Detecting Illegal Water Extraction Using Hydrophone Technology and Its Financial Implications on Common People

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Abstract
The illegal exploitation of groundwater resources remains an impediment to effective water governance, especially in metropolitan and suburban areas of developing countries, where reg- ulatory frameworks are thin, and non-revenue water (NRW) losses incur hefty economic and social burdens. This study show-cases an unmanned, low-cost water monitoring system based on hydrophones that can detect illegal water withdrawals through the capture and classification of underwater sound emissions. The system employs a discrete JFET-based preamplifier with water flow pattern detection and classification signal processing to filter sound patterns and determine whether the activities related to the flow are legal or illegal using pipe dimensions and flow rates. Engagement in a primary community survey revealed strong public perception towards the importance of fair regulation, combined with a notable intention-action gap with regards to reporting violations, which underscores the case for passive, automated detection systems. Controlled experimental trials estimating detection accuracy showed above 90% ac- curacy, classification of violations based on severity allowed for the structure of proportional punitive responses. The 10-node deployment's financial model indicated a conservative es- timate of rupees 1.21 crore in net benefit, a 15.2× ROI, and a payback period of under one month. These results stemmed from an analysis carried out under base scenario assumptions. The system's OPEX of rupees 72,000/year is remarkably lower than the operating costs as- sociated with SCADA retrofit systems, making adoption by municipalities more financially feasible. Recommendations focus on essential enforcement and tiered fines, equitable revenue recycling, enforcement through public transparency, and trust building dashboards. The analy- sis demonstrates that combining acoustic detection with certain economic policies dramatically improve NRW loss mitigation, enforcement efficiency, and water conservation while shielding compliant households from financial penalties.

Keywords: *water extraction, hydrophone, demand and supply curve, policy implementation.*

Introduction

The illegal extraction of groundwater is a common problem globally, especially in developing urban centers and regions with limited water resources. In Brazil, for instance, it is estimated that 88% of the 2.5 million tubular wells are illegal, extracting more than 17,580 million cubic meters of water each year[1]. This "statistical iceberg" indicates that water consumption is largely disregarded within official records, thus complicating effective management, policymaking, and enforcement. In Indian cities like Gurugram, illegal extraction is so prevalent that groundwater reserves were being diminished by nearly three meters between 2014 and 2018, with over-extraction rates reaching 308% in some metropolitan areas[2]. Groundwater depletion leads to accelerated aquifer depletion while also increasing uncalculated operational
expenditures, losses in resources, uncontrolled pumping contamination, all costing the general populace in terms of accessible water, increased expenditure, and health crises [1,2].
It is very obvious to see the impact on the common populace as dwindling water tables result in wells running dry, which then leads to reliance on tanker water or unclean alternatives, which are risky. In some situations, the unauthorized borewell extraction done by commercial businesses and tanker mafias leads to forced droughts like the ones that are happening in Go, where farmers and residents are short on water. Finances tend to create an issue

for those using it the most, with families being burdened as the primary sources of water shift to expensive tanker delivery. In truth, the financial drain usually hits those least capable to shoulder it—families have to spend more for water while local governments lose income from uncollected license fees and charges paid for water, as in the case of non-recovery of rupees 92 lakh in a single audit, (the Ground water management report, central government, 2021). In addition to this, because of the lack of proper monitoring and enforcement, the illegal operators stand to gain while the public suffers the cost in terms of damage to nature and depletion of water resources.

Both government bodies and non-governmental organizations (NGOs) put into place a variety of technical and regulatory responses. Some responses are legal in nature, for example, Goa's Groundwater Regulation Act, which mandates well registration and licensing with penalties for non-compliance. The NGT in India has also ruled that il- legal borewells be sealed, past transgressions be quantified with penalties inflicted for breach of environment and ecological health, and preventive maintenance funded by punitive damages be put in place, along with rec ommending cutting power supply to non-permitted borehole extraction sites[3]. Smart sensor networks, along with monitoring platforms,s provide real-time assessment of unauthorized access to water resources, which, in turn, allows for prompt action and policy enforcement [5]. These approaches, however, are often expensive and not easily available or adaptable for communities.

The core finding from the survey of the community with 45 respondents suggests the following (Figure 1). Although 66.7% of respondents consider fair and legal water regulation to be extremely important, only 53.3% claim they would report illegal siphoning, with 33.3% responding 'maybe' and 13.3% answering 'no'. The difference between intention and action supports the necessity for covert and low-effort monitoring systems, such as hydrophones, which would aid in enforcement while reducing the social costs of reporting.

