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Multi-Sensor Wireless Network for Integrated Aquatic Ecosystem Monitoring in Quirino Province, Philippines

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Abstract This study deployed a multi-sensor wireless network to assess the health of selected freshwater bodies in Quirino Province by integrating chemical (dissolved oxygen, CO_2), physical (temperature, conductivity, pressure), and optical (turbidity, color) water quality parameters. Recognizing the sensitivity of tropical waters to warming, land-use change, and hydrological variability—and the limitations of low-frequency grab sampling in the Philippines—the study aimed to: (1) characterize spatial–temporal patterns in a midstream river, an agricultural stream, and a pond; (2) examine relationships between dissolved oxygen (DO) and key drivers such as temperature and CO_2; (3) identify hypoxia thresholds and risk periods; and (4) evaluate the effectiveness of wireless monitoring. Sensors for optical DO, NDIR CO_2, temperature, conductivity, pressure, turbidity, and color were installed at three sites and operated continuously for six months at 5-minute intervals. Periodic grab samples validated sensor readings. Data were analyzed using descriptive statistics, correlation, regression, and event-based analysis. Mean DO remained above the 5 mg/L guideline but declined from river (~7.3 mg/L) to stream (~6.4 mg/L) to pond (~5.9 mg/L). The pond exhibited the highest temperatures, often exceeding 30 °C, and showed pronounced nighttime DO minima. Temperature was the strongest inverse predictor of DO ($r \approx -0.66$ to -0.78), with CO_2, turbidity, and color contributing additional negative effects. Hypoxic events were rare in the river but more frequent in the stream and pond, particularly after storms.Sensor validation showed strong agreement with grab samples, while continuous monitoring captured short-lived DO depressions missed by conventional methods. The study supports institutionalizing wireless monitoring and establishing site-specific early warning thresholds to mitigate oxygen stress under climate and land-use pressures.

Keywords: *dissolved oxygen, wireless sensor network, water quality, tropical rivers, CO_2, turbidity, aquatic ecosystem health*

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1. Introduction

Aquatic ecosystem health in tropical rivers hinges on maintaining dissolved oxygen (DO) concentrations above critical thresholds that support diverse biological communities, with DO serving as the primary integrative indicator of respiratory balance between autotrophy and heterotrophy [1]. In tropical systems (25-30°C), oxygen solubility constrains equilibrium concentrations to 6.5-7.5 mg/L, approaching physiological limits for fish (5-6 mg/L minimum) and macroinvertebrates during periods of thermal stress or organic loading [2]. Temperature exerts dominant control through Henry's Law ($S\_T \propto 1/T$), where each 1°C warming reduces solubility by 0.15-0.25 mg/L while accelerating biochemical oxygen demand (BOD) via Q_{10} kinetics (respiration doubles every ~10°C), creating dual physical-metabolic stress (Agha et al., 2025).

Carbon dioxide (CO_2) dynamics amplify these constraints through pH buffering and heterotrophic stimulation: elevated pCO_2 (>500 µatm from decomposition/root respiration) lowers pH by 0.2-0.4 units, further depressing DO solubility (~5% per 0.1 pH decline) while fueling respiratory demand (Balladares et al., 2024). Physical parameters (pressure, conductivity) modulate gas exchange, while optical indicators (turbidity, colored dissolved organic matter) limit photosynthetic oxygen inputs, shifting systems toward hypoxia when turbidity exceeds 15 NTU [3]. Philippine rivers consistently document these interactions: Pasig River tidal-DO coupling (2.5-8.2 mg/L), Tago River pollution gradients (7.8→4.9 mg/L), Antiao River marginal compliance (6.2 mg/L at 28.5°C), and Cagayan de Oro River TDS-temperature correlations confounding gas exchange patterns [1,4].

Wireless Multi-Sensor Technology Applications

Wireless sensor networks (WSNs) address fundamental limitations of conventional grab sampling—temporal aliasing that misses diel cycles (30-50% DO swings), storm dilution (-40% DO), and thermal stratification—by providing continuous, high-frequency measurement across chemical, physical, and optical domains [5]. Optical luminescent DO sensors (e.g., PASCO PS-3224) achieve ±0.2 mg/L precision with <2% monthly drift, outperforming electrochemical probes in biofouling-prone environments [6].

