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Safeguarding Public Health from Pesticide Contamination in Ground water: The Case for a Multi-Tiered Prevention Model

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ABSTRACT

Preventing groundwater contamination by pesticide residues is essential for protecting public health and promoting environmental sustainability. Excessive or improper use of pesticides can lead to the leaching of harmful chemicals into groundwater sources, which are often used for drinking and domestic purposes. Long-term exposure to pesticide-contaminated water has been associated with an increased risk of non-communicable diseases, including cancer, neurological disorders, endocrine disruption, cardiovascular diseases, and chronic kidney disease, which are also the leading cause of death worldwide. Detection of dimethoate, endosulfan, and their degradation products in shallow wells in Gokwe-Nemangwe in 2024 exposes smallholder farmers to untreated contaminated water. Continuous exposure in farming communities, coupled with rising NCD prevalence, estimated to account for 40% of deaths nationally in 2024, underlines the urgent need for preventive interventions. This paper, therefore, developed a comprehensive multi-tiered public health prevention model integrating risk assessment; regulatory enforcement; monitoring, public education and awareness; research and innovation; public engagement; emergency response and continuous evaluation. By safeguarding groundwater from pesticide residues, communities can reduce chronic exposure to hazardous chemicals, improve the quality of drinking water, and lower the burden of NCDs. Protecting groundwater resources is therefore not only an environmental priority but also a vital public health strategy for preventing disease and enhancing the well-being of present and future generations. Recommendations include strengthening national regulatory frameworks, expanding community-based monitoring systems, and integrating indigenous knowledge into water resource management. These measures are positioned not only as health interventions but also as investments in long-term resilience and development.

Keywords: *Groundwater pollution; Pesticide residues; Public health prevention model; Environmental health risk, Chronic diseases, Sustainability.*

Introduction

Pesticide exposures, especially in groundwater, exert profound impacts on human health and well-being [1,2]. Mounting evidence indicates that chronic, low-level exposure to such residues contributes significantly to the global burden of non-communicable diseases (NCDs), which remain leading drivers of morbidity and mortality worldwide [3–8]. The intensification of agricultural activities to meet rising food demand has accelerated pesticide use, resulting in widespread contamination of environmental media and deterioration of both ecological integrity and public health [9,10]. This rise, consequently, has heightened pesticide use, whose residues are causing deterioration of environmental quality and health [11–14].

Groundwater pollution has primary and secondary effects on human health, accounting for a significant proportion of disease burden. Globally, environmental exposures are estimated to cause 12.6 million deaths annually, with 8.4 million attributable to chronic diseases linked to environmental risks [5]. Subsequently, health outcomes of pesticide residue exposure include cancers, cardiovascular disorders, and neurodegenerative diseases among others [2,15,16]. Vulnerability is further exacerbated by age, pre-existing health conditions, and lifestyle factors such as smoking and alcohol consumption [9,17,18]. Epidemiological and toxicological studies consistently demonstrate associations between pesticide exposure and carcinogenesis, cardiovascular disease, metabolic disorders, and adverse reproductive outcomes [19–24]. Moreover, chronic low-dose exposure over extended periods may result in cumulative toxicity due to bioaccumulation and the lipophilic nature of some pesticides [25,26]. Despite these findings, existing cohort studies often focus narrowly on individual compounds, neglecting the "cocktail effects" of multiple residues at real-world exposure levels [9].

Globally, pesticide residues have been detected in drinking water supplies [13,27–29].

Dimethoate, endosulfan, and their degradation products were reported in shallow wells in Gokwe-Nemangwe, exposing smallholder farmers to contaminants in untreated water [30]. Although concentrations of endosulfan were below WHO drinking water limits, its persistence and bioaccumulation may pose long-term health risks [31]. Continuous exposure, intensified by lifelong residence and farming in contaminated areas, is strongly linked to chronic disease development [2,15,16,32]. This is particularly concerning in Sub-Saharan Africa, where wells are often located within fields where spraying occurs [28]. In Zimbabwe, NCDs accounted for approximately 39% of deaths in 2019, with age-standardized mortality rates for cardiovascular disease, cancers, diabetes, and chronic respiratory illnesses reaching 822 per 100,000 among men and 701 per 100,000 among women [33]. By 2024, NCDs were estimated to cause 40% of deaths nationally [34] with cancer incidence, particularly breast, cervical, and prostate cancers, showing marked increases [35].

