**UNIVERSITI PUTRA MALAYSIA**

***OPTIMISATION OF WATER QUALITY MONITORING NETWORK BASED ON LAND USE CHANGES***

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**FPAS 2021 4**

# OPTIMISATION OF WATER QUALITY MONITORING NETWORK BASED ON LAND USE CHANGES

By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

March 2021

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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The evaluation of the importance of having accurate and representative stations in a network for river water quality monitoring is always a matter of concern. The minimal budget and time demands of water quality monitoring programme may appear very attractive, especially when dealing with large-scale river watersheds. This research proposes an improved methodology for optimising water quality monitoring network for present and forthcoming monitoring of water quality under a case study of the Selangor River basin in Malaysia. To achieve this goal, various data and analyses were utilised. In the first stage, two sets of water quality data acquired from 9 stations of Department of Environment (DOE) monitoring network and 12 monitoring stations proposed by Selangor Water Management Authority (SWMA) were used. A geo-statistical technique coupled with Kendall's W was first applied to analyse the performance of each monitoring station in the existing networks under the monitored water quality parameters. Based on this approach, four stations were identified as the most informative, five stations were identified as the least informative while another 12 stations were moderately informative. In the second stage, land use data for 2006, 2010 and 2015 and the corresponding years of frequently sampled water quality data were utilised to analyse the spatiotemporally varying relationship between land use and water quality by using Geographically Weighted Regression (GWR). The results indicated that, in 2015, agricultural land most predicted the change in most water quality variables compared with its prediction proportion in 2010 and 2006, while urban area most predicted the change in most water quality variables in 2010 compared to other years. However, other land uses were more positively associated with most of the water pollutants compared to forest, agricultural, and urban areas. In the last stage, the present and future changes in non-point pollution sources were simulated through land use mapping by using the integrated Cellular Automata and Markov chain model (CA–Markov). The performance of the model was very good in its overall ability to simulate the actual land use map of 2015, with $K_{standard}$ (90 %), $K_{no}$ (92 %) and $K_{location}$ (97 %), which indicated the reliability of the model to successfully simulate land use

changes in 2024 and 2033. Therefore, the Station Potential Pollution Score (SPPS) determined based on Analytic Hierarchy Process (AHP) was used to weight each station under the changes of non-point pollution sources for 2015, 2024, and 2033 prior to prioritisation sequencing of stations in the monitoring networks. Finally, according to the Kendall's W test on kriging results, the weights of non-point sources from the AHP evaluation and fuzzy membership functions, six (6) most efficient sampling stations were identified to build a robust network for the present and future monitoring of water quality status in the Selangor River basin. Additionally, six (6) other stations considered to be the second most efficient sampling stations were also identified for possible expansion of the monitoring network in the future. The methodology proposed in this study implies an optimal procedure for the evaluation and allocation of an optimised water quality monitoring network. The method also enhances the reliability in data classification and rankings.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
Sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**PENGOPTIMUMAN JARINGAN PEMANTAUAN KUALITI AIR BERDASARKAN PERUBAHAN GUNATANAH**