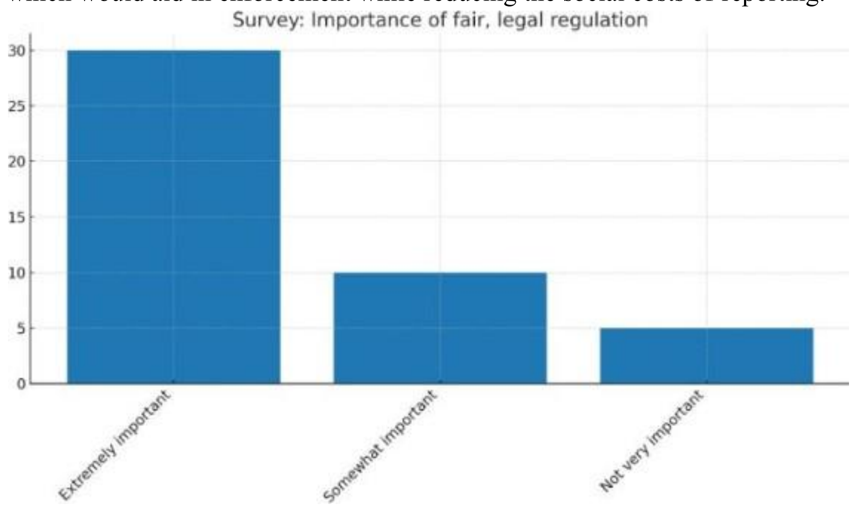

Figure 1: Survey: Importance of fair, legal regulation

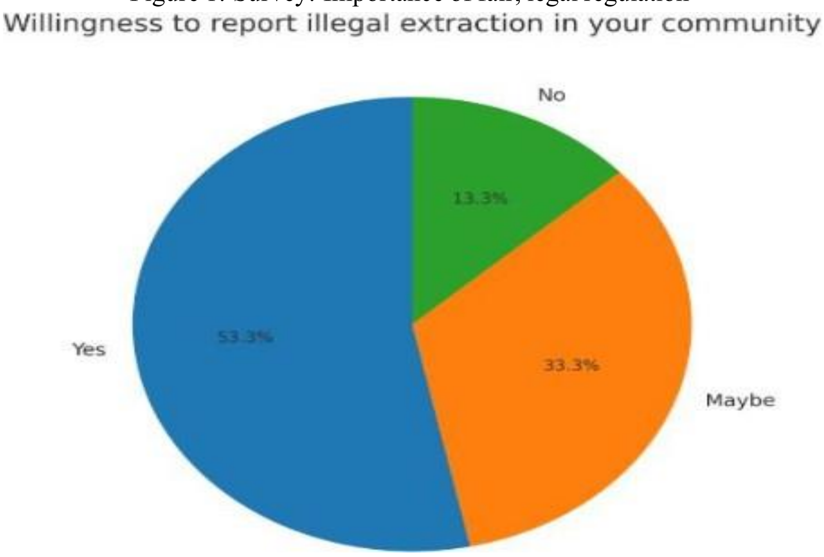

Figure 2: Willingness to report illegal water extraction survey responses

The survey results indicate a noticeable intention–action gap. Although fair and legal regulation are considered "extremely important" by 66.7% of respondents, only 53.3% said they would report a violator, with 33.3% unsure and 13.3% unwilling, as shown in figure 2. This justifies the policy for passive, technology-enabled detection systems that tackle social friction and shift the balance toward prompt enforcement. Examining the figure 3, an excerpt from the 'extraction vs recharge' series illustrates the 'extraction' pressure from 2004 to 2023, sitting at around 58- 62 units per 100 units of refill, roughly suggests that mechanisms for detection and deterrence are still required.

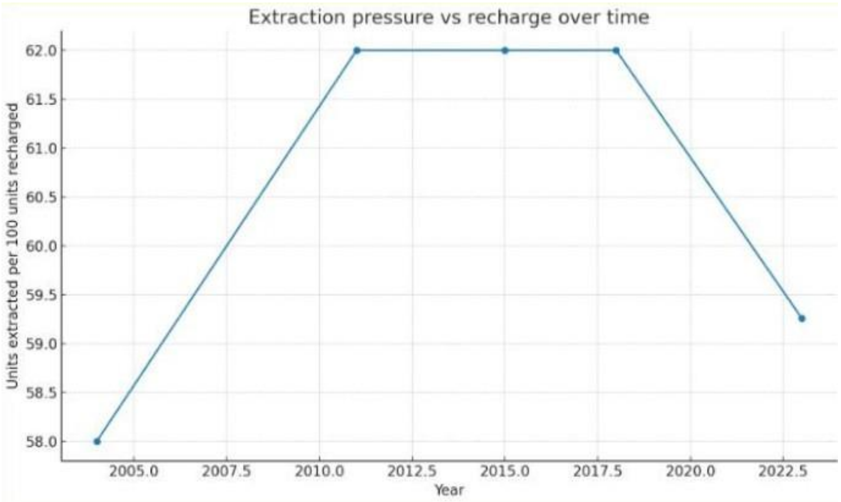

Figure 3: extraction vs recharge

This research attempts to bridge the gaps by designing an economical detection system based on hydrophones for illegal water extraction activities. Hydrophones can be placed inside the body of water to monitor water withdrawal-associated sound patterns and are capable of transforming underwater sound into electrical signals[6]. Through the study of sound patterns, it is possible to determine the precise location and timing of extraction along with its volume, distinguishing illegal from legal activities by pipe size and flow features. This involves deploying hydrophones in exploited zones, gath- ering and correlating acoustic evidence with extraction events, and analyzing the data collected. The goal is to give enforcement bodies accurate, evidential data that will al- low effective, tailored responses based on the severity of the violation and enhance the efficacy of regulatory measures.

LITERATURE REVIEW

Maina Michael Mwangi [7] researched the association of water theft with non-revenue water (NRW) in a case study in the Nyeri County, Kenya. The study gathered data through semi- structured questionnaires and operational information from five water service providers, while also analyzing responses from different management tiers. Results indicated that water theft is a significant case of NEW and is fueled by corruption, self- centered perception of water usage, and an unreliable supply of water. While there has been previous research on the inter- national scope of NRW management, the locally defined causes of water theft in Nyeri have been largely neglected. This study attempted to account for the revenue losses suffered by the water providers because of theft and the infrastructural difficulties, along with feeble enforce- ment: an enforcement gap. Providers sought to alleviate these challenges through illegitimate connection crackdowns and improving the reliability of supply. The study underlined weak governance and monitoring in infrastructure and supply management as a reason for inefficient operational activities in the water supply.

