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# Citizen Science as an Early-Warning System for Non-Native Freshwater Invertebrates in Saudi Arabia

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**Research Article**

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## Abstract

Freshwater ecosystems in Saudi Arabia are increasingly shaped by dams, reservoirs, irrigation networks, and urban water management, yet baseline information on non-native freshwater invertebrates remains extremely limited. This study provides an early-warning assessment of potential introductions by synthesizing publicly available occurrence signals and screening them for geographic consistency and supporting photographic evidence. The records were summarized spatially to identify clustering patterns associated with engineered freshwater habitats and areas of high human activity. The occurrence signals for high-risk freshwater invertebrate taxa were geographically concentrated in urban and peri-urban water bodies in central Saudi Arabia, with repeated observations near managed wadis and reservoirs suggesting plausible human-mediated introduction pathways. Because records derived from citizen-science platforms remain unverified in the absence of voucher specimens or molecular confirmation, they are treated conservatively as early-warning signals rather than confirmed occurrences. These findings identify priority areas for targeted surveillance around reservoirs, irrigation schemes, and recreational waters and recommend proactive screening and early-detection programs to protect freshwater biodiversity and fisheries resources. This study represents the first synthesis framing publicly available occurrence signals as a management-relevant early-warning baseline for non-native freshwater invertebrates in Saudi Arabia.

**Keywords:** Freshwater Biodiversity, Aquatic Invasive Species, Early Detection, Citizen Science, Saudi Arabia

## Introduction

Freshwater ecosystems in arid and semi-arid regions are increasingly influenced by human water management, including dam construction, irrigation networks, and the creation of artificial reservoirs. These engineered habitats can enhance habitat connectivity and propagule pressure, thereby increasing susceptibility to biological invasions, particularly by aquatic invertebrates that are tolerant of environmental variability [1,2].

In Saudi Arabia, freshwater environments are spatially limited and largely artificial, concentrated in wadis, oases, reservoirs, and irrigation canals. Although non-native freshwater fish have been documented widely across these systems Alharthi, et al. [3], comparable information on freshwater invertebrates remains largely absent. This lack of baseline data constrains ecological risk assessment and limits the ability of managers to detect emerging invasions at an early stage. Furthermore, aligning these early-warning frameworks with national conservation priorities, such as those spearheaded by the National Centre for Wildlife and the Saudi Green Initiative, is essential. Translating these occurrence signals into scalable, nature-positive management actions can proactively safeguard endemic aquatic biodiversity and support the sustainable

development of the region's emerging blue economy. Here, early-warning signals are defined as unverified occurrence records that indicate potential introductions but do not confirm establishment.

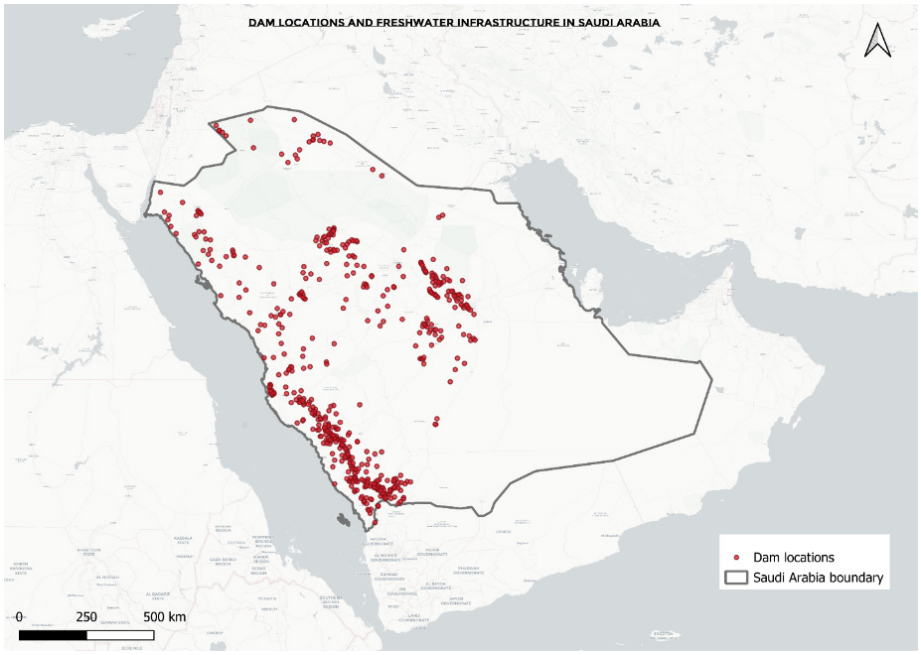



**Figure 1:** National distribution of engineered freshwater systems in Saudi Arabia and locations of early-warning occurrence signals.

