneconomical result due to the differences between the developing and developed countries' physical and economic.

The choice of which approach to be used generally depends on data availability and time constraints. Although the HEA accounts for only direct and tangible impacts of floods when used as a tool to recommend the most economical level of protection, it requires data to quantify the cost of damages for the various storm frequencies. Such data is not always readily available and so is the time and cost to collect and process said data. However, the CPI approach in advising an acceptable budget for flood mitigation works can be done in a shorter space of time in the absence of flood damage data. Work needs to be done to determine how many persons in the country is willing to pay for flood protection and set that against the CPI values reported for developed countries.

4. Conclusion

The study executed two (2) economic approaches used to inform a developing country on the budgets and the associated optimal design storm frequencies to be used for flood mitigation works. The results show a disparity in recommendations provided by the HEA and the CPI approach adopted from the Witteveen + Bros 2019 study (Ravenstijn, 2019). It is important that policyholders, decision makers and other stakeholders are aware of the disparity in results that are possible when implementing each approach and understand why such occurs to aid in managing the process and risks. Further investigations and studies are required to improve these methods and reduce the disparity in results.

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Water Distribution Challenges in Northeast Trinidad and Tobago

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Abstract: *Provision of a reliable supply of water with adequate pressures is a paramount challenge for the water distribution network in Northeast Trinidad and Tobago. Customers in this region, served by the Water and Sewerage Authority of Trinidad and Tobago experience difficulties in obtaining a pipe borne supply of water as they reside on areas of high elevation or are at the farthest end of the distribution system. Areas where water supply challenges are a problem are Oropoune Gardens Piarco, Upper Five Rivers Arouca, Windy Hill Arouca, Edna Hill Arouca, Lillian Heights Arouca, The Foothills Arouca, Pineridge Heights Housing Development and Ridgeview Heights Housing Development Bon Air North. Sources of supply to these impacted areas are the North Oropouche Water Treatment Plant, the Hollis Water Treatment Plant, the Tacarigua High Lift Station and Arouca wells. Challenges in the water supply are a consequence of obsolete pipelines, numerous leaks, failure of mechanical equipment and a shortened duration of supply. This paper identifies the inefficiencies and challenges of the water distribution system in this region by simulating flow through crucial transmission and distribution pipelines using ANSYS Fluent simulation. The Hazen-Williams equation was used to calculate frictional pressure loss in the respective crucial pipelines. Using the results from both analyses, prospective solutions to alleviate and eliminate the inadequate water supply experiences faced by customers in these areas were advocated.*

Keywords: *ANSYS Fluent, Hard-hit areas, Hazen-Williams Equation, Northeast Trinidad and Tobago, Transmission and distribution pipelines, Water distribution*

1. Introduction

Distribution systems are a series of interconnected component pipes and storage facilities accountable for the direct transport of drinking water from the water treatment plants to the customers or from the source of supply to customers (US EPA, 2022a). The water transported is used for drinking, fire protection, commercial purposes, and industrial purposes (AWWA, 2003). The four types of water systems are surface water systems, groundwater system, purchased water system and rural water system. In surface water systems, the water treatment plants, and distribution systems are operated by a public utility that also supervises the said system.

By treating the surface water, particles and other contaminants are removed, following the injection of a disinfectant. The treated surface water is transported using large transmission mains. However, the water may or may not be treated in groundwater systems before it enters the distribution system. If treated, it is an indication that the water contains iron and excessive hardness, making the water unpotable. Additionally, in groundwater systems consisting of several wells spaced around a distribution system, a large transmission system is not needed. If there is a large quantity of groundwater in one area, a well field is installed to allow the collection and treatment to occur in one designated place. The advantage of this is that the quality is easier to control, and this reduces costs.

Conversely, purchased water systems entail one utility purchasing water from another utility. The advantage of purchased water systems is that good quality water is produced and is accounted for using a bulk meter. Bulk metering incorporates the cost of water passing through the mains and includes leaks and wasted water. Purchased water systems consist of a greater-than-average storage capacity, as the source of water is a single source.

Moreover, storage is practiced if there is a limited rate of drawing water or if it is cheaper to purchase water during the night. Rural water systems serve communities and rural homes widely spread where there is no groundwater, or the water quality is very poor. Water is drawn from a surface water source or a groundwater source and provided to customers living many miles away. The disadvantage to this type of system is that the pipelines are not large enough to supply water for firefighting (AWWA, 2003).

Water distribution systems face many challenges. In public water systems, a major challenge identified is the water age. Water age is the time water spends in a distribution system before it is used. Low water usage, collection of more water than being needed and poor water circulation result in water aging. When this happens, water quality in the distribution systems is affected since there is an increase in disinfection by-products, increased consumption of residuals and

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microbial growth. Water age can be controlled by identification of areas in the distribution system with high water age. Correcting the sizes of mains and storage tanks will allow the water age to be monitored and controlled (US EPA, 2022b).

Water utilities also experience external corrosion of pipes, causing pipeline failure and water contamination because of soil entering the pipes through the defective parts. Testing synthetic groundwater revealed the high presence of galvanic currents between steel and copper electrodes and the mass loss of pipe grade steel (Klassen and Roberge, 2008). This can be rectified by replacing corroded, obsolete, and leaking pipelines. According to Mehta et al. (2017), pressures investigated in the junctions of the pipes proved feasible and that pressure variations did not significantly affect the hydraulic capacity in the pipelines.

As leakage is a common and grave concern in water distribution pipeline systems, studies were initiated for leak detection in pipelines using CFD analysis from ANSYS Fluent (ANSYS, 2016). Pressure drop, mass flow rates and outlet velocities were investigated in the presence of leaks. All varied because of leaks on the system. In summary, the accuracy of which leaks are detected would highly depend on these respective flow characteristics (Singh and Nandwana, 2020).

Water is a precondition for human existence and sustainability for the planet (United Nations, 2022). Trinidad and Tobago is one of the most developed countries in the Caribbean (European Commission, 2023) and just as many other regions in the country, Northeast Trinidad and Tobago (T&T) is quickly developing both socially and economically in the areas of industry, commerce, and residential development. These developments result in population growth as there is a migration of people to the Northeast region. Migration and population growth go 'hand in hand' and in turn results in the increased demand for water, and in some cases the demand exceeds the supply.

The Water and Sewerage Authority (WASA) of Trinidad and Tobago is exclusively responsible for extracting, treating, and distributing potable water to customers throughout the country. WASA extracts water from surface water sources, groundwater sources, and rural intakes. Northeast of the island consists of two large surface water sources that is, the North Oropouche River and the Hollis Dam. Water withdrawn from the North Oropouche River by the North Oropouche Water Treatment Plant (WTP) is treated and distributed to customers. The water from this Plant supplies most of the areas in Northeast Trinidad from Valencia and Sangre Grande, East of the region and to Five Rivers, Arouca on the Western side of the region. Similarly, Hollis WTP withdraws water from the Hollis Dam, treats the water and then distributes it to customers from as far as Arima in the East to Bon Air North Arouca, in the west.

This paper identifies the inefficiencies and challenges of the water distribution system, focusing on:

1) the flow of water in pipes using ANSYS Fluent Fluid software.
2) the frictional pressure drops occurring in pipes using the Hazen-Williams equation, and.
3) prospective solutions that can alleviate/eliminate the inadequate supply of water.

2. Site Descriptions

Figure 1 shows the Northeast region of Trinidad where the study sites are located. These sites are:

1) Oropune Gardens, Piarco
2) Upper Five Rivers, Arouca
3) Windy Hill, Arouca
4) Edna Hill, Arouca
5) Pineridge Heights Housing Development, Bon Air North, Arouca
6) Ridgeview Heights Housing Development, Bon Air North, Arouca
7) Lillian Heights, Arouca
8) The Foothills, Arouca

These areas are located at the farthest end of the transmission and distribution system and include customers residing on extremely high elevations where water must be supplied and is expected to reach the customer according to schedule.

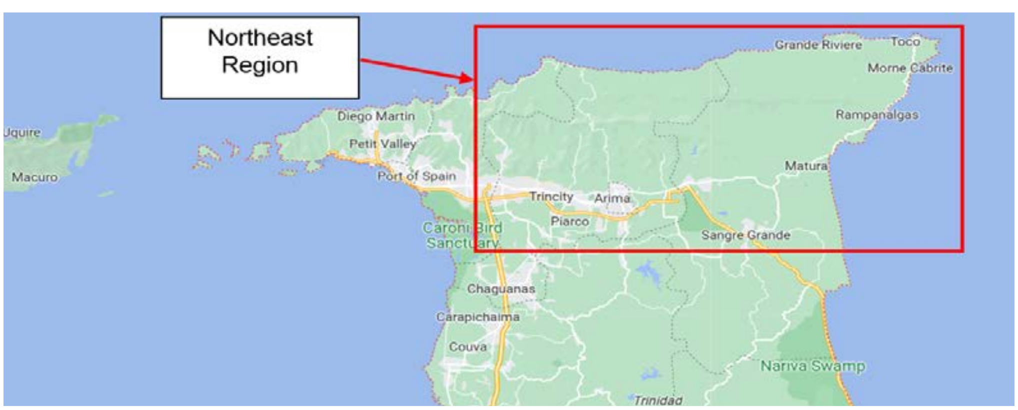

Figure 1. Map of Trinidad (Source: Abstracted from Google Maps (2023))

3.1.1 Oropune Gardens Piarco

Oropune Gardens Piarco is a housing development, south of the Churchill Roosevelt Highway and Northwest of the Piarco International Airport. It was established by the Housing Development Corporation of Trinidad and Tobago. The source of water to this area is the North Oropouche WTP. Customers reside both in low-rise buildings and mid-rise buildings in the area. The challenge experienced with this development is the supply of water that can suffice customers. Particular attention is also paid to customers residing on the top floors of mid-rise buildings. These buildings are located at the farthest end of the Oropune distribution system.