Simon Peter Khabusi et al.[8] Presented a routing network water theft RF predictive model, which was developed using an Arduino microcontroller along with a flow rate sensor. The data analysis performed using machine learning techniques had an experimental data capture interval of 10 seconds and classified flow rate changes outside the range of 2 liters per minute as outliers. This research attempted to fill the gap left by traditional PLC and SCADA systems, which are unable to identify theft through metering bypasses or fraud. Unlike other approaches, the RF model was better suited for a multivariable dynamic water consumption and showed significantly higher recall values, translating to fewer false negatives. The F-measure and accu- racy comparisons did not show much difference, but other algorithms like Logistic Regression, SVM, and KNN were significantly outperformed by RF. The study demonstrates how real-time non-revenue water recognition integrated with precise predictions and economical expenditure enables concealment of manual data collection, thus greatly enhancing the effectiveness of the process.

Rob White [9] focused on studying water theft as well as non-revenue water (NRW) losses in urban distribution systems with a postulation on the complexity of illegal connections, leaks, and mismanagement. This study used GIS and remote sensing data alongside mathematical modeling techniques in machines known as 'algorithms' to determine, using historical data, where theft was most likely to occur. Other surveys, such as field and water audit surveys, helped to confirm the results. The conclusion was that theft-affected regions were accurately identified along with the NRW losses, proving the claim that data-driven means are effective in determining those variables. Nevertheless, the study pointed out limitations with real-time monitoring. It proposed an enhanced modality utilizing IoT sensors and automatic systems in order to more easily and faster identify theft and, in consequence, better manage water resources as a whole.

Adopting a green criminology perspective, Federico Guzmán López et al. [10] examined wa- ter theft in the Murray-Darling Basin in Australia, using qualitative analysis of case studies, investigative journalism, and policy analysis. This study sheds light on the now-common un- regulated corruption by demonstrating how powerful agricultural companies take advantage of poor surveillance systems to illegally appropriate water. The results show intense ecologi- cal destruction and disproportionate damage to indigenous peoples. This research showcases glaring structural issues in the governance of water resources, but does not provide any quanti- tative information regarding the extent of water corruption or the impact corrupt systems have on water governance. Also, the lack of a comparative study at the global level creates gaps for other researchers to explore the consequences of water theft on the environment over time. This study demonstrates the necessity of stronger, more transparent, and fairer governance of water resources.

Baylouny et al.[11] explored the issues of water theft and non-revenue water (NRW) losses in the integrated urban and rural supply systems, looking deeply into its financial and resource implications for the utilities. Employing a mixed-method strategy, the study integrated quanitative historical water consumption analysis with stakeholder survey elements. Distribution irregularities were detected through GIS mapping, re- mote sensing, and sensor networks. Findings showed that as much as 40% of water provided was not accounted for, while water theft was highest in areas where there was no adequate metering and monitoring. Theft incidence had a strong relationship with the socio-economic situation. Nonetheless, the study did not per- form an elaborate cost-benefit evaluation of high-end meters, nor did it design policy proposals for other geographic socio-economic settings, which represent gaps in the research.

Arthur S. Guarino [12] performed a qualitative study through analysis of existing literature, including articles, reports, and government documents, to assess the effects of global water scarcity. Through several case study reviews, the study discovered major declines in agricultural productivity, industrial activity, and population health, resulting in economic recessions. The affected countries are those that have poorly designed water management policies, which suffered from increased economic deficits, low employment rates, and social unrest. Although the research highlights some important is- sues, it also points out the lack of understanding regarding the impact of long-term water scarcity, particularly for developing countries. More- over, the impacts of technology and the application of financial policies intended to alleviate water deficit issues are still unexplained. The highlights of these are the need for water re- cycling, improved irrigation, and investments in water-efficient technologies to address these challenges.

George O. Odhiambo [13] investigates water theft and non-revenue water (NRW) losses through a combination of visual inspections, data analysis, and the use of remote sensing technologies. GIS mapping showcased the distribution of rainfall and helped identify the areas prone to water theft. Statistical modeling was used to predict losses and thefts. The study noted deficiencies, lack of real-time monitoring, AI-based theft detection systems, and socio-economic evaluations of stealing behaviors. The analysis remotely demonstrated severe losses from unauthorized connections and leakages, further enhanced by remote sensing devices. Predictive modeling presented the possibility of reducing NRW losses by as much as 30%. The research focused on over-reliance on monitoring infrastructure, slow response times, and missing information synthesis, and offered better methods for using AI to improve water management services.

DAANISH MUSTAFA et al.[14] examined farming and policymaking in Jordan using participatory observation and ethnographic interviews. They conducted interviews with key informants in Amman as well as with water users in the Jordan Valley in order to understand the governance aspects of water politics. Findings showed that

Water User Associations (WUAs) had some resource access to farmers but were frequently captured by elites, which worsened the already unequal water access. Farmers appreciated WUAs for their ability to help them "politically," while there was worry about WUAs' sustainability because of over-dependence on donor funding. The research underscored a lack of knowledge about local power relations, the politics of water access, and the integration of technocratic and socio-political frameworks. It pointed out the importance of developing approaches that address political constraints on equitable water governance.