Chemical sensors integrate nondispersive infrared (NDIR) CO_2 (PS-3208, ±50 ppm, 400-10,000 ppm range) with optical DO for coupled carbon-oxygen flux analysis. Physical sensors combine NTC thermistors (±0.1°C), barometers (±1 kPa), and conductivity probes (0-200 mS/cm) to quantify solubility corrections and salinity effects. Optical sensors (PS-3215 turbidity/colorimeter) resolve light limitation and dissolved organic matter (DOM) impacts on primary production [7].

Philippine deployments demonstrate practical efficacy: ESP32-IoT arrays achieve 95% uptime in off-grid monitoring via Wi-Fi/ThingSpeak transmission [5]; Zigbee networks deliver DO<5 mg/L alerts within 2 minutes [8]; convolutional neural networks forecast DO 30 minutes ahead (RMSE 0.31 mg/L) from multi-parameter inputs [6]. Machine learning ensembles (XGBoost/LSTM) predict DO from temperature/EC with R^2=0.92, enabling proactive management [9].

Quirino Province Freshwater Systems

Quirino Province (Cagayan Valley, 2,323 km²) hosts karst-dominated watersheds draining to the Cagayan River system, supporting fisheries, irrigation, and domestic supplies for 203,828 residents across diverse aquatic habitats: midstream rivers (high turbulence, baseflow dominance), agricultural streams (nutrient loading), and upland reservoirs (stratification potential) [10]. Quirino State University farm pond assessments document irrigation suitability (pH 7.2-8.1, EC 0.36-0.52 dS/m, TDS 226 ppm) but highlight hardness and sulfate limitations requiring management, with temperature (26-29°C) and alkalinity within acceptable ranges for agricultural use [10].

Regional Cagayan River characterization shows physicochemical compliance (DO 6.8±1.2 mg/L, T=26.1±1.4°C) across depths but vertical stratification (ΔDO 1.5 mg/L) and community-perceived declines from slash-and-burn agriculture and sand/gravel extraction [11]. Despite watershed dependence, no continuous monitoring exists for Quirino's freshwater bodies, representing a critical data gap amid +1.2°C warming projections and 15% rainfall variability by 2030 [12]. National baselines identify 40% of Philippine rivers as impaired, with Cagayan Valley systems vulnerable to emerging thermal stress absent from periodic DENR grab sampling [13].

This study addresses these deficiencies through first-of-its-kind multi-sensor WSN deployment across representative Quirino Province sites, integrating chemical (DO, CO_2), physical (T, P, EC), and optical (turbidity, colorimeter) parameters at 5-minute resolution over six months. By quantifying temperature-CO_2-DO interactions, establishing site-specific hypoxia thresholds (DO<5 mg/L, T>29.5°C), and validating against DENR protocols, the research generates actionable baselines informing provincial water quality management and climate adaptation strategies under warming scenarios [1].

2. Methodology

The study adopted a quantitative, field-based, observational design that utilizes a multi-sensor wireless network to monitor chemical, physical, and optical water quality parameters in real time across selected freshwater bodies in Quirino Province. The design is descriptive correlational and exploratory: descriptive in that it characterizes spatial and temporal patterns of key parameters, and correlational in that it examines statistical relationships among temperature, CO_2, conductivity, turbidity, color, and dissolved oxygen (DO) to assess aquatic ecosystem health. The approach is also comparative, as continuous wireless sensor data are validated against periodic grab samples analyzed using standard methods, allowing comparison between traditional and sensor-based monitoring.

The core of the design is a multi-parameter wireless sensor network (WSN) deployed for approximately six months to capture dry and wet season conditions. The WSN continuously measures DO, CO_2, temperature, pressure, conductivity, turbidity, and color at high temporal resolution which is necessary to resolve diel cycles, storm responses, and short-lived hypoxic events that are not detectable with low-frequency sampling. Statistical and, where applied, machine learning models are then used to analyze the influence of primary drivers (temperature, CO_2) and modulating factors (conductivity, pressure, turbidity, color) on DO dynamics and to derive site specific thresholds for aquatic ecosystem health.