Prevention has long been recognised as the most cost-effective strategy for mitigating environmental health risks [5,33,36]. Effective management of environmental determinants being central to sustainable public health protection [37,38]. However, existing measures such as regulatory enforcement, water monitoring, and public education are often fragmented, inconsistent, and narrowly targeted [39,40]. To address these limitations, this study develops a multi-tiered public health prevention model which integrates the diverse preventive elements into a coherent system, ensuring continuity, efficiency, and resilience. By embedding risk assessment, regulation, education, and health system preparedness into a unified approach, the model provides a sustainable pathway to safeguard groundwater resources and likely reduce chronic disease risks. The prevention model also aligns with the 2030 Agenda for Sustainable Development (SDG 6.2).

Public health prevention model

Shallow groundwater contamination by pesticide residues presents a persistent, cumulative, and often irreversible threat to public health [2,15]. Long-term exposure has been linked to chronic conditions such as malignance, neurological illnesses, and endocrine disruption [19–24]. Because remediation of contaminated wells is technically challenging and prohibitively expensive, prevention must be prioritised.

A multi-tiered public health prevention model offers a proactive and comprehensive framework to protect communities from these risks. Unlike fragmented interventions, a tiered model integrates source reduction, interception, and consumption-level safeguards into a coherent system, ensuring continuity, optimizing resource allocation, and strengthening institutional resilience [41]. By embedding universal, targeted, and intensive measures, the model reduces environmental exposures, mitigates health risks, and enhances the ability of public health systems to address evolving challenges.

The model, Figure 1 consolidates currently fragmented elements such as risk assessment, regulatory and policy interventions, water quality monitoring, public education and awareness, research and innovation, public engagement, emergency response, and continuous evaluation with feedback mechanisms into a unified framework. Fragmented approaches, by contrast, suffer from duplication of effort, misallocation of resources, reliance on ad hoc strategies, and inequitable coverage, leaving them reactive and poorly adapted to emerging threats.

Effective deployment of this model requires collaboration among environmental health officials, non-governmental organizations, and agricultural extension officers. Such partnerships ensure that interventions are technically sound, socially acceptable and institutionally sustainable, thereby securing long-term protection of groundwater resources [37].

Risk Assessment

The intensive use of pesticides in agriculture poses significant risks of groundwater contamination through leaching and runoff [42]. Such contamination introduces pesticide residues into drinking water, thereby creating direct hazards to population health [38,43]. To address these hazards, risk assessment serves as a critical pillar in both preventing and managing pesticide residue-related impacts on public health. Similarly risk assessment enables public health officials to systematically evaluate possible adverse health outcomes linked to pesticide contamination in drinking water [38,44,45].

This process involves systematic identification, evaluation, and prioritisation of potential risks to determine both their likelihood and severity [44]. This structured approach enables organizations and public health authorities to understand the health implications of pesticide use and to design effective mitigation strategies.

By embedding risk assessment within the public health prevention framework, institutions can make informed decisions regarding pesticide regulation, agricultural practices, and water safety. Ultimately, risk assessment provides the evidence base for proactive interventions, ensuring that public health is safeguarded while promoting sustainable environmental practices [45].

Hazard identification

Hazard identification (HI) is the initial and most critical stage of pesticide risk assessment within the public health prevention framework. Its purpose is to determine whether a pesticide has the propensity to generate detrimental health impacts in humans, thereby laying the foundation for subsequent analytical steps such as dose-response evaluation, exposure assessment, and risk characterisation [44,45].

Public health personnel to detail the description of the pesticide's active ingredient(s), formulation, and physicochemical properties. Attributes such as solubility, volatility, half-life, degradation products, and persistence are examined to understand how the compounds behave in the environment, including their likelihood of leaching into groundwater [42,46]. Organophosphates such as dimethoate, widely used in cotton production in Gokwe-Nemangwe are highly soluble and exhibit moderate half-life, making it prone to leaching into shallow groundwater wells. Furthermore, dimethoate and endosulfan exhibit both acute and chronic toxicological profiles. Endosulfan, despite being restricted under the Stockholm Convention, remains detectable in groundwater due to its slow degradation and bioaccumulation potential [2]. Reviewing toxicological data reveals that these pesticide residues pose carcinogenic and mutagenic risks, with their persistence amplifying exposure pathways in vulnerable rural communities [9,18].

Furthermore, the public health personnel to extend beyond recognizing potential adversative effects and establish known human health risks. The detection of dimethoate and omethoate, in shallow groundwater [30], highlights their acute and chronic toxicity. Epidemiological evidence links organophosphate chronic exposure to endocrine disruption, reproductive toxicity and possible carcinogenicity [47].