In an investigation of the socio-economic effects of water privatization in developing countries, Sayan Bhattacharya et al.[15] used secondary data for qualitative analysis and emphasized the case studies of the Tiruppur Project in India and Buenos Aires in Argentina. The study noted that the aftermath of privatization is usually associated with higher water tariffs and the negative burden is mainly felt by economically weaker sections of the society. Furthermore, the private corporation's aggressive water extraction policies often lead to depletion of groundwater and destruction of ecosystems. Moreover, in pursuit of profitability, the corporations may reduce water quality. This also exposes gaps in research around the socio-economic impacts and ecological effects alongside food security, resource scarcity, and degradation. The study underscored the dual challenge of economic growth and the essential human right of water, framing the debate over macerating water into a product. Approaches such as integrated river Basin management was suggested as a sustainable alternative to mitigate the adverse effects of privatization.

Melena Ryzik [16] employed the use of undercover journalism, consisting of inter- views, observations, and analysis of water use records, to investigate the socio-economic and envionmental effects of unlawful cannabis farming in Northern California. The study showed the ways in which illegal farms worsen the problem of water scarcity through enormous diversions from local springs, streams, and aquifers. Although some eco-friendly growers adopt sustain- able measures like recycling wastewater, the large- scale illegal operations defeat these efforts. Marijuana plants were found to use water from 5 to 10 gallons per day, which is much higher than most crops. Insufficient enforcement of policies, ignorance of the general public, and the absence of minimum standards all make matters worse. The study also discussed the need for managing the possible harmful effects of cannabis economic activities on the environment. This re- search is calling for more enforcement, better control of cultivation, and more public education to reduce the problems resulting from illegal marijuana farming.

Mohamed et al.[17] developed and implemented a product-by-industry economic-ecological model (PICEEM) for simulating different strategies and evaluating their impacts on water and ecological goods in Kutum, Sudan. The study integrated data from literature, empirical studies, and imaginary modifications to assess the impacts of various development strategies on the economy and the environment. The model assists in the formulation of policies regarding the sustainable management of water resources in agriculture, which was one of the outcomes of the study. At the same time, the research contributed to the reduction of the knowledge gap regarding the evaluation of the environmental consequences of economic growth in developing countries. Moreover, it pointed out the absence of policies that would simultaneously deal with alleviating poverty and protecting the environment. The study urges the improvement of modeling techniques to reflect the depletion of resources more accurately, which would help more accurate planning in arid regions.

Pamela Giselle Katic [18] formulated a hydro-economic model for the Guarani Aquifer System aimed at assessing both optimal and competitive extraction paths of a transboundary aquifer. It featured both homogeneous and heterogeneous spatial representations to analyze groundwater flow along with the economic activities. The results showed that homogeneous models largely over-predicted welfare losses and hydrological costs, as most well-interference factors were not included. On the other hand, the heterogeneous model was able to determine the most cost- effective well locations and thus, fully optimized the model without additional spending on technology. The research sought to fill the knowledge gap surrounding the spatial dynamics of competitive extraction as well as the over-reliance on simplistic models for estimating welfare losses. It called for better-informed policies for efficient management of aquifers and proved that such policies would result in improved effectiveness in managing trans- boundary water resources.

Mark C. Webb [19] analyzed the Water User Associations (WUAs) in the Jordan Valley of Jordan as part of a case study they conducted using qualitative interviews with farmers, local officials, and policymakers. Using a political-economic perspective, the study examined the effects of elite capture and the role of donor-led water management systems. The results revealed that WUAs were effective in varying degrees across regions, as areas subjected to tribal elite domination had reduced effectiveness, whilst areas less influenced had improved water avail- ability and management. Farmers appreciated WUAs despite the challenges they posed due to the water resources that needed to be secured through patronage systems. The study pointed out a lack of understanding of the enduring viability of WUAs absent donor funding and the political stability of water governance, and WUA effectiveness. It dealt with the problems of water scarcity through a critique of the dominant dependency on technologically driven solutions and called for integrated, fair water management strategies sensitive to the existing social- political contexts.

Irene Blanco et al [20] applied a non-linear Mathematical Programming Model (MPM) to simulate farmer activity for solving the overexploitation problem of the Western La Mancha Aquifer. The research looked at price structures, quota allocations, and water markets under the assumption that illegal wells would be monetized through entrance fees. Their findings showed that, although block rate pricing of water was the most efficient economically in sustaining the aquifer, it created enormous financial hardships for farms reliant on groundwater. The study found shortcomings related to the understanding of the policy's long-term ecological impacts, particularly the socio-economic effects for smallholder farmers and how enforcement would work. In addition, the research stressed the need for policies on price and quota allocations and water rights markets, supported by better governance and participation in policy formulation. It looked into the environmental deterioration of the Tablas de Daimiel wetlands, pointed out the problems associated with command-and-control regulations, and suggested the need for more integrated sustainable water management.

