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Management in Practice

Integrated management of the raw water transfer invasion pathway

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Abstract

Raw Water Transfer (RWT) schemes move large volumes of freshwater between separate waterbodies via complex infrastructure networks, and are a pathway of freshwater invasive non-native species (INNS) spread in most nations globally. Environmental regulators in England and Scotland have recently introduced progressive policies outlining requirements for pathway stakeholders to manage RWTs. This is a positive step; though no known management methods currently exist, and the development of effective methods will be a long and challenging process. Additionally, under the current policy, not all RWTs will have to be managed. Multilateral stakeholder collaboration and co-ordinated action is therefore needed to deal with the invasion risk posed by the ever-increasing number of RWTs. RWT information is disparate and difficult to access in Great Britain however, and the INNS management community remains generally unaware of the pathway. We therefore present information to illustrate the scale and prevalence of RWTs in England and Wales, and highlight that many of the approximately 162 major RWTs (> 45 million litres/day) in England and Wales cross Water Framework Directive management catchments and river basins boundaries, and in some cases political borders. We discuss the consequent need to integrate RWTs into well co-ordinated surveillance and management plans at multiple scales, and explore options to improve information access and stakeholder collaboration, in support of improved management efficacy and the attainment of national INNS targets.

Key words: freshwater, resource management, policy, stakeholders, data access, surveillance, eDNA

Introduction

Raw Water Transfer (RWT) schemes occur in most countries globally, though are currently an esoteric and poorly understood pathway of active freshwater invasive non-native species (INNS) spread (Snaddon et al. 1998; Shumilova et al. 2018; Waine et al. 2023). RWTs move large volumes of untreated freshwater between separate waterbodies such as reservoirs, rivers and artificial watercourses, using complex networks of tunnels, pipelines, aqueducts, and water supply canals (Davies et al. 1992). The purpose of RWTs is to provide humans with access to water resources, or to manipulate environmental flow regimes in a particular area (Rollason et al. 2022; Garrote 2017).

RWTs operate at a range of scales, from intra-catchment schemes which may move water relatively short distances, to long distance transfers which create hydrological connections between waterbodies that cross operational catchment/river basin/political boundaries, which may not otherwise occur (Petitjean and Davies 1988; Sinha et al. 2020).

In Great Britain (GB) for example, the Elan Valley scheme transfers water over 177 km from the hills of Wales to Birmingham, England, through a network of tunnels, aqueducts, and multiple reservoirs (ICE 2018). Similarly, 455 million litres per day (Ml/d) can be transferred from the Ely Ouse River in Cambridgeshire to the Rivers Stour and Blackwater, and several reservoirs in Essex, via a complex RWT scheme covering 114 km, which passes through several catchments (Boon 1988; National Rivers Authority 1990, 1994a; EA 1996).

RWTs have been linked to diverse invasive taxa spread in several countries globally (Ellender and Weyl 2014; Jiao et al. 2021; Gutierre et al. 2023) and in Great Britain (Boon 1988; Copp and Wade 2006). Consequently, in England and Scotland, environmental regulators have set ambitious targets for pathway stakeholders (water resource managers) to manage RWT-related spread (UK Government 2022a; House of Commons 2019, 2022; SEPA 2022). This is a positive step towards achieving national and international pathway management targets (notably the protection of surface waters required by The Water Environment (Water Framework Directive) (England and Wales) Regulations 2017, which transposes the EU Water Framework Directive into domestic law in England and Wales, and the Water Environment and Water Services (Scotland) Act 2003 (WEWS Act) in Scotland, and Target 6 of the Kunming-Montreal Global Biodiversity Framework (CBD/COP/DEC/15/, 2022), and the presence of relatively defined and accountable set of stakeholders increases the potential for effective pathway-level measures to be adopted (McGeoch et al. 2010; Beninde et al. 2014; Novoa et al. 2018). However, novel management techniques will take some time to develop and implement, and the efficacy of any future methods is yet to be determined. Importantly, under the current policy, not all RWTs will be subject to management.

The nationwide RWT network therefore has clear implications for INNS management and surveillance programmes, and the level of stakeholder collaboration required for integrated approaches to strategy development at the scales across which RWTs operate; though information exchange between RWT pathway stakeholders and the wider INNS community (termed here as all academic and non-academic researchers, practitioners, Local Action Groups and other stakeholders participating in the research and management of INNS) is currently limited, and RWT awareness beyond the water industry and associated regulatory sectors is low (Gallardo and Aldridge 2018; Waine et al. 2023).

Indeed, despite the introduction of specific management policies in 2017, and environmental regulators recognising RWTs as a high invasion risk in England as early as 1978 (Boon 1988; National Rivers Authority 1992, 1994a, b), neither the GB comprehensive pathway assessment (WGIAS 2018; Defra 2019) nor the GB INNS strategy 2023–2030 identify RWTs as a pathway of spread (Defra 2023).

