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Distribution of Freshwater Alien Animal Species in Morocco: Current Knowledge and Management Issues

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Abstract: This work presents currently available knowledge on alien species (AS) found in the inland waters of Morocco. The objective is to provide an updated list of alien species and identify the main introduction pathways and possible threats to native biodiversity. The dataset was built from an extensive literature search supplemented by our own research work (published or in progress). The main areas harboring xenodiversity in Moroccan freshwaters correspond to protected areas (e.g., Ramsar Site and SIBE). These areas are currently home to 41 confirmed AS belonging to different taxonomic groups. Fish are the most abundant taxonomic group with 21 species, followed by molluscs (7 species) and arthropods (7 species). The presence of 15 more species was also noticed but considered doubtful. Almost half of these AS were introduced intentionally. They correspond to restocking programs and are likely the most serious threat to native biodiversity through predation, competition, and hybridization. Commercial activities around aquarium and ornamental species appear as the second source favoring colonization by AS. Implementing protective regulations regarding the import of exotic species in Morocco appears very urgent to protect local native diversity. In addition, detecting and monitoring the expansion of AS within the colonized areas and studies improving biological and ecological knowledge seem crucial to mitigate their possible impacts on native communities and preserve Moroccan freshwater ecosystems.

Keywords: biological invasions; checklist; Mediterranean biodiversity; alien species; biodiversity hotspot; North Africa

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1. Introduction

Thanks to its geographical position and its different natural barriers, Morocco is one of the most interesting biogeographical regions of the Western Mediterranean region, recognized as a hotspot of biodiversity, with a high rate of endemism in its fauna and flora [1]. However, this high endemicity makes communities vulnerable to the introduction of alien and invasive species without a common evolutionary history [2]. Biological invasions are indeed globally considered one of the most important human impacts on a wide range of ecosystems [3–5]. Introduction of and invasion by alien species are one of the top threats to biodiversity and ecosystem functioning worldwide. Alien species can also drive the degradation of ecosystem functions by altering trophic interactions, nutrient cycling, and habitat structures [6]. Freshwater ecosystems are particularly vulnerable to this phenomenon around the globe, with proportionally more invaders than terrestrial systems [7,8]. Many alien and invasive species have often been implicated in native species displacement within freshwater ecosystems [9,10]. The consequences of biological invasions on freshwater biodiversity are most dramatic in Morocco, where native species

are restricted by the Atlas Mountains to the east, the Sahara Desert to the south, and the sea to the north and west, so that no displacement is possible.

More and more exotic and invasive animal species are recorded in Moroccan freshwaters, belonging to a wide range of taxonomic groups, including fish, annelids, molluscs, and arthropods [11–16]. As a result, new communities of species are formed, with unknown ecological and evolutionary consequences. Therefore, monitoring the presence and expansion of alien species and studies improving their biological and ecological knowledge seem to be a crucial concern for managing the environment and indigenous communities.

In this work, we summarize currently available knowledge on the alien species (AS) present in the inland waters of Morocco. The objective is to provide the first and most up-to-date list of alien species and to identify the main introduction pathways and possible threats to native biodiversity.

2. Materials and Methods

The list of the AS reported in Morocco (and their geographical coordinates) was compiled from (i) freely available web databases, including the Global Biodiversity Information Facility GBIF (http://www.gbif.org/ (accessed on 1 April 2022)) and the Global Invasive Species Database GISD (http://www.iucngisd.org/gisd/ (accessed on 1 December 2022)); (ii) an extensive literature search through published articles [17–47]; (iii) our own research, whether published or in progress [11–15,48–55]; and other personal observations.

The introduction pathways of each species were designated by an extensive analysis of literature dealing with biological invasions and summarized in seven categories, following the same method as previously published articles on the same topic of alien animals and aquatic species (e.g. [56]).

After a careful review of the data, we classified the species with a confirmed presence in Morocco into two groups, namely "widely distributed" and "locally distributed". The "widely distributed" species have self-sustaining breeding populations in different hydrosystems and watersheds, and their presence is attested to by specialists through publications in scientific journals. The species whose distribution area is still restricted to certain watersheds, a smaller geographical area, and a small number of localities were considered "locally distributed". The taxa whose presence in Morocco is doubtful were marked as "Unconfirmed". A distribution map of AS hotspots in the inland waters of Morocco was built by processing all the gathered data in ArcGIS GIS software (ArcGIS, hot spot analysis, spatial statistics, version 10.2). Occurrence data are available in the Supplementary Materials (Table S1).

