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PERSPECTIVES AND PARADIGMS

Understanding and classifying the raw water transfer invasion pathway

Ava Waine · Peter Robertson · Zarah Pattison

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Abstract Raw Water Transfer (RWT) schemes move large volumes of freshwater between separate waterbodies to supply water as a specific commodity. Water is translocated by complex purpose-built networks of pipelines, tunnels and water supply canals. RWTs form hydrological connections between waterbodies across various spatial scales, and create a pathway of introduction and spread for a diverse range of invasive non-native species (INNS). Though occurring globally in large numbers, RWTs are not currently well represented by the standard pathway classification framework adopted by the Convention on Biodiversity (CBD). At present, RWTs are included within the 'corridor' category, which denotes the natural spread of organisms to neighbouring regions through transport infrastructure i.e. navigable canals/artificial waterways. However, RWTs are not routes for vehicle transport, and species are translocated between often non-adjoining waterbodies by the intentional transfer of water, not via natural spread. We provide a background for the complex RWT pathway and evidence of INNS spread through RWT schemes globally, and explore several options for improved RWT classification within the CBD framework—we recommend that the current corridor category is modified slightly to accommodate the addition of RWTs as a distinct sub-category, as separate from a clearly defined 'navigable canal/artificial waterways' sub-category. Accurate classification will increase understanding and awareness of this high-risk pathway, and support much-needed insight into its distinct stakeholders and drivers. Further, delineating RWTs from navigable canals/artificial waterways will help to identify widespread opportunities for pathway management and policy development, in addition to supporting more accurate future assessments of the risks and economic costs of the corridor pathway category.

Keywords Invasion pathway · Spread · Classification · Infrastructure · Corridors · Water resources

A. Waine (✉) · P. Robertson
Modelling, Evidence and Policy Research Group, School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, UK
e-mail: a.waine2@ncl.ac.uk

Z. Pattison
Biological and Environmental Sciences, University of Stirling, Stirling FK9 4LA, UK

Introduction

Invasive non-native species (INNS) are a major threat to ecosystems and a significant driver of biodiversity loss worldwide (Reid et al. 2018). INNS are particularly damaging within freshwater habitats, where increasing invasion rates are endangering endemic communities globally (Moorhouse and Macdonald 2014; Seebens et al. 2020). Identifying,

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understanding, and controlling the pathways of INNS dispersal to prevent novel introductions and limit the secondary spread of existing populations is therefore a key management strategy (Vander Zanden and Olden 2008), and a requirement of international legislation including the Convention on Biodiversity (CBD, 2022) (Target 6 of the Kunming-Montreal Global Biodiversity Framework CBD/COP/15/L.25, 2022) and Article 13 of the EU IAS Regulation (1143/2014) (European Parliament 2014).

Invasion pathways can be complex, and it can be difficult to distinguish between similar or related pathways (Harrower et al. 2018; Essl et al. 2015). Pathway classification frameworks, such as that developed by Hulme et al. (2008) and adopted by the CBD (UNEP/CBD/SBSTTA/18/9/Add.1, 2014) as an international standard, are therefore useful tools for differentiating pathways based on key characteristics, such as the underlying introduction mechanism and degree of human interaction involved (Genovesi and Shine 2004). For example, within the CBD framework, the movement of INNS by ships/boats can be described by three distinct sub-categories within the 'vector stowaway' category—'hitchhiking on ship', 'ballast water' and 'hull fouling' (Fig. 1). A separate 'vector contaminant' category can also describe the transport of INNS-contaminated material by ships/boats, with sub-categories including 'transportation of habitat material' and 'contaminant nursery material'.

Both 'vector contaminants' and 'vector stowaways' categories can involve INNS introduction via the same mode of transport—however, the key distinction is that unlike 'vector contaminants', 'vector stowaways' are not associated with the movement of a specific commodity (Hulme et al. 2008).

Making these distinctions between related yet functionally different pathways is important, as it enables stakeholder identification, pathway prioritization, policy development and targeted pathway management (McGeough et al. 2016; Pergyl et al. 2020). Improved pathway understanding also contributes to the wider study of invasion biology, as pathways can significantly influence the eventual success of introduced organisms (Ruiz and Carlton 2003; Wilson et al. 2009).

