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(Research Article)

Study on real-time environmental monitoring using IoT sensors on assessing water quality anthropogenic impacts and seasonal dynamics (case study: Urban area and Souphanouvong University), Luang Prabang City, Luang Prabang Province, Lao PDR

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Abstract

As Luang Prabang experiences rapid socio-economic growth, the resulting intensification of urban land use has placed significant pressure on the city's water resources. This study addresses the urgent need for continuous water quality monitoring by deploying an Internet of Things (IoT)-based sensor network across five sites, including the historic Pond No. 70 and Souphanouvong University. Over four months, January–April, we monitored key parameters: temperature, depth, electrical conductivity (EC), and turbidity, to evaluate the impact of residential and institutional wastewater runoff. Our findings reveal that all monitored sites consistently exceeded the national turbidity standard of 30 NTU, with averages ranging between 43.6 NTU and 50.46 NTU. Seasonal transitions to summer, March–April, exacerbated these conditions, as high temperatures peaking at 37.65°C and reduced water volume triggered increased sediment resuspension and thermal agitation. While EC levels remained within safe thresholds, the data confirm that urban drainage infrastructure is currently overwhelmed by sediment and untreated domestic effluent. Our research demonstrates that Pond No. 70 acts as a critical, albeit overloaded, natural drainage sink. The successful deployment of low-cost, real-time IoT nodes provides a scalable diagnostic tool for municipal planning, proving superior to traditional intermittent sampling. These results offer actionable insights into implementing Nature-based Solutions (NbS) and support Luang Prabang's strategic vision of becoming a Green Smart City through evidence-based environmental management.

Keywords: Water Quality Monitoring; Internet of Things (IoT); Urban Runoff; Turbidity Dynamics; Nature-based Solutions (NbS)

1. Introduction

Luang Prabang, a UNESCO World Heritage City, is experiencing rapid socio-economic and tourism-led growth. While this development drives regional prosperity, it simultaneously increases anthropogenic pressure on natural resources, particularly regarding urban water quality. Effective wastewater management from residential communities and educational institutions has emerged as a critical challenge, requiring continuous and precise monitoring. Urban area, a densely populated urban area, and Souphanouvong University, a major educational center, serve as primary sites for this study. Traditional water monitoring methods in these areas are often hindered by budgetary constraints, labor-intensive sampling, and the absence of real-time data (Lal et al., 2024). Consequently, integrating Internet of Things (IoT) sensor systems capable of real-time collection, analysis, and environmental alerting provides a scalable, cost-effective alternative to conventional laboratory testing (Jan et al., 2021). This research establishes a vital environmental database to support management planning, disaster mitigation, and the city's vision of evolving into a "Green Smart

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City." A focal point of this study is Pond No. 70, a historic water body in the heart of Luang Prabang that historically functioned as a natural retention pond, providing flood mitigation and supporting local livelihoods. However, rapid urban expansion has transformed surrounding areas, such as Nasageway village and Phong Kham village, from agricultural landscapes into dense residential and commercial zones. In the absence of comprehensive public utility systems, this pond now serves as a drainage sink for untreated wastewater and sediment runoff. This influx of domestic sewage introduces high concentrations of nutrients (nitrogen and phosphorus), which significantly increases the risk of eutrophication and water turbidity (Ullah Bhat & Qayoom, 2022).

By utilizing Pond No. 70 and its surrounding community as a field model for real-time IoT water quality monitoring, this study will generate essential scientific data. Beyond protecting public health, these findings will inform the design of Nature-based Solutions (NbS), such as constructed wetlands, to restore the natural heritage of Luang Prabang and promote long-term ecological resilience. The primary objective of this study is to implement and evaluate an IoT-based real-time monitoring network to assess water quality parameters—specifically pH, turbidity, dissolved oxygen, and nutrient load—within the Pond No. 70 ecosystem. By comparing data trends from the residential sector of Ban Mano and the institutional setting of Souphanouvong University, this research aims to: (1) characterize the temporal dynamics of water pollution in response to urban development; (2) validate the efficacy of low-cost IoT sensor nodes for long-term environmental surveillance in the Luang Prabang climate; and (3) provide actionable data to support the implementation of Nature-based Solutions (NbS) for urban water remediation.

2. Materials and Methods

2.1. Study Area

A spatial sampling strategy was employed, with five monitoring nodes strategically installed along the drainage path leading to Pond No. 70 and on the campus of Souphanouvong University. These sites were chosen to represent a gradient of urban influence:

- Source Zones: Nassaney Village (Point 3) and Phongkham Village (Point 4) represent the upstream residential runoff.
- Catchment Zone: Pond No. 70 (Point 2 - Inlet and Point 1 - Outlet) represents the final sink.
- Institutional Control: Souphanouvong University (Point 5) represents an academic area with managed infrastructure.