3.1.2 Upper Five Rivers Arouca

The community of Five Rivers consists of a few areas of extremely high elevation, referred to as 'Upper Five Rivers'. These highly elevated areas are:

1) Manimore Road
2) Bertie Road (inclusive of Bertie Road Extension
3) Manoram Road
4) Mission Road
5) William Hill
6) Spring Road (inclusive of Spring Road Extension)

The challenge with this area is that it is extremely difficult to supply water to these areas on a scheduled basis because of inadequate water supply pressures, as the respective areas are located at the farthest end of the distribution system. Since elevation is a challenge in this area, water from the Tacarigua well field via the aid of the Tacarigua High Lift Station is used for supplying water to customers.

3.1.3 Windy Hill and Edna Hill, Arouca

Windy Hill and Edna Hill, both located in Arouca, are supplied by the Arouca High Lift Station. The Arouca High Lift Station is a mixture of dam water from the Hollis Water Treatment Plant and groundwater from the Arouca wells. Both areas are located off the Arima Old Road and are highly elevated.

3.1.4 Pineridge Heights and Ridgeview Heights Housing Developments, Arouca

The Pineridge Heights Housing Development and Ridgeview Heights Housing Development, both establishments of the Housing Development Corporation of Trinidad and Tobago are located Bon Air North, Arouca. The source of supply to this area is strictly dam water extracted and treated by the Hollis WTP. Like Oropune, this area also consists of low-rise and mid-rise buildings, in addition to the area being highly elevated.

3.1.5 Lillian Heights and The Foothills, Arouca

Lillian Heights and The Foothills are both nearby residential communities also receiving a mixture of groundwater and dam water from the Arouca High Lift Station. These areas are located directly off the Arima Old Road. Lillian Heights is a mixture of both low-rise and mid-rise buildings and is still being developed as construction of similar buildings and developments within the area is ongoing.

3. Methodology

3.1 Customer Statistics, Sources of Supply and Production

A site visit to the respective hard-hit areas was made and the numbers of houses were physically counted. Then, the total number of customers for each area was calculated by multiplying the number of houses by 3.3, the average household size on the island (CSO, 2011). Table 1 shows the customer statistics. Terrain on Google maps was used to determine the elevations for each hard-hit area and the required distribution pressure for the respective area was calculated by multiplying the distribution pressure by 0.7m head of water, the equivalent unit of measuring water pressure (RIC, 2020). The water demand was calculated by multiplying the total number of customers by the per capita water demand used by WASA that is 82 US gallons per day. Figure 2 depicts the water demand for hard-hit areas.

Table 1. Customer Statistics

Street Name	Population	Elevation (m)	Required Distribution Main Pressure (kPa)
Manimore Road	366	80	386
Bertie Road	92	90	434
Bertie Road Extension	50	50	241
Manoram Road	581	90	434
Mission Road	155	100	483
William Road	208	90	434
Spring Road	228	120	579
Spring Road Extension	168	120	579
Windy Hill and Edna Hill	1389	70	338
Oropune Gardens	403	0	0
Pineridge Heights Housing Development (HD)	750	80	386
Ridgeview Heights Housing Development (HD)	750	90	434
Lillian Heights Housing Development (HD)	248	90	434
The Foothills Housing Development (HD)	175	80	386

Table 2. Areas in Northeast Trinidad and Tobago affected by Inadequate Water Supply

Essential Parameters	**Impacted Areas**					
	Oropune Gardens, Piarco	**Upper Five Rivers, Arouca**	**Windy Hill and Edna Hill, Arouca**	**Pineridge Heights and Ridgeview Heights Housing Developments**	**Lillian Heights, Arouca**	**The Foothills, Arouca**
Source of Supply	North Oropouche WTP	Tacarigua High Lift Station	Arouca Well field and Hollis WTP	Hollis WTP	Arouca Well field and Hollis WTP	Arouca Well field and Hollis WTP
Type of Source of Supply	Surface water	Groundwater	Groundwater and Impounding reservoir	Impounding reservoir	Groundwater and Impounding reservoir	Groundwater and Impounding reservoir
Water Production of Source of Supply (U.S MGD)	26.4	3.5	0.52	10.2	0.52	0.52
Distance of source of supply from Hard-hit area (km)	29	30.5	1.11	0.736	2.9	2.6
Size and Type of Distribution Main	200 mm PVC	150 mm PVC	150 mm PVC	200 mm PVC	150 mm PVC	150 mm PVC
Booster Station required to boost pressures	No; Gravity flow	Yes; Khandahar Booster Station	Yes; Arouca High Lift Station	No; Gravity flow	Yes; Arouca High Lift Station	Yes; Arouca High Lift Station
Minimum discharge pressure on distribution main required to reach customers water service connection (kPa)	414	1724	345	414	276	965
Minimum water pressure required at point of water service connection (supply pressure) (kPa)	138	138	138	138	138	138
Type of Supply	Intermittent	Intermittent	Intermittent	Intermittent	Intermittent	Intermittent
Scheduled supply (hr./day)	12/3	12/3	12/3	12/3	12/3	12/3
Class of supply	4	4	4	4	4	4
Customer Class	A4	A3	A3	A4	A4	A4

For each of the hard-hit areas, the following was determined and listed in Table 2:

1) The source of supply.
2) The distance of the hard-hit area from the source of supply.
3) Size and type of distribution main.
4) Minimum pressures in the water service connection to reach customer.
5) The type of supply.
6) Scheduled supply.
7) The class of supply.
8) Customer class.

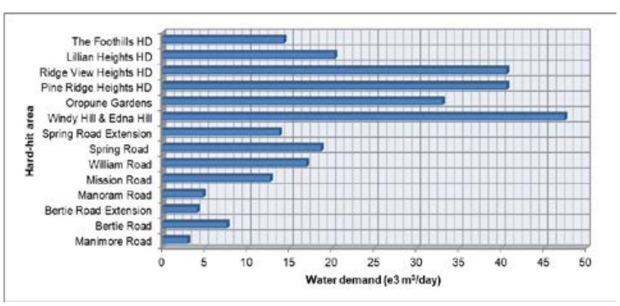

Figure 2. Water Demand for Hard-hit Areas

4.2 ANSYS Fluent Fluid Simulation Software

ANSYS Fluent is used for modelling fluid flow. ANSYS Fluent became the first commercial computational fluid dynamics (CFD) software to attain a graphical user interface and workflow instead of the just a command-line input, in the early 1980s. As the years passed, the software became popular in industries. In 2006, Fluent Inc. was acquired the software and added it to ANSYS (ANSYS, 2023).

In this study, ANSYS Fluent was used for simulating the flow of potable water through crucial transmission and distribution pipelines supplying water directly to the hard-hit areas in Northeast Trinidad and Tobago. Pipelines ranging from sizes 1,100 mm, 200 mm and 150 mm were drawn using ANSYS Fluent 2021 R1 Fluid workbench and meshed (ANSYS 2016). The operating conditions selected for simulation was atmospheric pressure including the selection of the standard reference values for water.

The conservation equations of mass and momentum are solved using ANSYS (ANSYS 2013) during the simulation of fluid flows in ANSYS Fluent. Several limitations are identified for modelling fluid flow with ANSYS. These are:

1) The flow must be incompressible.
2) A specified pressure gradient is recommended when performing unsteady-state simulations.
3) In using density-based solvers, only the pressure-jump or the mass flow rate can be specified.
4) Net mass addition through inlets/exits or extra

source terms are prohibited.

5) The species can only be modelled if there are inlets/exits and reacting flows are prohibited.
6) Multi-phase modelling and discrete phase modelling are prohibited.
7) By specifying a periodic mass-flow rate, Fluent assumes that the entire flow rate only passes through one periodic continuous face zone.

For this study, the constant parameter was that of the length of an individual pipe. The standard length of one (1) pipe measures approximately 6 m. Construction of the pipe was done in ANSYS workbench. The manipulated variables were the pipe diameters and the responding variable in this analysis was that of the wall shear stress and total pressures experienced in the pipes and indicated by colour changes along the length of the pipes.