Our knowledge of various pathways is still developing, and some complex pathways of secondary spread are missing or not well-represented by the current CBD framework (Faulker et al. 2020; IPBES 2023a). One such pathway is the globally occurring Raw Water Transfer (RWT) pathway. RWT schemes are infrastructure systems designed specifically to move large volumes of freshwater from a donor waterbody (river, reservoir, natural/artificial watercourse) to a recipient waterbody, for the purpose of increasing water supply in a given area (Gohari et al. 2013). Water is typically transferred via underground pipelines or tunnels, or water supply canals, which may create connections both within and between hydrological catchments.

RWTs can generate high levels of introduction pressure (Ellender and Weyl 2014) and have been linked to many cases of INNS introduction and spread worldwide (Kimberg et al. 2014; Silva et al. 2020; Zhang et al. 2022). Though not directly referenced within the current CBD framework (Waine et al. 2023), RWTs have been linked to the 'corridor' pathway category (Woodford et al. 2013; Hulme 2015), because of the physical similarity between RWT water supply canals, and navigable canals. According to the CBD framework, corridors permit the natural spread of organisms from a neighbouring region, through vehicle transportation infrastructures i.e. navigable canals (also known as waterways) with limited human intervention, and are not linked to a specific commodity (Hulme et al. 2008; Hulme 2015; CBD 2014; Harrower et al. 2018). Under the current definition, the corridor category is ill-fitting for the RWT pathway for several key reasons: (1) RWTs are not routes for vehicle transport (2) species introduction and dispersal through infrastructure is a consequence of water movement between often distant waterbodies, not natural spread through adjoining routes (3) RWTs move water as a specific commodity.

As it currently stands, this categorisation of RWTs overlooks the mechanistic basis of INNS introduction and transfer between environments, and the subsequent potential for management by defined stakeholders, water resource managers (Table 1). Indeed, it is considered that RWTs have fallen within a gap in international regulatory frameworks (Miller et al. 2006; Shine 2007; Perrings 2010; Hulme 2015), presumably as natural spread through navigable canals is considered difficult to manage (Rahel 2007; Woodford et al. 2013) and is not associated with a specific stakeholder. However, as recent RWT-specific management policies in England and Scotland

	Category	Subcategory	COP decision
Movement of COMMODITY	**RELEASE** IN NATURE (1)	Biological control	VIII/27
		Erosion control/ dune stabilization (windbreaks, hedges, …)	
		Fishery in the wild (including game fishing)	VIII/27; X/38
		Hunting	X/38
		Landscape/flora/fauna "improvement" in the wild	
		Introduction for conservation purposes or wildlife management	
		Release in nature for use (other than above, e.g., fur, transport, medical use)	
		Other intentional release	
	ESCAPE FROM CONFINEMENT (2)	Agriculture (including Biofuel feedstocks)	X/38
		Aquaculture / mariculture	VIII/27; IX/4
		Botanical garden/zoo/aquaria (excluding domestic aquaria)	XI/28
		Pet/aquarium/terrarium species (including live food for such species)	VIII/27, X/38, XI/28
		Farmed animals (including animals left under limited control)	VIII/27
		Forestry (including afforestation or reforestation)	
		Fur farms	
		Horticulture	
		Ornamental purpose other than horticulture	
		Research and *ex-situ* breeding (in facilities)	VIII/27
		Live food and live bait	
		Other escape from confinement	
	TRANSPORT – **CONTAMINANT** (3)	Contaminant nursery material	
		Contaminated bait	
		Food contaminant (including of live food)	VIII/27; XI/28
		Contaminant on animals (except parasites, species transported by host/vector)	XI/28
		Parasites on animals (including species transported by host and vector)	XI/28
		Contaminant on plants (except parasites, species transported by host/vector)	XI/28
		Parasites on plants (including species transported by host and vector)	XI/28
		Seed contaminant	VIII/27
		Timber trade	
		Transportation of habitat material (soil, vegetation,…)	
VECTOR	TRANSPORT - **STOWAWAY** (4)	Angling/fishing equipment	VIII/27
		Container/bulk	VIII/27
		Hitchhikers in or on airplane	VIII/27, IX/4
		Hitchhikers on ship/boat (excluding ballast water and hull fouling)	
		Machinery/equipment	VIII/27
		People and their luggage/equipment (in particular tourism)	VIII/27
		Organic packing material, in particular wood packaging	
		Ship/boat ballast water	VIII/27
		Ship/boat hull fouling	VIII/27; IX/4
		Vehicles (car, train, …)	
		Other means of transport	
SPREAD	**CORRIDOR** (5)	Interconnected waterways/basins/seas	VIII/27
		Tunnels and land bridges	
	UNAIDED (6)	Natural dispersal across borders of invasive alien species that have been introduced through pathways 1 to 5	