Limited awareness of the RWT pathway is also apparent internationally. RWTs are not explicitly referenced within the internationally adopted pathway categorization framework developed by the Convention on Biological Diversity (see Convention on Biological Diversity 2014, UNEP/CBD/ SBSTTA/ 18/9/Add.1), or other key databases including the IUCN's Global Invasive Species Database (GISD) and the DAISIE European Invasive Alien Species Gateway. RWTs are currently conflated with transportation infrastructure which facilitates passive species dispersal through unmanaged corridors i.e. waterways/navigable canals (Hulme 2015; Saul et al. 2017). Water resource managers are therefore overlooked within international analyses of pathway stakeholders; and whilst land and sea use changes are considered major primary drivers of biological invasions, freshwater resource manipulation is not generally viewed as a direct driver (Novoa et al. 2018; IPBES 2023a, b; Schwindt et al. 2023).

In GB specifically, a key barrier to RWT awareness stems from the relationship between the invasion pathway and water supply infrastructure, which is classed as "Critical National Infrastructure". Consequently, information access may be limited due to potential security concerns. Additionally, as direct management can only be carried out by pathway stakeholders, there is a general perception that knowledge sharing with the wider INNS community is not required. Indeed, the Environment Agency (EA) river basin management plan 2021 (EA 2021) states that the EA are working directly with the water industry to understand and manage the invasion risk that RWT networks pose, though reference to integrating the pathway within wider management programmes is currently lacking.

Human population growth and climate change are exerting growing pressure on water resources worldwide, leading to an increase in the number of global RWT schemes (Kibiiy and Ndambuki 2015; Shumilova et al. 2018; Flörke et al. 2018). In GB, work is already underway to create over 17 new major RWT schemes to ensure future freshwater resource availability (House of Commons 2019; OFWAT 2019). The number of biological invasions is also predicted to increase, and with the compounding effect of a warming climate allowing range expansion of existing populations, the interaction between climate change and water resource manipulation is set to have a significant influence on freshwater biodiversity at national levels (Rahel and Olden 2008; Pyke et al. 2008; Seebens et al. 2020).