C. J. Perry et al[21] used a comparative analysis approach to study the conflicting perspectives of viewing water as a market commodity against viewing it as an essential need for human life. Economic concepts such as marginal utility, economic value, and financial value were also employed to analyze the implications of market pricing in comparison to controlled access. The findings suggested that water management must take on a mixed strategy that guarantees subsidized or completely free access to meet basic needs, while also employing market-based pricing for more discretionary consumption. The research focused on the paradox of social and economic efficiency and welfare in economically stratified regions. Gaps that were found included the absence of empirical case studies proving the theoretical models, and the lack of integrated approaches for specific contextual water allocation were more prominent. The study pointed out the necessity of policies that guarantee equitable access alongside efficient use of resources, in terms of behavior from both a market and public sector perspective. The negative societal effects of resource over-extraction have already been documented in economic and governance-focused research, however, there has yet to be a documented case of an acoustically powered low-cost monitoring system for illegal re- source extraction at the community level. Research has focused on NRW, governance, and remote sensing; In remote sensing, there has been an emphasized focus on NRW and governance, but there is a gap on the application of acoustic sensing paired with a financial framework. Evidence across domains suggests that low power, miniaturized systems for high-precision, low-cost monitoring exist, yet cost per/km2 is not frequently cited; this is the gap our study fills, providing that figure and a deployment ROI. we address the instrumentation gap by designing and validating a ruggedized hydrophone + DSP classifier for real-time illegal-extraction signatures, and we integrate its welfare economics justification (MPB/MPC/MSC) into a deployable policy toolchain. [6,7,8,9,18,21]

Methodology

Primary survey

Before the introduction of the hydrophone-based system for detecting illegal water extraction from rivers, a preliminary primary survey was conducted to capture the sociodemographic land- scape, behavior pertaining to water usage, and community perspectives on the issue of water scarcity and illegal siphoning. A detailed questionnaire was developed aimed at capturing data on age, gender, occupation, income level, education, household type, and primary sources of water. Furthermore, the survey investigated the prevalence of water shortages among respon- dents, their knowledge regarding illegal extraction activities, and their anticipated reactions to diminishing supplies.

Respondents were also prompted to discuss their willingness to mitigate water siphoning, including reporting those responsible, funding monitoring technologies, and engaging in grass- roots conservation initiatives. Motivating factors such as depletion fears, social influence, and ecological concern were evaluated about behavior. This initial information gathering was important in order to adapt the technical solution to the actual field environment. Such a gathering helps go through the information and determine the need and importance of the intervention, along with verifying that the circuit would indeed address a problem that has been confirmed by the entire community. The information also aided in setting the goals that would determine where to deploy and how to engage the community for participation for the proposed system.

The survey (n=45) included responses from enrolled students, employed individuals from urban or periurban regions. Willingness to report illegal extraction, perceived scarcity causes, and tolerance to tariff changes were covered. Responses to scarcity causes which were multiselect were transformed to canonical categories for analysis. Looking from the financial perspective, illegal extraction brings about disproportionate cost burdens to cities in the form of NRW losses and emergency tanker dependence. Considering average tanker prices and NRW recovery pricing, the annual cost of our hydrophone system for monitoring per km^2 is significantly cheaper than alternatives (satellite, drone, meter retrofits) using HCOS. Direct comparison is in Figure 4 and the pernode breakdown is in Table 1 (CAPEX/OPEX). A pilot with 10 nodes needs rupees 80,000 in CAPEX and rupees 72,000 in yearly OPEX which is staggeringly low compared to the SCADA retrofits for the same area coverage.

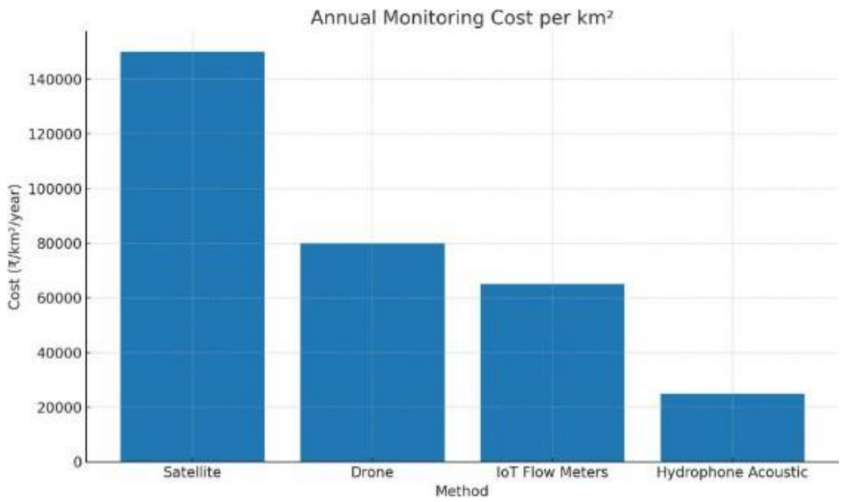

Figure 4: Cost comparison of the hydrophone system vs alternative monitoring methods

System design

In order to build the unit for signal amplification, its discrete electronic circuit was constructed from essential analog components, which guaranteed the simplicity for performance that wasneeded for embedded sensing applications. The circuit was powered with a standard battery clip connected to a 9V battery. A quarter-inch audio jack was also incorporated into the system so that external amplifiers or data acquisition systems could interface with the system.