Oleh

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Penilaian mengenai pentingnya mempunyai stesen yang tepat dan representatif dalam rangkaian pemantauan kualiti air sungai sering menjadi perhatian. Bajet minima dan kekangan masa dalam melaksanakan program pemantauan kualiti air merupakan cabaran, terutamanya bagi kawasan lembangan sungai berskala besar. Kajian ini mencadangkan kaedah yang ditambahbaik bagi mengoptimumkan rangkaian pemantauan kualiti air semasa dan akan datang, menggunakan kajian kes di lembangan Sungai Selangor. Bagi mencapai matlamat kajian, pelbagai jenis data dan analisis digunapakai. Di tahap pertama, dua set data kualiti air daripada sembilan stesen pemantauan Jabatan Alam Sekitar (JAS) dan 12 stesen pemantauan Lembaga Urus Air Selangor (LUAS) digunakan. Gabungan teknik geostatistik dan Kendall's W digunakan bagi menilai prestasi stesen pemantauan sedia ada mengikut parameter kualiti air yang dipantau. Hasil analisis ini, empat stesen dikategorikan sebagai paling informatif, lima stesen paling kurang informatif, manakala 12 stesen selebihnya adalah sederhana informatif. Dalam tahap kedua, data guna tanah tahun 2006, 2010 dan 2015 dan data pemantauan kualiti air tahun tersebut digunakan bagi menganalisis hubungan ruang-masa di antara jenis guna tanah dan kualiti air menggunakan Regresi Pemberat Geografik (GWR). Hasil menunjukkan, pada 2015, tanah pertanian diramalkan paling ketara dalam perubahan kebanyakan pembolehubah kualiti air berbanding nisbah ramalannya bagi tahu 2010 dan 2006, manakala kawasan perbandaran paling banyak diramalkan terkait dengan perubahan kualiti air pada tahun 2010 berbanding tahun lain. Walaubagaimanapun, jenis guna tanah lain terkait secara positif dengan kebanyakan bahan cemar berbanding hutan, pertanian dan kawasan perbandaran. Dalam tahap ketiga, perubahan semasa dan akan datang bagi sumber pencemaran tidak bertitik disimulasi menggunakan pemetaan guna tanah Model Rantaian Markov dan Automata Selular (CA-Markov). Prestasi model tersebut amat baik dalam pencapaian keseluruhan bagi simulasi guna tanah 2015 dengan $K_{piawai}$ (90%), $K_{no}$ (92%) dan $K_{lokasi}$ (97%), iaitu menunjukkan kebolehpercayaan model bagi simulasi perubahan guna tanah tahun 2024 dan

2033. Oleh itu, Skor Pencemaran Potensi Stesen (SPSS) yang ditentukan berdasarkan Proses Hierarki Analitik (AHP) digunakan untuk menimbang berat setiap stesen bagi perubahan sumber pencemaran tidak bertitik tahun 2015, 2024 dan 2033 sebelum penyusunan rangkaian stesen pemantauan mengikut turutan keutamaan. Akhirnya, berdasarkan hasil ujian kriging Kendall's W, berat bagi sumber pencemaran tidak bertitik daripada penilaian AHP dan fungsian keahlian kabur, enam (6) stesen persampelan paling efisien dikenalpasti bagi membentuk rangkaian stesen pemantauan paling berkesan bagi pemantauan kualiti air semasa dan akan datang di lembangan Sg Selangor. Tambahan pula, kaedah yang dicadangkan dalam kajian ini menyiratkan prosedur optimum bagi penilaian dan pengagihan bagi mengoptimumkan rangkaian pemantauan kualiti air. Kaedah ini juga meningkatkan kebolehpercayaan dalam pemeringkatan dan klasifikasi data.

## ACKNOWLEDGEMENTS

All praises and thanks be to Allah, the Lord of the Universe and the Master of the Day of Judgment for granting me life, health and the opportunity to go this far in my academic journey. In particular, I would like to express my deep and sincere gratitude to my main Supervisor Assoc. Professor Dr. Nor Rohaizah Jamil for her excellent advice, guidance and constant support in making this research work a good read throughout my studentship period. To my co-supervisors, Assoc. Professor Dr. Ahmad Fikri B. Abdullah and Dr. Rohasliney Binti Hashim, I would like to express my gratefulness for their mentoring, guidance and constructive criticism throughout this period of study which have contributed significantly to attaining the ultimate goal of this PhD work.

I remain especially grateful to my family members in general for their support in different ways, through love, care, understanding and most importantly through their prayers. Special thanks to my father Ibrahima, brothers Oumar and Bangaly, and my sister Aicha and all the other brothers and sisters who have supported me financially and morally during this PhD journey. I will not forget to give my last thanks to my charming wife, Aminata Traoré, for all her actions and her patience in the face of the success of this academic journey. May Allah reward you and all the others who directly and indirectly helped me to make this study a success.

Part of this research was funded by the Grant: GP-IPS/9672800 from the Faculty of Forestry and Environment, Universiti Putra Malaysia (UPM). I would therefore like to express my profound gratitude to the Malaysia Departments of Environment, Agriculture, and Surveying and Mapping, as well as the Faculty of Forestry and Environment for material and financial supports.

Finally, this thesis is dedicated to my late mother, Nantenin Keïta, who passed away on April 7, 2020 without witnessing the final day of this academic journey which she supported unceasingly. May Allah bless her soul with eternal peace and grant her the highest rank in Jannah, Ameen.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy.