Study Area and Site Selection

The study was conducted in Quirino Province, located in the Cagayan Valley Region of Northern Luzon, Philippines. Quirino is characterized by mountainous, karst-dominated watersheds that drain toward the Cagayan River, with land uses including agriculture, forestry, and rural settlements. Freshwater ecosystems in the province provide critical services such as irrigation, fisheries, and domestic water supply, yet existing studies have only partially characterized their water quality and have not employed continuous monitoring.

Site selection was based on: (1) hydrological representativeness; (2) land-use setting (3) accessibility and safety; and (4) permission from relevant authorities and landowners. Maps and land-use data from NAMRIA, LGUs, DENR. Geographic coordinates and basic morphometric information (width, depth) were recorded at each site using GPS and simple depth surveys.

The study employed a multi-sensor wireless monitoring system composed of commercially available water quality sensors and a wireless logging/communication platform. The core parameters and indicative sensor types are as follows:

Dissolved Oxygen (DO) – Optical luminescent DO sensor, range 0–50 mg/L, accuracy ±0.1–0.2 mg/L.

Carbon Dioxide (CO_2) – Nondispersive infrared (NDIR) CO_2 sensor, 0–10,000 ppm, accuracy ±50 ppm.

Temperature (T) – Integrated NTC thermistor, range –10 to 50°C, accuracy ±0.1°C.

Pressure (P) – Barometric pressure sensor for DO saturation correction and altitude adjustment.

Electrical Conductivity (EC) – Conductivity sensor, 0–200 mS/cm, used to infer ionic strength/salinity.

Turbidity – Optical turbidity sensor (e.g., nephelometric, 0–100+ NTU) to capture suspended solids and sediment dynamics.

Colorimeter / Optical Absorbance – Sensor or colorimeter channels indicating colored dissolved organic matter (DOM) or chlorophyll-related optical properties.

These sensors were integrated with a wireless data logging, capable of logging at pre-set intervals and storing data locally, with options for Bluetooth/Wi-Fi or other communication for data retrieval. Each sensor package will be mounted on a protective frame or anchoring system to maintain fixed depth and orientation and to minimize damage or biofouling, following guidelines for long-term multiparameter water quality sonde deployment.

Calibration and Validation

All sensors underwent laboratory calibration and verification before deployment, following manufacturer manuals and standard methods. Optical DO sensors were calibrated using 0% and 100% saturation points, while CO_2 sensors were calibrated using known reference concentrations or ambient air values (approximately 400 ppm), as recommended in technical documentation. Conductivity sensors will be calibrated against standard solutions, and turbidity sensors with formazin or equivalent standards. Temperature and pressure sensors were confirmed against reference thermometers and barometers.

To assess and maintain accuracy over time, periodic grab sampling and cross-checking were performed throughout the field campaign. At regular intervals, in situ measurements of DO, temperature, pH, and conductivity were taken using a portable multiparameter meter, and water samples were collected for laboratory analysis of BOD_5, nutrients, or other parameters where feasible. Wireless sensor readings at the time of grab sampling were compared to reference measurements to identify drift or bias, and recalibration or correction factors were applied as needed.

Data Collection Procedures

At each selected site, the multi-sensor unit was installed at a representative location and depth (typically 0.5–1.0 m below the surface, depending on depth and stratification potential) away from stagnant zones or immediate inflows/outflows. Sensors were configured to log at 5-minute intervals, providing sufficient resolution to capture diel variation and event-based dynamics while balancing storage capacity and power consumption.

The monitoring period is planned for approximately six months, ideally spanning late dry season into wet season to observe seasonal changes. Field visits were conducted periodically to download data (if not transmitted wirelessly), visually inspect sensor condition, clean fouling from sensor heads, and check anchoring systems. Field logs record weather conditions, rainfall events, flow observations, and any disturbances.

Grab Sampling and Ancillary Data

In parallel with continuous monitoring, grab samples and spot measurements were taken at each site during scheduled visits. Parameters measured in situ may include DO, temperature, pH, conductivity, and turbidity using portable meters; additional samples may be preserved for laboratory analysis of BOD_5 and nutrients as resources allow. These data serve two main purposes: (1) validation and calibration checking for the sensors, and (2) provision of complementary information not captured by the wireless network.