Regulatory thresholds established by the World Health Organisation (WHO) [48], provide benchmarks for safe drinking water, yet a study in Gokwe-Nemangwe revealed exceedances for dimethoate and omethoate [30]. Likewise, Hazard Quotient values greater than one were calculated for children, indicating significant non-carcinogenic risks through ingestion [30].

Endosulfan, was also detected at concentrations averaging 0.009 mg/L, with peaks up to 0.012 mg/L in the wet season [30]. Despite its restriction under the Stockholm Convention on Persistent Organic Pollutants [49], endosulfan remains in use and persists in the environment due to its long half-life and bioaccumulation potential [31]. Epidemiological evidence links endosulfan exposure to endocrine disruption, developmental abnormalities, immunotoxicity, and increased cancer risk [50,51]. These findings provide real-world evidence of health outcomes associated with pesticide exposure, thereby strengthening the overall framework for public health prevention.

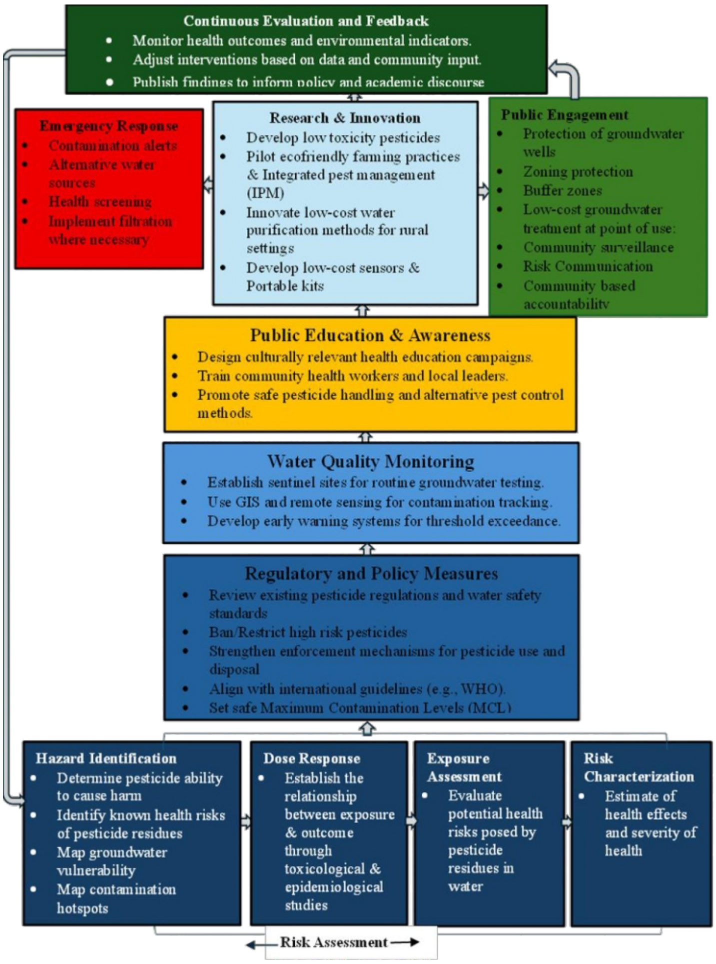

Figure 1: Public Health Prevention Model

The presence of these residues in groundwater poses disproportionate risks to sensitive groups, including children, pregnant women, and immunocompromised individuals [52]. Children are particularly vulnerable due to higher water intake relative to body weight and developing neurological systems [20]. Pregnant women face risks of fetal developmental toxicity, while immunocompromised individuals may experience amplified effects from endocrine and immune system disruption.

These findings emphasize the urgent need for systematic monitoring of groundwater, stricter enforcement of pesticide regulations under Zimbabwe's Environmental Management Act, and targeted interventions such as community education.

Conducting HI is not without complexity, for environmental exposures present unique challenges. The causal pathways linking pesticide residues to adverse health outcomes are often intricate, involving multiple interactions and extended latency periods between exposure and effect [53]. Similarly, many pesticide residue hazards consist of mixtures of toxic components, whose combined or synergistic effects make it difficult to isolate the specific agent responsible for a given negative health outcome [54]. Furthermore, there is no single metric that can adequately capture the association betwixt exposure to a harmful chemical and the resulting health impacts. HI must therefore account for a range of factors, including populations that are susceptible due to intrinsic biological characteristics, vulnerable because of environmental or contextual conditions, and sensitive, reflecting the overlap of both susceptibility and vulnerability [54].