3. Results

Forty-one AS are present in Moroccan inland waters, plus 15 considered doubtful or unconfirmed. Only half of them (21 species) have well-established populations across the country (Table 1). About 560 records of alien animal species occupying the inland waters of Morocco have been gathered with the GPS coordinates of the localities. 374 records come from specialized published literature, of which 104 are our publications (among which some are also present in GBIF), followed by 142 new records (presented in the Supplementary Materials of this work), and completed by 24 records coming from GBIF. The geographical positions of alien animal species present in the inland waters of Morocco, collected from the bibliography, in addition to our data (published and unpublished), are offered in Supplementary Materials (Table S1).

Table 1. List of alien animal species known to be present in the inland waters of Morocco.

Taxon	Detection Date	Mode of Introduction	Origin	Status	Reference
		Cnidaria			
Craspedacusta sowerbyii (Lankester, 1880)	2015	Ornamental plant trade	Asia	Locally distributed	[41]
		Turbellaria			
Girardia tigrina s.l. (Girard, 1850)	2019	Aquarium/ornamental plant trade	America	Locally distributed	[18,50]
		Nematoda			
Anguillicola crassus (Kuwahara, Niimi and Itagaki, 1974)	1994	Aquaculture/international trade	Asia	Locally distributed	[24,42]
		Annelida			
Helobdella europaea (Kutschera, 1987)	2014	Aquarium/ornamental plant trade	South America	Widely distributed	[11]
		Gastropoda			
Physella acuta (Draparnaud, 1805)	1972	Aquarium/ornamental plant trade	North America	Widely distributed	[51,57]
Ferrissia fragilis (Tryon, 1863)	2022	Aquarium/ornamental plant trade/hitchhiking?	North America	Locally distributed	[50]
Helisoma duryi (Wetherby, 1879)	2022	Aquarium trade	North America	Locally distributed	[55]
Melanoides tuberculata (O.F. Müller, 1774)	1934?	Aquarium/ornamental plant trade	Tropical Africa and Asia	Locally distributed	[29,34]
Potamopyrgus antipodarum (J.E. Gray, 1843)	2021	Aquarium/ornamental plant trade/hitchhiking?	New Zealand	Locally distributed	[54]
		Bivalva			
Sinanodonta woodiana (Lea, 1834)	2021	Aquaculture	Asia	Locally distributed	[48]
Corbicula fluminea (O.F. Müller, 1774)	2008	Aquaculture	Asia	Widely distributed	[22,51]
		Crustacea			
Potamobius astacus (Linnaeus, 1758)	1914	Intentional (restocking)	Europe	Locally distributed	[39,46]
Orconectes limosus (Rafinesque, 1817)	1937	Intentional (restocking)	North America	Widely distributed	[32,39]
Procambarus clarkii (Girard, 1852)	2008	Probably intentional	North America	Widely distributed	[25,44]
Callinectes sapidus (Rathbun, 1896) *	2017	Ballast waters	North America	Widely distributed	[14]
Lernaea cyprinacea (Linnaeus, 1758)	2013	Aquaculture	Asia	Locally distributed	[23]
		Hexapoda			
Stegomyia albopicta (Skuse, 1894)	2015	International trafficking /propagation?	Asia	Locally distributed	[20]
Trichocorixa verticalis verticalis (Fieber, 1851)	2010	Aquaculture/propagation from Europe?	North America	Widely distributed	[35,52,53]
		Aves			
Oxyura jamaicensis (Gmelin, 1789)	1990	Propagation from Europe	North America	Widely distributed	[45,58]
		Piscis			
Lepomis gibbosus (Linnaeus, 1758)	1955	Intentional (restocking)	North America	Widely distributed	[23,39]
Lepomis macrochinus (Rafinesque, 1819)	1966	Intentional (restocking)	North America	Locally distributed	[27,39]
Lepomis microlophus (Rafinesque, 1859)	1966	Intentional (restocking)	North America	Unconfirmed	[39]