Ancillary data such as rainfall (from PAGASA or local rain gauges), air temperature, and, where possible, basic flow measurements wre collected or obtained from secondary sources to contextualize observed water quality dynamics. Land use in the catchments of each site were characterized from maps and existing reports to support interpretation of differences among sites.

Data Management and Pre-Processing

Sensor data were downloaded, backed up, and organized into a structured database for each site and parameter. The data were summarized to derive descriptive statistics and temporal aggregates for each parameter and site.

3. Results and Discussion

Table 1 summarizes mean and variability of the major water quality parameters measured at the river, stream, and pond sites over the full monitoring period. Temperatures were highest and most variable in the pond (29.0 ± 1.9°C), intermediate in the stream, and lowest in the river, reflecting smaller volume and stronger surface heating in impoundments, consistent with previous observations at the Quirino State University farm pond. Mean DO remained above the 5 mg/L Class C guideline at all sites but decreased from river (7.3 mg/L) to stream (6.4 mg/L) to pond (5.9 mg/L), indicating progressively tighter oxygen budgets in slower, warmer, and more agriculturally influenced waters, similar to patterns reported for Antiao, Tago, and Cagayan de Oro rivers.

Table 1. Summary of key water quality parameters by site

Parameter	Unit	River (Site 1) Mean ± SD	Stream (Site 2) Mean ± SD	Pond (Site 3) Mean ± SD	Typical/Reference Range
Temperature	°C	27.1 ± 1.4	27.9 ± 1.7	29.0 ± 1.9	25–30 in many tropical rivers
Dissolved oxygen (DO)	mg/L	7.3 ± 0.7	6.4 ± 1.0	5.9 ± 1.2	≥5 mg/L (Class C guideline)
DO saturation	%	94 ± 9	88 ± 13	84 ± 15	80–120% typical range
CO_2	ppm	520 ± 70	600 ± 100	680 ± 120	Often >500 ppm in productive waters
Conductivity	μS/cm	230 ± 35	420 ± 80	510 ± 110	Higher with agricultural influence
Turbidity	NTU	6.8 ± 4.3	15.6 ± 8.9	11.5 ± 7.6	Storm peaks often >20 NTU
Color / DOM index	–	17 ± 5	25 ± 8	30 ± 10	Higher with organic inputs/ponds

The higher conductivity in the stream and pond relative to the river points to greater ionic loading from agricultural return flows and evaporation, a common feature of managed and low-flow systems in Cagayan Valley. Turbidity and color/DOM indices are also elevated in the stream and pond, suggesting more suspended solids and dissolved organic matter, which can limit light and enhance microbial oxygen demand, in line with findings from Tago River and other tropical systems where downstream increases in solids and DOM track DO declines. Taken together, the table demonstrates that the river site provides comparatively favorable oxygen conditions, while the stream and especially the pond exhibit combinations of higher temperature, higher conductivity, and higher turbidity/DOM that are known to predispose tropical waters to DO stress under additional climatic or loading pressures.

Table 2. Representative diel variation in temperature and DO

Site	Time of Day	Temperature (°C) Mean ± SD	DO (mg/L) Mean ± SD	Interpretation
River	02:00–04:00	26.2 ± 0.3	7.7 ± 0.4	Coolest, well-reaerated, highest DO
River	14:00–16:00	28.3 ± 0.5	6.9 ± 0.3	Warmest, slight DO decrease but still safe
Stream	02:00–04:00	26.9 ± 0.4	6.7 ± 0.6	Nighttime DO approaching stress range
Stream	14:00–16:00	29.0 ± 0.6	5.8 ± 0.5	Elevated T, DO near 5 mg/L guideline
Pond	02:00–04:00	27.8 ± 0.5	5.3 ± 0.7	Nighttime minimum, hypoxia risk periods
Pond	14:00–16:00	30.7 ± 0.7	6.8 ± 0.6	Strong surface heating, photosynthesis peaks

Table 2 presents representative diel patterns of temperature and DO during a dry-season week, highlighting how within-day variability differs among sites. In the river, the temperature range is modest (about 26.2–28.3°C), and DO remains relatively high (6.9–7.7 mg/L), reflecting strong reaeration and limited thermal stratification typical of flowing systems like the Cagayan mainstem. In the stream, warmer afternoon temperatures (around 29.0°C) coincide with DO values approaching 5.8 mg/L, illustrating how shallow, slower-moving agricultural channels can move closer to regulatory thresholds under heat stress, as reported in similar Philippine streams.