2.2. Materials

- Perception Layer: Uses various sensors to measure values
- Network Layer: Transmit data from sensors to the cloud via communication technologies such as Wi-Fi, 4G/5G, LoRaWAN (popular for long-distance and energy-saving applications).
- Application Layer: Dashboard or mobile app for the user to view data and send alerts.
  - Microcontroller: ESP32 or Arduino-compatible board, selected for its low power consumption and built-in connectivity (Wi-Fi/Bluetooth).
  - Sensor Suite
  - Turbidity Sensor
  - pH Sensor
  - Electrical Conductivity (EC) Sensor
  - Temperature Sensor

2.2.1. Data Communication and Power

- Connectivity Nodes transmitted data via LoRaWAN / 4G GSM modules to a centralized server. This transmission protocol was selected to overcome the signal attenuation caused by the mountainous topography and dense urban foliage in Luang Prabang.
- Power Supply: Each station was equipped with a 10W solar panel paired with a 5000mAh lithium-ion battery, ensuring continuous, autonomous operation.

2.2.2. Data Collection Protocol

The IoT system was programmed for autonomous operation, capturing data at 15-minute intervals to account for diurnal fluctuations in water quality due to domestic activity patterns.

- Transmission: Data packets were encapsulated via the MQTT protocol and pushed to a cloud-based server.
- Redundancy: To prevent data loss during power outages or connectivity drops, each node featured an on-board SD card for local data logging.
- Visualization: Real-time data was processed and displayed on a web-based dashboard, enabling immediate identification of pollution spikes.

2.2.3. Statistical Analysis Framework

To analyze the efficacy of the IoT monitoring and environmental stressors, the following statistical methods were applied:

- Time-Series Analysis: Used to correlate temperature and precipitation with turbidity levels (NTU).
- Comparative Statistics: An Analysis of Variance (ANOVA) was performed to determine if the differences in water quality between the five sites were statistically significant.
- Correlation Mapping: Pearson's correlation coefficient (r) was used to evaluate the relationship between water depth, EC, and turbidity across the four-month study period.

3. Results

3.1. Water Quality Assessment at Pond No. 70

The water quality monitoring conducted from January to April revealed distinct seasonal trends in the physical and chemical properties of the water at the outlet of Pond No. 70. The summary of recorded parameters is presented in Table 1.

Table 1 Water quality parameters at the outlet of Reservoir at No. 70 (January – April)

Month	Temp (°C)	Depth (m)	EC (μS/cm) *	Turbidity (NTU)*	CSQ
January	23.27	14.16	71.22	39.11	31
February	24.32	14.35	85.33	37.87	30
March	29.39	14.54	71.54	61.35	31
April	35.47	14.61	62.65	60.1	32
Average	28.11	14.42	72.69	49.61	31
Standard	-	-	500	30	-

*Note: Units corrected for scientific notation (EC in μS/cm, Turbidity in NTU).

The data indicate that while water depth remained relatively stable, averaging 14.42 m and Electrical Conductivity (EC) remained well within safety limits (averaging 72.69 μS/cm against a 500 μS/cm threshold), turbidity levels represent a significant environmental concern.

As shown in the data, the average turbidity of 49.61 NTU exceeds the permissible standard of 30 NTU. Notably, a sharp increase was observed in March, 61.35 NTU and April 60.10 NTU, where levels were nearly double the threshold. The correlation between the temperature spikes in April, 35.47°C and the high turbidity suggests a compounding environmental stressor.

This deterioration can be attributed to two primary drivers, such as the transition between seasons in Luang Prabang, which often brings erratic, high-intensity rainfall. These early-season thunderstorms likely trigger surface runoff, transporting accumulated topsoil and sediment into the pond and As a primary drainage sink for the surrounding residential zones of Nasangweay Village and Phongkham Village, the pond receives consistent influxes of untreated domestic wastewater. The elevated turbidity levels observed in the latter half of the study period likely reflect increased sediment and particulate matter from these drainage pathways.

3.1.1. Water Quality Assessment: Pond No. 70 Inlet

Table 2 Water quality parameters at the inlet of Reservoir No. 70 (January – April**)**

Month	Temp (°C)	Depth (m)	EC (µS/cm)	Turbidity (NTU)	CSQ
January	22.23	15.17	68.22	38.13	31
February	25.31	15.25	73.03	38.48	30
March	28.29	15.57	67.34	62.35	31
April	36.46	15.65	69.54	62.86	32
Average	28.07	15.41	69.54	50.46	31
Standard	-	-	500	30	-

The data from the inlet point confirms the environmental stress detected at the outlet. With a four-month average turbidity of 50.46 NTU, the inlet consistently exceeds the standard of 30 NTU. The sharp escalation in March and April, reaching over 62 NTU, highlights a critical seasonal vulnerability. The data suggest that the inlet is the primary source of particulate matter. Because this point serves as a discharge zone for surrounding residential runoff, the elevated turbidity is likely a direct result of urban drainage, specifically, sediment and household wastewater influx. The physical consequences are significant: the sustained high turbidity >60 NTU in peak months limits light penetration, creating a "shading effect" that threatens the photosynthesis of aquatic flora and degrades the dissolved oxygen levels necessary for local aquatic life.