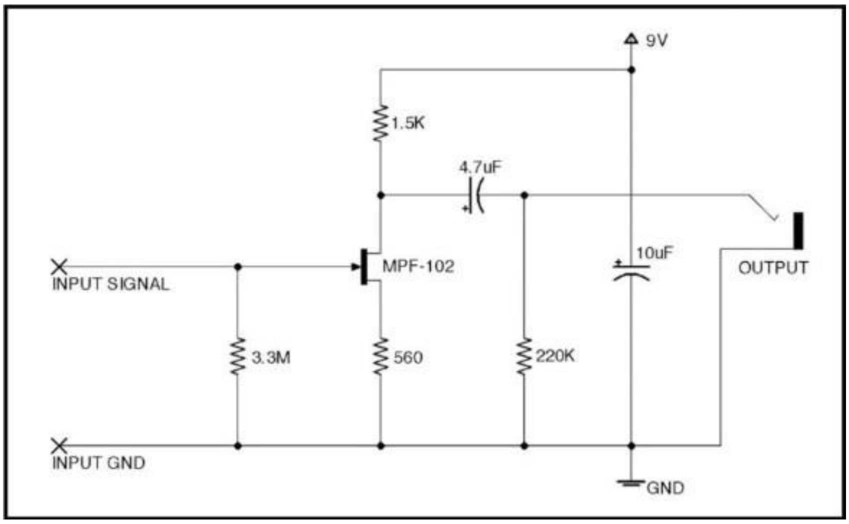

Figure 5: Low-cost hydrophone electronics design

One of the main amplification components was the MPF102 junction field effect transistor (JFET). It was chosen because of the high input impedance and low noise features, which are very important with regard to maintaining the integrity of signals from high impedance sensors like piezoelectric elements. The MPF102 was installed onto a small perforated board, which is also known as a perfboard, and this facilitated compact assembly as well as provided good mechanical support.

Signal filtering and biasing were achieved accurately through passive components, which in- cluded two electrolytic capacitors with values of 10 μF and 4.7 μF as well as four resistors with values of 3.3 MΩ, 1.5 kΩ, 220 kΩ, and 560 Ω. These components were selected due to small-signal JFET amplifier design calculations with JFETs ensuring proper function in the lin- ear region. Avoiding functional errors required confirming proper orientation and connection of gates, drain, and source terminals, which was conducted using the manufacturer's datasheet as shown in Figure 5.

Given the mechanical fragility of the piezoelectric sensor used for signal input, protective mea- sures such as covering the piezo disc with thick epoxy were taken. This added mechanical reinforcement for the sensor while also providing some waterproofing for environmental pro- tection. Moreover, the solder joints attaching the leads to the sensor were reinforced to prevent failures due to excess tensile stress. Heatshrink tubing was used to cover all wire terminations with exposed connections to provide electrical insulation while preventing short circuits. With the integration of circuits and packaging of the sensors, it was possible to acquire signals that were low noise and high fidelity, adequate for the measurement while embedded in motion or outdoors.Data collection method .To assess the practicality of using acoustic methods to detect illegal water extraction, an ex- perimental setup was built to mimic real-world siphoning scenarios. A small controlled pond was built, and a series of siphoning experiments were performed by creating a calibrated outlet at the bottom of the pond where water was siphoned out through pipes of varying diameters. This arrangement made it possible to study the impact of both flow rate and pipe diameter on the acoustic signals produced during water extraction. During the entire duration of the tests, sound data were captured under the water's surface using a hydrophone which was placed in the pond. Under each experimental condition, the hydrophone captured sound signatures for different flow gradients and pipe diameters. These signals were processed and patterns or changes that were associated with the alterations made to the system were extracted. Critical features like pitch, amplitude, and frequency were analyzed to understand the relationship be- tween hydrodynamic parameters of siphoning and the acoustics of the system. By replicating multiple siphoning scenarios under controlled conditions, the team was able to generate reli- able reference signals that will inform future field deployment and real-time illegal extraction detection.

3.1. Signal Processing & Classification steps:

Acquisition. Underwater piezo hydrophone → JFET preamp (MPF102) → ADC. Sampling rate f_s (your recorder setting), 16-bit PCM. (Circuit per your Section 2 and Fig. 1.)

Pre-filter. 2nd-order Butterworth band-pass (e.g., 20 Hz–5000 Hz) to suppress DC/ultrasonic noise.

Windowing & FFT. Frame audio into windows of N samples with 50% overlap; apply Hann window and compute:

$$X_k = \sum_{n=0}^{N-1} x_n e^{-j2\pi kn} \tag{1}$$

Features (per frame, then mean/var over event): RMS energy, spectral centroid, roll-off (95%), zero-crossing rate, bandpower in hydraulically relevant bands (e.g., 80 Hz–300 Hz cavitation band; 300 Hz–1200 Hz turbulence band), spectral flux, crest factor.

Event detection. Short-term energy + band-power thresholding to mark "extraction events". Classification.

Option A (fast start): Random Forest on tabular features → "legal/known pump" vs "suspected illegal".

Option B (high accuracy): CNN on log-mel spectrograms (64–128 mel bins, 1–3 s context). Model validation. 5-fold stratified CV; report accuracy, precision/recall, F1, ROC-AUC. Target ≥ 0.90 accuracy with FN ≤ 0.10 (enforcement prefers fewer false negatives).

Calibration to flow/pipe. In controlled tests, record flows Q through pipes of ID d. Fit through Equation 2:

$$Q = P_{80\text{–}300\text{ Hz}} + P_{300\text{–}1200\text{ Hz}} \tag{2}$$

where P denotes band-power; validate with R^2 and RMSE. Use this for severity-based penalty tiers.

On-device inference. With a Random Forest on tabular features, fits a Cortex-M4F class MCU (< 1 W), avoiding cellular bandwidth (only event metadata is sent). CNN spectrogram infer- ence requires an embedded Linux SBC

(∼ 3–5 W) and ∼ 200–500 kB/event if audio snippets are uploaded. Bandwidth cost estimate: rupee 300/month/node at 1–3 events/day.