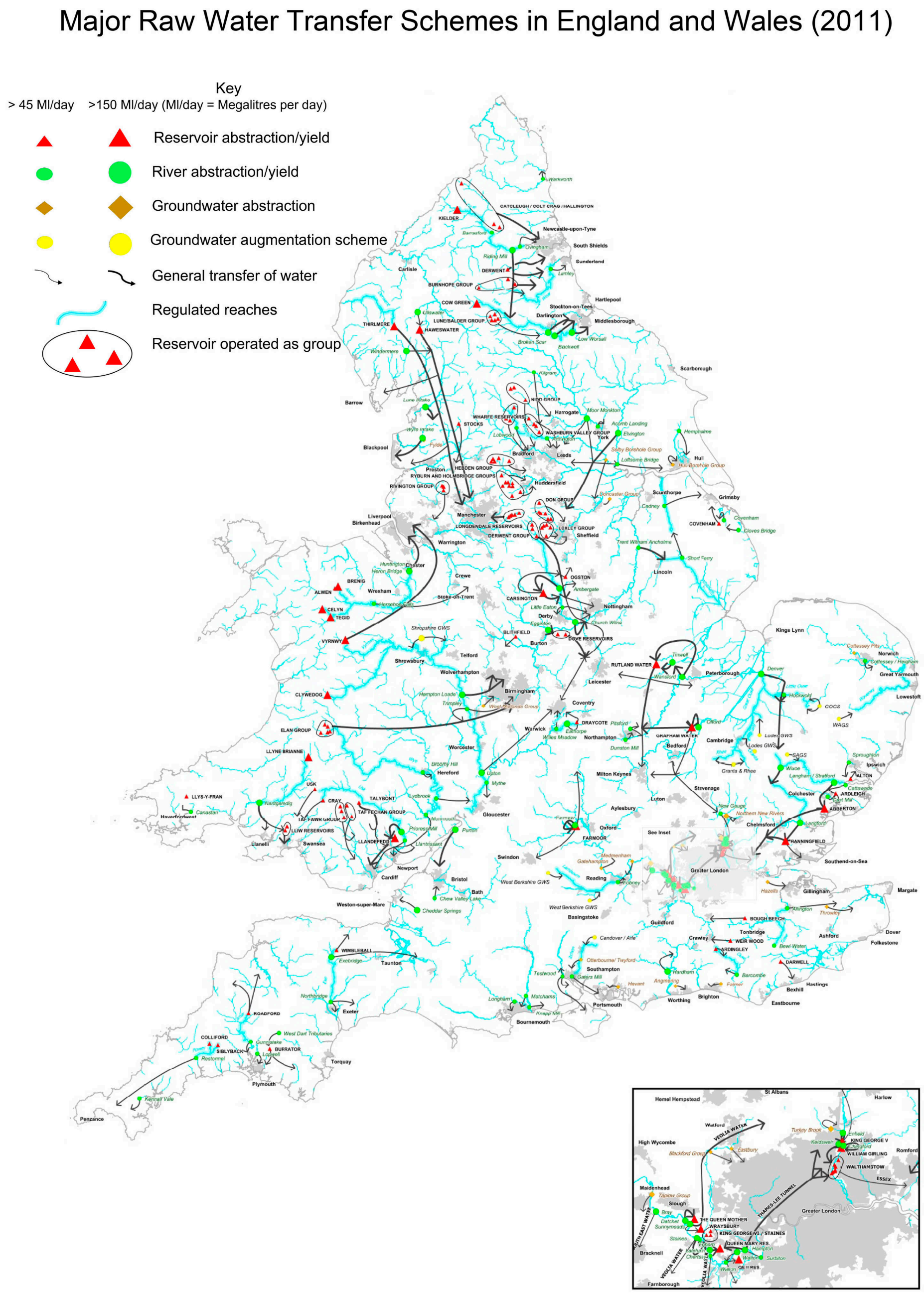

Figure 1. A schematic of "major" RWTs in England and Wales. Produced by Thomas Mackay Ltd on behalf of the Environment Agency. © Environment Agency, 2011. Accessible via https://commons.wikimedia.org/wiki/File:Major_water_transfer_schemes_in_England_and_Wales,_2011.jpg. The schematic is included in the present article with permission from the Environment Agency.

Aim

Given the current lack of knowledge of RWTs as a pathway of freshwater INNS spread, and lack of integration of RWTs within management strategies, we aim to raise awareness of RWTs as a major pathway of invasion in England and Wales specifically, but stress the wider relevance to other nations.

We therefore 1) present novel information on a subset of RWT schemes in England and Wales to illustrate the scale and relevance of the pathway (Figure 1) 2) discuss the direct implications of RWTs for INNS management and surveillance programmes 3) discuss key barriers to knowledge exchange

Table 1. Summarising the level of RWTs knowledge and awareness in Regional Invasive Species Management Plans (RIMPs) published in 2018. All RIMPs accessed via https://www.nonnativespecies.org/local-action-groups-lags/rapid-life-project/.

RIMP	Explicit reference to RWTs as a defined pathway	Reference to Water company as stakeholders of the RWT pathway	Details on RWTs	Other relevant information
North	Yes	"utility companies"	No	Reference to requirements for companies to put mitigation measures, mentions changes to routing or abstraction times.
East	No	Water companies listed as a general stakeholder, however not in direct relation to RWTs	Mention of Trent, Witham Ancholme transfer scheme, only in relation to management of water levels	No
Midlands	No – "waterway network"	No - Canal and Rivers Trusts/ EA/ Defra/ Natural England / British Canoeing mentioned in relation to waterway network. Water companies mentioned as stakeholders for awareness and education only.	No	No
South East	No	No	No	No
South West	No	No – water companies Water companies mentioned as stakeholders for awareness and education only		

and provide evidence of limited pathway awareness (Table 1) 4) provide recommendations for improving information access in support of achieving national INNS management targets (Table 2).

RWTs in Great Britain

Responsibility for water resource management varies between counties globally, though RWTs are typically managed by private water companies or local/central government (Speight 2015; Bosch et al. 2021; Zhu et al. 2023). In England, the majority of RWT schemes are owned/operated by private water companies. The Environment Agency (EA) also control a number of RWTs, and are the government agency responsible for environmental regulation of water companies. In Scotland, Scottish Water is the single publicly-owned government body responsible for water resource management nationally and is regulated by the Scottish Environmental Protection Agency (SEPA) (House of Commons 2022). Wales have a similar model to Scotland, where the not-for-profit water company Dŵr Cymru is regulated by Natural Resources Wales (NRW).

The extensive network of navigable canals (also known as waterways) in England and Wales, owned by the Canal and Rivers Trust (CRT), can also interact with water transfer schemes by acting as a donor or recipient waterbody, or a conduit for the downstream movement of transferred water. This can allow the active introduction of species to areas which would naturally be inaccessible via autonomous species movement through adjoining navigable canals. The CRT is currently funded by the Department for Food,

Table 2. Summarising the key recommendations for integrating RWTs within freshwater surveillance and management programmes.