3.1.2. Water Quality Assessment at Nasangwey Village (Upstream Source)

Table 3 Water quality parameters at the Nasangwey Village collection point (January – April)

Month	Temp (°C)	Depth (m)	EC (µS/cm)	Turbidity (NTU)	CSQ
January	23.24	13.19	63.23	34.23	29
February	27.28	13.35	69.23	35.44	28
March	28.36	13.52	61.44	58.45	32
April	35.55	13.75	63.15	62.16	31
Average	28.61	13.45	64.26	47.57	30
Standard	-	-	500	30	-

The data from Point 3 confirms that the water quality degradation begins at the source. The upstream community of Nasangwey Village serves as the primary point of entry for pollutants, with a consistent average turbidity of 47.57 NTU.

The observation regarding the concentration effect during the transition to summer (March–April) is a sophisticated insight. As temperatures climb to 35.55°C, reduced water volume from evaporation, coupled with continuous household wastewater discharge, increases the concentration of total suspended solids (TSS). This confirms that the pond's turbidity is not just a result of internal sediment but is being actively fed by upstream urban activities.

3.1.3. Water Quality Assessment at Phongkham Village

Table 4 Water quality parameters at the Phongkham Village collection point (January – April)

Month	Temp (°C)	Depth (m)	EC (µS/cm)	Turbidity (NTU)	CSQ
January	24.25	14.59	61.72	33.33	30
February	26.58	14.65	65.43	34.14	30
March	29.36	14.55	59.45	57.65	31

April	37.65	14.65	60.12	61.26	29
Average	29.46	14.61	61.68	46.59	30
Standard	-	-	500	30	-

Phongkham village exhibits the most extreme thermal profile, with water temperatures peaking at 37.65°C in April. The combination of open-ditch drainage, which exposes water to direct solar radiation and the discharge of heated greywater from household activities creates a localized "thermal heat island" effect in the water. The turbidity trend at this site, rising to 61.26 NTU, mirrors that of Point 3 Nasangwey village, providing strong evidence that the degradation of Pond No. 70 is driven by systemic urban runoff. The consistency of these findings across two separate residential zones significantly strengthens your research argument.

Across all points, the turbidity standard of 30 NTU is consistently violated, particularly as the season transitions to the summer heat (March–April). The high temperatures observed at Point 4 (37.65°C) and the high turbidity suggest that low flow conditions in the dry season effectively trap pollutants, preventing natural flushing or dilution.

3.1.4. Water Quality Assessment at Souphanouvong University

Table 5 Water quality parameters at the Souphanouvong University monitoring point (January – April)

Month	Temp (°C)	Depth (m)	EC (µS/cm)	Turbidity (NTU)	CSQ
January	25.35	10.55	61.72	30.13	29
February	27.28	10.61	61.42	31.12	30
March	30.16	10.25	58.55	53.55	30
April	36.15	10.45	57.12	59.6	31
Average	27.24	10.47	59.7	43.6	30
Standard	-	-	500	30	-

The data at this site reveals a unique environmental mechanism: The Depth-Turbidity Relationship. Being the shallowest site (10.47 m), the university pond is hypersensitive to temperature-driven fluctuations. Because the water column is shallower, the rate of evaporation is higher, and the energy from solar heating reaches the bottom sediments more effectively. This triggers "thermal agitation," causing settled sediments to re-suspend, which explains the dramatic climb to 59.6 NTU in April. The observation regarding Electrical Conductivity (EC) is a brilliant piece of scientific reasoning. By noting that EC decreased as turbidity increased,

Table 6 Analysis and comparison of water quality in each study area

Variables	Point 1 Outflow water	Point 2 Inflow water	Point 3 Nasangwey Village	Point 4 Phongkham Village	Point 5 Souphanouvong University
Temperature (°C)	28.11	28.07	28.61	29.46 (maximum)	27.24 (minimum)
Depth (m)	14.42	15.41	13.45	14.61	10.47 (shallowest)
EC (µS/cm)	72.69 (maximum)	69.54	64.26	61.68	59.7
Turbidity (NTU)	49.61	50.46 (maximum)	47.57	46.595	43.6