Table 1. *Cont.*

Taxon	Detection Date	Mode of Introduction	Origin	Status	Reference
Micropterus salmoides (Lacépède, 1802)	1934	Intentional (restocking)	North America	Established	[19,39]
Pomoxis annularis (Rafinesque, 1818)	1961	Intentional (restocking)	North America	Unconfirmed	[39]
Pomoxis nigromoculatus (Cuvier, 1829)	1964	Intentional (restocking)	North America	Unconfirmed	[39]
Lates niloticus (Linnaeus, 1758)	1954	Intentional (restocking)	Ethiopia (Afrotropic)	Unconfirmed	[19,39]
Perca fluviatilis (Linnaeus, 1758)	1939	Intentional (restocking)	Eurasia	Locally distributed	[27,39]
Sander lucioperca (Linnaeus, 1758)	1939	Intentional (restocking)	Europe	Locally distributed	[27,39]
Alburnus alburnus (Linnaeus, 1758)	2013	Probably intentional	Europe	Widely distributed	[23]
Pseudorasbora parva (Temminck and Schlegel, 1846)	2013	Probably intentional	Asia	Widely distributed	[23]
Carassius auratus (Linnaeus, 1758)	1950	Aquarium trade	Eurasia	Widely distributed	[23,28]
Phoxinus phoxinus (Linnaeus, 1758)	1934	Intentional (restocking)	Europe	Unconfirmed	[39]
Ctenopharyngodon idella (Valenciennes, 1844)	1981	Intentional (restocking)	Asia	Locally distributed	[19,39]
Cyprinus carpio (Linnaeus, 1758)	1924	Intentional (restocking)	Asia	Widely distributed	[19,39]
Hypophthalmichthys nobilis (Richardson, 1845)	1981	Intentional (restocking)	Asia	Widely distributed	[27,39]
Gobio gobio (Linnaeus, 1758)	1935	Intentional (restocking)	Europe	Locally distributed	[27,39]
Hypophthalmichthys molitrix (Valenciennes, 1844)	1981	Intentional (restocking)	Asia	Widely distributed	[27,39]
Rutilus rutilus (Linnaeus, 1758)	1934	Intentional (restocking)	Eurasia	Locally distributed	[27,39]
Scardinius erythrophthalmus (Linnaeus, 1758)	1934	Intentional (restocking)	Eurasia	Locally distributed	[27,39]
Tinca tinca (Linnaeus, 1758)	1934	Intentional (restocking)	North America	Locally distributed	[27,39]
Gambusia holbrooki (Girard, 1859)	1929	Intentional (restocking)	North America	Widely distributed	[12,15,39]
Xiphophorus hellerii (Heckel, 1848)	2019	Aquarium trade	Central America	Locally distributed	[49]
Fundulus heteroclitus (Linnaeus, 1766)	2019	Aquarium trade	North America	Locally distributed	[15]
Esox lucius (Linnaeus, 1758)	1934	Intentional (restocking)	Europe	Widely distributed	[27,39]
Esox masquinongy (Mitchill, 1824)	1964	Intentional (restocking)	North America	Unconfirmed	[19,39]
Esox niger (Lesueur, 1818)	1966	Intentional (restocking)	North America	Unconfirmed	[19,39]
Oncorhynchus mykiss (Walbaum, 1792)	1925	Intentional (restocking)	North America	Widely distributed	[19,27]
Salmo gairdneri (Richardson, 1836)	1925	Intentional (restocking)	North America	Unconfirmed	[39]
Salmo kamloops (Jordan, 1982)	1955	Intentional (restocking)	North America	Unconfirmed	[39]
Salmo clarkii (Richerdson, 1836)	1955	Intentional (restocking)	North America	Unconfirmed	[39]
Salvelinus namayeush (Walbaum, 1792)	1953	Intentional (restocking)	North America	Unconfirmed	[39]
Salvelinus alpinus (Linnaeus, 1758)	1948	Intentional (restocking)	North America	Unconfirmed	[39]
Salvelinus hucho (Linnaeus, 1758)	1953	Intentional (restocking)	North America	Unconfirmed	[39]
Salvelinus fontinalis (Mitchill, 1915)	1941	Intentional (restocking)	North America	Unconfirmed	[39]
Thymallus thymallus (Linnaeus, 1758)	1948	Intentional (restocking)	North America	Unconfirmed	[39]
		Reptilia			
Trachemys scripta elegans (Wied, 1839)	2002	Aquarium trade	North America	Locally distributed	[38]

* Marine species but can be found in brackish and slightly brackish waters.

Within the confirmed alien taxa, chordates are most abundant (56%), followed by molluscs (17%) and arthropods (17%); other groups constitute a minority (Figure 1).