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Date: 08 July 2021

## TABLE OF CONTENTS

# LIST OF TABLES

## LIST OF FIGURES

## LIST OF ABBREVIATIONS

| | |
|---|---|
| AHP | Analytic hierarchy process |
| AICc | Corrected Akaike Information criterion |
| ANOVA | Analysis Of Variance |
| ANP | Analytic Network Process |
| BOD | Biochemical Oxygen Demand |
| CA | Cluster Analysis |
| CA–Markov | Cellular Automata and Markov Chain |
| CCME | Canadian Council of Ministers of the Environment |
| COD | Chemical Oxygen Demand |
| CR | Consistency Ratio |
| DA | Discriminant Analysis |
| Dept. | Department |
| DID | Department of Irrigation and Drainage |
| DMS | Data Management System |
| DO | Dissolved Oxygen |
| DOA | Department Of Agriculture |
| DOE | Department Of Environment |
| DOE-WQI | DOE Water Quality Index |
| DQO | Data Quality Objective |
| EC | Electrical Conductivity |
| EMCs | Event Mean Concentrations |
| Eq. | Equation |
| etc. | Et cetera |

| | |
|---|---|
| FA | Factor analysis |
| Fig. | Figure |
| GIS | Geographic Information System |
| GPS | Global Positioning System |
| GWR | Geographically Weighted Regression |
| H0 | Null hypothesis |
| H1 | Alternative hypothesis |
| HAC | Hierarchical Agglomerative Clustering |
| HACA | Hierarchical Agglomerative Cluster Analysis |
| Klocation | Kappa for grid-cell level location |
| Km | kilometre |
| km2 | Square kilometre |
| Kno | Kappa for no information |
| Kstandard | Kappa index of agreement |
| LCM | Land Use Change Modeller |
| LUAS | Lembaga Urus Air Selangor |
| LU/LC | Land Use/Land Cover |
| m | Meter |
| MCE | Multi Criteria Evaluation |
| mg/L | milligrams per litre |
| MK | Mann-Kendall |
| mm | Millimetre |
| MPM | Mathematical Programming Methods |
| NH3-N | Ammonia nitrogen |
| NH4-N | Ammonium-nitrogen |

| | |
|---|---|
| NO3-N | Titrate nitrogen |
| NPS | Non-Point Source |
| OAM | Outranking Aggregation Methods |
| OLS | Ordinary Least Squares |
| OWA | Ordered Weighted Average |
| *p* | Probability |
| PCA | Principal Component Analysis |
| pH | Potential of hydrogen |
| QQ | Quantile-Quantile |
| RBA | Risk-Based Analysis |
| RML | River Mixing Length |
| SI | Subindex |
| SMC | Site Average Concentration |
| SMCA | Spatial Multi-Criteria Analysis |
| SPPS | Station Potential Pollution Score |
| SS | Suspended Solids |
| SWMA | Selangor Water Management Authority |
| TDS | Total Dissolved Solids |
| TEMP | Temperature |
| TKN | Total Kjeldahl Nitrogen |
| TN | Total Nitrogen |
| TOPSIS | Technique for Order Preference by Similarity |
| TP | Total Phosphorus |
| TSS | Total Suspended Solids |
| UNEP | United Nations Environment Programme |

| | |
|---|---|
| WHO | World Health Organisation |
| WLC | Weighted Linear Combination |
| WQ | Water Quality |
| WQI | Water Quality Index |
| WQMNs | Water Quality Monitoring Networks |
| WQMP | Water Quality Monitoring Programme |
| WQVs | Water Quality Variables |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the study

Today, the importance of rivers and surface water resources for society has been recognized worldwide. For this reason, most cities, industrial centers and agricultural activities have been located very close to rivers and other surface water resources (Dubois, 2011). Due to rapid urbanisation, population growth and economic factors, megacities and suburban areas around the world are facing increasing challenges such as water scarcity, water resource degradation and the risks of flood. Achieving coherence between river basin management and sustainable/integrated urban water management is more difficult in megacities and suburban areas due to the presence of diverse forms of land use that necessitate constant control policy. Vanden-Brandeler ( 2018) conclude that river basin management and water governance for cities of multiple land use types deserve much more attention than they currently receive in the academic and policy focuses. Urbanisation augment the impervious surface, generates pollution and transforms the configuration, composition and context of land cover and therefore has direct or indirect impacts on aquatic systems (Yu et al., 2013). Detecting the relationship between land use and water quality is important for sustainable urban development and environmental risk management (Rodrigues et al., 2018).