Moreover, groundwater vulnerability mapping, which evaluates the intrinsic susceptibility of groundwater to pollution based on natural hydrogeological factors rather than contamination levels [55], is performed. It focuses on the potential risk of groundwater contamination by integrating parameters such as soil type and permeability, depth to the water table, recharge rate, and structural settings like fractures [56]. This method is widely applied in water resource management to identify areas where groundwater is more likely to be impacted if contaminants are introduced, thereby guiding preventive planning and land-use regulation. For instance, shallow groundwater wells composed of sandy soils with rapid recharge rates are particularly susceptible to contamination [55]. Even in the absence of current pollutants, these systems remain at high risk because contaminants can easily infiltrate and migrate quickly into the groundwater. Such mapping provides a proactive tool for safeguarding water resources and ensuring sustainable utilization in regions dependent on groundwater for domestic and agricultural use [57]. Where resources are readily available, Geographic Information System (GIS) mapping can serve a critical role in assessing and visualizing the spatial distribution of pesticide residues in groundwater. For instance, [58], applied GIS-based index-overlay methods to evaluate shallow groundwater susceptibility to pesticide residues leaching in agricultural zones, highlighting the importance of spatially explicit data for targeted risk mitigation strategies. This approach not only enhances monitoring efficiency but also supports informed decision-making for sustainable pesticide management. To this end risk assessment supports evidence-based decision-making and prioritisation of mitigation strategies.

Additionally, contamination hotspot mapping can be used to identify specific locations where pesticide residues are present in groundwater based on direct monitoring data [59]. Unlike vulnerability mapping, which anticipates areas at risk, hotspot mapping captures the present extent of contamination. It combines measured concentrations of pesticide residues with spatial analysis to trace contamination plumes and identify their sources, such as agricultural runoff [60]. Thus, this approach provides critical evidence for prioritising monitoring efforts and informing public health interventions.

For instance, identifying pesticide residue hotspots near areas of intensive farming allows authorities and local communities to locate zones of greatest risk, direct resources more effectively, and safeguard populations that rely on groundwater for drinking [61].

Dose Response

Public health personnel to establish the relationship between pesticide exposure and health outcomes, relying on combining toxicological mechanisms with epidemiological evidence. Toxicology clarifies how compounds such as dimethoate, omethoate, and endosulfan exert neurotoxic, endocrine-disrupting, and carcinogenic effects through pathways like acetylcholinesterase inhibition and bioaccumulation. Epidemiological studies then link these mechanisms to observed outcomes in exposed populations, including cancer, neurological disorders, and reproductive toxicity. Findings from Zimbabwe, where shallow groundwater in Gokwe-Nemangwe contained residues above WHO guideline values, demonstrate hazard quotients greater than one for children, confirming real-world risks (31,42). Sensitive groups children, pregnant women, and immunocompromised individuals are disproportionately affected, underscoring the causal link between exposure and adverse outcomes and the need for regulatory enforcement and targeted interventions.

Exposure Assessment

Public health personnel can evaluate potential health risks posed by pesticide residues in water through a structured exposure assessment process. This begins with systematic sampling of groundwater sources in agricultural areas, followed by laboratory analysis to quantify pesticide concentrations against WHO guideline values. Then, Chronic Daily Intake (CDI), the average daily dose of a contaminant ingested over an extended period expressed in mg/kg/day, is integrated with exposure scenarios, including ingestion rates, frequency, and duration of water use [44,62]. In Gokwe-Nemangwe, a study conducted applying the CDI calculations demonstrated that ingestion of contaminated groundwater posed non-carcinogenic risks, particularly among at-risk groups, including children [30]. Such findings highlight the pressing need for region-specific exposure models, continuous monitoring, and the establishment of national water quality standards to mitigate long-term health risks. Having established the CDI, the health officials must proceed to the last stage of risk assessment, which is risk characterisation. Elsewhere, [62], used this approach in a global study of neonicotinoid residues in bottled water, applying Monte Carlo simulations to estimate CDI across age groups, the results showed that infants had the highest CDI values due to lower body weight and higher water intake per kilogram, though all values remained below the reference dose of 0.057 mg/kg/day.

Risk characterization

Risk characterisation is achieved by calculating hazard quotients (HQ) and lifetime cancer risk (LCR) indices, with particular attention to sensitive groups such as children, pregnant women, and immunocompromised individuals. By combining chemical monitoring, toxicological data, and population health studies, public health personnel can establish a clear relationship between pesticide exposure and adverse outcomes, enabling targeted interventions such as community education, stricter regulation, and promotion of safer agricultural practices.