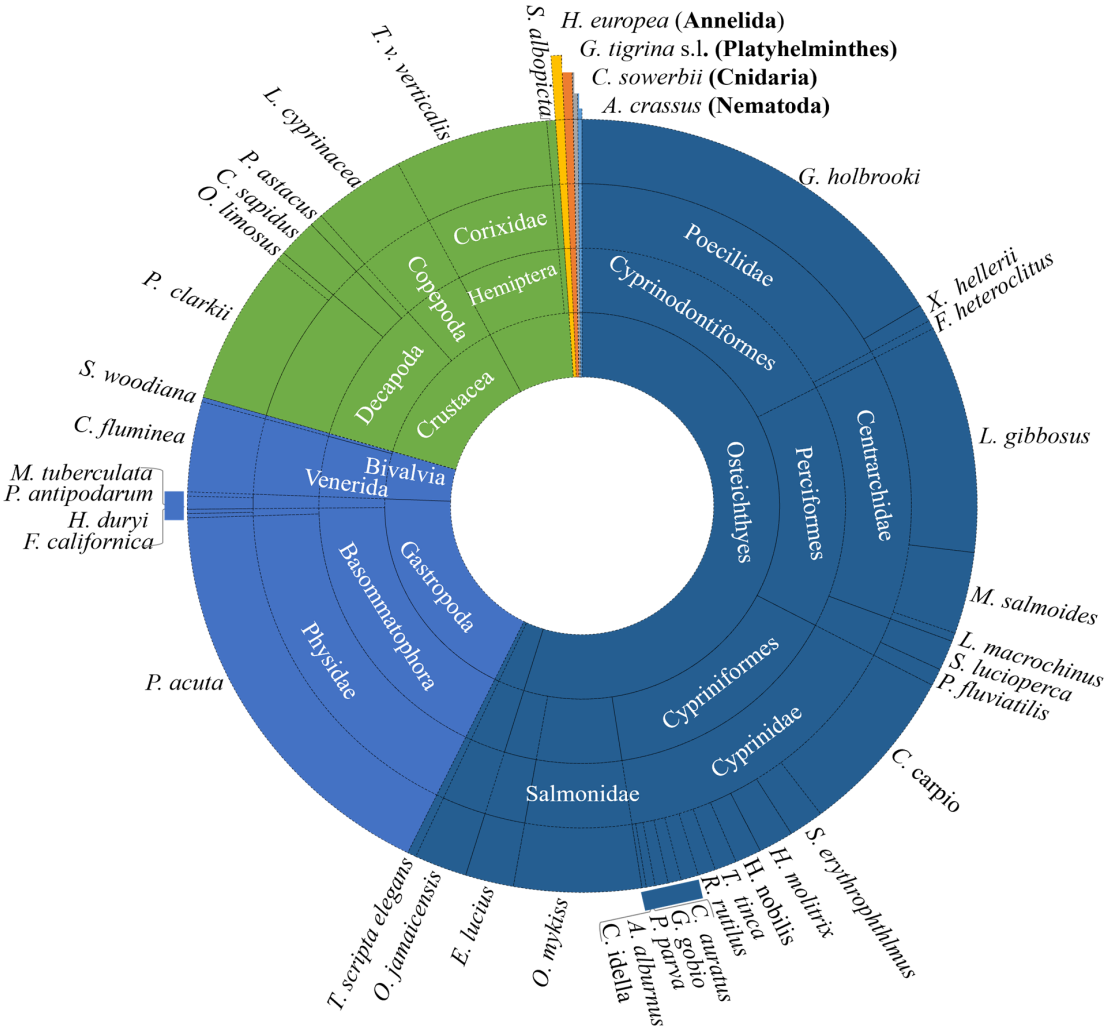

Figure 1. The main faunal groups of AS present in the inland waters of Morocco (according to the number of localities in the list).

The mosquitofish (*Gambusia holbrooki*) is the most reported NI chordate species in the freshwaters of Morocco, followed by sun perch (*Lepomis gibbosus*) and common carp (*Cyprinus carpio*), while the acute bladder snail (*Physella acuta*) is the most widespread NI mollusc species, with the southernmost record (Laayoune-Sakia El Hamra region). Within arthropods, Louisiana crayfish (*Procambarus clarkii*) is the most widely distributed NI crustacean species, and the American boatman (*Trichocorixa verticalis verticalis)* is the most widespread NI aquatic insect. The other branches (Annelida, Platyhelminths, Cnidaria, and Nematodes) are represented by one species each.