Nowadays, what concerns water resource managers is how to simultaneously control several types of water pollutants. Therefore, identifying the relationship between land use and water quality is particularly useful when taking into account various sources of pollution together. However, a certain number of current publications have addressed this problematic such as Giri and Qiu (2016); Namugize et al. (2018); and Yu et al. (2013). Obviously, water quality of river globally has been affected by anthropogenic activities, in many cases in a way that still needs to be fully quantified. While these impacts are increasingly recognised, our ability to understand the magnitude of anthropogenic forcing is restrained due to the limited availability of long-term water quality data sets, which are essential for understanding the system behavior (Myroshnychenko et al., 2015).

The relationships between land use and water quality studies through various means and approaches have permitted to estimate and understand water quality in rivers distressing from diffuse pollution. However, knowledge in such relationships at a catchment scale across seasons is still lacking due to the large area and monitoring difficulties (Rodrigues et al., 2018). In order to address this issue, the WHO recommends to take into account residential development and waste disposal amongst others in assessing the influence of land use on water quality (vander-Hoven et al., 2017). In fact, the monitoring activities of water quality enable us to understand and interpret the actual influence of these change drivers (such as land use, spatial and temporal changes) on water quantity and water quality. According to Giri & Qiu (2016), monitoring water quality data in the stream is important not only for a healthy ecosystem, but also provides us with knowledge that facilitates rapid implementation of corrective actions for a sustainable environmental system.

Large river basins pose many challenges for monitoring and management of water quality, particularly in multinational basins where legislative frameworks and priorities for water resources management may differ (Bloesch et al., 2012). But either to a local or global context, in order to contribute to the management at the river basin scale, Chapman et al. (2016) find it essential to harmonise the monitoring activities into the following: (i) indicate trends over time; (ii) obtain a full understanding of the impacts of activities and their interaction within the basin; (iii) determine the impacts of downstream; and (iv) take most appropriate direct corrective actions. In addition, the objective of water quality monitoring is to obtain quantitative information on the physical, chemical and biological characteristics of water through statistical sampling (Chapman et al., 2016; Sanders et al., 1983). However, the purpose of monitoring is usually set by laws or other regulatory actions (guidelines, water quality standards, action plans) and aims to assess the state of the environment and detect trends (EEA, 2016).

From the 1960s and 1970s, water quality monitoring has been established to describe the general state of water quality, and these early monitoring efforts generally implied subjective approaches without a coherent or logical design strategy (Strobl & Robillard, 2008). Until today, the monitoring of water quality remains a complex process, this is in general due to the larger number of factors to take into consideration. For this reason, the reliable assessment of water conditions through Water Quality Monitoring Programme (WQMP) is essential for decision makers to understand, interpret and use the generated information to support their management strategies, to protect water resource, and the challenge of WQMP planning and optimisation for surface waters (Behmel et al., 2016). In this regard, effective water quality monitoring is indispensable for assessing the influence of various point and non-point pollution sources on surface water quality and evaluating the expected compliance with monitoring goals and water quality standards.

In recent years, the design of water quality monitoring networks has evolved into more focused topics such as salinisation, eutrophication, acidification, heavy metals, and microbial contamination, among many others (Strobl & Robillard, 2008). An effective-designed water quality monitoring network detects water quality issues while providing baseline information for short- and long-term trend analysis. The need to assess observed water quality conditions and their appropriateness for intended uses reflects the need for cost-effective and efficient water quality monitoring network design and evaluation approaches (Strobl & Robillard, 2008). The widely used methods and techniques for assessing and designing monitoring networks are summarised by Xu et al. (2017) as: (i) statistically based; (ii) spatial interpolation; (iii) information theory-based; and (iv) hybrid approach. These methods are more consistent and specific with regards to meeting the expectations of monitoring objectives. However, early monitoring networks were designed without adequate methodology, and thus were missing reliability and consistency (Beveridge et al., 2012; Strobl & Robillard, 2008). The inadequacy of a network design methodology often results in the collection of water quality data with little analysis or ultimate goal (Council, 2002).