Fig. 1 The framework for "Categorization of pathways for the introduction of alien species" from Convention on Biological Diversity 2014 (UNEP/CBD/SBSTTA/18/9/Add.1)

demonstrate, RWT management by stakeholders is possible and can be legislated for (Waine et al. 2023).

Climate change, human population growth and urbanization are exerting growing pressure on

Table 1 Definitions and descriptions of key pathway terminology

Terminology	Definition and description
Raw water transfer scheme Also known as 'water transfer', 'water diversion', 'water transmission', 'river transfer', 'river transposition' and 'bulk transfer'	Large infrastructure network designed to move raw (untreated) freshwater from a donor waterbody to a recipient waterbody. Waterbodies typically include rivers and reservoirs
Inter-basin raw water transfer	Water is typically transferred via underground pipelines or tunnels, or water supply canals
	Transfer distances can vary, but donor and recipient waterbodies are often separated by significant distances and/or hydrological boundaries
	Inter-basin' describes RWTs that cross natural watersheds. The term is useful for illustrating potential transfer distance and the risk of INNS introduction into separate catchments. Note: intra-basin RWTs can also negatively impact habitats and may introduce INNS to otherwise inaccessible areas
Water supply canal	Infrastructure created specifically to carry freshwater input from donor waterbody to a recipient waterbody, as part of a RWT scheme
	Water supply canals are typically shallow, concrete lined structures, constructed to maximise the efficiency of water flow
	Water supply canals are not typically used for vessel transport, and do not permit public access/recreational use
	Water supply canals often form a part of a wider complex network of a RWT scheme that is overseen by water resource managers
	Initial INNS introduction to water supply canal likely results from the transfer of water from a donor waterbody
	Further INNS spread along water supply canals can come from mechanical pumping of water through dams/barriers, or via natural spread
Navigable canal (also known as waterways)	Transportation infrastructure which allows the movement of vessels along adjoining routes
	Navigable canals may contain freshwater, or create transport routes between isolated marine waters e.g. the Suez Canal
	Navigable canals are often used for recreation (e.g. kayaking) and angling
	Initial INNS introduction occurs via natural spread from adjoining waterways (also potentially through hull fouling/ballast water/recreation), and further spread along a route is autonomous
Water resource	Those tasked with developing and managing water resources to maintain water supply for human use
	Management is typically carried out by local/state/central governments, or by private industry in conjunction with regulators

freshwater resource availability, leading to a dramatic increase in the number of RWT schemes globally (Meador 1996; Kadye and Booth 2013). RWTs now support the water requirements of many towns and cities worldwide (Flörke et al. 2018) and the number is expected to grow rapidly, as current estimates suggest that urban water demand will increase by 80% by 2050 (Kibiiy and Ndambuki 2015; Garrote 2017; Shumilova et al. 2018).

It is therefore important that the RWT pathway is correctly classified, to increase pathway awareness and develop the understanding needed for widespread management. The aim of this review is to advocate for the classification of RWTs as a specific sub-category under a revised corridor category within the CBD framework. Specifically, by (1) providing an overview of the RWT pathway (2) providing an overview of the global evidence for INNS spread via RWT (3) describing the mechanistic basis of INNS introduction and spread via the RWT pathway, and how this differs from the current corridor category.

Overview of raw water transfer pathway

Scale and impacts

A single RWT can translocate hundreds of millions of litres of water per day. The collective volume transferred by RWTs at regional/national levels can be hugely significant. In North America for example, over 615 inter-basin RWTs are present. Of the 192 RWTs for which flow data is available, 24.9 km^3 of water is transferred annually (Siddick et al. 2023).