Chordates are represented by three classes—bony fish, birds, and reptiles. The last two classes are represented by one species each, i.e., the ruddy duck (*Oxyura jamaicensis*) and the Florida slider (*Trachemys scripta elegans*). Other chordates belonging to the class of mammals, with possible negative impacts on aquatic biodiversity in Morocco, were excluded from this study because of insufficient data, e.g., the Norway rat *Rattus norvegicus* (Berkenhout, 1769) (personal observations).

The vast majority of alien species present in Morocco are alien fish introduced during the 20th century (the first peak was observed between 1940 and 1970), while most invertebrates have been detected recently (the second peak started in 2010) (Figure 2).

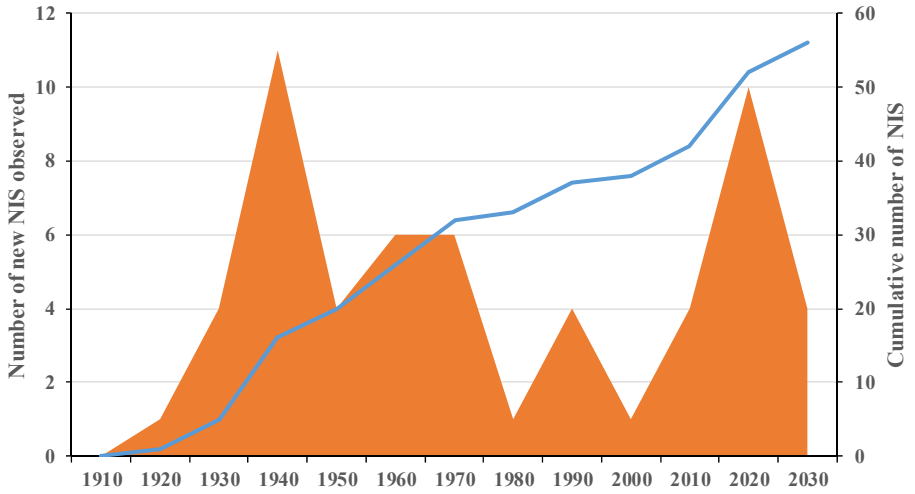

Figure 2. Cumulative number of AS (blue line) and numbers recorded per year (orange curve).

AS are concentrated in the northern part of the country (Figure 3). The highest number of citations was recorded about the Middle Atlas (Fès-Meknes region), followed by the north of the east Regions (Lower Moulouya and Nador lagoon) and the northern part of the Occidental Meseta (the Rabat-Salé-Kenitra region). A file in the Supplementary Materials is also added to specify the names of the invasive species reported for each region (Table S2).

