SUSTAINABLE UP-FLOW SAND FILTER FOR DOMESTIC WATER SUPPLY

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DECLARATION

I hereby declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sabah. I also certify that the writing and data presented are my own, unless otherwise indicated or acknowledged as referenced. This thesis has not been submitted to any other academic institution or non-academic institution for any other degree or qualification.

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ABSTRACT

A decentralised system is among the solutions to providing treated water to isolated areas. Upflow sand filtration systems offer comparable treatment efficiency to downflow slow sand filters without clogging susceptibility. Upflow sand filter application as a point-of-use water treatment system was studied. The current study aimed to identify the characteristics and suitability of local river sands as upflow sand filter media, evaluate the effects of sand grain size and filter bed height on operational pressure drops, and the efficiency of the upflow sand filter in removing total suspended solids (TSS), turbidity, total coliform, and ammonium (NH_4^+) at varied flow rates. The spatial and temporal profiles of microbial growth during acclimatisation and clogging effects throughout the filter operation were also assessed. Three river sand samples were studied regarding their physical characteristics and trace elements with a beach sand specimen as a comparison. The pressure drop of three sand sizes (0.15, 0.17, and 0.25 mm) and five bed heights (0.3–0.8 m) were determined. The results were contrasted against the Ergun, Kozeny-Carman, and Fair and Hatch equations. A pilot scale of the upflow sand filter was utilised to evaluate the removal efficiency of three operational velocities (0.072, 0.181 and 0.481 m h$^{-1)}$. An eight-week acclimatisation period was adopted to develop the microbial community within the filter bed, resulting in a total operational duration of 135 days. The river sand ranged from 0.075 to 1.7 mm in size and possessed a uniformity coefficient (U_c) of 1.8–2.7. Sands with a U_c of 3 and lower are preferable for filter applications. The samples also demonstrated high silica contents at 704.5, 604.24, and 405.41 g/kg, indicating purity. Conversely, beach sand contained the lowest silica (371.02 g/kg) and high chloride (30.15 g/kg) and calcium (537.17 g/kg) contents, which could leach out if employed as a filter media. Reduced grain size and increased bed height improved pressure drop. Similar maximum pressure drop velocities were recorded (0.835 m s^{-1} V_s), except at 40 and 80 cm bed heights at 0.747 and 0.878 m s^{-1} V_s, respectively. Subsequently, the filter bed was fluidised and stabilised following the maximum pressure drop. The prediction model exhibited that pressure drop could be projected with the Kozeny-Carman and Fair and Hatch equations pre- and post-fluidisation, while the minimum fluidisation velocity could be simulated via the Wen and Yu equation. The minimum fluidisation velocity was affected by grain size but was independent of the filter bed height. The turbidity and TSS removal ranged from 75 to 100% and 93.98% for NH_4. Removal was mainly achieved deeper in the bed, where 90% turbidity and TSS removal occurred in the middle layer (30 cm deep), and over 86.73% NH_4 was removed at 50 cm depth. The total coliform removal was beyond 89% but dropped at higher flow rates due to disturbances from the increased flow rate. The field emission-scanning electron microscopy (FE-SEM) images demonstrated that the microbial grew from the bottom and progressively moved upward in the filter bed. After eight weeks, substantial growth was observed at the bottom and middle layers and lesser on the top section. Dissolved oxygen concentration was also documented as the lowest (1.32 mg/L) in the middle layer, followed by the bottom layer (3.24 mg/L), indicating rapid microbial activities. Clogging was insignificant, with R^2 of 0.0339, 0.4273, and 0.476. The current research demonstrated that upflow sand filters could be fabricated in isolated areas by employing local river sand. Moreover, for an average of 100 L per capita per day usage, the upflow sand filter would cater to a household of six.