Selecting appropriate water quality sampling locations is according to Alilou et al. (2018) a crucial step in designing a robust monitoring network. They further mentioned, due to the time and cost constraints, it is essential to identify and select these locations using an accurate and efficient approach. Moreover, Sanders et al.(1983) also affirm that, designing suitable locations for sampling points is one of the most important steps to monitoring quality. Therefore, time and cost which affect much on the process of the WQMP can effectively be managed by identifying and selecting the best locations for sampling points (Alilou et al., 2018). Thus, the frequency of sampling and the method of data collection, presentation and interpretation become unimportant if the samples collected are not representative of the water body (Do et al., 2012).

Distinguishing between the required and provided data is directly linked to understanding the accuracy and efficiency of monitoring networks. So, monitoring of surface water quality is a continuous process, therefore, monitoring system should be revised and modified (Boroumand et al., 2017) and thus optimised in order to acquire useful information, comply with standards, and prevent financial loss due to high monitoring costs. However, optimisation does not necessarily involve reducing the number of monitoring stations, sampling frequencies or WQMP, on the contrary, optimisation involves verifying that the initial monitoring objectives have been achieved and whether additional monitoring objectives have been identified that need to be addressed (Behmel et al., 2016).

Many approaches have been applied to objectify the allocation of sampling stations in river basins. Many of the most efficient methodologies are based on optimisation. For instance, Néstor-Jiménez et al. (2005) elaborated a methodology for designing quasi-optimal monitoring networks for lakes and reservoirs. The main elements of their methodology were a numerical model, used due to lack of field data; a kriging-based technique for spatial interpolation and obtaining estimates from available monitoring networks; and an optimisation model based on a genetic algorithm to generate the set of non-dominated optimal (costs vs accuracy) monitoring networks. Beveridge et al.( 2012) applied a geo-statistical technique to identify the optimal water quality monitoring stations of Great Lake Winnipeg by clustering the lake monitoring stations and omitting those with redundant information. They used Kriging method, which indicated the redundant stations among all the existing stations, and Local Moran's I values, which suggested the redundant stations in each group. In addition, Ou et al. (2012) applied a complex approach for an integrated assessment of sampling locations of water quality monitoring networks in Lake

Winnipeg. Their techniques include geo-statistical methods coupled with principal component analysis and fuzzy optimal model.

According to the 2016 report of the United Nations Environment Programme (UNEP), since the 1990s water pollution in many rivers of Asia, Africa, and Latin America has worsen (UNEP, 2016). However, most of the rivers of these continents still remain in good conditions and there are great opportunities to reduce pollution and restore polluted rivers, but management and technical supports from good governance are indispensable for these tasks (Pérez et al., 2017). The protection of water quality is one of the major challenges facing human beings in both developed and developing countries. The impact of degraded water quality is severe and can affect numerous sectors of society, such as health, the economy and recreation (Giri & Qiu, 2016). Appropriate access to drinking water is considered to be one of the central aspects of water management, strategic population management and future urban development planning at the macro level (Shooshtarian et al., 2018). Undoubtedly, Luby (2008) found it difficult to improve water quality throughout South Asia although 85% of South Asia's drinking water reaches the target of the Millennium Development Goal that is, obtaining an improved source. He believes that a renewed commitment to water quality is needed whereby the research community can help by conducting water quality assessments and rigorously evaluating efforts to improve water quality.

In Malaysia, pollution of river waters poses a serious risk to the health of the public. River water quality monitoring is the responsibility of the Department of the Environment (DOE) in Malaysia. According to DOE (2018), the monitoring programme of DOE began in 1978 for Peninsular Malaysia. In 1985, Sabah and Sarawak were included in the monitoring programme, this was followed by the Island's Marine Water Quality Monitoring Programme in 1998. Currently, 233 coastal and estuarine monitoring stations are established in all States of Malaysia and 73 islands with 86 stations for the island monitoring programme (Figure 1.1). These islands are categorised into four, namely, development islands, resort islands, protected islands and marine park islands. The monitoring programme includes in situ measurements of water quality parameters such as pH, temperature, dissolved oxygen, turbidity, conductivity, salinity, as well as laboratory analyses of parameters such as Escherichia coli. Cadmium, copper, mercury and lead. The sampling frequency is between four and six times a year. This monitoring activity provides important information on the state of water quality of different water bodies (DOE, 2018).