From the real-time monitoring of water quality through the IoT sensor system at all 5 installation points over a period of 4 months, it was possible to explain the scientific relationship between the environment and the impact of human activities in 3 main areas: Sediment distribution behavior and turbidity. When considering the turbidity value, it was found that all installation points had an average value exceeding the national standard of 30 NTU. The point with the highest turbidity value was Point 2, the Nha Khao Ngok, equal to 50.46 NTU. While the wastewater transfer points from external communities, point 3, Nassawey Village, 47.57 NTU, and Point 4, Phong Kham Village, 46.595 NTU, also had high values at similar levels. This phenomenon indicates that Pond No. 70 is the final wastewater receiving source that receives sediment and suspended solids that are accumulated from many directions of the surrounding communities. However, as the water flows into the pond and out to Point 1, the pond outlet, the turbidity value decreases slightly to 49.6 NTU. This is scientific evidence that the pond ecosystem has a natural physical treatment process by allowing some sediment to settle to the bottom of the pond during periods of stagnation and the influence of depth and temperature. Point 4 Phong Kham Village has the highest average temperature of 29.46 degrees Celsius and reaches a maximum of 37.65 degrees Celsius in April. This reflects the impact of urban heat radiation, as the drainage ditches in Ban Phong Kham Village are open ditches that receive direct sunlight, combined with the discharge of high-temperature wastewater from household activities.

On the other hand, point 5, Souphanouvong University, is the point with the shallowest water level at 10.47 meters and the lowest turbidity value at 43.6 NTU. Although the turbidity value is the lowest in the group, the shallowness of the water source poses a high risk during the dry season because when the temperature rises and the water level drops, the sediment at the bottom of the water source is easily disturbed and raised, causing rapid deterioration of water quality. As seen in April, the turbidity value rose to 59.6 NTU and the concentration of dissolved solids and the electrical conductivity (EC) trend. The electrical conductivity (EC) value has a different trend from the turbidity value. It was found that point 1, the outlet of the pond, had the highest average EC value of 72.69 ug/m3, even though the turbidity value was lower than the inlet. The reason for this can be explained by the high temperature from March to April, which caused rapid evaporation of water in pond No. 70. Water evaporation has resulted in higher concentrations of salts and dissolved inorganic substances in the water at the outlet of the pond. However, the EC values at all installation points ranged from 59.70 to 72.69 ug/m3, which is still many times lower than the standard value of 500 ug/m3, indicating that the wastewater flowing into the system is currently free of high levels of serious chemicals or heavy metals.

4. Discussion

The data from this four-month longitudinal study clearly demonstrates that water quality in the Pond No. 70 ecosystem is under significant stress. While Chemical Conductivity (EC) remains within safe levels, suggesting the absence of significant industrial chemical contamination, the consistent violation of turbidity standards averaging ~47–50 NTU across all sites indicates that physical pollution is the primary environmental threat. The correlation between seasonal temperature increases peaking in April and turbidity spikes indicates that the current urban drainage infrastructure is inadequate. The Inlet vs. Outlet comparison suggests that while Pond No. 70 provides a marginal natural sediment-trapping service, the sheer volume of influx from residential areas like Nasangwey Village and Phongkham Village is overwhelming the system's natural capacity for self-purification. Our research highlights a critical vulnerability: the seasonal concentration effect. As the dry season transitions into the summer months, March–April, two factors create a perfect storm for pollution. Reduced dilution, lower water levels and flow rates in drainage ditches lead to higher pollutant concentrations. and Thermal Agitation. As observed at the Souphanouvong University site, higher water temperatures increase the resuspension of bottom sediments, while evaporation in the pond increases the concentration of dissolved substances. This confirms that the urban heat island effect in Luang Prabang is not just an atmospheric phenomenon; it is a thermal stressor on aquatic ecosystems that accelerates the degradation of water quality in shallow, urban-adjacent water bodies. The deployment of this IoT sensor network provides a high-resolution, real-time diagnostic tool that is far superior to traditional, intermittent laboratory sampling. The ability to track turbidity spikes in real-time allows municipal authorities to pinpoint exactly when and where pollution enters the urban water system. For Luang Prabang to achieve its vision as a Green Smart City, this data suggests a shift from reactive management to proactive Nature-based Solutions (NbS)

Compliance with ethical standards

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Disclosure of conflict of interest

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Author Contribution

Khamphanh Kanyavong and Anousith Vannaphon conceived the idea and designed the experiments. Khamphanh Kanyavong, Anousith Vannaphon, Vongpasith Chanthakhoun, and Thavone Panmanivong conducted the experiments. Khamphanh Kanyavong, Anousith Vannaphon, Vongpasith Chanthakhoun, and Thavone Panmanivong wrote the manuscript. All authors read and agree to the submission of the manuscript to the journal.

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