ABSTRAK

PENAPIS PASIR ALIRAN NAIK TERLESTARI BAGI BEKALAN AIR LUAR BANDAR

Sistem nyahpusat adalah penyediaan altenatif air terawat bagi kawasan terpencil. Sistem penapis pasir beraliran naik berkesan yang setaraf dengan sistem penapis pasir aliran bawah tanpa kebarangkalian tersumbat. Kajian dilakukan atas penggunaan penapis pasir beraliran naik sebagai rawatan air nyahpusat untuk mengenal pasti kesesuaian pasir tempatan sebagai media penapis, menilai kesan saiz zarah and ketinggian penapis terhadap penurunan tekanan, mengukur kecekapan penyingkiran jumlah pepejal terampai (TSS), kekeruhan, jumlah koliform dan ammonium *(NH_4^+). Profil ruang dan temporal pertumbuhan mikrob dalam tempoh penyesuaian dan kesan tersumbat sepanjang operasi juga dinilai. Tiga sampel pasir sungai dikaji dari segi ciri fizikal dan unsur surih dan dibandingkan dengan ciri-ciri satu sampel pasir pantai. Penurunan tekanan dikaji pada tiga saiz pasir (0.15, 0.17, dan 0.25 mm) dan lima ketinggian dasar (0.3–0.8 m). Hasil kajian dibandingkan dengan persamaan* Ergun, Kozeny-Carman, *dan* Fair and Hatch*. Sistem skala rintis digunakan untuk mengkaji kecekapan penyingkiran tiga kapasiti kelajuan, 0.072, 0.181 and 0.481 $m\ h^{-1}$. Tempoh penyesuaian lapan minggu diadaptasi dalam kajian ini untuk pertumbuhan komuniti mikrob. Tempoh operasi penapisan ialah selama 135 hari. Keputusan menunjukkan pasir sungai tersebut bersaiz 0.075–1.7 mm dan mempunyai pekali keseragaman (U_C) 1.8–2.7, yang mana U_C 3 dan lebih rendah adalah lebih baik. Pasir sungai tersebut mengandungi kandungan silika yang tinggi (704.5, 604.24, dan 405.41 g/kg), menunjukkan ketulenan. Pasir pantai menunjukkan kandungan silika paling rendah (371.02 g/kg) dan nilai klorida (30.15 g/kg) dan kalsium (537.17 g/kg) yang tinggi, yang boleh terlarut jika digunakan sebagai media penapis. Penurunan tekanan air meningkat apabila saiz butiran berkurang dan ketinggian penapis meningkat. Tekanan maksimum berlaku pada halaju yang sama (0.835 $m\ s^{-1}$ Vs) kecuali pada ketinggian 40 dan 80 cm, iaitu 0.747 dan 0.878 $m\ s^{-1}\ V_s$, masing-masing. Setelah tekanan tertinggi dicapai, pasir penapis terapung dan menjadi stabil. Model ramalan menunjukkan penurunan tekanan dapat diramal menggunakan persamaan* Kozeny-Carman *dan* Fair and Hatch *sebelum dan selepas keapungan tercapai. Halaju keapungan minimum boleh diramal menggunakan persamaan* Wen and Yu*. Halaju minimum dipengaruhi saiz butiran tetapi tidak bergantung pada ketinggian penapis. Penyingkiran kekeruhan dan TSS direkod dalam julat 75–100%, manakala 93.98% bagi NH_4. Majoriti penyingkiran dicapai di kedalaman yang tinggi yang mana 90% penyingkiran kekeruhan dan TSS berlaku di lapisan tengah (kedalaman 30 cm) dan 86.73% NH_4 telah disingkirkan di lapisan bawah (50 cm). Penyingkiran koliform melebihi 89%, tetapi pada kadar alir yang tinggi, penurunan berlaku akibat gangguan semasa peningkatan kadar alir. Imej* field emission-scanning electron microscopy *(FE-SEM) menunjukkan mikrob tumbuh dari bawah dan beransur ke atas. Selepas lapan minggu, pertumbuhan ketara didapati pada lapisan bawah dan tengah, dan hanya sedikit pada lapisan atas. Oksigen terlarut didapati paling rendah (1.32 mg/L) di lapisan tengah diikuti lapisan bawah (3.24 mg/L). Kesan tersumbat didapati tidak signifikan, dengan nilai R^2 0.0339, 0.4273, dan 0.476. Hasil kajian menunjukkan penapis pasir aliran naik boleh diaplikasikan di kawasan terpencil dengan penggunaan pasir sungai tempatan.*