RWT can significantly impact donor and recipient waterbodies in numerous ways (Snaddon et al. 1999; Gupta and van der Zaag 2008). Water loss from donors can alter natural flows and cause localised drought (Ghassemi and White 2007), and recipient waterbodies can be impacted by pronounced changes in water flow and velocity leading to flooding, channel erosion and sediment deposition, in addition to changes in water temperature, chemistry, turbidity, and pollutant concentration (Boon 1987, 1988; Gallardo and Aldridge 2018; Bui et al. 2020). Water input can also change the nature of recipient habitats—the majority of water flow within a recipient river can be input from a donor waterbody (Dynesius and Nilsson 1994; Snaddon et al. 1998), enough to transform irregular, seasonal rivers to fast-flowing perennial rivers (O'Keefe and DeMoor 1988).

RWT infrastructure

Individual RWT schemes can take different forms (see Davies et al. 1992; Snaddon et al. 1998), and wider network composition may vary between countries/regions; reflecting local water availability, requirements and stakeholder practices (Lund and Israel 1995). For example, in England and Wales, subterranean pipes and tunnels are typically used to convey water across large distances. In contrast, China's South-North scheme, the world's largest RWT, uses purpose-built water supply canals as the main route of movement, though pipelines and tunnels are also part of the wider network (Rogers et al. 2019). RWT infrastructure can operate at multiple geographic scales, from relatively local transfers to those hundreds of kilometres long, in some cases crossing national borders (Zhang 2009; Prasad et al. 2012).

In large part, RWT infrastructure is purpose-built to maximise energy efficiency and reduce water losses incurred by transfer (Farias et al. 2017). However in some cases, RWT systems will harness parts of existing artificial waterways to convey water to an abstraction point.

Examples of RWT pathway dispersal

There is evidence of diverse invasive taxa spread via RWT schemes globally (Table 2). Examples were gathered by searching the databases 'NCBI', 'Web of Science','google scholar' and 'ResearchGate' using the terms 'invasive', 'alien', 'non-native', 'water transfers' and 'water diversion' across all years. Many examples were also obtained via 'snow-balling'. Only examples pertaining to species movement within RWT networks were included, and not reports of natural spread via navigable canals (see Leuven et al. 2009; Galil et al. 2015).

Pathway classification

Current RWT classification

RWTs are not explicitly referenced in the CBD framework (Fig. 1) but are considered to fall within the corridor category (Woodford et al. 2013; Hulme 2015). Corridors permits the natural/autonomous spread of organisms from a neighbouring region through vehicle transport infrastructure—navigation canals (Hulme et al. 2008; CBD 2014; Harrower et al. 2018) (Fig. 2).

Corridors relate only to the physical route created by artificial transportation infrastructure and are not associated with a specific vector or commodity (Hulme 2009). As such, the water within the navigable canal is not a discrete vector of invasion or a commodity purposefully moved—it is a medium for vehicle transit, which also supports the incremental colonisation and spread of aquatic species. As permanent structures, corridor-based dispersal events are considered to occur continuously (Wilson et al. 2009). Human involvement is minimal and no stakeholders are directly responsible for species introduction and movement through pathway infrastructure, beyond perhaps fouled boats (Hulme 2009).

Table 2 Examples of INNS dispersed via raw water transfer schemes grouped according to country, RWT scheme and taxonomic group, with reference to the main type of water conveyance infrastructure