4.3 Pressure Drop in Pipes using Hazen-Williams Equation

The Hazen-Williams equation is used for designing water distribution lines (Menon 2004, 50). In this paper, it was used for calculating the frictional pressure loss of water in the crucial transmission and distribution pipelines. The Hazen-Williams equation used was:

$$h = [4.73L(Q/C)1.852 \div D4.87] \qquad \text{Eq.1}$$

Where:

h = Friction loss per foot of pipe (ft); L= Pipe length (ft); D = Pipe internal diameter (ft); Q = Flow rate (ft^3/s); C = Hazen-Williams coefficient or C-factor (dimensionless)

Google Maps were used to measure the distance of the hard-hit areas from the source of supply as 'the crow flies'. Using the distances measured, along with the crucial pipe diameters of 1,100 mm, 200 mm, 150 mm, the Hazen-Williams constant of 150 for PVC pipes, and the flow rate from the source of supply, the friction loss in the respective pipes was calculated. Friction loss calculated in feet (ft) was then converted to SI units that is meters (m).

The constant parameter in this analysis was the standard length of the pipelines. Manipulated variables were the pipe diameters and the distance of the pipelines from the source of supply. The responding variable on the other hand, was that of the friction loss or head loss occurring in the pipes as the distance from the source of supply increases.

Using the head loss calculated and the elevations measured, a graph was plotted to show the relationship between head loss and elevation for the affected areas.

5. Results and Discussion

The areas focused on in this research are deemed as 'hard-hit' areas. 'Hard-hit' areas, as perceived by the author, are areas severely impacted by a deficient supply of water because they are either highly elevated or are located at the farthest end of the transmission and distribution system. The water distribution networks investigated in this study are looped networks. Water distribution difficulties to the hard-hit areas all experience one common dilemma that is, inadequate pressures. Inadequate pressures are water pressures in the distribution system that is too low resulting in the supply not being able to reach the customers in the hard-hit areas. In other words, the water pressures occurring in the respective pipelines are not the standard water pressures or design pressures required to supply customers.

In Table 1, the number of customers ranged from 50 to 1389 respectively, whereas elevation ranged from 0 m to 120 m respectively and required minimum pressures ranged from 0 kPa to 579 kPa, respectively. Moreover, the per-capita water demand illustrated in Figure 2 for each hard-hit area ranged from 3 e3 m^3/day to 47 e3 m^3/day. The water demand in Figure 2 varies because of the differences in population of the hard-hit areas. In addition, water demand would vary because of the various reasons customers use water. For example, the duration of a shower, the washing of a car or yard, a car wash business, the possibility of a hairdresser's salon at one's home or a food stall or mini mart, a swimming pool, the number of storage tanks at each home, etc.

Per capita demand and water supply goes 'hand in hand' as the supply must be sufficient to satisfy the demand. When providing a supply of water, elevation is a key factor that must be paid attention to, as water pressures are affected by elevation. For this reason, the author found it necessary for it to be included in the study. Customers who reside on the 120 m elevation are expected to receive an adequate supply of water from WASA, according to schedule just as those on the lower elevations. For this reason, water pressures are expected to be high enough to reach the customer at the highest elevation. The Arouca High Lift Station consists of a series of pumps used for further boosting the supply and pressures to the affected customers, again because of elevation differences.

Moreover, 'A3' customers are domestic customers whose premises are fitted with internal plumbing whereas 'A4' customers are domestic customers whose premises are also fitted with internal plumbing but are metered (PUC, 2008). WASA classifies its customers into types (industrial, commercial and residential), schedule and class of supply. In this study, the customers are domestic and are scheduled to receive a supply 12 hours 3 days per week (12/3). A 12/3 schedule is considered a class 4 supply at WASA.

Table 2 shows the source of supply and the total water production supplied to said areas. The volume of water available for supply to customers is dependent on the latter two. Adding to the importance of supplying water to the hard-hit areas is dependent on the distance of the customer from the source of supply, the diameter of the distribution mains and the importance of the location of a booster station. Sources of supply range from surface water to groundwater and even include an impounding reservoir (see Table 2).

Moreover, the supply is a mixture of groundwater and surface water from the impounding reservoir as is the case with Windy Hill, Edna Hill, Lillian Heights, and The Foothills. The reason for mixing the water is that the individual source of supply is insufficient by itself to provide customers in these areas with an adequate supply.

Pipe diameter plays an important role in the flows and pressures occurring in the crucial transmission and distribution pipelines. Flow and pressures taking place in the individual pipelines would vary according to the diameter of the pipe and material resistance of the pipeline. The minimum water pressure required at the point of water service connection is 20 psi (Regulated Industries Commission, 2020). This is approximately 138 kPa. ‘psi’ (pounds per square inch) is a unit of measuring water pressure and is equivalent to 0.7 m head of water.

If the required pressures listed in Table 1 are attained in the distribution pipelines, then it is guaranteed that a minimum 138 kPa would be provided to customers at the farthest end of the distribution system, including those at the highest elevations. Because the supply to customers is 12 hours, 3 days per week and not 24/7, the supply is intermittent. Intermittent supply means that the supply is not continuous but rather on a scheduled basis, on selected days and times of the week.

A critical contributing factor that must be taken into consideration for the highly elevated areas, is that the required discharge pressures can only be attained when the low-lying areas are first fully saturated. ‘Fully saturated’ low-lying areas mean customers on the low elevations, in particular elevations of 0 m must first receive an adequate water supply at 138 kPa. Customers on low-lying areas just like any other customers would fill their tanks and carry on with their domestic chores.

After these customers are filled, no water would be used or the usage of water on the low elevations would decrease thereby allowing an increase in pressures and supply to those on the higher elevations and farthest ends. As these areas often experience challenges in their supply, ‘panic filling’ would often occur. ‘Panic filling’ as defined by the author is the filling of storage tanks and the excessive usage of water by customers with the intention of completing all their chores in a very short period of time, since it is not expected to be received on the next schedule due to the supply challenges.

Continuation of investigating the water distribution challenges in the Northeast region was done using simulation. Simulation of flow in the major transmission and distribution pipelines using ANSYS Fluent (Fluid) was performed for the author to have a better sapience of the flow of water in the pipelines. The 1,100 mm diameter transmission pipeline transporting treated water directly from the NOWTP tank was analysed (see Figure 3).

The depiction of wall shear stress varies along the length of the pipeline via the colour variation. Closer to the source of supply, the wall shear stress was the highest, but as the water travels farther away from the source, shear stress decreases. Shear stress was indicated by the colour change from blue to red. The red colour indicates a lower shear stress in the pipes as the distance from the source of supply increases.

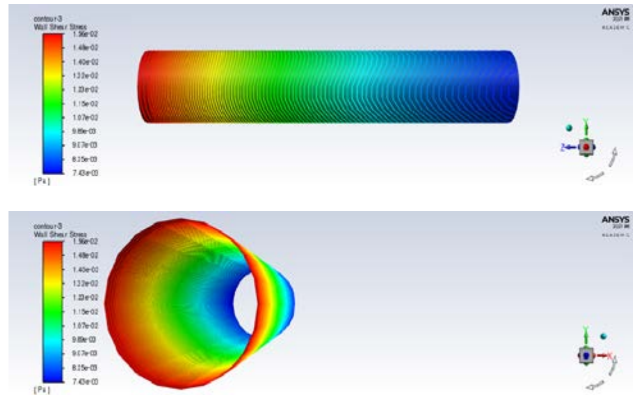

Figure 3. Contours of Wall Shear Stress inside a 1,100 mm Diameter Transmission Pipeline

It proves that the farther away from the source of supply, shear stress tends to decrease. Similar occurrences were observed from simulating total pressure in the pipes. This occurs when the water travels farther along the transmission and distribution pipeline system, hence the reason why customers at the farthest end of the distribution system tend to experience water supply challenges. In some instances, to aid in combating this problem, high lift stations and booster stations are strategically placed along the transmission and distribution systems with the aim of boosting pressures. The Arouca High Lift Station is one such station used for boosting pressures to the customers served by it and not only the mentioned hard-hit areas. The Golden Grove Booster Station was recently constructed where the pressured decreased on the transmission system, to assist the area of Five Rivers with its supply. The same reaction of wall shear stress and total pressure were depicted in Figures 4 to 8 for the distribution pipelines of diameters 200 mm and 150 mm, respectively.

Pressure drops due to friction in the pipelines occurs as this transmission pipeline is a long distant one (Menon 2004). Distances in the source of supply to the hard-hit areas were also measured. Table 2 shows that the distance from the source of supply to the hard-hit area ranged from 2.6 km to 30.5 km. For this reason, it is important in any water transmission and distribution system to maintain the pressures whilst the water is in transit, no matter the distance it needs to travel for it to reach the customers. For adequate pressures to be achieved, the flow of water in the pipelines must be sustained or kept constant since pressure and flow are dependent on one another.