In their article, Prabhakaran et al. (2017) summarised the statistics on the DOE monitoring efforts of the Malaysian rivers' water quality: "Of the 473 rivers monitored by DOE in 2012, 278 rivers (59%) were reported as clean, 161 (34%) as slightly polluted and 34 (7%) as polluted. However in 2013, 72% of 473 rivers monitored were regarded to be polluted, with 25 rivers (∼12%) classified as highly polluted. In 2014, a total of 473 rivers were monitored, out of which 244 (52%) were found to be clean, 186 (39%) slightly polluted and 43 (9%) polluted. A total of 477 rivers were monitored in 2015 and it was found that 276 (58%)

rivers were clean, 168 (35%) slightly polluted and 33 (7%) polluted." According to these authors, the report of DOE in 2015 indicated that the water quality of Malaysian rivers has improved between 2014 and 2015, as the percentage of clean rivers had increased to 6%. This was due somehow to the management and monitoring efforts of the authorities, although concerns today are much oriented to the newly pollutant sources such as heavy metals, endocrine disruptors, and other emerging pollutants contributing decisively to environmental degradation.

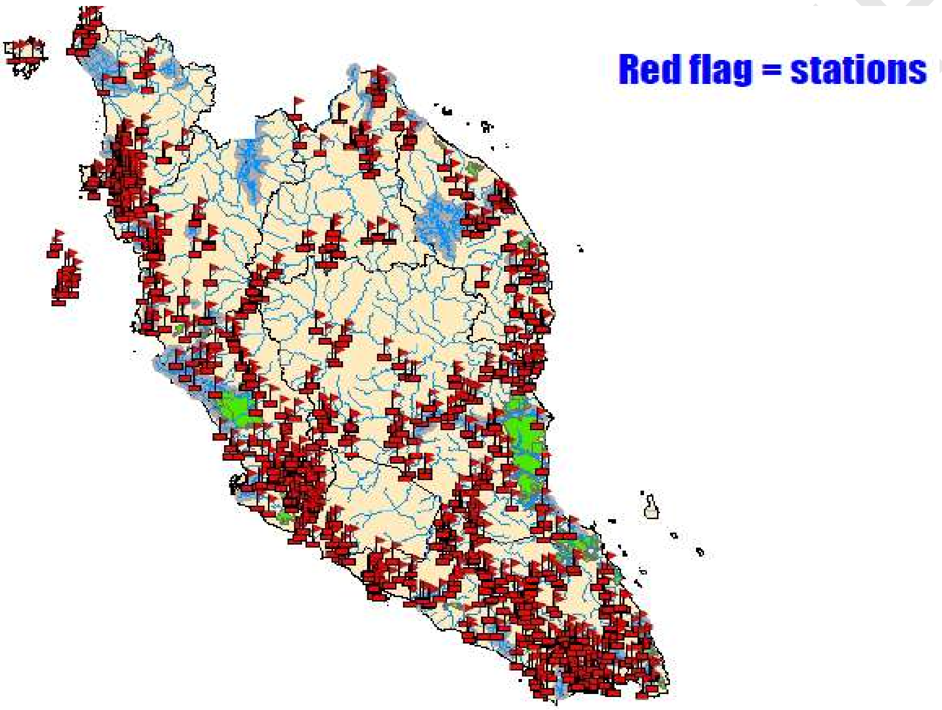


**Figure 1.1: Distribution of DOE water quality monitoring stations in Peninsular Malaysia** [Adopted from DOE (2008)]

## 1.2 Problem statement

Effective monitoring of water quality in large rivers provides adequate information on the impacts of activities within the catchment throughout the river basin as a whole. However, traditional monitoring of water quality implemented by individual agencies usually relate to specific objectives, such as meeting quality standards for pollution discharges, and do not provide sufficient information on basin-scale impacts, particularly in large river basins (Chapman et al., 2016). Today, computational methods and techniques can help to assess and optimise the design of monitoring networks, in particular, those established to monitor the influence of land use activities on river water quality at a local scale. Many approaches have been used to evaluate the significance of monitoring networks, WQMP, as well as to assess the similarity influence between monitoring stations and the provided data (e.g. Alilou et al., 2018; Chapman et al., 2016; Lee et al., 2014; Maymandi et al., 2018; Néstor-Jimênez et al, 2005; Park et al., 2006). In this regard, knowing the difference between the required and provided data help to understand the accuracy and efficiency of monitoring networks, this pays the way for preliminary steps in locating informative sampling sites.