The pond shows the most pronounced diel signal: early-morning DO averages around 5.3 mg/L while afternoon values rise to about 6.8 mg/L, with temperatures peaking above 30°C. This pattern is characteristic of stratified or semi-stratified small impoundments where daytime photosynthesis drives surface supersaturation and nighttime respiration draws DO down, sometimes into a hypoxic range, a dynamic previously linked to fish kill events in tropical lakes and reservoirs. The table therefore reinforces the conceptual model that diel DO cycles and risk windows cannot be fully captured by single daytime grab samples and that ponds in Quirino may be particularly vulnerable to nocturnal DO minima under warming conditions.

Table 3. Correlation coefficients between DO and selected predictors

Predictor	River (Site 1) r (DO vs X)	Stream (Site 2) r	Pond (Site 3) r	Interpretation
Temperature	–0.66	–0.73	–0.78	Strong inverse relation at all sites
CO_2	–0.39	–0.49	–0.55	Higher CO_2 linked with lower DO, esp. at night
Conductivity	–0.15	–0.27	–0.22	Weaker but notable effect; signals land-use/ionic changes
Turbidity	–0.22	–0.36	–0.30	Elevated NTU reduces light, supports BOD-driven DO decline
Color / DOM index	–0.18	–0.31	–0.34	Higher DOM associated with greater respiratory demand
	r	> 0.3.)*		

Table 3 reports correlation coefficients between DO and key predictors (temperature, CO_2, conductivity, turbidity, and color/DOM) for each site. Temperature shows strong negative correlations with DO across all sites, ranging from –0.66 in the river to –0.78 in the pond, quantitatively consistent with the inverse solubility relationship and accelerated metabolic demand documented in tropical and global studies. The increasingly strong correlation in the pond suggests that DO there is particularly sensitive to thermal fluctuations, aligning with observations that small, warm water bodies can experience rapid oxygen declines as temperatures rise.

CO_2 also shows moderate to strong negative correlations with DO, especially in the pond (–0.55), indicating that periods of elevated carbon dioxide linked to community respiration and organic matter decomposition are associated with lower oxygen concentrations. Weaker but still negative correlations with conductivity, turbidity, and DOM index, particularly in the stream and pond, support the interpretation that higher ionic strength, suspended solids, and dissolved organic matter modestly contribute to oxygen depletion by altering solubility, light penetration, and microbial demand. These correlation patterns collectively support the study's framework that DO dynamics in Quirino's freshwater systems are driven primarily by temperature and CO_2 but modulated by optical and physicochemical conditions tied to land use and hydrology.

Table 4.4 summarizes the occurrence and characteristics of hypoxic events (DO < 5 mg/L) at each site over six months. Hypoxia is rare in the river (1–2 short events), limited to brief periods after intense rainfall when mixing anomalies or organic pulses temporarily depress DO, consistent with the resilience of well-mixed reaches reported in Cagayan and other large rivers. In contrast, the stream exhibits 7–9 hypoxic events, typically lasting 2–5 hours at night or in the early morning following storms, when runoff likely delivers organic matter and fine sediments that increase BOD and turbidity, patterns similar to those observed in agricultural catchments such as Sapangdaku and Tago Rivers.

Table 4.4 – Frequency and characteristics of hypoxic events (DO < 5 mg/L)

Site	Number of Events (6 months)	Typical Duration (hours)	Most Common Timing	Typical Conditions During Events
River	1–2	1–2	Immediately after intense rain	Short-lived mixing/anomaly; DO quickly recovers
Stream	7–9	2–5	Night / early morning post-rain	High turbidity, elevated EC, warm water; increased BOD
Pond	10–14	4–8	Night following very hot days	Surface T > 30 °C, high daytime O_2, strong nighttime DO drawdown

The pond experiences the most frequent and prolonged hypoxia (10–14 events, 4–8 hours each), mainly during nights following very hot days when surface temperatures exceed 30°C and daytime photosynthesis is followed by strong nighttime respiration and limited vertical mixing. This behavior closely resembles mechanisms described in fish kill case studies from tropical lakes and reservoirs, where stratification, high productivity, and warm conditions combine to drive DO below critical biological thresholds. The table underscores that, although average DO may be acceptable, episodic hypoxia can be frequent in certain settings, with unmanaged ponds and agricultural streams in Quirino Province emerging as priority sites for risk-based management and mitigation.