Analysis showed that Oropune Gardens, unlike Upper Five Rivers is a low-lying area with an elevation of 0 m. Once the supply is on and the tank height at the North Oropouche WTP is maintained, the water reaches the

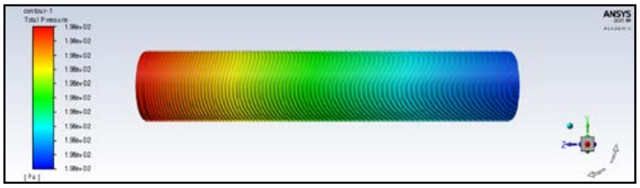

Figure 4. Contours of Total Pressure inside 1100 mm Diameter Transmission Pipeline

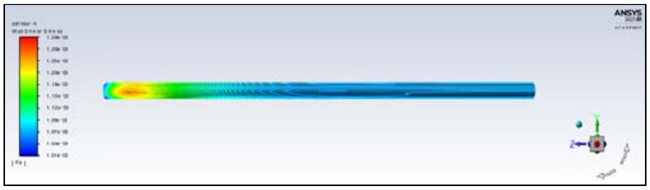

Figure 5. Contours of Wall Shear Stress inside a 200 mm Diameter Distribution Pipeline

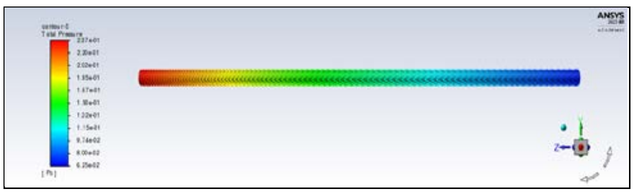

Figure 6. Contours of Total Pressure inside a 200 mm Diameter Distribution Pipeline

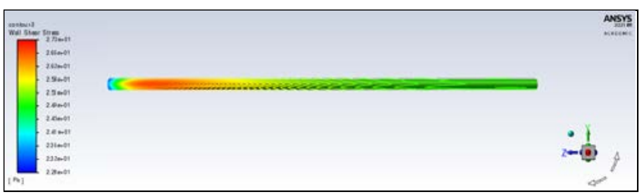

Figure 7. Contours of Wall Shear Stress inside a 150 mm Diameter Distribution Pipeline

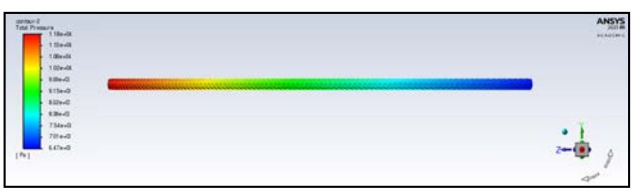

Figure 8. Contours of Total Pressure inside a 150 mm Diameter Distribution Pipeline

customer at the farthest end of the Oropune Gardens distribution system in due time. Maintaining the tank height would ensure that the required pressures and flows are achieved.

WASA recently switched the source of supply to Oropune Gardens from the North Oropouche WTP to the Caroni Arena WTP. Although the source of supply is still surface water, the duration and transport of water to the area has decreased because the area is located a mere 6.3 km from the Caroni Arena WTP, as measured from Google Maps. This is quite shorter than the 29 km from the North Oropouche WTP as stated in Table 2, or a 78% decrease in the distance from the source of supply, thus proving that distance can indeed impact pressures. Ridgeview Heights and Pineridge Heights Housing Developments on the other hand, receive a supply from the Hollis WTP. Once this plant is producing its maximum, water is expected to reach the customers, according to schedule without major setbacks in the system, for example leaks.

On the other hand, the Hazen-Williams equation was used to calculate the head loss occurring in the distribution pipelines in the respective areas. Elevation ranged from 0 m to as high as 120 m whereas the head loss occurring in the pipes ranged from 0 m to 17.4 m respectively. Figure 9 depicts the elevation compared to head loss. A maximum head loss of 17.4 m in the pipes is indicative and proof that friction losses in the pipes can be considered minor when compared to the range of elevations of 90 m, 120 m etc. Head loss usually occurs in long-distance pipelines in which pressure drop due to friction in the pipeline contributes to a significant portion of total fricitional pressure drop (Menon 2004). Once there are friction losses occurring in pipes, then there will be a loss of energy of the water flowing in the pipes.

Friction losses indicate resistance in pipes. Figure 9 also shows that head loss is greater in the pipeline of smaller diameter. Friction losses vary according to the pipe diameter and the material the pipe is made of, as well as the converging and diverging boundaries in pipes. The distance of the source of supply to the pipe is also a major factor affecting friction loss in pipes. During gravity flow, friction loss will be greater and flow rate will be smaller. However, as seen in Figure 9, friction loss in pipes is extremely small and can be considered negligible when compared to elevation of the hard-hit area.

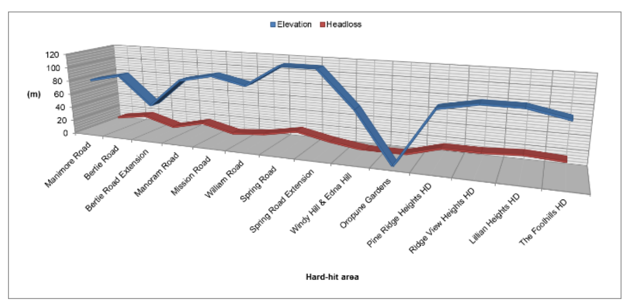

Figure 9. Head Loss in Pipelines Compared to Elevation of Hard-hit Areas

Several mitigation measures are critical to ensure an efficient supply of water to customers. These include:

1) Maintaining an adequate tank height from the source of supply as it would affect flow and pressures in the pipelines.
2) Closing the off-takes or crucial valves along the distribution system, in particular those on the

transmission system to areas not scheduled to receive a supply. This would also enable respective targeted flows and pressures to be achieved. It is also a way of managing and adhering to the water supply schedules for the respective areas.

3) Obsolete infrastructure results in leaks as there are often 'weak points' on the transmission and distribution pipelines. 'Weak points' as defined by the author, are areas on the pipeline that are unable to withstand the flows and pressures in the pipelines and thereby break or crack gradually or immediately, according to the material type of the pipeline, resulting in leaks.
4) Currently, the region has a total of 1,018 leaks (WASA, 2022). The number of leaks is dynamic and changes on a daily and weekly basis and adds to the volume of unaccounted-for water. The solution is to maintain the number of leaks existing by excessive leak repair exercises, taking into consideration, and not forgetting the order of priority leaks are to be repaired. Leakage is a significant reason for an inadequate supply of water to the highly elevated customers as well as those farthest on the distribution system. With less leaks, the pressures and flows in pipes will be greater.
5) Another possibility is the consideration, identification, and utilisation of an additional source of supply. Alternative and/or additional sources of supply are current projects being done by WASA. For example, the drilling and commissioning of additional wells, the installation of larger tanks and tank farms that can store more water and the replacement of obsolete pipelines. Storage of more water can enable a longer duration of supply to customers and assist in improving the pressures and flows of water in the pipelines.

7. Conclusion

Although the dilemma of an inadequate supply experienced by customers on highly elevated areas and those at the farthest end of the transmission and distribution system is ongoing, it can be solved. Maintaining flows and pressures begin from the source of supply and can continue along the transmission and distribution system if all mitigation measures mentioned earlier are adhered to. Water distribution challenge is a 'work in progress' but close monitoring and maintenance of the transmission and distribution system can definitely alleviate and even eliminate water supply problems to hard-hit areas in Northeast Trinidad and Tobago.

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Thanks to Professor Edwin I. Ekwue, Dean at the Faculty of Engineering, The University of the West Indies, St Augustine Campus, for his expert advice. Thanks also go to the Water and Sewerage Authority of Trinidad and Tobago for the opportunity to investigate one of their major transmission and distribution systems.

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Excerpted Abstracts of the 7th Water Efficiency Conference 2022

Theme: "Water Resources Resilience for Small Island Developing States (SIDS)" 24th-16th December 2022

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Abstract: *In an increasingly uncertain world, water is constant and central to most things: the economy, energy, transport, agriculture, health, leisure, wellbeing, social and cultural life. The 7th Water Efficiency (WATEF) Conference 2022 was, for the first time, held outside Europe in the Caribbean, at the Faculty of Engineering, The University of the West Indies, Saint Augustine Campus, Trinidad and Tobago on 14th-16th December, 2022. Many challenges reflect the changing climate, increasingly unpredictable weather, and the efforts towards sustainable development necessary for social equity and economic growth. Proactive partnerships and collaborations across civil society is necessary to succeed in this effort. A conference on water efficiency and resilience is justified in the face of these challenges and during an energy, cost-of-living, food, and other crises. The WATEF-2022 Conference's theme was "Water Resources Resilience for Small Island Developing States (SIDS)". Trinidad and Tobago has a relatively high reliable water infrastructure (including desalination plants) for its population but in recent times water resources have been impacted by unforeseen climate change events. This twin-island republic was best suited for this conference, geographically and technically. Parallel with invited keynotes and feature speeches, technical presentations and panel discussions were made addressing various topics and areas associated with the conference's theme. This paper contains a total of 28 abstracts excerpted from the Conference proceedings that address towards collaborative solutions to the water and resilience challenges faced globally and experienced more intensely by SIDS.*

Keywords: Water efficiency, resources, resilience, SIDS, WATEF, Trinidad and Tobago

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1. Optimal Design Storm Frequency for Flood Mitigation