Nowadays, a major problems in water quality studies is the number of parameters that can be monitored as well as the time and costs associated with collecting, analysing, and interpreting these data (Hernández-Romero et al., 2004). To address this, Malaysia adopted end-use-specific water quality indices to effectively classify water quality according to a set of water quality parameters generally recognised as informative, the DOE (2007) and Gazzaz et al. (2012) described more on these water quality indices and monitoring parameters. These water quality parameters are continuously monitored at specific established sampling locations. However, monitoring of surface water quality is a continuous process, therefore, monitoring network locations should be revised and modified (Boroumand et al., 2017) and thus optimised in order to acquire useful information, comply with standards, and prevent financial loss due to high operational monitoring costs. Currently, there is neither regularly reassessment of the effectiveness of Malaysian water quality monitoring networks, nor literature directly examining the impacts of land use changes on the existing monitoring locations.

According to Fulazzaky et al. (2010), the statistics of DOE in 2003 indicated that the trend of water demand in Malaysia has been estimated to increase from 9 543 $m^3$ / day in 1995 to 15 285 $m^3$ / day in 2010, an increase of 60% in 15 years to 20 338 $m^3$ / day in 2020, or 113 % in 25 years. As such, about 60% of the capital region's water supply comes from the Selangor River basin and the rest comes from the Klang and Langat River basins in the central and southern parts of the region (Sakai et al., 2017). The main use of water resources in these basins is the transfer of usable water supply to provide water to more than four million people and industries in Kuala Lumpur, Gombak, Petaling, and Hulu Selangor. However, most human activities in these basins affect the quality of water, directly through the discharge of wastewater and other sewage or indirectly through changes in land use (Chowdhury et al., 2018). The monitoring of the impacts of these activities has been the preoccupation of Malaysian DOE since 2000. Its monitoring activities are regularly carried out on the established monitoring stations throughout the river basins. These monitoring points required performance assessment because the existing data are insufficient to accurately estimate the pollutant loads quantitatively (Fulazzaky et al., 2010). As such, the investigation of the present study found that till today no specific study has been conducted for assessing, revising and optimising monitoring networks of Malaysian rivers' water quality and certainly no such attempt has been made in the context of Selangor River basin, thus an urgent need for this study to be implemented in order to generate the updated knowledge about the current situation of the existing monitoring networks.

Moreover, the impacts of land use activities on surface water quality have also been evaluated by various studies in Malaysia, (e.g. Ezatul, 2016; and Yen et al., 2017). But most of these studies analysed water quality with no attention to the implication of varying pollution sources. As such, finding an appropriate method to discover spatiotemporal characteristics of land use and water quality relationship across multi-scales for a river system is challenging. However, predicting the impact of land use change on locating and relocating sampling points for future water quality monitoring is more needed. In this regard, implementing this research in Selangor is ideally of great impacts because the States of Selangor and Kuala Lumpur are undergoing rapid development, population growth, urbanisation, and industrialization. These developing activities accompanied by continuous land use changes are not without significant impact on water quality of the Selangor River basin, therefore, this study would directly examine the impacts of land use changes on water quality and monitoring locations.

## 1.3 Research questions

In this study, the following research questions are drawn from the above research problems:

1. What are the most informative monitoring stations in the Selangor River water quality monitoring networks?
2. Which types of land use contribute more to the river pollution that necessitate more management focus?
3. How do the land use changes vary over time and space in the study area?
4. How do the future changes in land use affect the allocation of monitoring sites?

## 1.4 Research objectives

The main objective of this research was to develop an improved methodology for identifying critical sampling locations in existing WQ monitoring networks based on current and future changes in land use under a case study of the Selangor River basin. To attain this goal, the following specific objectives are drawn:

1. To assess the location efficiency of existing DOE's and SWMA's WQ monitoring stations based on selected water quality parameters
2. To analyse the spatiotemporally varying relationships between land use and water quality in the Selangor River basin
3. To simulate and predict land use changes for 2024 and 2033 in the Selangor River basin
4. To determine the impact of land use changes on the existing WQ monitoring network locations

## 1.5 Significance of the Study

The design of a water quality monitoring network is an iterative procedure whereby an existing network should be periodically re-evaluated in response to changing environmental requirements and objectives in water quality management. Therefore, this research provides a new approach to revising the effectiveness of individual water monitoring station used by the local authorities to assess the condition of water quality in the case study area.