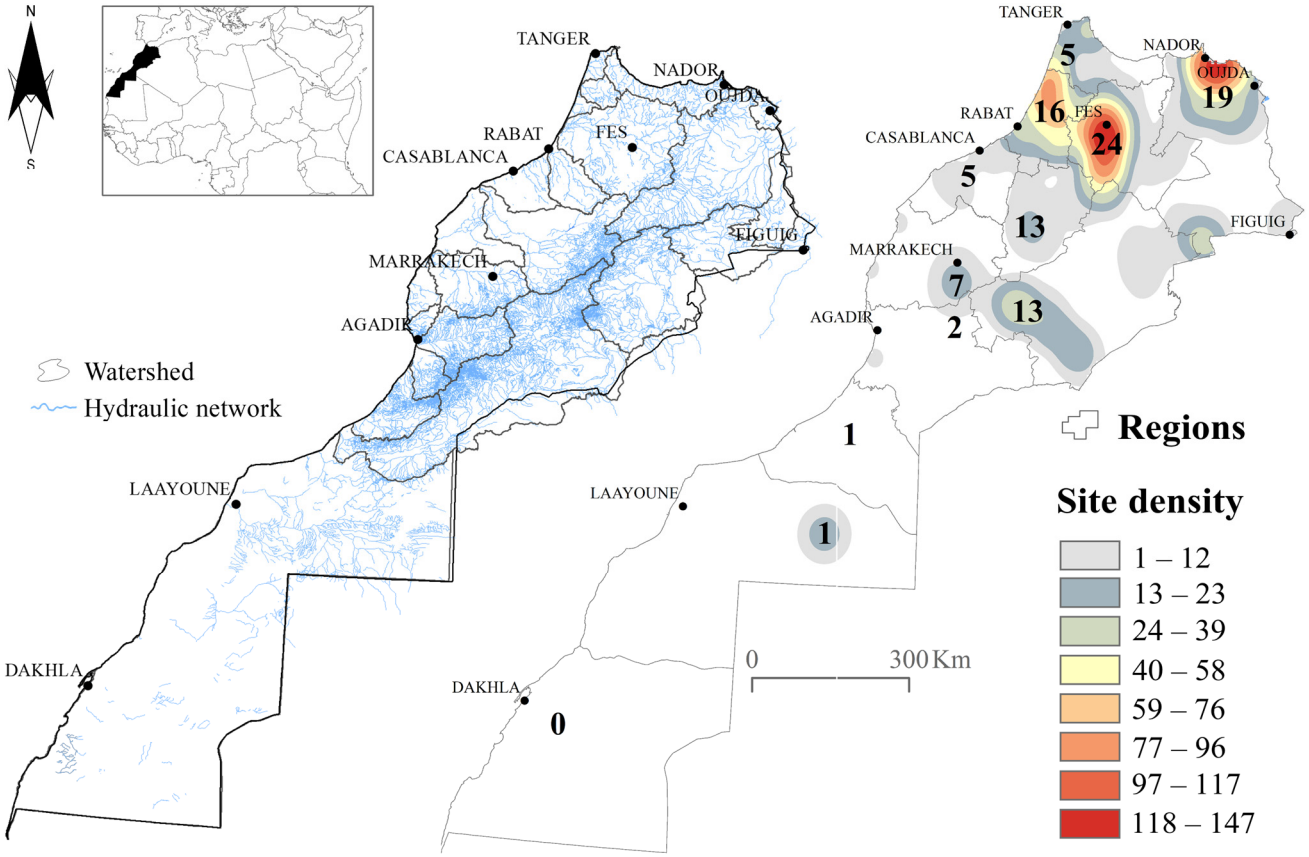

Figure 3. Spatial distribution of alien species in the inland waters of Morocco (**right**). The map was built by interpolating point data using the Spatial Statistics algorithm in ArcGIS software (the numbers from 0 to 24 represent the number of AS per region). In addition to the hydrographic networks of Morocco and the main watersheds (**left**).

Almost half of AS introductions in the freshwater ecosystems of Morocco were intentional through the restocking programs of water bodies with exotic fish (42.85%), followed by aquarium and ornamental animal and plant trades (28.57%), aquaculture (9.52%), and so-called "natural" spread from colonized areas (7.14%) (Figure 4a).

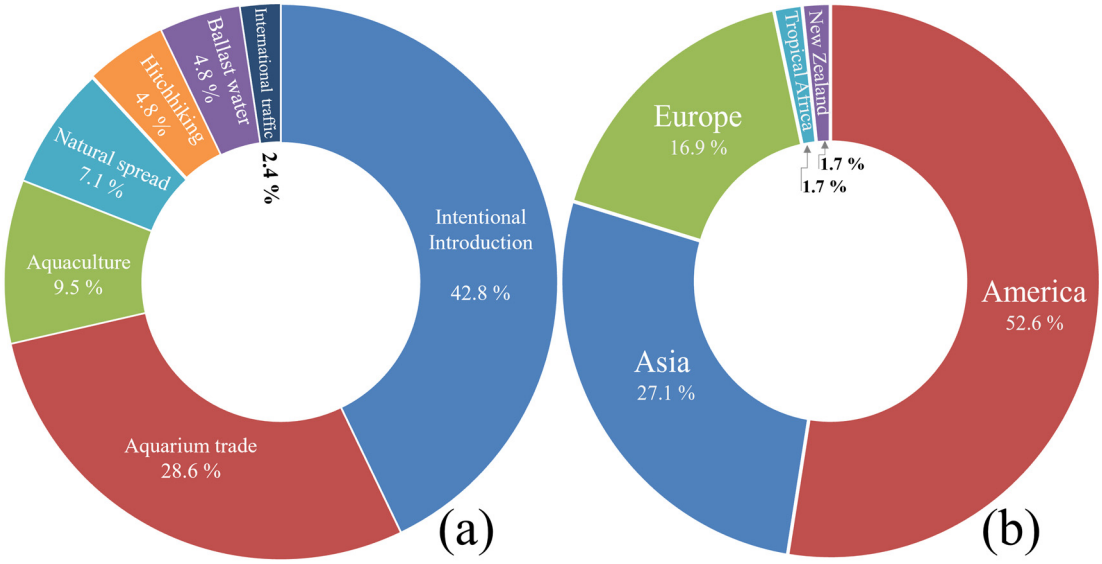

Figure 4. Main routes of introduction of the AS found in the inland waters of Morocco (**a**) and geographical origins (**b**).