Taxonomic group	Species	Location	Main method of water conveyance and notes	Reference
Fish	African sharptooth catfish (*Clarias gariepinus*)	South Africa, Orange River-Fish River inter-basin RWT (OFR)	Enclosed infrastructure (pipeline and tunnel). 82.45 km transfer system, fish survived high pressures, pepper-pot valves, baffle plates, turbines and screens to enter recipient river	Ellender and Weyl (2014), Weyl et al. (2009), Snaddon et al. (1998), Cambray (2003), Kadye and Booth (2013), Laurenson and Hotcutt (1986)
Fish	Clanwilliam yellowfish (*Labeobarbus capensus*)	OFR		Laurenson et al. (1989), Weyl et al. (2009)
Fish	Common carp (*Cyprinus carpio*)	OFR		Snaddon et al. (1998), Cambray and Jubb (1977)
Fish	Rock catfish *Austroglanis sclateri*	OFR		Laurenson et al. (1989), Weyl et al. (2009)
Fish	Sailfin catfish (*Pterygoplichthys disjunctivus)*	OFR South Africa Mhlathuze River to Nseleni River RWT	Enclosed infrastructure (tunnel)	Ellender and Weyl (2014), Woodford et al. (2013), Cambray and Jubb (1977), Laurenson and Hocutt (1986) Jones (2014)
Fish	Smallmouth yellowfish (*Labeobarbus aeneus*)	OFR		Cambray and Jubb (1977), Kadye and Booth (2013), Kimberg et al. (2014), Laurenson et al. (1989)
Fish	*Cichla temensis*	Brazil, São Francisco River Inter-basin RWT (SFRWT)	Mainly water supply canals, though a large complex system consisting of 477 km of canals, pipes, aqueducts, numerous pumping stations and 28 reservoirs	Gutierre et al. (2023)
Fish	Guppy (*Poecilia reticulata*)	SFRWT		Silva et al (2020), Gutierre et al. (2023)
Fish	*Hoplosternum littorale*	SFRWT		Gutierre et al. (2023)
Fish	Jaugar cichlid (*Parachromis managuensis*)	SFRWT		Gutierre et al. (2023)
Fish	*Metynnis lippincottianus*	SFRWT		Gutierre et al. (2023)
Fish	Nile tilapia (*Oreochromis niloticus*)	SFRWT		Gutierre et al. (2023)
Fish	Peacock bass (*Cichla monoculus*)	SFRWT		Silva et al. (2020), Gutierre et al. (2023)
Fish	*Plagioscion squamosissimus*	SFRWT		Silva et al. (2020), Gutierre et al. (2023)

Table 2 (continued)

Taxonomic group	Species	Location	Main method of water conveyance and notes	Reference
Fish	Tetra (*Moenkhausia costae*) endemic in donor basin but not recipient basin	SFRWT		Silva et al. (2023)
Fish	*Apareiodon ibitiensis* Native to Brazil but not non-native in recipient river basin	Brazil, Piumhi River to São Francisco River (PRFR)		Bellafronte et al. (2010)
Fish	*Apareiodon piracicabae* Native to Brazil but not non-native in recipient river basin	(PRFR)	Several open water supply canals, one of which is 18 km canal and a series of reservoirs. Dam creation caused flow reversal in recipient river	Bellafronte et al. (2010)
Fish	*Eigenmannia virescens* Native to Brazil but not non-native in recipient river basin	(PRFR)		Bellafronte et al. (2010)
Fish	*Gymnotus sylvius* Native to Brazil but not non-native in recipient river basin	(PRFR)		Bellafronte et al. (2010)
Fish	*Palleon nasus* Native to Brazil but not non-native in recipient river basin	(PRFR)		Bellafronte et al. (2010)
Fish	Zander (*Sander lucioperca*)	England, Ely Ouse-Essex inter-basin RWT	Enclosed pipeline and tunnels. Fish survived transfer under high pressures (over 50 m head of water), pumping stations and 8 mm mesh screening	Snaddon et al. (1999), Boon (1998), National Rivers Authority (1994), Copp and Wade (2006)
Fish	Worm goby (*Taenioides cirratus*)	China South-to-North RWT (STN)	Open water supply canals	Qin (2019), Zhang (2009), Schmidt et al. (2019)
Fish	Shimofury goby (*Tridentiger Bifasciatus*)	STN California, California State Water Project	Mixture of open and enclosed infrastrucutre – fish spread along canals, and directly sampled passing through pipelines	Jiao et al. (2021), Schmidt et al. (2019) Moyle and Marchetti (2006) Howard (2016)
Fish	Climbing galaxias (*Galaxias brevipinnis*) Species native to Australia but non-native to the region of introduction	Snowy Mountain to Murray River RWT, Australia	Mixture of open and enclosed infrastrucutre, 15 reservoirs, 150 km tunnels, pumping station, 80 km aqueducts	Todd 2002 Morison and Anderson (1991)

Table 2 (continued)