Globally, freshwater invertebrates such as crayfish, mollusks, and planktonic taxa are among the most successful aquatic invaders, often introduced via aquarium and ornamental trade, aquaculture activities, and water transfers [1,2,4]. Climate warming further amplifies invasion risks by expanding the thermal suitability of recipient habitats and increasing per capita impacts of some invaders [5,6].

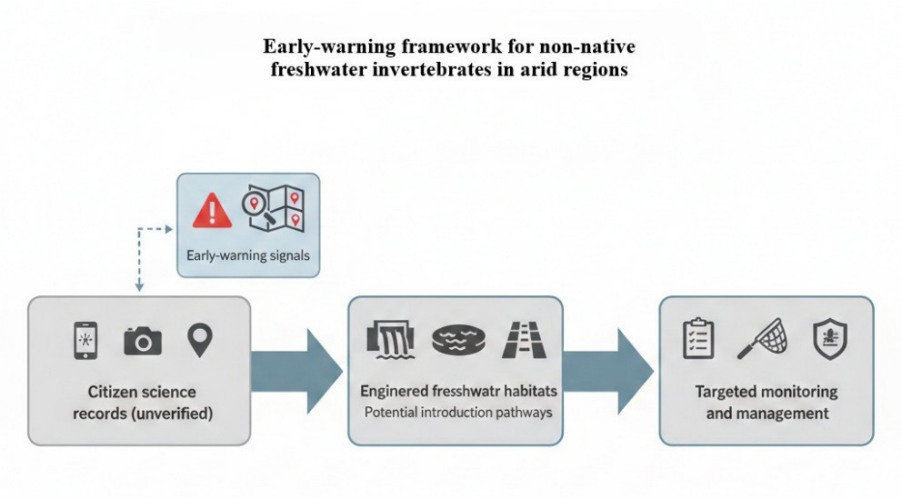



**Figure 2:** Conceptual framework illustrating the role of citizen-science observations as early-warning signals for potential introductions of non-native freshwater invertebrates. Unverified occurrence records provide preliminary spatial signals that, when associated with engineered freshwater systems, can inform targeted monitoring and management actions prior to confirmed establishment.



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In regions with limited monitoring capacity, citizen-science platforms increasingly provide valuable early-warning information on potential biological invasions. While such records cannot substitute for verified occurrence data, they can reveal spatial patterns that help prioritize surveillance and guide management actions [6].

Freshwater fisheries in arid regions are particularly vulnerable to biological invasions due to limited habitat redundancy and strong reliance on engineered systems. These patterns are consistent with the concept of "invasion hubs," where anthropogenic habitats act as focal points for species introductions and subsequent spread across landscapes [1]. In arid regions, such hubs may be disproportionately important due to the scarcity of natural freshwater habitats. This study represents the first effort to explicitly conceptualize citizen-science observations as an early-warning system for freshwater invertebrate invasions in arid, highly engineered ecosystems. By integrating spatial occurrence signals with anthropogenic freshwater infrastructure, this work provides a novel, management-oriented framework for invasion risk screening in data-limited regions.

The objective of this study is to synthesize publicly available occurrence signals of non-native freshwater invertebrates in Saudi Arabia and to evaluate their spatial association with engineered freshwater systems. By framing these observations explicitly as early-warning signals rather than confirmed records, this study aims to establish a preliminary baseline to inform freshwater management and invasion risk screening.



**Figure 3:** Photograph associated with a citizen-science observation of a suspected non-native crayfish in central Saudi Arabia, treated as an unverified early-warning signal.

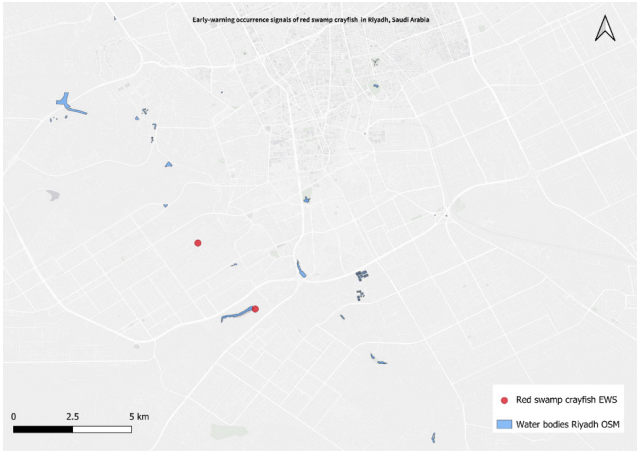



**Figure 4:** Early-warning occurrence signals of red swamp crayfish (Procambarus clarkii) in Riyadh, Saudi Arabia.



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## Materials and Methods

Publicly available occurrence records of freshwater invertebrates in Saudi Arabia were compiled from citizen-science biodiversity platforms (iNaturalist). Records were rigorously screened based on the presence of verifiable geographic coordinates, precise observation dates, and high-quality photographic evidence. Taxonomic plausibility was assessed visually using key morphological diagnostic features visible in the submitted photographs (e.g., prominent pointed rostrum, dark brownish to red coloration, and elongated chelae with distinct red tubercles), which are characteristic of high-risk species such as *Procambarus clarkii*. Observations lacking sufficient spatial information or clear images were excluded (Figure 3). Occurrence records were obtained from publicly available citizen-science biodiversity platforms that provide georeferenced observations with photographic documentation.