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LIST OF EQUATION

LIST OF SYMBOLS

D_{10} - Effective Size, 10 Percent Passing

D_{60} - 60 Percent Passing

D_{90} - 90 Percent Passing

D_{eq} - Equivalent Diameter

$(NH_4)_2SO_4$ - Ammonium Sulfate

ρ - Density

ρ_B - Bulk Density

ρ_P - Particle Density

ρ_S - Sand Media Density

Ψ - Sphericity

ϵ - Porosity

N - Number of Grains

Re - Reynold Number

v - Filtration Rate (Superficial Velocity)

V - Volume of Sample

D - Media Grain Diameter

μ - Dynamic Viscosity of Fluid

V_{mf} - Minimum Fluidization Velocity

Ga - Galileo Number

G - Gravitational Acceleration Constant

LIST OF ABBREVIATIONS

COD - Chemical Oxygen Demand
DBPs - Disinfection By-products
E_s - Effective Size
FE-SEM - Field Emission Scanning Electron Microscopes
HAAs - Haloacetic Acids
HANs - Haloacetonitriles
HDPE - High Density Polyethylene
INWQS - Malaysian Interim National Water Quality Standard
MF - Microfiltration
NF - Nanofiltration
NOM - Natural Organic Matter
NTU - Nephelometric Turbidity unit
RMSE - Root Mean Square Error
RO - Reverse Osmosis
RWS - Malaysian Raw Water Standard
SDG - Sustainable Goal Development
TDS - Total Dissolved Solid
TP - Total Phosphorus
THMs - Trihalomethanes
TSS - Total Suspended Solids
U_c - Uniformity Coefficient
UF - Ultrafiltration
V_{mf} - Fluidization Velocity
WHO - World Health Organization
XRF - X-Ray Fluorescence Test

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CHAPTER 1

INTRODUCTION

1.1 Background

Water scarcity has long been a pressing issue, affecting almost every country worldwide (Distefano & Kelly, 2017). Even in regions with abundant water resources, inaccessibility to clean water is not uncommon. Statistics demonstrated that 183 million of the global population lack basic drinking water (UNICEF & WHO, 2017). The issue essentially affects the economic growth of a country (Distefano & Kelly, 2017), food security (Liu et al. 2020), socioeconomics (Zhou, Deng, and Wu 2017), and especially health (Nabi et al. 2019).

Inaccessible water leads to no clean drinkable water and proper sanitation (UNICEF & WHO, 2017), which are directly linked to poor hygiene that induces various diseases. A total of 88% of worldwide diarrhoea cases have been attributed to unsafe water, inadequate sanitation, or an unsanitary lifestyle. Diarrhoea includes some of the more severe diseases, such as cholera, typhoid, and dysentery, more significantly in young children under five years of age (UNICEF & WHO, 2017; H. Zhang et al., 2017).

The Sustainable Development Goal supported by the United Nations has outlined its 6th goal (SDG 6), which was to provide access to clean water and sanitation by 2030 (Herrera 2019). Consequently, with the emergence and spread of infectious diseases, including coronavirus 2019 (COVID-19), it is crucial, now more than ever, to re-evaluate and transform water resources, treatment, and distribution management to ensure accessibility to clean water to promote good hygiene and prevent the spread of diseases.

In Malaysia, access to treated water is not a luxury enjoyed equally throughout the nation, especially in Sabah. Numerous rural communities still depend on unimproved water resources, such as gravity, ponds, rivers, rain, and groundwater. The inaccessibility is primarily due to the remoteness of the locations. Expansion of current distribution networks would demand massive developmental, operational, and maintenance costs due to the large distances between the populated areas. Consequently, a decentralised water treatments and distributions would be more advantageous.