Regulatory and Policy measures

Effective regulation of groundwater is a cornerstone of public health strategies aimed at preventing chronic diseases linked to pesticide residues contamination of groundwater. Regulatory and policy measures must therefore integrate the reviewing on existing pesticide regulations and water safety standards, banning/restricting high risk pesticides, strengthening enforcement mechanisms for pesticides use and waste disposal, aligning with international guidelines, and setting of Maximum Contamination Levels (MCLs) among others.

The Pesticides Regulations, 2012 (S.I. 144 of 2012) remain the principal subsidiary legislation governing pesticide registration, importation, distribution, labelling, and use in Zimbabwe. A major concern is the apparent lack of regular legislative review. Since the pesticide regulations were promulgated in 2012, there is little publicly available evidence of a comprehensive revision despite significant developments in pesticide science and toxicology; international chemical governance standards; climate change effects on pest management; emerging biopesticides and biological control products; digital traceability and supply-chain monitoring technologies. In a sector characterised by rapid scientific and technological change, a legislative framework that remains substantially unchanged for more than a decade risks becoming outdated. Thus, without scheduled reviews, Zimbabwe's framework may lag evolving international approaches to risk assessment, residue management, and environmental protection. This is particularly important because pesticide regulation increasingly emphasizes human health and environmental sustainability.

Despite having legislation on pesticide registration, [63], highlighted that of the registered pesticides, 7.2% are highly hazardous. Thus, there is need to revisit the list of registered pesticides to deregister those pesticides indicated as highly hazardous such as endosulfan. Other strategies include banning or restricting high risk pesticides such as glyphosate in vulnerable areas and tightening enforcement teeth [63,64].

The persistence of endosulfan as alluded to earlier, despite its restriction under the Stockholm Convention on Persistent Organic Pollutants, exemplifies poor compliance [49]. Therefore. strong enforcement through routine inspections, farmer training, and penalties for misuse ensures compliance with safe handling and disposal practices. This reduces leaching into shallow groundwater and minimises chronic exposure. Also, the SADC- GMI Gap Analysis and Action Plan for Zimbabwe argued that strong enforcement ensures adherence to regulatory requirements. [65]

Likewise, enforceable national water quality standards establish permissible contaminant thresholds, thereby safeguarding public health and preserving environmental integrity. However, it appears that there is limited information regarding the public health implications of pesticide residue contamination of shallow groundwater resources in Zimbabwe. This inconsistency is mirrored in the drinking water guidelines, which establish standards for pesticides [66]. Even though WHO guidelines are used, there is a need of setting national drinking water maximum contaminant levels (MCLs) and have them reflected in the existing Drinking Water Act. Establishing enforceable MCLs for pesticides in groundwater provides a measurable threshold for intervention. Regular monitoring against these limits enables early detection of contamination hotspots and guides public health responses.

Monitoring

Environmental technicians are central to groundwater protection, applying sampling, chemical analysis and remote sensing to detect and map pesticide residues [67–69]. Reliable monitoring requires rigorous protocols and advanced methods such as GC-MS and LC-HRMS/MS, which quantify pesticides and their degradation products at trace levels [70,71]. Sentinel wells across hydrogeological units, sampled seasonally, capture contamination peaks and provide spatially representative data [72].

Monitoring results reinforce regulatory compliance [73]. Exceedances of WHO guideline values should trigger enforcement actions, including restrictions on pesticide use during recharge periods and accelerated adoption of integrated pest management [73,74]. Emerging tools such as wireless sensor networks (WSNs) and GIS-integrated remote sensing enable real-time detection and dynamic risk mapping, strengthening early warning systems [75,76].

In contexts like Gokwe-Nemangwe, where seasonal contamination was observed [30], continuous monitoring linked to policy updates creates a feedback loop that informs timely interventions. This integration of surveillance and regulation is essential for reducing chronic disease risks and advancing sustainable groundwater management.

Public Education and Awareness

Public education initiatives are pivotal in advancing sustainable agriculture and reducing groundwater contamination risks. When combined with risk assessment, monitoring, and regulation, education strengthens community resilience. Collaborative engagement among farmers, policymakers, and local stakeholders fosters context-specific solutions and effective mitigation strategies [77]. Evidence shows that culturally relevant training and promotion of safer practices significantly lower pesticide-related risks to groundwater and public health [38,73,78]. In this way, education becomes a critical complement to technical and regulatory interventions, ensuring long-term protection of both environmental and human health.

Culturally relevant health education campaigns are essential for reducing pesticide-related groundwater contamination and associated health risks. To be effective, they must align with local languages, traditions, and farming practices, using accessible tools such as illustrated posters, radio broadcasts, and community theatre to reach diverse audiences [79–81]. Central to these efforts is clear communication of the link between pesticide misuse, groundwater contamination, and adverse health outcomes, reinforced by incorporating indigenous knowledge systems to enhance credibility and acceptance [38].