Recommendations	Stakeholder responsible	Outcome
Clearer delineation of publicly accessible water bodies from 'critical national infrastructure'	Environmental regulators and other policy departments across GB	Facilitate improved information access for INNS stakeholders.
Improved RWT information synthesis, to provide a comprehensive national overview of the pathway - should include RWTs <45 Ml/day, location of all donor and recipient waterbodies, entry points, water volume and frequency of use.	Environmental regulators, water resource managers, research bodies e.g. UKWIR	Provide greater insight to pathway scale and activity. Support a better understanding of the potential impact of the RWT on INNS dispersal at various scales.
Increased levels of RWT information sharing with LAGs, catchment partnerships	EA/Water companies	Facilities co-ordinated INNS management and surveillance programmes
Integrate RWTS within surveillance and management programmes, particularly in relation to areas of high recreational use or ecological importance	INNS community including LAGs, catchment partnerships, environmental regulators, water resource managers	Support the containment and eradication of INNS.
Account for RWTs within academic research activities	Academic researchers and their collaborators	Improved predictions of INNS/disease spread, modelling of habitat and restoration mapping, pollution modelling, increase accuracy of sediment fingerprint etc.
Account for potential influence of RWTs within sampling investigations using environmental DNA (eDNA)	Environmental regulators, water resource managers, INNS community	Potential to improve the validity of species detections and assessments of population sizes.

Environment and Rural Affairs (Defra), following a transfer of assets from The British Waterways Board to the CRT in 2012 (Statutory instrument 2012/1659, 2012). Unlike water company/EA RWTs which are present across England and Wales, CRT-managed water transfers are relatively few and only occur in specific locations (navigable canal sites), and do not appear to cross large distances underground; though the extent to which CRT transfers operate is unclear. Importantly, there are no comparable pathway management requirements for CRT assets. Water company/EA operated RWTs and the associated management policies are therefore the focus of the current work.

The EA possess an up-to-date schematic (2020) of water industry RWTs in England and Wales. Unfortunately, as the water supply network is considered part of "Critical National Infrastructure" (UK Department for Business and Trade 2023), it is not possible to present this publicly (EA personal comms. Nov 2021). Comparative information for Scotland could not be found.

An earlier schematic (2011) has recently been published online (Wikimedia) following a Freedom of Information request and can therefore be included in the current article with permission (Figure 1). It illustrates the general location and water flow direction of "major" RWTs in England and Wales, defined as those which transfer volumes over 45 million litres per day (Ml/day).

The schematic depicts approximately 110 surface water transfers in England and Wales which can transfer between 45–150 Ml/d, around 43 of which cross one or more catchment boundary (39%) (Supplementary material Figure S1), and five cross river basins (Figure S2). Approximately 52 RWTs transfer over 150 Ml/day, around 23 of which cross one or more catchment boundary (44%), and eight which cross river basins. There are also approximately 16 RWTs for which either the donor or recipient waterbody straddles a river basin boundary, which makes it difficult to accurately determine if these are inter or intra-basin transfers. Transfers from ground water sources have not been included in this count.

In England and Wales, very few studies investigating species dispersal via RWT have been conducted owing to low pathway awareness, though there is evidence of invasive zander fish (*Sander lucioperca* (Linnaeus, 1758) and zebra mussels (*Dreissena polymorpha* (Pallas, 1771)) introduction into new regions via RWT pipelines (Linfield 1984; Boon 1988; Copp and Wade 2006), in addition to several native species of fish, invertebrates and microorganisms (National Rivers Authority 1992, 1994a, b; Archer and Gibbins 1995; Snaddon et al. 1998; Gibbins et al. 2000). It is therefore reasonable to conclude that analogous invasive species can also be dispersed.

RWT management Great Britain

In 2017 the EA introduced requirements for RWT management in England (EA 2021, 2022). Accordingly, pathway stakeholders must take steps to risk assess existing RWTs and mitigate spread through "high risk" RWTs. Management measures must also be integrated within any newly created RWTs that will connect otherwise hydrologically unconnected catchments. In Scotland, the Scottish Environmental Protection Agency released a similar Position Statement in 2022 (SEPA 2022). In Wales, water resource managers are only required to risk assess RWTs and discuss implications with NRW on a case-by-case basis. Currently there does not appear to be an explicit mandate for management, unless a RWT crosses the border to England (Natural Resources Wales 2017, 2020, 2023).

To our knowledge, these are the first specific RWT management policies enacted globally (Miller et al. 2006; Shine 2007; Perrings et al. 2010; Hulme 2015) and represent a relatively rare and very positive step for the management of pathways not directly linked to animal and plant health (Essl et al. 2015).