The system would generate water remotely based on the capacity required in each community. The available water resources in each area could be utilised, and the treatment system could be developed based on the available water quality. The treatment system should be simple enough for the communities to operate and maintain to reduce dependencies on outside agencies and increase the sustainability of the water provision systems (Sarbatly, Lahin, and Ken 2020).

One of the most simplified water treatment systems utilisable is sand filters, and slow sand filters, particularly, have been around for hundreds of years. The system effectively removes major pollutants by depending on its granular media bed to retain contaminants. Consequently, sand filters are ideal alternatives to be employed in isolated areas, in which the primary goal is to eliminate particulate matter and pathogenic microorganisms with simplified operations and maintenance at lower costs. Nevertheless, conventional downflow sand filter treatments heavily depend on the downward gravity strain of the water flow.

The straining process occurs at the top of the sand filter bed due to the granular sand distribution, downflow configuration, and microbial development, known as the Schmutzdecke layer (Mutsvangwa & Matope, 2017; Wakelin et al., 2010). Nonetheless, clogging is a common occurrence, leading to reduced treated water yield, thus requiring backwashing of the sand filter. Backwashing downflow sand filters, however, would result in considerable filter downtime and, consequently, a drop in the water quality.

An upflow configured sand filter is proposed as an alternative to solve the clogging issue. The system was initially proposed as a self-cleaning treatment that removes regular backwashing requirements (Smith 1979). Nevertheless, early designs necessitated a towering six feet vessel and constant mixing of sand media, which demand high energy and are not necessarily suitable for applications in rural areas. Accordingly, a simplified version that could be assembled and operated in isolated areas with limited resources and skilled personnel was proposed.

The novel treatment system employs similar mechanisms and presents comparable efficiency to downflow sand filters. Furthermore, the production capacity is adjustable to the required volume demand in upflow configurations by manipulating the feed water flow rate. Nevertheless, modifying upflow sand filter systems to the expected scale and standard presents uncertainties concerning materials suitability, operational capabilities, and longevity, which the current study aimed to answer.

The material employed as the granular media in sand filter beds possesses the most significant impact on treatment efficiency and water productivity of the filter. Physical characteristics, such as particle size distribution, porosity, and sphericity, affect the nature of biofilm development and straining mechanism. Generally, finer sand records higher separation capabilities, however, it might lead to higher pressure drop within the filter bed. Alternatively, sand with lower porosity increases bed resistance and filtration efficiency, but it is more prone to clogging.

Sand from local rivers is the ideal choice as the material for the media must be obtained locally. Previous studies have also proposed a similar application for biosand filter modifications(CAWST 2012). Nevertheless, the chemical compositions of the media must be studied to prevent contamination of the filtered water. The collected sand also requires thorough cleaning to remove impurities and meet the standard of commercially available media before it is utilised in upflow sand filters.

As water flows upward within filter beds of upflow sand filters, resistance and pressure would build up due to barrier or drag force produced by the granular particles. The forces create pressure differences at the beginning and end of the filter bed, hence reducing flow capacity and increasing energy demand (Bové et al. 2015). Moreover, a further increase in the operational flow rate would fluidise the filter bed and hinder the straining treatment process. Although pressure drop is unavoidable, optimum operational parameters could be replicated based on experimental findings or prediction models to diminish excessive pressure drop and prevent fluidisation of filter beds.

Primarily, sand filters remove contaminants via physical and biological processes. Pollutants are removed physically through sedimentation, straining, attachment, diffusion, and interceptions, while pathogens are removed chiefly through straining and transport mechanisms. Nonetheless, pathogen inactivation is achieved by predation or natural death (Ranjan & Prem, 2018).

Ammonium in the water source is separated through nitrification and denitrification by two bacteria, *Nitrosomonas sp*. and *Nitrobacter sp*. In a down-flow configured sand filter, most of the process occurs at the top of the filter, leading to frequent clogging. Principally, upflow configured sand filtration systems rely on deep filtration mechanisms, reducing the possibility of clogging. Nevertheless, with flow rate variations, the efficiency of pollutant removal might also differ. Consequently, it is critical to fundamentally understand how the removal rate is influenced by the height of the sand filter bed in upflow sand filters.