Taxonomic group	Species	Location	Main method of water conveyance and notes	Reference
Fish	Gudgeon (*Gobio gobio*)	Spain Tajo-Segura transfer	Mixture of open and enclosed infrastrucutre 292 km long scheme	Garcia de Jalón (1987), Snaddon et al. (1999), Gallardo and Aldridge (2018)
Invertebrates (Diptera)	Blackfly (*Simulium chutterii)*	South Africa, ORF	Enclosed infrastructure (pipeline and tunnels)	O'Keeffe and De Moor (1988)
Invertebrates (snail)	Quilted Melania (*Tarebia granifera*)	South Africa, Mhlathuze River—Lake Nsezi	Enclosed infrastructure (pipeline and tunnels). Co-transferred with invasive water hyacinth	Jones (2014)
Invertebrates (mussel)	Zebra mussel (*Dreissena polymorpha*)	England, Ely Ouse-Essex inter-basin RWT RWT pipelines in California, USA	Enclosed infrastructure (pipeline and tunnel)Transfer via pipeline to water treatment works from rivers and reservoirs	Boon (1987), Linfield (1984), Mant et al. (2011), Elliott et al. (2001), Stockton-Fiti et al. (2023)
Invertebrates (mussel)	Golden mussel *Limnoperna fortunei*	China, STN	Colonization of RWT pipelines, machinery and associated reservoirs	Zhang et al. (2017), Zhang et al. (2022), Wang et al. (2022), Guo et al. (2024)
Invertbrates (clam)	*Corbicula largillierti*	Brazil, (PRFR)		Azevêdo et al. (2016)
Macrophytes	Common water hyacinth (*Eichhornia crassipes*)	South Africa Mhlathuze River—Lake Nsezi	Enclosed infrastructure (pipeline and tunnels)	Jones (2014)
Micro-organisms	Phytoplankton	China, unknown scheme	Unknown	Zhan et al. (2015)
Pathogens	*Bothriocephalus acheilognathi*	South Africa, ORF	Enclosed infrastructure (pipeline and tunnels). Endoparasite co-transferred with invasive smallmouth yellowfish	Stadtlander et al. (2011)

*Related to **natural spread** from a **neighbouring** region:*

(5) Corridor refers to movement of alien organisms into a new region following the

*construction of **transport infrastructures** in whose absence spread would not have been possible. Such transbiogeographical corridors include international canals (connecting river catchments and seas) and transboundary tunnels linking mountain valleys or oceanic islands.*

Fig. 2 Description of the corridor category from *CBD UNEP/CBD/SBSTTA/18/9/Add.1,* 2014, *page 4*., which pertains to navigable canals. As it currently stands, this description does not apply to INNS introduction or spread via raw water transfer infrastructure

The RWT pathway – what is it not?

Enclosed RWT infrastructure (pipelines and tunnels) clearly differs from the corridor category as defined currently—it does not support vehicle transport, and has been specifically constructed to move water as a commodity.

Importantly, INNS introduction to recipient waterbodies through pipes/tunnels is not due to natural movement to an adjoining habitat. Organisms are entrained by pumping stations or the pressure generated by gravity-release of water at the donor waterbody, and forcibly transferred to a separate waterbody. The donor/recipient waterbodies are highly likely to be separated by considerable distance, often across watershed boundaries, and are not otherwise adjoining. Dispersal events are unlikely to be continuous, unless the RWT is constantly operational—though many RWTs operate seasonally. RWT pipes/tunnels therefore do not generally provide a continuous habitat for natural spread and colonisation (except for biofouling organisms).

For **open** RWT infrastructure (artificial watercourses including water supply canals, aqueducts, irrigation channels), the distinction is slightly more ambiguous at first glance. Similarly to navigable canals, water supply canals create a physical link between waterbodies and enable a degree of natural spread locally. However, there are several key characteristics which distinguish RWT water supply canals from the current corridor category:

1. Initial INNS introduction to water supply canals likely results from the input of water from a discrete donor waterbody (typically a river or reservoir), which may be a considerable distance away, and not from the natural movement of species through an adjoining watercourse.
2. Water/species movement along water supply canals is often subject to human intervention—water can be mechanically pumped against gravity, facilitating movement across barriers which organisms could not naturally pass.
3. Water can be abstracted from water supply canals and transferred to other separate waterbodies—water supply canals can therefore represent both a donor and receiving waterbody, in addition to routes for dispersal. For example, in the Eastern Route of China's South-North RWT, water from the Yangtze River is transferred into a purpose-built water supply canal, along which 34 mechanical pumping stations lift water to higher elevations and move it against gravity (He et al. 2010). The water supply canal is part of a complex network of tunnels and reservoirs, and water is transferred from the main water supply canals to other watercourses (Rodgers et al. 2019). Similarly, the Integration Project of the São Francisco River in Brazil comprises two large main water supply canals each over 200 km long. Water from the São Francisco River is pumped into the purpose-built water supply canals, and flow is regulated by a series of 28 reservoirs and numerous pumping stations (Asth et al. 2021; Gutierre et al. 2023).
4. Water supply canals do not generally form transportation routes for vehicles. As diverse systems, some RWTs networks may utilise sections of existing navigable canals to convey water, or abstract water from navigable canals. Interrelation is not common however – for example, of the 26 large inter-basin RWTs in Canada, none have the primary purpose of transferring water for navigation (Siddick et al. 2023) suggesting no or limited links with navigable waterway infrastructure.

5. Navigation canals can connect marine and freshwaters e.g. the Suez navigation canal. In contrast RWT systems are designed to move freshwater.

Moving forwards with RWT classification

An invasion pathway includes both the vector that carries an organism and the route along which it travels (Essl et al. 2015). For RWTs, this means considering water as a discrete vector that is intentionally being moved, in addition to the routes created by complex pathway infrastructure. Human activity is also an important factor to consider when classifying pathways (Genovisi and Shine 2004).

How can we classify the complex RWT pathway within the CBD framework, if the present corridor category does not accommodate it?

Adding RWTs to other CBD categories

RWTs could be added to a different category based on similar features. The ballast water pathway, a sub-category of the ‘transport-stowaway’ category, is mechanistically similar to RWTs. As the name suggests, the ballast water itself is the vector of invasion, rather than the vessel directly. This distinction separates ballast water from two other similar ‘transport-stowaway’ subcategories – ‘hitchhikers on ship/boat’, and ‘ship/boat hull fouling’.

A similar view could be applied to RWTs, reflecting that INNS are moved between non-adjoining waterbodies as a result of water translocation, not through natural spread.

However, the category is explicitly linked to trade and transportation (Hulme 2009; Harrower et al. 2018) (Fig. 3), and stowaways are not associated with any specific commodity (Hulme et al. 2008; Essl et al., 2020).

The ‘transport contaminant’ category, relating to co-movement with the commodities that species directly associate with, may be better suited (Fig. 3), as water is essentially a commodity being transported. In simplistic terms, RWTs appear similar to the ‘habitat material’ sub-category, as water is a specific habitat/commodity being moved. However, this category is inherently linked to the trade and transport of goods via vehicles (Hulme et al. 2008; Hulme 2009; CBD 2014). Additionally, given the efforts to separate different types of a habitat materials and

Related to transport of a commodity:

Transport–Contaminant refers to the unintentional movement of live organisms as contaminants of a commodity that is intentionally transferred through international trade, development assistance, or emergency relief. This includes pests and diseases of food, seeds, timber and other products of agriculture, forestry, and fisheries as well as contaminants of other product.

Related to a transport vector:

Transport–Stowaway refers to the moving of live organisms attached to transporting vessels and associated equipment and media. The physical means of transport-stowaway include various conveyances, ballast water and sediments, biofouling of ships, boats, offshore oil and gas platforms and other water vessels, dredging, angling or fishing equipment, civil aviation, sea and air containers. Stowaways of any other vehicles and equipment for human activities, in military activities, emergency relief, aid and response, international development assistance, waste dispersal, recreational boating, tourism (e.g., tourists and their luggage) are also included under this pathway.

Fig. 3 Description of the transport-stowaway and transport-contaminant category from *CBDUNEP/CBD/SBSTTA/18/9/Add.1,* 2014, *page 3.* Each of these separate categories can describe INNS introduction via boats/ships other products into different sub-categories (Fig. 1) to be as specific and informative about pathways as possible (Harrower et al. 2018), adding 'water' to the list of habitat materials would be counter-productive. For example: 'contaminant nursery material', 'timber trade' and 'contaminants on plants', whilst all similar, are all distinct subcategorises from contaminant 'habitat material'.