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Abstract: *Determining the right amount of money or budget to be spent on flood mitigation works has always been a challenge in developing countries. Recent work has identified a recommended budget based on the value accepted for flood mitigation works in developed countries, measured as the Cost per Inhabitant. In addition to this approach, the industry also utilises the hydroeconomic analysis (HEA) to determine an optimal design storm frequency that yields the most economical budget and design approach to flood mitigation works. This study investigates both economic approaches to determine the level of protection or the optimal design storm frequency for flood mitigation works. These economic approaches were executed for flood mitigation works within the North Valsayn community of Trinidad. To facilitate these economic assessments in determining the optimal design storm frequency, flood hazards were identified using a calibrated 2D hydraulic model done in LIS-FLOODFP. A Flood Damage Curve was used as a measure of the community's vulnerability using data collected from social surveys. Flood mitigation works were identified for the various design storm frequencies and the associated life cycle costs were determined. Upon execution of both economic approaches, the HEA indicated that it is most economical to maintain the existing flood condition as the annual cost of mitigation works far outweighs the annual damage cost. On the contrary, when implementing the Cost per Inhabitant approach, flood mitigation works performed for a design storm frequency of 1 in 50years was found to be optimal or comparable to the recommended budget. The study shows a disparity in defining a project's budget and the Optimal Design Storm Frequency using both approaches for decision/policy makers, and various stakeholders although both are acceptable.*

Keywords: *Storm Frequency, Flood Mitigation, Hydroeconomic Analysis, Trinidad*

2. The Value of Hydrometry in Reducing Fluvial Flooding Footprints across The Caribbean – A Case Study in Dennery, Saint Lucia

Fazir Khan[1] and Fey Mohammed[2]

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Abstract. *The work reported in this paper was initially carried out by Alpha Engineering and Design (2012) Limited (Alpha) for the Government of Saint Lucia (GOSL) on a World Bank (WB) Disaster Vulnerability Reduction Project (DVRP) for Flood Mitigation. Part of the scope involved setting up rainfall and streamflow gauges in the Dennery Watershed to observe rainfall depth and river stage for a limited period congruent with the engineering consultancy contract, to guide the selection of hydrological parameters and calibrate hydraulic models. Alpha then sought to extend the observation period so that larger datasets could be captured to improve the reliability and utility of the data. The aim of this paper is to present the real-world benefit of investing in hydrometric instrumentation to increase one's capacity when Analysing the hydrological and hydraulic impacts of storm events in Caribbean Watersheds and improve reliability in flood mitigation analyses for more resilient solutions. This is done through a case study in Dennery Village, Saint Lucia. This paper briefly presents the challenges associated with setting up and maintaining gauging stations, describes the technology used, lists the high benefits for the comparatively low cost of the investment, and finally the analyses of the data using standard methodologies in engineering hydrology and hydraulics to generate catchment-specific information relating to rainfall and runoff especially in terms of flooding, such as the role of antecedent moisture content on the severity of floods and the impact of rainfall structure, in space and time, on a flood hydrograph for specific catchments..*

Keywords: *Rain-Gauge, Streamflow-Gauge, River Stage, Stage Discharge, Flood Hydrograph, Hydrological Parameters, Watercourse baseflow, Irrigation*

3. Considerations for Use of Permeable Pavement Systems within Urban Settings across Caribbean Small Island Developing States

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Abstract. *Increasing imperviousness caused largely from urban development coupled with global warming, sea-level rise and change in weather patterns contribute immensely to frequent flooding events across numerous urban municipalities across Caribbean Small Island Developing States (SIDS). Existing conventional drainage systems fail to meet stormwater runoff peak flow and volume demands generated by today's changing environment. Land or service constraints often restrict expansion of these drainage systems. Despite those challenges, Caribbean SIDS authorities and drainage engineers continue to recommend and use conventional drainage systems as the dominant infrastructure for the collection and conveyance of stormwater away from urban areas. Sustainable Urban Drainage Systems (SUDS) or Low Impact Development (LID) practices such as porous or Permeable Pavement Systems (PPS) are designed to effectively manage stormwater runoff at the source as opposed to conventional drainage systems. PPS reduce urban runoff and peak flows via development of on-site temporary storage measures for potential water reuse and minimisation of impervious areas. Water quality benefits of PPS include thermal mitigation and reduced pollutant loadings of suspended solids, heavy metals, hydrocarbons, and some nutrients to receiving natural waters. It is recommended that SUDS such as PPS be incorporated within urban drainage systems across Caribbean SIDS to help mitigate the frequent flooding events being experienced annually. PPS installations must be fit for purpose and this paper discusses key considerations for use of PPS within urban settings across Caribbean SIDS.*

Keywords: *Permeable Pavements, Stormwater Management, Sustainable Urban Drainage Systems (SUDS), Small Island Developing States (SIDS), Surface runoff*

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4. Analysing Climate Gentrification in Coastal Neighbourhoods: A Case Study of Lagos, Nigeria

Godson Chizara Wogu[1], Kemi Adeyeye[2], Alex Copping[3]

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Abstract. *The concept of climate gentrification emerged to redefine our understanding of how climate change impacts (sea-level rise, flooding, water storms, tsunami) and adaptations drive inequality in human settlement and probable displacement of low-income households through changes in housing property value. However, the concept of climate gentrification lacks adequate parameters for application in diverse coastal locations. In response, this qualitative case study proposes a climate resilience integrated approach (framework) for identifying the parameters to analyse climate gentrification in the coastal neighborhoods of Lagos (Nigeria). In doing so, a pilot investigation was conducted using naturalistic observation to explore events and lived experiences of residents in Lagos coastal neighborhoods. Findings indicate a preference for built/engineered resilience infrastructures and higher return on physical asset investments as core variables driving climate gentrification patterns in Lagos coastal neighbourhoods.*

Keywords: *Climate Change, Sea Level Rise, Flooding, Climate Gentrification, Housing Displacement*

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5. Multi-Step Flood Forecasting in Urban Drainage Systems Using Time-series Data Mining Techniques

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Abstract. *While early warning systems are recognised as the most cost-effective solution in urban flood risk management, highly accurate flood forecasting is limited to short-term timesteps, usually less than a few hours especially for prediction of* *overflowing in urban drainage systems. This study aims to provide a framework for more accurate overflow predictions for longer lead times by using data mining models applied to time series data for multi-step flood forecasting. The framework including event identification, feature analysis and developing models is demonstrated by its application to a pilot study in London. All numerical rainfall data and water levels in urban drainage systems are first turned to the categorical events on which 6 common weak learner models are developed. Then, three new time-series models, including overflowing-based, non-overflowing-based, and accuracy-based, are developed based on these models to predict overflow states among all identified events. Three weak learner models, i.e. discriminant analysis, naive Bayes, and decision tree are considered as the best models based on accuracy, total overflowing detection and total non-overflowing detection. Furthermore, while the accuracy of these models is changed between 95 to 85% from 1 to 12-step ahead of prediction, these models can detect the non-overflow conditions better than overflow detection. To cover this gap, new time series developed models could significantly reduce the overestimation and underestimation of water levels, including correct predicting of 50% of the total events after 12-step ahead by overflow-based model. This result shows the potential of using time-series data-demanding models for effective and highly accurate predictions of overflow events..*

Keywords: *Data mining; Drainage system; Flooding classification; Multistep prediction Overflow prediction*

6. Suitability of the SCS Type Temporal Distributions for Local Rainfall in Trinidad and Tobago, West Indies

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Abstract. *Stormwater management facilities are intended to convey the peak flows generated by some critical storm. A major feature of that storm controlling the resulting peak flow is its temporal distribution, that is, how the rainfall depth is distributed in time. The chosen distribution should be representative of the rainfall observed in the local vicinity of the facilities, and this is obtained by Analysing fine temporal resolution records (between 5 minutes to 1-hour intervals) collected from local rainfall stations. Often, the only records available are ones collected on a daily scale, which are too coarse for the small watersheds that typify small island states. For estimating design peak flows, designers frequently refer to the temporal distributions published within the SCS peak flow estimation procedure. The problem is these temporal distributions were developed for the United States and they may be markedly different from local distributions. This study analysed fine resolution data from a few stations in Trinidad. It found that the representative temporal distributions were bi-modal, unlike the strong uni-modal distributions in the SCS procedure. A comparison of peak flows derived from the various distributions found that the NRCS distributions over-estimated peak flows by more than 100%. Although this may suggest the possibility of oversizing infrastructure for drainage, caution is required in realising that while not frequent, from time to time, recorded storms have mimicked the SCS curves. Clearly the work needs to be extended to consider longer rainfall series, from a larger number of rainfall stations across the country.*

Keywords: *Rainfall temporal distribution; SCS hydrologic procedure; oversizing infrastructure; HEC-HMS; Trinidad and Tobago*

7. Examining the Feasibility of GeoAI and IoT for Smart Flood Early Warning Systems for Local Communities in Caribbean Urban Spaces

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Abstract. *Over the last few decades, flooding has resulted in many problems that significantly impact countries in the Caribbean. This has been especially challenging in urban areas where widespread damage has occurred. In addition, given that over 50% of the world's population lives in urban areas, these locations are deemed to be vulnerable to climate-related disaster events that would further exacerbate the challenges in the region. These urban spaces in the Caribbean have limited access to real-time flood monitoring data for formulating and supporting policies for disaster practitioners to coordinate timely preparedness and mitigation efforts. While flooding is complex, with a series of negative impacts on social and economic sectors, it is essential to provide a basis to support decision-making information on vulnerability and resilience through early warning systems (EWS). However, the main obstacle in creating early warnings in the Caribbean is the suitability and* *availability of data for real-time flood prediction. Consequently, there is a research gap from the perspective of short-term forecasting for sudden rainfall events in urban spaces in the Caribbean. Given the early warning system culture in the Caribbean has an environment of real-time data of scarce resources, it is necessary to forge an approach for real-time forecasting flooding impact in urban spaces. The paper will provide a preliminary analysis of the feasibility of machine learning and IoT use in supporting EWS in Caribbean urban spaces.*