Each record was classified according to its identification status as reported on the source platform. No records were treated as confirmed occurrences due to the absence of voucher specimens or molecular verification. Instead, all retained records were categorized as unverified early-warning signals. Records spanned a limited temporal window and were evaluated for geographic consistency rather than temporal trends.

Spatial analyses were conducted using geographic information system software to visualize the distribution of occurrence signals across Saudi Arabia. Records were overlaid with layers representing major reservoirs, managed wadis, and urban areas to assess spatial correspondence with engineered freshwater habitats. Analyses were descriptive and exploratory, aimed at identifying geographic clustering rather than testing formal hypotheses. Spatial analyses and map production were conducted using QGIS (version 3.34, QGIS Development Team), including manual digitization, layer overlay, and visualization of early-warning occurrence signals in relation to engineered freshwater systems. To strengthen spatial inference, we evaluated the proximity of occurrence signals to engineered freshwater systems using a buffer-based approach (e.g., 1–5 km zones around reservoirs, irrigation canals, and urban water bodies). This allowed us to assess whether observations were non-randomly associated with anthropogenic freshwater infrastructure, which is commonly linked to invasion pathways [1,2].

## Results

A limited set of geographically coherent occurrence signals for non-native freshwater invertebrates was detected in central Saudi Arabia. These records were spatially aggregated within urban and peri-urban freshwater systems, including engineered wadis and reservoir-associated habitats. Within the taxa represented by these early-warning signals, crayfish species were most frequently recorded, with multiple observations concentrated within a restricted spatial extent over a short temporal interval. All detections originated from artificial or heavily modified freshwater environments, rather than from natural perennial streams. The spatial distribution of these signals exhibited pronounced proximity to urban infrastructure and recreational water bodies (Figure 1), indicating plausible anthropogenic introduction pathways such as aquarium releases, inter-basin water transfers, or informal stocking activities. A finer-scale examination of the central Riyadh area further highlights the strong spatial association between reported observations and managed freshwater systems (Figure 4).

## Discussion

The observed spatial clustering of early-warning signals is unlikely to be random and instead reflects underlying invasion mechanisms driven by propagule pressure, habitat stability, and increased connectivity among engineered freshwater systems [2]. Such conditions are known to facilitate both the establishment and spread of non-native aquatic invertebrates. Although inferred from unverified records, the apparent spatial clustering of early-warning signals in managed freshwater systems raises substantial concerns for freshwater fisheries and native fish assemblages in Saudi Arabia. Non-native crayfish are well documented to affect fish populations via multiple mechanisms, including direct predation on eggs and juveniles, competition for refugia, alteration of benthic habitats, and restructuring of food-web architecture [7-9]. In systems where native fish communities have evolved in the absence of crayfish, these impacts may be particularly severe due to limited predator recognition and broader ecological naivety [10,11].

Engineered freshwater habitats, including reservoirs and regulated wadis, are widely exploited for recreational fisheries and can function as critical refugia for both native and stocked fish species in arid landscapes [1,12]. The potential introduction of crayfish into these systems therefore constitutes not only a biodiversity threat but also a fisheries management challenge, as crayfish invasions have been associated with reduced fish recruitment success and modifications in fish habitat use [13,14]. Early detection of crayfish introductions is particularly crucial because effective population control becomes progressively more difficult once self-sustaining populations are established [15,16].

By conceptualizing unverified citizen-science records as early-warning indicators rather than as validated occurrence data, this study adopts a precautionary framework consistent with contemporary fisheries management objectives and



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invasive alien species risk-screening methodologies [6,16]. Focused monitoring within identified hotspot areas can enable managers to more accurately evaluate threats to native fish assemblages and to implement proactive management actions prior to the onset of potentially irreversible ecological degradation and associated economic losses [17]. To overcome the inherent limitations of unverified citizen-science records, future surveillance frameworks must strategically integrate these early-warning signals with environmental DNA (eDNA) monitoring. As a highly sensitive and non-invasive tool, eDNA can rapidly empirically validate the presence of low-density invasive populations within the specific hotspot corridors identified by citizen scientists, bridging the gap between public observation and formal ecological validation [18]. This aligns with broader policy recommendations emphasizing proactive prevention and early detection as the most cost-effective strategies for managing biological invasions [17].