Environmental technicians, agricultural workers, and local leaders act as trusted intermediaries, translating technical information into practical guidance on safe handling, storage, and disposal of pesticides, as well as identifying contamination-related health symptoms [68,82,83]. Their involvement strengthens participatory monitoring and community-level enforcement, while collaboration among extension services, non-governmental organizations, and public health agencies ensures consistent and accurate messaging [37,84,85].

Education campaigns should also promote integrated pest management (IPM), emphasizing biological controls, crop rotation, and reduced reliance on hazardous chemicals. Demonstration plots and policy incentives for biopesticides can accelerate adoption, showing farmers that yields can be maintained under safer practices [67–69,86]. Strengthening health education and awareness programs empowers smallholder farmers to make informed choices, reduces preventable contamination, and embeds sustainable practices within local governance and everyday agriculture [87].

Research and Innovation

Research and innovation are critical to preventing pesticide contamination of groundwater, particularly through the development of low toxicity formulations and promotion of biopesticides that degrade quickly and reduce leaching [88]. Additionally, biopesticides are both cost-effective and compatible with sustainable agriculture. Evidence from case studies shows that affordable biopesticides are particularly vital for smallholder farming systems, with minor financial resources [88]. Locally available options such as neem oil, pyrethrins, and botanical extracts have proven effective as repellents and growth disruptors, while advances in nano-emulsion technology enhance their stability and commercial viability [89]. Future directions, including engineered microbial consortia and eco-friendly materials like biochar, further strengthen sustainable pest management and water protection [90,91].

Innovation also supports community level monitoring and education. Low-cost sensors, portable kits, and GIS based early warning systems expand surveillance capacity and provide real time data for risk communication [75,92] National research on Maximum Contamination Levels (MCLs) establishes scientifically validated thresholds that guide both enforcement and public education campaigns, ensuring communities understand contamination risks and safe practices [45].

Crucially, education initiatives can leverage research outputs by demonstrating the effectiveness of integrated pest management (IPM), showcasing safer alternatives through training and demonstration plots, and embedding findings into culturally relevant awareness programs. In this way, research and innovation not only advance technical solutions but also reinforce education and awareness campaigns, creating a holistic prevention model that integrates science, regulation, and community engagement to reduce pesticide-related health risks.

Emergency response

Emergency response is designed to protect smallholder communities when pesticide residues in groundwater exceed safe thresholds. When monitoring systems detect contamination threshold exceedance, rapid spreading of contamination alerts ensures timely community awareness and behavioural change. Alerts can be communicated through mobile platforms, radio, or community health workers, and when integrated with GIS-based monitoring systems, they allow geographically targeted warnings to populations at risk [69]. Messages must be clear, concise, and action-oriented, specifying the geographic area affected, the health risks, the prohibition on using contaminated water, and the location of alternative water sources. Failure to communicate effectively can exacerbate health risks and erode public trust [93].

The immediate priority following the identification of elevated hazardous pesticide residue levels is to ensure the affected community has access to alternative water sources for domestic use.

Options include rainwater harvesting, or community boreholes. Diversifying water sources reduces dependency on vulnerable groundwater reserves and enhances resilience against pesticide-related risks [94].

Simultaneously, with ensuring access to safe water, emergency responses must include health screening to detect early symptoms of pesticide residues exposure, such as neurological, dermatological, or gastrointestinal conditions. Screening programs conducted by community health workers link environmental monitoring with medical surveillance, ensuring that contamination alerts are accompanied by health interventions [95]

For household-specific contamination, deploying filtration and purification technologies provide immediate mitigation when contamination is detected. Low-cost methods such as activated carbon filters and *Moringa oleifera* coagulation can be adapted for rural settings, offering practical solutions to reduce pesticide residues in drinking water [96–98].

Responding effectively to pesticide contamination in groundwater demands more than technical fixes; it is a multifaceted undertaking that relies on close coordination among water regulators, public health institutions, emergency services, and the wider community. By having robust plans for alternative water provisioning, clear communication protocols, and a prepared healthcare system, communities can significantly reduce the acute public health burden of such incidents and build resilience against future contamination events.