Keywords: *GeoAI, Machine Learning, Internet of Things, Early warning systems (EWS), Caribbean*

8. Advancing Solar Energy Driven Heterogeneous Photo-Fenton Processes for River Water Remediation

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Abstract. *Water is essential for life. Many of the countries across the globe that have poor management of potable water resources and lack critical infrastructure for managing wastewater. As the population of the Earth grows exponentially, the demand for water increases. More than 1 billion people across the world do not have access to potable water and they are struggling with epidemic level disease outbreaks, limited water supply among other large-scale public health risks. Large-scale critical infrastructure chains are required in order to produce potable water from raw water sources, and developing countries continue to struggle economically and cannot afford the same treatment chains as the developed world. This research project evaluated the feasibility of two photocatalytic and photo-Fenton solar reactors on their capabilities to breakdown water contaminants present in natural hydrosystems and freshwater resources namely rivers. The approached adopted to achieve this was the photo-Fenton reaction and solar-photochemical reactors designed constructed and tested for the removal efficiencies of Chemical Oxygen Demand (COD), ammonia, nitrates, nitrites and phosphates via LCK curvette tests, in addition to turbidity and colour. The water quality analysis and results showed that oversaturation of the photo-Fenton reagents reduces the effectiveness of the reaction, and that finding the correct chemical balance has a greater impact on the removal efficiencies of the five pollutants than the use of UV light catalyst. The difference in the reactor builds was their diameter, and the results showed that the reactor of smaller diameter achieved the best removal efficiency across all five pollutants.*

Keywords: *Photo-Fenton, Heterogeneous Fenton, Photochemical treatment, Solar Energy, River Water, Detoxification, Drinking water, Solar radiation*

9. Potential Impact of Oil Spills in Coastal Waters on Water Supply

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Abstract. *It is apparent that oil exploration poses an inherent risk to water resources and water quality. This is exemplified by oil spills resulting from broken pipelines, underwater blowouts and oil transport vessel accidents. In these instances, water is usually the first casualty, as some form of water body is vulnerable to spilled oil, resulting in oil contaminated water. The freshwater resources of Small Island Developing States (SIDS) are often said to be stressed from anthropogenic pollution, which can lead to freshwater scarcity. In an effort to ensure the sustainability of freshwater resources resilience in SIDS, desalination is increasingly being used to provide potable water. Hence the quality of seawater deserves serious consideration. It is in this light that oceanic oil spills are of significant relevance to the provision of a guaranteed supply of potable water. For an oil producing small island developing state as Trinidad and Tobago, which has considerable oil and gas activities on land and in shallow waters along its coasts, the island's oceanic water can become increasingly stressed from oil spills, possibly leading to the shutting down of seawater intakes in the desalination process. A real-life seawater surface oil spill in the Gulf of Paria, south-west coast of Trinidad, not far from the largest desalination plant in the Caribbean, is investigated and its behaviour modelled, using numerical mathematical modelling techniques to produce trajectory plots. These plots are analysed to infer the potential impacts of the oil behaviour in the coastal waters on the island's domestic water supply.*

Keywords: *Small Island developing states (SIDS), oil spills, coastal water quality, freshwater resources, desalination, numerical mathematical modelling, Gulf of Paria, Trinidad*

10. The Impact of Climate Change on the Navet Reservoir, Trinidad

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Abstract. *A hydrologic study of the Navet reservoir and its catchment was conducted to investigate and evaluate the potential impacts of climate change on it, using the Soil Moisture Accounting algorithm in HEC-HMS to perform continuous simulations. The catchment is partially gauged, with a single rainfall gauge located within it and with the absence of a stream gauge, stage data from the reservoir was used to evaluate catchment response. The selection of model parameters was based on previous work done on the nearby Nariva catchment and were improved on by a manual optimisation technique. The model was subject to a split-sample test with a calibration period of 24 months (2003, 2004) on a daily time-step followed by validation over a period of 60 months (2005-2009). Upon successful validation, the model was used to evaluate the system's response to climate change. The meteorological data for this was generated by the PRECIS software for this region. The model was subject to three scenarios based on the SRES A1B scenario. The results of simulations for the period 2030-2096 showed that for successful operation, production rates at the Navet reservoir requires a 40% reduction of present values for two of these scenarios and by 30% for the most optimistic scenario.*

Keywords: *Continuous Hydrologic Modelling; Soil Moisture Accounting; HEC-HMS; Navet Reservoir*

11. Cumulative Fatigue Damage of Small-Bore Piping Subjected to Flow Induced Vibration

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Abstract. *The structural fatigue of a vertically oriented small-bore connection due to flow induced turbulence emanating from an upstream piping manifold is experimentally investigated. Dynamic strain measurements are taken at two perpendicular locations on a small-bore connection and the method of rain flow counting is used to determine the cumulative damage incurred. The influence of a number of factors on the cumulative damage are investigated and explained. These include the effects of (1) single phase and multiphase flow, (2) the upstream flow path through the manifold, and (3) steady-state and transient conditions. Specifically, key observations that may be useful to piping designers and engineers are observed and reported. For instance, for single phase water or air the largest bending stresses are due to the out-of-plane vibration of the small-bore piping, whereas the pulsating characteristics of the multiphase flow results in significantly larger in-plane bending stresses. It is also observed that under certain manifold outlet conditions, transient effects upon pump start-up can produce more than 300 times the cumulative fatigue damage compared to steady-steady operation.*

Keywords: *Cumulative damage, Fatigue, Flow induced vibration, Rainflow counting, Small bore connections.*

12. Improving Monetary Valuation Methods Used in Cost Benefit Analysis of Water Infrastructure Projects

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Abstract. *An assessment of social utility and project benefits in the water sector should include financial, environmental and socioeconomic impacts that are comparable over the same unit in an analysis. Cost benefit analysis (CBA) is a decision support tool that can cover impacts identifiable within these three impact categories. However, most water sector CBA are only invested in forecasting future financial cost-benefits, while environmental and socioeconomic impacts are assessed by environmental impact assessments (EIA), life cycle assessments (LCA) and other qualitative assessments, or entirely ignored. Studies identify a need for more guidance on application of relevant monetary valuation methods to water infrastructure specific project impacts. This is feasible if a more approachable and implementable CBA framework tailored for the sector is* *made available. This paper suggests a universal set of umbrella categories for wastewater treatment plant (WWTP) impacts across the five project phases that comprise a project lifespan. The paper identifies literature on accessible and relevant monetary valuation methods for each impact category typical to a WWTP infrastructure project. The findings originate from literature on current practices in the water sector, academic innovations theoretically applicable to water sector projects, and methods borrowable from comparable sectors. These origins are the building blocks for consolidating knowledge of monetary valuation methods relevant to the water sector, which we tabulate in a reference matrix.*

Keywords: *CBA, WWTP, roadmap, monetary valuation methods*

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13. Rainwater Harvesting Design Approaches

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Abstract. *Different approaches have been developed to design rainwater harvesting systems. However, these have not been widely applied in schools and are not well understood. This paper presents findings from a study in which different rainwater water harvesting design approaches are selected and applied to a case study school. The approaches are introduced and the results of their application to the case study school are critically evaluated. The study finds that the methodologies have different strengths and weaknesses. A critical analysis of the results indicates that one approach may be too simplistic and provide misleading results. Another approach does not provide adequate outputs to fully design rainwater harvesting systems. A third methodology is complex to apply and requires data that is difficult to obtain. Based on the study, recommendations are made on how the selected approaches can be improved to enable these to be used more easily to design school rainwater harvesting systems.*

Keywords*: Schools, rainwater harvesting, rainwater harvesting modelling and calculators*

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14. School Water and Rainwater Use Modeller

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Abstract. *With climate change, schools in hot and dry areas are increasingly experiencing water shortages. This can affect the health of students and teachers, disrupt education and in the worst case, lead to school closures. Rainwater harvesting can help address water shortages by providing a safe alternative source of water. However, there is limited research and guidance on how rainwater harvesting systems can be applied to schools. A lack of guidance and knowledge has meant that schools are not aware of the potential of rainwater harvesting systems and do not adopt these systems. There is a need, therefore, for a simple tool that can be used by schools to understand the potential of rainwater harvesting systems at schools. This study aims to address this gap by developing the School Water and Rainwater Use Modeller (SWARUM). The modeller is presented and applied to a case study school in a drought-stricken area of Southern Africa. The findings of the application and the modeller are critically evaluated. The study finds that the modeller can be used to show the potential of a rainwater harvesting system at schools and enables different scenarios to be modelled and understood. The study makes recommendations for the improvement of the modeller and its application.*

Keywords: *Schools, rainwater harvesting, School Water and Rainwater Use Modeller*

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15. An Elementary Review of Wave Energy Potential at Mauritius Island