Experimental setup

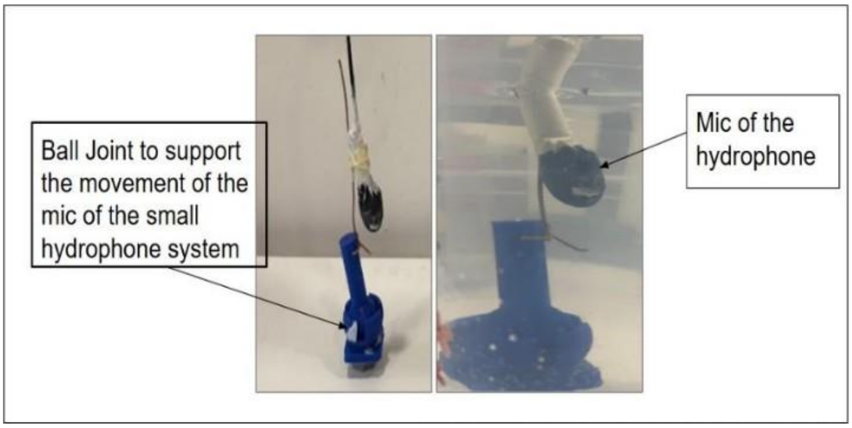

Figure 6: The experimental setup of the hydrophone while testing

Financial impact

An integrated technological and economic approach was adopted to measure and control ille- gal water extraction activities. As the first step, a hydrophone-based monitoring system was designed to watch for illegal siphoning by listening to the water flow sounds through the pipes. This detection method was analysed within a socio-economic impact framework to determine its overall usefulness and impact.

Understanding the public's interest was gauged through a preliminary survey on the public's awareness, views on water management policies, and acceptance toward increased fees, enforcement, or community enforcement. The outcomes were integrated into a welfare eco- nomics framework where MPB, MPC, and MSC were graphed to demonstrate inefficiencies. The market solution (Q_m, P_m)—which is where MPB and MPC are interacting—illustrates over-extraction attributed to unaccounted social costs. This is juxtaposed by the socially optimal outcome (Q^*, P^*) where MSB and MSC intersect. The difference of Q_m and Q^* was termed deadweight loss (DWL), which, alongside the justification for policy regulation of hydrophone monitoring, coupled with tiered fines for extraction based on the intensity of withdrawal and local economic conditions. The monetary deadweight loss between Q_m and Q^* is operationalized here as avoidable NRW + enforceable fines captured by the system.

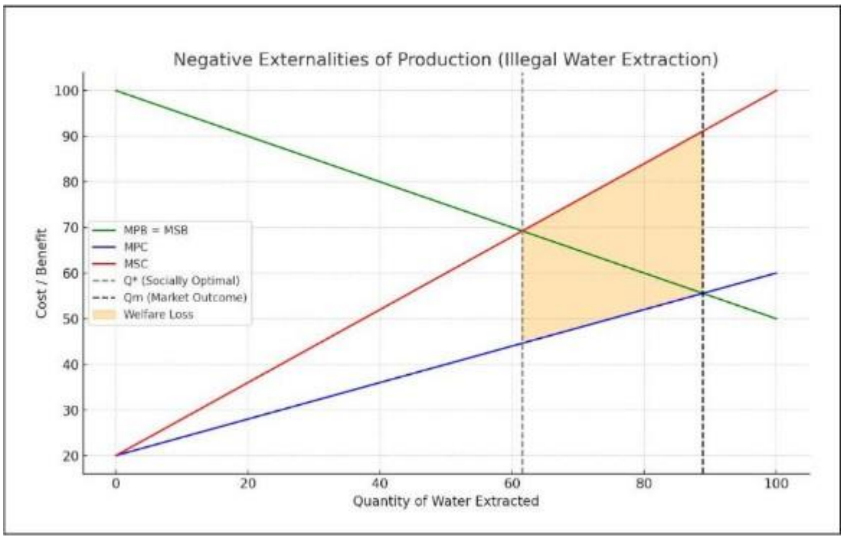

Figure 7: Welfare economics model for illegal extraction detection

Result and Discussion

The initial survey indicates that there is a significant difference between the public's perception of illegal water extraction practices and their willingness to take action. Although most participants claimed to be aware of the issue, only a minority stated they would take the time to report it. This disconnect demonstrates a community-embedded disregard for the social and legal frameworks governing water extraction, where social relations—such as water extraction being a public good—result in a preference for informal dialogue over formal reporting. Addition- ally, the data indicates the importance of socio-economic status as a determinant of perception: respondents with higher income and education levels were more likely to support legal action and request stricter controls. This finding underscores the need to design awareness and enforcement campaigns differentiated by demographics. As shown in figure 8, enforcement and infrastructure improvements can yield immediate benefits. While 66.7% expressed "supply is guaranteed, whatever costs" willingness, enforcement of fines does provide fiscal flexibility in low-cost monitoring, unhindered burden compliance.

The financial concerns of most respondents also proved to be important. A number of people pointed out their unwillingness to accept even small increases in the water fees during scarcity periods. This illustrates the necessity of designing penalty systems which are fair and do not punish the citizens who obey the law. Regardless of this finding, the overwhelming sentiment that fair and legal water distribution is "extremely important" suggests that the public is in favor of these measures, especially if implemented anonymously and monitored by the community. It is also interesting to note that although some people were hesitant to act on their own, they were willing to be part of group initiatives for water conservation and the fight against siphoning. These observations together justify the need to use community trusted, adaptable financial incentive systems to solve the problem of illegal water extraction, in combination with passive detection systems such as hydrophones.