RWTs are clearly not well-represented by either of the two aforementioned categories for the reasons outlined. Beyond this, both categories are strongly linked with primary introductions resulting from long-distance jumps in dispersal, whereas RWTs are more closely related to intranational secondary spread. Further, whilst both categories would highlight the role of water as defined vector of invasion, both would overlook the integral role of the complex purpose-built and permanent infrastructure underlying the dispersal route. Additionally, the change in category description needed to accommodate RWTs would be unhelpful for the current sub-categories, which *are* all well-represented.

Modifying the CBD corridor category

Given the limitations of the transport-stowaway and transport-contaminant categories, modifying the corridor category, the category to which RWTs most naturally align, offers the most straightforward means of accurate representation. This modification requires several steps outlined below:

1. *Update the main corridor category description:*. Changes from original description in bold: Related to natural or **assisted** spread from neighbouring or **hydrologically connected** regions. Corridors refer to the movement of alien organisms into a new region following the construction of **infrastructure** in whose absence spread would not have been possible. Such transbiogeographical corridors include **navigable canals/waterways** (connecting river catchments and seas), **raw water transfer infrastructure,** and **terrestrial** tunnels linking mountain valleys or oceanic islands.
2. *Create a distinct sub-category for 'navigable canals/artificial waterways':* The navigable canal/artificial waterways sub-category would maintain the original description applied to inter-connected waterways/basins/seas subcategory (Fig. 1).
3. *Create a distinct sub-category for raw water transfer within the corridor category:* Infrastructure systems (including tunnels, pipelines, aqueducts, water supply canals) which form connections between otherwise hydrologically separate waterbodies, through which the movement of water as a specific commodity occurs. Species spread is assisted by the intentional movement of water to different locations.

Other classification frameworks

Whilst the CBD framework is the accepted global standard, two key INNS information databases, the European Invasive Alien Species Gateway (DAISIE), and the IUCN's Global Invasive Species Database (GISD), have their own pathway classification systems. Though largely similar to the CBD's, some categories are not directly or indirectly represented by DAISIE or GISD. For example, DAISIE has a 'dispersal' category which includes only 'canals', and the GISD has no directly analogous category (Saul et al. 2016). Integrating RWTs within these frameworks to allow consistent application across other databases is also highly recommended.

Discussion

RWTs are a globally occurring dispersal pathway for diverse taxa, operating at multiple scales and across a range of habitat types. The number of RWT schemes worldwide is growing quickly in response to the impacts of human population growth, urbanization and climate change on fresh water resources. The relevance of this pathway will continue to increase, though RWTs are currently poorly understood within invasion science (Waine et al. 2023). Consequently, water resource managers are overlooked within international analyses of pathway stakeholders (Bellard et al. 2016; Novoa et al. 2018), and freshwater resource use is not currently viewed as a direct driver behind freshwater invasions (IPBES 2023a, 2023b; Schwindt et al. 2023).

Clearer representation of RWTs within pathway classification frameworks and consistent usage of pathway-related terminology is needed to improve pathway understanding and awareness. We suggest modifying the current 'corridor' category definition in the CBD framework to allow the inclusion of RWTs as a distinct sub-category, differentiated from a separate 'navigable canal/waterways' sub-category. Elements of the two pathways may appear superficially similar where artificial watercourses are concerned, but the mechanistic basis of introduction and spread via water supply canals is different to navigable canals. Importantly, pathway stakeholders, drivers, invasion risks, environmental impact, management, and policy opportunities also differ significantly.

Increasing RWT pathway awareness will have benefits for many areas of invasion science, including enhancing INNS spread predictions, pathway risk analyses, pathway prioritization exercises and cost calculations. Indeed, the economic cost of corridors as they are currently understood has been calculated at around $0.5 million annually (Turbelin et al. 2022). However, a single water company in the UK spends over 800 k annually to remove invasive mussels from RWT pipelines (Aldous et al. 2016, and zebra mussel removal from raw water infrastructure in the Pacific Northwest region of the United States of America is estimated to be over $500 million annually (Stockton-Fiti et al. 2023). The economic and environmental impact of corridors will continue to be overlooked if RWTs are not better understood and properly accounted for within pathway classification frameworks.

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