### Implications for freshwater fisheries and fish recruitment

Beyond broader biodiversity concerns, the potential introduction of non-native crayfish into managed freshwater systems raises specific risks for freshwater fisheries in Saudi Arabia. Crayfish are known to reduce fish recruitment directly through predation on eggs and early life stages, particularly for species that spawn in shallow littoral habitats or utilize gravel substrates. Furthermore, as highly adaptable ecosystem engineers, invasive crayfish extensively modify benthic habitat complexity and restructure aquatic food webs. Their physical bioturbation diminishes essential refugia for juvenile fishes, exacerbating recruitment bottlenecks in spatially constrained, highly managed environments [19]. Such impacts have been documented in both lentic and lotic systems, where crayfish predation pressure can lower hatching success and juvenile survival, ultimately reducing year-class strength. From a fisheries perspective, early-stage crayfish introductions may have disproportionate ecological impacts, as predation on fish eggs and juvenile stages can reduce recruitment before population-level declines become detectable [13,9].

In arid regions, where freshwater fisheries are often concentrated in reservoirs and managed wadis, recruitment bottlenecks already exist due to variable hydrology and extreme seasonal temperatures. The addition of a novel benthic predator may therefore disproportionately affect native fish populations that have not evolved alongside crayfish. From a fisheries management perspective, early detection of crayfish introductions is particularly important because recruitment impacts may occur well before adult population declines become apparent, reducing opportunities for effective intervention once impacts are detected.

### Engineered freshwater systems as invasion corridors in arid landscapes

The spatial association between early-warning signals and engineered freshwater systems highlights the role of dams, reservoirs, and irrigation networks as functional invasion corridors in arid environments. In Saudi Arabia, large dams and interconnected irrigation channels create persistent aquatic connectivity across otherwise dry landscapes, effectively linking isolated water bodies that would remain disconnected under natural conditions.

These engineered networks may facilitate both the initial introduction and subsequent spread of non-native freshwater invertebrates by increasing habitat availability, reducing dispersal barriers, and maintaining permanent water during prolonged dry periods. As illustrated in Figure 1, the concentration of engineered freshwater infrastructure across the country suggests that once introduced, non-native species could disperse stepwise through managed systems rather than relying on natural hydrological connectivity. This corridor effect has important implications for invasion risk screening, as it suggests that individual introduction events may have broader spatial consequences in highly managed desert freshwater networks. A key limitation of this study is the reliance on unverified citizen-science observations, which may include taxonomic uncertainty and spatial bias. However, the consistency of spatial clustering near engineered freshwater systems suggests that these signals are unlikely to be entirely random and warrant further investigation. Climate change is expected to further amplify invasion risks in arid regions by increasing thermal suitability for non-native species while simultaneously stressing native freshwater communities [5]. This interaction may enhance the role of engineered freshwater systems as refugia for invasive taxa.

## Conclusions

Publicly available occurrence signals suggest the potential introduction of non-native freshwater invertebrates into engineered freshwater systems in Saudi Arabia. Although unverified, these early-warning signals provide a valuable foundation for proactive invasion risk screening in arid, highly managed freshwater landscapes.

From a management perspective, the findings of this study highlight the opportunity to develop a national early-warning system that integrates citizen-science observations with formal monitoring and regulatory frameworks. Establishing a centralized national database that links public reporting platforms with governmental agencies responsible for freshwater management and fisheries would improve detection efficiency, enhance data validation, and support



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rapid response strategies before ecological impacts become widespread.

Climate change is expected to further amplify invasion risks in arid regions by increasing thermal stress on native freshwater communities while enhancing the suitability of engineered freshwater systems as refugia for non-native species. Rising temperatures and prolonged dry periods may therefore increase both the likelihood of establishment and the ecological impacts of invasive freshwater invertebrates, reinforcing the need for early detection and coordinated management responses.

By positioning citizen-science observations as a management-relevant early-warning baseline, this study contributes a practical framework that can support adaptive freshwater fisheries management and biodiversity conservation under increasing climatic and anthropogenic pressures. Ultimately, the proactive management of these interconnected freshwater corridors must incorporate nature-based solutions (NbS) and rigorous biosecurity protocols. This integrated approach is critical to prevent engineered infrastructure from functioning as unobstructed highways for aquatic biological invasions, thereby ensuring the long-term ecological resilience of arid aquatic ecosystems. We recommend the development of a national early-warning monitoring system that integrates citizen-science platforms with environmental DNA (eDNA) surveillance and targeted field validation in identified hotspot regions. Such an approach could substantially improve detection capacity and enable proactive management responses before invasive populations become established [16].

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## Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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