Despite these regulatory advances and the active engagement of many water companies to meet the requirements (pers comms. several water companies), effective management will take some time to implement as it poses a significant technological, logistical, and financial challenge. RWT schemes are large and complex systems of infrastructure which supply water to habitats and ultimately to humans. Management technologies must therefore remove organisms from extremely large volumes of (typically flowing) water, whilst not undermining water quality or impeding water supply. No such proven measures currently exist, and the efficacy of any future methods is yet to be determined. Importantly, even when implementation has been completed under the current mandate, not all RWTs will be managed. Only schemes deemed to pose a "high risk", or those that create a new connection with a previously unconnected catchment will be managed. Existing "low risk" RWTs, and some new RWTs, will still pose a risk of introducing organisms to waterbodies that would be otherwise inaccessible.

Pinpointing the pathway responsible for spread and determining the relative importance of different pathways is often difficult (García-Berthou et al. 2005; Smith et al. 2020). However, given the evidence of diverse taxa spread through RWTs worldwide (Ellender and Weyl 2014; Liu et al. 2017), the national RWT network is likely to significantly influence INNS dispersal at multiple scales. A key challenge for the INNS management community will therefore be how to include the pathway within comprehensive management and surveillance strategies, and how to contend with RWT mediated spread at catchment, river-basin and regional scales.

Implications for collaborative management

Catchment wide partnerships and regional stakeholder collaborations form a key strategy for aquatic INNS management (Defra 2013; Lambin et al. 2020; EA 2021, 2022). Efforts to improve catchment-scale stakeholder co-ordination have precipitated various partnerships and national strategies in England, notably the EU LIFE funded Regional INNS Management Action Plans (RIMPs), developed by the "Reducing and Preventing Alien Species Dispersal" project. This comprehensive approach divides England in to 5 large management regions: North, East, Midlands, Southeast and Southwest (Figure 2) and aims to form a link between high-level national INNS strategies and the co-ordinated action of regional stakeholders and Local Action Groups (LAGs) (RAPID 2020; Defra 2023). LAGs are an invaluable management and knowledge resource, and carry out a significant proportion of practical INNS management within GB using well-coordinated catchment-based approaches (Defra 2023).

Despite the substantial number of RWTs present within individual RIMP regions (Figure S3), and high-level of effort and stakeholder expertise involved in development (which includes water companies and the EA), references to the RWT pathway are limited and inconsistent between regions. Only one RIMP (North) contained a clear reference to RWTs as an invasion pathway, and the requirement for management by stakeholders (Table 1). Three RIMPs (East, Midlands and Southwest) contained no mention of RWTs or water companies as a pathway stakeholder, except in reference to their role in promoting education and awareness for vector-based recreational pathways. The Southeast plan contained no references to RWTs or water companies in any capacity. No RIMPs identified the Environment Agency as a pathway stakeholder, in their capacity as RWT owners or as environmental regulators. Limited reference to RWTs within RIMPs does not preclude local knowledge and awareness of the pathway, though it does strongly suggest that RWT information sharing between stakeholder groups is low. Crucially, it demonstrates that RWTs are unlikely