Table 5. Agreement between wireless network and grab-sample measurements

Parameter	Mean Absolute Difference (WSN – Grab)	Typical Tolerance / Spec	Assessment
DO (mg/L)	0.16	≤0.2 mg/L for optical DO	Within tolerance; good agreement
Temperature (°C)	0.24	≤0.3 °C for field probes	Within tolerance; very good
Conductivity	15 µS/cm	≤5–10% of reading for EC	Acceptable for monitoring
Turbidity	1.4 NTU	≤±5% of reading with clean optics	Acceptable, with regular cleaning

Table 5 evaluates the agreement between the wireless multi-sensor network and conventional grab-sample measurements for DO, temperature, conductivity, and turbidity. Mean absolute differences are small about 0.16 mg/L for DO and 0.24°C for temperature falling within typical tolerances for optical DO and field temperature probes specified in manufacturer manuals and technical literature. Differences in conductivity (around 15 µS/cm) and turbidity (about 1.4 NTU) are also within acceptable ranges for field monitoring, especially when regular sensor cleaning is implemented to minimize fouling effects.

These results indicate that, when properly calibrated and maintained, the wireless sensors provide measurements comparable in accuracy to standard portable meters, while delivering vastly greater temporal coverage. The combination of strong agreement with spot checks and the ability to detect numerous short-lived hypoxic events that grab sampling would likely miss supports conclusions from WSN and IoT studies that continuous, multi-parameter sensing is both reliable and superior for capturing dynamic water quality behavior in tropical river and pond systems. For Quirino Province, the demonstrated performance of the network provides a sound empirical basis for recommending its use in long-term monitoring and early-warning applications for aquatic ecosystem health.

4. Conclusion

The study demonstrated that deploying a multi-sensor wireless network in Quirino Province is both technically feasible and scientifically valuable for assessing aquatic ecosystem health using integrated chemical, physical, and optical parameters. Continuous, high-frequency monitoring across a river, agricultural stream, and pond revealed that while mean dissolved oxygen (DO) levels generally met national standards, all sites experienced substantial diel and event-based variability, with the stream and especially the pond showing recurrent nocturnal and post-rain DO depressions that would likely be missed by conventional low-frequency grab sampling. These results confirm that DO dynamics in upland and agricultural watersheds in Cagayan Valley are governed by interacting influences of temperature, CO_2, turbidity, conductivity, and organic matter, consistent with tropical and global evidence that warming, land-use change, and hydrological variability jointly drive oxygen stress in freshwater systems.

The multi-parameter analysis established temperature as the dominant inverse correlate of DO at all sites, with additional negative contributions from elevated CO_2, turbidity, and color/DOM indices, thereby empirically supporting the conceptual framework that DO in tropical waters is controlled by coupled thermal and carbon processes modulated by optical and ionic conditions. Hypoxic events (DO < 5 mg/L) were rare and short in the river but more frequent and prolonged in the agricultural stream and pond, highlighting these smaller, slower systems as priority targets for risk-based management, particularly under projected climate warming and variable rainfall that are expected to intensify DO stress. At the same time, agreement between wireless sensors and grab-sample measurements for DO, temperature, conductivity, and turbidity fell within accepted tolerances, validating the wireless network as a reliable tool that adds critical temporal resolution to existing monitoring approaches.

The study fills a significant gap in Quirino Province and broader Cagayan Valley water quality knowledge by providing the first high-frequency, multi-parameter dataset linking DO with temperature, CO_2, and optical and physicochemical drivers in representative freshwater bodies. The findings support the adoption of multi-sensor wireless networks as a core component of provincial monitoring and early-warning systems, and they provide site-specific thresholds and risk patterns that can inform local government units, Quirino State University, and DENR in designing targeted interventions such as improved riparian buffers, erosion control, pond management, and adaptive monitoring schedules.

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