More than half of the AS present in Moroccan inland waters are of American origin (52.54%), followed by Asian (27.12%) and European (16.95%) taxa (Figure 4b).

To date, only a few studies have addressed the impact of alien species on native ones or their autoecology in the inland aquatic ecosystems of Morocco. Most of them were published recently or are in progress (Table 2).

Table 2. Data alien species monitoring studies in the inland waters of Morocco.

Taxon	Topic of the Study	References
Anguillicola crassus	Native fish infection.	[42,59]
Physella acuta	Auto-ecology and potential competition with native gastropods.	[16,49,60]
Procambarus clarkii	Carrier of toxins and heavy metals to higher trophic levels. Disturbance of riparian vegetation and rice paddies. Competition with native Decapods.	[44,61] + unpublished data
Callinectes sapidus	Auto-ecology and predation on native aquatic fauna.	[14] + unpublished data
Trichocorixa v. verticalis	Auto-ecology and competition with native Corixidae.	[53,62]
Lepomis gibbosus	Auto-ecology and predation on native aquatic fauna.	[31] + unpublished data
Oxyura jamaicensis	Hybridisation with the white-headed duck (*O. leucocephala*) (Scopoli, 1769).	[21,58]
Gambusia holbrooki	Auto-ecology and predation on native amphibians; competition with native fish.	[12,15]
Fundulus heteroclitus	Auto-ecology and competition with potential *Aphanius* species.	[15]

4. Discussion

Given the lack of a robust national database recording alien species on a regular basis and the huge gaps in research on invasive species in Morocco in particular or in Africa in general, studies of the distribution and detection of invasive species are extremely important and useful for researchers working on the spread, impacts, and management of biological invasions [56]. The present work represents a first step toward the management of AS

in Morocco by providing the first annotated list of AS present in the inland waters of the country. This list includes 41 confirmed AS, some of which are ranked in the top hundred worst invasive species worldwide (*Stegomyia albopicta*, *Micropterus salmoides*, *Cyprinus carpio*, *Gambusia holbrooki*, *Oncorhynchus mykiss*, *Trachemys scripta elegans*, and others) [63].

Most of these AS are concentrated in the Mediterranean—northern—part of the country (where the human population density is the highest). This could be explained by the relatively high number of surveys carried out in the north of Morocco, but also by the high availability of surface waters compared to the south of the country, which is associated with many commercial activities and the presence of the biggest Moroccan harbors in the area. Surprisingly, most AS originate from the US, not Europe (the closest continent), suggesting that geographical barriers are not a limiting factor [15]. Careful examination of the data showed that AS from America (mainly the US) were introduced recently: only eight American species (25%) were present in Morocco before 1950. On the contrary, all AS from Europe were introduced before 1950, except the common bleak (*Alburnus alburnus*) present only since 2013. Most AS were introduced intentionally for fish restocking or aquaculture between 1914 and 1980. These introductions likely explain why AS are not concentrated along the coast and in big harbors. This observation is also congruent with the fact that the only species introduced from ballast water—the main source of AS worldwide [64]—was the blue crab (*Callinectes sapidus*) in 2017.

Most other AS have more recently come from aquariums or other sources related to the ornamental pet trade, contributing to 72% of the total AS introduced over the last 20 years. These recent occurrences correspond to the second peak of introduction observed since 2000 and explain the strong increase in the proportion of invertebrates among AS. The phenomenon has been described as one of the leading pathways for the introduction of aquatic invasive species around the world [65–67], and the second one in Morocco. For instance, it was the main route of introduction in freshwaters in Morocco of the mummichog (*Fundulus heteroclitus* Linnaeus, 1766), the green swordtail (*Xiphophorus hellerii* Heckel, 1848), and successful freshwater gastropod invaders such as the New Zealand mudsnail (*Potamopyrgus antipodarum*), the American limpet (*Ferrissia californica*), the red-rimmed melania (*Melanoides tuberculata*), the Seminole ramshorn (*Helisoma duryi*), and the acute bladder snail (*Physella acuta*) [15,49–55].