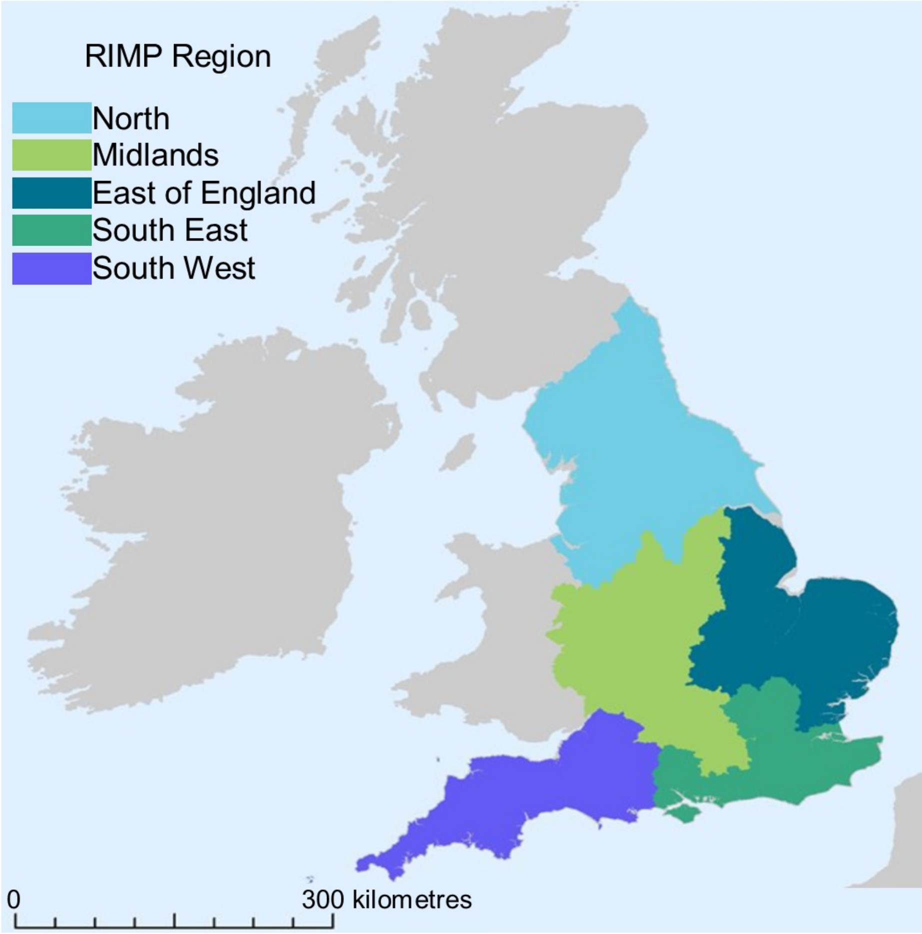

Figure 2. Map showing the five regions in England for which regional invasive species management plans (RIMPs) were developed. Original map accessed via https://www.nonnativespecies.org/local-action-groups-lags/rapid-life-project/.

to be considered within current regional freshwater INNS management and surveillance programmes.

It is worth noting that the RIMPs were created in 2018, only a year following the EA's management policy introduction. If renewed today it is possible that RWTs would feature more widely. Though as RWTs do not appear in the Defra GB strategy 2023–2030, and key information barriers remain, it is likely that awareness levels would be equally low.

We stress that this analysis is not intended to criticise the efforts of those involved in RIMP development – these documents have been diligently prepared and are extremely useful. The limited reference to RWTs likely reflects the limited information sharing beyond the water industry and regulatory spheres, and the perception that RWTs will be managed by pathway stakeholders *in silo*.

Implications for INNS containment and eradication

Species containment and rapid removal responses may be challenged by RWTs. In England and Wales the spread of several native fish species via RWT infrastructure has been documented (National Rivers Authority 1992, 1994a, b). Invasive zander spread has also been linked to several RWT pipelines (Linfield 1984; Boon 1988; Copp and Wade 2006). Invasive fish spread has similarly been documented in China (Qin et al. 2019; Jiao et al. 2021), South Africa (Laurenson and Hocutt 1986; Snaddon et al. 1999; Kadye and Booth 2012; Ellender and Weyl 2014), Australia (Todd 2002) and Brazil (Silva et al. 2020; Gutierre et al. 2023).

Given the significant ecological impacts associated with invasive fish (Copp et al. 2017), RWT-related fish spread may be of particular concern for the INNS community, and a factor for consideration within management prioritization exercises (Kimberg et al. 2014; McGeoch et al. 2016).

Strategic eradication efforts may also be undermined by repeated introduction of target INNS following removal. Catchment-wide efforts to remove an aquatic plant may follow best practice by starting at the head of the catchment/river and working downwards. However, if a RWT occurs upstream of removal sites, from a donor waterbody which also contains the target species, there is a high risk of re-introduction. The re-establishment of water hyacinth (*Pontederia crassipes,* Mart. Solms) introduced through an inter-basin RWT pipeline following local eradication has been observed in South Africa (Jones 2014).

The survival potential of different taxa may vary according to the type of RWT scheme – whether water is mechanically pumped under high pressure generated by pumping stations, (Schmidt et al. 2020; van Esch 2012) or if water is moved by gravity. As some invasive plant species can propagate from a small fragment or seed (D'hondt et al. 2016) the risk of plant dispersal through most types of RWTs is likely high (Liu et al. 2017). Given the significant impact of aquatic plants on ecological processes and human activities, plant management is a key target for LAGs and catchment partnerships, and a core aim of national INNS strategies. Assessing donor waterbodies for inclusion within local plant eradication strategies may therefore be a factor for consideration.

Small-bodied invertebrate species are also susceptible to dispersal, as evidenced by the introduction of the livestock pest *Simulium chutteri* (Lewis) through RWT pipelines in South Africa (O'Keeffe and De Moor 1988). Bivalve molluscs with robust shells are a particularly high risk for spread through various types of RWT, as evidenced by invasive mussel dispersal in RWT pipelines in the UK (Boon 1998) and US (Stockton-Fiti et al. 2023), and golden mussel (*Limnoperna fortunei* Dunker, 1857) spread throughout various RWT tunnels and pipelines in China (Zhang et al. 2017; Wang et al. 2023; Guo et al. 2024).