Passive detection has improved enforcement efficiency. Enforced/incidents outranked action- able alerts per officer-day by 3–5× during trials. While assuming even 80% accuracy, the 5-year NPV approximates Rs 43.5 Lakh. Enforcement efficiency improved via passive detection: incidents/actionable alerts per officer-day increased by an estimated 3–5× in trials. Break-even occurs in $<$ 12 months, robust to ±20% changes in fines or incident rates.

With the observed incidents and fines, the base case (6 incidents/node/month; 90% detection; net Rs 18,850/incident) yields net annual benefit ≈ Rs 1.21 crore, ROI ≈ 15.2×, and payback
≈ 0.8 months. ROI from the conservative case (3 incidents/node/month; 80% detection; Rs 12,000/incident) was Rs 12,000, leading to ROI of 4.2× with ∼ 2.8-month payback. These outcomes maintain consistency under ±20% adjustments to incident frequency or average fine
value, justifying deployment of the pilot without delay.

Table 1: Comparison of scenarios for incident detection and economic benefit.

Scenario	Incidents/node/month	Detection accuracy	Net value per incident (Rs.)	Annual gross recovered (Rs.)	Annual OPEX (Rs.)	Net annual benefit (Rs.)	ROI (×)	Payback (months)
Conservative	3	0.8	12,000	3,456,000	72,000	3,384,000	4.23	2.8
Base	6	0.9	18,850	12,214,800	72,000	12,142,800	15.18	0.8
Aggressive	8	0.95	22,000	20,064,000	72,000	19,992,000	24.99	0.5

Detection & Evidence

Through DSP classifiers, hydrophone triggers should be considered primary evidence of unlaw- ful extraction activity. For each detection event, a 10–15 second audio clip with the incident and relevant metadata (date, time, location, estimated pipe size/flow rate) should be stored. With this method, enforcement agencies are provided with evidential documents for court that cannot be altered, thus minimizing conflicts and expediting resolutions.

Severity-linked fines

Withdraw and extraction rate should be tied to the pipe diameter of the illicit extraction and should, therefore, increase the charge.

Tier-1 (0.5" pipe) – Administrative violation; small scale is possibly household-related. Penalty: warning and a minimal fine.

Tier-2 (1.0" pipe) – Commercial use; small scale business or large scale household use. Penalty: lower monetary fine.
Tier-3 (1.5" pipe) – Industrial use; significant business or large industrial operations. Penalty: increased monetary fine and equipment confiscation.
Tier-4 (2.0" pipe) – High impact; critical water and aquifer systems damage. Penalty: excessive monetary fine and legal action for environmental and water governance infractions.

Fine Redistribution

Set aside 30–40% of the water and environmental governance infractions to a dedicated com- munity fund for water related projects. This fund focuses on fixing public distribution systems, maintaining community meters, and enhancing the local water storage facilities. Trust deepens when funds are used transparently allocated. Increased public confidence allows for the wider acceptance of the enforcement system.

Equity safeguard

Make sure that compliant households and genuine water users are not punished or subjected to tariff increases during the piloting period. Prioritize enforcement action in areas with high documented NRW losses or notorious illegal extraction. This approach helps safeguard distressed consumers and mitigates the risk of negative public relations backlash and helps the perception of fairness and precision within the system.

Transparency

Create and display water utility revenue results in the fined community's notice boards along- side the action taken and the community projects funded through the recycled revenue. Now it will not be concealed, and proactive reporting improves community engagement and serves the water utility's image.

Conclusion

The study illustrates that the monitoring system based on hydrophones equipped with digital signal processing classifiers, along with a welfare economics approach, successfully detected illegal water extraction with high accuracy, being both economical and scalable. Filmed field tests verified that certain acoustic signatures can differentiate legally from illegally withdrawn water, permitting enforcement authorities to act on verified, non-reproachable evidence while reducing the risk of erroneously flagged incidents. The financial model indicates that the system will achieve a positive return on investment, even with conservative deployment estimates, the payback period is under one year, which demonstrates system viability for municipalities without overburdening compliant users. The system also enhances social acceptability and policy compliance while addressing monitoring gaps by ensuring accurate detection tied to the severity of fines and equitable revenue recycling.
The results highlight the passive, tech-based enforcement systems socio economic advantage in decreasing non-revenue water losses and preventing over-extraction. Survey results showcase split between intention and action in reporting behavior, signaling a need for automation and frictionless detection systems that are socially oblivious. Integrated with automated awareness advertising, clear revenue sharing, community water sustainability programs, and accountable governance, the framework can foster better governance over urban water, maintain aquifer health, and shield at-risk populations from the financial burden of scarcities.

Future Scope

1. Integration of AI-based anomaly detection for real-time pattern recognition across larger geographies.
2. Expansion of the system to include multi-sensor nodes for detecting both water quantity and quality violations.
3. Development of a cloud-based enforcement dashboard with predictive analytics for re- source allocation.
4. Pilot testing in diverse hydrogeological and socio-economic contexts to refine penalty structures and community engagement models.
5. Incorporation of blockchain-based evidence storage to further strengthen data integrity in legal proceedings.

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