Managers of water quality monitoring programme are often confronted to the limitation in budget, time, and laboratory capacity for sample analysis. In such situation, reducing the number of sampling sites to diminish monitoring time and cost is the ideal solution. In such case, selecting preferable sites is challenging. To overcome such issue, this study was needed to assist water quality managers as it aims to systematically evaluate, prioritise and rank the existing sampling stations considering their individual performance and similarity in information provided.

As Malaysia is experiencing a rapid and continuous change in land use associated with the government's development policies, this study would equally contribute to understanding of the impact of land uses on water quality in the study region taking into consideration the varying sources of pollution, which is commonly ignored by land use-water quality based studies in Malaysia.

Another major contribution of this research is the development of an improved methodology for identifying critical sampling locations for future water quality monitoring in future conditions of the non-point pollution sources under a case study of Selangor River basin. The method would also be useful and applicable for natural resource managers, land use management planners and policy makers to understand and manage the patterns of projected changes in land use.

Lastly, the present study would provide water managers with the necessary information on the design and evaluation of a reliable water quality monitoring network with a high level of assurance in the context of certain changes in non-point sources of pollution. In addition, the results would be useful to water quality monitoring agencies that are seeking an optimal approach for the selection of sampling locations.

## 1.6 Scope and limitation of the Study

The scope of this study is limited to a case study of the Selangor River basin, which is one of the crucial raw water sources in the State. This study strictly focuses on monitoring networks for water quality and not for water systems, therefore, hydrometric and eco-hydrological information for water resources is not directly discussed in the research. This thesis research mainly uses available land use data from 1997, 2006, 2010 and 2015 and the corresponding years of frequently sampled water quality data from different existing sources. However, the field data collection was carried out in order to assess the accuracy of the secondary water quality data used in this study. In addition, land use attributes are grouped into broad categories according to level I of the classification system. The assessment of the existing network approach is based on the six selected parameters such as Dissolved Oxygen (DO mg / L), Chemical Oxygen Demand (COD mg / L), Biochemical Oxygen Demand (BOD mg / L), Suspended Solids (SS mg / L), Ammonia Nitrogen (NH3-N mg / L), and Potential of Hydrogen (pH) which are used to calculate the Malaysian Water Quality Index (DOE-WQI). Nevertheless, Event Mean Concentrations (EMCs) and expert opinions survey data are used in the final stage in order to obtain the locations of an optimized monitoring network for the present and future context. The proposed methodology implies an optimal procedure integrating geostatistical and Kendall's W approach, GWR and OLS models, CA-Markov model, and multi-criteria evaluation and fuzzy approach to achieve the ultimate goal of this study. However, the proposed methodology does not incorporate into the analysis the effects of unpredictable events such as flooding, climate variability, sediment loading, and disease outbreak to the monitoring network locations.

## 1.7 Organisation of the thesis

The research objectives of this study are achieved through the development of five interconnected chapters. Chapter 1 provides the details related to the background of the study, the statement of the research problem, the fundamental questions raised and the objectives of this thesis research. The chapter also includes the significance of the study, the scope and limitation, and organisation of the thesis.

Chapter 2 describes in detail the essential concepts and main components resulted in a deep literature review for the purpose of this thesis. It presents the fundamentals and theories used in the course of the thesis.

Since chapter 2 looked at an in-depth review of the methods and techniques used in the design and evaluation of the monitoring network, the concept of network optimisation, issues related to land use change and water quality, as well as many other components of this research work. Chapter 3 however, presented the different approaches, techniques and analyses implemented to achieve the objectives of this thesis research. This includes the procedures for data analysis, models development, comparison and validation.

Chapter 4 presents and discusses in detail the results and findings of the study, as well as the approaches, methods and techniques used in different analyses to achieve each of the objectives of this research.

Finally, the conclusions and recommendations in the order of the main stages of this thesis are provided in Chapter 5. The chapter also includes the general conclusions drawn from this research work.

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