Public Engagement

While regulatory and technological solutions discussed earlier are critical in mitigating pesticide contamination of groundwater, they are insufficient without robust public engagement strategies. The approaches often fail to address the root cause of on-farm behaviors related to pesticide handling, application, and disposal. Consequently, engaging the public has become essential, serving to reinforce accountability within communities, integrate cultural practices that enrich and support technical monitoring and regulatory systems, enhance the identification of potential risks and support more precise monitoring efforts [69,99,100]. Additionally, active involvement in monitoring initiatives empowers the public to become advocates for the sustainable management of local groundwater resources. Also, public engagement enhances early detection of groundwater contamination challenges, as local observers are often the first to notice shifts in water quality [69]. In turn this vigilance enables timely responses to potential contamination events. Moreover, public involvement is crucial for the successful adoption of sustainable pest management approaches, helping to limit the movement of pesticides into groundwater supplies [38,83,101].

Protection of Groundwater Wells

Active public participation is essential for protecting groundwater wells from pesticide infiltration. Community-driven measures such as fencing, controlled access, and routine maintenance enhance effectiveness when tailored to local needs and priorities [38,69]. Wellhead protection programs are most successful when communities are engaged in their design and enforcement [83]. Structural safeguards including lining wells with durable materials, sealing mouths with slabs, installing aprons, and diverting runoff through drainage channels, further reduce contamination risks and improve water safety [102].

Linking these protective measures with education and awareness campaigns, research and innovation strengthen local capacity, ensuring communities understand both the importance of well integrity and their role in sustaining clean groundwater.

Zoning Protection

In Gokwe-Nemangwe, the inability to follow regulations governing the siting and construction of shallow wells fails to account for site-specific hydrogeological conditions that can compromise drinking-water quality. Evidence indicates that land-use zoning policies restricting pesticide-intensive agriculture near drinking-water sources are essential to safeguard groundwater [103,104]. Moreover, effective public engagement ensures that such zoning measures are not perceived as externally imposed directives but rather as locally negotiated safeguards, thereby enhancing compliance and long-term sustainability [105].

Buffer Zones

Establishing vegetative buffer zones around water sources is a proven strategy for reducing pesticide runoff and leaching [38,73,103]. Active community involvement in planting and maintaining these buffers enhances local ownership and strengthens ecological resilience [83]. Additionally, [104], reported that a 500-m buffer radius can effectively mitigate pesticide infiltration into groundwater, while more recent findings reported by [103], suggested that a 32.5-m radius may also be sufficient. However, the effectiveness of buffer zones is highly dependent on terrain, soil type, and hydrological conditions, meaning that no universal distance can be prescribed [105]. Despite this variability, buffer zones remain essential for groundwater protection, site-specific research, for example in Gokwe -Nemangwe, is therefore critical to determine the most appropriate buffer zone radius for local conditions.

Low-Cost Groundwater Treatment at Point of Use

Occurrence of pesticide residues in ground drinking water sources is not desirable; hence, they must be removed. Low-cost, culturally acceptable methods can provide practical solutions in rural settings. Techniques such as activated carbon filtration, natural coagulants (e.g., *Moringa oleifera* seeds), boiling, and constructed wetlands have shown promise [42,43,98,106]. Adsorption remains the most effective and affordable approach, with locally available materials like charcoal, clay, maize cobs, and nut shells serving as natural adsorbents. Studies demonstrate that powdered activated carbon can remove over 90% of pesticide residues such as atrazine under optimal conditions, though efficiency depends on water chemistry and requires regular regeneration [107,108].

Similarly, Moringa seed powder offers a sustainable coagulant, improving turbidity and microbial safety while avoiding the health risks of chemical coagulants [96,109]. Step-by-step preparation and use of Moringa powder make it accessible for smallholder farmers, while boiling provides an additional safeguard against microbial contaminants. Because no single method removes all pesticide types, combining techniques yields better results.

Community engagement in pilot projects enhances uptake and sustainability [110]. Linking these treatment practices with education and awareness campaigns ensures households understand preparation, safe use, and maintenance of filters and coagulants.

This integration empowers rural populations to adopt low-cost technologies, reduce pesticide exposure, and protect public health.

Community Surveillance

Smallholder farmers' community-based surveillance initiatives enable households to track groundwater quality indicators and flag irregularities. These approaches are intended to enhance early warning capacity and work alongside formal GIS and sensor technologies. By involving residents directly in the stewardship of their water resources, such systems broaden participation in environmental monitoring and highlight the unique value of local knowledge and engagement in advancing sustainable water management [111].

Risk Communication

Effective risk communication depends on timely, accurate, and credible information that enables communities to act during contamination incidents. Approaches tailored to cultural contexts improve adoption of protective behaviors [112]. Warning systems must be clear, actionable, and transparent, specifying risks and required actions for example, "groundwater in area B is unsafe due to elevated dimethoate levels". To ensure broad coverage, alerts should be disseminated through multiple channels such as radio, SMS, social media, community loudspeakers, and clinic notices, reaching rural and marginalized groups [75]. Authorities must acknowledge uncertainties, provide regular updates, and maintain trust, which is central to effective crisis messaging. Linking these communication strategies with education and awareness campaigns strengthens public confidence and empowers communities to adopt protective practices.