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Abstract. *During the last decade renewable energy sector has attracted a significant interest from a range of stakeholders. Ocean Renewables in specific are an attractive solution for covering countries' high energy demand with low or none* *environmental impacts. Within this context wave energy power generation potential around small islands has extendedly been investigated as well. Following that a review has been carried out in here, to compile existing research findings on wave energy potential, in specific around Mauritius Island. The island is geographically favored for ocean energy extraction in the context of energy extraction from offshore winds, waves and currents, and ocean thermal and saline energy. Mauritius relies on fossil fuels to cover its energy needs. But the island has set a target to be able to cover its electricity needs by utilising 35% from renewable energy sources by 2025. From the reviewed literature and a range of secondary calculations two sites come through as highly favorable locations for WECs (Wave Energy Converters) installation. Findings highlight that the wave source itself is abundant stressing out the need for further research to understand when and if WECs at the Mauritian sites could be fully commercialised in the future. For these sites and from the point of better understanding the spatial distribution of wave energy resource, high resolution wave transformation and hydro-morphodynamic numerical modelling is further suggested. Numerical modelling can support exercises to identify precise locations for WECs deployment along the coastline, prior to reaching any commercialisation.*

Keywords: *Mauritius Island, Wave Energy Converter (WEC), Ocean Wave Energy, Renewable Energy, Small Island*

16. Digitalisation in the Water Sector: Opportunities and Challenges in the Next Decades

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Abstract. *The water sector is undergoing rapid digitalisation providing new opportunities for improved, more efficient and economical services. Digitalisation may efficiently enable water utilities to overcome numerous challenges in the next decade by implementing, for example, real-time detection of water quality, process optimisation, efficient management of transport systems' rehabilitation, and reduction of utilities' physical and energy footprints. Many countries consider water supply and wastewater management critical services, and small islands are not an exception. Disruption of these services can lead to devastating consequences for the functioning of a society. In addition to natural catastrophes, the increasing number of manmade disruptions requires the earliest possible detection. The rapid digitalisation of the water sector has increased its vulnerability to cyberattacks, making it the third most attacked sector based on probability. Preparedness for immediate control of the attacks and the recovery actions after the incident is vital and should be planned. When a utility is under attack, identification is also critical, as man-made attacks can last several hours or days before being identified. This paper presents the emerging opportunities of digitalisation and the challenges associated with cyberattacks. Examples requiring increased preparedness, efficient detection, and the use of digital tools to minimise the impacts are outlined.*

Keywords: *Water utilities, Digitalisation, Remote control, Cyber risks*

17. Potential Implications for Deployment of Low Carbon Construction Materials in the Water Industry

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Abstract. *The introduction of sustainable and low-carbon construction materials into the built environment is one approach to reduce emissions of greenhouse gases to the atmosphere. By increasing the use of renewable energy and waste, new materials and processes can be incorporated into the materials supply chain. The present work relates to the mineralisation of anthropogenic CO_2 gas in construction materials, and their potential for use in water treatment, particularly in small island nations. We provide an overview of developments in this area of interest, with specific reference to the capture and use of point-source emissions, carbonate-able cementitious binders and waste in the manufacture of construction aggregates/monolithic products, including concrete and potential filter media. As the amount of construction materials used in new and existing water-related infrastructure is significant, there is potential for meaningful long-term carbon sequestration. In respect of this, we discuss the potential sustainability gains from replacing/reducing carbon intensive materials, quarried and crushed stone* *with low-carbon substitutes with particular reference to typical water supply and wastewater treatment facilities in the SE of England. Further, we estimate this potential more widely in order to gain a 'global' for carbon storage potential figure within fresh and waste water infrastructure.*

Keywords: *Low Carbon Construction Materials, Water Industry, Water infrastructure, England*

18. Development of Sustainable Building Design in Hong Kong: Exploring Lean Capabilities

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Abstract. *When a building design fails to meet the end-users' requirements after construction, it is regarded as a faulty design. Faulty designs often lead to renovation, demolition, and material waste. The need to implement innovative tools and systems that continuously provide designers with the end-users' design requirements and feedback in the built environment cannot be ignored. This study explores the potentiality of implementing a Lean Premise Design (LPD) scheme in Hong Kong to facilitate sustainability practices, ensure energy conservation, promote innovative green technologies and water efficiency, and reduce abortive works in high-rise residential (HRR) buildings. A comprehensive review of literature on concepts similar to the LPD scheme and sustainability practices in the design and development of high-rise buildings was undertaken. In addition, interviews were adopted to validate the identified barriers and drivers to the LPD scheme. These facilitated the identification of perceived barriers to the LPD scheme adoption in the local context. Furthermore, the relevant drivers that can promote its implementation were examined. The study focused on sustainable building design relating to users' behaviour patterns and expectations, social needs, green maintenance technologies, and government initiatives. About 77% of the experts affirmed the availability of comprehensive building codes and guidelines. Nevertheless, 62% of the experts confirmed the insufficiency of the current regulations to promote sustainable building design. Similarly, the literature review revealed that while there are many sustainable concepts in the development of high-rise buildings, little or none of these concepts focused on LPD.*

Keywords: *High-rise buildings; Lean Premise Design; Residential buildings; Sustainability, Waste; Hong Kong*

19. Higher Education Institutions in the Sustainable Transition: A Study at the University of Aveiro

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Abstract. *In accordance with the United Nations 2030 Agenda for Sustainable Development, Higher Education Institutions (HEIs) play a key role in raising environmental awareness and implementing practices to contribute to the Sustainable Development Goals (SDGs), in a scenario of protecting the environment and promoting innovation and resilience – social, cultural, scientific, and technological. Considering HEIs as active agents of change in the global network for sustainability, the present study aims to present the main strategies and current initiatives of HEIs in the implementation and development of sustainable campus, regarding institutional physical interventions. Using the literature review, it is intended to identify the various contributions of HEIs in the Portuguese and European panorama for this emerging challenge, about the categories evaluation that include energy, greenhouse gas (GHG) emissions, waste, procurement practices and the built environment, mobility, biodiversity, water and food security, also highlighting the initiatives to increase environmental sustainability on the campuses of the University of Aveiro (UA). The conclusions of this research indicate that the HEIs, at the European level are implementing good practices in the management of the campus as a living and evolving laboratory, but there are potential interventions, still little explored, to make the operations of the HEIs more sustainable and effective.*

Keywords: *Sustainable Campus, Circular Economy, Higher Education Institutions, University of Aveiro.*

20. Nearly Zero Water Buildings: Contribution to Adaptation and Mitigation Processes in Urban Environments

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Abstract. *Extreme weather events related to heat waves and heavy rainfall are expected to intensify in the coming decades in various regions of the planet as a result of climate change. The impacts of these events on urban environments will be particularly significant, given that, according to the United Nations, around two-thirds of the world's population will live in cities by 2050. Buildings and other urban infrastructures therefore have an important role to play in the processes of mitigation and adaptation to climate change. The implementation of nearly zero energy buildings (NZEB), for example, can contribute to very significant reductions in greenhouse gas emissions, which is why the European Union has established special requirements in new buildings. However, "nearly zero buildings" for all resources, not just energy, should employ integrated and enhanced construction solutions in the future, not only contributing to increasing environmental sustainability in urban areas, but also playing an important role in adaptation and mitigation in relation to climate change. In the case of "nearly zero water buildings", they can increase the resilience of urban environments in the face of extreme events such as prolonged droughts or extreme precipitation and, considering the water–energy nexus, can also contribute to a significant reduction in emissions. The "zero building" concept is not, however, similar for all resources. In the case of energy, the usual concept of NZEB does not mean a circular use of the resource, but rather that the total amount of resource used by the building is approximately equal to the amount of renewable resource produced or available on the site. In the case of water, part of the resource can be used in a circular way (water recycling), but renewable local sources alternative to the supply from the public network can also be considered. The design of "nearly zero water buildings" should be based on the 5R principle of water efficiency: Reduce consumption; Reduce losses and waste; Reuse water; Recycle water; and Resort to alternative sources (rainwater, salt water, etc.). It is obvious that water efficiency is of the utmost importance in the face of prolonged droughts, but the use of rainwater in urban areas has an additional known effect in dampening flood peaks. Considering the water–energy nexus, reducing water consumption in a building (the 1st R) also produces significant energy savings. This is a result of reducing the energy needs for domestic hot water, to pressurise water in buildings, and also in public systems, in pumping and treatment of water and wastewater.*

Keywords: *Climate change, Water efficiency, Zero building*

21. Interpreting the Technical versus the Physical as Drivers for Shower Water Use

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Abstract. *Showering is informed by the person, their preferences and the affordances provided by the showering device and supporting systems. People shower for different reasons, including reasons of health, hygiene, wellbeing, leisure, relaxation among others. Studies have explored water use and efficiencies in showering in homes and other buildings. The lack of granularity of showering data can however mean that findings and deductions are typically made at the household or building level, rather than at the individual, shower end-user level. This study helps to address this gap about showering. This paper presents further analysis from an in-home trial with 12 adult participants: 6 male and 6 female, with a particular focus on interpreting the shower performance factors against the shower user. The findings highlight the contextual and physical characteristics e.g., shower positioning and user anthropometrics, and the showering needs (perceived shower functionality) as important drivers of water use.*