Spatial Implications for INNS surveillance

Developing surveillance strategies for high-risk pathways and INNS is a key aim of the GB INNS strategy (Defra 2023). Optimising surveillance for multiple taxa across numerous waterbodies at large spatial scales is challenging and costly (Cacho et al. 2010), hence strategies may employ a risk-based approach by choosing sites which are geographically close to known invaded areas (Perry et al. 2017; Koch et al. 2020), or with a high density of recreational pathways (Chapman et al. 2019). As illustrated in Figure 1, RWTs can create hydrological connections between waterbodies across significant distances. This presents an issue for the spatial scale at which surveillance is considered, and the level of cross-catchment co-ordination required. Whilst waterbodies near to known sites of invasion remain high priorities for surveillance, monitoring of sites linked to invaded areas by RWT would also be beneficial. Such sites may be further away than those typically considered, in other catchments or river basins.

Surveillance in the context of RWT networks may consider a waterbody which donates to multiple other waterbodies as a high priority target for surveillance (Kvistad et al. 2019; Yemshanov et al. 2015; Muirhead and MacIsaac 2005), particularly if this also supports recreational pathways. A waterbody which receives water from numerous sources may also be a surveillance priority, owing to the increased potential for INNS accumulation.

Implications for eDNA surveillance

Environmental DNA (eDNA) surveys are commonly used to detect aquatic INNS, and are promoted by environmental regulators in England (Barnes and Turner 2016; Hänfling et al. 2016; Mauvisseau et al. 2018; EA 2021; Schenekar 2022). Downstream transport of eDNA is a key factor for consideration, as species detection may occur in the absence of a local population - the eDNA of some aquatic species can be detected over 10 km downstream from the source population (Deiner and Altermatt 2014; Jo and Yamanaka 2022).

The water volume moved by some RWTs is so large that the majority of water flow in a recipient waterbody can originate from the hydrologically separate donor water body (Holmes and Whitton 1972; Dynesius and Nilsson 1994; Snaddon et al. 1998). RWTs may therefore cause positive detections of INNS that are not present or established in the target waterbody. eDNA metabarcoding techniques are also increasingly being used to estimate population size (Carraro et al 2018; Sint et al. 2021). Where target species are present both in donor and recipient habitats, artificial eDNA input may lead to overestimations of population size. Conversely, the removal of large volumes of water may lead to underestimations of population size at donor sites.

Further research is needed to understand the impact of RWTs on eDNA surveys. However, future surveillance programmes may consider whether a waterbody of interest is hydrologically linked to another by RWT, and increase the accuracy of assessments by avoiding sampling immediately downstream of water input points, or sampling both the donor and recipient waterbody.

Improving RWT information synthesis

Publicly available documents from the National Rivers Authority, the forerunner of the EA, (National Rivers Authority 1990, 1992, 1994a, b; Davies and Gee 1993;), and from the contemporary EA, contain references to RWTs in England and Wales (EA 1996; 2010). Additionally, water companies are required to publish Water Resource Management Plans every five years – these documents refer to some RWTs, the general locations of donor and recipient bodies, and transfer volumes (for examples see United Utilities 2019; Severn Trent Water 2022). Scientific publications detailing a small number of transfers in England are also available (Archer and Gibbins 1995; Gibbins et al. 2000; McCulloch 2006; Copp and Wade 2006; Khadem et al. 2021).

Taken together these documents provide a limited account of some RWTs in England and Wales, though we understand that no comprehensive RWT database currently exists. The 2011 RWT schematic (Figure 1) and the updated (2020) version provide the most detailed overview of RWTs in England and Wales at present, though only the 2011 version is publicly available. No comparable document was found for Scotland.

Whilst the 2011 schematic broadly illustrates the scale and prevalence of the RWT pathway in England and Wales, it is insufficient for supporting decision making by the INNS management community. Firstly, transfers below 45 Ml/day are unrepresented. Within just the Northumbrian Water region, there are over 10 < 45 Ml/day RWTs in operation (Northumbrian Water *personal comms*). This is also likely to be to be the case within other company operating regions. Lower volume RWTs still present a significant invasion risk – just 20 Ml/day equates to the repeated transfer of 8 Olympic-sized swimming pools per day. In the context of marine ballast water, 20 Ml is considered a high introduction risk (Seebens et al. 2013).

Secondly, many individual reservoirs have been classed as "operating in groups", and any RWT infrastructure linking the reservoirs is not shown. As hubs of recreational activity (including angling for purposefully introduced non-native fish), and highly disturbed environments which can favour invaders (Havel et al. 2005; Agostinho 2010, 2016), reservoirs and their connectivity are important for INNS management.