Community-Based Accountability

Community-based accountability embeds groundwater protection into local governance through committees that oversee pesticide use and water safety. With training, farmers can report unsafe practices, while mechanisms for public feedback foster transparency and trust [83]. Clear communication across multiple channels provides immediate protection, and community participation in monitoring builds long-term resilience. Engagement strengthens regulation through local enforcement of guidelines, enhances education by integrating indigenous knowledge, and supports risk assessment by linking community surveillance with scientific monitoring [69]. Together, these elements create a holistic prevention model where education, monitoring, and accountability converge to reduce pesticide contamination and safeguard public health.

Continuous evaluation and feedback

Ongoing evaluation and feedback help ensure that prevention measures remain flexible, evidence driven, and responsive to both environmental conditions and community needs [113]. Programs can be designed to track health outcomes in parallel with environmental indicators. Routine monitoring of groundwater quality, pesticide residues, and related health outcomes, such as cancers, endocrine disruptions, or neurological disorders, provides the scientific foundation needed to guide interventions. Furthermore, environmental monitoring highlights contamination pathways and persistence of pesticides in groundwater, which are critical for understanding long-term exposure risks [38].

Based on these findings, interventions are adjusted continuously. This includes refining water treatment technologies, promoting safer agricultural practices, and incorporating community feedback to ensure solutions are culturally acceptable and feasible. Involving communities builds trust and ensures that interventions are tailored to local circumstances, such as dependence on untreated groundwater [78]. Similarly, engaging communities enhances both the sustainability and fairness of programs, increasing the likelihood that preventive measures succeed across diverse settings [114].

Finally, sharing research results is a vital part of the feedback process, ensuring transparency and maximising impact. Disseminating results through policy briefs, academic journals, and public reports informs policymakers, guides resource allocation, and contributes to the global evidence base. This feedback loop fosters accountability, encourages innovation, and prevents replication of ineffective strategies [115]. The dissemination of lessons learned enables public health systems to strengthen prevention frameworks and expand their capacity to safeguard communities from chronic diseases associated with pesticide residues contaminated groundwater. By fostering continuous learning and adaptation, these systems can more effectively anticipate risks and implement evidence-based interventions [116]. This exchange of knowledge supports continuous improvement, enabling institutions to anticipate risks more effectively and implement evidence-based protective measures.

Conclusion

Shallow groundwater pollution by pesticide residues creates a complicated environmental and public health challenge, predominantly in areas where shallow groundwater is the main source of drinking water. The detection of pesticide residues in these sources in Gokwe-Nemangwe and the increase in NCDs in Zimbabwe underscores significant risks, demanding coordinated interventions by smallholder farmers, policymakers, agricultural workers, and environmental officers to mitigate exposure, safeguard water quality and indirectly reduce NCD incidence. The public health prevention model for safeguarding communities against risks such as pesticide residues in groundwater is most effective when approached as a multi-tiered system. Beginning with risk assessment, where scientific evaluation identifies hazards, assesses hazards and characterizes risk in vulnerable populations. This foundation informs regulatory and policy measures, ensuring that laws and standards are in place to limit pesticide use, protect groundwater sources, and establishing maximum contamination levels.

Environmental health officials can play a pivotal role in mitigating groundwater pesticide residue pollution by establishing strong water quality monitoring systems. It serves as the ongoing safeguard, detecting contamination trends and providing early warnings. Coupled with this, public education and awareness empower communities to understand risks, adopt safer practices, and demand accountability. Concurrently, research and innovation drive the enhancement of new technologies for water treatment, safer agricultural alternatives, safe pesticide residues thresholds, improved monitoring methods, pesticide residue risks and regulatory gaps.

Preparedness is reinforced through emergency response mechanisms, which allow rapid action when contamination spikes or health crises emerge. Sustained public engagement ensures that communities are not passive recipients but active partners in prevention, shaping interventions to fit local realities. Finally, continuous evaluation and feedback close the loop monitoring outcomes, adjusting strategies, and publishing findings to inform both policy and academic discourse.

Together, these tiers create a dynamic, adaptive, and evidence-based prevention model. By integrating scientific rigor, regulatory oversight, community participation, and innovation, public health systems can effectively reduce risks, protect water quality, and prevent chronic diseases linked to environmental contaminants.

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