The establishment of AS in Morocco co-occurred in many protected parks, sites of biological and ecological interest (known as SIBE), and Ramsar sites, e.g., Sidi Ali Lake, the lagoon of Nador, the lower Moulouya wetlands, Zerrouka Lake, Sidi Boughaba, and Merja Zerga. These protected areas are the cornerstone of biodiversity conservation. However, they are also environmentally suitable for alien species invasion and establishment [68]. Chordates and particularly fish are potentially the most impacted species. Deliberate stocking by alien fish is still continuous nowadays in the reservoirs, especially by "Asian carps". Some of the reservoirs are also protected areas, e.g., Barrage Mohamed V and Barrage Al Massira, which are also listed as Ramsar sites. These alien and invasive fish not only conceal natural genetic patterns (hence difficulties in discerning evolutionary patterns; [69]); they also potentially represent the most serious threat to native aquatic biodiversity in general and particularly to native fish species and amphibians through predation, competition, and hybridization, sometimes leading to local extinctions [12]. The piscivorous "Nile perch" (*Lates niloticus* Linnaeus, 1758) is a classic example: its introduction in Lake Victoria (East Africa) in the 1950s led to the extinction of over 200 endemic fish species [9].

Our survey highlighted a huge gap between the number of recorded species and the number of studies devoted to their impacts. Only nine species out of all 41 AS have been studied from an autoecological angle or assessed for their impacts on native biodiversity and the aquatic ecosystems of Morocco. Most of these studies were published only recently or are still in progress [12,14,15,31,44,53,61,62] + unpublished data. They all highlight the potential negative role of AS on local environments through bioaccumulation of heavy metals, predation/infection, competition, and hybridization with the native fauna. However, these works remain largely insufficient, and further studies are urgently needed to

fully understand the impacts of AS in Morocco. This step is crucial for implementing management strategies that are currently lacking. For instance, there is no eradication program to eliminate or stop the spread of AS in Morocco, except for the ruddy-headed duck (*Oxyura jamaicensis*). Morocco has had a control plan since 2003, which includes four components: (i) a survey of captive and wild birds, detection, and monitoring of favorable sites; (ii) administrative and regulatory procedures to allow access to sites and shooting; (iii) designation of agents dedicated to control actions, purchase of equipment, training and awareness; and (iv) destruction of birds [70]. The same scenario should be applied for the other AS, especially those qualified as invasive or highly invasive.

Developing effective strategies to prevent the ecological and economic impacts of harmful invasive species is considered fundamental to national-scale policies [67–72]. Global warming and salinization of freshwater ecosystems bring about favorable factors for invasive species [73], which may acclimate more easily [15,49,74,75], and end up in a better position against the native fauna [76].

Morocco is in the red zone in terms of climate change predictions, i.e., at risk of water scarcity with decreasing precipitation [77], and Moroccan freshwater ecosystems are likely to become increasingly scarce, especially under a warming climate scenario where higher evapotranspiration rates are likely to intensify saline stress. All of this is exacerbated by anthropogenic disturbances through the withdrawal and diversion of large amounts of water for irrigation, especially during the dry seasons. The majority of rivers suffer from bank alteration caused by agricultural practices and substrate extraction as well as enormous environmental degradation from domestic, industrial, and agricultural wastewater pollution [78–81].

It is more necessary than ever for Morocco to develop adaptive management strategies to identify and minimize the impact of invasive species on the native fauna through the following urgent steps:

1. Intensify research on AS detection, and monitor their expansion within invaded areas, and carry out studies to improve knowledge on their biology and ecology in relation to the local conditions of Moroccan aquatic ecosystems.
2. Question fish stocking programs using AS and consider using native fish species instead to replenish freshwater ecosystems.
3. Enforce strict laws, policies, and procedures about the trade of aquatic species as a preventive measure to preserve the native biodiversity.
4. Take management decisions to eradicate animal AS from the freshwater ecosystems of Morocco to ensure conservation of the native biodiversity.
5. Finally, inform citizens about the importance of the biological endemism that Morocco enjoys, involve them in its conservation and make them aware of the dangers of invasive species on the native fauna and aquatic ecosystems of Morocco.

5. Conclusions

Moroccan freshwaters are colonized by a large number of invasive species, most of which were voluntarily introduced from the USA during the second half of the 20th century. Over the last 20 years, the origin of AS has changed dramatically with the introduction of AS of multiple origins due to the aquarium and ornamental plant trade. To preserve the exceptional diversity of Moroccan freshwaters, it has become very urgent to develop adaptive management strategies to identify and minimize the impact of invasive species on native fauna and to strengthen environmental regulation through new legislation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d15020169/s1, Table S1: GPS points and references of alien aquatic animal species of Morocco. Table S2: Invasive species by region.

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