Keywords: *End-users, showerhead, showering, time, purpose, water efficiency*

22. Water Distribution Challenges in Northeast Trinidad and Tobago

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Abstract. *Provision of a reliable supply of water with adequate pressures is a paramount challenge for the water distribution network in Northeast Trinidad and Tobago. Customers in this region, served by the Water and Sewerage Authority of Trinidad and Tobago often have trouble in obtaining a pipe borne supply of water as they reside on areas of high elevation or at the farthest end of the distribution system. These areas where water supply challenges are a problem are Oropoune Gardens Piarco, Upper Five Rivers Arouca, Windy Hill Arouca, Edna Hill Arouca, Lillian Heights Arouca, The Foothills Arouca and Bon Air North that is made up of Pineridge Heights Housing Development and Ridgeview Heights Housing Development. Sources of supply for these impacted areas are the North Oropouche Water Treatment Plant, the Hollis Water Treatment Plant, Tacarigua Highlift Station and the Arouca Wells. Challenges in the water supply are a consequence of obsolete pipelines, numerous leaks, failure of mechanical equipment and the shortened duration of supply to the respective areas. The aim of this paper is to identify the inefficiencies and challenges of the water distribution system in this region by simulating flow through pipes using ANSYS Fluent simulation and the Hazen-Williams equation and advocate prospective solutions that can alleviate or even eliminate the inadequate water supply experiences faced by customers in these highly elevated areas.*

Keywords: *ANSYS Fluent, Distribution pipelines, Hard-hit areas, Hazen-Williams Equation,Northeast Trinidad and Tobago, Transmission pipelines, Water distribution*

23. Impact of Climate Changes on Domestic Hot Water Consumption

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Abstract. *Domestic hot water consumption is the second largest source of energy consumption in residential buildings. Moreover, the growing trend towards more energy efficient buildings, from a thermal performance point of view, is increasing its relevance. As such, more accurate modeling of domestic hot water consumption is required, including the consideration of the impact of climate change. A new approach that accounts for the variability of the domestic hot water consumption and cold-water temperature throughout the months is used to forecast the amount of energy and carbon emissions associated. It was found that in climate change context, despite the forecasted increase in air temperature in the summer months, the decrease in the remaining leads to higher domestic hot water consumption and, proportionally, higher energy and carbon emissions.*

Keywords*: Domestic hot water consumption, energy consumption, carbon emissions, climate change*

24. Water Demand Modelling and Analysis United Kingdom, North American and Sri Lankan Data

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Abstract. *The aim of this research is to study real water consumption data to determine the most appropriate statistical distribution function to address the peak water demand. Moreover, the study is expected to contribute to finding a better fitting water demand model, which could apply to any water network. To achieve the objective, this study selected water usage of three different countries with diverse socio-economic backgrounds, climate, and geography to get an overall picture of water usage patterns. The countries selected for the analysis were United Kingdom, North America, and Sri Lanka. The most widely used probability distribution functions to represent a continuous random variable such as normal, log-normal, exponential, logistic, log-logistic, 3- parameter log-logistic and Weibull were applied to comprehend the suitability of fitting. The normal, log-*

logistic and 3- parameter log-logistic distributions are suitable to represent demand data with lower and high demand values and were selected for further analysis and is described here to provide their suitability for modelling water demand..

Keywords: *Uncertainty in water demand, log-logistic distribution, 3- parameter log-logistic distribution, probability distribution function, sustainable design*

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25. Microbial Activity in Potable Water Storage Tanks of Barbados

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Abstract. *As water supplies are strained, distributed infrastructure can often help stabilise a water distribution system. Recently, the Barbados Water Authority, in collaboration with Caribbean Community Climate Change Center, installed 400, 450, and 1000-gallon potable water storage tanks to residential and school properties to increase the reliability of distributed drinking water to residents. However, there is minimal knowledge on the potential microbial impact of these storage tanks on water delivered to the tap. Preliminary data from this project confirmed that temperatures within these tanks can exceed 25 degrees Celsius, the lower threshold for increased growth of the premise plumbing pathogen Legionella. Inhalation and ingestion of Legionella pneumophila is known to cause Legionnaire's disease, a lifethreatening lung disease with pneumonia-like symptoms and tends to grow with long water stagnation periods, low disinfectant residuals and elevated temperatures. Seven sites located in the northern parishes of Barbados and one site located in a western parish were tested for temporal fluctuations of temperature, nitrate, total chlorine, total coliforms, and Escherichia coli (E. coli) with Legionella tested at select times of the day. Five of these sites were installed within the past year and three were installed up to four years prior to this study. All tanks showed values below the nitrate recommended range of less than 10 mg/L given by the USEPA. Only three tanks maintained the minimum chlorine residual of 0.2 mg/L given by the USEPA. Five sites showed positive total coliform tests and three sites showed positive E. coli tests and Legionella tests. With these results in mind, more quality assurance testing must be performed to ensure the true activity inside these tanks at various times of the year, location on the island and with continually flushed and finished systems. Unintended consequences from infrastructure upgrades are a threat, especially as climate change will continue to strain drinking water source supplies.*

Keywords: *Legionella pneumophila, water scarcity, potable, temperature, Barbados*

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26. Biomass-based Sorbents for Stormwater Treatment

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Abstract. *Rapid urbanisation coupled with climate change necessitates the use of bespoke facilities to treat waste and stormwater to prevent contamination of ground and surface water. The contaminants of interest are wide-ranging including heavy metals, organic pollutants and micro plastics. There is mounting interest in the management of significant amounts of biomass waste available around the world and the exploration of utilisation potential. For example, large amounts of filter media including 'active' materials such as charcoal and plant based fibres are used. Nevertheless, the use of biomass-based sorbents and filter materials are of importance as they can offer both technical and economic advantages over traditional treatments. For example, studies are on-going on biomass-based sorbents coupled with conventional filter media such as graded sand and gravel gravity filters. The present work reviews developments in this area and introduces new potential materials for consideration, including biowaste from crustaceans, shells, and agriculturally derived biomass waste. With reference to example water supply and wastewater treatment facilities in the SE of England, the potential scale and benefits for resource recovery of biomass waste whilst also harnessing its water remediation potential will be discussed.*

Keywords: *Biomass-based Sorbents, biowaste, Stormwater Treatment, urbanisation*

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27. Renewable Energy-powered Reverse Osmosis Desalination: Solutions and Opportunities for Large-scale Implementation

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Abstract. *Operating reverse osmosis (RO) systems using renewable energy (RE) is fundamental for meeting water security challenges, especially for small islands and developing states. Their integration requires RO systems to accommodate variations from RE sources to avoid reliance on backup systems. This study presents the outcomes of a research project that aimed to optimise the operation of RE powered RO by improving their variable-speed and modular operation for handling a wide range of RE variations. An industrial-scale pilot RO plant with 3.2 m3/h production capacity was designed, commissioned and tested at Aston University, UK, to be the basis for this project. It includes an isobaric pressure exchanger and delivers similar performance to large RO systems to develop solutions suitable to such scale. Several operation strategies were investigated for operating RO systems using RE. An advanced control system using Model predictive control was developed to control the RO power consumption based on RE variation. RE availability prediction using neural networks was developed for scheduling the startup/shutdown cycles of RO units during modular operation. The project concluded that operation at variable recovery and constant brine flowrate delivered the lowest specific energy consumption and widest operation range for systems using an isobaric energy recovery device. Model predictive control enhanced energy utilisation compared to a proportional-integral controller leading to a 2.35% improvement in permeate production for a defined power input. Overall, the solutions developed showed that RO systems can operate efficiently by direct RE using variable operation, which showcased the opportunities for further testing and development towards large-scale implementation.*

Keywords: *Reverse osmosis; renewable energy; variable operation; model predictive control; wind speed prediction*

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28. Comparative Study of Solar-Enhanced Advanced Oxidation Processes for Water Treatment

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Abstract. *Water is an essential resource for human survival but in the 21st Century there is a lack of potable water in many parts of the world. In several developing countries people resort to consuming heavily polluted water obtained from rivers which contain life threatening diseases. The study used two methods, Photo Fenton and photocatalytic semiconductor as an advanced oxidation process to eliminate various water contaminants and provide an effective water treatment solution. Experiments were performed on polluted river water. Both methods were assessed by evaluating the physiochemical parameters that define the characteristics of safe water. The two methods successfully eradicated about 80-100% of pollutants that was measured in the river water samples. This shows the technology has potential in eradication of the contaminants.*

Keywords: *Titanium Dioxide, Solar Photo Fenton, Solar photocatalytic semiconductor, Photocatalysis*

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The Caribbean Academy of Sciences 23rd Biennial Conference 2023 (CAS23-2023), 24th-25th November 2023

Faculty of Engineering, The University of the West Indies, St Augustine Campus, Trinidad and Tobago, West Indies

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Conference Theme on:
"**The Sustainability and Development Initiatives of the Caribbean**"

Issues of sustainability and development remain as critical in the Caribbean. Amongst sustainability and development goals are fostering sciences, technology and education to initiate transformative actions for safeguarding ecosystem conservation and improving our common future of the region.

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• Dates of the Conference	24th-25th November 2023

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WIJE aims at contributing to the development of viable engineering skills, techniques, management practices and strategies relating to improving the performance of enterprises, community, and the quality of life of human beings at large.

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