The exclusion of < 45 Ml/day RWTs and the grouping of reservoirs may be a consequence of the schematic being produced within the context of water resource management, rather than with the explicit intent to map the RWT invasion pathway. Without this information however, it is not possible to understand the true prevalence and scale of the pathway, or to account for RWTs within management plans.

Comprehensive RWT data synthesis, such as the work of Siddick et al. (2023) in North America, is therefore recommended. In collaboration with local, state and federal partners, the authors produced an accessible database of 612 inter-basin RWTs, including the location of donor and recipient waterbodies, the type of RWT infrastructure, purpose, and transfer frequency. This dataset appears to be the most comprehensive publicly available national dataset on RWTs worldwide.

We recommend that environmental regulators and water resource managers across GB take steps to map national RWT network in detail, including both *inter* and *intra* catchment transfers. Incorporating CRT transfer infrastructure is also recommended. Indeed, the statutory requirement for river basin planning enshrined in England and Wales by The Water Environment (Water Framework Directive (England and Wales) Regulations 2017) and the Water Environment and Water Services (Scotland) Act 2003 (WEWS Act) may warrant this work.

Improving awareness and information access

The UK Department for Business and Trade (2023) currently regards water supply infrastructure as "critical national infrastructure", as damage to it could cause widespread disruption to essential public services. Including all RWT infrastructure within this category is excessive – information concerning water treatment works, treated water supply pipelines and treated water reservoirs should clearly not be published. However, information on the publicly accessible rivers, reservoirs, artificial watercourses, and the general location of connecting infrastructure would support improved decision making within integrated management and surveillance strategies (Simpson et al. 2009; Mauser et al. 2013; Moon et al. 2015). Indeed, accessing relevant information is a key facet of democratic decision making for environmental governance (Singh and Singh 2006; Fontaine et al. 2022), as the retention of information by private businesses can lead to an erosion of public knowledge and limit research progress (Ylönen and Kuusela 2018).

Encouragingly, the need for greater collaboration and public information sharing to support improved decision making and community partnerships has already been identified within the UK Water Innovation Strategy 2050, a collaborative plan for long-term innovation developed in 2020 by all UK water companies, alongside UK Water Industry Research and Water UK (UK 2050 Water Innovation Strategy 2020).

Similarly, an industry-wide move to share data on elements of "sensitive" water company infrastructure is currently underway in the UK. The Geospatial Commission is working with the owners of underground pipes and cables within the water, power and telecoms sectors to produce a National Underground Asset Register (NUAR), which will be available to external contractors working with water companies. A similar scheme is in place in Scotland, called 'Vault' (Geospatial Commission 2023). These initiatives demonstrate the increasing need for access to water sector data for strategy development, and that sharing information responsibly is possible.

Regulators clearly have a key role in facilitating information synthesis and accessibility, though are only one part of the complex landscape of environmental policy, politics and industry in which RWTs operate (Gupta and vander Zaag 2008; Sinha et al. 2020). In the absence of a comprehensive national database, it may fall to regional water resource managers to share relevant information directly with their local LAGs and catchment partnerships. In turn, this collaborative approach is likely to yield positive benefits for decision making and environmental conservation in a wider context, and improve stakeholder engagement (Moon et al. 2015; Maggs et al. 2019; Ricciardi et al. 2020).

Conclusions

RWTs are a high-risk pathway of INNS spread in the UK and worldwide, and present a unique challenge for direct pathway management, and the management and surveillance of freshwater INNS more broadly.

Recent policy advances in and England and Scotland are extremely positive and represent a first of their kind. However, given the inherent difficulties in managing the large number of RWTs that already exist, and the on-going work to create more RWTs to ensure future water resource availability, more widespread understanding and collaborative action is needed. Particularly as not all RWTs will be subject to management under the current policies.

Whilst public awareness and education are typically integral to INNS control strategies (Melly and Hanrahan 2020), for RWT management this has not been the case, and awareness of the pathway in the INNS community remains low.

The key challenge going forward therefore will be how to resolve the issues regarding data access, and addressing how the patchwork of policy makers and water resource managers across GB work cooperatively with the INNS community.

Creating a system in which RWTs can be incorporated into multilateral management and surveillance programmes will contribute significantly to the achievement of national and international INNS management targets, and will support the conservation of freshwater biodiversity in a rapidly changing world.

Authors' contribution

Ava Waine conceptualized this research and wrote the original draft, Peter Robertson and Zarah Pattison contributed to reviewing the manuscript.

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Supplementary material

The following supplementary material is available for this article:

Figure S1. Raw water transfer schematic overlaid with a map of catchment boundaries.
Figure S2. Raw water transfer schematic overlaid with a map of river basin boundaries.
Figure S3. Raw water transfer schematic overlaid with a map of Regional Invasive Species Management Plan (RIMP) areas.

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